Developing closure plans using performance based closure objectives: Aitik Mine (Northern Sweden)

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Abstract At Boliden's Aitik Mine, closure planning has been ongoing over the last 25 years. Recently set national environmental quality standards (EQS) for surface waters, developed in relation to the implementation of the Water Framework Directive within the European Union, provide the opportunity to evaluate the overall requirements for the integrated closure of the mine. Based on site-specific information, a base-case closure scenario was developed fulfilling the water quality objectives in the recipient. Performance-based closure objectives showed to provide an efficient approach to optimise mine closure planning.

Introduction

Developing viable closure plans for large mines represents a significant challenge in the mining industry which relates to the complexity associated with scale, multiple sources and recipients as well as multiple closure objectives. In performance-based design, closure measures that make up the closure scenario are selected based on predictions of impact to the recipient environment. The relationship between closure measures and predicted impacts to the environment can be quantified by conducting numerical analysis. For example, quantification of the impacts of cover performance for waste rock, in the form of net percolation and oxygen ingress design criteria on recipient water quality, requires an integrated analysis of site-specific components including geochemical reactions, gas exchange as well as flow and transport processes occurring in the waste along the flow path. This approach provides an opportunity to develop site-specific performance-based design criteria based on quantification of the acceptable loadings to the recipient environment. A review of design approaches concludes that the process usually consists of the three steps: 1) Determine acceptable recipient water quality standards; 2) Determine the maximum acceptable loading that can be discharged to the recipient without exceeding these water quality standards; and, 3) Select a closure system resulting in discharges less than this maximum.

Within the European Union (EU), the implementation of the Water Framework Directive has given the mining industry overall performance criteria in the form of environmental quality standards (EQS) for Priority Substances for receiving waters. When additional EQS for Specified Pollutants were introduced in Sweden in 2015 (HVMFS 2013:19), a full set of regulatory EQS became available to use as overall performance based closure objectives (tab. 1). The EQS provide increased clarity as to what is considered acceptable, not just from an eco-toxicological point of view, but that also includes a specified factor of safety.

Table 1 *Swedish Environmental Quality Standards (EQS) for surface waters (HVMFS 2013:19).*

Substance	Annual average concentration (µg/l)	Maximum concentration (µg/l)
Cd	≤ 0,08 (class 1)	≤ 0,45 (class 1)
	0,08 (class 2)	0,45 (class 2)
	0,09 (class 3)	0,6 (class 3)
	0,15 (class 4)	0,9 (class 4)
	0,25 (class 5)	1,5 (class 5)
Ni	4 bioavailable concentration	34 bioavailable concentration
Pb	1,2 bioavailable concentration	14
As*	0,5	7,9
Cu	0,5 bioavailable concentration	
Cr	3,4 total concentration Cr^{VI}	
U*	0,17	8,6
Zn*	5,5 bioavailable concentration	
*above background		

Site description

The Aitik copper mine is located 17 km east of Gällivare in Northern Sweden. The Aitik deposit forms a mineralisation 5 km long and averaging 500 m in width. Production started at Aitik in 1968 at a permitted production rate of 2 Mt ore per year. Numerous expansion projects have been permitted and implemented over the years and the current permit allows for the extraction and processing of up to 45 Mt ore per year. High productivity compensates for the low head grades, which during 2016 were 0,11 g/t Au, 2.1 g/t Ag and 0.22 wt% Cu. Historic production amounts to 744,5 Mt ore at a stripping ratio waste/ore of 1.04. Proven and probable mineral reserves at the end of 2016 were 1,194 Mt.

The main closure components include: 1) 700 ha of waste-rock storage facilities (WRSF) of which 400 ha contain potentially acid generating (PAG) waste-rock while 300 ha contain non-acid generating (NAG) waste-rock; 2) a 1700 ha tailings management facility (TMF); 3) the 3 km long, 1 km wide and 525 m deep Aitik open pit; and 4) the smaller Salmijärvi pit which is 1 km long, 0.7 km wide and 270 m deep. After closure, surface and subsurface water will ultimately flow from the site to the Lina River, which forms part of the Kalix & Torne river system.

