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Modelling of pit lake filling scenarios using a coupled physical and biogeochemical model

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ABSTRACT

Pit lakes are a common post-closure feature at mine sites where open pits are allowed to fill with groundwater and surface runoff. The large volume of pit lakes and their potential role in water management make them a focal point of closure planning. Pit lakes can be allowed to fill passively, or alternatively, filling can be engineered to best meet closure objectives. In this paper, engineered filling scenarios are modelled using PitMod, a coupled physical-biogeochemical pit lake model. The filling scenarios considered include: 1) slow filling, involving the routing of clean surface waters away from the open pit; and 2) staged filling, involving initial filling of the pit with contaminated seepages, followed by freshwater inflows. The model results indicate that considerable benefits can be realized for pit lake surface water quality under engineered filling scenarios. Benefits relate to: 1) development of permanent stratification (meromixis) and development of sulfate reducing conditions in anoxic lake bottom waters; 2) physical and chemical isolation of poor water quality in pit bottom waters; 3) development of surface water quality conditions more conducive to in-pit bioremediation; and 4) delay of pit filling, allowing greater time to reduce contaminant concentrations prior to pit lake overflow.

Keywords: meromixis, ARD, bioremediation, water management, modelling

1 INTRODUCTION

Pit lakes are a common post-closure feature at mine sites where open pits are allowed to fill with groundwater and surface runoff. Due to the oxidation of exposed sulphide minerals on pit walls, and to the flushing of soluble metals during pit filling, many pit lakes are characterized by poor water quality (Gammons and Duaime, 2006)). Further, the large volume of pit lakes and their potential role in water management make them a central focus of closure planning. Given the implications for environmental protection, regulatory compliance and potential long-term environmental liability of pit lakes, considerable attention has been given to their management, characterization and remediation (Castro and Moore, 2000; Martin et al., 2003).

Lakes formed by flooding of open pits are typically deep and steep-sided, with a much smaller surface area to depth ratio than most natural lake systems. A consequence of a small fetch (i.e., length of lake surface exposed to wind-energy) and relatively deep water is the ineffective transfer of wind energy to pit lake bottom waters. These properties can greatly limit vertical mixing and contribute to the tendency of pit lakes to form stratified water columns with suboxic bottom waters. For some systems, passive or engineered stratification can offer significant benefits relating to: 1) potential for passive treatment through alkalinity generation and metal sulfide precipitation in anoxic bottom waters; 2) isolation of poor water quality in the pit lake bottom layer, thereby minimizing impacts to surface waters.

Most pit lakes are allowed to fill passively, whereby surface and groundwater inflows are driven by natural water balance variables. In some cases, engineered filling can offer an effective means to improve the water quality of surface discharges from the pit. Engineered filling options may include:

- Staged Filling: This involves the preferential filling of the pit with saline (i.e., denser) waters in the early stages of filling, followed by capping with low salinity water (e.g., Poling et al., 2003). The objective of this scenario is to maximize the potential for meromixis (permanent stratification), development of bottom water anoxia, and natural bioremediation processes (alkalinity generation and metal sulfide precipitation in lake bottom waters).
- Deep Water Injection of Acid Rock Drainage (ARD): This scenario is related to Staged Filling, and entails the conveyance of ARD to the pit bottom as a means to: 1) isolate poorer water quality in the pit bottom; and 2) under conditions of meromixis, allow for neutralization of acidic waters (through alkalinity generating reactions in anoxic bottom waters) and passive metal removal through metal sulfide precipitation.
- Slow Filling: This involves the exclusion of clean waters from entering the pit, which could include surface runoff from reclaimed surfaces or treated effluents. The objective of this scenario is to delay the onset of pit lake overflow; thereby allowing for greater time to reduce contaminant concentrations prior to discharge (e.g., through in-pit bioremediation).

