Creating lakes from open pit mines: processes and considerations, with emphasis on northern environments

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2009

Canadian Technical Report of
Fisheries and Aquatic Sciences 2826

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Cat. No. Fs 97-6/2826E ISSN 0706-6457

Correct citation for this publication:

Gammons, C. H., Harris, L.N., Castro J.M., Cott, P.A., and Hanna, B.W. 2009. Creating lakes from open pit mines: processes and considerations - with emphasis on northern environments. Can. Tech. Rep. Fish. Aquat. Sci. 2826: ix + 106 p.

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ABSTRACT

Gammons, C. H., Harris, L.N., Castro J.M., Cott, P.A., and Hanna, B.W. 2009. Creating lakes from open pit mines: processes and considerations - with emphasis on northern environments. Can. Tech. Rep. Fish. Aquat. Sci. 2826: ix + 106 p.

This document summarizes the literature of mining pit lakes (through 2007), with a particular focus on issues that are likely to be of special relevance to the creation and management of pit lakes in northern climates. Pit lakes are simply waterbodies formed by filling the open pit left upon the completion of mining operations with water. Like natural lakes, mining pit lakes display a huge diversity in each of these subject areas. However, pit lakes are young and therefore are typically in a non-equilibrium state with respect to their rate of filling, water quality, and biology. Separate sections deal with different aspects of pit lakes, including their morphometry, geology, hydrogeology, geochemistry, and biology.

Depending on the type and location of the mine, there may be opportunities to enhance the recreational or ecological benefits of a given pit lake, for example, by re-landscaping and re-vegetating the shoreline, by adding engineered habitat for aquatic life, and maintaining water quality. The creation of a pit lake may be a regulatory requirement to mitigate environmental impacts from mining operations, and/or be included as part of a closure and reclamation plan.

Based on published case studies of pit lakes, large-scale bio-engineering projects have had mixed success. A common consensus is that manipulation of pit lake chemistry is difficult, expensive, and takes many years to achieve remediation goals. For this reason, it is prudent to take steps throughout mine operation to reduce the likelihood of future water quality problems upon closure. Also, it makes sense to engineer the lake in such a way that it will achieve its maximal end-use potential, whether it be permanent and safe storage of mine waste, habitat for aquatic life, recreation, or water supply.

Key words: Pit lakes, reclamation, mining, fish habitat, water quality

RÉSUMÉ

Gammons, C. H., Harris, L.N., Castro J.M., Cott, P.A. et Hanna, B.W. 2008. La création de lacs dans les mines à ciel ouvert : processus et points à examiner – en mettant l'accent sur les environnements du Nord. Rapp. tech. can. sci. halieut. aquat. 2826: ix + 106 p.

Le présent document résume la documentation des lacs miniers (jusqu'en 2007), en mettant un accent particulier sur les enjeux susceptibles d'être particulièrement pertinents à la création et à la gestion des lacs miniers dans les climats du Nord. Les lacs miniers sont tout simplement des plans d'eau formés en remplissant d'eau le puits à ciel ouvert laissé à la fin des opérations minières. À l'instar des lacs naturels, les lacs miniers présentent une immense diversité dans chacun de ces domaines. Cependant, les lacs miniers sont jeunes et donc généralement dans un état hors d'équilibre en ce qui a trait à leur taux de remplissage, la qualité de leur eau et leur biologie. Des sections distinctes traitent de différents aspects des lacs miniers, notamment leur morphométrie, leur géologie, leur hydrogéologie, leur géochimie et leur biologie.

Selon le type et l'emplacement de la mine, il pourrait y avoir des possibilités d'améliorer les avantages récréatifs ou écologiques d'un lac minier, par exemple en refaisant l'aménagement paysager et en remettant en végétation le rivage, en ajoutant un habitat aménagé pour la vie aquatique et en maintenant la qualité de l'eau. La création d'un lac minier pourrait être une exigence réglementaire afin d'atténuer les répercussions des opérations minières sur l'environnement ou faire partie intégrante d'un plan de fermeture et de remise en état.

Selon des études de cas publiées au sujet des lacs miniers, les projets de bio-ingénierie de grande envergure ont connu certains succès. On s'entend pour dire que la manipulation de la chimie d'un lac minier est difficile et coûteuse et qu'il faut de nombreuses années pour atteindre les objectifs de restauration. Pour cette raison, il est prudent de prendre des mesures pendant l'opération minière pour réduire la probabilité de futurs problèmes de qualité de l'eau à la fermeture de la mine. De plus, il est logique d'aménager le lac de façon qu'il atteigne son potentiel maximal d'utilisation finale, que ce soit le stockage permanent et sécuritaire des déchets miniers, un habitat pour la vie aquatique, récréative ou l'approvisionnement d'eau.

Mots clés : lacs miniers, remise en état, exploitation minière, habitat du poisson, qualité de l'eau

1. INTRODUCTION

Exploration and development of non-renewable natural resources is occurring rapidly in northern Canada (Cott et al., 2003; Birtwell et al., 2005; Sibley et al., 2008) with some of the most prolific industry sectors being diamond and metal mining (Birtwell et al., 2005). A common extraction method for these resources is open pit mining (Fig. 1). Open-pit mining results in residual pits, overburden or waste rock piles, and sometimes tailings impoundments left on the landscape. The excavated pits are of various depths and sizes, but all require environmental reclamation. One possible reclamation endpoint could be the creation of end-pit lakes.

Figure 1. Aerial view of open pit diamond mines in the Northwest Territories, Canada.

Pit lakes are formed by water filling the open pit left upon the completion of mining operations. These pits can be filled by artificially flooding or allowing the pits to fill naturally through hydrological processes such as precipitation or ground water infiltration (Castro and Moore, 2000). For example, a gravel quarry pit that has filled with rain water would be one form of pit lake. Pit lakes may have long-term benefits as a water source for industrial activities rather than relying on natural systems (Cott et al., 2008a). Depending on water quality, it may also be possible to modify or enhance pits to create aquatic habitat for fish and wildlife.

Often environmental regulations require that closure and reclamation plans are developed by proponents in the initial stages of environmental assessment and updated on a regular basis as the project proceeds through the regulatory phase (INAC, 2007). Other regulatory instruments, such as Canada's *Fisheries Act* administered by the Department of Fisheries and Oceans (DFO), require that fish habitat lost, for example due to mining operations, be compensated by the creation of new fish habitat or enhancement of existing habitat (DFO, 1986). However, the lack of information on pit lake creation, from a biological perspective, makes it difficult for government regulators and resource managers to make informed decisions. In the Northwest Territories (NWT), knowledge gaps regarding pit lakes have been recognized as a major issue by regulatory agencies, proponents and other interested stakeholders such as Aboriginal groups during the review of large mining operations.

As Birtwell et al. (2005) identified, there are also many information gaps regarding habitat requirements for fish species in the north that would make development of viable fish habitat in a pit lake all the more challenging. Very few projects - of any type - intended to create or enhance fish habitat have been properly documented (Smokorowski et al., 1998, Quigley et al., 2006). In the north the paucity of information is even more pronounced with only two fish habitat enhancement projects in the NWT having been assessed and published (see Jones et al., 2003; Cott, 2004). Documentation on the successful creation of pit lakes as self sustaining aquatic ecosystems is scarce, particularly for northern environments. Information on the creation of pit lakes as a result of diamond mining activities in the NWT is absent because none of the active diamond mines have been closed. Proactive planning is required to make the best use of these pits if they are to be made into pit lakes.

This report is an effort to address some of these data gaps regarding the state of knowledge on pit lakes as part of environmental reclamation activities. Although the impetus for this report was related to the current need for information to properly address pit lake issues in northern Canada, it was recognized that many characteristics of pit lakes are similar regardless of their geographical location or what resource is being extracted. Therefore, the scope of the paper provides a representative overview of pit lakes in general, with an emphasis on northern environments.

Section 2 of this report describes the characteristics of pit lakes in terms of their morphometry, geology, hydrogeology, limnology, chemistry, and biology. This section concludes with a description of some unique aspects of pit lakes in northern environments and considerations for their development. Section 3 briefly summarizes some numerical models currently available that can be used to predict the internal dynamics of pit lakes. Section 4 deals with methods to enhance pit lakes depending on what are deemed to be their most beneficial end uses, from storage of mine wastes to being platforms for limnological study. Section 5 includes several case studies of mining pit lakes in North America, including a review of the literature on mine waters associated with kimberlites and diamond mines. For reader convenience, a glossary including acronyms and technical terms is included following the references cited.

Rather than an exhaustive review of all literature pertaining to pit lakes, this report is meant to be an overview of relevant information on the creation of pit lakes as ecologically functioning systems. The information herein can be used as a resource for the varied stakeholders that could be involved in the development or review of projects that include the creation of pit lakes.

2. CHARACTERISTICS OF PIT LAKES

2.1 TYPES OF MINING PIT LAKES

By definition a *pit lake* is a lake that forms by flooding of an excavated mining pit. Other mine impoundments, such as tailings ponds, are not included in this definition. Different kinds of mines produce pits with various physical, geochemical, and ecological characteristics. Pits from mining of chemically inert materials tend to mirror the geochemistry of their surroundings, and lakes that form in such pits do not commonly present environmental problems. Their value as resources for recreation, fisheries, water supply, and wildlife habitat depends mostly on their topography, their safety characteristics (susceptibility to slides, rock falls, etc.), their hydrological characteristics (interaction with groundwater and surface waters and the quality of both), and climate. These inert materials include sand, gravel, clay (e.g., bentonite), limestone, talc, iron ore, and bauxite, among others.

Pits from other types of mining are more strongly affected by the chemistry of the mined resources. Silver and many nonferrous base metals such as copper occur as sulfide ores (Guilbert and Park, 1986). Many gold deposits are also rich in sulfides. Sulfide ore deposits commonly contain pyrite (FeS_2), which reacts with atmospheric oxygen and water to generate sulfuric acid according to the following equation (Nordstrom and Alpers, 1999):

$$FeS_2 + 15/4O_2 + 7/2H_2O \rightarrow Fe(OH)_3(s) + 2SO_4^{2-} + 4H^+ \qquad (1)$$

Coal deposits, except for those with very low sulfur contents, commonly contain significant levels of pyrite or its polymorph, marcasite. Organic-rich shales that are mined for phosphate fertilizer may also contain pyrite. Thus, mines of metals, industrial minerals, and solid fuels can all be potential sources of acid waters. Uranium deposits may or may not contain significant pyrite, but the radionuclides from the ore can present their own problems in pit lake water.

Gemstone deposits can occur in a wide variety of rock types or in unconsolidated sediments. Most of these deposits are mined as placers or in small mines that do not result in large pits at the end of mining. Diamond deposits are an important exception to this rule. Because of the high value of diamonds and the fact that they occur in fairly extensive bodies of kimberlite, diamond mines commonly produce deep pits and therefore potential pit lakes.

Besides the geochemical differences among types of pit lakes, the lakes from different mine types can also vary physically. Surface mines producing metal ores tend to be shaped like their ore bodies. Some are more or less circular in plan view, while others may have rectangular or irregular shapes (Fig. 2). What they all have in common is a tendency to be smaller at their bottoms than at their tops because of the need to build haul roads on the walls to reach the bottom. This produces a pit lake with little or no shallow littoral zone unless steps are taken to produce shallow zones in the pit after mining.

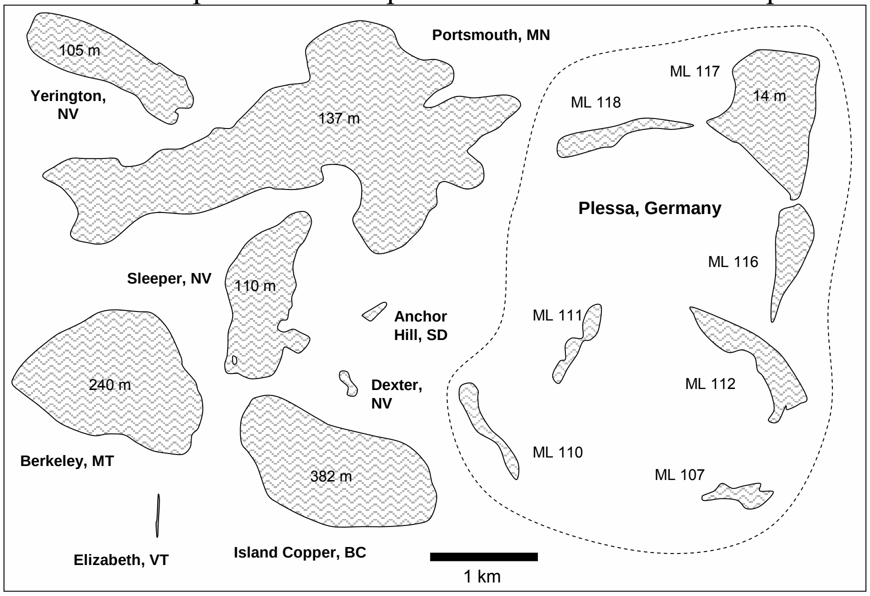


Figure 2. Comparison of the shape and size of selected pit lakes (drawn to scale from Google Earth images). The maximum depths of some of the larger lakes are also given. All of the lakes shown on the right from Plessa, Germany are filling former lignite strip mines, and are relatively shallow (most < 10 m).

Because kimberlite pipes are deep and generally have more or less cylindrical shapes, diamond pits tend to assume the shapes of steep-sided cones. In this respect they are similar to many metal-mine pits. Examples of such pits are the ones at the Ekati and Diavik mines in the Northwest Territories (Nowicki et al., 2004; Donnelly et al., 2007). In contrast, open-pit coal mines (strip mines) on relatively level terrain commonly use area-mining techniques, in which overburden is stripped off and coal is mined along a linear front. As the mine front advances, overburden is used to reclaim mined-out parts of the pit. At the end of the mine life, this commonly leaves a long, narrow linear pit lake, which sometimes is referred to as a "final cut lake." It is common for such a lake to have a steep highwall or cliff along its front side and a more gradual slope on the back side. The depth of the lake is the sum of the thicknesses of the overburden and the coal seam. However, other shapes are possible for coal pits (see Fig. 2).

The water in coal pit lakes can range from extremely acidic to somewhat alkaline, depending on the chemistry of the local groundwater, the coal bed, and the country rock. In a study of coal pit lakes in Montana, the Dakotas, and Wyoming, Anderson and Hawkes (1985) found the quality of water did not differ significantly from that of water in bentonite pits or stock-watering ponds. On the other hand, water in lakes formed from abandoned high-sulfur coal or lignite mines can be strongly acidic. Extensive strip mining of lignite deposits in Lusatia, Germany, has left a legacy of over 500 pit lakes

(Geller et al., 1998; Friese et al., 1998). Many of these lakes are strongly acidic ($pH < 3$). These lakes tend to be very large in surface area but relatively shallow, being for the most part < 10m in average depth. The cluster of pit lakes near Plessa is a good example (see Fig. 2). German scientists and engineers have used the acid pit lakes (in particular, Mining Lake 111, Fig. 2) as a natural laboratory to test different *in situ* and *ex situ* technologies for treatment and remediation. Many of these treatment concepts have focused on bioremediation, for example, through artificial stimulation of bacterial sulfate reduction.

2.2 HYDROGEOLOGY OF PIT LAKES

Hydrogeology determines how rapidly open pit mines fill with water after closure, and also influences the final steady state water budget of the lake that is formed. Most large open pits will eventually intersect the water table during mining, and consequently steps must be taken to dewater the pit during operation. After mining ceases, the dewatering pumps are usually shut down, allowing the water tables to rebound and – in some cases – a pit lake to form. A generalized water balance equation for a pit lake can be summarized as follows:

$$P + SW_{in} + GW_{in} = E + (T) + SW_{out} + GW_{out} \pm \Delta S \qquad (2).$$

The definition of the terms in equation (2) are as follows: P is direct precipitation falling on the surface of lake; SW_{in} is the sum of any surface water inputs such as diverted streams, stormflow, pit-wall runoff, or waste water being disposed of in the lake; GW_{in} is groundwater entering the lake; E is evaporation; T is plant transpiration (in parentheses because it is expected to be a minimal term for most pit lakes); SW_{out} is surface water exiting the system (including water that is pumped, treated, and discharged to receiving water bodies); GW_{out} is groundwater exiting the lake; and ΔS is the change in storage, i.e., the volume of water in the lake. Terms on the left side of equation (2) are water inputs, whereas terms on the right side (with exception of ΔS) are water outputs. If input > output, then ΔS is positive, and the lake volume will increase.

Left to their own devices, large open pit lakes can take a very long time (decades to centuries) to fill with water. This is particularly true in arid or semi-arid areas where P and SW_{in} are minimal. The rate of groundwater input varies quite a bit from mine to mine, and depends on the site geology, topography, and climate. A rough estimate of GW_{in} can be obtained by noting the amount of water that was pumped during active mining operations. Thus, if the dewatering pumps were removing 15,000 m^3/day on average during the mine life, then the rate of flooding from groundwater rebound will be around 15,000 m^3/day, at least during the early stages of flooding. However, this rate will change as the pit fills with water, as can be deduced from Darcy's Law:

$$Q_{gw} = K \cdot A \cdot (\Delta h / \Delta l) \qquad (3)$$

where Q_{gw} is the flux of groundwater into the lake (e.g., m^3/day), K is the hydraulic conductivity (e.g., m/day) of the fractured bedrock or overburden, A is the cross-sectional area of the flooded portion of the lake, and Δh/Δl is the hydraulic gradient, or steepness of the water table in the zone of groundwater capture surrounding the lake. As the pit floods and the surface of the lake rises, the hydraulic gradient will decrease. However, this effect is offset by the fact that the value of A increases with time as the volume of the lake increases. This is because groundwater enters the lake from all sides below the water line, not just from the bottom or top. The net result of these offsetting factors is that the filling rate of a pit lake may actually increase with time during the initial period of flooding, but will eventually level off and then slowly decrease to zero as the lake surface approaches its final equilibrium elevation. Figure 3 illustrates this concept. For these calculations, a hypothetical pit lake was assumed with the following characteristics: 1) a pit geometry equal to a right-circular cone with a radius twice its height; 2) fractured bedrock with K = 0.1 m/day; and 3) a change in elevation between the steady state water table surface and the bottom of the pit of 200 m. Following these assumptions, the maximum groundwater flux into the lake occurs ~ 25 years after flooding begins. Figure 3 also shows that the depth of the lake increases rapidly at first, but then levels off as the total volume of the lake increases and as Q_{gw} diminishes to zero.

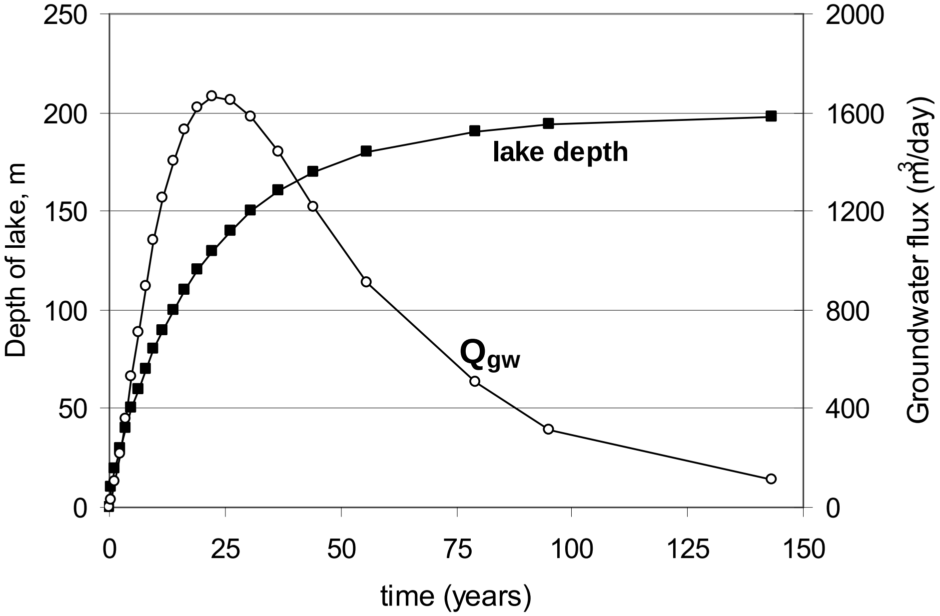
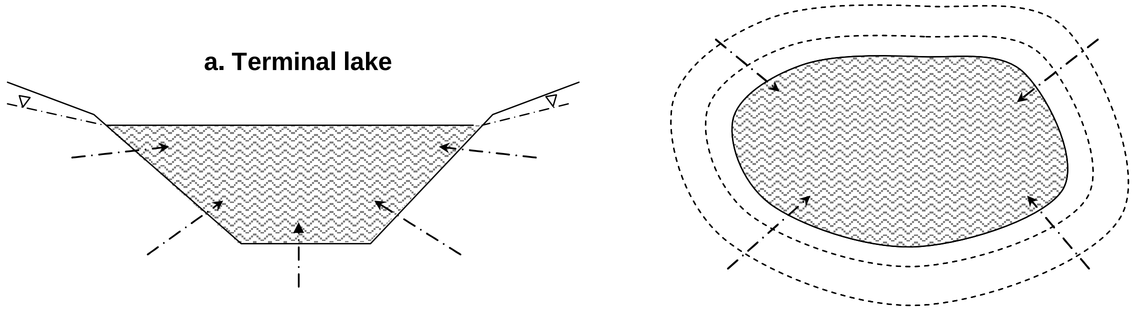
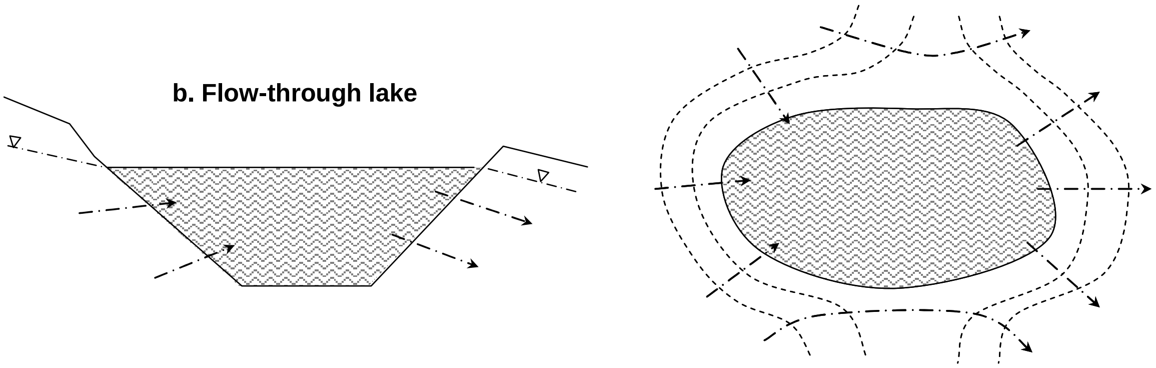


Figure 3. Example calculations showing the rate of filling of a pit lake by groundwater. Q_{gw} is the flux of groundwater entering the lake.

Once a pit lake has filled to its ultimate surface elevation, ΔS is zero (barring seasonal changes), and the input and output terms in equation (2) will cancel. There are now many different hydrogeological scenarios for the lake, and these are important factors to consider for "end use" decisions. For example, in an arid climate such as Nevada, it is very possible that evaporation will completely balance any water input terms, such that SW_{out} and GW_{out} are both zero at steady state. Such a lake is referred to as a "terminal" lake (Fig. 4a). A "flow-through" lake, on the other hand, will receive groundwater inputs from one side, but will lose groundwater to the other side (Fig. 4b). Flow-through lakes are especially common when the pit was excavated on a hillside with an initially sloping water table. Finally, if water inputs are high (such as in a wet climate, or where a stream is permanently diverted into the lake), then the final lake will probably have a surface water output. This could either be an engineered spillway or stream, or lake water that is pumped and (possibly) treated before discharging to a receiving stream or lake.



a. Terminal lake



b. Flow-through lake

Figure 4. Schematic diagrams comparing: a) a terminal lake, and b) a flow-through lake. Dashed lines on the right are groundwater table contours. Arrows are groundwater flow lines.

In some cases an open pit mine will be connected to underground mine workings. This is often the case for old mining districts where access to high-grade mineralization was first developed by vertical mine shafts. Later on, with the development of new technologies to beneficiate lower and lower grade ore bodies, much of the "in between" ore would then be mined by open pit. A good example of this situation is the Butte mining district in Montana. Beginning in the 1870s and continuing through the mid-1970s, miners dug over 16,000 km of underground passageways, including over 50 shafts, many of which were more than 1 km deep. Between 1956 and 1982, the Berkeley open pit mine excavated a very large hole right in the middle of this labyrinth of tunnels and shafts. The majority of the underground mine openings are now flooded, and the local hydraulic gradients are such that most of this water is slowly heading towards the Berkeley pit lake. In terms of hydrogeology, this complicates the picture considerably over what would be the case for a mine void that is simply filling with groundwater from fractured bedrock. Whereas some of the mine tunnels in Butte were backfilled with waste, many were not, and the latter most likely act as "plug-flow" corridors for rapid groundwater conveyance. During the early period of mine flooding, secondary salts that had accumulated in the mine tunnels over decades of active mining were flushed into the pit lake, contributing to the poor quality of the lake (Maest et al., 2004). Interestingly, the temperature of the majority of the mine shaft water in Butte is elevated (typically in the range 15 to 35°C, see Gammons et al., 2006a) compared to the adjacent groundwater (~ 10°C). The influx of this warm water into the deep lake is one reason for the fact that temperatures in the deep water (currently between 8 and 9°C) are higher than would be expected for a natural lake in Montana.

2.3 LIMNOLOGY OF PIT LAKES

2.3.1 Vertical structure and classification

Of fundamental importance to any pit lake study is information on the vertical structure of the lake and whether it is conducive to seasonal overturn. Most natural lakes in northern climates are holomictic, meaning that they typically undergo a complete top-to-bottom turnover during the Spring and Fall when surface water temperatures pass through their density maximum of ~ 4°C (Fig. 5). Holomictic lakes become vertically stratified in the summer, with a warmer, less dense "epilimnion" resting on top of a colder, denser "hypolimnion" (Fig. 6a). These two layers are separated by a thermocline (also known as the "metalimnion"), i.e., a zone of rapid temperature change with depth. In winter, temperatures < 4°C in the shallowest water (often under ice cover) again result in density-stratification. Rather than being a static horizontal plane, internal waves of large amplitude and period can set up at the thermocline interface, being driven by surface waves, episodic influx of groundwater, or landslides (Stevens and Lawrence, 1998; Hodges et al. 2000; Wetzel, 2001).

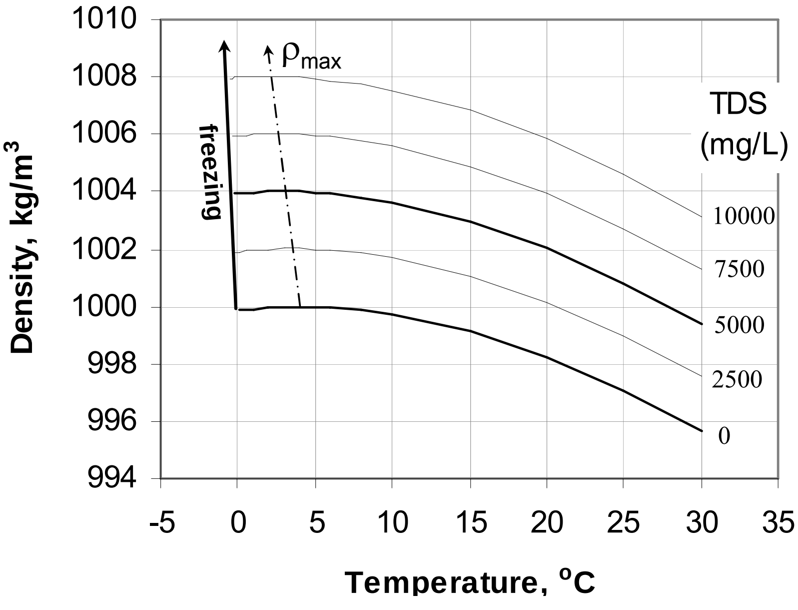


Figure 5. Density of water at different temperatures and salinities. The dashed line shows the maximum density at any given salinity. The freezing point depression (solid arrow) is approximate, and depends on the composition of the dominant salts in the water.

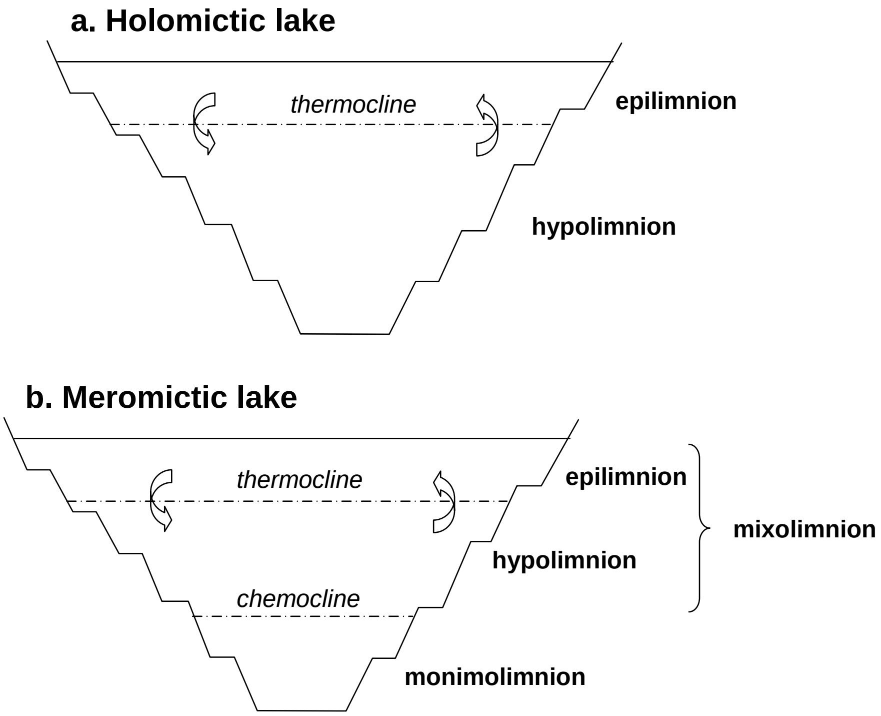


Figure 6. Schematic diagrams comparing: a) a holomictic lake, and b) a meromictic lake. Arrows denote zones of seasonal mixing.