Methods

Closure planning at the Mine has followed an iterative and systematic approach. Based on performance based closure objectives, the integrated effect of different closure options were evaluated, resulting in the development of a base-case closure scenario that fulfils water quality objectives in the recipient. The evaluation of different cover options and water management alternatives represented critical aspects of the assessment. Studies in support of these components and were based on site specific information and the development of a 200 year climate scenario, which includes anticipated effects of climate change. The evaluation also included modelling of cover system performance (oxygen ingress/availability and water infiltration/seepage), hydro-geological modelling, geochemical modelling of resulting drainage composition from the TMF and WRSFs, pit lake modelling, recipient water quality modelling in downgradient river system, and modelling of bioavailable concentrations of constituents. Finally, a Failure Mode and Effect Analysis (FMEA) was developed by the multi-disciplinary project team to address and manage risk related to the base-case closure scenario.

In order to ensure consistency with respect to the climate variables used in the modelling, a *common climate data set* was developed that accounts for predictions of climate change for the local region (Lorax 2015a and Fraser et al. 2017). A daily climate dataset was created for the 2015-2100 period based on proceedings of IPCC Fifth Assessment Report and selecting Representative Concentration Pathway (RCP) 4.5 (RCP 4.5 assumes radiative forcing is stabilized at 4.5 W/m^2 by 2100). Data from 2025-2100 were looped to create at database to 2225. Corresponding *flow rates for the recipients* were obtained from the Swedish Meteorological and Hydrological Institute (SMHI) using the hydrological model S-HYPE which was driven by the same regional climate model used to represent future climatic conditions for the site.

O´Kane (2015a and b) modelled *cover system performance* (oxygen ingress/availability and water infiltration/seepage) for the WRSF and for the TMF using VADOSE/W, a two-dimensional (2-D) finite element model that predicts suction and temperature profiles for materials in response to climatic forcing, such as evaporation, and lower boundary conditions. Based on these calculations, net percolation and gas movement are predicted. The modelling applied the common climate data set as well as site-specific material properties or functions derived from material characterisation and field trials. The results from the cover performance modelling were then used for the geochemical modelling of the WRSF and the TMF.

Geochemical modelling of the WRSF was performed by O´Kane (2015a) with the computer program REACT (Geochemist's Workbench). Mineral dissolution and precipitation reactions were all assumed to occur following kinetic rate laws obtained from the peer-reviewed literature. At Aitik, the integrated WRSF seepage is a function of multiple sources that flow under the WRSF and into the drainage collection ditch. Source terms for the TMF, environmental waste rock drainage and near-surface natural drainage were estimated from the available dataset of water quality monitoring results. An inverse modelling process was undertaken to recreate current water quality and derive WRSF drainage water quality based on waste-rock characterisation results and the conceptual flow model. Forward reaction path modelling was then used to derive long term WRSF drainage water quality after closure based on initial pore water quality, mineralogy, determined oxygen flux and net percolation through the final cover system. O´Kane (2015a) estimate the time frame for physical draining of the WRSF to transition from water quality after drain down to long term modelled water quality based on soluble acidity loads as represented by soluble melanterite-type available acidity.

Hatch (2015a) performed *hydro-geological modelling* of the closed TMF and *geochemical modelling* of resulting drainage composition from the different dams of the TMF. The geochemical modelling calculations relied on the use of the PHREEQC geochemical modelling software. It has the capabilities to simulate chemical equilibrium and kinetic processes as well as simultaneous reaction and transport. These capabilities were used to simulate the combined processes of sulphide mineral oxidation, equilibrium with secondary solubility-controlling minerals, and adsorption/desorption reactions. The thermodynamic and kinetic data used for calculations were based on the WATEQ4A.DAT, which is a standard database file for PHREEQC, with additions from the MINTEQ4.DAT database. Similar to O´Kane (2015 a), Hatch used inverse modelling and site specific data to recreate current drainage quality and initial pore water quality, mineralogy, determined oxygen flux and net percolation through the final cover system in the forward modelling to derive long term WRSF drainage water quality after closure.

