Pit Lake Modelling at the Aitik Mine (Northern Sweden): Importance of Site-Specific Model Inputs and Implications for Closure Planning

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Abstract The large volume of pit lakes and their potential role in mine water management make them a focal point of closure planning. In this paper, the modelling of pit lake physical structure and water quality for the Aitik Pit (Aitik Mine, northern Sweden) is used to illustrate: 1) the importance of developing robust site-specific model inputs for the development of defensible pit lake predictions; and 2) how pit lake water quality predictions can be used to inform and refine mine closure plans.

Key words meromixis, waste rock, tailings, water management, modelling

Introduction

Pit lakes are a common feature of the post-closure landscape at mine sites, where open pits are allowed to fill with various inputs including groundwater, pit wall runoff, precipitation, and surface runoff from the surrounding catchment. Due to the oxidation of exposed sulfide minerals on pit walls, the flushing of soluble metals during pit filling, and in many cases, the input of drainages from waste storage facilities (e.g., tailings and waste rock), 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 characterization, prediction and remediation (Castro and Moore 2000; Martin et al. 2003).

Boliden Mineral AB owns and operates the Aitik open pit copper mine and concentrator 17 km east of Gällivare in northern Sweden. Climate conditions at the site are subarctic in nature, with a mean annual temperature of 0˚C and mean annual precipitation of ~600 mm. Since 1968, the mine has exploited copper-, gold- and silver-bearing ores through the development of the Aitik Pit. During the closure period, the pit will flood to form a pit lake ~1 km wide, 3.5 km long and 525 m deep. Under the final closure configuration, the Aitik Pit will serve as the primary discharge location for mine waters to the receiving environment (Lina River). As part of an integrated closure planning process for the site (Eriksson 2017), the evolution of pit lake physical structure and water quality was modelled to support pit lake management as well as water quality predictions for downstream receptors. In this paper, key pit lake model inputs are described followed by an evaluation of pit lake model results for two closure options for the site. The discussion emphasizes the importance of developing robust model inputs which can then allow for the generation of defensible pit lake water quality predictions and closure plans.

Pit Lake Model Description

Pit lake model simulations were conducted using PitMod, a one-dimensional numerical hydrodynamic model used to predict the spatial and temporal distribution of temperature, density, dissolved oxygen and water quality parameters in lakes (Dunbar 2013). The principal physical processes simulated by PitMod include: 1) heating of the lake surface by incident long- and short-wave solar radiation; 2) sensible heat exchange between the atmosphere and the lake surface; 3) heat loss through black body radiation; 4) wind-driven mixing; 5) convective mixing; 6) ice formation and melting; 7) evaporation; and 8) input of various inflows (direct precipitation, pit wall runoff, surface runoff and groundwater inflow). The biogeochemical component of PitMod incorporates PHREEQC (mineral/gas equilibria, redox reactions) and dissolved oxygen (DO) consumption. A primary strength of PitMod is that it has undergone rigorous verification using empirical data collected from modelled sites in Canada, including the Island Copper Mine and Equity Silver Mine (Crusius et al. 2002; Dunbar and Pieters 2008).

Pit Lake Model Inputs and Scenarios

Inputs to the Aitik Pit during the filling period will include treated effluent (for period of 55 years), Tailings Management Facility (TMF) runoff from the Clarification Pond, TMF seepage, seepage/runoff from the potentially acid forming (PAF) waste rock storage facilities (WRSFs), non-PAF WRSF seepage/runoff, runoff from natural ground, pit wall runoff, groundwater recharge, and direct precipitation to the pit lake surface. Inputs to the Aitik Pit are illustrated conceptually in fig. 1.