In contrast to holomictic lakes, meromictic lakes contain a bottom layer of highly saline water than has a density too great to mix with overlying waters, regardless of the temperature profile. Figure 6b shows a typical meromictic lake with a shallow epilimnion, a mid-level hypolimnion and a deep monimolimnion (after Boehrer and Schultze, 2006). Although the epilimnion and hypolimnion may mix seasonally (together these zones are referred to as the “mixolimnion”), water in the monimolimnion is too dense and salty to overturn. The interface between the mixolimnion and monimolimnion is often referred to as a “chemocline” (i.e., an interface in chemical composition or salinity). Chemoclines can also coincide with temperature gradients. It is not uncommon for salty water in the monimolimnion of a meromictic lake to have a temperature well above 4°C, whereas the temperature of the overlying hypolimnion is typically colder and closer to the maximum density value (Stevens and Lawrence, 1998; Gammons and Duaime, 2006). Heat can be added to the bottom water either from the surrounding rocks (most continental settings have geothermal gradients of ~ 20 to 35°C/km) or from influent warm ground water, or both. In general, the effect of changes in salinity is greater than the effect of changes in temperature when determining the density of water in a pit lake. As shown in Figure 5, if the salinity of the deep water exceeds that of the overlying water column by 2500 mg/L, and if the hypolimnion is at the maximum density corresponding to 4°C, then turnover cannot occur until the temperature of the monimolimnion is raised above 20°C. Barring the existence of anomalous geothermal activity, such warm temperatures are extremely unlikely for deep lake waters. Limnological textbooks (e.g., Wetzel, 2001) have different terms for meromictic lakes, depending on the dominant mechanism that leads to density stratification. *Ectogenic meromixis* occurs when some external or human-induced event brings saline water into a freshwater lake, or fresh water into a saline lake. A good example is the Island Copper pit lake of Vancouver Island, B.C., which was flooded to > 90% volume with ocean water, and then capped with a fresh surface water layer (Fisher and Lawrence, 2006). *Crenogenic meromixis* occurs when high-salinity groundwater flows into deep parts of a lake. The Brenda pit lake near Kelowna, B.C. (Stevens and Lawrence, 1998) and the McLaughlin pit lake in California (Rytuba et al. 2000), are two examples. *Biogenic meromixis* occurs when a biological process increases the salinity of the monimolimnion. This situation may occur in pit lakes with high sedimentation rates of organic carbon combined with abundant hydrous oxides of Fe and/or Mn. In the anoxic bottom waters of the lake and underlying sediment, bacteria reductively dissolve the hydrous metal oxides, increasing the concentration of dissolved Fe and Mn. This process has been documented from Fe-rich natural lakes in northern Canada (Campbell and Torgensen, 1980). Finally, *cryogenic meromixis* occurs in some lakes or fjords at high latitude with thick, seasonal ice cover. Salt exclusion during crystallization of ice creates brine streamers that descend by gravity, sometimes to the bottom of the lake (see section 2.3.5). Thawing of ice in the summer adds low-salinity water to the lake surface, further stabilizing the density stratification.

2.3.2 Predicting lake turnover

Mining pit lakes with high depth to width ratio are less apt to undergo complete lake turnover (Doyle and Runnells, 1997; Castro and Moore, 2000). The aspect ratio of a given pit lake can be quantified by Z_r, otherwise known as the "relative depth" (Hutchinson 1957):

$$Z_r\,(\%) = 50 \cdot Z_m \cdot \frac{\sqrt{\pi}}{\sqrt{A}} \qquad (4)$$

where Z_m is the maximum depth, and A is the surface area of the lake. In a survey of mining pit lakes around the world, Doyle and Runnells (1997) suggested that most artificial lakes with $Z_r > 25\%$ are meromictic, although there were a few lakes with $Z_r > 25\%$ that were holomictic, and many lakes with $Z_r < 25\%$ that were meromictic. Clearly there are other factors which dictate whether a given pit lake is permanently stratified.

A more useful parameter in predicting lake turnover is the Wedderburn Number (Stevens and Lawrence, 1997, 1998):

$$W = \frac{h_e^2 g'}{u_*^2 L} \tag{5}$$

where h_e is the depth (m) of the surface layer (epilimnion), L is the fetch, or length of the surface of the lake (m), g' is the modified gravity of the interface between the surface and underlying water layers, and u_* is the friction velocity. Values of W (a dimensionless number) > 1 indicate a lake with stable stratification that is unlikely to mix, whereas values < 1 indicate instability and a greater likelihood of turnover. The modified gravity term is given by the following equation:

$$g' = \frac{g \cdot (\rho_2 - \rho_1)}{\rho_0} \tag{6}$$

where $g = 9.8 \text{ m/s}^2$, ρ_1 and ρ_2 are the densities of the epilimnion and the underlying hypolimnion, respectively, and ρ_0 is the reference density, usually taken as the average of ρ_1 and ρ_2. The friction velocity term is given as:

$$u_* = \left(C_D \frac{\rho_a}{\rho_0} U_{10}^2 \right)^{\frac{1}{2}} \tag{7}$$

where C_D is the drag coefficient (a dimensionless number with a value near 10^{-3} for water), ρ_a is the air density (1.2 kg/m^3 for dry air at 20°C and sea level), and U_{10} is the wind velocity (m/s) measured 10 m above the water surface. Combining the preceding 3 equations yields:

$$W = \frac{h_e^2 g(\rho_2 - \rho_1)}{C_D U_{10}^2 \rho_a L} \tag{8}$$

From equation (8), it follows that the probability of turnover increases as the epilimnion becomes thinner, as the density contrast between the surface and underlying water layers diminishes, as the wind speed increases, as the length of the lake increases, or as the density of air increases. Note that the effects of h_e and U_{10} are second-power. The ρ_a term changes slightly with changes in temperature or relative humidity, and is effected to a greater extent by changes in altitude. Thus, wind at high altitude where the air is thinner has less force than wind of the same velocity at sea level.

2.3.3 Landslides and lake turnover

Because open pit mines are typically steep-sided and barren of vegetation with highwalls composed of highly fractured and blasted bedrock, slope stability is always a major concern. The rebound in groundwater pressure after mine closure may actually increase the probability of a major slide by decreasing the effective stress borne by the rock matrix. After a mining pit is flooded, a large landslide has several potentially serious consequences: 1) possible threat to human health or damage to buildings or roads near the affected pit highwall; 2) drowning of individuals or wildlife on the shore of the lake due to "tidal waves"; and 3) possible inducement of turnover due to turbulent mixing. The latter scenario is of particular relevance to the present discussion, because it brings up the risk that a pit lake designed to be meromictic may nonetheless undergo a landslide-induced mixing event. Such an event occurred in the Berkeley pit lake of Butte, Montana, in September 1998, when a portion of the southeast highwall failed, sending an estimated 130,000 m^3 of poorly consolidated sediment and waste rock into the lake (Gammons and Duaime, 2006). A slope failure of this magnitude or larger could completely mix a pit lake that otherwise would be density-stratified. As another example, Pieters and Lawrence (2007) mention a smaller rock slide event that may have resulted in mixing of deep water in the Colomac Zone 2 pit lake.

2.3.4 Positive and negative consequences of lake turnover

Lake turnover may be a desirable or undesirable occurrence, depending on the end use of the pit lake in question. If a lake is dimictic (overturn in spring and fall) or polymictic (frequent overturns throughout the year) then the major element chemistry will be more or less evenly distributed with depth, and there is also a good chance that the entire water column will be oxygenated. This is good from the standpoint of supporting benthic organisms and fishes at different depths in the lake. However, because mine pits often contain potentially hazardous solid materials, there is also a chance that contaminants will be leached from weathered bedrock or mine waste on pit walls or in sediment and re-distributed to shallow waters. As well, infrequent turnover events may allow time for chemical or biological reactions to transform the water quality of the hypolimnion, which could have negative consequences when the lake undergoes a major turnover event. These include upwelling of water with low (or no) DO and upwelling of water rich in nutrients (such as ammonia, phosphate, or DOC). A sudden drop in DO could result in a fish kill, whereas a sudden influx in nutrients could result in eutrophication and blooms of algae or cyanobacteria (Wetzel, 2001). Finally, if the upwelling water has high concentrations of dissolved gas, such as carbon dioxide (CO_2), hydrogen sulfide (H_2S) or methane (CH_4), then these gases may exsolve or possibly even bubble out of the water, creating an O_2-depleted air column immediately above the lake surface. This phenomenon, sometimes referred to as a "limnic eruption", has been documented from a few natural lakes (such as Lake Nyos, a volcanic crater lake in Cameroon), but is less likely to occur in mining pit lakes (Murphy, 1997).

2.3.5 Brine exclusion and thermohaline convection

When the surface of a lake freezes, most of the dissolved salts are excluded from the ice crystals that are formed. In rare cases, the rejected salt may accumulate on the surface of the ice, forming interesting patterns (Fig. 7). More commonly, the salt (in the form of a dense brine droplet with low freezing point) will burrow its way downwards by gravity through the ice and thence to the underlying water. If the lake has moderate or high salinity to begin with, then salt exclusion during rapid ice growth can create high-density brine flows that descend by gravity through the water column (Fig. 8). For example, Wakatsuchi (1984) conducted benchtop experiments that showed "brine streamers" originating near the bottom of growing ice sheets. Wakatsuchi argued that this process likely takes place in the polar oceans where cold brines may drop appreciable distances (up to 400 m) before mixing with less dense seawater. Meanwhile, lower salinity water must rise to occupy the volume left behind. The overall process is a localized form of *thermohaline convection*, which is more familiar to most people as the process that drives the global circulation of water in the world's oceans.

Figure 7. Salt deposits forming in shallow ice on the surface of the Berkeley pit lake (March, 2002). The concentric salt bands are roughly 10 to 50 meters in diameter. The deposits were not analyzed for mineralogy, but are believed to be gypsum and other metal sulfate salts. (Photo: James Madison, Montana Bureau of Mines and Geology).

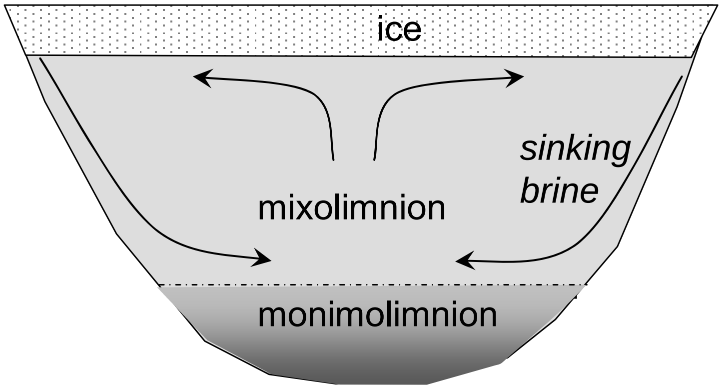


Figure 8. Schematic diagram showing thermohaline convection in a high-latitude meromictic lake (after Gibson, 1999a). Cold brines form during salt exclusion at the ice-water interface and sink through the water column. Warmer, less dense water rises to take its place. The maximum depth of penetration of the sinking brine flow may change from year to year.

Gibson (1999b) described thermohaline convection from lakes in Antarctica, and these processes may have relevance to mining pit lakes in northern Canada. Figure 9 shows in more detail how vertical changes in salinity of an ice-covered water body can develop with changing seasons. During the summer the lake is strongly stratified with an unfrozen, low-salinity epilimnion, a colder and intermediate-salinity hypolimnion, and a high salinity monimolimnion (Fig. 9a). With the onset of winter ice formation, excluded salt creates brines that circulate through the top layer of water, increasing the salinity of the epilimnion (Fig. 9b, 9c). This continues until later in the winter when the salinity of the epilimnion approaches that of the hypolimnion, at which point these two layers will mix (Fig. 9d) and any new brine streamers formed by salt exclusion can now descend all the way to the monimolimnion. Later in the year when the ice cover melts, a cap of low salinity water once again forms on the lake, and the process repeats itself.

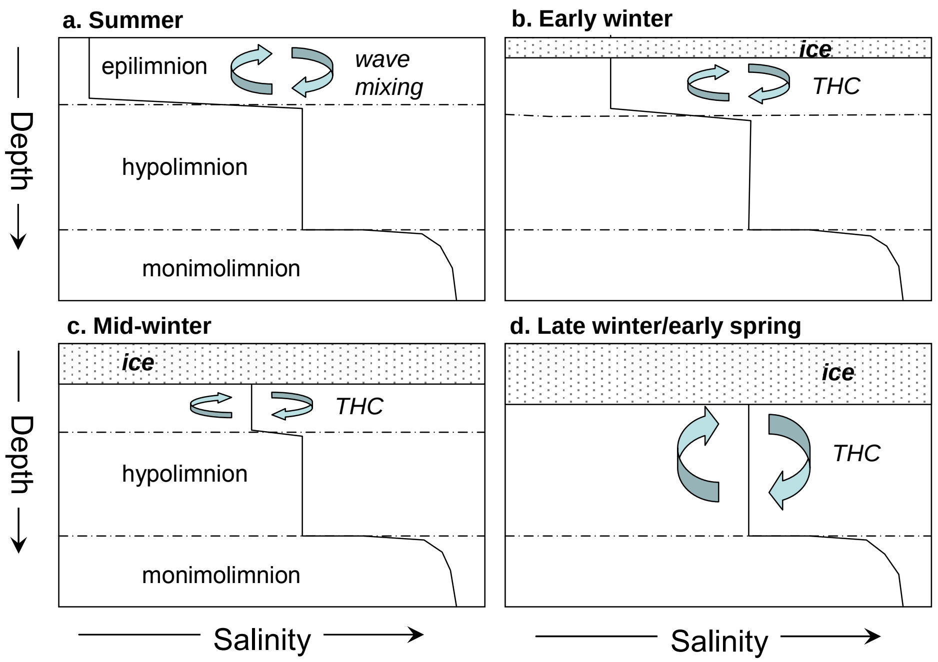


Figure 9. Hypothetical seasonal changes in water density profiles for a high-latitude meromictic lake (modified from Gibson, 1999b). THC refers to thermohaline convection.

2.3.6 Double-diffusion convection

Double-diffusion convection is an interesting limnological phenomenon that can set up in a meromictic lake when colder, lower-salinity water sits on top of warmer, higher-salinity water. In this situation, there is a net upwards diffusive flux of both heat and dissolved salt at the interface between the two water layers. However, the rate of diffusion of heat is roughly 100 times faster than the rate of diffusion of salt. Thus, the water immediately overlying the density interface (or *pyncnocline*) will warm up faster than it will become saltier, and the water immediately below will cool down faster than it will become less saline. The net result is that the upper parcel of water will rise (but only a short distance), whereas the lower parcel of water will sink (Fig. 10a). What results is a series of horizontal layers of vertically-mixed water separated by multiple pyncnoclines. Lakes or ocean waters undergoing double-diffusion convection exhibit a characteristic “staircase” vertical profile in salinity and temperature (Schmid et al., 2004) (Fig. 10b).

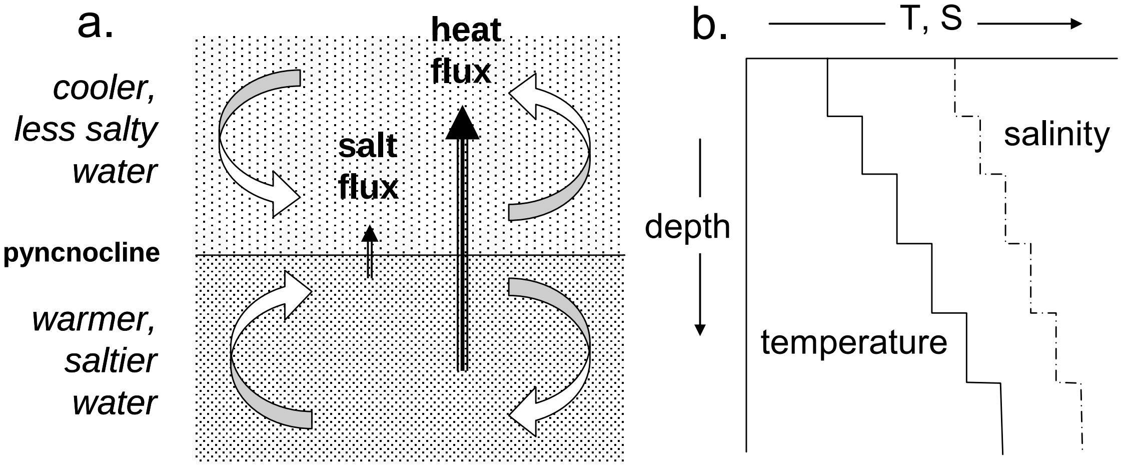


Figure 10. Illustrations of the double-diffusion convection process. a) Because the rate of diffusion of heat is much faster than salt, the upper water layer warms up and rises while the lower water sinks; b) Schematic diagram showing characteristic "stairstep" profiles in water temperature and salinity that can set up in a lake undergoing double-diffusion convection.

Although all meromictic lakes must undergo diffusion of dissolved solids and heat across the pyncnocline, this does not necessarily result in double-diffusion *convection*. To maintain meromictic conditions, the density difference due to salinity gradient must be greater than the density difference due to the temperature gradient. Turner (1965) developed a "density ratio" term R_p, which is given by:

$$R_p = \frac{\beta \cdot \Delta S}{\alpha \cdot \Delta T} \tag{9}$$

where S is the salinity, T is the temperature, β is the coefficient of saline contraction (0.78 kg/m^3/psu at 10°C), and α is the coefficient of thermal expansion (- 0.15 kg/m^3/°C at 10°C). [Note: 1 psu ~ 1000 mg/L of dissolved solid]. When R_p is >> 1, then the boundary separating the two layers is stable. Conversely, when R_p is < 1, the boundary is unstable, and the lake will overturn. Double-diffusion convection is most likely to occur when $1 < R_p < 10$, in other words, when conditions are favorable for meromixis, but just barely.

Although double-diffusion convection has been documented from some natural meromictic lakes (e.g., Lake Nyos, Cameroon, see Schmid et al., 2004), the authors are not aware of a mining pit lake where this has been observed. Unless a very detailed CTD (conductivity-temperature-depth) profile was obtained during field sampling, the relatively subtle "staircase" changes in salinity and temperature (Fig. 10b) could easily go unnoticed.

2.4 CHEMISTRY OF PIT LAKES

2.4.1 General trends in pit lake chemistry

Mining pit lakes display a wide diversity in water quality, reflecting the wide diversity in the style of mineral deposits that were extracted. General trends in pit lake chemistry have been reviewed by several workers (Davis and Eary, 1997; Friese et al., 1998; Eary, 1999; Castro and Moore, 2000). Many pit lakes from former gold, metal-sulfide, or coal mines contain elevated concentrations of heavy metals (e.g., Al, Cd, Cu, Fe, Mn, Ni, Pb, Zn, U) and/or metalloids (e.g., As, Sb, Se, Te) that can pose a threat to the environment. In contrast, pit lakes formed from mining of iron ore, gravel, or industrial minerals (e.g., talc, asbestos) may have quite low concentrations of dissolved metals. Depending on the end-use of a particular pit lake, other water quality parameters may also become important, such as salinity, turbidity, DO concentration, and nutrient content.

The single most important parameter that controls pit lake water quality is pH. This is because the mobility of most metals and metalloids is strongly pH-dependent, for reasons that are elaborated in the following sections. In addition, most aquatic life forms have relatively narrow ranges of pH tolerance. As shown by Davis and Eary (1997), pit lakes that are strongly acidic ($pH < 4$) tend to have high concentrations of "cationic" trace metals, such as Al^{3+}, Cu^{2+}, Fe^{2+}/Fe^{3+}, Mn^{2+}, and Zn^{2+}, in addition to high concentrations of the common cations Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}. In low-pH lakes, the dominant anion is usually sulfate (SO_4^{2-} or HSO_4^{-}). In contrast, pit lakes that have near-neutral to alkaline pH tend to have relatively low concentrations of cationic trace metals, and may contain appreciable bicarbonate (HCO_3^{-}) in addition to dissolved sulfate. Alkaline lakes may be highly elevated in metalloids, such as As or Se, present as dissolved anions such as $HAsO_4^{2-}$ or SeO_4^{2-} (Davis and Eary, 1997). Although these general trends exist, each mineral deposit is different and needs to be evaluated on a case-by-case basis. For example, pit lakes formed by flooding of uranium deposits may be rich in dissolved U and Th.

Through a combination of leaching of soluble salts on mine walls and evapo-concentration, most pit lakes – regardless of pH – have relatively high total dissolved solids (TDS). Elevated turbidity (i.e., total suspended solids, or TSS) is also a common characteristic of mining pit lakes, due to rapid physical erosion of steep mine walls combined with wave action along shorelines during stormy periods. Another common source of turbidity is oxidation of dissolved iron to hydrous ferric oxide (HFO), a red-brown substance that is very fine-grained and slow to settle by gravity (see section 2.4.2.5). Turbidity can block sunlight, resulting in reduced rates of photosynthesis.

DO is essential for many forms of aquatic life, in particular fishes. Most pit lakes will contain elevated DO levels in shallow water, due to free gas exchange with the atmosphere coupled with wave-mixing. However, the deeper zones of many pit lakes are susceptible to depletions in DO, and this is exacerbated by the often higher chemical oxygen demand of mining vs. natural lakes. For example, oxidation of pyrite and other metal sulfides on submerged mine walls provides a long-term sink for dissolved oxygen in the hypolimnion or monimolimnion of stratified pit lakes. Another important sink for DO is oxidation of dissolved ferrous iron (Fe^{2+}).

In terms of nutrient concentrations, most pit lakes are naturally oligotrophic (i.e., nutrient-poor), due to their young age, high volume to surface area ratio, and proximity to rock that is generally poor in organic carbon (exceptions include coal or lignite mines). Some pit lakes may initially have high nitrate concentrations from explosives residue, or in cases where cyanide-rich process water has been oxidized and disposed of in the pit. Chemical and/or biological reactions may sequester nutrients in near-surface water and store them in sediment at the bottom of the lake. Extremely low nutrient concentrations will limit primary productivity by algae and aquatic plants, which can leave a lake relatively barren with respect to higher forms of aquatic life.

2.4.2 Review of chemical processes

Geochemical processes taking place in mining pit lakes have been reviewed by Miller et al. (1996), Geller et al. (1998), Shevenell et al. (1999), and Eary (1998, 1999), among others. Figure 11 and Table 1 summarize some of the more important chemical processes that are likely to occur. Many of these reactions are mediated by microbes (algae and bacteria). The following sections provide additional details and discussion.

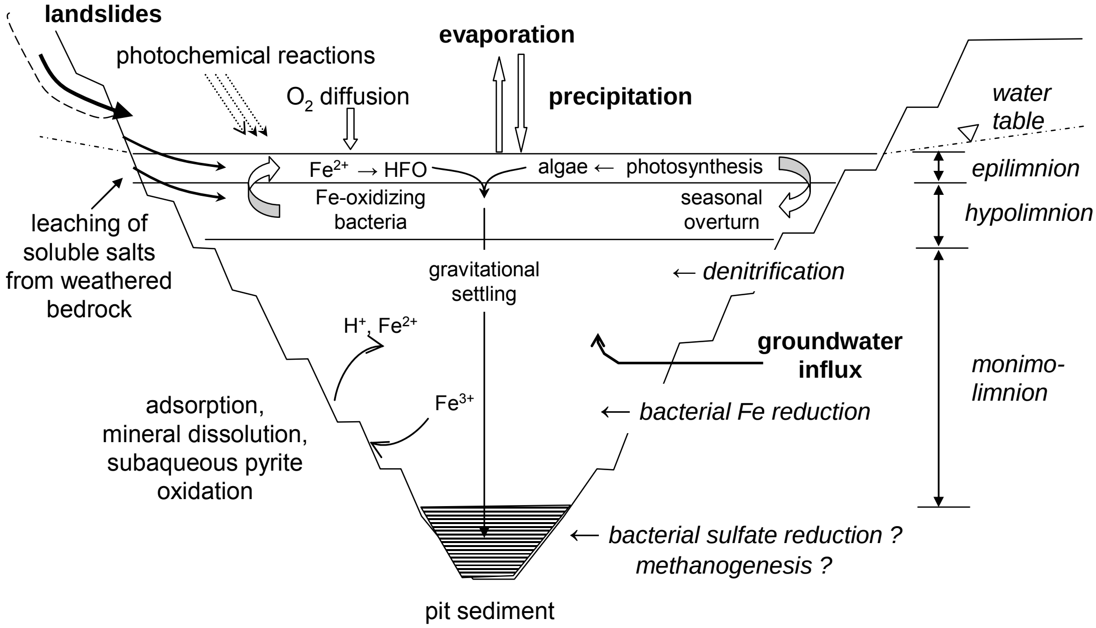


Figure 11. Summary of chemical processes occurring in mining pit lakes.

Table 1. Summary of chemical processes occurring in pit lakes. The information is arranged from top to bottom in the approximate order of increasing depth in the lake.

PROCESS	IMPACTS	REFERENCES
Shallow water		
Evaporation	Concentration of all solutes in proportion to the fraction of water lost to vapor. May lead to precipitation of gypsum, calcite, and other sparingly soluble salts.	Levy et al. (97); Eary (98); Shevenell (00a)
Photosynthesis by algae, cyano-bacteria, and plants	Increase in biomass which provides carbon source for bacteria, animals, and other decomposers. Increase in DO. Increase in pH (for non-acidic lakes). Possible uptake of trace metals by plants. Blockage of sunlight if conditions are eutrophic.	Ledin and Pederson (96); Nixdorf et al. (98a, 98b); Kalin et al. (01)
Photoreduction	Photoreduction of Fe^{3+} or hydrous ferric oxide to Fe^{2+}. Possible photoreduction of Mn oxides to Mn^{2+}. Rapid attenuation of visible light, especially at short wavelengths. Catalyst for breakdown of dissolved organic carbon.	Collienne (83); Friese et al. (02); Diez Ercilla et al. (in press)
Leaching of soluble salts stored above the water line	Increase in salinity and concentrations of trace metals and metalloids.	Newbrough and Gammons (02); Maest et al. (04)
Freezing	Increase in salinity of water during ice formation due to salt exclusion. May lead to thermohaline convection below ice cover. Dilution of surface water during spring thaw.	Gibson (99a, 99b)
Oxidation and precipitation of hydrous metal oxides	Decrease in concentration of dissolved Fe and Mn. Decrease in trace solutes that adsorb onto hydrous metal oxide (see below). Increased turbidity from suspended mineral particles. Possible drop in pH.	Jonas (00); Pellicori et al. (05); Eary (99); Dowling et al. (04)
Adsorption onto suspended mineral particles or organic matter	Decrease in concentration of heavy metals and metalloids. Enhanced removal of As, Se at low pH. Enhanced removal of Cd, Cu, Pb, Zn at high pH. Important sink for phosphate.	Eary (99); Smith (99); Tempel et al. (00)
Dissolution of minerals exposed on submerged mine walls	If carbonate minerals are present, can be important mechanism for buffering pH to near-neutral conditions. If lake is acidic, may see conversion of feldspar and other rock-forming minerals to clay.	Eary (99); Bowell and Parshley (05); Shevenell et al. (99)
Sub-aqueous oxidation of pyrite by O_2 and/or dissolved Fe^{3+}	Increase in concentration of dissolved heavy metals and sulfate. Drop in pH. Drop in dissolved oxygen and/or dissolved Fe^{3+} concentration.	Madison et al. (03); Pellicori et al. (05)

Table 2. (Continued from previous page)

Deep water		
Aerobic respiration of organic carbon	Dissolved oxygen is depleted or completely consumed.	Alvarez-Cobelas (90)
Subaqueous oxidation of pyrite by dissolved Fe^{3+}	If water is acidic, high concentrations of Fe^{3+} may persist at depth. Fe^{3+} is a strong oxidant of pyrite and other metal sulfides, resulting in a drop in pH and release of Fe^{2+}, sulfate, and other metals.	Madison et al. (03); Pellicori et al. (05)
Microbial reduction of Fe and Mn oxides	Increase in dissolved Fe^{2+} and Mn^{2+} concentration. Increase in pH. May be major cause of high-salinity bottom water that can induce meromixis. May release adsorbed metals and nutrients to water column, such as arsenic and phosphate.	Blodau et al. (98); Wendt-Potthoff et al. (02); Sanchez-Espana et al. (07)
Microbial reduction of nitrate	Reduction of dissolved nitrate (if present) to N_2 and/or ammonia.	Helmer and Labroue (93)
Microbial sulfate reduction	Decrease in dissolved sulfate. Increases in hydrogen sulfide (H_2S or HS^-), pH, and bicarbonate alkalinity. Drastic decrease in concentrations of metals (e.g., Cd, Cu, Fe, Ni, Zn) that form insoluble metal sulfide precipitates. Possible buildup of H_2S (a poisonous gas) to dangerous levels.	Blodau et al. (98); Castro et al. (99); Harrington et al. (04); Fauville et al. (04)
Methylation of Hg	If present, inorganic Hg may be converted to methyl-Hg, resulting in rapid bio-accumulation in organisms.	Wolfe and Norman (98); Gray et al (03)
Methanogenesis	May occur in pit lake sediment with a high organic C to sulfate ratio. Increase in concentrations of dissolved organic carbon, CH_4 and H_2.	Blodau et al. (98); Holowenko et al. (00)

2.4.2.1 Evaporation.

Evaporation increases the salinity of a lake, especially terminal pit lakes in dry climates. Eary (1998) gives a good discussion of predicted chemical pathways for pit lakes of contrasting starting chemistry. As a general rule, lakes that fill with acidic, metal-rich water will become more acidic and more metal-rich with evaporation, although mineral saturation may provide an upper limit to the concentrations that a given dissolved solute (e.g., Fe, Al, SO_4) may attain. Lakes that fill with alkaline water rich in bicarbonate and sulfate are likely to precipitate calcite and gypsum upon evaporation, and may end up with quite a high pH (e.g., > 9). This increase in pH may increase the concentration of certain dissolved contaminants, such as As and Al, whose solubilities increase at very high pH. Although evaporation will be most pronounced in hot, dry climates (such as

Nevada or Australia), it can still be a significant process in climates that are cold and dry. For example, Gammons et al. (2006b) estimated that the hypolimnion and epilimnion of the Berkeley pit lake in Butte, Montana, were about 25% evaporated, based on trends in the stable isotopic composition of the water column. Over long periods of time (e.g., 100s of years) evaporation of surface water in terminal meromictic lakes may result in an inversion in the density profile of the lake, thereby inducing overturn.

