Pit lakes: their characteristics and the potential for their remediation

J.M. Castro · J.N. Moore

Abstract Pit lakes form when open-pit mining operations are discontinued and dewatering ceases. The increase in open-pit metal mining since the 1970s will lead to the formation of numerous pit lakes over the next 50 years. Many of these lakes will develop acid sulfate conditions with high levels of dissolved metals. Approaches to remediation of these conditions that have been recommended include the addition of lime or other alkaline materials and the stimulation of sulfate-reducing bacteria. However, prevention rather than remediation is probably the preferable approach. Measures to prevent oxidation of mining waste and wall rocks, including measures to fill pits quickly with water, to inhibit the activity of acidophilic sulfur-oxidizing bacteria, and to promote anoxic conditions at the lake bottoms may minimize the formation of acids and dissolved metals.

Key words Mine · Pit lake · Geochemistry · Remediation

Introduction

Pit lakes form when open-pit mining operations are discontinued or abandoned. The pits usually fill with water, most commonly by inflow of groundwater and by runoff from adjacent drainage basins. During the first half of the twentieth century, most pit lakes in North America resulted from coal mining. With the introduction of high-powered steam shovels in 1911, the surface mining industry became a major source of coal in the United States (Gibb and Evans 1978). These mining operations left hundreds of pit lakes in the Appalachians and the Midwest. Since the enactment of the Surface Mining Control and Reclamation Act, the formation of coal pit lakes in the United States has virtually stopped (while the law does not specifically prohibit creating surface impoundments at coal mines, the circumstances under which they are permitted are limited). However, elsewhere in the world, coal pit lakes are still allowed and are sometimes considered desirable. For example, in recent years pit lakes have been deliberately constructed at coal-mining sites in Canada (Sumer and others 1995) and Germany (Bilkenroth 1993) to serve as fish and wildlife habitat and for recreational use.

Currently, the most concern in North America and elsewhere has been generated by pit lakes formed as results of mining for metal ores, especially sulfide ores. Relatively stable gold prices since the late 1970s and new mining methods have led to a large increase in open-pit gold mining, and open-pit mining of silver, uranium, and base metals is also widespread (Miller and others 1996). These mining operations will result in the creation of numerous new pit lakes during the next 50 years (Macdonald and others 1994). There are currently 86 major open-pit mining operations in the United States extracting precious metals and/or base metals other than iron or aluminum, 19 in Canada, 74 in Australia, and 37 in Chile (Anonymous 1999). Other countries with substantial numbers of open-pit metal mines are Brazil, Peru, Mexico, Indonesia, the Philippines, and Papua New Guinea (Anonymous 1999). Intensive gold exploration in West Africa (Anonymous 1997; Chadwick 1997) will likely lead to a large number of future open-pit mines in that region. Another area that will probably see a large increase in open-pit mining is Kazakhstan, where in 1995 the government opened up 75 metal-industry projects to foreign companies (Dorian 1997). Except for those in the most arid areas, most open-pit mines are expected to develop pit lakes when mining operations end. In Nevada alone, more than 30 such lakes are expected to form within 20 years, roughly quadrupling the number of pit lakes in the state; when filled, these new lakes will contain over 1.2×10^9 m^3 of water (Miller and others 1996). Given the large number of pit lakes that will form worldwide during the next half century and the large volume of water they will contain, the quality of the water in these lakes

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will be of profound importance, especially in areas with scarce water resources. Solutes are released into lake water by weathering of the wall rocks and of other exposed rocks in the surrounding drainage. A common situation is the one found in lakes like the ones in the Berkeley Pit in Montana (Davis and Ashenberg 1989), the Liberty Pit in Nevada (Bird and others 1994), or the Spenceville Pit in California (Levy and others 1996). These lakes are quite acidic ($pH < 3$), and their acidity is aggravated by toxic concentrations of one or more heavy metals.