2 MODELLING METHODS

Pit lake model simulations were conducted using PitMod, a one-dimensional numerical hydrodynamic model developed by Lorax to predict the spatial and temporal distribution of temperature, density, dissolved oxygen and water quality parameters in lakes (Dunbar, 2013; Crusius and Dunbar, 2002a). PitMod has been used at over 50 sites globally, and is an accepted tool by both Canadian and U.S. regulatory agencies. Through work in Idaho (Thompson Creek Mining Company) and Alaska (Donlin Gold), PitMod has gained regulatory acceptance by several U.S. agencies including the U.S. Environmental Protection Agency, U.S. Bureau of Land Management, U.S. Forest Service and the U.S. Army Corps of Engineers. A primary strength of PitMod is that it has undergone rigorous verification using empirical data collected from modelled sites, including the Island Copper and Equity Silver Mine (Main Zone Pit Lake) (Crusius et al., 2002 a,b; Dunbar et al., 2004; Dunbar and Pieters, 2008).

The physical limnology component of PitMod simulates the evolution of water column structure with time by calculating the vertical and temporal distribution of salinity, temperature and density (calculated from salinity and temperature). PitMod is a 1-dimensional model comprised of a vertical stack of 1 m-thick layers that assumes lateral homogeneity of a lake's physical and geochemical properties. The principal physical processes simulated by PitMod include: heating of the lake surface by incident long- and short-wave solar radiation, sensible heat exchange between the atmosphere and the lake surface, heat loss through black body radiation, wind-driven mixing, convective mixing, ice formation and melting, evaporation, and input of direct precipitation, pit wall runoff, and surface and groundwater inflows. The biogeochemical component of PitMod incorporates PHREEQC (mineral/gas equilibria, redox reactions), dissolved oxygen (DO) consumption and metal scavenging from the water column (e.g., scavenging by biogenic particles followed by particle settling). The latter process represents the dominant vertical transport mechanism for trace elements in lakes. Settling particles, especially organic aggregates (biogenic particles), play a dominant role in the binding and transfer of trace elements to lake bottom waters, thereby regulating the concentrations of dissolved species in surface waters (Sigg, 1985).

3 STUDY SITES

3.1 Aitik Mine, Sweden

Boliden Mineral AB owns and operates the Aitik open pit copper mine and concentrator located 17 km east of Gällivare in Northern Sweden. Since 1968 the mine has extracted copper-, gold-and silver-bearing ores contained within metamorphosed plutonic and volcano-sedimentary rocks. Development of the Aitik Pit entails the placement of both potentially acid generating (PAG) and non-PAG waste rock within the catchment of the pit. Climate conditions are subarctic in nature, with a mean annual temperature of -1˚C and mean annual precipitation of ~550 mm.

Post mine closure, groundwater and surface water inputs to the Aitik pit will result in the formation of a pit lake occupying a void ~1 km wide, 3.5 km long and 525 m deep (maximum depth), with a total volume of 579 million m^3. Key inputs to the pit during the closure period will include tailings management facility (TMF) runoff (first 10 years post closure), TMF seepage, non-PAG waste rock seepage/runoff, PAG wasterock seepage/runoff, runoff from natural ground, pit wall runoff, groundwater recharge and direct precipitation to the pit lake surface. Two filling scenarios are presented for the Aitik Pit:

- Passive Fill: This scenario entails the passive input of all inflows to the pit.
- Slow Fill: This scenario includes the collection and treatment of PAG waste rock seepages with discharge to receiving water courses. Clean sources of runoff within the pit catchment (i.e., runoff from covered waste rock dumps and natural ground) are also conveyed directly to the recipient. The objective of the Slow Fill scenario is to delay the onset of pit lake overflow, thereby allowing the benefits of PAG seepage quality improvements to be realized prior to pit lake overflow. Specifically, significant improvements in drainage quality from PAG wastes are expected between years 30 and 60 post-closure in response to cover system application. In this manner, discharges from the pit under a Slow Fill scenario can be managed to better align with the time scales of drainage quality improvements.