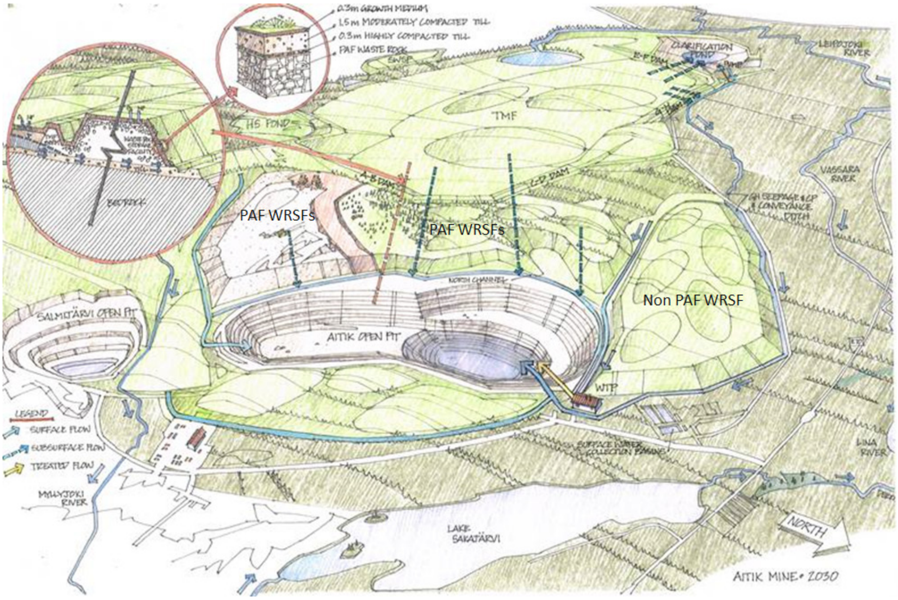

Figure 1 *Conceptual figure illustrating the various inputs reporting to the Aitik Pit during the filling period. Illustration shows partially reclaimed Tailings Management Facility (TMF) and Potentially Acid Forming Waste Rock Storage Facilities (PAF WRSFs). WTP = Water Treatment Plant.*

Key to the pit lake modelling exercise was the development of defensible flow and water quality values for all inputs. In this regard, extensive studies of the WRSFs, TMF and pit were conducted to support the development of robust flow and chemistry predictions. As part of model input development, site-specific data (flow, seepage water quality, groundwater quality, mineralogy, etc.) were used to the maximum extent possible in the development and calibration of flow and water quality models. Pit lake model inputs that underwent rigorous development included:

- Climate: A synthetic 200-year climate dataset (extending from 2025 to 2225) was used as a common source of input to the models in support of the pit lake, WRSFs and TMF. The dataset was scaled to account for predicted climate change in the region, as descried in Fraser et al. (2017);
- TMF and WRSF seepage inflows: Detailed hydrogeochemical modelling for the TMF and WRSFs included water/load balance development, seepage flow modelling, and geochemical modelling (described in Eriksson 2017). The use of site data (flow, seepage water quality, groundwater quality, mineralogy) were maximized to develop and calibrate flow and water quality predictions. For both the TMF and PAF WRSFs, modelling results demonstrate that the quality of seepages is predicted to improve markedly following cover system placement;
- TMF surface runoff: At the beginning of mine closure, surface runoff from the TMF will be diverted to the Aitik Pit for a period of 10 years. A combination of water balance and geochemical modelling was used to generate flow and water quality predictions for this term;
- Pit wall runoff: Pit wall drainage chemistry was based on site water quality data for pit sump samples. The increase in sulfur content with depth on pit wall exposures was used to develop elevation-dependent terms, with pit wall runoff quality improving as the pit lake fills; and
- Groundwater inflows: A function describing the relationship between groundwater inflow and the water level in the pit lake was developed using pit dewatering records.

Two model scenarios for the Aitik Pit were evaluated based on two engineered cover system options for the PAF WRSFs:

- Base Case Scenario: Under the Base Case scenario, the engineered cover system for the PAF WRSF consists of 0.3 m highly compacted till, underlying 1.5 m compacted till, underlying 0.3 m vegetation growth medium (illustrated in fig. 1). This configuration is designed to reduce oxygen ingress into the waste rock, thereby decreasing the potential for sulfide mineral oxidation and acid generation.
- Bentonite Scenario: The merits of this option were evaluated for the same cover configuration as that described for the Base Case, with the addition of 2-5 wt.% bentonite to the compacted till layer. The addition of bentonite can improve material water retention characteristics, increase the degree of saturation, and decrease oxygen ingress, thereby further decreasing the potential for sulfide mineral oxidation.

Both scenarios include a treatment period of 55 years (equivalent to the filling period) that entails lime treatment of recoverable seepages associated with the PAF WRSFs and the TMF. During the treatment period, treated effluents are discharged to the surface of the Aitik pit lake.

Results and Discussion

Water balance model results illustrate the addition of bentonite contributes to a reduction in PAF WRSF seepage to the Aitik Pit as compared to the Base Case. However, the pit filling period (55 years) and average annual discharge (~270 L/s) are the same for both scenarios (fig. 2).