Characteristics of pit lakes

Pit lakes differ physically from natural lakes in having markedly higher relative depths. Percent relative depth is defined in terms of a lake's maximum depth, z_m, and its width, d. Assuming an approximately circular lake, the width is a function of surface area, A_0:

$$d = 2\sqrt{\frac{A_0}{\pi}} \tag{1}$$

The percent relative depth, RD, is then defined as follows:

$$RD = \frac{z_M}{d} \times 100\% = 50\, z_m \sqrt{\frac{\pi}{A_0}} \tag{2}$$

A typical natural lake has a relative depth of less than 2%, although some may exceed 5%. Pit lakes commonly have relative depths between 10 and 40% (Doyle and Runnells 1997). This causes pit lakes to become stratified in many cases, and the chemical characteristics of the lake water can vary greatly with depth. Total dissolved solids and electrolytic conductivity tend to increase with depth; values near the bottom are often several times those at the surface. The hypolimnion (lower stratum) of a stratified lake has the tendency to lose dissolved oxygen if enough organic matter is present. The existence of a suboxic or anoxic layer in a pit lake can have significant effects on the lake's chemical and biological characteristics and thus on its potential for remediation. Tables 1 and 2 list depth profiles of key chemical parameters for two pit lakes – one of the world's largest (the Berkeley Pit) and a smaller one.

Table 1
Variations in lake water with depth, Berkeley Pit, Butte, MT. (Davis and Ashenberg 1989; Doyle and Runnells 1997)

Percent of lake depth (depth ≈ 250 m)	0% (Surface)	25%	50%
pH	2.7	3.2	3.2
Sulfate (mg/l)	4200	7000	6800
Al^{3+} (mg/l)	135	190	200
Fe^{2+} (mg/l)	0	900	960
Cu^{2+} (mg/l)	130	200	200
As (III) (μg/l)	0	60	100
As (V) (μg/l)	0	550	800
Electrolytic conductivity (dS/m)	4.2	7.1	7.1

Table 2
Variations in lake water with depth, Summer Camp Pit, Getchell, NV, June 1996. (Source: J. Castro, J. Gannon, T. DeLuca, J. Moore, unpublished data)

Percent of lake depth (depth ≈ 18 m)	5%	45%	80%
pH	8.6	7.5	6.1
Dissolved O_2 (mg/l)	7.3	4.2	1.0
As (mg/l)	10.8	4.7	5.4
Fe (mg/l)	0.03	0.08	154
Mn (mg/l)	0.04	0.48	1.04
Electrolytic conductivity (dS/m)	1.1	1.2	2.6

Many pit lakes contain high levels of acid, sulfate, and dissolved metals. A lake's chemical characteristics depend on the alkalinity of the local groundwater, the composition of the wall rocks, the chemistry of the surrounding vadose zone, and the quality and quantity of runoff from the surrounding land (Plumlee and others 1992; Davis and others 1993; Bird and others 1994). Rock that is exposed to oxidizing conditions during dewatering can be a major source of acid, even though it lies below the water table before mining operations begin and after the lake fills (Miller and others 1996).

Sources of acid and dissolved solids

The presence of reduced minerals in the area draining into a pit lake is a key contributor to the development of acid sulfate water in the lake. Abandoned bauxite mines may develop lakes, but the pervasively oxidized and leached host rock will generally not contribute acids to the water. Similarly, many iron ore deposits are heavily oxidized, and their host rocks will not release acids into the water. On the other hand, host rocks containing deposits of sulfide ores, gold, and high-sulfur coal tend to be in a reduced state and frequently contain accessory sulfide minerals. These rocks can act as sources of acid sulfate water.

