Forecasting long term water quality after closure: Boliden Aitik Cu mine

Matt McKeown[1], Dave Christensen[2], Seth Mueller[3], Mike O'Kane[4], Paul Weber[5], Belinda Bird[6]

[1]O'Kane Consultants Inc. 112-112 Research Dr.Saskatoon,, Saskatchewan,,-Canada, dchristensen@okc-sk.com
[2]O'Kane Consultants Inc. 112-112 Research Dr.Saskatoon,, Saskatchewan,,-Canada, mmckeown@okc-sk.com
[3]Boliden Mineral AB. SE 936 81, Boliden, -Sweden seth.mueller@boliden.com
[4]O'Kane Consultants Inc. 200-1121 Centre St NW, Calgary, Alberta,-Canada, mokane@okc-sk.com
[5]O'Kane Consultants Inc. Unit 2, 2 McMillan St, Darfield, Canterbury,-New Zealand, pweber@okc-sk.com
[6]New South Wales Minerals Council. PO Box H367, Australia Square, NSW 1215. bbird@nswmining.com.au

Abstract The Boliden Aitik Mine is located near Gällivare, northern Sweden. Since mining started in 1968, more than 500 Mt of waste rock have been deposited in storage facilities (WRSFs). This paper describes the approach to utilizing current hydrogeological and geochemical conditions for assessing contaminant loads emanating from the WRSFs. On the basis of this assessment, coupled with implementing closure management tools, and using modelling techniques, estimates for WRSF loading were developed. Modelling was used to estimate oxygen ingress and percolation rates for closure conditions based on inputs obtained from seven years of in situ cover system monitoring and field testing.

Key words Net percolation, oxygen ingress, long term water quality, geochemical modelling

Introduction

The Boliden Aitik Mine (Aitik) is a Cu-Au-Ag deposit situated in the Baltic shield near Gällivare, northern Sweden. Host rocks consist primarily of muscovite schists, biotite gneisses, and amphibole-biotite gneisses of volcaniclastic origin (Boliden, 2015). The mine area includes two open pits (Aitik and Salmijãrvi), service buildings, a tailings management facility (TMF), and WRSFs. (Eriksson, 2012). Since mining started in 1968, more than 500 Mt of waste rock have been deposited in WRSFs.

Waste rock is classified into PAF waste rock or Non Acid Forming (NAF) environmental waste rock. Environmental waste rock is described as waste rock that meets criteria rendering it suitable for construction and rehabilitation activities; environmental waste rock is not considered capable of producing acid or metalliferous leachate. Waste rock that does not meet the environmental waste rock definition is considered PAF, although some rock would be considered NAF based on industry standard acid base accounting techniques.

The primary objective of this study was to understand long-term water quality of PAF WRSF basal seepage for the purpose of determining environmental risk to aquatic receptors downstream of the mine site at closure. Evaluating risk in terms of impacts on the aquatic receiving environment, required determination of both current and long-term water quality and quantity from the WRSFs. This paper focusses on determination of long term water quantity and quality emanating as basal and toe seepage from the WRSFs.

Methods

Geochemical Characterization:

The initial basis for the geochemical conceptual model was a literature review of waste rock mineralogy, which has been discussed in various papers including Strömberg (1997), Strömberg and Banwart (1994; 1999) and Lindvall (2005). Additional field investigations were completed in 2014 to provide further geochemical characterization of the waste rock. Field investigations included a WRSF test pit sampling program, and a seepage sampling program. Waste rock samples were collected from 27 test pits excavated in WRSFs, and three water samples were collected from seepage points emanating from PAF WRSFs. Industry standard acid base accounting (ABA) geochemical testing was undertaken to understand sources of acidity and alkalinity within the PAF WRSF, including potential sulfide acidity, stored acidic oxidation products, and acid neutralization potential. Field rinse pH data from samples collected demonstrated a range of pH values representing acid forming and non-acid forming waste rock, with older samples generally having lower pH values. Key mineralogy is presented in Table 1. Key sulfide oxidation reactions with the PAF WRSFs were identified as pyrite, chalcopyrite, and sphalerite. Melanterite- and jarosite- type minerals represent soluble- and sparingly soluble-stored acidity respectively; acidity contained in these minerals would be released as a function of pore-water flushing. Calcite and anorthite are the key acid neutralizing minerals.