2.4.2.2 Photosynthesis. Most pit lakes, regardless of pH, contain planktonic algae and cyano-bacteria that photosynthesize. Lakes with near-neutral pH may also have rooted macrophytes (e.g., reeds or lily pads) along shorelines and in littoral areas. For aquatic plants, the overall photosynthesis reactions can be written as follows:

$$CO_2(aq) + H_2O(l) \rightarrow CH_2O(s) + O_2 \qquad (10)$$

$$HCO_3^- + H_2O(l) \rightarrow CH_2O(s) + O_2 + OH^- \qquad (11)$$

where $CH_2O(s)$ is an abbreviation for organic carbon. Although reaction (10) is more familiar to most readers, many plants and microbes can switch to reaction (11) under conditions of high pH when dissolved CO_2 concentrations are extremely low (Vymazal, 1995). In either case, photosynthesis by green plants and algae produces DO and usually results in an increase in pH either by consumption of CO_2 (reaction 10), or production of OH^- (reaction 11). Alkaline lakes with very high productivity may see mid-summer pH values in the 9 to 10 range (Alvarez-Cobelas et al., 1990), and may also exhibit diurnal (day-night) patterns of higher pH and DO during the day and lower pH and DO during the night. In contrast, photosynthesis has little or no influence on the pH of strongly acidic lakes. This is because the H^+ concentration of low pH lakes is controlled by reactions involving dissolved Fe, Al, and S species, and is less influenced by changes in CO_2 concentration. Besides influencing the DO concentration and pH of the epilimnion, photosynthesis is also important in fixing organic carbon which can provide food for higher organisms. Algae are known to "leak" sugars and other substances that can be used as organic substrate by bacteria and other decomposers (Vymazal, 1995).

The rate of photosynthesis in a lake is dependent on sunlight intensity and nutrient availability (Wetzel, 2001). The depth to which light penetrates the water column can be approximated by lowering a black and white secchi disk into the water and noting the depth where the disk is no longer visible to the eye. Photosynthesis can proceed at a significant rate under ice cover, particularly early or late in the winter if the ice is thin and snow is scarce. For lakes at high latitudes or altitudes with thick ice and abundant snowfall, very little sunlight will penetrate to the epilimnion, and therefore photosynthesis will be severely limited in mid- or late-winter. A negative consequence is that DO levels in the epilimnion may drop during winter if there are sources of biological or chemical oxygen demand (e.g., Greenbank, 1945).

Essential nutrients for photosynthesis include nitrate (NO_3^-) and phosphate (PO_4^{3-}). Algae uptake C, N, and P in the approximate ratio of 106:16:1 (in molar units), as shown by the following equation (Redfield et al., 1963):

$$106CO_2 + 16NO_3^- + HPO_4^{2-} + 122H_2O + 18H^+ = C_{106}H_{263}O_{110}N_{16}P(\text{algae}) + 138O_2 \quad (12)$$

Many pit lakes will have an excess of nitrate relative to phosphate compared to the ideal "Redfield ratio", due to inputs of nitrate from blasting residue or breakdown of cyanide. However, this is not always the case. For example, the Berkeley pit lake of Butte, Montana has PO_4 concentrations in the range of 0.1 to 1 mg/L as P (Jonas, 2000), but little or no detectable nitrate. Concentrations of nutrients in pit lakes can be increased by fertilization or addition of nutrient-rich waste water. Careful thought should be given to any nutrification project, as over-application of fertilizer or waste water may lead to eutrophic conditions that could have undesirable consequences, including growth of nuisance algae or rooted plants, or severe depletions in DO in parts of the lake where plant matter is decomposed.

2.4.2.3 Other photochemical reactions.

Besides providing energy for biological synthesis, a number of abiotic oxidation/reduction reactions are catalyzed by sunlight. These include photooxidation of dissolved organic carbon and photoreduction of dissolved or particulate forms of ferric iron (Fe^{3+}). Both of these processes attenuate visible light, and in extreme cases may result in water that appears black at depths of a meter or two, even in the absence of any turbidity. Although there are only a few studies documenting this phenomenon (Friese et al., 2002; Sanchez-Espana et al., 2007; Diez Ercilla et al., in press), photoreduction of Fe is probably a ubiquitous process in the near-surface water of mining lakes that are acidic and iron-rich. Many studies have shown that photoreduction results in day-time increases in Fe^{2+} and total dissolved Fe in acidic rivers and streams (McKnight et al., 1988; Gammons et al., 2005, 2008), as well as in natural lakes with low pH (Collienne, 1983) or circumneutral pH (Emmenegger et al., 2001). During the night, Fe^{2+} is re-oxidized to Fe^{3+}, and may precipitate as HFO or other ferric compounds such as schwertmannite or jarosite. Although photoreduction of dissolved iron is faster than photoreduction of particulate iron, the latter reaction can also occur. The soluble Fe^{2+} produced by photoreduction can then be utilized by algae as an essential nutrient (Emmenegger et al., 2001) or may be re-oxidized to Fe^{3+} by iron-oxidizing bacteria (IOB).

2.4.2.4 Leaching of soluble salts.

Open pit mining creates large areas of fractured and blasted rock that are freshly exposed to the elements. This accelerates the rate of physical and chemical weathering. If the rock contains sulfide minerals, then exposure to oxygen and water will result in acid formation and leaching of metals from the rock (Nordstrom and Alpers, 1999). During wet periods, the acid and metals released may be washed directly into the pit lake, or may infiltrate into the subsurface along cracks to the water table, and thence to the lake via groundwater inflow. In contrast, during extended dry periods much of the acid and metals released from chemical weathering may accumulate on the outcrop surface as efflorescent (i.e., water-soluble) salts. There are a very large number of secondary phases that can form in this environment (e.g., see Alpers et al., 1994; Bowell and Parshley, 2005), but most of the common minerals are sulfates of rock-forming elements such as

Al, Ca, Fe, and Mg, and sulfates or other compounds containing trace metals such as Cu, Pb and Zn. In low pH environments, some of these salts may also contain hydronium ion (H_3O^+), which is one form of "stored acidity". Later on, if the pit lake waters rise or during the next major rain event, the soluble salts will dissolve and be flushed into the lake, possibly leading to episodic water quality problems. The potential for poor quality water to reach the shallow lake by this process can be quantified by performing laboratory or field leaching tests (described below).

2.4.2.5 Precipitation of hydrous ferric oxide.

Many mining pit lakes contain elevated concentrations of dissolved Fe. Figure 12 is an Eh-pH diagram that shows environmental conditions where Fe is soluble as ferric (Fe^{3+}) or ferrous (Fe^{2+}) ions, and where it is insoluble and will precipitate as HFO ($Fe(OH)_3$), siderite ($FeCO_3$), or pyrite (FeS_2). Because most meromictic pit lakes have anoxic deep waters, they often contain elevated concentrations of dissolved Fe^{2+}, even at pH values greater than 6 (see location "A" in Fig. 12). In such cases, Fe^{2+} will be oxidized to HFO or another ferric compound (such as schwertmannite, see Bigham and Nordstrom, 2000) in the overlying oxygenated water column, as shown by the following reaction:

$$Fe^{2+} + \tfrac{1}{4}O_2(aq) + 5/2H_2O \ = \ Fe(OH)_3(s) + 2H^+ \qquad (13)$$

This reaction is normally catalyzed by IOB, such as *Acidithiobacillus ferrooxidans* (Nordstrom, 2003). Although this reaction is effective at decreasing the dissolved Fe concentration of mine waters, it has two deleterious effects: 1) bacterial oxidation of Fe^{2+} can deplete the water column of DO; and 2) the protons released in reaction (13) can result in a drop in pH at shallow depths in the lake. Whether or not pH drops to problematic levels depends on the balance between the rate of Fe-oxidation and the presence or absence of alkalinity in the water. For example, a pH-neutral or alkaline lake with high concentrations of bicarbonate ion (HCO_3^-) can normally buffer the acid generated by reaction (13) without much drop in pH (see path C in Fig. 12). In contrast, if the shallow water has low TDS and low or zero alkalinity, then the protons released during Fe oxidation and hydrolysis may well drop pH below 4 or, in some cases, below 3 (path B in Fig. 12).

Precipitation of HFO near the anoxic/oxic interface of mining pit lakes can lead to scavenging of dissolved solutes that have a high affinity for adsorption onto the Fe-oxide surfaces. Because of its very small grain size and irregular shape, freshly precipitated HFO has a huge specific surface area, estimated to be as high as 250 to 600 m^2 per g of solid (Langmuir, 1997). A large proportion of the unsatisfied bonds at the surface of HFO particles wind up as potential sites for adsorption of solutes from the bulk water. Different solutes have different affinities for adsorption onto HFO, and these affinities are strongly pH-dependent. In general, HFO will selectively adsorb anions (negatively charged solutes) at low pH, and cations (positively charged solutes) at near-neutral to alkaline pH. The reason for this behavior is that the HFO surfaces behave in an analogous fashion to a polyprotic acid. At low pH, the surfaces are protonated and carry a net (+) charge which attracts negatively-charged anions. As pH increases, the surface sites become deprotonated, develop a neutral or (-) charge, and attract cations. Examples of anions that are strongly adsorbed onto HFO in low pH waters include arsenate ($HAsO_4^{2-}$ or $H_2AsO_4^-$), sulfate (SO_4^{2-}), selenate (SeO_4^{2-}), phosphate ($H_2PO_4^-$ or HPO_4^{2-}) and DOC. Although DOC is a mixture of molecules of different stoichiometry, many of these are weak acids that lose their protons and carry a (-) charge at pH > 2, and therefore adsorb strongly onto Fe-oxides (Tipping, 1981). As pH increases, anionic solutes desorb from the HFO surfaces and are sequentially replaced by metal cations. As shown in Figure 13, each metal cation has a characteristic pH where it will adsorb onto HFO, often referred to as the adsorption edge. Because Pb^{2+} and Cu^{2+} have a higher chemical affinity for HFO surface sites, they adsorb at lower pH than other solutes such as Zn^{2+} or Ca^{2+}. In reality, the situation is more complex than is depicted in Figure 13, since different solutes "compete" for available sorption sites. As well, it has been shown that some solutes that are attracted to hydrous metal oxide surfaces, such as dissolved organic carbon, can act as a "bridge" between the positively-charged HFO surface and the positively charged metal cations in solution. This phenomenon is sometimes referred to as "co-adsorption" (Sheals et al., 2003).

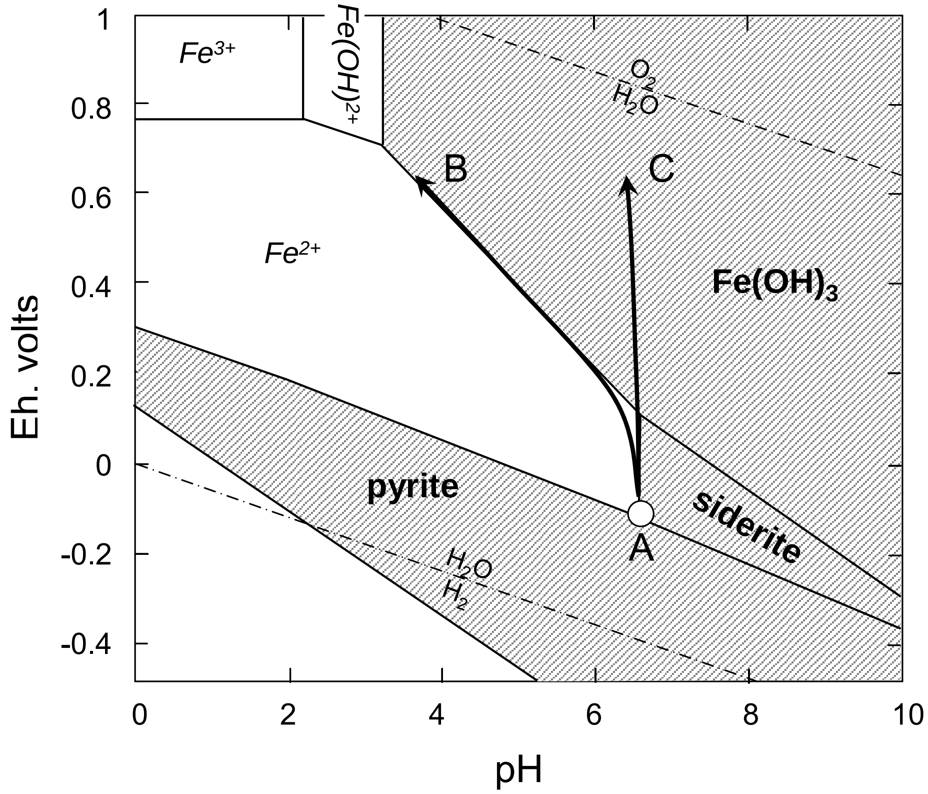


Figure 12. Eh-pH diagram showing the general conditions where Fe is soluble (unshaded areas) and insoluble (shaded areas). The diagram was drawn for 10 mg/L Fe, 10 mg/L C, and 100 mg/L S.

Adsorption of trace solutes onto HFO can be either good or bad. Clearly any process that lowers the dissolved concentration of a toxic substance such as As or Pb is good. On the flip side, sorption of phosphate and DOC may leave shallow water impoverished in nutrients, resulting in lower primary productivity by algae and aquatic plants which are the base of the aquatic food chain. In either case, it is important to remember that adsorption is a reversible process, and therefore ions will exchange freely as conditions in the water column change (Drever, 1997).

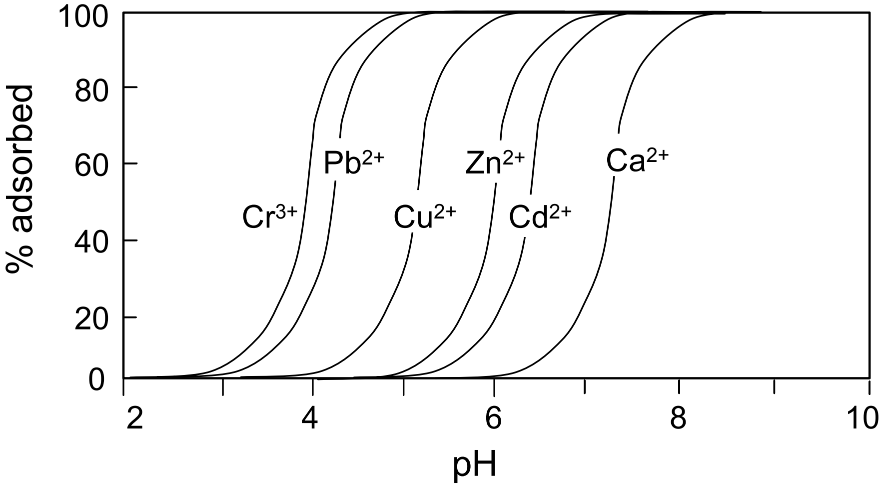


Figure 13. Adsorption of selected cationic trace metals onto hydrous ferric oxide as a function of pH. Diagram modified from Drever (1997).

2.4.2.6 Subaqueous water-rock interaction.

After the initial flush of secondary salts during filling of a pit lake, the rate of leaching of minerals from submerged bedrock will diminish. However, water-rock interactions may still play a role in modifying or buffering the chemistry of the lake. For example, if limestone, dolomite, or other carbonate-rich rock types are present, then dissolution of the carbonate minerals will add alkalinity and help maintain pH values > 6. The key acid-buffering reaction can be written as follows:

$$CaCO_3(s) + 2H^+ = Ca^{2+} + H_2O + CO_2(aq) \qquad (14)$$

Even if the host rocks are igneous, carbonate minerals may be present in veins or disseminated through hydrothermally altered rock. This material can be an important source of acid neutralization potential (ANP or NP) that will help maintain circum-neutral or alkaline pH values.

Compared to carbonate minerals, most rock-forming silicate minerals are much slower to react with water. However, some silicate minerals are more reactive than others. In general, the rate of weathering of silicate minerals found in igneous rock is more or less proportional to their position in “Bowen’s Reaction Series” (Fig. 14). Anhydrous minerals such as olivine or Ca-rich plagioclase that crystallize from magmas at the highest temperatures and pressures are furthest from equilibrium in the near-surface weathering environment. If present on the submerged walls of a pit lake, such phases will break down or transform to more stable minerals, such as clay, and will release silica and metal cations (e.g., Ca^{2+}, Mg^{2+}, and Fe^{2+}) to solution Example reactions for anorthite (Ca-rich plagioclase) and forsterite (Mg-rich olivine) can be written as follows:

$$CaAl_2Si_2O_8(s) + 2H^+ + H_2O = Al_2Si_2O_5(OH)_4(\text{kaolinite}) + Ca^{2+} \quad (15)$$

$$Mg_2SiO_4(s) + 4H^+ = 2Mg^{2+} + H_4SiO_4(aq) \quad (16)$$

Because these reactions consume protons, the presence of minerals like Ca-rich plagioclase, olivine, or pyroxene can add a significant amount of acid neutralization potential to the wallrock. In contrast, minerals such as quartz, K-feldspar, and muscovite that are near the bottom of Bowen's Reaction Series are closer to equilibrium with ambient conditions at the Earth's surface, and therefore are extremely slow to react. Following this train of thought, if follows that mafic or ultramafic rocks (e.g., basalt, gabbro, amphibolite, peridotite) will have higher reactivity and acid neutralization potential than felsic or silicic rocks (e.g., granite, rhyolite, sandstone, quartzite).

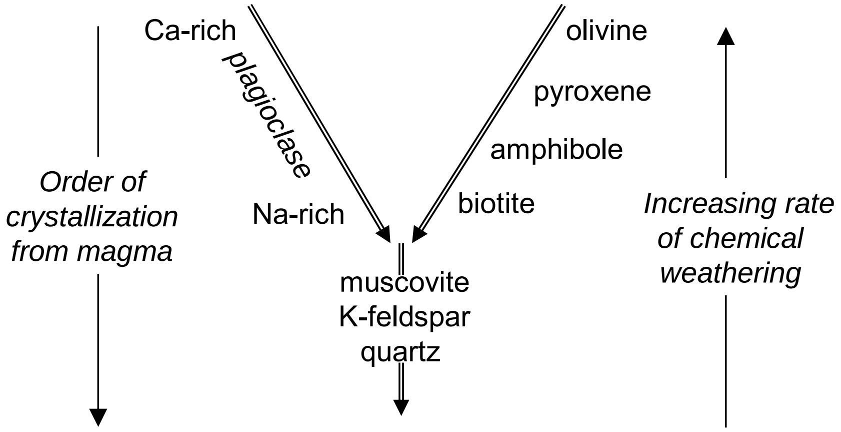


Figure 14. Bowen's Reaction Series, showing the sequence of crystallization of common silicate minerals from magma. Minerals near the top of the series are furthest from equilibrium with the Earth's surface and will chemically weather at a faster rate.

2.4.2.7 Subaqueous pyrite oxidation.

It is commonly stated that the three essential ingredients for pyrite oxidation are pyrite, oxygen, and water, and the overall reaction is often written as follows:

$$FeS_2(s) + 7/2O_2(aq) + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad (17)$$

DO concentrations in lakes are typically < 10 mg/L, or approximately 0.3×10^{-3} mol/L. About 0.2×10^{-3} mol/L of H^+ would be generated if all of this DO was used up by reaction (17), enough protons to drop the pH of the water to ~ 3.5 to 4 assuming no competing reactions. However, because diffusion rates of O_2 in water are extremely slow, water below the wave zone that has lost its DO may not see oxic conditions again until the next turnover event. This effectively shuts off the pyrite oxidation reaction with respect to equation (17) for water in the hypolimnion or monimolimnion of stratified lakes.

Although O_2 is the most familiar chemical species that drives pyrite oxidation, Fe^{3+} – if present - is actually a much more aggressive oxidant than O_2. The overall reaction for pyrite oxidation by Fe^{3+} can be written as follows (Nordstrom and Alpers, 1999):

$$FeS_2(s) + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \qquad (18)$$

Ferric iron is insoluble at pH > 4, but in strongly acidic waters (pH < 3) it can accumulate to concentrations greater than 100 mg/L. Under these conditions, pyrite on submerged mine walls may be rapidly oxidized by Fe^{3+}, releasing a large quantity of protons (16 moles for each mole of pyrite reacted) and Fe^{2+}. Although this reaction consumes Fe^{3+} quickly, there is normally a large reservoir of Fe^{3+} in acidic pit lakes, especially when one considers secondary minerals (HFO, schwertmannite, jarosite) on mine walls and suspended in the water column. If dissolved Fe^{3+} concentrations diminish through pyrite oxidation, these Fe-rich minerals can re-dissolve, releasing more Fe^{3+} that can drive reaction (18) to the right. In this way, pyrite oxidation can continue in the complete absence of O_2 (Madison et al., 2003).

The only studies that have stressed the potential importance of subaqueous pyrite oxidation in a mining pit lake are those of Madison et al. (2003) and Pellicori et al. (2005), both of whom focused on the Berkeley pit lake of Butte, Montana. Madison et al. (2003) concluded that millions of moles of protons are probably added to the deep pit lake each year via reaction (18), and Pellicori et al. (2005) gave stable isotope data in support of this hypothesis. Although subaqueous oxidation of pyrite by Fe^{3+} is probably a common (and usually overlooked) phenomenon in acidic lakes, this process is not expected to be important in pit lakes with near-neutral or alkaline pH, mainly because the solubility of Fe^{3+} is so low at pH > 4.

2.4.2.8 Bacterial reduction of iron and sulfate

Most redox reactions taking place in deeper waters of mining pit lakes are catalyzed by bacteria (Nordstrom, 2003). Heterotrophic bacteria utilize dissolved organic carbon (DOC) as a source of electrons to reduce compounds such as dissolved oxygen, nitrate, Mn or Fe oxides, or sulfate. Example balanced reactions are given below wherein the source of organic carbon in each case is taken as acetate (CH_3COO^-), a common form of DOC:

$$CH_3COO^- + 2O_2(aq) + H^+ \rightarrow 2CO_2(aq) + 2H_2O \qquad (19)$$
$$CH_3COO^- + 8/5NO_3^- + 13/5H^+ \rightarrow 4/5N_2(g) + 2CO_2(aq) + 14/5H_2O \qquad (20)$$
$$CH_3COO^- + 4MnO_2(s) + 9H^+ \rightarrow 4Mn^{2+} + 2CO_2(aq) + 6H_2O \qquad (21)$$
$$CH_3COO^- + 8Fe(OH)_3(s) + 17H^+ \rightarrow 8Fe^{2+} + 2CO_2(aq) + 22H_2O \qquad (22)$$
$$CH_3COO^- + SO_4^{2-} + 3H^+ \rightarrow H_2S + 2CO_2(aq) + 2H_2O \qquad (23)$$

Under strongly reducing conditions where elevated levels of dissolved H_2 gas are present, microbes may *reduce* DOC to form methane, a process that is referred to as methanogenesis:

$$CH_3COO^- + 4H_2(aq) + H^+ \rightarrow 2CH_4(aq) + 2H_2O \qquad (24)$$

All of these reactions are thermodynamically favorable, and the energy gained by catalyzing each redox reaction helps drive the microbes' metabolism. In general, the relative amount of energy to be gained from each of the above reactions decreases in the approximate order given. As a result, aerobic bacteria who make use of reaction 19 will typically dominate as long as DO is present. When all DO is consumed, then anaerobic bacteria will reduce nitrate next, then Mn, then Fe, and lastly sulfate. In reality, most of these reactions occur over a range in redox conditions, and the Eh (i.e., oxidation state) at which a given reaction begins is also strongly pH-dependent, as illustrated in Figure 15. For example, the Eh ranges corresponding to Fe reduction and sulfate reduction overlap at high pH, but are widely separated at lower pH.

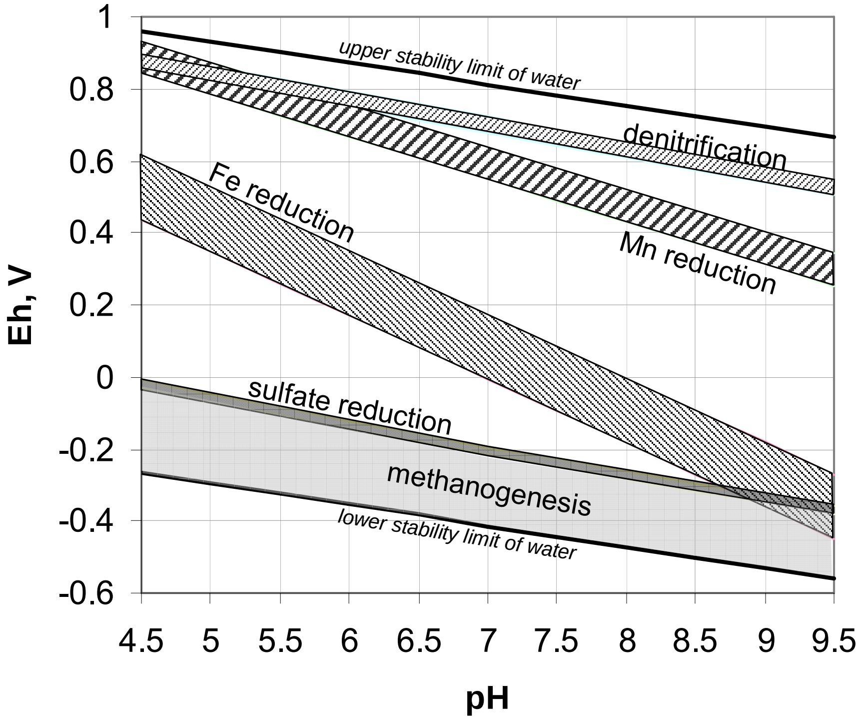


Figure 15. Diagram showing the approximate Eh and pH conditions of selected bacterial reactions that may be important in mining pit lakes. All data used to draw this diagram were taken from Drever (1997). Fe and Mn reduction lines assume equilibrium with ferrihydrite and birnessite, respectively. Upper and lower limits for Fe and Mn reduction were taken at 1 µmol/L and 1 mmol/L dissolved Fe^{2+} and Mn^{2+}, respectively. Upper and lower limits for sulfate reduction were taken at $SO_4^{2-}/(H_2S+HS^-)$ ratios of 1000 and 1, respectively. Upper and lower limits for nitrate reduction were taken at NO_3^- = 0.1 mmol/L, and $P(N_2)$ = 0.001 and 1 bar, respectively.

Examination of reactions 19 through 23 shows that bacterial oxidation of DOC typically consumes protons (thereby raising pH) and produces CO_2. The increase in pH accompanying reactions such as iron or sulfate reduction can be significant, and may improve the water quality of deeper waters in acidic pit lakes that are iron- or sulfate-rich. This is particularly true of sulfate reduction, as the H_2S that is produced by bacteria will combine with dissolved heavy metals to form insoluble metal sulfides, as shown in the following generic reactions:

$$Me^{2+} + H_2S = MeS(s) + 2H^+ \qquad (25)$$
$$Me^{2+} + HS^- = MeS(s) + H^+ \qquad (26)$$

where Me^{2+} refers to a divalent heavy metal such as Cd^{2+}, Cu^{2+}, Fe^{2+}, Ni^{2+}, Pb^{2+}, or Zn^{2+}. Reaction (25) applies at pH ≤ 7, whereas reaction (26) applies at higher pH. Metal sulfides formed by either reaction will slowly settle by gravity to the bottom of the lake and will accumulate in sediment, where they may undergo diagenetic transformations that increase their particle size and crystallinity. Such a process drives the slow conversion of nanocrystalline FeS(s) to micron- or millimeter-sized grains of pyrite (FeS_2).

Although bacterial iron and sulfate reduction may raise the pH of a lake, they may also have undesirable consequences. For example, reactions (21) and (22) will increase the dissolved concentrations of Fe and Mn, which may then diffuse or convect (during lake overturn) upwards to shallower levels where re-oxidation occurs, resulting in re-precipitation of hydrous Fe and Mn oxides and release of protons. Reductive dissolution of Fe and Mn oxides may release trace metals or metalloids that were adsorbed onto the solid particles (Hongve, 1997). This is particularly true of arsenic, phosphate, and DOC, all of which have a strong affinity for sorption onto HFO. In some lakes, bacterial Fe reduction can be an important factor in increasing the TDS of bottom water, thereby promoting meromixis. This may be good or bad, depending on the intended end-use of the pit lake. Lakes with high microbial activity may also see dramatic increases in the partial pressure of CO_2 and possibly H_2S, especially in deep waters near the sediment interface. In extreme cases, high concentrations of dissolved gas may be dangerous in the event of a top-to-bottom turnover (see Section 2.3.4).

2.5 BIOLOGY OF PIT LAKES

Understanding the biology of mine pit lakes, including the invasion of pioneer and successional species, is vital when considering effective reclamation strategies. Although the physical, chemical and limnological characteristics of pit lakes are relatively well understood, there is little information available regarding the biological characteristics of such systems. Since pit lakes are often contaminated with heavy metals and/or low pH (Nixdorf et al., 1998a, 1998b; Wollmann et al., 2000), much of the research on the biology of pit lakes has focused on trying to understand the trophic organization in such inhospitable environments (Klapper and Schultze, 1995). Information on the ecology of pit lakes that have chemical and physical properties similar to other natural lakes in similar areas is still quite scarce. Furthermore, most research on pit lake colonization and habitat use have focused on bacteria, phytoplankton, zooplankton, and to a lesser degree invertebrates (e.g., Nixdorf et al., 1998a, 1998b; Steinberg et al., 1998). Information on the establishment of macrophytes in and around these water bodies, and the use of habitat in such systems by wildlife and fishes is much less available.

