Modelling of Pit Lake Filling Scenarios using a Coupled Physical and Biogeochemical Model

Donald Dunbar
Alan J. Martin
Colin Fraser
Seth Mueller

1Lorax Environmental Services Ltd., Vancouver, Canada
2Boliden Mineral AB, Boliden, Sweden
Introduction

- Pit lakes are a common, and important post-closure feature at mine sites.
- Fill rates vary widely
- Pit lakes are a central component of closure planning
- Focus on pit lakes:
  - Characterization
  - Management
  - Remediation
- Models can assist in evaluating and selecting a fill strategy
- Examples
Pit lakes generally have a much greater depth relative to surface area
- $Z_r > 20\%$ vs. $< 2\%$

Vertical mixing is restricted due to:
- Large relative depth (small fetch)
- Topographic sheltering from pit walls
- Seasonal and/or permanent stratification due to high TDS/density in the hypolimnion. Sources of TDS include:
  - Pit wall runoff
  - Waste rock drainage
  - Treatment flows, backfill, ARD, etc.

Pit lakes can have extensive zones of suboxia and anoxia
- Caused by bacteria-mediated oxidation of organic detritus
- Leads to nitrate & sulfate reduction, increased alkalinity, and metal sulfide precipitation; hence, lower acidity and trace metals

Relative Depth ($\%$)

$$= 50 \cdot Z_{\text{max}} \sqrt{\frac{\pi}{A_{\text{surf}}}}$$
Pit Lake Filling Strategies

- Pit lake water balance often complex
  - May lead to multiple fill strategies

- Passive Filling
  - Little or no outside intervention

- Engineered Filling: may lead to improved quality of discharge
  - Staged Filling
    - Preferential input of high TDS water + diversion of clean water for an initial period
    - Followed by capping with low TDS water
    - Maximize potential for meromixis and anoxia $\rightarrow$ alkalinity + metal sulfide precipitation
  
  - Deep Water Injection of ARD
    - Discharge poor quality water near the lake bottom
    - Maximize potential for meromixis and anoxia $\rightarrow$ alkalinity + metal sulfide precipitation
    - Acid neutralization

- Slow Filling
  - Preferential exclusion of clean water during an initial period (e.g., surface runoff, treated effluents)
  - Extend fill time to allow for improvement in water quality of one or more surface inflows
Deep Water ARD Injection: ICM pit lake

Objective: create a meromictic lake by injecting high TDS ARD near the bottom to promote anoxia, acid neutralization via increased alkalinity, and metal sulfide precipitation in the hypolimnion.

1996 – The pit was flooded with seawater from Rupert Inlet.
Model Overview - PitMod

1-dimensional physical & bio-geochemical model developed for application to the ICM in 1992

Key Components:

- Mass Balance
- Heat Balance
- Biogeochemical Processes
  - PHREEQC
    - Speciation
    - Mineral saturation
    - Adsorption
    - Redox reactions
  - Oxygen consumption
  - Biological scavenging
- Faster execution and less inputs
Each inflow / outflow has associated values for (T,S) that determine its density and heat content.
PitMod: Heat Budget

Heat Budget

- Solar short- and long-wave radiation
- Surface (Black Body) long-wave radiation
- Atmospheric & reflected long-wave radiation
- Latent Heat of Evaporation
- Sensible (Conductive) Heat
- Meteorological Inputs
  - Short-wave radiation
  - Long-wave radiation / cloud cover
  - Vapour pressure of air
  - Wind speed at 10 m
  - Air temperature
  - Precipitation (evaporation)

Plus addition / loss of heat from terms in the Mass Budget

Ta<Tw
Ta>Tw

Ta
Tw

affected by albedo & water clarity

affected by wind and P

affected by

Plus addition / loss of heat from terms in the Mass Budget
Equity Mine – Main Zone Pit Lake
- 14 month simulation
- Surface sludge discharge
- [Zn] at 1, 5, and 100 m depth
PitMod Verification
Case Study #1 – Aitik Mine Sweden
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- 67° N (sub-arctic climate, $T_{avg} = -1^\circ C$)

- Pit lake:
  - 279 ha
  - 525 m deep
  - 579 M m$^3$
  - $Z_r = 28\%$

- Main inputs:
  - TSF runoff/seepage
  - Waste rock runoff/seepage
  - Natural runoff
  - Pit wall runoff
  - Direct precipitation to pit lake surface.