At closure it was estimated that potential acidity associated with unoxidised pyrite within the PAF WRSF was 4.5 Mt $CaCO_3$ eq. Stored soluble acidity associated with melanterite type minerals is ~61,000 tonnes $CaCO_3$ eq. Stored sparingly soluble acidity associated with jarosite type minerals is ~497,000 tonnes $CaCO_3$ eq. Potential acid neutralization capacity for the PAF WRSF was estimated to be ~1.4 million tonnes $CaCO_3$ eq, based on measured calcite content. With such significant potential acidity, control of oxygen ingress and hence sulfide mineral oxidation is the key management tool required to control long term acid generation and seepage water quality from the PAF WRSF.

***Table 1** Mineral composition of unoxidized waste rock (percentage by volume).*

Mineral	Strömberg and Banwart (1994) Volume % (mean± 1 SD)	Strömberg and Banwart (1999) Volume %	2014 WRSF sampling program (wt%) (OKC, 2015)
Anorthite	6 4	3 – 9	
Calcite	0.1 0.5	0.5	
Pyrite	0.57 (0.08 – 1.7)		
Chalcopyrite	0.09 (0.02 – 0.3)		
Jarosite			0.41
Melanterite			0.02

Conceptual Flow Model:

Characterization of each component of the conceptual flow model in terms of water quality and flow rate was necessary to determine current and long term water quality from the PAF WRSF. Physical characterization of current conditions included development of a conceptual model for flow mechanisms, and controls on those mechanisms, at site. Pre-mine contours were used to analyze surface topography, infer flow direction and delineate underlying catchment areas. The majority of surface and shallow groundwater flow at site reports to water monitoring location 558, along the main WRSF collection channel (Fig. 1). Each flow component contributing to water monitoring location 558 was characterized to allow for development of a conceptual model as to how flow quantity and quality would evolve in the long term Flow components include infiltration through WRSFs (PAF and environmental), flow emanating from the TMF, and near surface ground flow.

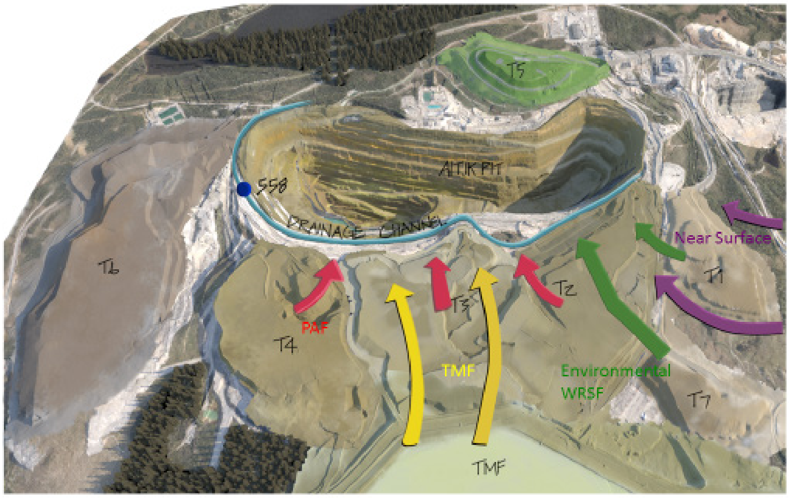

Figure 1 *Conceptual flow model contributing to drainage collection channel.*

Flow rates of each component were estimated based on footprint areas. For WRSFs, a net percolation rate (55 – 60% of annual precipitation) was applied to the bare waste rock surface based on numerical modelling for current conditions. Applying annual precipitation of 600 mm, total seepage from the PAF and environmental WRSFs was estimated to be 40 L/s and 10 L/s, respectively. A comparison between flow volume measured in the WRSF collection channel and estimated flow emanating from WRSF catchments and adjacent natural ground catchments indicated that a large flow component was being contributed by the TMF area, which is consistent with the flow model for the site (e.g., Eriksson and Destouni 1997). A seepage flow rate of 160 L/s was assumed based on a literature review of previous work at site, flow rates recorded in the collection channel, and dimensions of the TMF area and structure adjacent to the WRSF catchments. Finally, near surface groundwater flow was calculated as the difference between the flow measured in the channel and remaining characterized flow components, which was 20 L/s.