Lorax (2015 b and Martin et al. 2017) modelled *pit lake chemistry* using PitMod, a one-dimensional numerical hydrodynamic model. The model assumes uniform horizontal mixing and combines physical mixing processes in combination with non-conservative removal mechanisms. One-dimensional approximation is applicable to pit lakes due to their high depth to surface area ratios and the few if any barriers to horizontal mixing. Based on site characterisation data, Lorax (2015b) modelled pit lake water quality and outflow quality as well as volumes for different closure scenarios accounting for the common climate data set, hydro-geochemical behaviour of the TMF (Hatch 2015a) and the WRSF (OKC, 2015a).
The closure of the Aitik Mine will involve reclamation of surface facilities, including the tailings management facility (TMF), waste rock storage facilities (WRSF), Aitik and Salmijärvi pits, industrial areas, and implementation of water management and treatment systems. The surface drainages will be recontabled to allow water from reclaimed facilities to flow to the rivers. Seepage from the E-F dam on the TMF will mix with catchment runoff and flow to the Leipojoki River, seepage from the G-H dam on the TMF will mix with catchment runoff and flow to the Vassara River, while seepage and surface runoff from the north face of the T6 environmental WRSF will flow to the Lina River (fig. 1). Seepage from A-B/C-D dam on the TMF and seepage from the PAG WRSF will flow towards the Aitik open pit. Once the pits have filled to capacity, the overflows will be routed to the Lina River.

A simulation model was developed using the GoldSim modeling framework to predict the individual and cumulative future effects of the chemical loads and flows from the reclaimed mine facilities on water chemistry in the receiving rivers, referred to as the *"Recipient Model"* (Hatch 2015b). The model was developed through a sequential process in which it was initially compared and calibrated to reproduce existing water chemistry in the receiving rivers using monitoring data from 2010 to July 1, 2015. The model then was projected forward in time for the closure period using predictions of future water flows and chemistries from the reclaimed mine facilities. Future flows in the mine and rivers were based on the RCP 4.5 climate scenario as provided by SMHI as described above. Future chemistries of source terms were accounted for including the closure of the TMF, WRSF, and pit lake overflows. Model results were accumulated as yearly average concentrations in the receiving rivers (Leipojoki River, Vassara River, and Lina River) as illustrated in fig. 1.

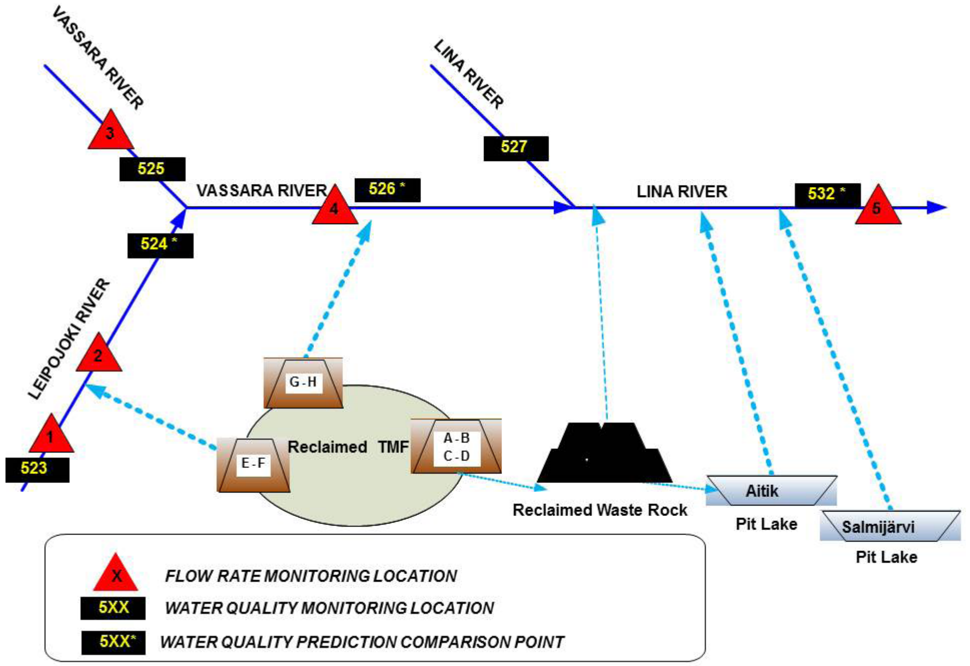

***Figure 1** Schematic illustration of the post closure water flow at the Aitik mine (modified from Hatch 2015b).*

Resulting *recipient water quality* was assessed against the EQS (SWECO, 2015). For some of the constituents, it was necessary to model future bioavailable concentrations using Biomet ver. 2.3 based the results from the Recipient Model (SWECO, 2015).

