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

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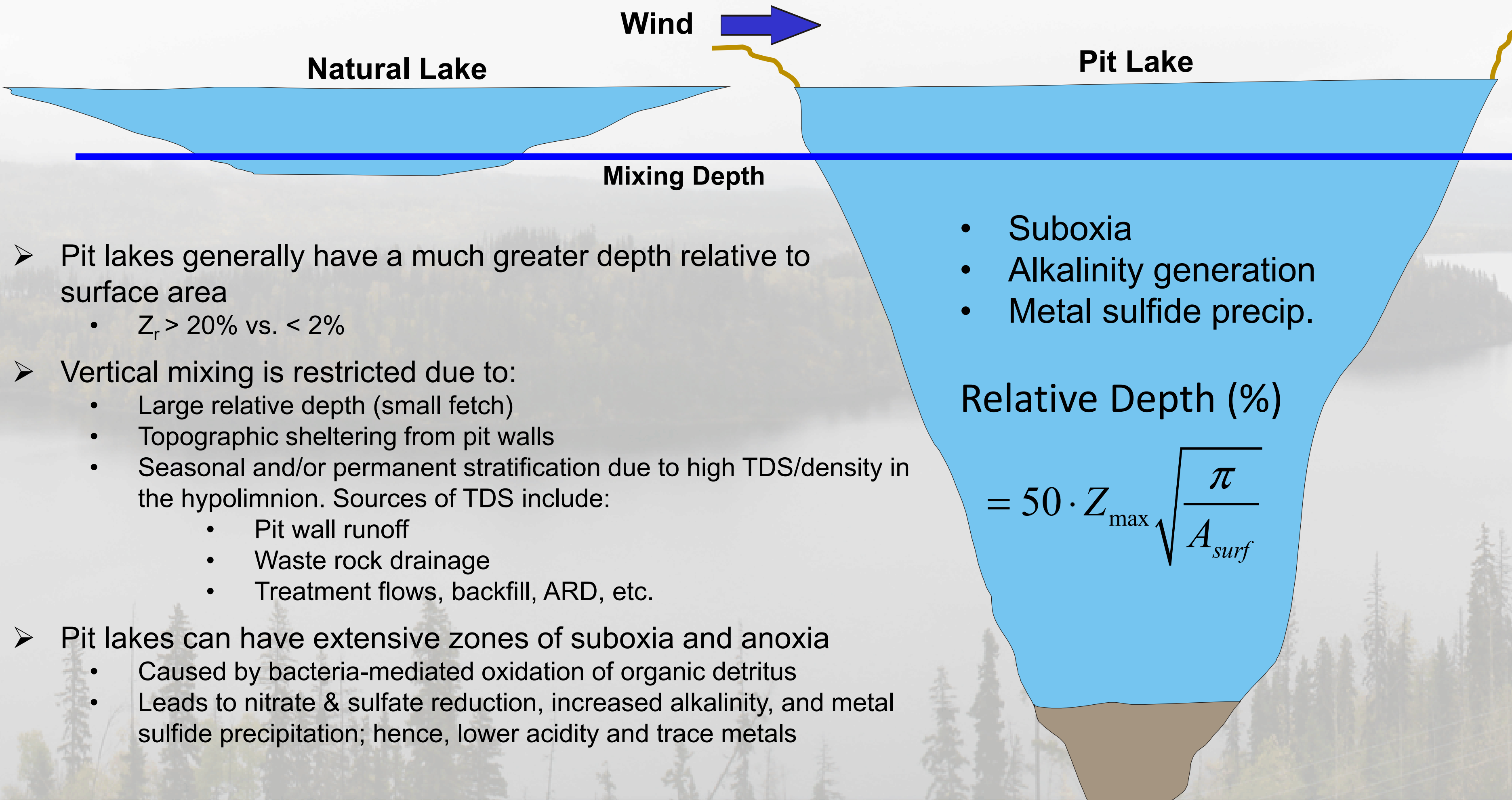
# Introduction