The species diversity of a mine pit lake will be highly influenced by the specific natural biological diversity that persists in other waterbodies in the vicinity. Biocenoses in pit lakes, additionally, will be dependant on various and complex factors including how the lake was filled and the initial physical and chemical conditions of the water body (Tandonleke et al., 2000; BHP 2005). In many cases, immediately after pit lake formation, these habitat conditions (e.g., light availability, metal concentrations, nutrient levels, and pH) are quite stressful resulting in biological diversity that is low, or even absent, especially at higher trophic levels (Roch et al., 1985; Klapper and Schultz, 1995; Nixdorf et al., 1998a, 1998b). Additionally, littoral zones and associated habitat are often scarce or absent due to the steep-sided contour of these pits (Kalin et al., 2001). The lack of this productive habitat will limit the establishment of aquatic vegetation and therefore micro- and macro-invertebrates, fishes, and other wildlife. Finally, these water bodies are often deep, with small surface area to depth ratios often resulting in meromixis and permanent anoxia at depth (Castro and Moore, 2000; BHP, 2005). Because of these characteristics, pit lakes tend to have limited biological activity and chemical interactions dominate (Castendyk and Webster-Brown, 2006). Not surprisingly, the biological community of a newly formed pit lake differs markedly from that of natural lakes in the same area (BHP, 2005), with diversity and abundance being much lower in the former (Klapper and Schultze, 1995). Since many of these characteristics will naturally change with time after lake formation, the biological diversity will be different depending on the age of the water body, with more taxa being present in older lakes (Lipsey and Malcolm, 1981).

2.5.1. Bacteria

Initially, in newly formed pit lakes some bacteria will exist (Klapper and Schultze, 1995), but taxa richness and abundance will be dependant on lake-specific habitat characteristics such as those listed above. If conditions are unfavourable, which is often the case when pits are filled naturally with ground and surface water, the first colonists will be micro-organisms that can tolerate such conditions (Steinberg et al., 1998; Wollmann et al., 2000). These, in turn, could be abundant in certain cases due to reduced competition (Klapper and Schultze 1995). For example, many studies document the presence of acidic tolerant species of bacteria (e.g., *Ochromonas spp., Acidithiobacillus spp.*) (Klapper and Schultze, 1995; Wollmann et al., 2000) when pH is quite low (pH < 3), a characteristic often typical of pit lakes (Castro and Moore, 2000). As these acidic lakes stabilize and water chemistry evolves towards a steady state (e.g., pH increases from acidic to neutral), the community structure will change and the number of species can be expected to increase (Kalin et al., 2001; Wollmann et al., 2000). Often mine pits are manually filled by force flooding the pit with nearby water bodies to create the lake. If this is the case, then initial bacterial and microbiota communities can be expected to be similar to the contributing water body, however, usually with a fewer number of total species (eg., Tones, 1982). Additionally, in these manually filled waterbodies, the number of species will be expected to increase with time since filling (Lipsey and Malcolm, 1981; Kalin et al., 2001). In these systems, depending on the species, bacteria can cause acidification, reduce DO levels, contribute to the cycling of metals and organic decomposition which may in turn improve water quality (BHP, 2005), all important roles in aquatic ecosystems.

2.5.2. Plankton

Phytoplankton and zooplankton communities may dominate the biota of pit lakes, depending again on the water quality variables. Overall, plankton abundance is expected to be low in acidic pit lakes or lakes contaminated with heavy metals (e.g., Zn and Cu). Previous studies have shown that water chemistry is the main determinant of species composition and diversity, but nutrient levels were the main determinant of biomass (Nixdorf et al., 1998a,b; Lessmann and Nixdorf, 2000; Kalin et al., 2001). Additionally, algae biomass can be expected to increase linearly with an increase in chlorophyll a concentrations in the waterbody (Brenner et al., 1987). Regarding both phytoplankton and zooplankton, marked differences in species composition is noticed with differences in pH (Klapper and Schultz, 1995; Kalin et al., 2001). Although some acid tolerant species may become established in pit lakes, as might be expected, these are often low in biological diversity and total biomass (Wollann et al., 2000). Nixdorf et al. (1998a,b) found species of *Ochromonas* and *Chlamydomonas* were dominant in acidic pit lakes of Germany and more diverse algal assemblages with diatoms and cryptophytes persisted in lakes with moderately acidic or alkaline conditions. Similarly, Klapper and Schultze (1995) found that pioneer phytoplankton communities in acidic lakes were similar to those in acidic bog water bodies in the same area of eastern Germany. Furthermore, if newly formed pit lakes are characterized by extremely acidic conditions due to a lack of bicarbonate, all algae groups of the *Scenedesmus*-type of photosynthesis are missing (Klapper and Schultz, 1995) as they require this inorganic compound in order to exist. Heavy metal contamination may also hinder zooplankton and phytoplankton diversity and abundance in lakes as shown by Roch et al. (1985). In this study, it was found that in Buttle Lake, Vancouver Island, diversity of planktonic species declined as a result of nearby mining operations that have increased Zn and Cu concentrations in the waterbody. They also found that some metal sensitive forms had disappeared altogether.

Zooplankton and phytoplankton density and diversity is also a function of the elapsed time since lake creation. Brenner et al. (1987) studied phytoplankton and zooplankton assemblages in 60 surface mine lakes in Pennsylvania and found that virtually all lakes supported diverse aquatic plankton communities. The authors found, with respect to phytoplankton, that the types present varied with the age of the lake. For example, Pryophyta were more prevalent in younger lakes (< 10 years) and Chlorophyta and Chrysophyta being more abundant in older lakes (20-30 years). Furthermore, they found phytoplankton were not evenly distributed through the water columns of these pit lakes. Pryophyta were more numerous at lower depths, whereas Cyanophyta and diatoms prevailed at shallower depths. In the same study, 42 taxa of zooplankton were identified and diversity of these organisms was found to correlate positively with the age of the lake (Brenner et al., 1987).

If newly formed pit lakes are not acidic and have properties similar to other lakes in the area then phytoplankton and zooplankton communities will initially first be colonized by pioneer species that exist in the area, and will follow successional stages that are typical in other lakes of the area (Tones, 1982). In some cases plankton establishment in pit lake water bodies may also be mediated through the transfer of these species by waterfowl (Arauzo et al., 1996). If pit lakes are created via flooding with surface water, then the initial phytoplankton and zooplankton communities will be very similar to those of the source water body (Kalin et al., 2001). Although usually not as biologically diverse as the contributing water body (Tones 1982), the number of taxa should increase with time (Lipsey and Malcolm, 1981). An open pit that is rapidly filled with water upon closure is apt to have very high turbidity and poor light penetration. With time, suspended sediment will settle to the bottom of the lake, which may allow the establishment of phytoplankton communities (Kalin et al., 2001). Additionally, there may be diel or seasonal changes in phytoplankton and zooplankton community structure (Armengol and Miracle, 2000; Kalin et al., 2001).

2.5.3 Macrophytes

Literature pertaining to macrophytes is even scarcer than for the micro-biota. Pietsch (1993) distinguished four stages of development of pit lakes: a macrophyte-free initial stage (I), an early stage (II), a transition stage (III) and an old-age stage (IV) (cf. Klapper and Schultz, 1995). The establishment of macrophyte communities in pit lakes will depend on several factors including geographic location of the lake, stage of development, water quality characteristics and physical lake characteristics. In the absence of planting, and with favorable conditions with respect to the variables mentioned above, the first aquatic macrophytes to colonize the lake will be pioneer plant species native to the area. This will of course depend on the geographic location, but for instance typical aquatic macrophyte pioneer species may include pondweed (*Potamogeton spp*.) cattails (*Typha spp*), bulrushes (*Scirpus spp*) and sedges (*Carex spp*). Tones (1982), assessing the Gunnar uranium mine in Northern Saskatchewan, found that macrophytes were restricted to locations where haul roads entered the pit. Despite their aerially restricted coverage, the aquatic vegetation was nonetheless fairly typical of the area. This highlights the importance of mine reclamation in the form of landscaping or backfilling to create littoral zones where aquatic vegetation can establish. Sumer et al. (1995) found that lake morphometry and water levels had a bigger influence on macrophyte abundance than did increasing nutrient levels in East Pit Lake, Alberta (see section 5.3). This lake is relatively shallow (mean depth = 3.3m, Sumer et al., 1995) indicating that littoral habitat is likely quite extensive.

2.5.4. Invertebrates

The presence of invertebrates in pit lakes depends on several characteristics, but the establishment of littoral habitat with aquatic vegetation is crucial. If productive littoral zones are established, either naturally over time, or created during the reclamation process, invertebrates may be quite common. For instance, Sumer et al. (1995) found diverse aquatic invertebrate assemblages in East Pit Lake, Alberta, a waterbody created as part of a coal mine reclamation project. Tones (1982) found 22 taxa of invertebrates, dominated by leeches, in the Gunnar uranium mine pit lake, most abundant in littoral habitat. This pit was filled with water from a nearby lake, therefore pits filled passively may exhibit quite different community structure. In deeper parts of the lake, invertebrate numbers may be low, or they may be absent altogether (Tones, 1982). The persistence of meromixis and anoxic conditions of bottom waters, combined with the steep-walled nature of pit lakes, can result in the complete absence of a benthic community (BHP, 2005). Pelagic invertebrate communities can also be limited or absent due to reduced nutrient availability and/or inhospitable conditions caused by low pH or high toxicity caused by leaching of metals into the system (BHP 2005). Low pH may be a limiting factor for many invertebrates, but some acid tolerant species (e.g., some species of corixids) may nonetheless establish (Wollmann et al., 2000). Species richness will typically be low in acidic lakes (Wollman et al., 2000), and pioneer species will need to be able to tolerate harsh environmental conditions (Kalin et al., 2001).

2.5.5. Fish

Fish can come to inhabit pit lakes two ways: (1) introduction by flooding with source water that contains fish or (2) deliberate stocking effort. Several examples exist in the literature and both scenarios are discussed in further detail in section 4.2.5. If conditions are favourable for fish survival, regardless of the method used for introduction, fish can be abundant in pit lakes. Each fish species can tolerate a specific range of temperature before being stressed. In Canada, freshwater fish species typically fall into two categories: (1) coldwater fish species that prefer temperatures between 10-18^{o}C, and (2) coolwater fish species preferring temperatures ranging from 18-26^{o}C (Nelson and Paetz, 1992). Fishes of northern Canada are represented by both groups of fish although the majority would typically fall into the former category, including species such as lake trout (*Salvelinus namaycush*), arctic char (*Salvelinus alpinus*) and Arctic grayling (*Thymallus arcticus*). Thermal tolerance of a species is an important consideration when deciding which species to introduce if supplementation is used to establish fish communities in pit lakes.

Fishes also require waterbodies with an adequate supply of DO. Fishes will vary in their DO requirements, depending on their stage of life history, weight, activity level, water temperature, and feeding habits (Moyle and Cech, 2003). Since temperature and biological processes directly influence DO concentration, there will be DO level variations throughout the water column of the lake and levels will change depending on the time of year or even time of day. Because of this, fishes may be forced to actively move throughout the water column or to different parts of the lake to meet their DO requirements. Coldwater fishes require relatively high DO concentrations in comparison to coolwater fish species (Nelson and Paetz, 1992), and mortality in these groups of fishes can occur if DO concentration falls below 2.0 mg/L (Doudoroff and Shumway, 1970). This may become an important consideration in northern pit lakes as they can be isolated from atmospheric oxygen by ice cover for a large portion of the year.

Fishes also require a wide array of different habitats to complete their life cycle which will vary depending on the species, time of year, life history stage and sex. Fish require, directly and indirectly, very specific habitat for spawning and breeding, feeding, rearing, habitat for cover and protection and habitat that will allow for the migration of fish between these areas of use. In lakes, this will include areas such as gravel beds or rocky shoals, and structures such as boulders, collections of woody debris, and undercut banks. For example, juvenile fish will typically require areas that will provide sufficient cover and therefore protection from predators whereas spawning adults may require rocky shorelines or aquatic vegetation depending on the species. Since newly created pit lakes are usually devoid of such habitat, it is important to incorporate reclamation practices that include the creation and maintenance of fish habitat. For example, the creation of underwater structures (logs, boulder clusters or rock piles) for cover or shoals for spawning will be important for newly formed pit lakes. Additionally, since aquatic vegetation is one of the most important factors for habitat selection (Pratt and Smokorowski, 2003) the establishment and maintenance of littoral zones which include a diverse array of aquatic macrophytes will be important for fish survival in pit lakes. Such areas will undoubtedly provide more food and cover especially for small or juvenile fishes.

2.5.5.1. Metal toxicity and fish.

Relative to uncontaminated, natural lakes in the same area, newly created pit lakes often have elevated levels of metal concentrations and there is an enormous body of literature on the negative effects of metals on the health of aquatic life (see Kelley, 1988, for a comprehensive summary). For fishes, metal toxicity is often quantified by the so-called "LC_{50}" - the lethal concentration of a particular metal that would kill 50% of a batch of organisms during a specified time period, usually 48 to 96 hours. As discussed by Kelley (1999), the LC_{50} varies from species to species and from metal to metal, and also is a function of the bulk characteristics of the water, such as its salinity, hardness, and pH. It is generally agreed that heavy elements are most toxic in their simple ionic forms, e.g., Al^{3+}, Cu^{2+}, Pb^{2+}, Zn^{2+}, and these "free ions" are most stable at low pH. Complexation of the metal with a strong ligand, such as dissolved organic carbon, can significantly reduce the bioavailability of the metal of concern (Santore et al., 2001). The presence or absence of competing ions in solution is also a major factor determining metal toxicity. High concentrations of Ca^{2+} and Mg^{2+} ions, in particular, are known to reduce the LD_{50} for most divalent heavy metals. This is why regulatory standards for protection of aquatic life for many heavy metals (including Cd, Cu, Ni, Pb and Zn) are often not reported as single values, but rather are a non-linear function of the water hardness (i.e., the combined $Ca^{2+} + Mg^{2+}$ concentration of the water). It is also known that the presence of multiple environmental stresses (e.g., the presence of both Cu and Zn in a water) can be either additive, synergistic, or antagonistic. If *additive*, this means that the combined effect is essentially the sum of the individual effects. If *synergistic* or *antagonistic*, this means that the combined effect is greater than or less than the individual effects, respectively. Kelley (1999) points out that very little is known about stress due to co-exposure to different metals in aquatic ecosystems, especially when other forms of environmental stress – such as extremes in temperature, dissolved oxygen, turbidity, or pH – are involved.

Figure 16 (from Kelley, 1999) lists ranges in reported values of LC_{50} for fishes based on exposure to Ni, Cu, Zn and Pb. The large range in LC_{50} for each metal is partly a reflection of inter-species variation (e.g., note how salmonid species are more sensitive to Cu than non-salmonid species), and partly a reflection of changes in the laboratory conditions of each study, such as the duration of exposure, and also the pH and hardness of the water used in the study. Nonetheless, it is clear from Figure 16 that the presence of trace amounts (< 1 mg/L) of Cu, Pb, and Zn can be lethal to fishes. Much lower concentrations of each metal would be expected to have a deleterious effect on overall fish survival, such as lower reproduction rates or decreased ability to avoid predators.

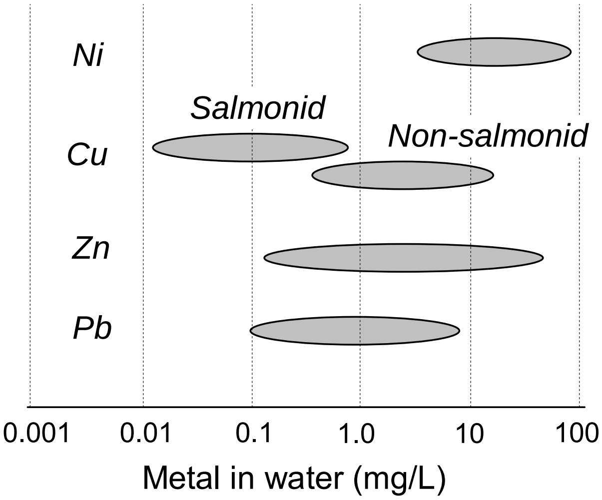


Figure 16. Ranges in published data for LC_{50} concentrations of selected heavy metals to fishes (from Kelley, 1999).

2.5.6. Waterfowl

The literature on pit lake use by other forms of wildlife is quite scarce, and virtually all studies to date have focused on habitat use of gravel pit lake systems by waterfowl. In the Great Linford gravel pit, England, Phylips (1992) showed that waterfowl were common inhabitants of the lake. In the newly flooded lake dabbling ducks dominated but as the lake aged, macrophyte-feeding waterfowl became more common. In six gravel pit lakes of France, Santoul et al. (2004) recorded 39 species of waterfowl. In this study, the presence of paths also reduced abundance and diversity owing to human disturbance, which is certainly an important factor in habitat selection. Therefore pit lakes where there is an abundance of recreational use would also deter waterfowl from inhabiting the lake. The most important factor influencing waterfowl use in pit lakes, however, is likely food availability, which undoubtedly relates to the quantity and quality of vegetation found in the water body (Phylips, 1992; Santoul et al., 2004). This may relate to the age of the lake, water quality and physical characteristics of the waterbody. Additionally, other factors such as competition for breeding locations and food will influence abundance and diversity in these systems.

2.6. UNIQUE ASPECTS OF PIT LAKES IN NORTHERN ENVIRONMENTS

Pit lakes in northern areas such as the Northwest Territories of Canada may share certain characteristics in common with lakes at lower latitude, but at the same time are likely to have profound differences. The hypolimnion or monimolimnion of deep lakes in temperate climates are cold year-round, with temperatures near or slightly above 4°C, the maximum density of water. Stratified lakes in northern regions should have similar temperatures for their deeper waters. Thus, many of the processes that take place below the metalimnion of stratified lakes should be similar regardless of the latitude of the lake. As an example, the limnology and geochemistry of the Udden pit lake in northern Sweden (Ramstedt et al., 2003) is very similar to pit lakes with similar geology in more temperate environments. On the other hand, some large differences are expected in northern climates with extremely cold temperatures, especially with regards to ice formation, permafrost, and biology of the epilimnion and surrounding terrestrial habitat.

Two key factors that have an impact on the limnology of northern lakes include low average temperatures and very large, seasonal variations in solar insolation. At the Ekati Diamond Mine located 300 km north of Yellowknife, NT, Canada, temperatures range between -40^{o} and $+25^{o}$C with only four months having mean temperatures above freezing (BHP, 1997). As a result, snow dominates the landscape for the majority of the year and lakes are ice-covered more than they are ice-free (e.g., Pienitz et al., 1997a, b; Rikiishi et al., 2004). The thickness of the ice cover depends on many factors, but can exceed 2 m (Duguay et al., 2003). At some extreme northern locations, ice-cover can persist year round (Doran et al., 1996). As a comparison, in Minnesota where there are more than 4000 abandoned quarry pits and over 200 abandoned iron ore pits, ice cover usually persists for less than 5 months, from December to April (Axler et al., 1998).

In addition to extensive ice cover, northern regions are subject to large variations in light availability, from near-total darkness during the winter to continuous sunlight during the summer months. The Diavik Mine near Lac de Gras, NWT experiences two hours of daylight during midwinter and 22 hours of sunlight during midsummer (Diavik Diamond Mine Incorporated, 2007). Further north, at Colour Lake on Axel Heiberg Island, in Nunavut, there are four months of darkness in the winter and four months of continuous sunlight in the summer (Doran et al., 1996). The amount of solar radiation reaching the surface is also influenced by cloud cover and cloud opacity (Young et al., 1995).

The combination of extensive ice cover and variable solar insolation has several possible ramifications to pit lake dynamics, including the following:

- extreme seasonal variation in primary productivity
- seasonal variation in other photochemical reactions (such as Fe photoreduction)

- increased risk of oxygen depletion during winter
- thermohaline convection
- increased likelihood of meromixis

Ice decreases light penetration to the underlying water column, and this can be further exacerbated by the presence snow cover (Roulet and Adams, 1984; Duguay et al., 2003). This means that photosynthesis (and other photochemical reactions, such as Fe photoreduction, see Section 2.4.2.3) will be greatly diminished during periods of the year with thick ice cover, especially during mid-winter months when the number of hours of sunlight are at a minimum. In contrast, the long days of summer are conducive to much higher rates of photosynthesis, provided that sufficient nutrients are available. Most large lakes in northern Canada (e.g., Great Slave, Great Bear) are highly oligotrophic, with low crops of planktonic or benthic algae and relatively sparse fish populations (Northcote and Larkin, 1963; Livingstone, 1963). Barring an influx of nutrients from a man-made source, similar oligotrophic conditions would be expected for mining pit lakes in the far north. If so, primary production would most likely be nutrient-limited in the summer, and light-limited in the winter. Interestingly, there is some evidence that primary production in arctic lakes has been on the rise in the past century, most likely due to global warming trends (Michelutti et al., 2005).

Once a lake is covered with ice, it is no longer possible for oxygen to freely diffuse into the water column from air. If photosynthesis is diminished by ice cover and/or dim sunlight, then there is also very little *in situ* production of oxygen. Given these conditions, any biological oxygen demand (BOD, e.g., from bacteria or other respiring organisms) or chemical oxygen demand (COD, e.g., from oxidation of pyrite or dissolved Fe^{2+}) could result in a reduction in the amount of DO in the water column. In extreme cases (so-called "hypoxic" conditions), DO levels can fall below thresholds for fish survival, a phenomenon known as a "fish winterkill" (Greenbank, 1945; Nickum, 1970; Magnuson et al., 1989). Mortality for cold water fish species, such as those found in most northern regions, may occur if DO concentrations fall below 2.0 mg/L (Doudoroff and Shumway, 1970), and fishes inhabiting lakes with long-lasting ice cover are more vulnerable to such hypoxic conditions (Evans, 2005). Alternatively, if the ice and snow cover has a high transparency then photosynthesis can continue, albeit at a reduced rate due to the low angle of the sun. Fish winterkills are a phenomenon most often associated with shallow, eutrophic lakes as opposed to deep, oligotrophic lakes (Nickum, 1970). However, the fact that pit lakes often have higher COD (e.g., from oxidation of dissolved Fe^{2+} or pyrite) means that they may be more susceptible to winterkill than natural lakes with similar morphometry and climate.

As discussed in Section 2.3.5, formation of ice results in exclusion of dissolved solids, which can then form brine streamers that sink by gravity through the water column. The end result of this process (i.e., thermohaline convection) is an increase in the salinity of deeper water in the lake. Later in the year, melting of the ice cover results in a low-salinity, low-density layer on the top of the lake. Because of these two factors (ice formation and ice melting), it is very possible that deep lakes in northern climates will become density-stratified. The likelihood of meromixis is further increased if deeper portions of the lake receive salty groundwater. According to one recent study (Kuchling et al., 2000), the salinity of groundwater near the Diavik diamond mine in the NWT increases with depth, attaining an average of ~ 1000 mg/L at 500 m below surface, and ~ 6400 mg/L at 1000 m below surface. Highly saline groundwater is also common beneath permafrost in the diamond fields of northern Russia (Borisov et al., 1995; Alexeev and Alexeeva, 2003).

Associated with the cold climate, pit lakes in northern environments must also contend with permafrost conditions. Permafrost is defined as ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years (NRC Canada, 1988). Approximately half of Canada, and virtually all of northern Canada, has permanently frozen ground (Heginbottom et al., 1995). Overlying the permafrost is the active layer, a layer of substrate of varying depth depending on regional conditions that thaws annually (NRC Canada, 1988). Permafrost is typically absent beneath large lakes and rivers, even in northern climates (Mackay, 1997). However, when a natural lake is drained, such as may happen when a diamond deposit is mined, permafrost will build downwards from the newly exposed lake bottom and upwards from the depth where permafrost starts until the two points of freezing merge (Mackay and Burn, 2002). In the event that the open pit is later flooded, conduction of heat from the water column may cause the newly formed permafrost to re-thaw. Besides these local effects, permafrost can have substantial impacts on the regional flow of groundwater and surface water, and can also lead to terrain instability with associated geotechnical problems (Environment Canada, 2004). Permafrost must be taken into account for accurate predictions of runoff and groundwater seepage and how these relate to filling rates of pit lakes upon mine closure. The presence of frozen ground is also critical in the design of treatment systems for contaminated drainage (Environment Canada 2004).

Figure 17 shows one possible scenario that could result when an open pit mine in permafrost terrain is subsequently flooded. Besides the fact that the excavation opens up a direct connection between the lake and the adjacent, sub-permafrost groundwater, flooding of the mine void could result in thawing of the pre-mining permafrost zone along the lake margins. Although each mine would need to be evaluated on a case-by-case basis, it seems logical to assume that melting of permafrost on any steep slope would increase the likelihood of slope failure (i.e., landslides). Other negative consequences may include release of biogenic gas, such as methane or H_2, either through enhanced microbial activity due to the thawing conditions, or from thermal decomposition of methane clathrate solids.

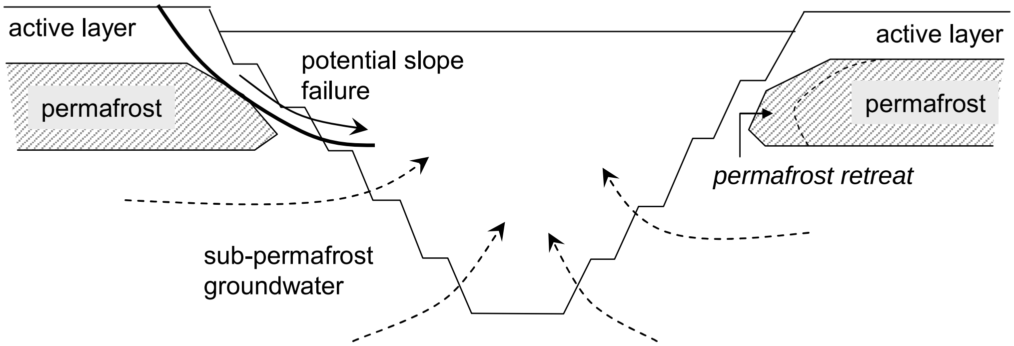


Figure 17. Schematic diagram of a pit lake in a permafrost setting. Conduction of heat from the deep lake may gradually melt back the permafrost layer, resulting in decreased slope stability and slope failure. Lakes that penetrate the permafrost layer may also serve as conduits for deep groundwater recharge or discharge, depending on local hydrogeological conditions. (The sketch depicts groundwater discharge).

The number of plant and animal species endemic to northern environments is low in comparison to more southerly locations, and this is another factor to take into consideration. For example, in the Northwest Territories and Nunavut combined, 46 species of fish have been identified that inhabit freshwater at least periodically during their life cycle (Evans et al., 2002). In comparison, Minnesota, a state a fraction of the size of Canada's northern territories, harbors 160 species of freshwater fish (Hatch et al., 2003), many of which reside in decommissioned pit lakes. This means that there are fewer choices of candidate fish species in northern climates whenever decisions need to be made regarding stocking or other efforts to establish a functional fishery. The same observation applies for other types of biota, such as vascular plants. In the continental Northwest Territories, Porsild and Cody (1980) describe 1113 plant species, whereas Minnesota in comparison has nearly 2400 species (Ownbey and Morley, 1991) inhabiting a much smaller area. The few number of species described at northern locales is undoubtedly due to a combination of cold mean annual temperatures, and subsequent short growing seasons and permafrost laden ground which makes it difficult for plants to establish. Since plant growth is difficult in these northern environments, the vegetation in such areas is typically composed of smaller trees in comparison to their southern counterparts, and dwarf shrubs, graminoids, herbs, lichens and mosses, which all grow relatively close to the ground (Porsild and Cody, 1980). This will be important for reclamation considerations since the successful establishment of riparian and aquatic vegetation will be integral for establishing and sustaining natural diversity in mines that have been reclaimed into lakes. Furthermore, success in establishing vegetation in such reclamation situations depends on proper plant species selection (Buttleman, 1992) which is unquestionably limited in northern environments.

3. PIT LAKE MODELING AND PREDICTION

There are many methods that have been proposed to predict the future water quality characteristics of mining pit lakes. This section will first give the reader some idea of the types of field or laboratory procedures that can be used to predict pit lake water quality. This will be followed by a short review of computer models, with specific reference to some of the more popular programs that are freely available from the web. What follows is not meant to be an exhaustive review of the literature, as this is outside of the scope of the document.

3.1 EXPERIMENTAL PROCEDURES

3.1.1 Acid-base accounting (ABA) tests

Acid-base accounting (ABA) is commonly used to quantify the long-term potential for a given rock or waste material to generate acid. A large number of ABA testing procedures have been developed over the past 3 decades (White et al., 1999; Mills, 2007). The basic idea is to compare the acid-generating potential (AP or AGP) of a given rock or soil sample with its acid-neutralizing potential (NP or ANP). Values of AP and NP are usually reported in units of kg $CaCO_3$/ton of rock. The neutralization potential ratio (NPR) is simply NP/AP. A general rule of thumb is that if a sample has an $NPR < 1$ then it is likely to generate acidic leachate, whereas if the $NPR > 3$, then it is unlikely to generate acid. Samples with NPR between 1 and 3 may or may not generate acid, depending on the abundance and relative rates of weathering of the various mineral components, among other factors.

The acid-generating potential (AP) of a sample is usually determined by measuring the concentration (wt %) of sulfide-S in a given volume of sample. A common assumption is that each mole of S in the rock or soil sample will generate 2 moles of acid upon weathering (see reaction 1). However, this assumes that all of the sulfide-S in the rock is present as pyrite. Although pyrite is by far the most abundant sulfide mineral in the Earth’s crust, it is by no means the only one. Some other common sulfide minerals and their acid-base behaviors during weathering are listed in Table 2.

The most widely-used method for NP determination is the Sobek test (Sobek et al., 1978), which was developed by the US-EPA. In brief, this procedure entails reacting a known volume of crushed rock or soil sample with a known volume of acid, and then determining by titration the amount of acid consumed by the rock. By far the most reactive sources of NP in a rock are carbonate minerals (e.g., calcite, dolomite), although some silicate minerals such as plagioclase and olivine can also help to neutralize acid (see Section 2.3.2.6). There are many variants of the original Sobek method being used by environmental laboratories, and for this reason it is a good idea for a client to get documentation of laboratory procedures when NP analyses are performed.