Oxidation of the sulfide ion (S^{2-}) does not by itself produce acid. Depending on the other elements present in a sulfide mineral, its oxidation may be a base-producing, neutral, or acid-producing reaction. For example, oxidation of chalcocite [Eq. (3)] consumes acid, while arsenopyrite oxidation produces the weak arsenous acid [Eq. (4)], and pyrrhotite oxidation is a neutral reaction [Eq. (5)].

$$Cu_2S + 2\frac{1}{2}\,O_2 + 2H^+ \rightarrow 2\,Cu^+ + SO_4^{2-} + H_2O \quad (3)$$

$$2\,FeAsS + 5\frac{1}{2}\,O_2 + 3\,H_2O \rightarrow 2\,Fe^{2+} + 2\,H_3AsO_3 + 2\,SO_4^{2-} \quad (4)$$

$$FeS + 2\,O_2 \rightarrow Fe^{2+} + SO_4^{2-} \quad (5)$$

However, oxidation of disulfide (S_2^{2-}), the anion in pyrite and marcasite, does produce acid.

$$FeS_2 + 3\frac{1}{2}\,O_2 + 3\,H_2O \rightarrow Fe^{2+} + 2\,SO_4^{2-} + 2\,H^+ \quad (6)$$

Oxidation of iron (II) also produces acid under most pH conditions by the hydrolysis of Fe^{3+} cations.

$$2\,Fe^{2+} + \frac{1}{2}\,O_2 + 5\,H_2O \rightarrow 2\,Fe(OH)_3 + 4\,H^+ \quad (7)$$

If the combined effects of oxidation of disulfide and of iron (II) are considered, it may be seen that oxidizing 1 mol of pyrite produces 4 mol of acid.

$$2\,FeS_2 + 7\frac{1}{2}\,O_2 + 7\,H_2O \rightarrow 2\,Fe(OH)_3 + 4\,SO_4^{2-} + 8\,H^+ \quad (8)$$

Considering pyrite's ubiquity in reduced rocks and its high acid-producing potential, it is evident that a large portion of the acid in pit lakes is a product of pyrite oxidation (Nordstrom and Alpers 1997).

Pyrite oxidation is greatly accelerated by the activity of bacteria of the *Thiobacillus* and *Ferrobacillus* genera, which promote oxidation of both iron and sulfur (Tuttle and others 1968). These bacteria are acidophilic; several species, e.g., *T. ferrooxidans*, are most active at pH values between 2 and 3.5 (Kleinmann and others 1981; Tate 1995). Thus abiotic pyrite oxidation may proceed slowly for some time until it produces enough acid to stimulate *Thiobacilli*. At that point the rate of oxidation – and acid production – can accelerate by up to three orders of magnitude (Nordstrom and Alpers 1997).

Another factor that accelerates pyrite oxidation is its exothermic character; the standard heat of reaction (ΔH^0) is –349.2 kcal/mol (Weast 1981). In open piles of waste rock, the heat of oxidation sets up convection cells that draw in fresh air from the bottoms of the piles, commonly producing steam vents near the tops of waste rock dumps (Schafer 1992).

Other acid-producing reactions include hydration of arsenic (III) and (V) following oxidation of arsenic-bearing minerals [Eq. (4)] and hydrolysis of transition metal anions at near-neutral pH [Eqs. (9) and (10)].

$$Cu^{2+} + H_2O \rightarrow CuOH^+ + H^+ \quad (9)$$

$$CuOH^+ + H_2O \rightarrow Cu(OH)_2 + H^+ \quad (10)$$

While sulfide minerals other than pyrite are not major sources of acids, they are a major source of dissolved metals in acidic pit lakes. Other metal sources include minerals that react with the acid in the water, such as carbonates, oxyhydroxides, and silicates (Macdonald and others 1994). As mentioned above, a common situation is the one found in the Berkeley, Liberty, and Spenceville Pits, where the water is very acidic and contains toxic concentrations of heavy metals. Sulfate, generated by oxidation of monosulfides and pyrite, is the dominant anion in most acid mine drainage water, and thus in acidic pit lakes (Nordstrom and Alpers 1997).

Controls on acidity

Despite the prevalence of acidic pit lakes, some are neutral or even alkaline. If a lake is in contact with a source of carbonate [such as limestone or dolomite, a carbonate-cemented sedimentary rock (Davis and Eary 1997), or carbonate veins in an ore body (Silberman and others 1974)], it may neutralize some or all of the acid produced by oxidation of pyrite and other minerals. If enough carbonate is present to neutralize all the acid produced by oxidation, the lake water will be neutral or alkaline (Macdonald and others 1994; Miller and others 1996). It is possible that a lake in host rock containing limited carbonate minerals will remain neutral for some period of time, until the carbonate is depleted, then become acidic as further oxidation of pyrite and other sulfides occurs. Conversely, an inflow of alkaline groundwater may eventually neutralize an initially acidic lake (Miller and others 1996).