Risk represents an engineering tool for developing informed closure planning decisions; in other words, uncertainty is not used to inform on closure planning decisions. Risk is measurable and quantifiable, can be controlled and managed through application of appropriate measures, and can be minimized by taking necessary precautions. These aspects are developed through utilization of a top-down, expert-based risk process that assigns a set of probabilities for site specific conditions; namely the *Failure Modes and Effects Analysis* (FMEA) (O´Kane 2015c).

Results

All sub-tasks within the closure assessment utilized the common climate dataset to provide the basis for consistent results and reporting. The purpose of the assembled climate data set is to capture trends and variability in the future climate, anticipated effects of climate change included (Lorax 2015a). RCP 4.5 was assessed to be a realistic scenario. The model output shows the annual average temperature will increase by 3.5 °C while annual average precipitation will increase by 15-20%. These factors will lead to 30 fewer ice-covered days by 2080.

Modelling of the cover system performance for the PAF WRSF (O´Kane 2015a) shows that a cover of 0.3 m highly compacted till (k_{sat} = 1 x 10^{-8} m/s), 1.5 m moderately compacted till and 0.3 m vegetated top soil results in an average annual oxygen ingress of 33 g/m²/yr for plateau areas and 37 g/m²/yr for sloping areas. Predicted net percolation was approximately 32% and 27% for plateau and sloping areas, respectively. In the compacted till layer, a degree of saturation >85% is maintained during the simulation period. For the TMF (O´Kane 2015b), the same cover, but with k_{sat} of the compacted till layer of 2.5 x 10^{-8} m/s, average annual oxygen ingress was 28 g/m²/yr if the water table is at 2.5 m or greater and decreased to <20 g/m²/yr if water table is at 1 m depth. Predicted net percolation was approximately 35% of annual precipitation and the compacted till layer maintains >85% degree of saturation, which is rule of thumb benchmark to control oxygen ingress.

Inverse geochemical modelling shows the PAF WRSF currently generates a low pH (pH 3.5) high acidity seepage with an acidity load of 2000 tonnes/year containing 80 tonnes/year of copper (O´Kane 2015a). Forward reaction path modelling indicates that after cover placement, there is a drain down period of approximately 20 years, where pH and contaminant load remains reasonably steady. This is followed by a transition period due to the flushing out of stored soluble acidity (mainly soluble melanterite-type acidity) of about 25 years, after which stable (long term) water quality conditions develop due to the limited oxygen and water transport through the cover. The long term seepage will be characterised by circum-neutral pH where sulphide oxidation is limited, where remaining soluble and sparingly soluble acidity is neutralised by dissolution of alumina-silicate minerals, mainly anorthite (O´Kane 2015a).

In a similar way as for the WRSF, geochemical modelling of the TMF shows that seepage water quality from the dams is currently a mixture of process water and seepage from unsaturated zones close to the dams which are affected by sulphide oxidation (Hatch 2015a). After cover placement, the seepage water quality will evolve in a similar way as for the WRSF, resulting in circum-neutral long-term dam seepage water quality where acidity from limited sulphide oxidation is neutralised by dissolution of alumina-silicate minerals (mainly anorthite).

The Aitik pit lake model includes 34 inflow terms (Lorax, 2015b). During pit filling, the dominant flows are from the Clarification Pond (CP), runoff from WRSFs and natural ground, precipitation and pit wall runoff. Pit lake overflow occurs in Year 55 post closure, with an overall mean annual flow of 270 L/s. During the filling period, a gradual freshening over time in the surface layer results in the development of permanent stratification in the water column (meromixis). Acidic pH values (pH<5) are realized in the early stages of pit filling due to the input of low-pH seepage waters associated with WRSFs and TMF. Prior to pit lake overflow the results demonstrate the presence of circum-neutral pH conditions in lake surface waters. The modelling shows the improvement of the pit overflow can be accelerated by treating the WRSF seepage during pit filling (Martin et al. 2017). The Aitik pit overflow will discharge to the Lina River. Filling time for the Salmijärvi pit is 100 years and the evolution of the pit water quality follows a similar pattern to the Aitik pit; however, Salmijärvi does not receive any seepage from the WRSF or the TMF. The Salmijärvi pit overflow will discharge to the Myllyjoki Creek which flows into Lina River.

