# Predictive Pit Lake Modelling for Aitik Mine, Northern Sweden

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## Abstract
Open pit mining at the Aitik Mine will result in the development of two pit lakes at mine closure. Post-closure water quality predictions for the pit lakes were modelled using PitMod, a one-dimensional hydrodynamic model. The pit lake model will be used by Boliden as a planning tool for assessing different closure scenarios. For example, water quality in the Aitik pit lake was found to be extremely sensitive to a hypothetical treatment scenario, in which the addition of lime-treated ARD maintained mixed conditions in the water column. In the absence of this hypothetical treatment scenario, the water columns of both pits evolve with permanently stratified (i.e., meromictic) density structures. Model output also showed that the water balances of both pit lakes were highly sensitive to predicted climate changes (i.e., higher temperatures and increases in precipitation). Model output for variables describing pit physics (e.g., density, salinity, pressure), likely redox condition and water quality are presented and the potential for long-term management discussed.

*Key Words: closure planning, climate change, water quality, pit lake*

## Introduction
Boliden Mineral AB owns and operates the Aitik open pit copper mine and concentrator 17 km east of Gällivare in northern Sweden. Since 1968, the mine has exploited copper-, gold- and silver-bearing ores through the development of the Aitik Pit, a void that will be ~1 km wide, 3.5 km long and 525 m deep at closure. Aitik pit development has entailed placement of waste rock around the northern, western, and eastern borders of the pit. The present mine footprint further includes a mill site, tailings impoundment and a clarification pond. The Aitik property is currently undergoing a mine expansion that will increase mining and processing capacity from 18 to 36 million tonnes per year. As part of the mine expansion, Boliden initiated development on a second open pit (Salmijärvi pit) 1 km to the south of the existing Aitik pit in Dec 2010. The Salmijärvi pit will be approximately 240 m deep and occupy an area ~800 m x ~600 m when complete. A total of 80 million tonnes of ore and 40 million tonnes of waste rock will be mined from the Salmijärvi pit, with waste rock placed within the catchment of the Aitik Pit. At mine closure, both the Aitik and Salmijärvi pits will form permanent pit lakes.

As part of closure planning for the site, an understanding of the final pit lake features is required from the perspectives of discharge flow and water quality. This paper reports the results of a predictive pit lake study that resolves lake physical and chemical structure, as well as flow and water quality for pit discharges. The study objectives were to:

1. Develop conceptual loading models for the pits based on site-specific/regional data and analogues from other sites as required;
2. Generate long-term (200-year) water quantity and quality predictions for the water column and spill points of the pit lakes; and
3. Provide the framework for testing various water/waste management scenarios and to identify knowledge gaps relating to closure planning efforts.

## PitMod – Model Description

PitMod is a one-dimensional (1-D) coupled hydrodynamic-geochemical model used for predicting the vertical distributions of pit lake temperature, salinity, density and water quality (Crusius et al., 2002; Dunbar et al., 2004). The physical processes simulated by PitMod include lake heating (solar, geothermal), vertical mixing and convection. The 1-D approximation is highly applicable to pit lakes given their high depth to surface area ratio and few, if any, barriers to horizontal mixing relative to those observed in the vertical dimension (e.g., thermoclines and haloclines).

PitMod is driven by climate/hydrometric data (e.g., air temperature, precipitation, unit runoff, shortwave and longwave radiation, relative humidity, wind) and geochemical information. The geochemical portion of PitMod computes water profile conditions in one of two ways: using a conservative reaction approach; or by making allowance for secondary processing via a customized version of PHREEQC (Parkhurst and Apello, 1999). Although water quality results presented in this study were computed using the conservative reaction approach, non-conservative mechanisms that may affect trace element behaviour were qualitatively assessed based on model output for lake physical structure (e.g., stratification) and redox conditions (as revealed by model output for dissolved oxygen). In PitMod, oxygen was introduced to surface waters, distributed throughout the water column by mixing and diffusion, and consumed in the water column respecting rates reported in the literature (Crusius et al., 2002; Castro and Moore, 2000).

## Conceptual Loading Models – Aitik and Salmijärvi

Two conceptual loading models were populated and refined iteratively using: geological block models of the two pits; maps and technical drawings showing final pit dimensions and waste rock configurations; historical reports relating to geology, water balances, hydrogeology, reclamation, cover system design and water quality; site- and regional climate and hydrology time series data; climate change scenario data; and a standard set of assumptions reached by consensus relating to water management, pit filling (passive), reclamation and effluent treatment.

### Aitik pit model

To test the sensitivity of the Aitik lake model to a hypothetical effluent treatment scenario, it was assumed that for years 1-50 waste rock runoff and seepage were treated using lime addition (low density sludge process) and the treated lime slurry (including sludge and liquid components) was discharged directly to the surface of the Aitik pit lake. Waste rock cover systems were assumed to produce surface runoff that mixed in contact ditches with waste rock seepage at a 5:1 ratio in accordance with design specifications. For years 1 to 50, a ditch efficiency of 90% was assumed, and therefore 10% of ditch flow was allowed to report to the pit without treatment. For the first fifty years post-closure, water inputs to the Aitik pit were assumed to include: direct precipitation to the pit lake; pit wall runoff; groundwater recharge; runoff from covered waste rock dumps; discharge of treated effluent; and conveyance losses from contact water ditches (Figure 1 upper). Additionally, combined runoff from a 14 $km^2$ tailings management area and a clarification pond was directed toward the pit for years 1 to 5. From year 51 to end of the model run, ditches were assumed to be decommissioned and that all waste rock runoff and seepage would report directly to the open pit untreated. For the duration of the model run, losses included evaporation and surface discharge once the pit reached the spillway elevation (Figure 1 lower).