In near-neutral pit lakes, bicarbonate is the principal species influencing the pH of the water (Campbell and Lind 1969), which will generally be above 6 (Brugam and others 1983). In some cases, hydrolysis of transition metals such as iron (II), copper, and zinc can also serve to buffer pH near 7 (Nordstrom and Alpers 1997). In acidic pit lakes, the main buffering system is that of hydrated aluminum, which maintains the pH below 4.5 (Brugam and others 1983). At very low pH (≤ 2), hydrated ferric ion and bisulfate also function as important buffers (Nordstrom and Alpers 1997). Pit lakes with pH between 4.5 and 6.0 are relatively rare because in most cases there is no effective buffer system in that range (Brugam and others 1983).

Although acid is often considered the primary water-quality problem in pit lakes, sulfate and dissolved metals and metalloids also can pose serious problems, even in neutral lakes. The secondary USEPA drinking water standard for sulfate allows a maximum concentration of 250 mg/l, which is exceeded by an order of magnitude in many pit lakes (Miller and others 1996). Essential nutrient metals such as iron, copper, manganese, zinc, and cobalt, as well as nonessential elements such as lead, cadmium, arsenic, and mercury in pit lake water can exceed concentrations safe for aquatic life or domestic, industrial, or agricultural use (Pillard and others 1996). Arsenic can be an especially troublesome contaminant in many cases as it is quite soluble at neutral or alkaline pH and toxic to humans and wildlife at concentrations well below 1 mg/l. An example of a neutral lake contaminated by arsenic was the Summer Camp Pit at Getchell, Nevada. Because of carbonate wall rocks, the water in this pit was nearly neutral, but it typically contained arsenic at levels between 1 and 5 mg/l (Castro and others 1999; cf. the USEPA maximum contaminant level for arsenic in drinking water, 50 μg/l). High arsenic is common in epithermal and mesothermal gold deposits of the Carlin Trend and related ore bodies in the Basin and Range. Two of the defining properties of a "Carlin-type" gold deposit are carbonate host rock and the presence of arsenic (Guilbert and Park 1986). Thus the water in a pit lake that forms in such a setting is likely to be near pH 7 but contains high concentrations of arsenic.

Yet some pit lakes exist that have good water quality. In some cases the reason is a lack of available sulfide minerals and/or large amounts of carbonate in the host rock. For example, a number of coal pits in Montana, Wyoming, and the Dakotas were investigated by Anderson and Hawkes (1985), who compared the coal-pit water quality to that of bentonite mining pits and livestock watering ponds in the same area. They found no significant differences among the waters from the different sources. Both alkaline ground water and the very low level of sulfur in and around the coal seams were probably responsible for the generally good water quality in the coal pits. Coal from the northern Great Plains averages just 0.6% sulfur, and much of that is in the form of refractory organosulfur compounds (Turbak and others 1979). Another set of coal-mine pit lakes with fair water quality are present in Illinois; some of them contain water that meets drinking water standards. One such lake has been used as a drinking water source by the town of Astoria since 1976 (Gibb and Evans 1978). The wall rock and overburden around most of these lakes contain limestone. The Cortez Pit, a former gold mine in eastern Nevada, also has water good enough to support a thriving bass population (Miller and others 1996). Again, the presence of limestone wall rock probably contributes to this situation.

In a few cases, initially acidic lakes have been neutralized by natural processes. Campbell and Lind (1969) investigated five coal strip-mine lakes in Missouri. Three of the lakes were still acidic 40 years after the end of mining, while the other two had attained neutral pH just 15 years after mining stopped. The acidic lakes received drainage from coal waste piles and had little vegetation around them. The neutral lakes received drainage from forested areas and farmlands. In the absence of continued acid input from mining waste, the latter two lakes had come to resemble natural lakes, with neutral water and mildly eutrophic conditions. The authors suggested that, in the absence of continued acid drainage from waste piles, the acidic lakes would also have become neutralized.