3.2 Mine B, Eastern Canada

This proposed mine (anonymously named Mine B), is located in the interior region of eastern Canada. Waste rock to be generated from the pit largely comprises felsic metalvolcanics, with smaller contributions from mafic volcanics and clastic metasediments. Approximately 42% of the waste volume is expected to be PAG. The site is characterized by a cold-interior continental climate, with a mean annual temperature of 3˚C and mean annual precipitation of ~700 mm. Post mine closure, groundwater and surface water inputs to the pit will result in the formation of a pit lake occupying a void ~1.5 km wide, 1.8 km long and 425 m deep (maximum depth), with a total volume of 253 million m^3. Two pit filling scenarios are presented for Mine B:

- Passive Filling Scenario: This scenario entails the passive input of all inflows to the pit, while maximizing the filling rate with freshwater sources (river withdrawal). Maximizing the flow rate to the pit serves to minimize the exposure time of wall rock to weathering reactions, thereby minimizing loadings to the pit.
- Staged Filling Scenario: This scenario entails the preferential filling of the pit with PAG waste rock seepages for the initial 10 years of pit filling. Other sources of clean water are diverted away from the pit during this phase. After 10 years, clean surface flows within the pit catchment are allowed to flow passively to the pit, while PAG seepages continue to be routed to the pit bottom. The objective of the Staged Filling scenario is to maximize the potential for permanent pit lake stratification, thereby isolating poorer water quality in pit bottom waters. The development of stratification will increase the potential for suboxic bottom waters and maximize the potential for in situ bioremediation processes (e.g., sulfate reduction, metal sulfide precipitation and alkalinity production).

4 RESULTS AND DISCUSSION

4.1 Aitik Pit – Slow Fill versus Passive Fill

In the Slow Fill scenario for the Aitik Pit, PAG waste rock seepages are collected, treated (lime) and conveyed directly to the recipient. This serves to: 1) remove significant loadings from entering the pit; and 2) increase the time to pit lake overflow from 55 to 130 years. Despite the removal of saline source waters from the system, there is still sufficient input of saline inflows to promote water column stratification, as illustrated by the model output for salinity (Figure 1). This relates to the input of saline runoff and seepages in the early stages of pit flooding associated with the TMF, waste rock dumps and pit walls.