### Salmijärvi pit model

The conceptual loading model for the Salmijärvi pit was more simplified in comparison to the Aitik pit (Figure 1 lower). This related largely to the absence of waste rock within the Salmijärvi catchment and the associated exclusion of treated effluent from the water balance. The Salmijärvi pit also excluded water inputs from the tailings impoundment. Therefore, water inputs for all years modelled were constrained to: direct precipitation to the lake surface; pit wall runoff; groundwater recharge and surface water runoff from undisturbed areas. Losses included evaporation and spill-over once full.

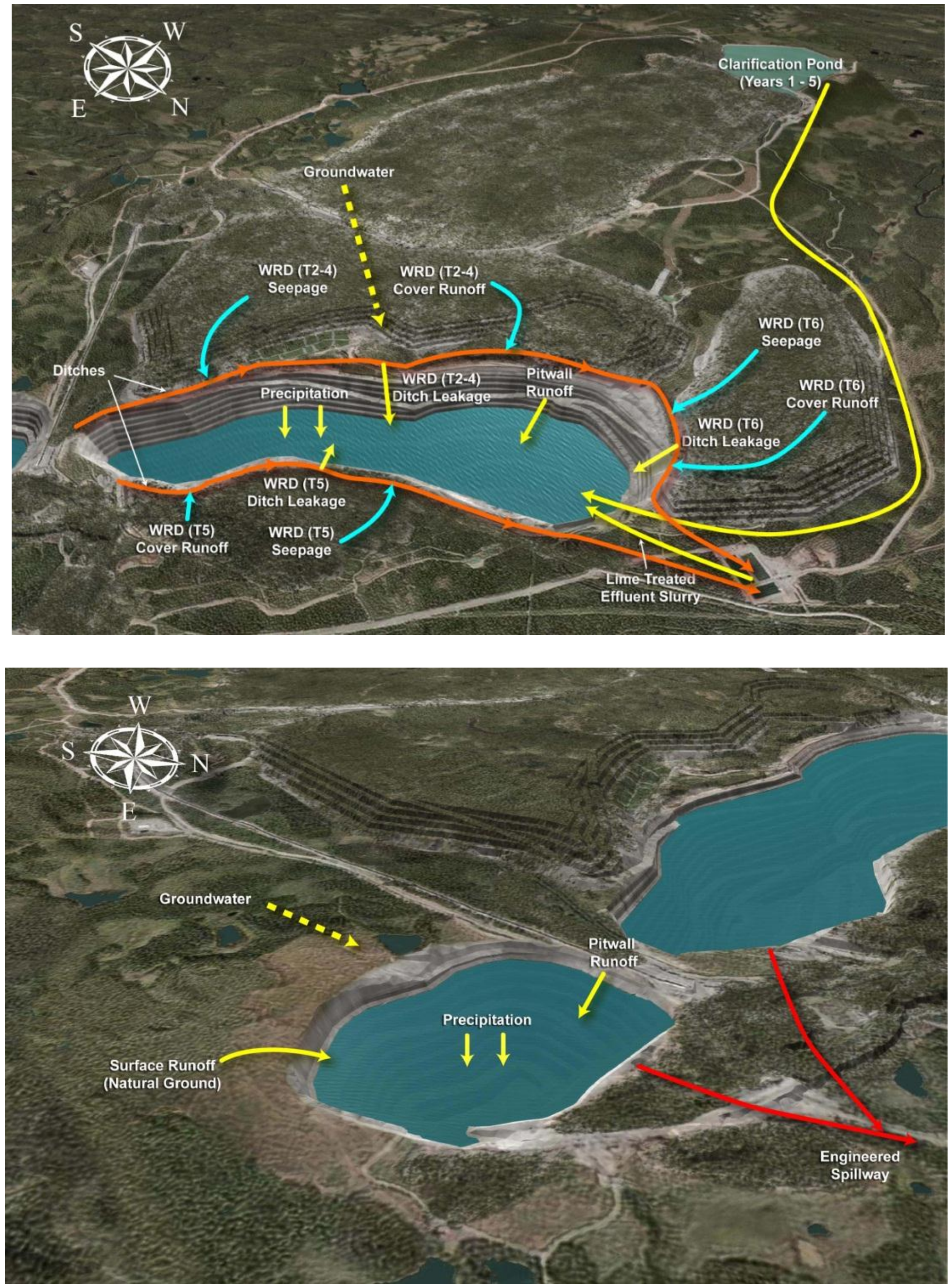


Figure 1. Conceptual loading models for Aitik pit (upper plot; years 1 to 50) and Salmijärvi pit (lower plot; years 1 to 200). For Aitik pit, contact ditch flows are shown in orange. Furthermore, for years 51-200 (not shown) it was assumed that lime treatment ceased and waste rock runoff and seepage reported directly to the Aitik pit untreated. Engineered spillways for the pits are shown in red (lower plot).