Good water quality in a pit lake is therefore the result of one or more of the following conditions: low pyrite availability, high carbonate availability, and/or plentiful inputs of organic matter and inorganic nutrients. Unfortunately, without substantial preventive or remedial work, these conditions are limited to relatively few pit lakes.

Improvement of pit lake water quality

The conditions that have led to the attainment of good water quality in some pit lakes may point to a way to remediate lakes with poor-quality water. The natural remediation of acidic pit lakes has frequently been due to the activity of dissimilatory sulfate-reducing bacteria (SRB). SRB obtain energy for their growth by coupling the oxidation of organic compounds or hydrogen with the reduction of sulfate to sulfide, thus lowering sulfate concentrations (Widdel 1988; Kerry and others 1991; Barton and Tomei 1995; Tate 1995). If enough reduced iron is present, sulfide will precipitate. The initially formed iron sulfide is usually amorphous FeS, pyrrhotite or mackinawite (approximate compositions FeS), or greigite (Fe_2S_3) (Morse 1995). These sulfides are metastable and eventually convert to one of the disulfides, pyrite or marcasite (FeS_2) (Berner 1970).

The best-known and most widespread sulfate-reducing genera are *Desulfovibrio*, *Desulfotomaculum*, and *Desulfomonas*. Bacteria of these genera are anaerobic heterotrophs, most of which can only utilize a relative handful of organic compounds: lactate, pyruvate, fumarate, malate, acetate, and ethanol (Ehrlich 1996). However, other SRB have been found which can oxidize a variety of organics. One *Archaeglobus* species uses molecular hydrogen (Ehrlich 1996) to reduce sulfate.

Tuttle and others (1969b) suggested remediating bodies of water affected by acidic mine drainage by promoting the activity of SRB. This was successfully demonstrated in field experiments on a small stream in Ohio the same year (Tuttle and others 1969a). In laboratory-scale studies, neutralization of acidic pit-lake water by SRB was demonstrated by Decker and King (1973). Numerous other laboratory studies have demonstrated the application of SRB to acidic mine waters (Wakao and others 1979; Ueki and others 1991; Dvorak and others 1992; Hammack and Edenborn 1992; Kar and others 1992; Béchard and others 1993; Hard and others 1996; Castro and others 1999).

Besides removing acid and soluble sulfates, SRB remove metals from solution by sulfide precipitation. Most transition metals form insoluble sulfides at neutral to mildly acidic pH. Even manganese, which is found in most ore deposits as a carbonate or oxide, can be precipitated as a sulfide under neutral conditions (Decker and King 1973). If conditions suitable for SRB can be established in a pit lake – anoxic conditions and the presence of suitable organic and inorganic nutrients – then it is possible that good water quality may be attained on a time scale of a few months to a few years.

Some workers have advocated simple neutralization of acid lake waters by addition of bases. For example, Rosso (1977) reported successful remediation of five coal pit lakes in Kentucky by application of agricultural limestone to the acid-generating areas (i.e., spoil piles) within the watershed of each lake, to the lakes themselves, or both. Some grading and planting were also done in the watershed areas. The pH values of the lakes before remediation were between 3.3 and 4.3. Within 18 months all had risen to pH 6.7 or higher. It should be pointed out that none of these lakes contained high concentrations of heavy metals other than iron, and only one lake contained high dissolved iron. Sulfate levels before or after the remediation work were not reported. After neutralization the lakes were stocked with channel catfish and largemouth bass, which maintained healthy populations, and also supported large populations of turtles, amphibians, and aquatic invertebrates. Fischer and Guderitz (1996) have advocated the application of lime, caustic soda, and other alkaline materials to the waters and drainages of lignite coal pit lakes in Germany to adjust the pH and precipitate iron. The authors did not address the problem of high sulfate levels in the water.