- Fill scenarios modelled:
  - Passive Fill
  - Slow fill – delayed pit lake overflow to realize water quality improvement of waste rock seepage
Improvements in WR seepage quality are predicted in response to a low-permeability till cover.

- Decreased $O_2$ ingress
- Eliminates pyrite oxidation

Predicted to occur between years 30 and 60 post-closure.

Strategy: delay pit filling to realize seepage quality improvements.

Delay filling via:
- diversion of clean runoff away from the pit
- discharge of treated effluents directly to receiver.
Aitik Pit – Model Results: Salinity (TDS)

- Fill time
  - Passive fill – 55 years
  - Slow fill – 130 years (reduce inflow volume by 40%)

- Meromixis
  - Occurs in both scenarios within bottom 1% of volume
  - Due to higher salinity inflows in early years

- Slow fill exhibits enhanced surface stratification: upper 50% of lake volume for SF vs. 15% for PF.
Aitik Pit – Model Results: Dissolved Oxygen

- O₂ loss due to continuous export at a rate suitable for an oligotrophic lake.
- Anoxic below the surface mixed layer:
  - Increased concentrations of redox reaction products: Fe, Mn, Alkalinity, Ammonia, and H₂S
  - Sulfate & Nitrate reduction
  - Metal sulfide precipitation
Aitik Pit – PitMod Results: Cu and Zn in Surface Waters

- Slow Fill Scenario - markedly improved water quality at time of pit lake overflow
- Relates to improvements in WQ associated with unrecoverable waste rock seepages.
Case Study #2 – “Mine B” Canada

- Anonymous mine in the interior of eastern Canada
- **Climate:**
  - Cold-interior continental climate
  - Mean annual temperature: 3°C
  - Mean annual precipitation: ~700 mm.
- **Pit Lake:**
  - 425 m depth
  - 208 ha
  - 253 M m³
  - $Z_r = 26\%$
- **Main inputs:**
  - Waste rock seepage/runoff
  - Natural runoff
  - Pit wall runoff
  - Direct precipitation to pit lake surface.
Case Study #2 – “Mine B” Canada

Filling scenarios modelled:

- Passive Fill
  - passive input of all inflows

- Staged Fill
  - Preferential filling of the pit with PAG waste rock seepages for the first 10 years, while other sources of clean water are diverted away from the pit.
  - After 10 years, clean surface flows within the pit catchment are allowed to flow passively to the pit surface, while PAG seepages continue to be routed to the pit bottom.

- Objectives:
  - Maximize potential for permanent stratification, isolating poor quality water at the bottom
  - Maximize potential for anoxic bottom waters that will promote in situ bioremediation (sulfate reduction, metal sulfide precipitation, and alkalinity production)
Staged fill:

- Strongly stratified water column
- PAG inflows: constrained to bottom layer
- Continued input of PAG seepage to pit bottom displaces water above
- With constant WB the introduction of PAG seepage water into the surface layer does not occur for at least 1200 years.
- Delay allows for mitigation of acidity and metal levels in pit bottom waters.
Mine B – Model Results: Copper

Spatial and temporal distributions of trace elements show strong parallels to salinity.

Dissolved [Cu] ppb
Mine B – Model Results: Dissolved O₂

- Strongly stratified water columns in both cases
- Passive fill: thicker surface mixed layer
- Staged fill: O₂ enrichment in bottom 1.5% caused by the input of oxygenated PAG seepage
Mine B – Model Results: Cu and Zn in Surface (<10 m)

- **COPPER**
  - Dissolved [Cu] μg/L
  - Model Year
  - Graph showing Passive Fill, Staged Fill, and Pit Overflow over model years.

- **ZINC**
  - Dissolved [Zn] μg/L
  - Model Year
  - Graph showing Passive Fill, Staged Fill, and Pit Overflow over model years.

- **Staged fill:**
  - PAG seepage to the pit bottom
  - Improved surface water quality

- **At initial discharge (Year 73):**
  - Significantly lower values for sulfate and trace metals
Conclusions

- Engineered pit lake filling strategies can lead to improved discharge water quality.
- Slow filling delays initial discharge and can take advantage of improving water quality of surface inflows.
- Staged filling can isolate poor quality drainages in the pit bottom thereby delaying their discharge from the lake and promoting bioremediation.
- Vertical stratification and mixing are key processes that must be assessed prior to selecting an optimal pit filling strategy.
- Pit lake modelling provides an effective tool for evaluating and selecting strategies for managing pit lake filling.
Thank You!