## Data and Model Inputs

### Climate data and climate change

In additional to the use of site-specific information, data for two climate stations maintained by the SMHI (Swedish Meteorological and Hydrological Institute) within 15 km of the site were utilized. Data for climate variables such as precipitation, air temperature, wind and relative humidity from these sites have been collected since the 1960s. Radiation data were collected at Kiruna, a climate station roughly 90 km from the mine site. Daily radiation data generated using the SMHI's STRÅNG model were also used. The STRÅNG model produces hourly fields of solar radiation, direct radiation, and sunshine duration for Sweden at a grid resolution of 11 km. 200-year input datasets were prepared for a Base Case (i.e., a synthetic dataset statistically identical to 1960-2010 climate) and a Climate Scaled Case (i.e., a climate perturbed synthetic dataset scaled to an A1B emission scenario). Specific details of the base case assumptions and the climate scaling approach are described in Fraser et al. (2011).

### Unit runoff and groundwater

Local climate and hydrometric data enabled a description of unit runoff at the site based on runoff coefficients (RCs), daily precipitation values and a temperature record. For 1996-2009, RCs from nearest watercourses ranged from 0.44 to 0.72 (mean= 0.62) and correlated strongly with annual precipitation. RCs were estimated for each year within the Base Case and Climate Scaled Case input datasets using precipitation as the predictor (r-square of 0.79) with daily precipitation being converted to runoff at air temperatures >0ºC. At air temperatures ≤ 0ºC, water was held as snow storage and subsequently discharged according to a site-specific snowmelt relationship (Fraser et al., 2011). Unit runoff computed this way was used to represent runoff from natural- and mine-impacted areas of the site.

To predict groundwater inflows to the two pits, a function describing the relationship between groundwater inflow and lake level was developed based on Aitik pit dewatering records, historical Aitik pit depths, and reported hydraulic conductivities in the mine area.

### Water quality data and source terms

The water quality of each pit lake was assumed to reflect the mixing of the various source waters entering the pit. Given the close proximity of the two pits, common geology and extensive monitoring history, site-specific data were largely used to generate source terms representing the following within the Aitik and Salmijärvi pit lake models: pitwall runoff; waste rock specific drainages; tailings impoundment runoff; clarification pond discharge; and runoff from non-contact surfaces. Proxies from the literature were used to represent regional groundwater and precipitation (Thunberg et al., 2001; Reimann et al., 1997). Figure 2 (Cd shown) is illustrative of the water quality data used to generate source terms for parameters of concern in the pit lake models.

## Results

### Water balance

Once full, the Salmijärvi pit lake has a surface area of ~50 ha, maximum depth 240 m and total volume of 52 million $m^3$. Accounting for the effects of climate change, the Salmijärvi pit is expected to spill to the receiving environment after 97 years at mean monthly rates ranging between 3 and 35 L/s. In contrast, the filled Aitik Pit is expected to fill after 91 years and discharge at mean monthly rates ranging from 66 to 315 L/s under a changed climate. Once filled, the Aitik pit lake will have maximum depth of 525 m, surface area of 288 ha and total volume of 556 million $m^3$. Climate scaled model runs for the pit lakes reached spill-over conditions earlier than predicted using Base case climate data (i.e., 25 years earlier for Aitk pit lake (Figure 3); 40 years earlier for Salmijärvi pit lake) .

For the Salmijärvi pit lake, cumulative data for pit inflows show non-linear relationships for parameters dependent on lake level and lake surface area (e.g., pit wall runoff, evaporation, groundwater and direct precipitation to the lake surface). For example, as the water level in the pit rises, the contribution from pit wall runoff decreases in response to a decrease in pit wall surface area, while evaporation increases in response to an increase in pit lake surface area. Modelled flows from the Salmijärvi pit at the time of pit overflow are (in order of significance): direct precipitation > pit wall runoff > runoff from natural ground > groundwater.