In contrast to simple base addition, biological reduction of acidic water has the potential to remove sulfate and most transition metals. The requirements for bioremediation include the establishment of anoxic conditions in the lake water; reduction of iron (III) and other oxidizing species; establishment of a pH regime suitable for SRB; and provision of the necessary nutrients for SRB.

Anoxic conditions in a pit lake can most easily be established by the addition of organic materials. A substantial amount of organic matter must be added in order to consume the dissolved oxygen and other oxidizing species, on the order of hundreds of grams carbon per ton of lake water. Therefore, for economic feasibility the added organic matter must be cheap and locally available. Wood sawdust (Tuttle and others 1969a; Wakao and others 1979), spent mushroom compost (Dvorak and others 1992), hay and straw (Béchard and others 1993), partially treated cattle manure (Ueki and others 1991), sewage sludge (Decker and King 1973), and waste potato skins (Castro and others 1999) are among the organic waste materials that have been more or less successfully used in acid mine water remediation.

When dissolved oxygen in water is depleted, anaerobic bacteria begin using other electron acceptors. These are used in order of their electrochemical reduction potentials, from highest to lowest. Manganese (IV) is used first, then nitrate, nitrite, and iron (III), and finally sulfate (Fish 1993). Other redox-active elements that may be present (arsenic, selenium, chromium, etc.) are reduced after species that lie above them in the electrochemical series and before the ones that lie below them. This rule assumes thermodynamic equilibrium, so in cases where kinetics are slow there may be departures from the strict reaction order, but large departures from the rule will be rare.

Several of the reduction reactions consume acid [(Eqs. (11)–(13)]:

$$2\,\mathrm{MnO_2} + \mathrm{C_{org}} + 4\,\mathrm{H^+} \rightarrow \mathrm{CO_2} + 2\,\mathrm{Mn^{2+}} + 2\,\mathrm{H_2O} \qquad (11)$$

$$2\,\mathrm{NO_2^-} + 3\,\mathrm{C_{org}} + 2\,\mathrm{H_2O} + 4\mathrm{H^+} \rightarrow 3\,\mathrm{CO_2} + 2\,\mathrm{NH_4^+} \qquad (12)$$

$$4\,\mathrm{FeOOH} + \mathrm{C_{org}} + 8\,\mathrm{H^+} \rightarrow \mathrm{CO_2} + 4\,\mathrm{Fe^{2+}} + 4\,\mathrm{H_2O} \qquad (13)$$

where C_{org} is organic carbon. Because of the high concentration of iron in most rocks and sediments, iron reduction generally removes the most acid.

When most of the more oxidizing species are consumed, at a redox potential of −75 to −200 mV (Connell and Patrick 1968), SRB are able to begin reducing sulfate, if conditions are otherwise suitable for their activity. Most SRB are not active at pH values less than 5.5 (Tuttle and others 1969a; Dvorak and others 1992), although some sulfate reduction has been reported at pH 4.2 (Connell and Patrick 1968). Some dissolved metals may retard the action of SRB. Ueki and others (1991) reported that the activity of SRB in mine drainage water was almost completely blocked by 1 mM concentrations of nickel, copper, cadmium, mercury, or zinc. Manganese at the same concentration did not retard SRB activity (Ueki and others 1991).

Besides promoting reduction of dissolved oxygen and other oxidizers, the added organic waste must also, directly or indirectly, supply the organic nutrients required by the SRB. This is usually accomplished indirectly by other microorganisms that metabolize the waste matter and excrete the needed nutrients. Enough nitrogen, phosphorus, and trace elements must also be present in the water or supplied by the added waste.

Since the water in coal pit lakes tends to be dominated by iron and sulfate, low pH and lack of organic matter are the main obstacles to establishing SRB activity. In metal-mine pit lakes, however, transition metals may be present in high concentrations and so limit SRB activity. It may be necessary to reduce metal concentrations by other means before the SRB will begin reducing sulfate. One possible approach would be to adjust the pH to ≥6 by adding limestone or another base. This would precipitate many of the transition metals as hydroxides or oxides and simultaneously supply optimum pH conditions for SRB. There would then be a strong probability that addition of organic waste would start sulfate reduction.