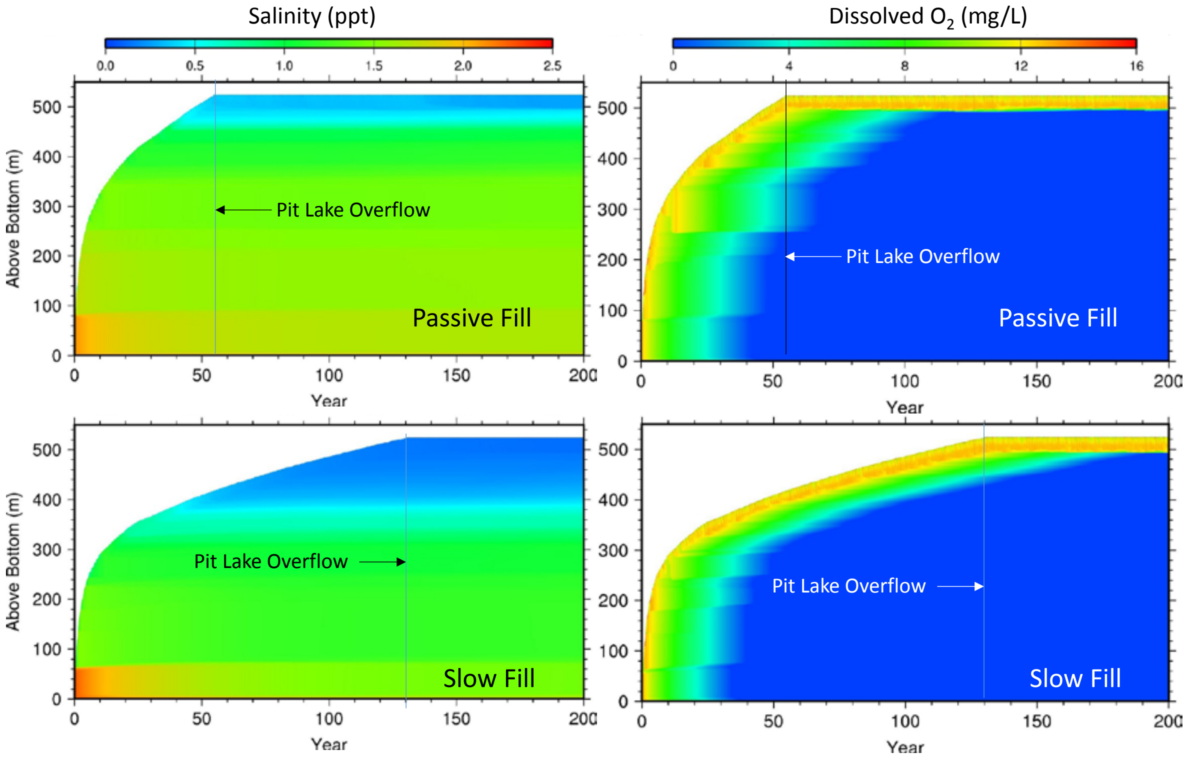

Figure 1. PitMod output showing the vertical and temporal distribution of salinity (left) and dissolved oxygen (right) for the Aitik pit lake (200 year simulation) for Passive Fill scenario (overflow in year 55) and Slow Fill scenario (overflow in year 130). Units of salinity are parts per thousand (ppT).

The redox structure in the water column of the Aitic pit lake will be governed by the balance of mechanisms that replenish and consume dissolved oxygen (DO). The primary source of DO is via atmospheric exchange with the lake surface and the input of oxygenated surface inflows. Dissolved oxygen levels are assumed to be less than 1 mg/L in groundwater, and therefore groundwater does not provide a significant source of DO. Conversely, the primary sink of DO will be through the bacterial respiration of organic matter produced through in situ primary production (algal growth). For both scenarios, the development of permanent stratification promotes the development of suboxic conditions below a mixed layer that extends seasonally to a depth of approximately 30 m (Figure 1).

The predicted absence of DO below the surface mixed layer in both scenarios will have a significant effect on the distribution of redox sensitive species. Specifically, suboxia can be expected to be accompanied by: 1) consumption of secondary electron acceptors such as nitrate, Fe oxides, Mn oxides and sulfate; and 2) increases in the concentrations of redox reaction products including dissolved Fe, Mn, alkalinity, ammonia and H_2S. The consumption of sulfate and liberation of dissolved H_2S is particularly relevant to natural bioremediation since this process will promote trace element removal via sulfide mineral precipitation. Another significant benefit of suboxia is the generation of alkalinity, which is produced through suboxic redox pathways (nitrate reduction, Fe/Mn-oxide reduction, sulfate reduction) (Sigg et al., 1991).

Surface water quality trends for dissolved Cu and Zn for the Passive and Slow Fill scenarios show similar absolute concentrations versus time (Figure 2). For both scenarios, surface water quality shows marked improvement over time, largely in response to improvement in the seepage quality from PAG waste rock in response to cover system application. Additional benefits to surface water quality over time relate to: 1) development of pit lake stratification which serves to isolate poorer water quality in pit bottom waters; 2) decrease in pit wall exposure area and pit wall runoff as the pit lake fills; 3) decrease in groundwater flux as hydraulic gradients lessen; and 4) increase in amount of direct precipitation to pit lake surface as area of pit lake expands. The benefits of Slow Fill are linked to the delay in pit lake overflow. Specifically, at the onset to pit lake overflow for the Slow Fill scenario (Year 130), pit lake surface water quality is considerably improved relative to the Passive Fill scenario (pit lake overflow at Year 55). At Year 130, for example, Slow Fill values for Cu and Zn reach concentrations of 77 µg/L and 28 µg/L, respectively. These values are considerably lower than the values predicted for the Passive Fill scenario at pit lake overflow (Year 55) for Cu (850 µg/L) and Zn (115 µg/L) (Figure 2).