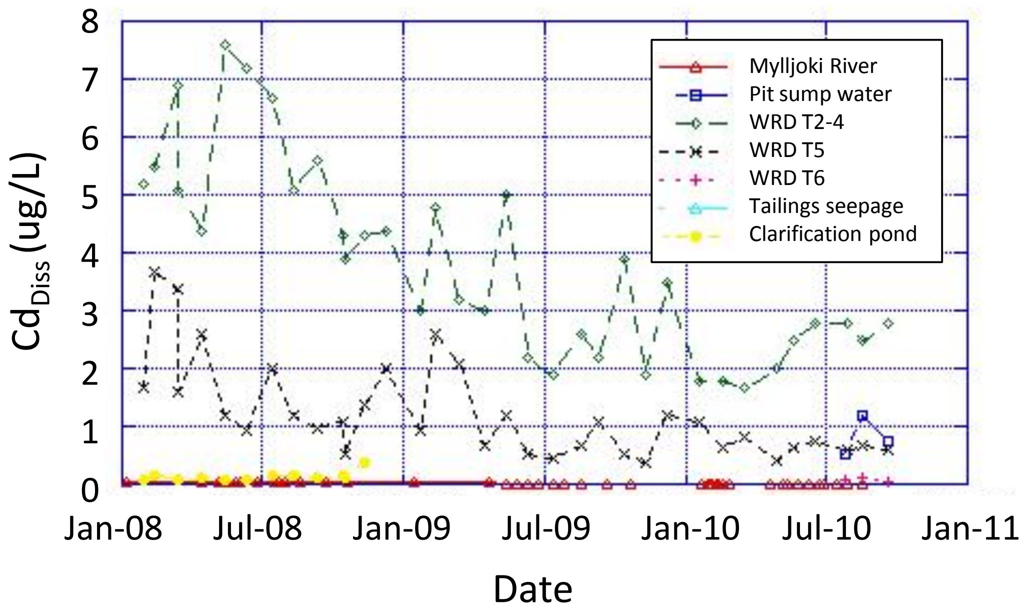


Figure 2. Background and mine-impacted water quality (2008-10) used to define project source terms for parameters of concern. Data for dissolved cadmium are shown.

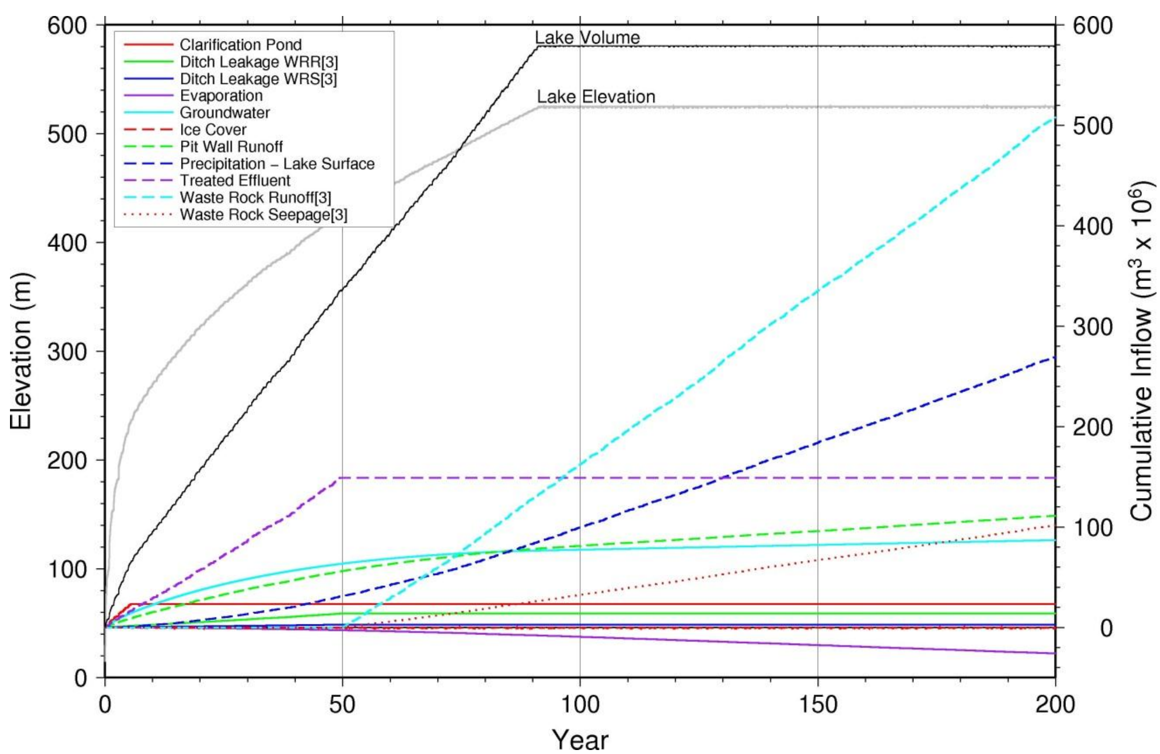


Figure 3. Post-closure water balance for the Aitik pit lake. Pit lake elevation data (grey solid line) are interpreted using the primary Y-axis. Flow data (cumulative inflows ($m^3 \times 10^6$)) are interpreted using the secondary Y-axis.

Results demonstrate that for years 1 to 5, inputs from the tailings impoundment (i.e., clarification pond discharge) represent the largest inflow to the Aitik pit (Figure 3). Following year 5, the input of lime-treated ARD dominates the water balance to the end of the 50-year treatment period. The pit wall runoff term decreases together with the exposed pit wall surface area as the pit lake fills. Furthermore, pit filling decreases hydraulic gradients between the lake surface and local water table, resulting in a decrease in the groundwater flux with time. Once filled, modeled flows from the Aitik pit in order of significance are: waste rock runoff > direct precipitation > waste rock seepage > pit wall runoff > groundwater.