Derivation of PAF Source Term:

Current water quality for the PAF WRSF drainage, for which no isolated data were available, was determined by empirical inverse geochemical modelling. Water quality and flow rates are available for the water monitoring location 558 in the WRSF collection channel. As such, contaminant loads from other flow components were deducted from the load measured at water monitoring location 558, and the remaining load was assigned to net percolation through PAF WRSFs to generate the source term for PAF drainage water chemistry. Characterization of other flow components is described below.

Contaminant load for each flow component is a product of concentration and flow rate. Flow rates for each component were estimated as described above. Water quality of the TMF seepage was derived from two seepage samples collected from the TMF dams in 2014 and 2015. Environmental WRSF drainage water quality was derived based on four seepage samples (three in summer, one in winter), from which a weighted mean value was calculated to address seasonal variation. Near surface water quality was derived based on median results for Aitik water quality monitoring location 522, which is located on Myllyjoki Creek. Water quality for water monitoring location 558 were derived based on a mean of monthly samples collected at the site. Water quality source terms are summarized in Table 2.

The source terms (key terms defined in Table 2) were modelled using the computer program REACT, which is part of Geochemists Workbench (GWb) suite (Bethke, 2005; 2008). The modelling program essentially determined PAF WRSF water quality by utilizing the difference in measured contaminant load at water monitoring location 558 and the loads from other flow components reporting to water monitoring location monitoring 558. The remaining load (mg/s) was allocated to the flow rate (40 L/s) through the PAF WRSFs to derive a concentration (mg/L). The derived concentration for PAF WRSF seepage was then modelled using GWb to determine final estimated water quality and solubility constraints. Based on this assessment, the dominant source of acidity and contaminants at water monitoring location 558 was PAF WRSF drainage, which contributes ~2,000 tonnes per year, while the TMF contributes ~390 tonnes per year. The source term derived for PAF WRSF drainage was used as the initial pore water quality in forward reaction path modelling.

Table 2 *Key water quality inputs for flow components.*

Flow Component	PAF WRSF	Environmental WRSF	TMF	Near surface	Monitoring location 558
pH	3.5	6.9	4.9	6.8	4.1
Acidity (mg/L)	1,490	0.2	79	2.5	280
Cu (mg/L)	69	0.007	2.7	0.002	13
Al (mg/L)	222	0.01	12	0.02	43
Flow rate (L/s)	40	10	160	20	230

Closure Cover System Design:

An engineered cover system will be implemented on the PAF WRSF as part of the mine closure process with the primary objective of improving the long term quality of seepage waters and surface water from the reclaimed WRSFs by substantially reducing ingress of oxygen and meteoric waters into the facility. The PAF WRSF cover system design is based on field studies and numerical modelling processes as described by McKeown et al. (2015) and includes a 0.3 m highly compacted till layer with an overlying 1.5 m of moderately compacted till and 0.3 m till and organic mix layer acting as a growth medium.

One dimensional soil-plant-atmosphere modelling was completed to simulate performance of the cover system over the long term and under selected sensitivity scenarios. Inputs to the modelling program included material properties obtained from field investigations, data obtained from cover system monitoring at site, and RCP4.5 climate change scenario generated by the Swedish Meteorological and Hydrological Institute.