- 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 Lake Properties

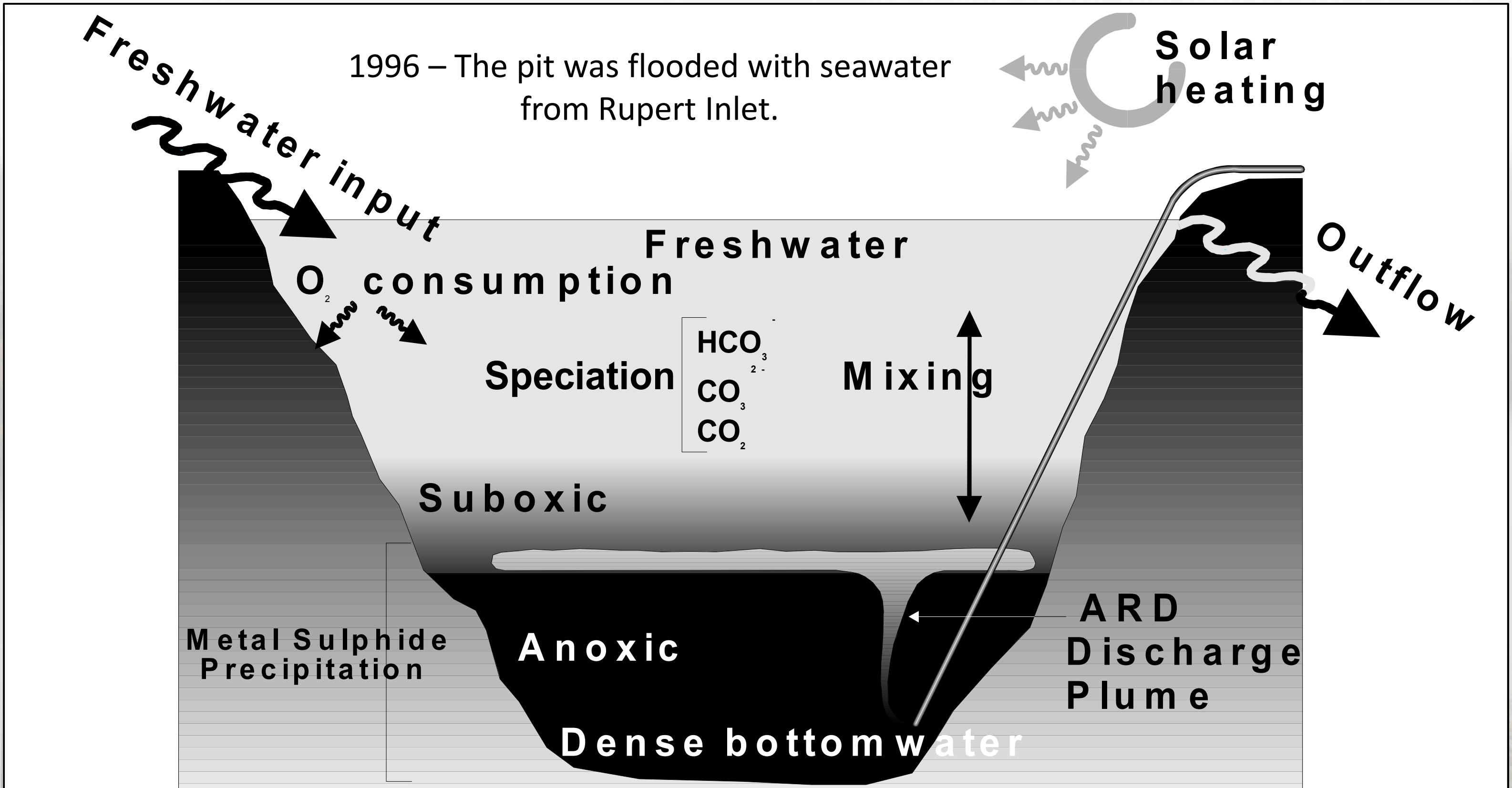



- Pit lakes generally have a much greater depth relative to surface area
  - $Z_r$ > 20% vs. < 2%
- Vertical mixing is restricted due to:
  - Large relative depth (small fetch)
  - Topographic sheltering from pit walls
  - Seasonal and/or permanent stratification due to high TDS/density in the hypolimnion. 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