**Water quality**

*Salmijärvi Pit*

The physical evolution of the Salmijärvi pit lake is illustrated by the spatial and temporal distributions of density and salinity shown in (Figures 4 and 6). Generally, the water column shows a weak, though permanent (*i.e.*, meromictic), density structure. The meromictic nature of the water column is most pronounced after year 100, at which time both density and salinity show well-defined vertical structures in the uppermost 20 m of the water column. The potential for large density gradients (strong stratification) in the Salmijärvi pit is limited by the relatively low salinity of the inflows, including pit wall runoff which represents the dominant source of salinity to the system. Over time, the decrease in saline pit wall runoff to the lake surface together with the constant supply of lower salinity groundwater to pit bottom waters decreases salinity in the bottom 50 m of the water column. The persistence of this lower salinity bottom layer relates to the effect of pressure on density (i.e., the salinity of the intermediate pit layers is not sufficient to offset the density difference imposed by higher bottom water pressure). Over the depth range of the Salmijärvi Pit (240 m), the change in pressure is equivalent to an increase in salinity of 1.8 ppt (at 4° C), a value that exceeds the maximum observed salinity values in the water column.

The redox structure in the water column of the Salmijärvi pit lake was found to be governed by the balance of mechanisms that replenish and consume dissolved oxygen (DO). The output from the lake physics model indicates that surface waters do not mix appreciably below a depth of 30 m with the onset of suboxia in lake bottom waters (5 m above bottom) evident after year 20. In lake surface waters, DO is sustained near saturation in the surface mixed layer that extends seasonally to a maximum depth of ~10 m.

The vertical and temporal distributions of select major ions and trace elements are shown in Figures 4 and 6 for Salmijärvi ($SO_4$ and Cu shown). Initial loadings for parameters are largely associated with pit wall runoff, accompanied by a continuous supply of lower salinity groundwater to the pit bottom. Major ion and trace element concentrations evolve to a generalized three layer system, with: 1) a surface layer (~10 m in thickness) showing relatively low concentrations of constituents; 2) a bottom layer (lower 50 m of profile) with values similar to the surface layer; and 3) a thick intermediate layer of higher salinity. This chemical structure relates to the influences of salinity and pressure with respect to density, as well as to the nature of the major ion and trace element loadings (i.e., primarily from pit wall runoff to the lake surface).

*Aitik Pit*

The physical evolution of the Aitik pit lake differs significantly from that of Salmijärvi, as illustrated by the vertical and temporal distributions of density and salinity (Figures 5 and 6). The introduction of a hypothetical lime-treated ARD into the Aitik pit lake has a pronounced effect on both the vertical and temporal distribution of salinity and density. During the treatment period from years 1 to 50, the introduction of lime-treated ARD generates vertical circulation in the pit resulting in a mixed water column (Figure 6).

Following the cessation of effluent treatment at year 50, strongly stratified conditions develop in the upper water column. The onset of meromixis is driven by the removal of appreciable vertical mixing imposed by the treated effluent, as well as the continual supply of lower-salinity water to the lake surface (Figure 5). Similar to the Salmijärvi pit lake, the persistence of slightly lower salinity in bottom waters of the Aitik pit ("10 m above bottom" in Figure 5) relate to the effect of pressure on density. Specifically, despite the lower salinity of bottom waters, a higher density is maintained due to the effect of increased pressure.