The key indicator of performance for the simulation was total oxygen ingress by diffusion, which previous performance monitoring had indicated was the dominant transport mechanism for the PAF WRSFs. Results indicated that the cover system reduced oxygen ingress by diffusion from >2,000 $g/m^2/yr$ (bare waste rock) to an average of 32 $g/m^2/yr$. Net percolation rates decreased from between 55 – 60% of annual precipitation (bare waste rock) to between 27 – 32% of annual precipitation in the long term after cover system installation (noting that annual precipitation increases from ~600 mm/yr currently to 820 mm/yr by 2100 under the RCP4.5 climate change scenario).

In the long term, acidity and metal loading from the PAF WRSFs will be a function of oxygen ingress associated with oxygen diffusion through the cover system, and dissolved oxygen in net percolation. Numerical modelling determined that oxidation occurs predominantly in the upper 5 m of the PAF WRSF surface, indicating that the remaining WRSF profile remains in an anoxic condition. For GWb modelling, it was assumed that all oxygen is consumed by pyrite oxidation within this zone. Long term closure annual acidity loading was derived based on area of the PAF WRSFs at closure (540 ha), the amount of oxygen ingress over this area, and the assumption that all this oxygen reacted with pyrite to produce 4 moles of H^+ ion per mole of pyrite oxidized. In current (bare) WRSF, the entire depth was assumed to be potentially oxidizing as oxygen moves freely within it as a result of advection and diffusion. Calculations for the WRSF after cover system construction (5 m oxidizing; 75 m anoxic) indicate that the system was non-acid forming from a conventional acid-base accounting perspective.

Basal Seepage Analysis

PAF WRSF draindown is important for forecasting long term water quality after closure as it controls the rate at which current water quality is replaced by a lower-acidity water type created by minimizing oxygen ingress to the WRSF. To determine draindown, one-dimensional seepage modelling was completed to simulate current conditions and long-term basal seepage from the WRSFs using SEEP/W, a software package designed to analyze groundwater seepage and pore-water pressure dissipation within porous materials. The seepage analysis was completed using a transient analysis of several 1D representative columns for both plateau and sloped areas of the WRSFs.

Results for current (bare waste rock) conditions indicate that the WRSFs are 'wetted up', there is no capacity for additional water storage within the WRSF profile. The response of the system is buffered due to the height of the WRSFs and the time required to percolate to the WRSF base, but water infiltrating into the top of the WRSF displaces seepage from the base of the facility. In the long term, construction of the cover system will reduce net percolation and ultimately basal seepage compared to the bare waste rock condition, but the magnitude of basal seepage volumes did not decrease dramatically, because long term annual precipitation is predicted to increase by 15 to 20% in the RCP4.5 climate change scenario.

Derivation of PAF Long Term Water Quality after Closure

Evolution of WRSF drainage water quality (prior to mixing with other flow components in the collection channel) was considered as three water quality phases, including current water quality, transition water quality, and long term water quality. Geochemical modelling performed with REACT estimated long term water quality and thus the risks associated with water quality after closure and after the installation of the cover system. Model inputs for forward path geochemical modelling were initial pore-water quality, mineralogy (based on field and laboratory data, company records), influent rainfall water quality, oxygen flux, and net percolation rates. Oxygen flux and percolation rates were determined by cover system modelling. Peer reviewed estimates were obtained for kinetic rate constants for dissolution of key initial waste rock components (pyrite, calcite, jarosite, anorthite) and precipitation of plausible secondary phases that might form from long term weathering. A numerical model was established to predict water quality during the transition period between current and long term water quality.

Modelling Approach

Current water quality is represented by the water-type derived from the inverse geochemical modelling process (*e.g.,* PAF source term derived above). Duration of the current water quality phase was a function of the draindown phase, which was estimated to be 20 years based on seepage modelling. That is, it will take an estimated 20 years for the current pore-water near the top of the WRSF to percolate to the base and be replaced by the new lower acidity water-type. It was assumed that the acidity load reporting to the base of the WRSF is derived from the available stored soluble melanterite-type acidity load that is present within the WRSF, as oxygen is excluded due to the presence of the cover system.