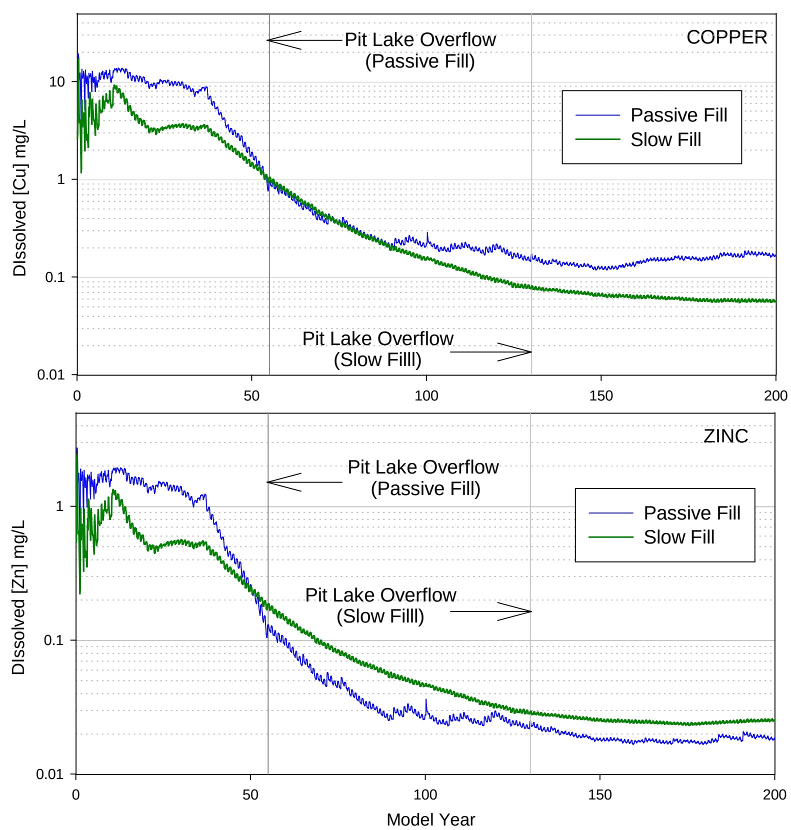

Figure 2. Model output showing the temporal evolution of dissolved Cu and Zn in surface waters of the Aitik pit lake (200 year simulation) for Delayed Filling scenario (overflow in year 130) and Passive Filling scenario (overflow in year 55).

Overall, the benefits of the Slow Fill scenario relate to lower loading rates (due to removal of PAG seepages from system) and due to the delay in pit lake flooding, which allows the full measure of surface water quality improvements to be realized prior to pit lake discharge. Specifically, given the volume and residence time of the Aitik pit, the benefits of PAG waste seepage quality improvements (associated with cover system application) are not fully realized in the pit until after Year 130. In this regard, the synchronous occurrence of pit flooding and water quality improvements results in more favourable water quality in pit lake discharges at the time of pit lake overflow for the Slow Fill scenario.

4.2 Mine B - Staged Fill versus Passive Fill

The evolution of physical properties of the Mine B pit lake for the Passive and Staged filling scenarios is illustrated by the spatial and temporal distributions of salinity and DO (Figure 3). For the Passive Filling scenario, permanently stratified (meromictic) conditions develop in the water column as revealed by the evolution of salinity. The meromictic nature of the water column is well established prior to pit lake overflow, at which time salinity shows a strong gradient (halocline) in the upper 50 m of the water column. The stratified water column for the Passive Filling scenario relates to both the large depth of the pit in relation to its surface area (limiting vertical mixing by wind) as well as to the evolution of pit inflows. Specifically, water quality associated with pit walls improves over time as the water elevation intersects the overburden, producing relatively clean runoff. In parallel, direct precipitation to the pit lake surface increases over time as the pit lake surface area expands. Collectively, these processes contribute to the development of permanent stratification.