Table 3: A list of some common sulfide minerals and their likelihood to generate acid on weathering.

mineral	*formula*	**Behavior on weathering**
pyrite	FeS_2	Acid-producing
pyrrhotite	FeS	Acid-producing
chalcopyrite	$CuFeS$	Acid-producing
bornite	Cu_5FeS_4	Acid-producing
arsenopyrite	$FeAsS$	Acid-producing
sphalerite	ZnS	Non acid-producing
galena	PbS	Non acid-producing
chalcocite	Cu_2S	Acid-consuming

A big advantage of ABA tests (also known as "static" tests) is that large numbers of samples can be processed and analyzed relatively quickly and cheaply. It is not uncommon for a mining operation to generate several hundred individual ABA analyses. This information is then used to make decisions regarding management of mine waste, both during and after the mine life. A major disadvantage of the ABA tests is that they give no information on the *rates* of reactions that lead to acid production or consumption in the field. They also give little or no information on chemistry, such as the concentrations of toxic metals that are likely to be present in a mine waste leachate.

3.1.2 Kinetic tests

Kinetic tests are often employed to get more detailed information on the chemistry of mine waters that are likely to be generated in different mine waste settings. One common procedure is the so-called "humidity cell" test (Lapakko, 2003; ASTM, 2007). A humidity cell is a plastic cylindrical chamber filled with 1 kg of crushed rock. The cell is fashioned with ports at the top and bottom for addition of water and/or compressed air. Humidity cell tests are performed on a one-week cycle, where dry (de-humidified) air is circulated through the sample for 3 days, followed by 3 days of humid air. On the 7th day distilled water is added. After 24 hours the sample is drained and the leachate is collected for chemical analysis. This procedure is repeated for a long time, typically > 1 year. The data obtained can be used, among other things, to determine the relative and absolute rates of sulfide depletion and NP depletion from the sample.

In addition to laboratory humidity cell tests, there are a number of possible field tests that can be set up – usually during the period of active mining operations – to help predict leachate chemistry. These include field test plots of waste rock piles or tailings dumps, as well as minewall runoff collection systems (Morin and Hutt, 2001). The big advantage of field kinetic tests is that they generate data on weathering rates and leachate chemistry *in situ*, under conditions of climate and microbial activity that are similar to the mine site.

3.1.3 Pit lake mesocosm experiments

Some simple but useful information to predict future pit lake chemistry can be obtained by gathering representative bulk samples of weathered bedrock from different parts of the pit-wall, crushing the samples to a gravel size, and then leaching with distilled water in the laboratory. This is similar to the leaching procedure used in a humidity cell test. Although crude, these "mesocosm" experiments (sometimes referred to as "pit lake in a can" experiments) are a simple, inexpensive way to get an initial idea of future mine water quality (Davis, 2003). For example, Newbrough and Gammons (2002) performed mesocosm experiments on weathered bedrock from the Berkeley Pit and showed that the leachate obtained had a major and trace metal chemistry remarkably similar to that of the Berkeley pit lake. If there are several different rock types exposed on the walls of an open pit mine, it may be possible to mix a proportionate mass of each unit into a single batch vessel and then measure the water quality of the ensuing leachate.

3.2 COMPUTER MODELING

3.2.1. Hydrogeological models

If a pit lake is part of the final plan for a closed mine, it is critical to have a good idea of how fast it will fill (Naugle and Atkinson, 1993). There are many ways to approach this problem, with differing levels of complexity. If the lake is slated to be filled rapidly (e.g., in a few years or less) by diverted surface water or rapidly pumped groundwater, then estimation of the rate of filling is straightforward, and can probably be done with a simple spreadsheet. The short-term water quality of the lake can be approximated if the chemical composition of each end-member water is known, and if the mixing ratio of the different waters is known. This type of mixing calculation can be done empirically via a laboratory experiment, or numerically using a geochemical modeling program (see below). Using relatively simple analytical equations, it is also possible to come up with initial estimates of the projected rate of groundwater inflow into an open pit (Hanna et al., 1994; Marinelli and Niccoli, 2000; Shevenell, 2000b).

For more sophisticated modeling, especially for long-range predictions or in cases where the lake is expected to fill slowly (e.g., > 10 years), a 3-dimensional groundwater flow model will be needed to predict the rate of groundwater seepage into or out of a pit lake. One example of a program with this capability is MODFLOW, developed and supported by the U.S. Geological Survey (USGS, 2000). MODFLOW requires a large amount of site-specific information including climate, topography, sources of groundwater recharge and discharge, and information on the hydrogeologic properties of geologic units in the subsurface, including both the vadose zone and zone of saturation. Two basic types of model can be created: static or transient. With a static model, one synthesizes and arranges input data until the predicted distribution of hydraulic head at all points in the system agrees with the measured hydraulic heads (e.g., from groundwater monitoring wells). Once calibrated, the static model can be expanded to a transient model that has the ability to simulate changes in the potentiometric surface of groundwater in response to changes in climate or land use.

3.2.2 Limnological models

Limnological models are used to predict vertical stratification in lakes, and the frequency and depth to which lake turnover is likely to occur. Probably the most common limnological model currently in use by pit lake researchers is the program DYRESM, which stands for Dynamic Reservoir Simulation Model (Imberger and Patterson, 1991). DYRESM is a one-dimensional model that is most commonly used to predict seasonal changes in the vertical density profile of a lake. Like MODFLOW, a large amount of site-specific information is required to create an input file. The exact morphometry (i.e., size and shape) of the open pit is first entered into the data base. Detailed seasonal (e.g., hourly or daily) meteorological information is needed, including precipitation, air temperature, relative humidity, wind direction and wind speed, and solar radiation. Because the climate inside a mine pit can be different from that in the surrounding local region (especially with regards to wind direction and wind speed), meteorological data collected within the pit near the lake surface is best. The initial salinity and temperature depth-profile of the lake must be specified, as well as the volume, temperature, and salinity of any groundwater or surface water inputs or outputs from the lake. With this information, DYRESM then calculates the future vertical density profile of the lake in the desired time-step (e.g., days or weeks). Apart from keeping track of salinity (which is needed to calculate water density), DYRESM does not deal at all with chemistry. A copy of DYRESM and a user's manual can be downloaded from the Center for Water Research at the University of Western Australia (CWR, 2007).

3.2.3 Geochemical models

Geochemical models are frequently used by pit lake researchers to determine the aqueous speciation of water in a lake and to predict possible chemical reactions, such as mineral dissolution/precipitation or adsorption of dissolved solutes onto mineral surfaces. Alpers and Nordstrom (1999) give a good review on the subject, including an overview of the different computer codes that are available. Two of the more commonly used modeling programs include Visual MINTEQ and PHREEQC. MINTEQ was developed by the U.S. Environmental Protection Agency (EPA), and has a large thermodynamic database for dissolved and solid inorganic substances, including many toxic metal compounds. Visual MINTEQ (KTH, 2007) is a user-friendly, windows-based version of the original MINTEQ program. PHREEQC is available with extensive documentation from the USGS (USGS, 2007). Of the two programs, PHREEQC has more advanced capabilities, such as inverse geochemical modeling, 1-dimensional transport, batch reaction (including evaporation), and stable isotope mass balance. For routine geochemical calculations, there is little difference between the results obtained by either program. It is important to realize when using a geochemical model that the results are only as good as: 1) the quality of the input data (e.g., laboratory analyses); and 2) the accuracy and completeness of the thermodynamic data in the program database. Both Visual MINTEQ and PHREEQC have periodic updates to their databases which can be downloaded from their respective websites.

3.2.4 Biological models

There have been relatively few attempts to model the biology of mining pit lakes. The University of Western Australia (UWA) has developed a program called CAEDYM, or Computational Aquatic Ecosystem Dynamics Model, which can be used to quantify biological influences on the water quality of lakes, including pit lakes. Some of the processes that are modeled include primary and secondary production rates, nutrient and metal cycling, oxygen production and consumption, and transport of particulate organic carbon. It is also possible to couple CAEDYM with DYRESM, as described at the UWA website (CWR, 2007).

The biotic ligand model (BLM) has recently been developed to better quantify the toxicity of various heavy metals to aquatic life (see Paquin et al. (2002) and Niyogi and Wood (2004) for good overviews of the BLM). Specifically, the BLM calculates the level of metal accumulation at the site of action of acute toxicity – referred to as the "biotic ligand" – in an aquatic organism (Paquin et al., 2002; Niyogi and Wood, 2004). For fish, the biotic ligand for the majority of metals of concern is located within the gill (Paquin et al., 2000). When the concentration of a metal toxin at the biotic ligand site exceeds a particular threshold, then mortality may ensue (Di Toro et al., 2001). An important aspect of the BLM is that it includes thermodynamic data to compute the aqueous speciation of each metal of interest for any site water chemistry (DiToro et al., 2001; Paquin et al., 2002; Niyogi and Wood 2004). Parameters such as pH, hardness, and DOC concentration are important variables that influence the aqueous speciation, and therefore the bioavailability, of each dissolved metal (see section 2.5.5.1). To date, the BLM has most frequently been used with fish and crustaceans to predict toxicity of some of the more common heavy metals, such as Cu and Zn. In the future, additions to the program will allow the BLM to speciate more metals of interest, and to be applied to more organisms (e.g., green algae and bacteria) (Paquin et al., 2002). The BLM may become an important tool to predict the biological impacts of water quality in pit lakes, especially if the potential for establishment of a fishery exists.

4. ENHANCING BENEFICIAL END USES FOR PIT LAKES

The concept of incorporating beneficial end uses for pit lakes in drafting mine closure plans is relatively new. There are at least some examples of mining pit lakes that were flooded many years ago and now have high recreational and ecological value. These include – among others – a number of large lakes in northern Minnesota and southern Ontario left behind from open pit iron ore mining. It is much more difficult to see a benefit to acidic, metal-rich lakes such as the Berkeley pit lake in Butte, Montana, and yet even this water body has some beneficial uses, as will be discussed in the following sections.

4.1 SUMMARY OF BENEFICIAL END USES

Possible beneficial end uses for mining pit lakes were recently reviewed by Doupé and Lymbery (2005) and McCullough and Lund (2006). Table 3 summarizes concepts presented in these two papers, with some additional ideas. Each of these end use categories is discussed in more detail in the following sections.

Table 4. Summary of beneficial end uses for pit lakes, with examples.

	Beneficial end use	**Examples**
1	Permanent storage of reactive mine waste	many
2	Water supply for industry or agriculture	Illinois coal mines (GE78); Enterprise Pit, Northern Territories, Australia (SF94)
3	Aquaculture	Highland Valley, BC (O04); Brazilian Amazon (O04); Minnesota (A96, A98, Y97)
4	Functional habitat for aquatic life	Highland Valley, BC (O04); East Pit Lake, AB (S95); Minnesota (A96a, Y97); Gunnar, SK (T82), Steep Rock, ON (S04); Lac des Roches, AB (S02)
5	Recreation and tourism	East Pit Lake, AB (S95); Portsmouth, MN; Steep Rock, ON (S04); Berkeley Pit, MT
6	Metal recovery	Berkeley Pit, MT (GD06)
7	Heat pump applications	none
8	Scientific study	many

References: A96 = Axler et al. (1996); A98 = Axler et al. (1998); GD06 = Gammons and Duaime (2006); GE78 = Gibb and Evans (1978); O04 = Otchere et al. (2004); S02 = Schwartz (2002); S04 = Sowa (2004); SF94 = Sinclair and Fawcett (1994); S95 = Sumer et al. (1995); T82 = Tones (1982); Y97 = Yokom et al. (1997)

4.1.1 Storage of mine waste

Probably the most common use of abandoned open pits is the permanent disposal of mine waste (e.g., waste rock or mill tailings). The concept of putting waste rock back into the pit it came from (i.e., backfilling) is compelling from the point of view of minimization of long-term disturbance of the land. It can also decrease the volume and severity of acid mine drainage at a closed mine site by burying reactive waste. However, it is stressed that backfilling of open pits is not always the best strategy. Each mine closure plan must be evaluated on a case-by-case basis.

Figure 18 summarizes some possible backfill options for an open pit that is dug into a hillside. Backfill can be complete (Fig. 18a) or partial (Fig. 18b), and the latter can be designed with or without a pit lake. Ideally, any reactive waste (i.e., material that is likely to generate acid or metal-rich leachate) will be isolated from surface water by a cover of non-acid-generating waste rock or clean fill. Oxidation of sulfide minerals will normally be negligible if the reactive waste is permanently submerged or saturated with groundwater. However, if any sulfide-rich rock is left exposed on mine walls above the lake surface or water table, then oxidation and weathering of this material could seriously compromise the long-term water quality of the lake and surrounding groundwater. In figure 18, the most likely areas of concern would be the highwalls on the left-hand side of the diagrams in “b” and “c”. In both cases, the post-mining, steady-state water table would be permanently drawn down on the left-hand highwall, due to the modification in the topography. This would result in long-term exposure of reactive rock to weathering and pyrite oxidation. To minimize problems of this sort, clean fill or non-reactive waste rock could be bulldozed over the exposed walls of the pit to cover the offending rock types. However, this will not completely stop pyrite oxidation in the “wedge” of de-watered rock between the pre-mining and post-mining water tables (see Fig. 18c).

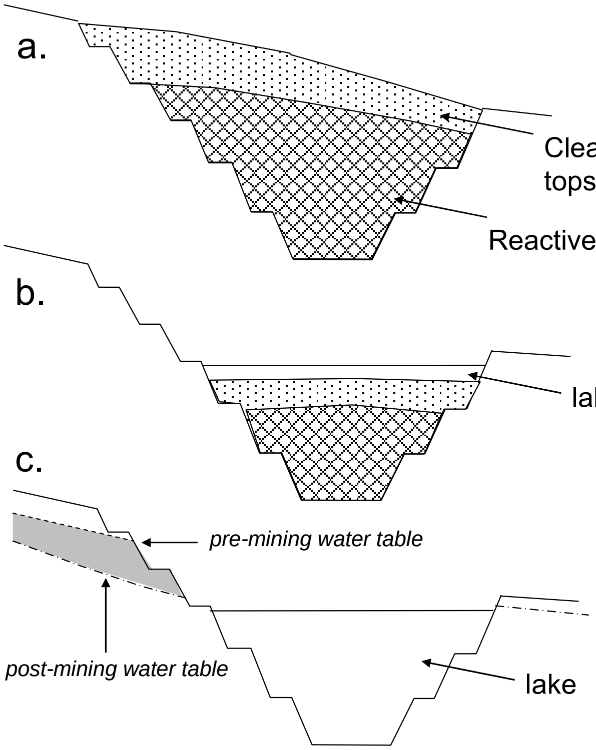


Figure 18. Diagram showing different possibilities for backfilling a mining pit on a hillside: a) complete backfill; b) partial backfill with a shallow lake; c) no backfill with a deep lake. The shaded region in “c” shows a wedge of permanently dewatered bedrock where acid mine drainage is likely to occur.

A common procedure when back-filling is to blend lime (CaO) or limestone ($CaCO_3$) into reactive waste rock as it is placed back into the pit. In this case, the amount of lime or limestone added to each truck load of waste is determined by acid-base accounting. Some back-fill designs include a layer of crushed limestone near the bottom to neutralize any acid leachate that may drain from the waste pile after closure. Another option is to lay down a highly permeable gravel layer at the bottom of the pit to divert any influent groundwater to a subsurface pipe or pumping well before it can reach the pyrite-bearing waste rock, thereby discouraging contact between groundwater and reactive waste. This type of design would only be appropriate for open pits in relatively dry climates where no lake is expected after closure.

4.1.2 Water supply

In northern Canada, there are relatively few opportunities for a flooded open pit mine to have beneficial use as a water supply, given the abundance of natural lakes and rivers in the Canadian Shield. One possible use of a pit lake would be as a supply of water for the construction of ice roads that are essential for heavy equipment to navigate the tundra (Cott et al., 2008b). Use of water from natural lakes could result in drawdown of the water surface, with possible negative impacts to native fish and other fauna. In contrast, pit lakes in arid or semi-arid parts of the world, such as Australia or the Great Basin of the USA, could represent a major local water resource with a number of possible end uses, depending on water quality (Sinclair and Fawcett, 1994; Doupé and Lymbery, 2005; McCullough and Lund, 2006). Possible uses include irrigation of crops or lawns (including golf courses, municipal parks, playing fields, etc..), irrigation of livestock, industrial uses, and public drinking water supplies. The latter would predictably have the most stringent water quality requirements. One example of a pit lake that is being used for drinking water is the city of Astoria, Illinois (USA) which since 1976 has been treating water from an abandoned open pit coal mine for drinking water (Gibb and Evans, 1978). Although water quality standards for irrigation of plants or livestock are typically less strict than those for human consumption, irrigation is sensitive to high salinity (especially high Na concentrations) and the presence of toxic substances, such as heavy metals or arsenic. Water quality requirements for industrial use will vary, depending on the nature of the commercial process involved. Given the fact that most mines in Canada are in remote locations far from industrial centers, it is unlikely that this would be a major beneficial use.

4.1.3 Ecological Habitat

Ideally, a “restored” pit lake will be a fully-functioning aquatic ecosystem, including fauna such as macroinvertebrates, fishes, and waterfowl. For example, Brenner et al. (1987) describe a large number of coal mine pit lakes in Pennsylvania that contain a diverse ecological community, including fishes, which reflects favorably on the quality of habitat provided by these waterbodies. Since pit lakes may in favorable circumstances be capable of supporting a diverse ecological community, the ecological benefits of these lakes must be considered during the reclamation process, especially in terms of habitat creation or restoration and the maintenance of such habitat. As discussed in Section 2.5, biodiversity of a newly-formed pit lake is likely to be low, but is expected to increase with time, and can furthermore be enhanced by re-landscaping the pit walls or treating the contained water, either chemically or biologically (see Section 4.2). As well, steep, rocky high walls above the lake surface can be potential habitat for birds, bats, rodents, and more charismatic animals such as mountain goats or wild sheep. For example, the authors of this report have observed bighorn sheep (Fig. 19) and cliff swallows inhabiting closed open pit mines in Montana.

Figure 19. Big horn sheep (*Ovis Canadensis*) inhabiting a reclaimed open pit gold mine in Montana (photo by Chris Gammons, 2007).

There are also possible negative consequences of pit lakes from the standpoint of habitat. For example, in arid, low-latitude regions (western Australia, SW USA, Africa), pit lakes may be breeding grounds for disease-carrying insects, such as mosquitoes (Norris, 2004; Doupé and Lymbery, 2005). Blooms of toxic blue-green algae or other poisonous phototrophs are also possible, especially for lakes that have been artificially nutrified.

In a recent review paper, Nixdorf et al. (2005) propose a new ecological classification scheme for pit lakes based on acidity and phytoplankton species and abundance. Nixdorf et al. (2005) suggest that pit lakes with low to moderate acidity have a good chance of being restored to a beneficial ecological end use through *in situ* treatment and long-term management of nutrient budgets. Interestingly, these same authors suggest that at least some pit lakes that are strongly acidic should be preserved as habitat for extremophilic microorganisms. However, if preservation of acidic lakes is the intended end use, then steps must obviously be taken to insure the protection of downstream water quality, and also to avoid accidental death of animals that may come into contact with the acid waters. In November of 1995, Butte, Montana became the focus of media attention when 349 migrating snow geese were found dead on the surface of the Berkeley pit lake (Adams, 1995). To avoid a recurrence of such an event, the lake is now equipped with a system of loud acoustic emitters to "haze" ducks and geese who may otherwise land on the water. There is also a permanent rifle shed mounted near the pit rim so that mine operators can fire warning shots to discourage waterfowl from landing on the lake.

4.1.4 Aquaculture

As summarized in the optimistic article by Otchere et al. (2004), the commercial or recreational use of pit lakes for aquaculture (fish farms) could be an innovative way to enhance the ecological, economic, and cultural sustainability of open pit mining. Pit lakes may in fact be *more* suitable for aquaculture in comparison to natural lakes since the former usually have no surface connection to any other water body, thereby eliminating the risk of introduction of non-native fish or other negative consequences of fish farms (e.g., disease, antibiotics, fertilizers) into the surrounding aquatic ecosystem (Otchere et al., 2004; Naylor et al., 2005). By virtue of their great depth and (often) meromictic characteristics, pit lakes have the potential to permanently sequester nutrients and decaying organic carbon in benthic sediment, thereby removing sources of biological oxygen demand that otherwise can plague aquaculture practices. On the other hand, there are several examples where extensive aquaculture in a mine lake had negative impacts on water quality due to eutrophication from nutrient overload (Yokom et al., 1997; Axler et al., 1996, 1998). The possibility of nutrient imbalance or spread of a pathogen-borne disease from aquacultural activities is made more likely in the case of a pit lake that has no outlet, due to the lack of any throughput of fresh water.

4.1.5 Recreation and tourism

If water quality is good and there are no site-specific safety concerns, there is no *a priori* reason why a pit lake could not be used for public recreation, such as swimming, boating, scuba-diving, fishing, or hunting for waterfowl. The numerous lakes left behind from iron ore mining in northern Minnesota, Wisconsin, and Ontario are good examples (see Section 5.2, below). Many people are fascinated by geographic oddities, and therefore a large pit lake could actually benefit the local community as a tourist attraction, even if it is widely considered to be an environmental disaster. Strange as it sounds, the famously toxic Berkeley pit lake is the largest tourist attraction in Butte, Montana, an historic mining center that is struggling to make the transition from resource extraction to a more diversified economy including tourist dollars as a major source of income. Another example is the locally-famous “Big Hole”, which is the site of the original Kimberley diamond mine in South Africa, which ceased operations in 1914 and now contains a pit lake. Although no scientific papers on this pit lake could be found, some touristic information is available at: http://www.thebighole.co.za/HOME.HTML. A photo of this historically-important mine and pit lake is given in Figure 20.

Figure 20. The “Big Hole” pit lake at Kimberley, South Africa. (Source: Wikipedia.org; photo by Rudolph Botha, March, 2005).

There are several examples in the literature highlighting the various recreational opportunities provided by pit lakes, with sport fishing opportunities being one of the most prevalent. Sport fishing is often a major contributor to the tourism economy of an area, therefore pit lakes that provide fishing opportunities can also contribute to the local economy and countless examples exist in the literature. In Pennsylvania, Brenner et al. (1987) surveyed 60 surface mine lakes in detail and found that many of the lakes were quite abundant in a variety of local sport fish species, although for the most part these water bodies were underutilized in regards to recreational fishing because of land access issues. In Alberta, the development of sport fisheries in lakes created by coal mining operations in the eastern slopes has become a common practice (Luscar Ltd., 1993). Several of these reclaimed coal mines that subsequently filled with water to create lakes are presently inhabited by native and nonnative fish species, all of which provide excellent sport fishing opportunities (Schwartz, 2002). Establishing sport fisheries in pit lakes is expanded upon in more detail in section 4.5.2.

Given favourable water quality conditions, wildlife may also be frequent visitors to, or common inhabitants of, pit lakes, and in such cases these waterbodies could provide exceptional wildlife viewing opportunities. As mentioned in section 2.4., waterfowl may often be common users of pit lakes (Phylips, 1992), and such a scenario would provide bird enthusiasts with a chance to view this wildlife. Additionally, opportunities may also exist for the viewing of other wildlife that are often associated with aquatic environments such as muskrat (*Ondatra zibethicus*), beaver (*Castor canadensis*) and potentially even large ungulates such as moose (*Alces alces*), although no literature was found to document this. Additionally, depending on the species and local regulations, hunting opportunities may exist for the above mentioned wildlife.

4.1.6 Metal recovery

Using an acidic, metal-rich pit lake for economic metal recovery can be a silver lining for an otherwise disastrous environmental situation. Besides being the city of Butte's main tourist attraction, the Berkeley pit lake is also a significant money-maker for the local mining company. At the time of this writing, water in the monimolimnion of the pit lake is being pumped at a rate of over 10^7 L/day to a copper recovery plant, where the majority of the dissolved Cu in the water is removed by a process referred to as cementation (Gammons and Duaime, 2006). The overall reaction is very simple:

$$Cu^{2+} + Fe(s) \rightarrow Fe^{2+} + Cu(s) \qquad (27)$$

Water containing 150 to 200 mg/L dissolved Cu is contacted with scrap iron for several hours, during which time > 80% of the Cu is extracted in elemental form. The cemented scrap is washed and mechanically separated to obtain a copper metal concentrate, which is then shipped for refinement. Meanwhile, the Cu-depleted water is returned to the pit. This process has been producing over 10^6 kg of Cu annually since 2003, but will eventually slow down or perhaps cease as the dissolved Cu in the pit lake is "mined out". An important question for the mining company is whether or not dissolved Cu concentrations in the pit lake will ever return to economically-exploitable levels with time. If so, then the copper recovery circuit would be an interesting variant of the heap-leach method of Cu-recovery that is commonly used for low-grade, bulk tonnage porphyry copper mines. There have been intermittent attempts at recovering other metals from the Berkeley pit lake. For example, concentrations of dissolved Zn in the lake (~ 600 mg/L) are even higher than Cu. However, an economically-viable technology for Zn recovery is yet to be developed.

4.1.7 Heat pump applications

By virtue of their immense volumes and proximity to mining-related infrastructure (mills, offices, employee residences, etc...), there may be potential to use pit lakes as heat exchangers for space heating and/or air conditioning. Heat pump technology has advanced in the past few decades, and it is now possible to heat or cool large buildings with groundwater or surface water that is near ambient temperature. There are several examples of projects where the potential for heat to be recovered from flooded underground mine workings is being evaluated (Arkay, 1992; NETL, 2006; Watzlaf and Ackman, 2006; Minewater Project, 2007), including in northern Canada (Ghomshei, 2007). Realistically, heat recovery from pit lakes may be more difficult owing to the relatively cold temperatures of most stratified lakes below the thermocline. However, with improved technology this may be something to look into, especially in frigid climates.

4.1.8 Scientific study

Mining pit lakes represent a unique opportunity for scientific study of limnological systems that – in many cases – have highly unusual morphometry, biology, chemistry, and hydrology. Detailed investigations of pit lakes have the potential to yield new advances in microbial ecology, biometallurgy, and biochemical engineering. For example, the Stierle research team at Montana Tech have been isolating and testing unique secondary metabolites from the Berkeley pit lake for possible cures for human diseases, including cancer and AIDS (Stierle and Stierle, 2005). Investigation of the microbial ecology of the Berkeley Pit and other acidic water bodies may even have applications to the emerging field of astrobiology. This is especially true given recent evidence collected from NASA missions for the past existence of acidic lakes and groundwaters on the surface of Mars (Squyres and Knoll, 2005).

4.2 STRATEGIES FOR ENHANCING END USES

4.2.1 Landscaping and backfilling

It is becoming more common during mine closure to change the profile of abandoned open pits to optimize end use strategies. Many open pit mines have extremely steep profiles: 1:1 slopes are not uncommon. Steep slopes of blasted bedrock and overburden are highly unstable, leading to mass wasting (creep, landslides) and making it virtually impossible to re-vegetate the mine walls. In addition, a uniformly steep-sided, deep lake lacking any littoral habitat (shallow water along shore lines) is undesirable from the standpoint of biodiversity and primary production by rooted macrophytes and benthic algae (BHP, 1999). A number of possible actions could help rectify this problem, including bulldozing of upper slopes into the pit, partial backfilling with mine waste (see section 4.1.1), and excavation of rock or soil along pit walls to create artificial habitat such as littoral bays, reefs, or shallow spawning beds (BHP, 1999).

It should be obvious that any large-scale re-landscaping of an open pit is best performed as soon as possible after mine closure, ideally by the mine operators themselves. Bulldozing large volumes of unconsolidated rock and soil into a lake that is already at full stage may be impossible without a safe way to discharge the displaced water. In addition, covering reactive, pyrite-bearing rock with overburden immediately after the mine is closed will lessen AMD impacts. Given the fact that mining companies are particularly adept at moving large amounts of rock quickly, failure to take these steps at the end of the mine life may be an opportunity missed.

4.2.2 Rapid flooding

Left to their own devices, pit lakes can take a very long time (decades to 100s of years) to flood completely (Section 2.2). This is undesirable, as it gives more time for natural weathering processes to deplete the rocks exposed on the walls of the pit of their neutralization potential, increasing the likelihood of severe acid mine drainage. To minimize the risk of AMD, it is generally recommended to flood open pits as rapidly as possible. Depending on the mine location, the source water for flooding could be ocean water (Fisher and Lawrence, 2006), a nearby reservoir or lake (Tones 1982), a river (Lessmann et al., 2003), or groundwater that is pumped into the lake at a rapid rate (Dowling et al., 2004). The source water should have good quality (e.g., low TDS and near-neutral pH), and if it contains elevated bicarbonate alkalinity then this is a bonus. On the other hand, if the end lake is designed to be meromictic, then it may be beneficial to flood the lower portion of the pit with high-TDS water, such as sea water or saline groundwater, and then flood the upper portion of the pit with lower density, low-TDS water. Such a design was used for the Island Copper pit lake on Vancouver Island, BC (Fisher and Lawrence, 2006).

If rapid flooding of a pit lake is planned, steps should be taken to ensure that a potentially harmful drawdown of the source water body is avoided (McAfee, 1980; Gaboury and Patalas, 1984; Mills et al., 2002). A rapid drop in the elevation of a natural lake could lead to erosion and re-suspension of unconsolidated lacustrine sediment, with a resultant sharp increase in turbidity of the water column. Lake drawdown could also expose high-quality littoral habitat to open air and – in the case of northern Canada – freezing temperatures. Rapid removal of water from shallow parts of frozen, natural lakes could also deprive over-wintering fishes of O_2-rich water in the epiliminion (Cott et al., 2008b).

In some special cases, it may be possible to flood an abandoned open pit mine with mill tailings waste from a nearby active mine. Because tailings are usually > 70% water, a mine void flooded in this manner would develop a sizeable lake with a thick pile of unconsolidated metalliferous sediment at the bottom. The authors are not aware of a pit lake that has been formed in this manner, although examples probably exist. A much more common practice is to discharge mine tailings into engineered repositories or to pre-existing natural lakes or ocean basins. There are several possible advantages of filling a mine pit with tailings, including: 1) flooding is likely to be rapid given the large volume of mill tailings generated each day at most large mines; 2) solid waste is permanently disposed of as partial backfill in the bottom of the lake, obviating the need for a separate tailings impoundment; and 3) due to pH adjustment in the mill, most tailings waters are strongly alkaline (pH > 10): the additional alkalinity could offset acid from AMD and help to buffer the final pH of the lake to neutral or weakly alkaline values. Possible disadvantages include uncertainty as to the final pit lake water quality, as well as the need for an alternate supply of make-up water for the mill during active mining operations and a multiple-pit mine plan.