# 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 ➡ alkalinity + metal sulfide precipitation
  - Deep Water Injection of ARD
    - Discharge poor quality water near the lake bottom
    - Maximize potential for meromixis and anoxia ➡ 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

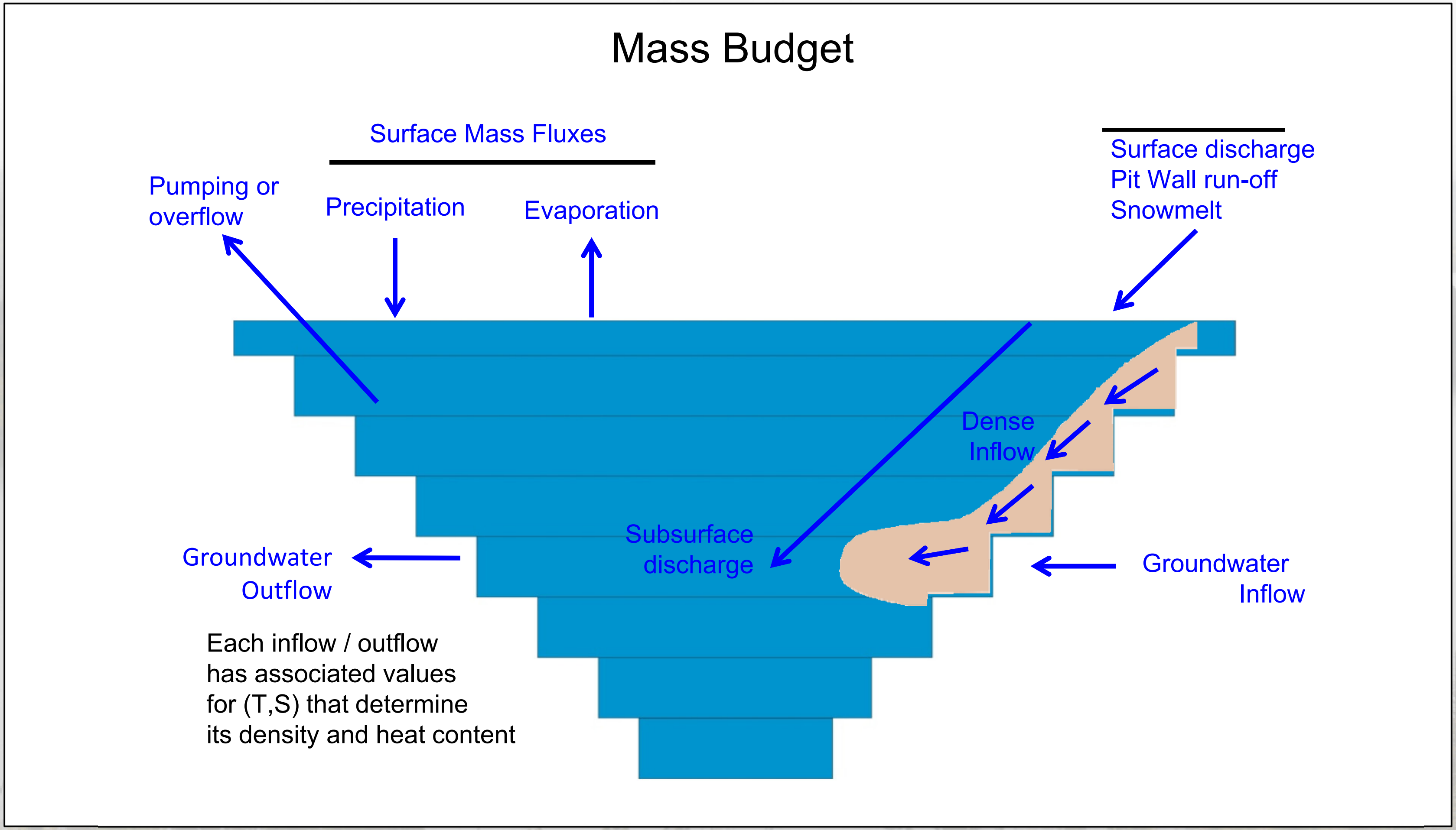
# Model Overview - PitMod

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

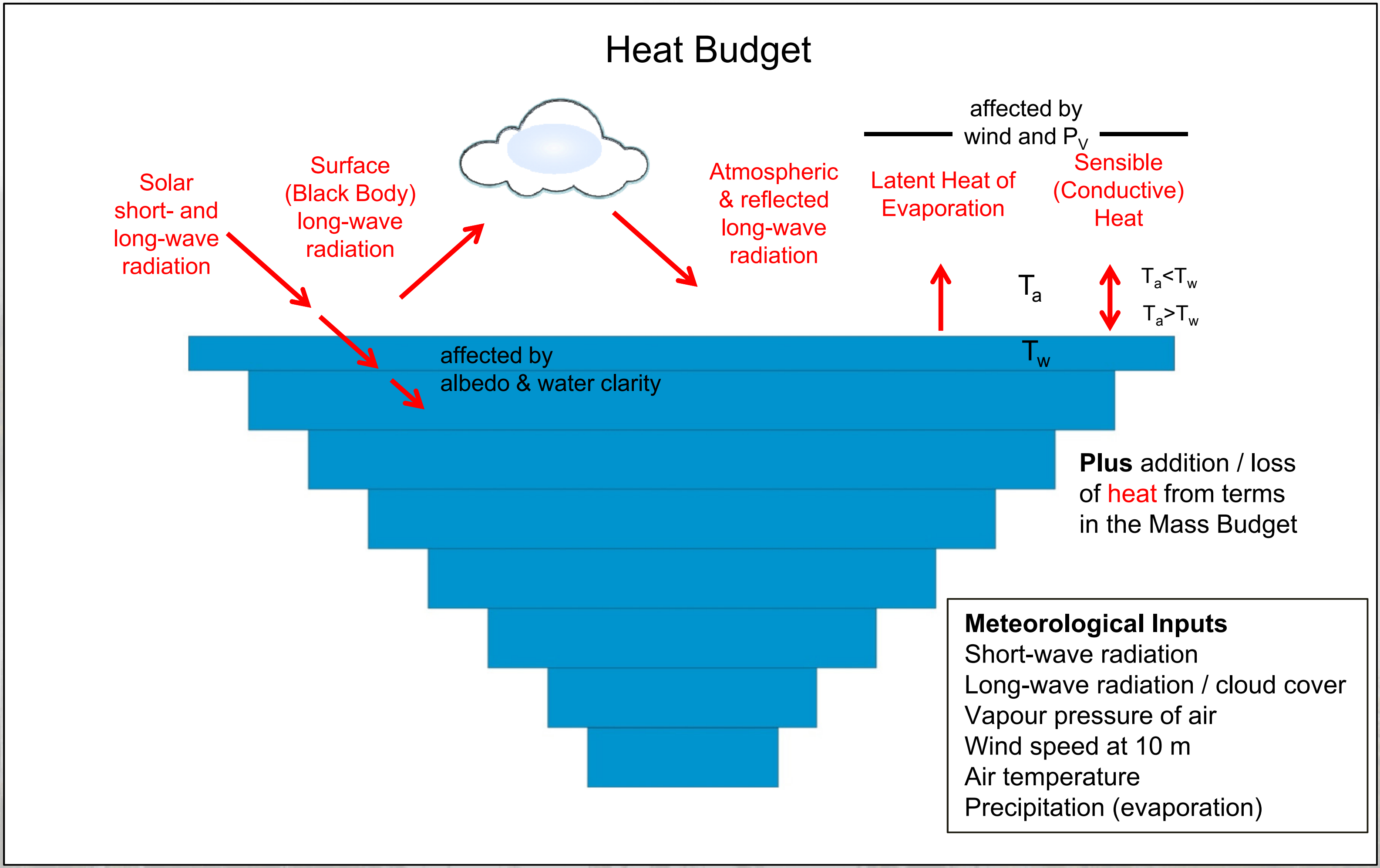
Key Components:

- Mass Balance
- Heat Balance
- Biogeochemical Processes
  - PHREEQC
    - Speciation
    - Mineral saturation
    - Adsorption
    - Redox reactions
  - Oxygen consumption
  - Biological scavenging
- Faster execution and less inputs

# PitMod – Mass Budget

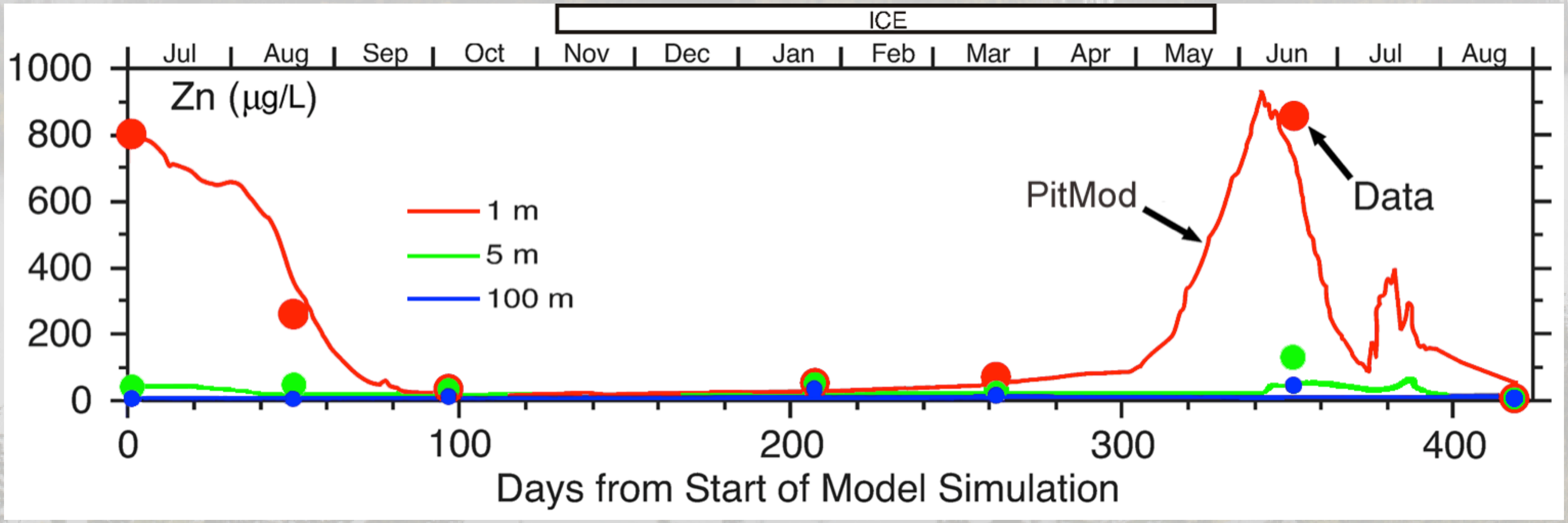


# PitMod: Heat Budget



# PitMod Verification

Equity Mine – Main Zone Pit Lake
- 14 month simulation
- Surface sludge discharge
- [Zn] at 1, 5, and 100 m depth