The evolution of lake physical structure is not appreciably affected by changes to the water balance that result from the addition of bentonite to the cover systems. Specifically, the Base Case and Bentonite scenarios are characterized by a common evolution in water column density structure, with both showing the development of a permanently stratified (meromictic) water column. In turn, permanent stratification promotes the development of suboxic conditions below a mixed layer that extends seasonally to a depth of ~30 m (results for Base Case scenario shown in fig. 3).

Water quality predictions for the bentonite scenario show significantly higher concentrations of trace elements (e.g., Cu and Zn) in lake surface waters at the time of pit overflow as compared to the Base Case (fig. 4). Cu, for example, which represents a parameter of potential concern, shows a mean concentration of 0.5 mg/L at the time over overflow for the Bentonite Scenario (compared to 0.12 mg/L for Base Case). The benefits of bentonite with respect to lake surface water quality are not realized until several decades post filling. Specifically, lower steady-state values for trace elements in pit lake discharges are not observed until Year 80-100 (fig. 4).

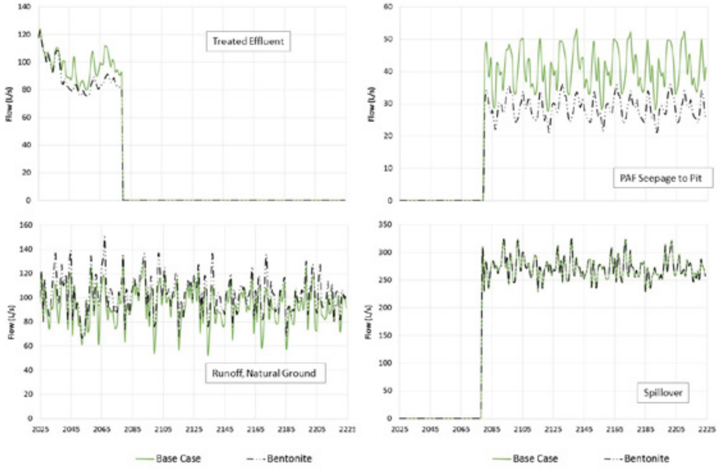

Figure 2 *Water balance plots comparing Base Case vs. Bentonite scenarios for treated effluent flow to Aitik Pit (represents treatment of seepage from Potentially Acid Forming (PAF) Waste Rock Storage Facilities for a period of 55 years), untreated seepage from PAF waste rock storage facilities (following treatment period), runoff from natural ground and pit lake spillover (occurs in Year 2080).*

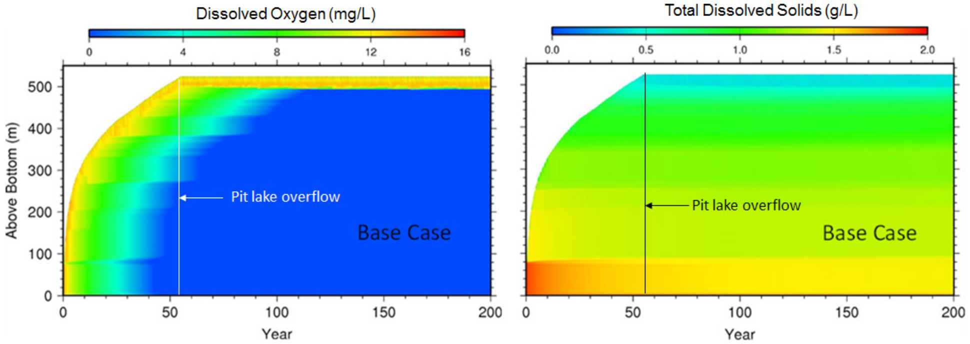

Figure 3 *Base case model output showing the vertical and temporal evolution of total dissolved solids and dissolved oxygen for the Aitik pit lake (200 year model period). The evolution of the pit lake surface (as measured from the pit bottom) shows the gradual filling of the pit, with pit lake overflow occurring in year 55.*

The higher trace element concentrations at the time of pit lake overflow observed for the Bentonite scenario can be linked to the longer transition period in drainage quality improvements associated with the PAF WRSFs. For a higher net percolation scenario (Base Case Scenario), PAF WRSF seepage quality improvements are realized prior to pit lake overflow, due to the more rapid flushing of soluble oxidation products stored in the WRSFs. Specifically, the rapid improvement in drainage quality for the Base Case allows the bulk of the stored load in the PAF WRSFs to be isolated in the bottom of the stratified pit. For a lower net percolation scenario (Bentonite Scenario), PAF WRSF seepage quality improvements extend over a longer period. This longer transition period allows for a greater proportion of the stored load to mix into the lake surface and be released as overflow, resulting in considerably higher metal concentrations in pit lake discharges.