4.2.3 Chemical Treatment

Chemical treatment of pit lakes is most often used to make pH adjustments. This can be done gradually, while the lake is flooding (Dowling et al., 2004), or in a single- or multiple-phase treatment operation after the lake is full (Peine and Peiffer, 1998; Lewis et al., 2003). Both of these scenarios are *in situ* treatment schemes, meaning that lime or some other alkaline reagent is added directly to the lake. Addition of lime to an already flooded lake is usually accomplished from a boat or barge, and is complicated by the possibility of incomplete vertical and/or horizontal mixing of lime into the water column. In some cases, chemical treatment of pit lake water is accomplished *ex situ* by pumping water from the lake, passing through a lime treatment plant, and then discharging the clean water to a receiving water body. Obviously, this type of treatment process will do nothing to improve the water quality of the pit lake, unless the treated water is returned to the mine pit to form a closed loop.

The most common reagent used to raise the pH of acidic mine water is lime. Lime is made from limestone by heating the rock to the point that CO_2 is driven off, leaving an anhydrous CaO compound behind. Because anhydrous CaO is slow to dissolve in water, many treatment plants first hydrate their lime to $Ca(OH)_2$ (sometimes referred to as "slaked" lime). Depending on cost and availability, other alkaline reagents can be used for pH adjustment, such as NaOH or MgO. Phosphate-rich rock has also been used to increase the alkalinity and nutrient content of acidic lakes (Davison et al., 1995). However, lime is by far the most common reagent used for large-scale treatment operations.

When lime or slaked lime is added to mine water, the pH is raised as shown in the following reactions:

$$CaO(s) + 2H^+ \rightarrow Ca^{2+} + H_2O \tag{28}$$

$$Ca(OH)_2(s) + 2H^+ \rightarrow Ca^{2+} + 2H_2O \tag{29}$$

Depending on the starting chemistry of the water, a number of side-reactions can occur as the pH increases. These include precipitation of gypsum ($CaSO_4 \cdot 2H_2O$), calcite, and/or hydrous oxides of Fe and Al, along with co-precipitation or adsorption of trace metals and metalloids (e.g., arsenic). Together, the solid precipitate that forms from lime treatment is usually referred to as "sludge". In aerobic environments (DO present), lime treatment sludge is usually brown or red, reflecting the presence of HFO. This type of sludge is notoriously slow to settle out of the water column, and may impart a strong turbidity to the water (Fig. 21a). In anaerobic environments (DO absent), sludge can take on a greenish color (Fig. 21b) due to the presence of a metastable, Fe^{II}-bearing compound known as "green rust". Green rust has a range of chemical composition, but when formed from initially acidic, sulfate-rich water it can be approximated by $Fe^{II}_4(Al,Fe^{III})_2(OH)_{12}SO_4 \cdot 3H_2O$ (Randall et al., 2001). Like HFO, green rust has a high affinity for trace metals and metalloids, and therefore precipitation of this compound can strip other toxins from the water column. Unlike HFO, green rust is quick to settle by gravity through the water column, and therefore has superior properties from the standpoint of turbidity. Unfortunately, it is unstable in the presence of oxygen, and will rapidly break down if exposed to air or water containing elevated dissolved oxygen. The conversion of green rust to Fe(III) compounds releases acid, and may drop the pH of surrounding waters. Thus, fore-thought needs to be given as to how any "green rust" sludge is permanently disposed of in a pit lake setting.

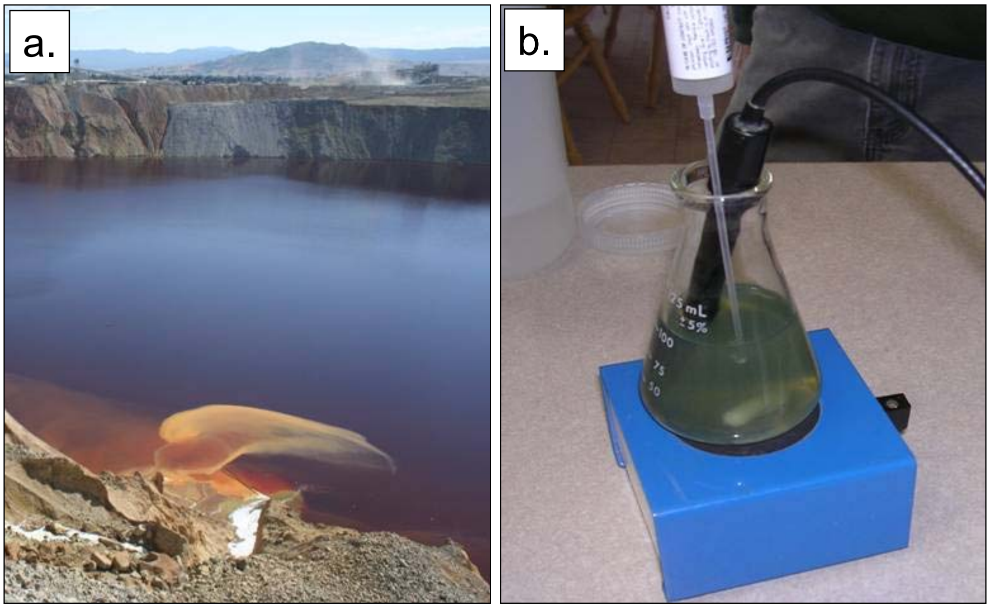


Figure 21. Photographs of lime treatment sludge: a) plume of hydrous ferric oxide in the surface of the Berkeley pit lake formed by disposal of alkaline lime treatment sludge (photo by Chris Gammons, June, 2006); b) "green rust" formed by rapid pH increase of Fe^{II}-rich mine water (Chris Gammons).

The optimal end pH during lime treatment of mine water depends on the initial water chemistry and which solutes are problematic. Most trace metals (e.g., Cd, Cu, Mn, Ni, Pb, Zn) are removed efficiently at pH's in the range of 9 to 10 (Fig. 22), whereas the common rock-forming metals Fe and Al are effectively removed at lower pH's (e.g., 6 to 8). The fact that the solubility minimum of Al occurs at a lower pH than those of the trace metals creates a dilemma for lime treatment engineers: namely, adjustment of pH to values > 9 is needed for complete Zn removal, whereas this can result in elevated dissolved Al concentrations. For this reason, many treatment plants employ a "two-stage" lime addition where the pH is first adjusted to ~ 7 to precipitate an Fe-Al sludge which is thickened and removed. The water is then passed into a second tank where pH is raised to 9 or higher to remove trace metals. Unfortunately, this type of two-stage lime addition is not really feasible for *in situ* lake treatment. This is because the Fe-Al sludge formed at neutral pH may back-react following later adjustment of pH to values > 9, releasing Al to the water column. Benchtop experiments and/or geochemical modeling are recommended to sort out all these complications beforehand.

Finally, it is important to consider what pH is optimal for micro- and/or macro-fauna, assuming that this is an important component of the end use of the lake. For example, many fish species including salmonids are sensitive to strongly alkaline pH (> 9). High pH interferes with the fish's ability to excrete ammonia and maintain a proper electrolyte balance (Wilkie et al., 1996). On the flip side, trout and other fishes are also highly sensitive to heavy metals, such as Cu, Ni, Pb, and Zn, at very low concentrations (section

2.5.5.1). To effectively remove these trace metals from a pit lake while maintaining pH values below 9 may require alternative strategies, such as biological treatment.

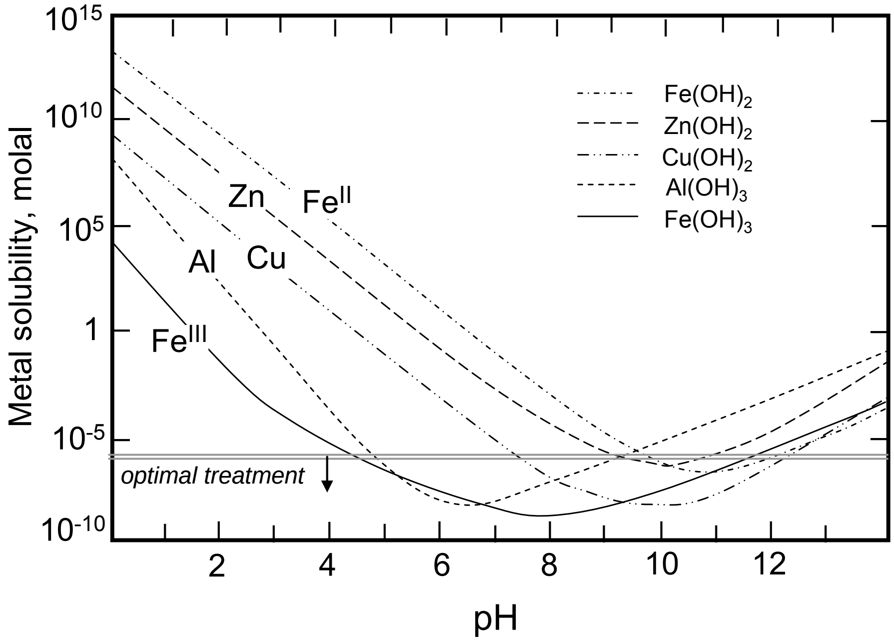


Figure 22. The dependence of the solubility of selected metal-hydroxide minerals on pH. The "optimal treatment" line is generalized. Water quality standards vary for each metal and from region to region. Note the high solubility of Fe^{2+} relative to Fe^{3+}. In mine waters, Fe^{2+} concentrations may be controlled by another less soluble mineral, such as "green rust" or siderite ($FeCO_3$). Diagram modified from Nordstrom and Alpers (1999).

4.2.4 Biological Treatment

Biological treatment of mine water is often referred to as "passive" treatment in reference to the fact that micro-organisms can often clean up polluted water on their own, with little or no external stimulation. However, it is also possible to artificially add organic compounds, such as straw, food waste, or livestock waste, to speed up the rate of biological activity (Klapper and Geller, 2001; McCullough, 2007). The microbiology of pit lakes is inherently a very complex subject. For the purposes of this document we will discuss biological treatment depending on whether conditions are aerobic or anaerobic. Both bacteria and algae play an important role in aerobic biological treatment, whereas only bacteria are active in anaerobic conditions.

4.2.4.1 Aerobic biological treatment.

The presence of O_2 in shallow pit lake waters will trigger growth of aerobic bacteria that use this compound to oxidize Fe^{2+}, Mn^{2+}, and/or reduced sulfur or nitrogen compounds. Oxidation of Fe^{2+} has already been discussed (section 2.4.2.5). This reaction produces fluffy precipitates of HFO with high surface area and a strong affinity to adsorb trace metals. On the negative side, precipitation of HFO releases protons and can lower the pH of the pit lake if there is insufficient bicarbonate ion dissolved in the water to buffer pH to circum-neutral values. Bacterial oxidation of Mn^{2+} is much slower than oxidation of Fe^{2+}, but is nonetheless thermodynamically favorable at neutral to alkaline pH (Walton-Day, 2003). Like HFO, hydrous manganese oxide (HMO) has a very strong tendency to adsorb trace metals, especially divalent cations such as Zn^{2+} and Cd^{2+}. Most Fe- or Mn-oxidizing bacteria are autotrophs, meaning that they use inorganic CO_2 as their source of C. Growth of autotrophic bacteria therefore constitutes a sub-type of primary production of organic carbon which, in addition to photosynthesis, can stimulate biological activity in a lake.

There are several ways in which growth of algae may improve the water quality of a pit lake. As discussed earlier (Section 2.4.2.2), photosynthesis consumes CO_2 and therefore will tend to raise the pH of near-surface water, leading to a decrease in the solubility of trace metals (Fig. 22). In addition, many microorganisms are effective at sorbing metals directly from solution (Ledin and Pederson, 1996). Although the exact mechanisms by which metals are taken up by microbes are often poorly understood, it appears that all algae and bacteria have an ability to adsorb trace metals to binding sites on the exterior of their cell walls, a process that is metabolism-independent. In other words, metal sorption occurs whether or not the cells are living. In contrast, "active" uptake implies that the metal is absorbed into the interior of the cell, where it presumably plays a metabolic role, e.g., in the construction of enzymes. Either way, algae may effectively "polish" the water quality of a lake that has chronically elevated concentrations of one or more trace metals but otherwise good water quality (MERG, 2003; Dessouki et al., 2005). Although there are many species of algae that can tolerate low pH, algae are less likely to play a role in cleaning up lakes that are strongly acidic and metal-rich because the concentrations of protons and dissolved metals are simply too large. It would take an algal bloom of unprecedented size to significantly impact the chemistry of the Berkeley pit lake, for example.

Besides raising pH and sorbing metals, algae play an important role in limnic environments by providing "food" for bacteria and higher life forms. Algae are very inefficient primary producers, and constantly "leak" photosynthates (e.g., sugars and other organic molecules) to the water column (Vymazal, 1995). This provides a source of organic carbon for heterotrophic bacteria. In addition, algae may be grazed by higher life forms, and as such constitute (along with autotrophic bacteria) the base of the food pyramid in the lake. Finally, when algae die they sink to the bottom of the lake and become a source of organic carbon for microbes that promote anaerobic treatment (see next section).

4.2.4.2 Anaerobic biological treatment

Anaerobic bacteria are likely to dominate the biology of deeper portions of the water column and underlying sediment in stratified pit lakes. Processes occurring during anaerobic breakdown of organic matter (see Section 2.4.2.8) include bacterial reduction of nitrate, iron, and sulfate, as well as fermentation and sometimes methanogenesis. Amongst this list, the most important reaction from the standpoint of water quality improvement is bacterial sulfate reduction (BSR). BSR raises the pH of the water, adds alkalinity, decreases the concentration of sulfate, and promotes precipitation of heavy metals as insoluble sulfide minerals. BSR is the keystone to the majority of engineered anaerobic passive treatment systems, whether they be *in situ* or *ex situ*. On the negative side, BSR may result in toxic concentrations of free H_2S, especially if the initial concentrations of dissolved sulfate are much greater than the combined concentrations of metals (such as Cu, Fe, Zn) available to form insoluble sulfide precipitates. As well, BSR has limited ability to attenuate arsenic and a few heavy metals (such as Mn) that have relatively high solubility in the presence of H_2S.

With regards to possible end uses for mining pit lakes, the question may well be asked whether BSR is a good thing or a bad thing. Certainly if BSR is occurring, then there is zero DO present, which of course means that no animals could survive under these conditions. Also, if BSR occurs in the monimolimnion or hypolimnion of a stratified lake, then there is the risk of exposure of organisms to poisonous H_2S accompanying an episodic top-to-bottom turnover event (Boehrer and Schultze, 2006). Nevertheless, BSR is the only *biological* process that can effectively clean up mine water that is initially strongly acidic and metal-rich. Most sulfate-reducing bacteria are intolerant of low pH (< 3 or 4) or high concentrations of heavy metals (e.g., > 10 or 20 mg/L of Cu or Zn). In acidic lakes, sulfate-reducing bacteria most likely gain a foothold in isolated microenvironments of higher pH, such as may occur around clots of decomposing organic matter within benthic sediment. The H_2S produced by the bacteria can then diffuse upwards into the overlying water column where it precipitates toxic metals as sulfides, thus creating a more benign environment where the bacteria can spread. Assuming a replenishable supply of organic carbon is present, this incremental process could eventually result in a monimolimnion and underlying sediment pore water that is uniformly sulfidic, with elevated pH and very low heavy metal concentrations. As long as the lake is permanently stratified, the benefits of BSR probably outweigh the dangers, especially for pit lakes that otherwise would have very poor water quality.

There have been several published case studies where organic substances were added to a pit lake (or a lake mesocosm) to stimulate BSR (Klapper et al., 1998; Castro et al., 1999; Koschorrek et al., 2002; Frömmichen et al., 2003; Fauville et al., 2004). For example, at the Anchor Hill pit lake of the Gilt Edge mine in South Dakota, US, the pH of the entire lake was first adjusted by *in situ* addition of lime (Lewis et al., 2003; Park et al., 2006a, b). This was followed by injection of a mixture of molasses and methanol to accelerate BSR and other anaerobic processes. This case study is described in more detail in Section 5.4. One thing to realize about Anchor Hill is that this lake is relatively small compared to many mining pit lakes (see Fig. 2). Similar whole-scale manipulations would be much more difficult and expensive for a larger system, such as the Berkeley pit lake of Butte, Montana.

Other anaerobic microbial processes that can significantly alter water chemistry include reduction of iron, nitrate, selenium, and uranium. Bacterial reduction of Fe^{3+} to Fe^{2+} consumes protons and can significantly raise the pH of deep lake water or sediment pore water (see Section 2.4.2.8). Like BSR, bacterial Fe reduction can be stimulated by addition of organic amendments and/or lime (Wendt-Potthoff et al., 2002). Possible negative consequences of iron reduction include an increase in the total dissolved Fe concentration (since Fe^{2+} is much more soluble than Fe^{3+}, see Fig. 20), and release of trace metals or metalloids that were adsorbed onto surfaces of the solid ferric compounds. Bacterial reduction of nitrate could be beneficial if nitrate concentrations are a concern. However, if Eh conditions are strongly reducing (e.g., H_2S stable), this process is likely to result in elevated concentrations of dissolved ammonia (NH_4^+ or NH_3) which may be more problematic than the nitrate itself (Park et al., 2006a, b). On the positive side, anaerobic environments typically result in near quantitative removal of soluble Se^{VI} (SeO_4^{2-}) and U^{VI} (UO_2^{2+}), through precipitation of elemental Se and uraninite. These reactions can be written as follows:

$$2SeO_4^{2-} + 3CH_2O + 4H^+ = 2Se(s) + 3CO_2 + 5H_2O \qquad (30)$$

$$UO_2^{2+} + ½CH_2O + ½H_2O = 2UO_2(s) + 2H^+ + ½CO_2 \qquad (31)$$

Ample evidence exists for the microbial catalysis of reactions 30 and 31 in anaerobic environments (e.g., Oremland et al., 1989; Lovley and Phillips, 1992).

4.2.5 ESTABLISHMENT OF FISHERIES

4.2.5.1 Fish introduction.

Fishes may accidentally enter a pit lake during flooding if the source water contains fish. For example, Lac Des Roche, a former open pit mine in Alberta, was inhabited by several fish species during rapid filling by nearby West Jarvis Creek (see Schwartz, 2002, and several references therein). Nearly twenty years after initial filling, the lake sustains a recreational fishery (Schwartz, 2002). Fish can also be introduced into a pit lake after flooding if there is a surface connection to a nearby, fish-bearing water body. For example, the open pit at the Gunnar uranium mine was flooded with water from nearby Lake Athabasca (Tones, 1982). Although the channel connecting the two water bodies had been closed for nearly 20 years at the time of the investigation, Tones (1982) found four fish species, including northern pike, in the pit lake. All of these species presumably dispersed from Lake Athabasca when there was a channel between the two lakes, allowing for floral and faunal exchange.

Fishes can also be introduced into pit lakes by human transplantation or supplementation (stocking), usually for recreational or aquaculture purposes, such as in East Pit Lake in central Alberta. This lake was created from the remediation and the reclamation of a former surface coal mine near the town of Wabamun, Alberta (Sumer et al., 1995). Subsequent to filling the pit with water, the newly created East Pit Lake was stocked with rainbow trout (*Oncorhynchus mykiss*; Sumer et al., 1995). Although this lake is essentially a put-and-take fishery, and is continually stocked, East Pit Lake continues to sustain a quality recreational fishery for rainbow trout. Fish may also be introduced to lakes for aquacultural purposes. In Minnesota, for instance, hundreds of abandoned iron ore pits have filled with groundwater and surface water to create lakes (Yokom et al., 1997) and a handful of these lakes have been reclaimed for the purpose of salmon aquaculture (Axler et al., 1998). These lakes may be more suitable for aquacultural purposes in comparison to natural lakes since they usually have no connection to any other waterbody, thereby eliminating the risk of fish escaping which could have drastic impacts on the aquatic ecosystem (Naylor et al., 2005). Extensive aquaculture could have severe impacts on the water quality of the lake, such as eutrophication (Yokom et al., 1997; Axler et al., 1998).

4.2.5.2. Fisheries habitat creation and enhancement.

Relative to natural lakes, the structural habitat complexity and diversity found in pit lakes is considerably reduced. For instance, in artificially created lakes, there may be minimal or no structural habitat important to fishes such aquatic vegetation and course woody debris. Therefore, habitat creation, enhancement, or rehabilitation should be an integral part of the initial reclamation process during mine decommissioning; especially if fisheries are to be established. Figure 23 provides a general summary of fisheries habitat creation and enhancement for pit lake water bodies.

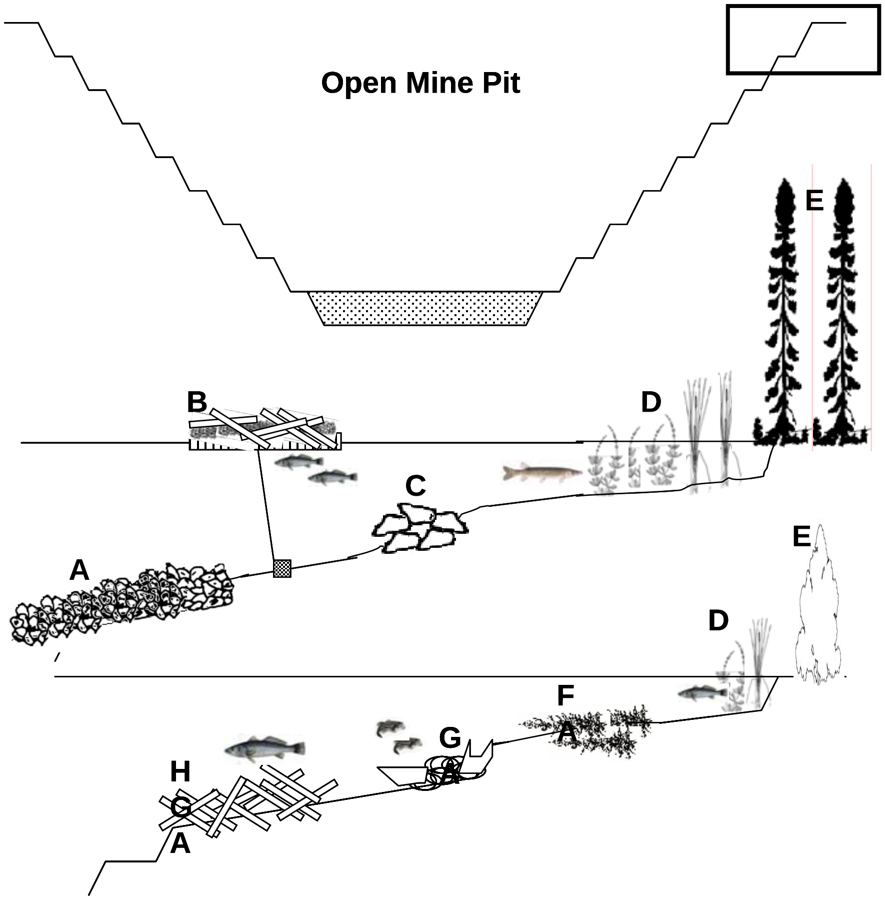


Figure 23. Examples of fish habitat creation and enhancement techniques as described in Section 4.2.5.2. Artificial reef created with rubble and waste-rock (A), floating reef-raft (B), large boulders for cover (C), the planting of littoral (D) and riparian vegetation (E), submerged conifers for providing cover (F), construction material such as donated concrete (G) and the addition of large woody debris (H).

Habitat creation and enhancement in pit lakes may be more easily facilitated, in comparison to natural lakes, since most of the reclamation activities can occur when the mine pit is free of water. Additionally, in many cases, pit lakes will be larger than the original waterbody thereby allowing for the creation of more fish habitat compared to that which was originally present (BHP, 1999). The ultimate goal for fish habitat restoration is to provide habitat that is specific to the target fish species for all life history stages, and habitat that will allow for the establishment of, or provide refuge for, their food source (e.g., aquatic invertebrates). In northern environments, overwintering habitat is also critical, but likely is not a limiting factor in pit lakes given the abundance of deepwater habitat that is usually present in these waterbodies (BHP, 1999). Subsequent to initial reclamation practices, pits will be filled with water, either naturally or from nearby water bodies. If filled directly from a nearby water body, or if viable stream connections are re-established, fish communities may establish naturally via the transfer of native fish. If not, fish species will have to be supplemented or re-stocked into the waterbody. Regardless of the method used, suitable fish habitat is a perquisite to the persistence of fishes in these new waterbodies.

Regarding newly created pit lakes, the riparian zone - the interface between the terrestrial and aquatic environments - will likely be deficient in structural habitat and riparian vegetation. Typically this zone provides many ecological functions important to surrounding waterbodies. For example, autochthonous inputs from riparian vegetation such as leaves and terrestrial invertebrates are an important food source for shredding invertebrates and fishes respectively. As such, it is important to determine appropriate reclamation strategies for the creation and enhancement of riparian habitats. Often, because of their physical profiles, large-scale landscaping is needed to facilitate in the alteration of the mine profile (see Section 4.2.1). Once completed, if landscaping is required, replanting or establishing native vegetation in riparian areas is likely the most effective way of rehabilitating, or creating, productive lake shore areas. This in turn will promote bank stability and if trees can be successfully established, large woody debris may be contributed to the lake over time, thereby increasing structural complexity of near shore environments. Native plant and tree species used in riparian plant establishment can either be transplanted from other nearby donor sites (e.g., Vincent, 1995), or planted from seed (e.g., Reid and Naeth, 2005a, b). Regardless of the method used, preference should be given to species that can withstand more rigorous conditions. Once vegetation is established, more environmentally sensitive species may be introduced (Vincent, 1995).

Given the steep-sided profile (sometimes 1:1 slopes) of most pit mines, critical littoral habitat is usually minimal or even completely absent in pit lakes. Shallow water may exist in localized areas, such as mine benches or haul roads (Tones, 1982). This has major ecological implications given that the majority of northern fish species will, at one time or another during their life cycle, be reliant on the littoral zone or the habitat structures within that area for spawning, feeding, or finding refuge. Shallow water habitat may be artificially created in a pit lake by bulldozing, drilling or blasting the upper walls onto the upper bench of the pit, partial backfilling with mine waste, dumping blast rock into the lake from shore or from ice cover, or manually constructing bays around the periphery of the pit (BHP, 1999). Following completion of these larger scale modifications the addition of smaller substrate features such as crushed rock, gravel, or materials of smaller sizes to fill some of the interstitial spaces will be important for benthos establishment, littoral macrophyte rooting, and for providing appropriate spawning substrates.

Artificially created littoral areas will need structural additions or modifications in order to increase the complexity of these habitats. Waste rock and/or excavated rock can be piled in nearshore habitats to create artificial reefs (BHP, 1999) that will increase interstitial refuge for juveniles and forage fish, create vertical relief or can be used for spawning by some species. Rock-rubble has been used to successfully create lake trout spawning habitat (Foster and Kennedy, 1995; Moy, 1995), and cover for fry and young-of-the year fish (Fitzsimons, 1996). Additionally, scrap concrete or stone rubble that may be present as a result of mine decommissioning can be used to increase structural habitat (Kelch and Reutter, 1995). In some cases, these artificial structures are used more by fishes than natural ones (Fitzsimons, 1996). The size of spawning substrates should be consistent with the needs of the target species to be stocked into the lake. For example, lake trout and arctic grayling, two candidate fish species for pit lakes in northern Canada, differ in their preferred spawning substrates (Scott and Crossman, 1998). Lake trout prefer to spawn over large boulder or rubble whereas Arctic grayling prefer to spawn over gravel-dominated substrates (Scott and Crossman, 1998). If the creation of artificial reefs is not practical, the creation of wooden reef-rafts may be more suitable. These artificially created rafts can be covered with a variety of material (earth, pebbles, grass, woody debris), anchored to the lake bottom and will provide cover for fish and nesting sites for aquatic birds (Blokpoel, 1995). The disadvantage of these structures is that they may have to be removed every year before freeze-up to avoid damage (Blokpoel, 1995).

Artificial "floating islands" have recently been used to improve water quality and enhance wildlife habitat in ponds and wetlands polluted by agricultural or urban runoff (Headley and Tanner, 2006; Stewart et al., 2008). The patented BioHaven© product is one example, and is essentially a moored platform constructed of recycled plastic containers which is then covered with sod and seeded with wetland plants. Case studies summarized by Headley and Tanner (2006) and on the internet (FII, 2008) document significant improvements in water quality where floating islands have been deployed, including a reduction in nutrient concentration and a decrease in turbidity. The islands also provide excellent habitat for macroinvertebrates, fish, waterfowl, and aquatic mammals. Although the authors are not aware of a case study where floating islands have been deployed in a mining pit lake, this would seem to be an interesting opportunity for future research.

In addition to artificial reefs, the addition of woody debris will be an important component of pit lake habitat restoration. Woody debris is most often used in stream habitat restoration (e.g., Cederholm et al., 1997). When used in lakes, woody debris increases structural habitat complexity and diversity and is mainly used to provide cover for juvenile and forage fishes (Roni et al., 2005; Roth et al., 2007), which are subsequently consumed by piscivorous fishes. Additionally, successful colonization and growth of aquatic invertebrates will likely depend on the establishment of suitable habitat features such as those provided by woody debris (Jones et al., 2003), which will in turn provide an important food source for non-piscivorous or juvenile fishes. Structures such as log piles, submerged logs, woody brush piles, or even bundles of conifers (e.g., black spruce, *Picea mariana*) native to the area and brush/tire bundles can be created and situated at varying depths throughout littoral areas of the lake. Several studies have shown that such artificially created structures of woody debris will often lead to an increase in fish diversity and abundance of fishes (Smokorowski et al., 1998, 2006, and references therein). For example, Koski (1992) showed that the density of parr of coho salmon (*Oncorhynchus kisutch*) increased significantly in streams with increasing volume of large woody debris. In a lacustrine setting, Newbrey et al. (2005) reported that fish abundance always increased in the presence of coarse woody debris, and that habitat provided by coniferous trees was more important than that provided by deciduous trees. Consequently, the role of woody debris as an important component in littoral habitat complexity must be taken into consideration in the creation and enhancement of critical fish habitat, specifically within littoral areas.

