Forecasting Long-Term Water Quality After Closure: Boliden Aitik Cu mine

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2018 Northern Latitudes Mining Reclamation Workshop
Whitehorse and Carcross, Yukon
September 11th, 2018
The main objectives of the WRSF program were to understand the long-term water quality of WRSF seepage for the purpose of determining environmental risk at closure.

- Develop a flow model for the WRSF area
- Determine PAF (potentially acid forming) WRSF basal seepage component – current water quality and flow rate
- Characterize the geochemistry of the PAF WRSF
- Derive other inputs for understanding long-term water quality
- Determine net percolation and oxygen flux into WRSFs
- Develop a long-term water quality model for the WRSFs
Köppen–Geiger climate classification system

Aitik Mine Site, Gällivare
Site Description

WRSF Current Conditions

Waste Rock Footprint

Potentially Acid Forming (PAF) WRSF footprint
~ 390 ha

Non-Acid Forming (Environmental) WRSF footprint ~ 280 ha
Site Topography – Pre-mining
Site Topography – Pre-mining

Future pit outline

Bog outline

Fen outline
Pre-mine contours were used to analyze surface topography and infer flow direction.
Site Topography – Pre-mining

Pre-mining contours were used to analyze surface topography and infer flow directions.

Catchments were delineated based on expected flow directions.

Catchment outlines
Water Quality Monitoring Location

- Majority of surface and shallow groundwater flow reports to T2-T4 collection channel which is monitored at location 558.
- Flow rate measurements and water quality data are available.
Infiltration and percolation through PAF WRSFs (T2, T3, T4) produces poor water quality.

Percolation through Environmental WRSFs (T1, T7) produces acceptable water quality.

TMF contributes a substantial flow volume.

Near surface natural ground flow contributes clean water.
Water Model Characteristics

- Estimation of WRSF basal seepage flow rates based on net percolation
  ~ 330 mm/yr
  (~55% of average annual precipitation) calculated based on bare waste rock conditions
- WRSF flow rates based on annual net percolation x footprint area

- PAF WRSFs ~38 L/s
  - Flow occurs as basal seepage that reports to the surficial aquifer in underlying moraine layer
  - Need to determine this Water Quality

- Env. WRSFs ~10 L/s
  - Flow occurs as basal seepage that reports to the surficial aquifer in underlying moraine layer
  - Water quality based on weighted mean from T6, representative of T1 and T7
    - pH ~ 6.9
    - Acidity ~0.2 mg/L
    - Cu ~ 0.007 mg/L
    - Al ~ 0.01 mg/L
TMF Flow and Water Quality

- TMF contributes substantial flow to collection channel.

- Estimated contribution ranges from 43 to 90% of flow in T2-T4 channel from previous research studies at site.

- ~157 L/s (70% of flow in T2-T4 channel) based on Dupuit analysis of anticipated phreatic surface in TMF and head gradient of flow path through PAF WRSF.

- **Water quality** from samples (mean of two representative data sources):
  - pH ~ 4.9
  - Acidity ~ 79 mg/L
  - Cu ~ 2.7 mg/L
  - Al ~ 12 mg/L
FIELD BASED INVESTIGATIONS
## Estimated PAF WRSF Mineralogy

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Key mineralogy used for PAF WRSF modelling (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anorthite</td>
<td>6.0</td>
</tr>
<tr>
<td>Calcite</td>
<td>0.43</td>
</tr>
<tr>
<td>Pyrite</td>
<td>0.65</td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td>0.12</td>
</tr>
<tr>
<td>Jarosite</td>
<td>0.41</td>
</tr>
<tr>
<td>Melanterite</td>
<td>0.02</td>
</tr>
</tbody>
</table>

- **Long term silicate neutralization source.** Key mineral for neutralizing acidity in the long term from pyrite oxidation and jarosite dissolution.
- **Rapid carbonate neutralization source.**
- **Potential acidity/metals, managed by limiting oxygen flux.**
- **Stored sparingly soluble acidity, kinetically controlled dissolution.**
- **Stored soluble acidity, reports as a function of net percolation.**
Derivation of Current PAF WRSF Source Term

GEOCHEMICAL MODELLING
Determination of PAF WRSF WQ

Environmental WRSF
- Flow Rate ~ 10 L/s
  - pH 6.9
  - Acidity 0.2 mg/L
  - Cu 0.007 mg/L
  - Al 0.01 mg/L

TMF Flow
- Flow Rate ~ 157 L/s
  - pH 4.9
  - Acidity 79 mg/L
  - Cu 2.7 mg/L
  - Al 12 mg/L

Near Surface Water
- Flow Rate ~ 22 L/s
  - pH 6.8
  - Acidity 2.5 mg/L
  - Cu 0.002 mg/L
  - Al 0.02 mg/L

PAF WRSF Flow
- Flow Rate ~ 38 L/s
  - Water quality to be determined

T2-T4 Channel (Norra Dikka)

Monitoring Point 558
- Measured flow rate ~ 225 L/s (Base flow)
  - pH 4.14
  - Acidity 280 mg/L
  - Cu 13.3 mg/L
  - Al 43 mg/L

Current PAF WRSF WQ requires determination to help understand long-term water quality evolution.
**Determination of PAF WRSF WQ**

- **Environmental WRSF**
  - Flow Rate ~ 10 L/s
  - pH 6.9
  - Acidity 0.2 mg/L
  - Cu 0.007 mg/L
  - Al 0.01 mg/L