Recipient water quality modelling of downgradient river systems (Hatch 2015b) and modelling of bioavailable concentrations of constituents followed by assessment against the overall objectives (Sweco 2015) shows that the highest impact will occur in the Lina River downstream all Aitik discharges (monitoring point 532 in fig. 1). Further, the assessment highlights that copper will be the critical parameter in order to comply with EQS (tab. 1), fig. 2.

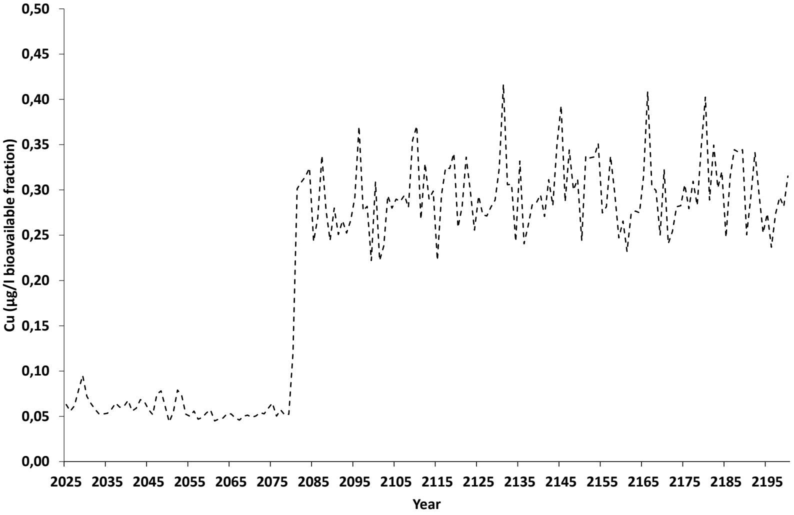

Figure 2 *Long term prediction of bioavailable copper concentration in the Lina River downstream the Aitik mine for the base-case closure scenario (modified from Sweco 2015).*

A site wide *base-case closure scenario* was developed using this iterative systematic approach. Results show that the EQS can be met in the recipient by applying a composite moraine cover system on the PAG WRSFs, as well as on the TMF embankments and unsaturated tailings zones of the TMF; remaining surface areas of the TMF will remain saturated. Non-PAG WRSFs will be covered with a simple moraine cover system and the pits will be flooded. Drainage from the WRSFs and the TWF will be diverted to the Aitik pit and treated for approximately 55 years until the drainage water quality reaches steady state. The Aitik pit is predicted to fill in approximately 55 years, at which time the site-wide integrated modelling illustrates the discharge will be suitable for direct discharge to the recipient. The FMEA identified technical, regulatory, societal, and economic risks to the the base-case closure scenario (O´Kane 2015c). Identification of these risks allowed for development of further studies, public consultation, and/or mitigation measures for each identified risk. Risks were prioritized based on whether being critical to the project meeting its objectives, to those having a limited effect on project success. All identified risks were assessed to be manageable within the closure scenario.

Conclusions

A full set of regulatory environmental quality standards (EQS) for water bodies are available to use as overall performance-based closure objectives in Sweden. These EQS provide the opportunity to evaluate the overall requirements for the integrated closure of the Aitik mine.

An iterative and systematic approach was used to develop a base-case closure scenario that fulfils water quality objectives in the recipient. The assessment was based on site-specific information and the development of a 200 year climate scenario, which includes anticipated effects of climate change, modelling of cover system performance, geochemical modelling of resulting drainage composition, hydro-geological modelling, pit lake modelling, and recipient water quality modelling and modelling of bioavailable concentrations of constituents.

Overall, the described approach provides an important case study in the area of developing methodologies used for optimising mine closure strategies at large base metal mines.

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