Littoral aquatic macrophytes are important contributors to fish habitat and increase shoreline diversity for aquatic organisms, and hence are important in the creation and enhancement of productive fish habitats in newly created pit lakes. Similar to woody debris, aquatic macrophytes provide cover for forage and juvenile fish, provide ambush cover for piscivorous fish, and will allow for the establishment and persistence of aquatic invertebrates. Aquatic vegetation and organic matter is an important food source for aquatic invertebrates, and the lack of this vegetation may result in a decrease in abundance of these organisms (Jones et al., 2003). Additionally, aquatic vegetation will also increase dissolved oxygen levels and, depending on the species, provide suitable spawning habitat. Several species of fish, including some species common to northern environments, require aquatic vegetation directly for spawning whether for adherence of eggs, or the building of nests (e.g., northern pike, yellow perch *Perca flavescens* and ninespine stickleback *Pungitius pungitius*; Scott and Crossman 1998). As such, it is important that both submergent and emergent aquatic vegetation, in addition to shoreline vegetation such as sedges and reeds, be included in reclamation practices to create, restore or enhance fisheries habitat in the littoral zones of newly created lakes. Aquatic vegetation can be collected from nearby donor sites (Grillmayer, 1995; Vincent, 1995), or possibly planted from seed, although no examples of this could be found (see Reid and Naeth, 2005b for a terrestrial example), therefore collection from donor sites may be more plausible. If donor plants from a nearby waterbody are used, tubers or whole plants can be relocated to the new site (e.g., Grillmayer, 1995). Plants should be transferred in soil, kept moist and with as much of the root as possible to increase the chance of establishment (e.g., Vincent, 1995). Potential emergent and submerged donor species typically found in littoral aquatic environments of the Northwest Territories include cattails *Typha lattifolia*, pondweed, *Potamogeton angustifolium*, and *P. minimum*, yellow pond lily *Nuphar variegatum*, and water milfoil *Myriophyllum exalbescens,* and *M. verticillatum*. Important shoreline vegetation might include a variety of sedges *Carex spp.*, cattails and rushes *Scirpis spp*. In general, the plant species used should be one common to the area of the newly created pit lake and preferably a rigorous pioneer species able to establish in areas of recent disturbance.

Several other factors must be taken into consideration with respect to enhancing the quality and quantity of pit lake fish habitat. For example, as discussed in detail in sections 4.2.3 and 4.2.4, biological or chemical treatment of the water may be necessary to improve water quality to ensure that it is non-lethal and/or non-harmful for the entire biological community of the lake including zooplankton, phytoplankton, invertebrates, macrophytes, fish and wildlife. To promote the bacterial community of the newly created lake, it may be necessary to transport natural sediment from nearby lakes in order to innoculate benthic bacteria in these systems. Burlap sacks can be used as they are durable, porous, and biodegradable (H. Larratt personal communication, Larratt Aquatic Consulting Ltd). Additionally, if stream courses have been altered, and upon mine decommissioning are being diverted back into the pit, stream habitat restoration may also be necessary. If so, most of the habitat creation and enhancement ideas mentioned above can also be applied to lotic systems as well. Lastly, if the end use of the pit lake is strictly for aquacultural purposes, then it may not be necessary to create and enhance habitat to the degree described since these fish will be artificially fed and often protected from predation.

4.2.5.3. Potential fish species.

If fish need to be transplanted from another water body, with intent of establishing a self-sustaining ecosystem, or even a put-and-take fishery, several important things must be considered. First, if the lake is connected to other water bodies in the area, only native fish species should be used. The negative impacts of the introduction of non-native fish have been reviewed extensively in the literature (e.g., Taylor, 2004). Ultimately, the introduction of non-native species can result in local extinctions of native species via competition, predation, disease transmission, habitat modifications or in some cases hybridization. Second, to promote self-sustaining fisheries and/or aquatic ecosystems a conscious effort must be made to attempt to mimic the composition and diversity of species in other lakes in the area. Replicating species composition increases the chances of establishing fisheries by fulfilling all trophic levels and ecological niches. Lastly, fish to be transplanted in the new waterbody should be collected from a disease free source for obvious reasons. For example Ogawa et al. (2004) discuss the dangers of translocating cyprinid fish infected with metacercariae trematodes, and how even one fish translocation could be devastating to an aquatic ecosystem.

Taking the above into consideration there are several fish species (both priscavors and forages fishes) in northern environments that can be considered suitable candidates for translocation, although this will have to be evaluated on a site specific basis. In the Northwest Territories for example, the list may include, but is not limited to burbot (*Lota lota*), northern pike, lake trout, arctic char, lake whitefish (*Coregonus clupeaformis*), least cisco (*C. sardinella*), arctic cisco (*C. autumnalis*), lake cisco (*C. artedii*) long nose sucker (*Catostomus catostomus*), white sucker (*C. commersonii*), walleye (*Sander vitreus*) and yellow perch, slimy sculpin (*Cottus cognatus*), spoonhead sculpin (*C. ricei*), brook stickleback (Pungitius pungitius), lake chub (*Couesius plumbeus*), pearl dace (*Margariscus margarita*), and long nose dace (*Rhinichthys cataractae;* Evans et al., 2002).

5. CASE STUDIES AND EXAMPLES

5.1 KIMBERLITE DIAMOND MINES

The rapid growth of diamond mining in northern Canada was a major impetus for this report. The following discussion gives more information on the geology, hydrogeology, and geochemistry of kimberlites and their associated groundwaters.

5.1.1 Kimberlite geology

Kimberlite is an altered ultramafic potassic igneous rock that originates in the earth's mantle at or near the base of the lithosphere (McBirney, 1993; Klein and Hurlbut, 1993). It has a brecciated or porphyritic texture, with relatively large megacrysts in a fine-grained groundmass. The groundmass contains minerals that are typically too small to see with the naked eye, including calcite, serpentine, and clay. The megacrysts include diamond, olivine, serpentine, phlogopite, ilmenite, pink garnet, bright green Cr-diopside, apatite, spinel, perovskite, enstatite, and/or monticellite (Klein and Hurlbut, 1993).

Kimberlite deposits (Fig. 24) typically occur as steep-sided cylindrical "pipes" that are filled with a mixture of kimberlite and country rock fragments (xenoliths). The kimberlite itself can have a coherent igneous texture (often referred to as the "hypabyssal facies"), or a fragmental texture (often referred to as the "pyroclastic" or "crater facies"). These two facies broadly define portions of the kimberlite that are intrusive (plutonic) or extrusive (volcanic) in origin, respectively. Pyroclastic kimberlite typically fills the top of the pipe and can drape over the crater rim to form a tuff-like volcanic layer. Kimberlites may form a crater lake at their surface, as evidenced by sedimentary re-working of the pyroclastic facies.

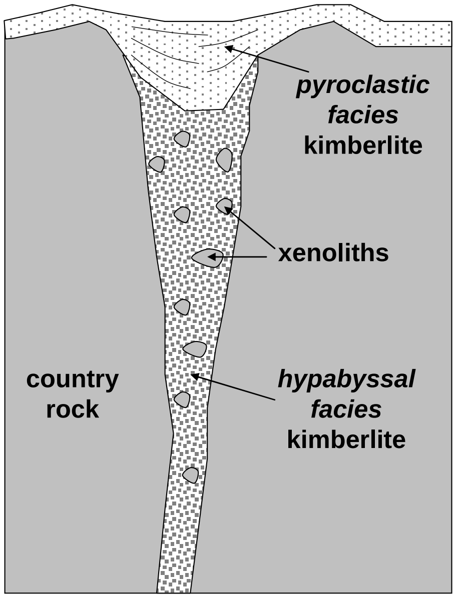


Figure 24. Simplified geology of a kimberlite pipe.

5.1.2. Kimberlite hydrogeology

Based on limited data, Morton and Müller (2003) obtained hydraulic conductivity (K) values of 2 x 10^{-5} m/day (a rather low value) to 0.4 m/day (quite high) for kimberlite at the Venetia diamond deposit, South Africa. This very large range in K may reflect primary geological heterogeneity (e.g., different kimberlite facies), differences in the degree of weathering, and also, importantly, the extent of secondary fracturing during blasting and excavation. The surrounding fractured country rock at Venetia had a range in K of 2 x 10^{-5} to 1 x 10^{-3} m/day. Morton and Müller (2003) include a table of published K values from other South African kimberlite deposits, and these vary in the range 2 x 10^{-5} to 0.04 m/day. In general, higher K values were reported for "sedimentary" kimberlite (equivalent to pyroclastic facies of this report) and lower K values for hypabyssal kimberlite. In a study of the hydrogeology of the Diavik mine in NWT, Kuchling et al. (2000) measured average K values of 0.017 to 0.043 m/day for kimberlite and country rock. Overlying lakebed sediments and till at Diavik had an average K value of 4 x 10^{-3} cm/sec (3.4 m/day). The rather high K values for kimberlite at Diavik may reflect the predominance of pyroclastic facies at this mine.

Kuchling et al. (2000) give a good description of the distribution of permafrost near Diavik. In this region, the total depth of penetration of the permafrost layer varies over a huge range, being as much as 350m deep below large land masses, to being nonexistent below most lakes with an average depth exceeding the depth of maximum winter ice cover (~ 1.5 to 2 m). The distribution of permafrost around a mine site is a key variable, as permafrost is essentially impermeable to water transport. Kimberlite deposits such as Diavik that are located near a lake would be expected to produce copious amounts of groundwater during mining which will need to be managed appropriately. This also means that such deposits have a good chance of filling rapidly upon closure, although this may depend on whether or not permafrost re-establishes itself on the exposed mine walls during the mine life.

Most open pit kimberlite mines are steep-sided and roughly circular in outline (e.g., see Figs. 1, 20). Related to this morphometry, Morton and Müller (2003) described concentric faults and fractures in a so-called "zone of relaxation" (ZOR) that opened up in the mine walls surrounding the Venetia open pit. These extensional cracks outcropped at the surface, and also penetrated to significant depths before attenuating. Morton and Müller (2003) point out that the concentric fractures act as corridors for enhanced groundwater flow, and that care should be taken so as not to locate mining facilities within the ZOR. For example, vertical cracks beneath a tailings pond could promote downwards infiltration of tailings water towards the pit. Given the similar shapes of diamond mines worldwide, it is plausible that concentric fractures of this type could develop elsewhere, although this will be depend on the mechanical properties of the country rock at each individual mine, which will vary widely from site to site.

5.1.3. Chemistry of groundwater associated with kimberlite deposits

A literature review uncovered only a few investigations of the chemistry of groundwater associated with kimberlite deposits, none of which dealt specifically with pit lakes. From an acid-base accounting perspective, most kimberlite deposits appear to have low AP and moderate to very high NP, meaning that they have a low to very low potential to generate acidic leachate. In a recent study of kimberlite ore at the Ekati mine, NWT, Rollo and Jamieson (2006) obtained average NP and AP values of 240 and 13 kg $CaCO_3$/ton, respectively, for an NP/AP ratio of 18. Similar values were reported for the Diavik mine, NWT (Baker et al., 2003). Kimberlite itself typically has a very low sulfide mineral content, although pyrite and other sulfides may be present in the surrounding country rock, or in xenoliths within the pipe itself. For example, Baker et al. (2003) found that mudstone xenoliths in the Diavik kimberlites contained up to 1% pyrite, and could be a potential source of acidic leachate in the event that the xenoliths were isolated by mining or milling activity from the surrounding kimberlite rock. Rollo and Jamieson (2006) also pointed to country rock xenoliths as a potential source of water contamination, and suspected that leaching of sulfate minerals (anhydrite, gypsum) from the country rock fragments may have been a major factor in increasing the TDS of groundwater near the mine site.

Given the high NP/AP ratio and presence of carbonate minerals in the altered groundmass of most kimberlites, pH values near or above neutrality would be expected. Rollo and Jamieson (2006) reported pH's of 7 to 8.5 for pore waters in contact with kimberlite at the Ekati mine. Interestingly, Sader et al. (2007) found that groundwater associated with unmined kimberlite deposits in northeastern Ontario had pH values in the range 8.5 to 12.4, with roughly half of the waters sampled having pH > 10. These remarkably high pH values were attributed to inorganic chemical reactions taking place during interaction of groundwater with olivine and serpentine. Worldwide, strongly alkaline groundwater is known to be associated with areas of the Earth where low temperature serpentinization of ultramafic rocks is occurring (Barnes and O'Neil, 1969). Kimberlite groundwater also appears to be enriched in Cl and F relative to regional groundwater, which may be due to leaching of halide elements from phlogopite, apatite, serpentine, and other hydrous minerals in the kimberlite pipe. The unusual chemistry of waters associated with kimberlite led Sader et al. (2007) to propose that groundwater sampling could be an important exploration tool for undiscovered diamond deposits. Sader et al. (2007) found elevated partial pressures of hydrogen (H_2) and methane (CH_4) gas in many of their kimberlite-hosted groundwater samples, and also report some of the lowest Eh values ever published for natural water samples (down to -500 mV). Based on stable isotope trends, the authors concluded that the methane was biogenic in origin.

In terms of TDS, Morton and Müller (2003) indicate that some of the groundwater samples at the Venetia mine were moderately to highly saline, with Na^+ and Cl^- being the dominant ions. Day et al. (2003) and Rollo and Jamieson (2006) also reported high salinity for pore waters associated with kimberlite at the Ekati mine, with Ca^{2+} and Mg^{2+} being the dominant cations and sulfate being the dominant anion. In contrast, most of the groundwater examined by Sader et al. (2007) had low to moderate salinity. It is difficult to generalize from these observations. In the case of Venetia, some of the high TDS groundwaters could be an artifact of evapo-concentration in the hot, dry climate (as suggested by Morton and Müller, 2003), whereas in the case of Ekati, the high TDS could reflect leaching of chemically unstable minerals from kimberlite and/or country rock xenoliths (as suggested by Rollo and Jamieson, 2006). Day et al. (2003) also pointed out that the TDS of some of the water at the Ekati mine site could have increased through freeze concentration (i.e., brine exclusion during freezing of water). This process is known to increase the concentration of solutes in pore water and shallow groundwater in the active layer of permafrost regions (Konrad and McGammon, 1990; Lacelle et al., 2007).

Day et al. (2003), Rollo and Jamieson (2006), and Sader et al. (2007) include tables of chemical analyses of trace elements in waters associated with kimberlite. From the combined results, it appears that kimberlite waters should have low concentrations of most metals and metalloids of concern, such as As, Cd, Co, Cu, Cr, Pb, Se, and Zn. Exceptions include Fe (up to several mg/L in some samples reported by Day et al., 2003), Ni (average of 150 µg/L in the study of Rollo and Jamieson, 2006) and Al (up to 0.5 mg/L in some of the groundwaters sampled by Sader et al., 2007). Given the generally high pH of kimberlite waters, elevated Fe concentrations would only be expected under anaerobic conditions where Fe is soluble as Fe^{2+}. Oxidation of Fe-rich water could result in locally acidic conditions, as was described by Day et al. (2003) for some small acidic seeps and pools near the toe of a kimberlite containment facility at Ekati. Dissolved Al concentrations in the 0.1 to 0.5 mg/L range are known to be harmful to many species of fish (Driscoll et al., 1980; Baker and Schofield, 1982). However, because kimberlite waters are also characterized by a high fluoride (F^-) content (Sader et al., 2007), it is likely that any dissolved Al will be strongly complexed with F^-, thus lowering the bioavailability of the metal (Driscoll et al., 1980).

A quick review of the literature suggests that high salinity may be a feature that is common to deep groundwater in northern, permafrost regions. Kuchling et al. (2000) found a regional trend of increasing TDS with depth from a number of wells in the Lac de Gras region. Groundwater samples collected at depths of up to 500m (i.e., the inferred range for most existing or planned mining operations) generally had less than 1000 mg/L TDS, although some exceptions exist. In contrast, many of the groundwater samples at depths greater than 1000m had TDS > 10,000 mg/L. Kuchling et al. (2000) pointed out the possibility that a deep mine could encounter upwelling, highly saline groundwater. Although we know of no example where this has happened for a Canadian diamond mine, very high salinity groundwater has been reported from diamond mines in northern Russia (Borisov et al., 1995; Alexeev and Alexeeva, 2003).

5.1.4. Implications to diamond mine pit lakes in northern Canada

Based on the preceding discussion, a number of conclusions can be drawn that have implications to end uses of diamond mine pit lakes in northern Canada. These ideas range from speculative to probable, and will likely vary in applicability from site to site.

- In the event that a mine is located some distance from a major body of water, thick permafrost (up to 350 m) is likely to be encountered. If the mine penetrates below the permafrost zone, there is the possibility of upwelling groundwater that could be moderately to highly saline. Such a situation would be favorable for development of a meromictic pit lake upon closure.
- In the event that a mine is located beneath or along the shoreline of a lake, permafrost is likely to be thin or absent. Water management will be a major factor during and after the period of active mining. Groundwater entering the mine will likely have a chemistry that is similar to that of the nearby surface water body, or will be a mixture of deeper groundwater and lake water.
- The hydraulic conductivity of bedrock within and immediately adjacent to a kimberlite open pit is likely to be highly variable, but will probably include at least some zones of high permeability along fractures and faults. Overall, permeability should decrease with depth in the mine.
- Groundwater associated with the kimberlite rock itself is unlikely to pose major problems from a water quality point of view, although the possibility exists of locally high TDS and/or high pH. The possibility of $pH > 10$ exists for deep, undiluted pore waters in contact with kimberlite. Such high pH values are probably unlikely for an entire pit lake, especially for the epilimnion where free exchange of CO_2 exists between air and the water column.
- Based on limited data from the literature, water associated with kimberlite rock should have very low concentrations of trace metals, with the possible exceptions of Fe, Ni, and Al.
- Although the kimberlite itself may pose few water quality problems, no general statement can be made about the surrounding country rock. As shown at both Ekati and Diavik, country rock xenoliths have a much higher potential to generate acidic or metal-rich leachate than the kimberlite bodies themselves. Because the geology of the country rock at each mine may be completely different, the environmental aspects of diamond mining will need to be evaluated on a case-by-case basis.

5.2 COLOMAC GOLD MINE, NORTHWEST TERRITORIES

The Colomac Mine is an interesting example of a mining pit lake at high latitudes which was remediated to reduce concentrations of cyanide and its by-products. Most of the following information stems from a presentation by Chapman et al. (2007) and a follow-up memorandum (SRK, 2007). Additional details on the limnology of this site appear in several publications by Pieters and Lawrence (e.g., Pieters and Lawrence, 2007).

The Colomac Mine operated between 1990 and 1997 and produced 16.7 tonnes of gold using a cyanide vat leaching process. Tailings wastes containing cyanide-rich water were discharged to two nearby lakes, one of which was completely filled with solids, and the other – the so-called Tailings Lake – was only partly filled. To prevent the discharge of cyanide-rich water from Tailings Lake, part of the lake was diverted into the nearby Zone 2 open pit, forming a pit lake. The Zone 2 lake is about 50% comprised of Tailings Lake water, the other half being natural groundwater inputs as well as rain and snowmelt.

The main contaminants of concern at Colomac include free cyanide (CN^- or HCN), complexed cyanide (e.g., $Fe(CN)_6^{2-}$), thiocyanate (SCN^-), ammonium (NH_4^+), and nitrate (NO_3^-). Whereas cyanide and thiocyanate are residual compounds left over from the metallurgical recovery of gold, ammonium and nitrate are products of the breakdown of cyanide and thiocyanate. These reactions can be written as follows (modified from Chapman et al., 2007):

$$CN^- + \tfrac{1}{2}O_2 + H^+ + 2H_2O \rightarrow HCO_3^- + NH_4^+ \qquad (32)$$
$$SCN^- + 2H_2O + 2O_2 + H_2O \rightarrow SO_4^{2-} + HCO_3^- + NH_4^+ + H^+ \qquad (33)$$
$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O \qquad (34)$$

Because all of these reactions consume oxygen, low concentrations of DO were also an issue, especially for the much deeper Zone 2 pit lake.

Early monitoring showed that both free and complexed cyanide in both lakes broke down rapidly after closure to values that met discharge requirements, presumably from a combination of oxidation and biological uptake. However, thiocyanate concentrations remained elevated. To enhance the breakdown of SCN^-, a decision was made to add mono-ammonium phosphate ($NH_4H_2PO_4$) to both lakes to stimulate growth of algae and thereby promote Enhanced Natural Removal (ENR). The P-amendments took place in 2002-2003. The results showed rapid and quantitative removal of thiocyanate from the relatively shallow Tailings Lake, but less complete removal from the Zone 2 pit lake. The main reason for the lower removal efficiency in the latter case was that the much deeper pit lake was meromictic during this time period so that thiocyanate was eliminated only in the upper 20m of the lake. To get around this problem, the operators constructed an aeration circuit in which compressed air was delivered to the deep lake to promote oxidation and to destratify the water column. Aeration was conducted in 2006 and 2007, and results indicate that not only was destratification successful, but also that thiocyanate and ammonia have been essentially removed from the entire Zone 2 pit lake (SRK, 2007).

Although the combination of ENR and aeration have been successful for eliminating cyanide, ammonia, and thiocyanate from the Colomac lakes, there are lingering concerns over elevated phosphate and nitrate concentrations. Fortunately, there is evidence that significant bacterial reduction of nitrate to N_2 gas (reaction 20) occurs in the Zone 2 pit lake during the frozen winter months (SRK, 2007). Projected to the future, it is possible that most of the nitrate in the Zone 2 lake will be gone in 3 to 5 winter seasons (SRK, 2007). However, this assumes that the water column will continue to become anoxic during the winter months, a prerequisite for denitrification to occur (see section 2.4.2.8). Seasonal anoxia may not occur now that the major sources of chemical oxygen demand (ammonia, cyanide, thiocyanate) have been removed. The removal of P also presents a challenge, although the long-term trends in monitoring data show a steady decline in total P load with in the Zone 2 pit lake (SRK, 2007).

5.3. EAST PIT COAL MINE, ALBERTA

Alberta has a long history of coal mining operations which have played an important role in the early development and colonization of the province. In the foothills and mountains of the province, mining for coal has been proceeding since the turn of the nineteenth century and the landscape in such areas has been altered drastically. Often as surface mining operations proceed and/or subsequent to mineral extraction the mined-out pits are backfilled with overburden, and where the pits cannot be filled completely an open pit remains. Eventually, after dewatering of the mine pit ceases, groundwater and surface water fills the pit resulting in an “end pit lake”, which is typically proposed as a reclamation technique for an end-use for such pits upon mine closure (Alberta Environment, 2004).

The resultant lakes vary in morphometry depending on the shape of the coal seam and the type of mining method used. For example, dragline mining typically results in long, narrow, deep lakes (usually < 30m) relative to their width whereas truck and shovel operations usually create larger more angular lakes that can be much deeper (up to > 70m) (Alberta Environment, 2004). Additionally, the shape and size of the newly created lakes will be highly influenced by the placement of the overburden used in backfilling operations and the shape of the coal seam that was mined. In Alberta, several examples exist where lakes have been created in decommissioned surface coal mines during the reclamation process.

East Pit Lake, near the town of Wabamun, Alberta, is a specific example of a pit created by dragline mining that has been reclaimed into a lake that currently supports a productive recreational fishery, and provides an array of other recreational opportunities. After mining, the East Pit was filled with groundwater to replace two small water bodies that had to be drained to access the coal (Sumer et al., 1995). Currently the lake is approximately 100m wide, 800m long with an average depth of 3.3m and a maximum depth of 10m (Sumer et al., 1995; Figure 25).

Prior to filling with groundwater, physical contouring of the final cut of the coal mine pit was required to meet the reclamation goals of creating a put-and-take fishery, and enhancing the surrounding area to be used for recreational activities such as picnicking and bird-watching (Sumer et al., 1995). Once water was drained from the original pit, major earthwork was completed using a dragline while finishing work was facilitated with the use of bulldozers where, in total, 1.82 million m^3 was moved during construction (Sumer et al., 1995). This was done to increase littoral habitat and to ensure adequate depths for fish survival. In addition to physical contouring, much of the reclamation strategy focused on the area surrounding the lake. For example, grass, trees and shrubs were planted, and fertilizer was applied to the surrounding area to promote revegetation of native plant species which would promote bank stability, provide a food source and cover for native animals, and promote the input of terrestrial insects into the lake.

Figure 25. East Pit Lake, Alberta was formed through the reclamation of a surface pit left over from a dragline coal mining operation.

As discussed in several places throughout this document, the weathering of newly exposed material in a mining environment can accelerate the release of acid and metals into newly created pit lakes. No water quality data were found for East Pit Lake during the preparation of this report other than the fact that East Pit Lake has similar DO concentrations to natural lakes in the area (Sumer et al., 1995). Given the successful establishment of aquatic organisms in this waterbody (Sumer et al., 1995), it is likely that other water quality parameters – such as pH, salinity, and metal concentrations – are also good.

Subsequent to groundwater filling, shoreline habitat creation and enhancement procedures commenced. For instance, logs and brush were submerged along the shoreline, and brush piles were placed at varying depths to provide cover in deeper parts of the lake (Sumer et al., 1995). Additionally, submergent and emergent aquatic vegetation, such as Richardson's pondweed (*Potamogeton richardsonii*) and northern watermilfoil (*Myriophyllum exalbescens*) were established in the lake (Sumer et al., 1995), and both are recognized as important fish habitat (e.g., Copp, 1997). This aquatic vegetation will provide refuge for aquatic invertebrates that are valuable food for stocked fishes and furthermore will increase dissolved oxygen within the waterbody.

As a combined result of the major earthwork and habitat modifications, East Pit Lake currently harbors a diverse community of aquatic plants, aquatic invertebrates, and fish (Sumer et al., 1995). Additionally, the lake provides excellent recreational fishing opportunities for rainbow trout (pers. observation), and provides users with opportunities for bird watching, hiking and picnicking. TransAlta Utilities, the company at the forefront of this habitat reclamation and creation project, has since received numerous awards for their efforts in establishing this well known sport fishery.

5.4 IRON ORE MINES, MINNESOTA AND ONTARIO

The Portsmouth Mine Pit Lake in Minnesota is a good example of a very large (Fig. 2) man-made lake formed after flooding of an iron ore (hematite) mine. This is one of the deepest lakes in Minnesota at 137 m, and is one of the largest of > 200 pit lakes in the region left behind from historical iron mining. No technical papers could be found on the chemistry or limnology of this lake. However, the lake apparently has excellent water quality as it is stocked with rainbow trout and – according to numerous websites, including Wikipedia – is used extensively for recreation, including swimming, boating, and scuba diving (Fig. 26). A recent fisheries survey indicated a trout density of 56 individuals per hectare, which is similar to natural lakes in Minnesota (Close et al., 2006). This relatively high fish density is somewhat surprising, considering that the lake is also reported to be essentially devoid of littoral habitat (Close et al., 2006). Two other large mining pit lakes in the same region with 13-14% littoral habitat had slightly *lower* fish densities than Portsmouth Lake (Close et al., 2006). However, these observations should be interpreted with caution since all of these lakes are stocked and therefore trout populations are artificially manipulated. As mentioned above, a number of pit lakes in Minnesota from former iron mines were used for large fish farms in the early 1990s, but much of this activity has ceased due to unwanted eutrophication of the lakes from aquaculture activities (Axler et al., 1996, 1998).

Figure 26. Photograph of the swimming beach at the Portsmouth Mine Pit Lake, Minnesota (taken from Wikipedia.org).

Mining of similar iron ore deposits in Ontario has also resulted in pit lakes, as well as dammed reservoirs. The Steep Rock mines of NW Ontario (near Atikokan) are one example where several large natural lakes were completely drained and buried with waste rock and overburden during iron ore mining operations (Sowa, 2004). Following closure of the mines, several of the mine pits were flooded and dams were built to raise the stage of the impounded water, creating a new reservoir/pit lake system that supports a population of bass (*Micropterus* spp.), walleye (*Sander vitreus*), northern pike (*Esox lucius*), lake whitefish (*Coregonus clupeaformis*), and cisco (*Coregonus artedi*). A large floating fish farm operation has also been established (McNaughton et al., 1999; Sowa, 2004).

A recent abstract (Godwin et al., 2007) reported possible water quality problems at Steep Rock associated with the anticipated release of water from two newly flooded mine pit lakes that are connected to the main lake system. The main contaminant of concern appears to be sulfate, with reported values of 1200-2000 mg/L SO_4 in one of the pit lakes that will be discharging to surface water. Godwin et al. (2007) state that one of the concerns is the health of aquatic plants such as duckweed (*Lemna minor*), which reportedly are impacted by sulfate concentrations as low as 1000 mg/L.

5.5 SLEEPER GOLD MINE, NEVADA

The Sleeper gold mine of NW Nevada was operated for roughly 10 years, from the mid-1980s to the mid-1990s. The history of closure and flooding of this large open pit mine (see Fig. 2) is an interesting case study (Dowling et al., 2004). During the period of active mining, a very prolific groundwater aquifer overlying the ore body was intercepted. Dewatering wells were pumped at rates up to 930 L/s, making this one of the largest dewatering operations worldwide. Meanwhile, geochemical studies and ABA tests performed during the mine life showed that a high percentage of the lower mine walls and excavated waste rock had a moderate to high potential to generate acidic and metal-rich leachate.

As described by Dowling et al. (2004), several steps were taken to mitigate the potential for AMD at this site. To begin with, the open pit was partially backfilled with 7.3 x 10^6 m^3 of waste rock, including 5.2 x 10^6 m^3 of potentially acid-generating material. Waste rock with the highest AP values was placed in the deepest portions of the pit. The waste was emplaced to elevations within 40 m of the ultimate pit lake surface, and was capped by a 2 m layer of oxidized, clay-rich material that had no acid-generating potential and low hydraulic conductivity. As well, large volumes of alluvial material were end-dumped over the mine walls to lower the slope of the walls and to form a buffer of non-reactive material between the bedrock and the pit lake and overlying weathering zone. The lake was then rapidly filled with groundwater pumped at a rate of 560 to 740 L/s from the same alluvial aquifer that was a burden during the period of active operation. In 14 months, the pit lake surface rose to an elevation that covered all of the reactive waste and pyrite-bearing bedrock exposed on the mine walls. By contrast, hydrogeological modeling predicted that – left to its own devices – the lake would have taken over 100 years to fill.