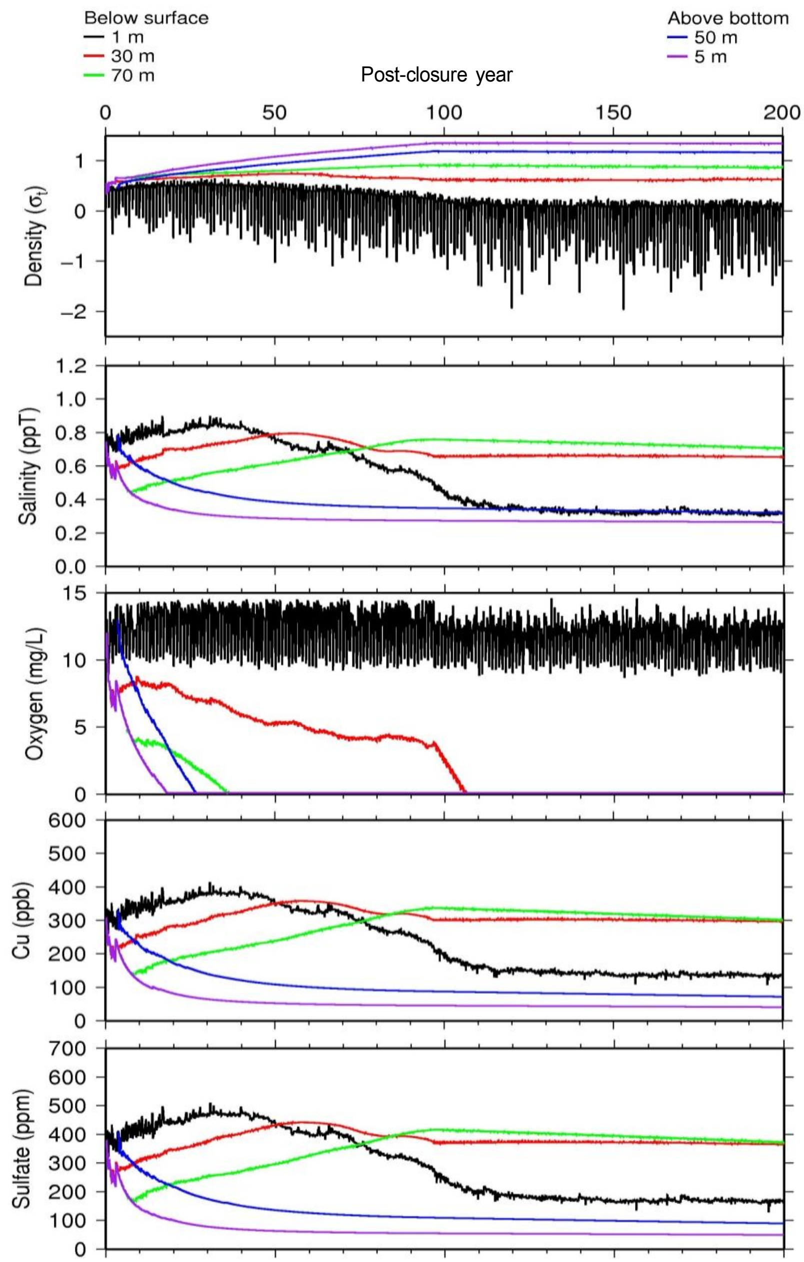


Figure 4. Predicted depth-time plots for density, salinity, oxygen, Cu and sulfate at the Salmijärvi pit lake. Pit filling is achieved after 97 years.

During the period of effluent treatment, oxygenated conditions (5-10 mg/L) are maintained throughout most of the water column (Figures 5 and 6) owing to the delivery of DO to deep waters by vertical circulation. Following the cessation of effluent treatment, the development of stratification in the water column restricts atmospheric exchanges with deep waters, resulting in the depletion of DO below water depths of ~12 m. The onset of suboxia in lake bottom waters (10 m above bottom; Figures 5 and 6) is evident after year 20, with the depth of the suboxic zone increasing in thickness as the lake level rises.

The spatial and temporal distributions of major ions in the Aitik pit lake parallel salinity (sulphate shown in Figures 5 and 6). Over the treatment period (years 1 to 50), concentrations of these parameters remain high and largely invariant with depth, reflecting the input of dense, gypsum-saturated treatment slurry. Following year 50, concentrations in the upper 50 m decrease markedly. In the intermediate horizons (100 m below surface to 100 m above bottom), the concentrations of sulfate remain high to the end of model runs.

The predicted concentrations of trace elements (e.g., Cu, Zn, Co and Ni) also respond markedly to a hypothetical treatment scenario (Cu shown in Figures 5 and 6). In general, the collection and treatment of waste rock seepages and runoff maintains low concentrations of trace metals in the water column. For example, concentrations of Cu, Zn, Co and Ni are maintained at ~50, 20, 8 and 5 ppb, respectively for years 1 to 50.

Upon cessation of effluent treatment, concentrations of trace elements exhibit pronounced increases in concentration in the lake surface layer (uppermost 75 m of the water column) (Figures 5 and 6). The rise in trace metal concentrations can be attributed to an increase in the metal loadings to surface waters associated with the input of untreated ARD. Under this scenario absent of lime treatment, concentrations of Cu, Zn, Co, and Ni increase to values of ~340, 84, 20 and 8 ppb, respectively. Owing to strong stratification and limited mixing with the metal-rich surface layer, metal concentrations below 75 m remain relatively low.

## Discussion

Comparison of the modelled metal concentrations to Swedish environmental criteria and local background values suggest that Cu, Zn, Co, Ni and Cd will be the primary parameters of concern. It should be noted that the predicted concentrations do not account for mechanisms that may act to remove metals from the water column, including: 1) particle scavenging in the surface layer and transport to deep waters via particle settling; and 2) precipitation of secondary sulfide minerals in anoxic bottom waters. This imparts an element of conservatism into the model predictions since non-conservative processes will likely be relevant for trace elements in these pit lakes.

The absence of DO below the surface mixed layer predicted for the lakes is supported by data for other pit lake systems (e.g., Castro and Moore, 2000). Although specific redox reactions were not modelled as part of this paper, the modelled DO results suggest the following processes may have importance in the suboxic portions of the water column: 1) consumption of secondary electron acceptors such as nitrate and sulfate; and 2) increases in the concentrations of redox reaction products including dissolved Fe, Mn, alkalinity and possibly $HS^-$. In particular, the potential for sulfate reduction implies that the bottom waters of the Aitik and Salmijärvi pits may serve as sites for natural bioremediation processes where dissolved metals (e.g., Cu, Zn, Co, Ni and Cd) are removed from solution through the precipitation of insoluble sulfide precipitates (Stumm and Morgan, 1981). Indeed, there is considerable evidence that the formation of secondary metal sulfides in anoxic water columns can strongly affect trace element concentrations in stratified lakes (Fisher and Lawrence, 2006; Oremland *et al.*, 2000; Green *et al*., 1989).