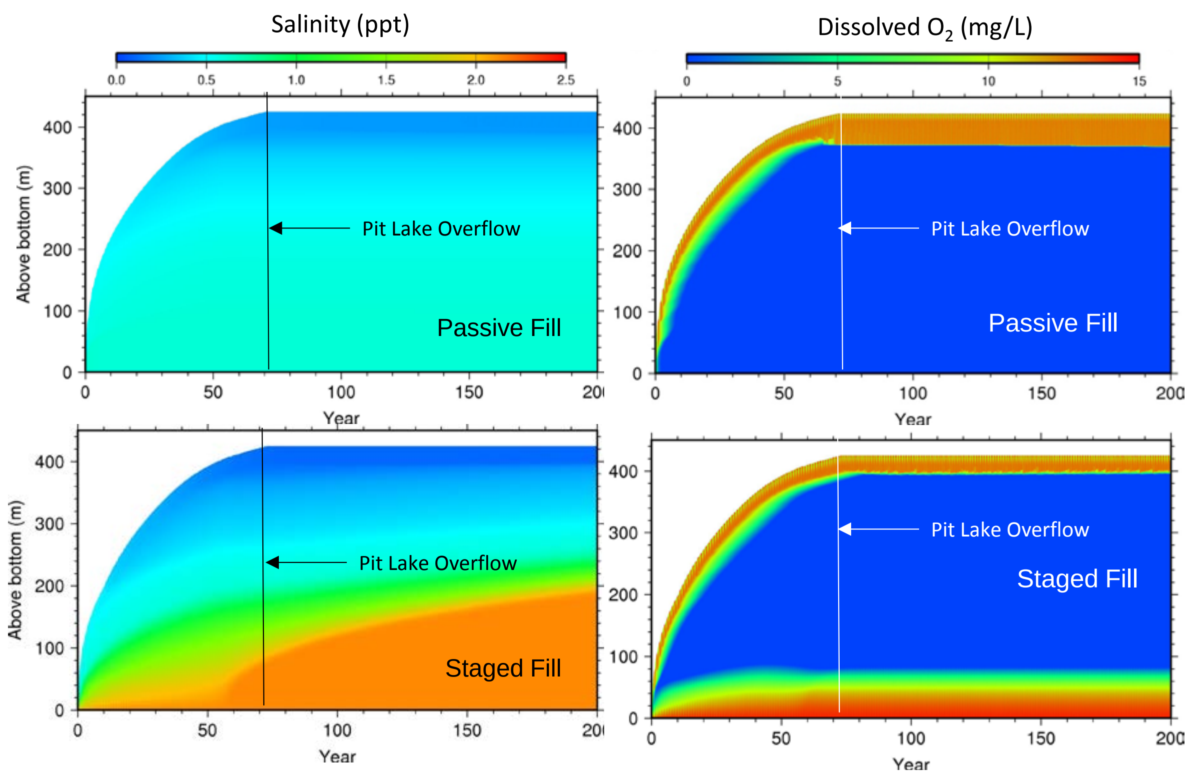

Figure 3. PitMod output showing the vertical and temporal distribution of salinity (left) and dissolved oxygen (right) for the Mine B pit lake (200 year simulation) for Passive Fill and Staged Fill scenarios. Pit lake overflow in year 72 is highlighted. Units of salinity are parts per thousand (ppT).