Long term water quality was a function of sulfide oxidation (pyrite), jarosite dissolution, and neutralization of this acidity by minor calcite and abundant anorthite. Water quality was determined by GWb. It was assumed that long term water quality could not develop until all available reactive soluble melanterite-type acidity present in the WRSF was flushed out by net percolation.

It was assumed that not all the soluble melanterite-type acidity would be flushed from the WRSF during the transition period; one third of acidity (and contaminants) would remain in stagnant areas of the WRSF, being generally immobile (as noted by Eriksson and Destouni, 1997). Thus two thirds of the soluble melanterite-type acidity reports to the base of WRSF prior to transition to long term water quality. Sparingly soluble jarosite-type acidity was not considered in the numerical modelling of the transition phase as it was confirmed (in GWb geochemical modelling of the longer term water quality) that the calcite and anorthite present would also neutralize acidity from this source.

Evaluation of Risk

In the context of this project, risk represents an engineering tool for developing informed closure planning decisions. Risk can be controlled and managed through application of appropriate measures, and can be minimized by taking necessary precautions. These aspects were developed through a top-down, expert-based risk process that assigned a set of probabilities for site specific conditions; namely, the Failure Modes and Effects Analysis, or process (FMEA).

A FMEA was completed to evaluate the closure design for Aitik site (Boliden, 2015), providing a comprehensive review of the closure strategy for the Aitik site. Each failure mode was evaluated based on the potential water quality risk for adverse impacts to aquatic receptors downstream of the mine site where water quality is evaluated primarily in terms of spatial extent, magnitude, and frequency. The majority of failure modes and effects ranked a 'low' risk score, meaning that the long-term risk of occurrence and severity of effects is within the broadly acceptable range. Failure modes and effects ranking a risk score of 'moderate' or higher highlighted the requirement for carefully considered risk controls. Additional studies been identified for completion to supplement available data and compare against the conceptual model for performance. In identifying mitigation measures, it was noted that regular maintenance in the initial stages of closure and monitoring are vital for managing risk at the site.

Conclusions

The WRSF evaluation involved desktop review and interrogation of previous studies completed at Aitik, a field based geochemical assessment, and development of conceptual and numerically-driven models to characterize the hydrological components in regards to flow and quality. It was concluded that post-closure water quality from the PAF WRSF area will improve over time as the closure cover system begins to limit oxygen within the WRSF profile. Oxidation reactions will continue to occur, but at a much lower rate due to decreased oxygen availability following closure cover system construction (Fig 2). As stored acidity is flushed out and neutralization reactions occur within the WRSF profile, pH will increase and acidity loads will decrease with time. In approximately 50 years, circum-neutral pH drainage and associated low dissolved metals are predicted to emerge from the PAF WRSF.

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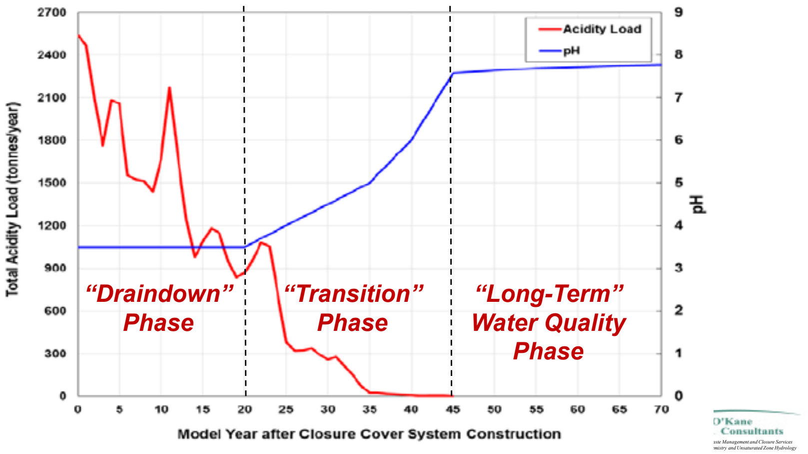

Figure 2 *Long term water quality model*

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