Following the cessation of treatment after 55 years, water quality conditions for the Bentonite Scenario temporarily worsen in the pit lake surface due to the input of relatively poor quality PAF WRSF seepage to the pit lake surface. This is illustrated for Cu and Zn, both of which show a rebound in concentration upon termination of treatment (fig. 4).

Conclusions and Implications for Closure Management

Overall, the pit lake model results highlight that the water quality of lake surface waters at the time of pit lake overflow is sensitive to the rate of improvement in PAF WRSF seepage chemistry. Under conditions of higher net percolation (Base Case Scenario), PAF WRSF seepage quality improvements are realized early in response to the rapid flushing of stored oxidation products. This allows the bulk of the waste rock load to be stored (and isolated) in the pit bottom. In contrast, under conditions of lower net percolation (Bentonite Scenario), the rate of PAF WRSF seepage quality improvement is slower. This results in the release of stored waste rock loads to the pit lake surface at the time of pit lake overflow, in turn resulting in higher metal concentrations in pit lake discharges.

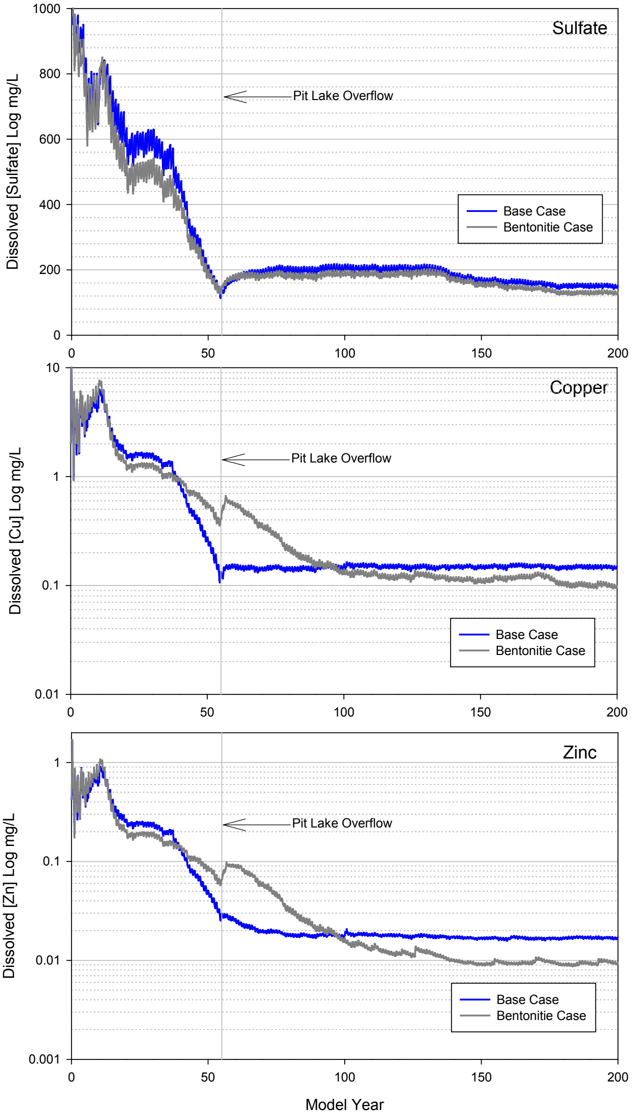

Figure 4 *Temporal evolution of dissolved Cu and Zn in surface waters of the Aitik pit lake for Base Case and Bentonite scenarios, both with an assumed treatment period of 55 years. Data represent mean monthly concentrations over the 200 year model period. Timing of pit lake overflow (year 55) is indicated.*

The results presented here specifically demonstrate that the benefits of a bentonite cover are limited, and are only realized in the long-term (after 80-100 years). This is perhaps a non-intuitive conclusion, that was only made possible through the development of robust pit lake model inputs. In particular, considerable efforts were required to: 1) quantify the abundance and mineralogy of stored oxidation products, acid-generating minerals and neutralizing minerals within the WRSFs; 2) predict net percolation into the WRSFs for contrasting engineered cover systems; and 3) predict how seepage quality responds to varying flushing rates.

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