An ounce of prevention

Those planning open-pit mining activities can work to prevent the development of acid sulfate conditions in pit lakes if they take into account the conditions that lead to acid generation in pit lakes and those conditions that promote sulfate reduction. Preventive measures are usually much less expensive than remediation.

Grading of the site and covering up of waste rock, tailings, and other sulfidic wastes is a good first step, since much of the acid in pit lakes originates as runoff from waste piles (Decker and King 1973; Rosso 1977). At many metal mines in arid or semiarid areas, there will be little chance of establishing a vegetative ground cover, but preventing water from running over and through wastes may go a long way toward slowing or stopping the formation of acids. Careful diversion of drainage away from waste rock, isolation of reactive waste in the interiors of waste piles, and covering of waste dumps with impermeable clay caps (Decker and King 1973; Rosso 1977; Schafer 1992) are common approaches that would substantially decrease metals and acid loading to pit lakes.

An approach that met with a surprising measure of success at one mine was to fill the pit with water as quickly as possible after mining stopped. This approach acknowledged that most oxidation of host rock takes place while the rock is above the zone of saturation. Once the rock is below the water table, the availability of oxygen is reduced and the rate of oxidation is very slow. When the Enterprise Pit, a gold mine in Australia's Northern Territory, was closed in 1992, a major stream was partially diverted into the pit, making the Enterprise Pit a flow-through lake along the stream's course. After the first wet season the lake was half full, and late in the second wet season it was about two thirds full. The pH of the lake water was 7.2 (Sinclair and Fawcett 1994). The lake is expected to serve as an aquatic habitat and as a water resource for the Pine Creek region.

The apparent success in maintaining good water quality at the Enterprise Pit is consistent with findings in other areas. Pyrite-rich mine tailings have been disposed of since 1979 in Anderson Lake, a shallow (8 m) eutrophic lake in Manitoba. Water quality is fairly poor because of process water that is also discharged into the lake, but the lake water is at pH 7.1 ± 0.3, and there is no evidence of metal or sulfate release from the tailings. The underwater tailings, in fact, are acting as a sink for dissolved metals. The large amount of organic matter on the lake bottom – a preexisting condition in the lake – keeps the benthic oxygen demand high and prevents oxidation of the tailings (Pedersen and others 1993). Mine tailings have also been dumped in suboxic to anoxic sections of several coastal fjords in British Columbia without major metal releases into the water (Pedersen and others 1993). The apparent stability of sulfidic waste in anoxic waters supports the idea that fast filling of a pit lake may be one of the best ways to prevent the formation of acid sulfate conditions. It also suggests that the best place to dispose of tailings around a pit may be the lake bottom. Advantage can be taken of the tendency of pit lakes to stratify due to their high relative depths. Once sulfidic tailings are in the anoxic hypolimnion of a stratified lake, it is highly unlikely that they will become oxidized.

In many dry areas, for example the western United States, water is not available to fill a pit quickly, and so filling must inevitably take several decades (Miller and others 1996). There may be no way to prevent these lakes from becoming acidic or from containing high metal loadings unless major efforts are taken up front. It would still be desirable to prevent the formation of an acid lake rather than to remediate it after the fact. Removal or covering of tailings and waste rock piles has been mentioned before as a useful preventive measure. Addition of limestone or other alkaline material to the lake to maintain circumneutral pH during filling would slow the oxidation of wall rock, which is catalyzed by acidophilic bacteria below pH 4. Addition of organic waste, where available, would also slow the oxidation of wall rock and tailings and hasten the formation of an anoxic deep layer in the lake. By a combination of the above actions – isolation of waste materials, optimization of drainage, and judicious addition of carbonate rock and organic waste – it might be possible to avoid the environmental impact of an acidic, metal-contaminated lake and the considerable monetary expense needed for its remediation.

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