For the Staged Fill, the physical structure of the water column is similarly influenced by the processes described above for the Passive Fill scenario (i.e., progressive increase in the contribution of freshwater to the pit lake surface). As an additional feature, the injection of PAG seepage at the pit bottom imparts strongly stratified conditions in the lower water column. This is illustrated by the model output for salinity, which shows the progressive accumulation of higher salinity PAG flows in the pit bottom and the presence of a strong salinity gradient (Figure 3). The model output demonstrates that the PAG inflows are contained within the lower portion of the pit and do not mix appreciably with the lower salinity waters above. At year 200, the model output show the accumulation of PAG seepages to a thickness of approximately 220 m in the pit bottom, with no incursion of the deeper saline water into the surface layer. Longer-term modelling indicates that the introduction of PAG seepage water into the surface layer does not occur for at least 400 years.

The model output indicates that surface waters do not mix appreciably below a depth of 50 m for both the Passive and Staged filling scenarios. Given these conditions, on-going bacterial respiration, in conjunction with negligible DO replenishment to deep waters, will result in the depletion of dissolved oxygen below the surface mixed layer. These conclusions are supported by the model predictions of DO, which show suboxic conditions below the surface mixed layer (Figure 3). For the Staged Fill scenario, the introduction of oxygen-rich PAG seepage to the pit bottom results in a deep layer of oxygen-replete water. Note that in contrast to salinity, DO does not progressively accumulate in bottom waters under the Staged Filling scenario. This steady-state distribution of DO is a function of the balance between the DO input (via PAG seepage discharge to depth) and DO consumption via bacterial respiration of organic matter.

As observed for salinity, surface waters for both scenarios show a progressive decline in trace element concentrations over time (Figure 4). This relates to a progressive increase in the contribution of freshwater inputs to the pit surface in response to an increase in pit lake surface area and a decrease in pit wall surface area. For trace metals the model output for the Staged Fill scenario shows markedly lower values in surface waters in comparison to the Passive Fill scenario (Figure 4). In this regard, the injection of PAG seepage to the pit bottom results in an immediate benefit to surface water quality due to the rapid onset of stratification and isolation of PAG seepages in the pit bottom. At the period of initial lake overflow (Year 73), the benefits of the Staged Fill are pronounced, with considerably lower values observed for Al, Cu, Ni and Zn, in comparison to the Passive Fill scenario (Figure 4).