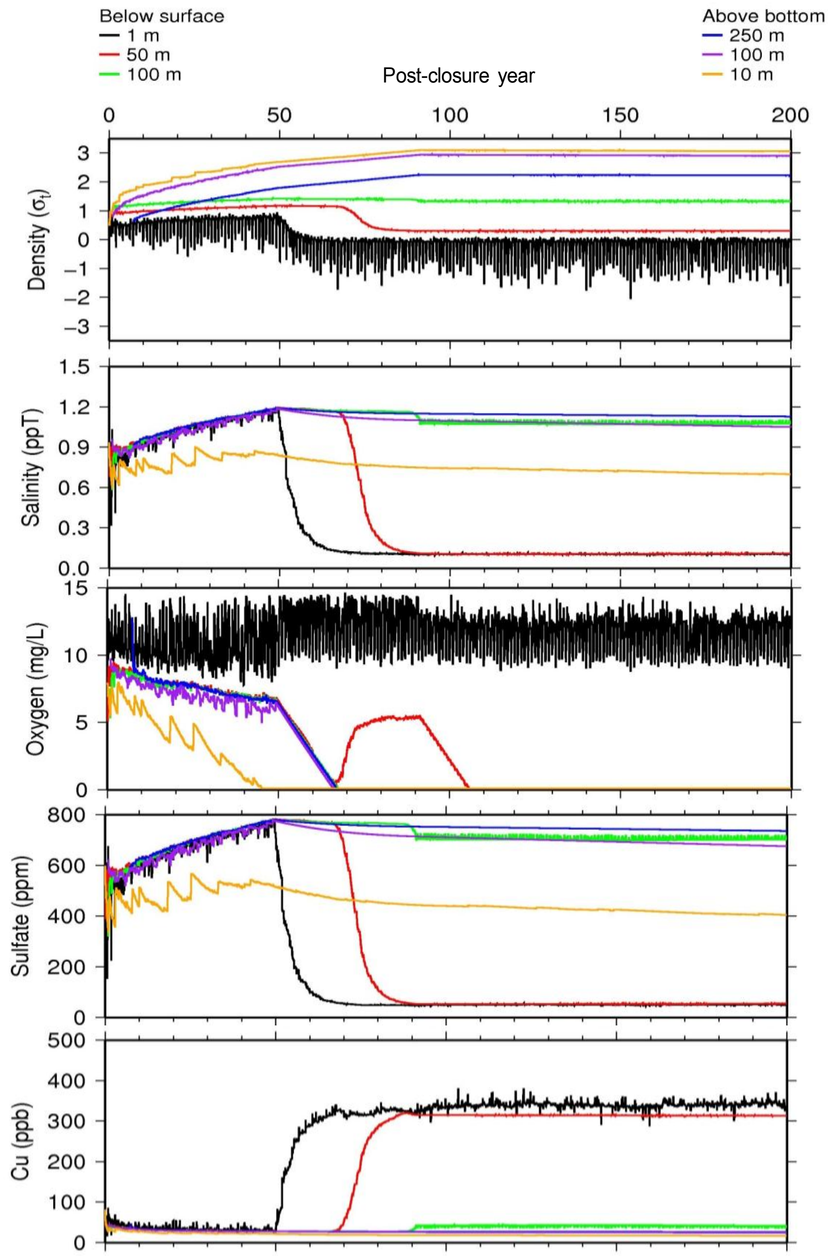


Figure 5. Predicted depth-time plots for density, salinity, oxygen, Cu and sulfate at the Aitik pit lake. Pit filling is achieved after 91 years. A hypothetical effluent treatment scenario is modeled (years 1 to 50).