A fortuitous circumstance for the Sleeper pit lake was that the groundwater used to rapidly fill the pit was not only unusually abundant, but also had good overall quality, with relatively low TDS, alkaline pH, substantial bicarbonate alkalinity, and very low toxic metal concentrations. Nonetheless, geochemical modeling prior to flooding predicted that locally-acidic conditions would occur due to leaching of low pH pore water from the mine walls and back-filled mine waste. Monitoring of water chemistry during the initial stages of mine flooding showed that this was indeed the case. It was also realized that slope failures during or after flooding could cause episodic influxes of acidic pore water. To mitigate the short- and long-term potential for AMD, the mine pro-actively added lime during, and for approximately one year after, the period of active flooding, at a maximum rate of 78 tons/day. An excess of lime was added, with the anticipation that a turnover event or major landslide after flooding might transport dissolved metal and acidity accumulated near the bottom of the lake into the upper portions of the water column. Also, to enhance biological activity in the lake, approximately 200 tons of manure were added in 4 separate events during and after the rapid filling program.

In the first two years after the end of the rapid filling program the Sleeper pit lake underwent several natural turnover events that completely homogenized the water column. During summer stratification, the epilimnion had 6-9 mg/L of DO, whereas deeper portions of the lake had little or no DO. After Spring and Fall turnover events, the DO concentration of the lake was homogenized to values near 5 mg/L. After mixing, concentrations of iron, arsenic, and other contaminants of concern in the lake were lower than originally predicted by geochemical modeling. This was attributed to precipitation of copious quantities of HFO when the deep, anoxic water mixed with shallow, oxygenated water after each turnover event. The freshly precipitated HFO stripped dissolved arsenic and heavy metals from the water column, and then settled to the bottom of the lake to accumulate in the benthic sediment.

Monitoring conducted in 2002, roughly 4 years after flooding, showed that the Sleeper pit lake met all of the State of Nevada water quality standards, with the exception of TDS, sulfate, and possibly manganese. Although elevated, levels of TDS and sulfate in the lake after chemical stabilization were actually lower than initially predicted. It remains to be seen whether or not this lake will become a viable ecosystem for aquatic life. No information of this type was reported in the paper of Dowling et al. (2004). Because the lake is terminal, the concentrations of sulfate and TDS are likely to increase with time owing to evapo-concentration.

5.6. ANCHOR HILL, SOUTH DAKOTA

Between 2001 and 2006, the US EPA and associated technical experts conducted a field-scale demonstration project to remediate the acidic Anchor Hill pit lake, South Dakota. This lake (Fig. 2) occupies one of three relatively small open pits at the Gilt Edge Mine Superfund Site. The mine produced gold between 1986 and 1998, shortly after which time the parent company declared bankruptcy and the EPA took over administration of the site. In March 2001, prior to remediation activities, the Anchor Hill lake was 30 m deep and contained 265,000 m^3 of acidic (pH 3.0) water with highly elevated concentrations of Al (223 mg/L), Cd (0.6 mg/L), Cu (43 mg/L), Fe (16 mg/L), Mn (27 mg/L), Zn (14 mg/L), sulfate (3270 mg/L), and nitrate (83 mg/L as N) (data from Table 1 of Lewis et al., 2003).

The original goals of the remediation project were twofold (Lewis et al., 2003; Harrington et al., 2004): 1) to adjust the pH of the entire lake to 7.0±0.2 via lime addition; and 2) to add organic carbon to stimulate microbial reactions that would improve water quality to site-specific standards. For the first objective, approximately 265 tonnes of lime were added to the lake in March to May of 2001 using a patented "Neutra-Mill" system (Earth Systems Pty Ltd, Australia). The Neutra-Mill is essentially a semi-autonomous floating barge that can dispense lime as it moves across the lake surface, thereby achieving a better mixing of lime within the lake. Using this method, it was hoped that a lime efficiency of 85% could be attained. Due in part to practical difficulties caused by cold winter conditions, the actual lime efficiency that was achieved was closer to 71% (Lewis et al., 2003), meaning that roughly ¼ of the lime added to the lake did not initially react with the bulk of the overlying water column. Furthermore, the pH of the lake drifted down over a period of weeks from values near 7.0 immediately after lime addition to steady-state values of 4.5 to 5.0. The reason for the drop in pH after lime addition was not clear, although influx of low pH water during rain events may have been a contributing factor (Lewis et al., 2003), along with a longer-than expected time for the lake to reach equilibrium.

Following the pH manipulation described above, a series of organic carbon amendments commenced in May of 2001. The exact sequence of events was complicated, and is chronicled in detail by Lewis et al. (2003) and Park et al. (2006a, b). In brief, copious quantities of methanol and animal feed-grade molasses (sometimes with phosphate added) were pumped into the pit on numerous occasions by use of a hose (Fig. 27). It was anticipated that the organic carbon amendments would stimulate microbial reactions, such as reduction of nitrate and sulfate, and that this would generate alkalinity and raise the pH of the lake. However, the target pH of 7.0±0.2 proved difficult to achieve, and was not attained until a batch of NaOH solution was added to the lake in September of 2002. Lewis et al. (2003) speculated that high concentrations of dissolved Al may have inhibited microbial activity at lower pH.

Figure 27. Addition of methanol to the Anchor Hill pit lake. (Photo by Brian Park, May, 2001).

By the summer of 2003, denitrification was essentially complete, and bacterial sulfate reduction was established, as evidenced by detectable concentrations of H_2S (Park et al., 2006a). Dissolved concentrations of most of the metals of concern had dropped to levels below regulatory standards, although total (unfiltered) concentrations remained somewhat elevated, presumably due to suspension of fine-grained metal sulfide particles. Although the water quality of the lake in 2003 was a definite improvement compared to 2001, the presence of excess quantities of H_2S became a problem, especially in 2004 when levels as high as 100 mg/L were measured in the deeper waters (Park et al., 2006b). Besides the fact that H_2S is toxic to most forms of aquatic life, there was a concern for human health in the event that the lake turned over and released H_2S gas to the air. As well, the surface of the lake took on a turbid and milky white appearance, due to the presence of suspended particles of elemental S formed by oxidation of H_2S. To rectify the problem of excess H_2S, yet another large-scale amendment was undertaken in August 2005, this time using 50% hydrogen peroxide (H_2O_2) to oxidize H_2S to S and/or sulfate. By late 2005, after a probable lake overturn event, most – but not all – of the H_2S in the lake had been oxidized. The demonstration project at Anchor Hill effectively ended in 2006, when many millions of gallons of acidic water were transferred from the nearby Sunday Pit into the Anchor Hill Pit.

Overall, the Anchor Hill project was a success in terms of lowering dissolved metal concentrations. An important lesson learned was that it can take a very long time (years) for a pit lake to mix and achieve overall equilibrium after an *in situ* manipulation in chemistry. Although preliminary modeling suggested that neutral pH could easily be attained by a combination of lime addition and microbial reactions, this proved not to be the case without additional NaOH amendments. Also, the Anchor Hill example shows that one should not add too large an excess of organic carbon to stimulate microbial activity, as this may result in undesirably high BOD and H_2S concentrations, with associated depletion in dissolved oxygen.

6. ACKNOWLEDGEMENTS

The authors would like to thank Derrick Moggy, Ernie Watson, Julie Dahl, and Marc Lange of the DFO – Fish Habitat Management Program for support of this project; Jim Jonas and Karen Smokorowski for helpful peer review comments; and Donna Laroque, Donna Patterson, and Marge Dyck for administrative support and editing assistance. Financial and in-kind support for this project was provided by Fisheries and Oceans Canada and the Montana Department of Environmental Quality.

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8. GLOSSARY OF TERMS AND ACRONYMS

ABA: Acid-Base Accounting. Usually used in reference to batch laboratory tests that determine the acid potential or neutralization potential of a rock or soil sample.

Acid Mine Drainage: the oxidation of exposed sulfide minerals contained in waste rock, mine tailings and exposed cut rock which subsequently reacts with water to create acidic conditions.

Absorption: The process by which a dissolved solute passes through the cell wall into the interior of a living organism. Absorption only occurs in living cells.

Adsorption: The process by which a dissolved solute attaches to the outer surface of an inorganic or organic solid.

Aerobic: In close contact with air, especially referring to the presence of oxygen.

Algae: Photosynthesizing microbes that contain a cell nucleus (i.e., eukaryotes). Includes both green algae and diatoms (algae with silica shells).

Alkalinity: The sum of titratable bases in a water sample. Usually determined by titration of the sample with a dilute acid, such as H2SO4. The higher the alkalinity, the more strongly buffered a water sample is with respect to a drop in pH.

AMD: Acid Mine Drainage

Ammonia: A chemically reduced form of nitrogen. Occurs mainly as NH_4^+ (ammonium ion) at pH < 9.25, or as NH_3 (dissolved ammonia gas) at pH > 9.25.

Amphibolite: A metamorphic rock rich in the mineral amphibole.

Anaerobic: Isolated from air, especially referring to the absence of oxygen.

Anhydrite: $CaSO_4$. Similar to gypsum, but with no water.

Anion: A negatively charged dissolved ion. Examples: Cl^-, SO_4^{2-}, HCO_3^-

Anorthite: Calcium rich plagioclase. Formula: $CaAl_2Si_2O_8$

Anoxia: the absence of oxygen. Relating to pit lakes it refers to conditions where oxygen is completely absent from, at least in one area, of the lake.

Anthropogenic: resulting from the influence of human beings on nature, as opposed to those occurring in natural environments without human influences.

AP: Acid Potential. Usually determined by a total sulfide analysis, this is the acid-generating potential of a rock or soil. Most commonly expressed in units of kg $CaCO_3$/ton.

Apatite: A common accessory mineral in many igneous rocks: $Ca_5(PO_4)_3(OH, F, Cl)$. Human teeth are composed of hydroxy-apatite.

Aquaculture: the cultivation and rearing of aquatic organisms under controlled conditions. Also referred to as fish farming.

Astrobiology: The scientific study of the origins of life on Earth and other planets.

Autotrophic bacteria: These are prokaryotic micro-organisms that use carbon dioxide (CO_2) as the source of carbon they need to grow and multiply.

Backfill: The process of filling an open pit mine with soil or rock.

Bacteria: Primitive micro-organisms (i.e., prokaryotes) that lack a cell nucleus.

Bacterial sulfate reduction: An important reaction involving the conversion of sulfate (SO_4^{2-}) to sulfide (H_2S or HS^-). This reaction does not occur at low temperature without microbial catalysis, and requires a source of electrons, such as hydrogen gas or low molecular weight organic compounds.

Basalt: A common volcanic rock composed of the minerals pyroxene, plagioclase, and sometimes olivine.

Benthic: Referring to sediments or biota at the bottom of a water body.

Bicarbonate: HCO_3^-, the main source of alkalinity in most natural waters.

Biaovailability: the rate and quantity of toxic substances that may occur in the body

Biocenoses: a group organisms interacting within a particular habitat that in turn form an ecological community.

Biogenic meromixis: A sub-type of meromixis in which the total dissolved solids of the bottom water layer is increased due to micro-biological reactions, such as iron reduction.

BOD: Biological oxygen demand. A measure of the potential for aquatic biota to lower the oxygen content of water in the absence of photosynthesis.

Brine exclusion: The process by which salt is excluded from growing bodies of ice. The salt concentrates into high salinity brines which can descend by gravity through the ice and underlying water column of a frozen lake.

Cation: A positively charged dissolved ion. Examples: Na^+, K^+, Ca^{2+}, Mg^{2+}

Cementation: A metallurgical term referring to the precipitation of copper onto metallic iron.

Chemocline: An interface separating two layers of water in a lake that have differing chemical properties, such as salinity.

CO_2: Carbon dioxide.

COD: Chemical oxygen demand. A measure of the potential for inorganic reactions to lower the oxygen content of water.

Crenogenic meromixis: Development of a meromictic lake due to the influx of deep groundwater of high salinity.

Cryogenic meromixis: A sub-type of meromixis in which the total dissolved solids of the bottom water layer is increased due to brine exclusion and thermohaline convection during ice formation.

Cyanobacteria: A sub-type of bacteria that photosynthesize. Formally referred to as "blue-green algae".

Dimictic: A lake that regularly turns over in the fall and spring of each year.

Double-diffusion convection: A rare phenomenon that can occur when the monimolimnion of a water body is both warmer and saltier than the overlying water column. Results in a characteristic "stair-step" vertical profile in salinity and temperature.

Diagenesis: The process by which the texture and mineralogy of recently-deposited sediment is slowly transformed by a combination of organic and inorganic processes.

Diopside: A green pyroxene mineral: $MgCaSi_2O_6$. In kimberlites, trace amounts of Cr in the mineral gives an intense emerald green color.

DO: Dissolved oxygen (O_2).

DOC: Dissolved organic carbon.

Eh: The difference in electrical potential (or redox potential) of a water sample with respect to a standard solution. By convention, the universal standard for Eh measurement is the standard hydrogen electrode. Most common units are volts (V) or millivolts (mV).

Ectogenic meromixis: Development of a meromictic lake due to human manipulation, e.g., by filling the lower portion of a lake with salty water, and then capping with water of low salinity.

End use: The permanent, sustainable use that is selected for an environmental system – such as a mining pit lake – after human intervention ceases. End uses can be biological, recreational, socio-economic, or scientific.

Enstatite: Mg-rich pyroxene: $MgSiO_3$

EPA: The United States Environmental Protection Agency.

Epilimnion: The shallow layer of a lake.

Eutrophic: Characterized by high rates of algal photosynthesis and high nutrient load. Often resulting in large fluctuations in dissolved oxygen concentration.

Eutrophication: Nutrient overload to a water body. Symptoms of eutrophication include copious growth of algae and aquatic macrophytes and large seasonal and diurnal (24-h) changes in dissolved oxygen concentration.

Evapoconcentration: The process by which the concentration of a dissolved substance increases due to loss of water to evaporation.

Extremophile: A microbe that can thrive in conditions that would normally be considered hostile to life, such as very high or very low pH, unusually high or low temperatures, or extremely high salinity.

Facies: A geologic term, broadly equivalent to the word "sub-type".

Felsic: A descriptive geologic term for a rock with a predominance of light-colored minerals, such as feldspar and quartz.

Fermentation: A process by which microbes gain energy by breaking down large organic compounds into smaller organic compounds. Methane (CH_4) and carbon dioxide (CO_2) are common by-products.

Ferric iron: The most oxidized form of iron, with a valence state of +3. Often written as Fe^{3+} or Fe^{III}.

Ferrous iron: A reduced form of iron, with a valence state of +2. Often written as Fe^{2+} or Fe^{II}.

Flow-through lake: A lake that has groundwater entering on one side but exiting on the other side.

Forsterite: A Mg-rich olivine mineral, Mg_2SiO_4. Common in mafic and ultramafic igneous rocks, including kimberlite.

Gabbro: A coarse-grained, intrusive igneous rock with the same chemical and mineralogical composition as basalt.

Graminoid: grasses and grass like plants.

Granite: A very common, coarse-grained, felsic intrusive igneous rock that is rich in the minerals quartz, feldspar, and biotite.

Green rust: This is a metastable solid compound with an olive- to emerald-green color that is rich in ferrous iron. Often forms when the pH of Fe^{II}-rich mine waters is rapidly raised, e.g., by addition of lime. Green rust is unstable in air and will quickly oxidize to red rust, i.e., Fe^{III} oxide.

Gypsum: $CaSO_4{\cdot}2H_2O$. A common mineral in marine sediments, especially in environments that have undergone evaporation.

HFO: Hydrous ferric oxide. Often poorly crystalline, with the approximate formula $Fe(OH)_3$. One of many red-brown ferric compounds that can form in AMD settings.

H_2S: Hydrogen sulfide. A toxic gas formed by sulfate-reducing bacteria.

Heterotrophic bacteria: These are prokaryotic micro-organisms that need organic carbon for their source of carbon to grow and multiply. Most heterotrophic bacteria respire CO_2 as a waste product.

HMO: Hydrous manganese oxide. A poorly crystalline substance, usually dark brown or black in color, that is a mixture of various oxidized forms of manganese, i.e., Mn^{III} and Mn^{IV}.

Holomictic: Referring to a lake that completely turns over, on average, at least once per year.

Humidity cell: An apparatus used to simulate accelerated weathering of mine waste materials.

Hydraulic conductivity: Usually abbreviated “K”, this is the ability of a rock or soil to transmit groundwater in response to a hydraulic gradient. Although sometimes referred to as permeability (k), the units are different. K has dimensions of velocity (e.g., m/day) whereas k has units of area (e.g., cm^2).

Hypabyssal: Referring to an intrusive igneous rock that crystallizes at relatively shallow depth (e.g., less than 1 or 2 km below the ground surface).

Hypolimnion: The deep portion of a lake, which is normally separated from the overlying epilimnion by a thermocline.

Hypoxic: Being severely depleted in dissolved oxygen.

Ilmenite: $FeTiO_3$. A fairly common accessory mineral in igneous rocks.

Insolation: Flux of photons (sunlight) at a particular location.

IOB: Iron-oxidizing bacteria. Includes the common species *Acidithiobacillus ferrooxidans*.

Jarosite: A common secondary ferric mineral in mine waste settings, this mineral is only stable at low pH. The most common variety has the formula $KFe_3(OH)_6(SO_4)_2$, although sometimes Na^+ or H_3O^+ can substitute for K^+.

K-feldspar: $KAlSi_3O_8$. A common rock-forming mineral, especially in granite.

Kimberlite: The main bedrock source of diamonds, this is a very rare igneous rock that has a K-rich ultramafic composition. Often occurs as vertical “pipe-shaped” intrusive bodies that can extend > 1 km in depth with a diameter of a few 100 m or less. Also can occur as sub-horizontal volcanic layers.

Kinetic test: In the context of this report, a kinetic test is any laboratory or field procedure that can be used to quantify changes in the chemistry of water in contact with mine waste over a long time period (e.g., one year or longer). Humidity cells are one common example.

L: Liter

Lacustrine: Referring to a lake.

Leachate: Water that has had its chemistry modified by contact with another substance, such as solid mine waste.

Life History: typical pattern of stages followed by most individuals within a group of organisms follow throughout their lives. Can refer to the history of changes that occur within a taxonomic group.

Ligand: an ion, a molecule, or a molecular group that binds to another chemical entity to form a larger complex.

Lignite: A solid biofuel with a density less than that of coal.

Lime: CaO, a chemical often used to raise the pH of mine water.

Limestone: A common sedimentary rock, mainly composed of the mineral calcite ($CaCO_3$).

Limnology: The science understanding the biological, physical, chemical, geological and hydrological properties of inland waters.

Littoral: Referring to shallow water, as along the shoreline of many natural lakes.

Lotic: relating to, or living in, moving (flowing) water.

Macrophyte: A multicellular plant, usually with a vascular system to transmit water and nutrients.

Macroinvertebrates: typically used to refer to aquatic organisms large enough to see without a microscope.

Mafic: A descriptive geologic term for a rock with a predominance of dark-colored minerals, such as pyroxene, olivine, and Ca-rich plagioclase.

Marcasite: A metastable form of FeS_2, similar to pyrite but with a different internal atomic structure.

Megacryst: Usually used in relation to volcanic or hypabyssal igneous rocks, a megacryst is an individual crystal that is readily visible to the eye surrounded by a matrix of very fine-grained, microscopic mineral matter.

Meromictic: Referring to a lake that is permanently stratified.

Mesocosm: A small-scale model of the real world that highlights one or another process of interest. Usually used in reference to bench-top laboratory experiments that attempt to simulate the natural environment.

Metalimnion: see Thermocline

Metalloid: A term that has a strict metallurgical definition, but is commonly used in the environmental literature for the elements arsenic (As), antimony (Sb), selenium (Se) and tellurium (Te).

Metastable: Referring to a compound that is thermodynamically unstable and should convert to a more stable compound, but does so at a sufficiently slow rate that it can persist for a significant length of time in the environment.

Methane clathrate: A solid composed of molecules of methane gas that are trapped in a three-dimensional “cage” of water ice. Thermodynamically stable over a rather narrow range of temperature and pressure, methane clathrates are most abundant in subarctic soils (permafrost), or in oceanic sediment off continental shelves.

Methanogenesis: The process by which bacteria use hydrogen gas or another source of electrons to convert organic carbon compounds into methane (CH_4).

Methylation: The process – usually sped up by microbes – by which an inorganic metallic compound is transformed into an organo-metallic compound, as in the methylation of mercury (Hg^{2+}) to form methyl-mercury ($HgCH_4^+$).

mg/L: milligram per liter, also known as ppm, or part per million

Mixolimnion: That portion of a meromictic lake that mixes seasonally. Usually includes the epilimnion and the hypolimnion, but not the monimolimnion.

Mole: An Avogadro's number of atoms; i.e., 6×10^{23}. The mass of one mole of a compound is equivalent to its "gram formula weight".

mol/kg: Also known as molal (m), this is a unit of concentration equivalent to the number of moles of a dissolved substance per kg of water.

mol/L: Also known as molar (M), this is a unit of concentration equivalent to the number of moles of a dissolved substance per liter of solution.

Monimolimnion: This term refers to the deepest layer of a stratified, meromictic lake which – because of its high density – does not mix with the overlying water column.

Monticellite: Rare mineral of the olivine group with the formula: $CaMgSiO_4$.

Morphometry: Exact details regarding shape and size.

Muscovite: A common rock-forming mineral, usually transparent or light brown, also known as mica. Formula: $KAl_3Si_3O_{10}(OH)_2$.

Nanocrystalline: Solid particles that are less than roughly 0.1 µm in size. Such particles can easily pass through most filters used in the field to collect "dissolved" water samples.

Nitrate: NO_3^-, an important nutrient for growth of algae and plants.

NP: Neutralization Potential. Usually determined by ABA analysis (e.g., Sobek test), this is the acid-neutralizing potential of a rock or soil. Most commonly expressed in units of kg $CaCO_3$/ton.

NPR: Neutralization potential ratio. This is NP/AP, and is normally determined by ABA analyses. NPR values < 1 indicate a high probability that the rock or soil will generate acidic leachate during weathering.

Nutrient: A chemical compound essential for growth of algae or plants. Usually used in reference to nitrogen (either as nitrate or ammonia) and phosphorous (usually as phosphate), but may include other elements such as iron (Fe) and potassium (K).

Oligotrophic: Referring to a water body that is low in nutrient content and therefore has a relatively low rate of primary production by plants and algae.

Olivine: A common rock-forming mineral in mafic or ultramafic igneous rocks. Usually green in color. Formula: $(Mg, Fe)_2SiO_4$, but may also contain Ca, as in monticellite.

Peridotite: A rare ultramafic igneous rock rich in olivine and pyroxene.

Permafrost: Permanently frozen ground in land masses at high latitudes. Overlain by a thin "active layer" which thaws seasonally. Can be up to 500m thick, but can also thin or disappear beneath large bodies of water, such as a large river or lake.

Perovskite: This is a rare mineral found in some metamorphic rocks or mafic to ultramafic igneous rocks, including kimberlite. Formula: $CaTiO_3$.

pH: A common field measurement that quantifies whether a water is acidic ($pH < 7$) or alkaline ($pH > 7$). pH is based on a log scale, and is defined as $-\log(aH^+)$, where log is base 10 and aH^+ is the chemical activity (molal concentration adjusted for non-ideal behavior) of protons in the water sample.

Phlogopite: A Mg-rich (and Fe-poor) variety of biotite mica: $KMg_3AlSi_3O_{10}(OH)_2$. Phlogopite is relatively rare but is found in K-rich mafic or ultramafic igneous rocks, such as kimberlite.

Phosphate: PO_4^{3-}. A common nutrient, the most common forms in natural waters are $H_2PO_4^-$ and HPO_4^{2-}.

Photoreduction: The process by which sunlight causes a decrease in valence of a transition metal, as in photoreduction of Fe^{3+} to Fe^{2+}.

Photosynthesis: The process by which plants, algae, and some forms of bacteria combine carbon dioxide and water to form organic carbon molecules. This reaction requires sunlight, and produces oxygen (O_2) as a byproduct.

Phototroph: Any organism that requires sunlight to metabolize. Includes all plants and algae and some forms of bacteria.

Pioneer Species: organisms which are the first to invade and establish in an area subsequent to a disturbance (natural or human induced).

Plagioclase: A very common rock-forming mineral whose chemical composition can vary from $CaAl_2Si_2O_8$ (anorthite) to $NaAlSi_3O_8$ (albite).

Plankton: Microorganisms that are suspended in a water body. Includes phytoplankton (algae) and zooplankton (microscopic animals).

Polymictic: Referring to a lake that turns over, on average, more than twice a year.

Polyprotic acid: A chemical compound that has more 2 or more protons, each of which can be lost in sequence, depending on the pH of the water. Examples: carbonic acid (H_2CO_3), phosphoric acid (H_3PO_4), sulfuric acid (H_2SO_4).

Porphyrytic: A textural term referring to an igneous rock with a bimodal grain size distribution: i.e., coarse-grained phenocrysts in a groundmass of very fine-grained minerals.

Potentiometric surface: This is the elevation to which groundwater will rise in a well or bore hole. For shallow, unconfined aquifers, the potentiometric surface is equivalent to the water table. For deep, confined aquifers, the potentiometric surface may be above or below the elevation of the ground surface.

Primary productivity: A measure of the combined rate of carbon-fixation by aquatic plants, algae, and autotrophic bacteria.

Put-and-take Fishery: the stocking of a waterbody with hatchery reared fish for recreational fishing purposes. These are fisheries that are not self-sustaining and require the continual addition of sport fish from an outside source (hatchery or fish farm).

Pyncnocline: An interface between two water layers of varying density.

Pyrite: A very common sulfide mineral, FeS_2. Weathering of pyrite can result in acid mine drainage (AMD).

Pyroclastic: Literally “fire” and “fragment”, this is a sub-type of fragmental volcanic rock that forms during an explosive eruption.

Pyroxene: A common rock-forming mineral in mafic or ultramafic igneous rocks. It is usually green, brown or black in color, and can have a wide range in chemical composition. Most pyroxenes are rich in Fe and Mg.

Quartzite: A rock mainly composed of quartz formed from the metamorphism of sandstone.

Reactive waste: In the context of this report, reactive waste refers to any solid waste product generated during the mining process that has the potential to generate leachate of poor water quality.

Relative depth: A limnological term that can be thought of as the aspect ratio (i.e., depth/surface diameter) of the lake.

Respiration: A biological process in which an electron donor (usually an organic carbon compound) is oxidized and an electron acceptor (usually O_2, but sometimes nitrate, sulfate, or metal compounds) is reduced. Most respiring organisms (including humans) generate carbon dioxide (CO_2) as a waste product.

Rhyolite: A common, usually light-colored volcanic rock with a felsic (silica-rich) composition.

Sandstone: A sedimentary rock composed of cemented sand grains, usually rich in quartz.

Schwertmannite: A common yellowish-brown to reddish-brown Fe^{III} oxy-hydroxide mineral that forms in AMD settings. It’s chemical formula can vary, but is approximately $Fe_8O_8(OH)_6(SO_4)$.

Serpentine: A green phyllosilicate mineral, $(Mg, Fe)_3Si_2O_5(OH)_4$, that most often forms during the weathering or low-temperature hydrothermal alteration of mafic or ultramafic igneous rocks.

Sludge: The technical term for the solid precipitates and contained water that form due to a rise in pH after lime treatment of AMD.

Spinel: This rare mineral, $MgAl_2O_4$, is a semi-precious gemstone and is sometimes found in metamorphic or igneous rocks of unusual chemistry, such as kimberlite or peridotite.

Stoichiometry: The number and relative proportion of reactants and products for a given reaction.

Subaqueous: Taking place below the water line of a lake or river, as in subaqueous water-rock interaction.

Sulfate: SO_4^{2-}, a common anion in natural waters, especially AMD waters.

TDS: Total dissolved solids. Usually expressed in mg/L, this is the sum of the concentrations of all dissolved substances in a water sample.

TSS: Total suspended solids. Usually expressed in mg/L, this is the sum of the concentrations of all non-dissolved substances in a water sample.

Tailings: The waste produced after ore is crushed and processed in the mill. Tailings is a slurry-like mixture of sand- or silt-sized rock particles and water, and can contain a high percentage of pyrite.

Terminal lake: A lake that has no surface or sub-surface outlet for water.

Thermocline: An interface between two layers of water of contrasting temperature.

Thermohaline convection: General term for the movement of water in a lake or ocean due to density gradients that are caused by differences in salinity and temperature. With respect to pit lakes, salt exclusion during freezing of surface water could possibly induce thermohaline convection.

Till: A type of glacial sedimentary deposit composed of boulders and gravel in a fine-grained clay or silty matrix. Usually very poorly sorted.

Titration: A laboratory or field procedure in which a reagent is added dropwise to a volume of water until a reaction of interest is complete. An alkalinity titration is one example, in which dilute acid is added to a water sample until the pH is lowered to an endpoint of pH 4.5.

Turbidity: A quantitative measure of the amount of suspended solid in a sample. Most common units are NTU (nephelometric turbidity units).

Turnover: The process of vertical mixing of a stratified lake. May occur in spring and fall when the temperature of the epilimnion passes through the density maximum of ~ 4° C.

Ultramafic: A rock – usually igneous – that has a very low silica content and forms at extremely high temperatures and pressures. Most ultramafic rocks have a mineralogy dominated by olivine and/or pyroxene.

USGS: United States Geological Survey

Vadose zone: A hydrogeological term referring to the zone of unsaturation between the water table and the ground surface.

Waste rock: Rock that is blasted and hauled away during excavation of a mine, but is too low in grade to be processed in the mill. Unlike tailings, waste rock is not crushed.

Wedderburn number: A quantitative measure of the likelihood that a lake will turn over which takes into account variables such as relative depth, vertical gradients in water density, and wind speed.

Winterkill: A massive die-off of fish in a frozen lake, usually brought on by a severe depletion in dissolved oxygen.

Xenolith: Literally “alien rock”, this is a fragment of country rock that fell into a molten magma and is now frozen in place within an igneous intrusion.

ZOR: “Zone of Relaxation”. Rock immediately surrounding an open pit mine that may undergo extensional cracking due to a drop in lithostatic pressure.