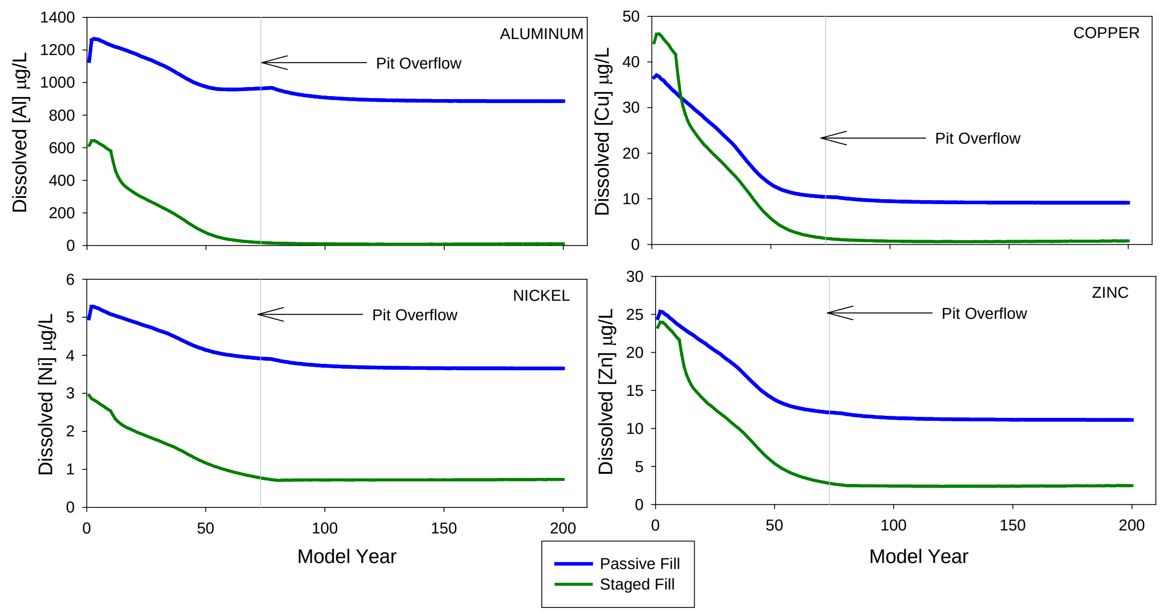

Figure 4. Model output showing the temporal evolution of dissolved Al, Cu, Ni and Zn in surface waters of the Mine B pit lake (200 year simulation) for Passive and Staged Filling scenarios. Pit lake overflow in year 72 is highlighted.

Over time, the progressive input of saline metal-rich waters to depth under the Staged Fill scenario displaces overlying water in the Mine B pit (as illustrated for salinity in Figure 3). Specifically, the progressive accumulation of PAG seepages over time in bottom waters will eventually result in the displacement of this water mass into the surface layer. However, for the Mine B pit, the incursion of poor quality water into the lake surface is not predicted to occur for at least 400 years. Given the time scales of this delay, there is considerable time to invoke remediation measures to reduce acidity and soluble trace element concentrations in lake bottom waters prior to their introduction to the surface layer.

For example, in-pit bioremediation offers a potentially effective means to mitigate acidity and reduce metal concentrations in pit bottom waters (Martin et al., 2003). The in situ bioremediation of mine site pit lakes typically involves the addition of nutrients and/or organic matter to create conditions conducive to contaminant removal. The addition of organic matter, in the form of liquid or solid amendments provides a direct source of organic carbon to the water column. In contrast, the addition of nutrients (i.e., nitrogen and phosphorus) adds organic carbon indirectly to the system through enhanced algal and bacterial growth (Dessouki et al., 2005). For both direct and indirect forms of organic enrichment an increase in organic matter content in the water column serves several functions critical to successful bioremediation. For metal sulfide precipitation to occur, suboxic conditions must be achieved to allow sulfate reduction and precipitation of secondary sulfide minerals (e.g., ZnS, CdS). Since the oxygen demand in pit lakes is governed by the oxidation of organic matter the depletion of oxygen and onset of sulfate reduction in pit lakes can be accelerated through the addition of nutrients and/or organic matter. In this regard, the promotion of sulfate reduction and metal sulfide precipitation in stratified pit lakes can promote the removal of dissolved metals from suboxic bottom waters.

A second benefit of increased oxygen demand is the generation of alkalinity, which can serve to neutralize acidity associated with the input of acidic seepages. These are the same principles that facilitate the neutralization of acidity for various forms of bioremediation that rely on sulfate reduction, such as permeable reactive barriers (Blowes et al., 2000).

5 CONCLUSIONS:

Pit lake stratification and mixing are key processes that must be assessed prior to selecting an optimal pit filling strategy. In this regard, PitMod provides an effective tool for modelling both the physical and chemical evolution of pit lake systems.

All model scenarios show the development of permanently stratified (meromictic) water columns and suboxic bottom waters below a surface mixed layer. Slow filling can be viewed as a means to delay the onset of pit lake overflow. In the Aitik Pit example the timing of pit discharges is congruent will improvements in pit lake surface chemistry, allowing for more favourable water quality at the time of pit lake overflow.

Staged filling, and the promotion of strong stratification in the water column, can be viewed as a means to isolate poor quality drainages in the pit bottom, and to delay the introduction of these waters into the surface layer. The time scales of this delay (> 400 years) for the Mine B pit example afford an opportunity to reduce acidity and metal levels prior to pit lake overflow. In particular, in-pit bioremediation offers an effective means to promote alkalinity generation and metal sulfide precipitation in anoxic bottom waters.

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