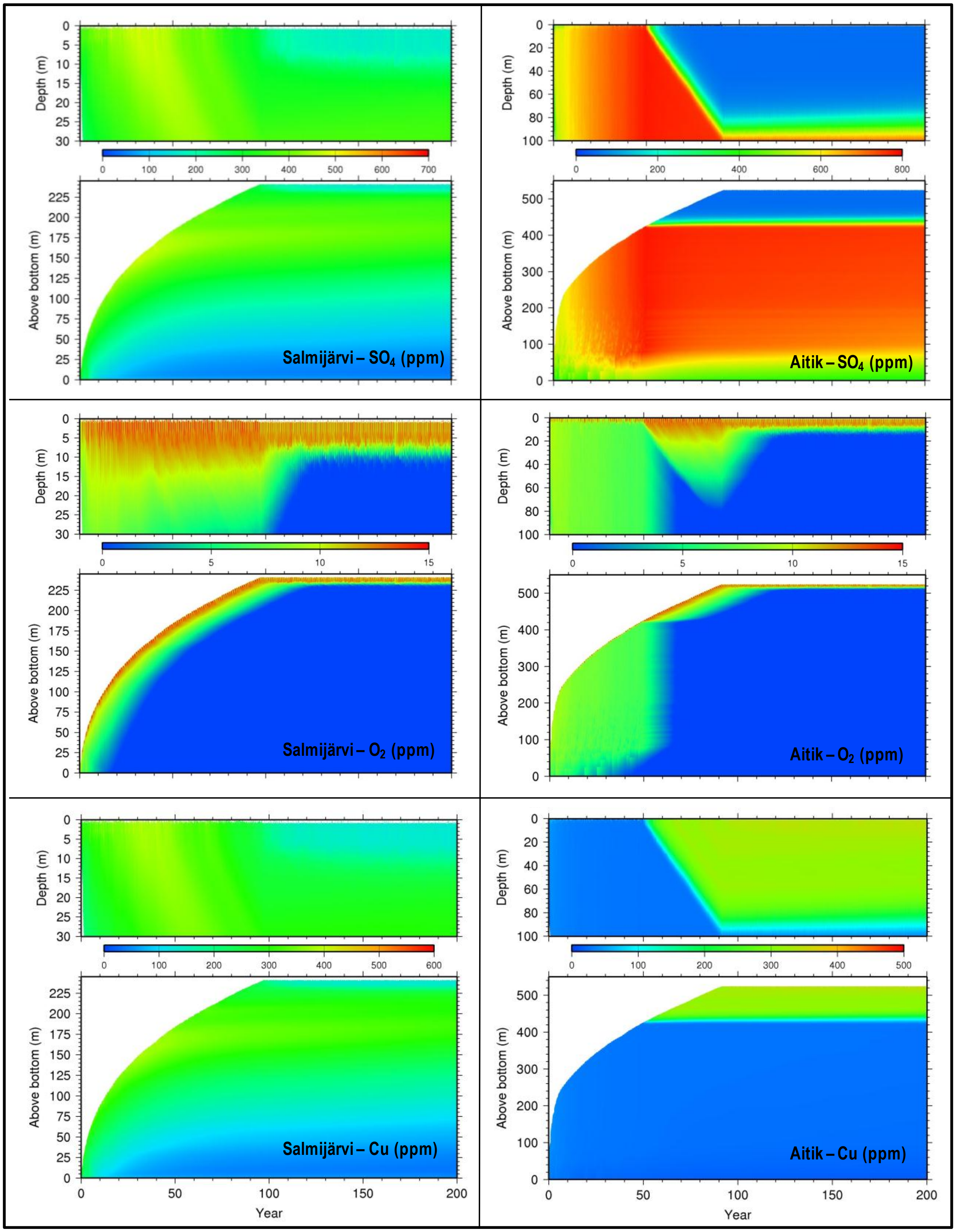


Figure 6. Predicted pit lake profiles for Salmijärvi (left) and Aitik (right) pit lakes. Plots for sulfate, dissolved oxygen and Cu are shown. All units are in ppm.

Model output demonstrates that pit lake water balances are sensitive to the effects of climate change (i.e., pit fill times reduced by 25 to 40 years), which is expected to result in an increase in air temperature, precipitation and the proportion of rain to snow. Furthermore, results presented here show that water quality conditions in the Aitik pit are highly sensitive to a hypothetical treatment scenario. As part of future modelling work, a suite of scenarios will be assessed to explore the effects of site reclamation, water management, effluent treatment, climate change and non-conservative removal mechanism on pit lake behavior and closure planning for the Aitik site.

## References


Castro, J. M. and Moore, J.N. (2000) Pit lakes: their characteristics and the potential for their remediation. Environmental Geology Vol. 39, pp. 1254-1260.

Crusius, J., Dunbar, D., and McNee, J. J. (2002) Predictions of pit lake water column properties using a coupled mixing and geochemical speciation model. In, Transactions for the Society for Mining, Metallurgy and Exploration, 26-28 Feb, 2001, Vol. 312: pp 49-56, Denver, CO, USA.

Dunbar, D., Pieters, R., and McNee, J.J. (2004) *Modeling a Negatively Buoyant Plume and Related Surface Dissolved Metal Removal in the Equity MainZone Pit LakePit Lakes*, US EPA. Reno, NV.

Fisher, T. and Lawrence, G. (2006) Treatment of Acid Rock Drainage in a Meromictic Mine Pit Lake. Journal of Environmental Engineering, Vol. 132, pp. 515-526.

Fraser, C.J.D., Martin, A.J. and Pedersen, T.F. (2011) Climate scaled water balances for mine closure planning. In, Australian Centre for Geomechanics Mine Closure 2011 Proceedings, Vol. 2, pp. 357-66.

Green, W. J., Ferdmelman, T. G., and Canfield, D.E. (1989) Metal dynamics in Lake Vanda (Wright Valley, Antarctica). Chemical Geology, Vol. 76, pp. 85-94.

Ormeland, R. S., Dowdle, P. R., Hoeft, S., Sharp, J. O., Schaefer, J. K., Miller, L. G., Blum, J. S., Smith, R. L., Bloom, N. S., and Wallschlaeger, D. (2000) Bacterial dissimilatory reduction of arsenate and sulfate in meromictic Mono Lake, California. Geochimica et Cosmochimica Acta, Vol. 64, pp.

Parkhurst, D. L., and Appelo, C. A. J. (1999) *User's guide to PHREEQC (version 2) - a computer program for speciation, reaction-path, 1D-transport, and inverse geochemical calculations*. Rep. 99-4259, United States Geological Survey.

Reimann, C., De Caritat, P., Halleraker, J.H., Volden, T., Äyräs, M., Niskavaara, H., Chekushin, V.A., and Pavlov, V.A. (1997) "Rainwater composition in eight arctic catchments in northern Europe (Finland, Norway and Russia)." Atmospheric Environment. Vol. 31, pp. 159-170.

Stumm, W. and Morgan, J.J. (1981) *Aquatic chemistry: an introduction emphasizing chemical equilibria in natural waters.* Wiley-Interscience, New York.

Thunberg J., Ohlander B., and Land, M. (2001) Groundwater geochemistry in a mineralized area, Liikavaara, northern Sweden. In, Securing the Future, International Conference on Mining and the Environment, Skelleftea, Sweden, pp. 860-871.