- **TMF Flow**
  - Flow Rate ~ 157 L/s
  - pH 4.9
  - Acidity 79 mg/L
  - Cu 2.7 mg/L
  - Al 12 mg/L

- **Near Surface Water**
  - Flow Rate ~ 22 L/s
  - pH 6.8
  - Acidity 2.5 mg/L
  - Cu 0.002 mg/L
  - Al 0.02 mg/L

- **PAF WRSF Flow**
  - Flow Rate ~ 38 L/S
  - pH 3.5
  - Acidity 1,490 mg/L
  - Cu 69 mg/L
  - Al 222 mg/L

- **T2-T4 Channel (Norra Dikka)**

- **Water Monitoring Location 558**
  - Measured flow rate ~ 225 L/s
  - pH 4.14
  - Acidity 280 mg/L
  - Cu 13.3 mg/L
  - Al 43 mg/L

- **Geochemical Modelling w/ Geochemists Workbench**
## Summary of Key Parameters

<table>
<thead>
<tr>
<th>Component</th>
<th>Concentration (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>3.5</td>
</tr>
<tr>
<td>Acidity (as CaCO$_3$)</td>
<td>1,490</td>
</tr>
<tr>
<td>HCO$_3^-$</td>
<td>1.2</td>
</tr>
<tr>
<td>NH$_4^+$</td>
<td>0.37</td>
</tr>
<tr>
<td>NO$_3^-$</td>
<td>19.3</td>
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<tr>
<td>NO$_2^-$</td>
<td>0.01</td>
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<tr>
<td>Cu$^{2+}$</td>
<td>69</td>
</tr>
<tr>
<td>Zn$^{2+}$</td>
<td>9.5</td>
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<tr>
<td>Ni$^{2+}$</td>
<td>0.79</td>
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<tr>
<td>Na$^+$</td>
<td>91</td>
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<tr>
<td>K$^+$</td>
<td>59</td>
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<tr>
<td>Ca$^{2+}$</td>
<td>729</td>
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<tr>
<td>Mg$^{2+}$</td>
<td>192</td>
</tr>
<tr>
<td>Sr$^{2+}$</td>
<td>3.3</td>
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<tr>
<td>Al$^{3+}$</td>
<td>222</td>
</tr>
<tr>
<td>Fe$^{3+}$</td>
<td>14</td>
</tr>
<tr>
<td>Mn$^{2+}$</td>
<td>40</td>
</tr>
<tr>
<td>SO$_4^{2-}$</td>
<td>3,830</td>
</tr>
</tbody>
</table>

1,490 mg/L Acidity x 37.5 L/s ~ 56,000 mg/s or ~1,760 tonnes acidity/year

PAF WRSF contributes dominant source of acidity to water monitoring location 558 (being ~2,000 tonnes/year).

Reducing the load from the PAF WRSF will significantly reduce overall catchment load.
EVALUATION OF POST CLOSURE WATER QUALITY
The WRSF cover system design objective is to integrate at source control of oxygen and water with the other elements of the closure plan such that the system as a whole meets recipient water quality criteria. This is achieved through:

- Primarily a focus on managing oxygen ingress to very low levels to limit development of further stored acidity,
- Understanding net percolation rates to inform on transport of stored acidity,
- Utilizing site-specific climate conditions, and
- Incorporating locally available borrow materials.
Field investigation programs continued the previous cover design philosophy and focused on improving key areas.

- Addition of highly compacted till layer enhanced its water retention characteristics and increased degree of saturation within the cover system leading to improved oxygen ingress management.

- **Compaction trials determined achievable field $k_{sat}$ and density using locally available materials.**

- **Results of compaction trial study used to determine optimal compaction methodology.**

- **Improved cover system alternatives built into cover system field trials to monitor in situ cover system performance over time.**
- Predicted oxygen ingress by diffusion and dissolved oxygen in percolation reduced to a very low value
- Degree of saturation >85% is maintained during the simulation period in HCT layer
- Oxygen moving through the cover system was consumed in the upper 5 m of PAF profile
Evaluation of Long-Term Water Quality

- **“Draindown” Phase**
  - Seepage water quality influenced by:
    - Current pore-water quality;
    - Draindown time frame of WRSF

- **“Transition” Phase**
  - Seepage water quality influenced by transition from:
    - Current pore-water quality;
    - Draindown time frame of WRSF;
    - Net percolation rate from cover system;
    - Eventually resulting in “new water” reporting as basal seepage

- **“Long-Term” Water Quality Phase**
  - Seepage water quality influenced by:
    - Long-term oxygen ingress rate from cover system (low oxidation rates);
    - Long-term net percolation rate from cover system (dissolution of alkalinity and sparingly soluble acidity)
Evaluation of Long-Term Water Quality

“Draindown” Phase
- Circum-neutral seepage water quality
- Remaining soluble and sparingly soluble acidity removed
- Dissolution of alumina-silicate minerals

“Transition” Phase
- ~2/3 of soluble acidity removed

“Long-Term” Water Quality Phase

Base Case
Acknowledgements

This study and presentation was part of the Aitik mine closure planning study driven by New Boliden AB. Acknowledgments to:

- Seth Mueller / Nils Eriksson
- Ted Eary
- Alan Martin / Colin Fraser
Thank You!

O'Kane Consultants Inc.
Habitat for Humanity Initiative – El Salvador