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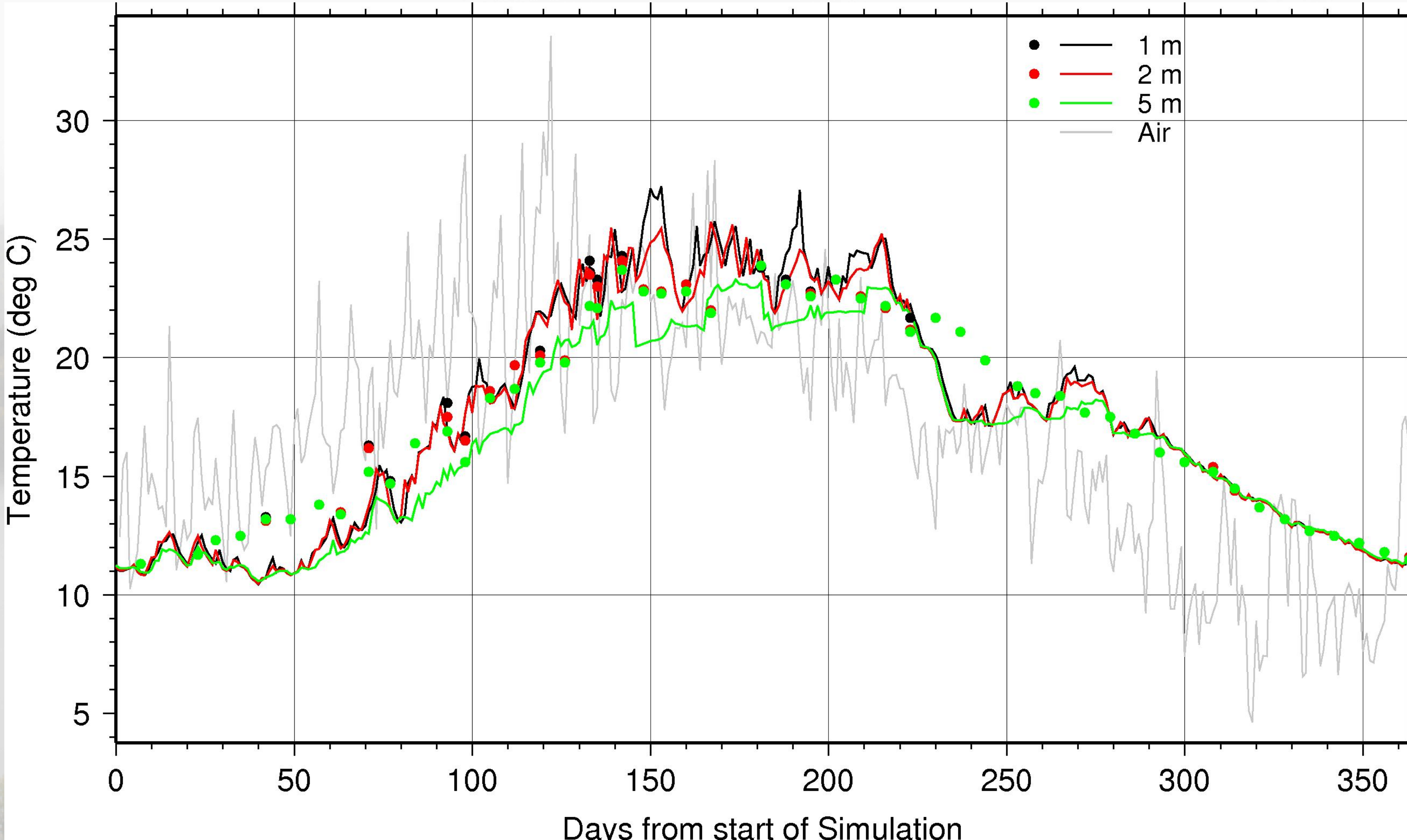

# Case Study #1 – Aitik Mine Sweden

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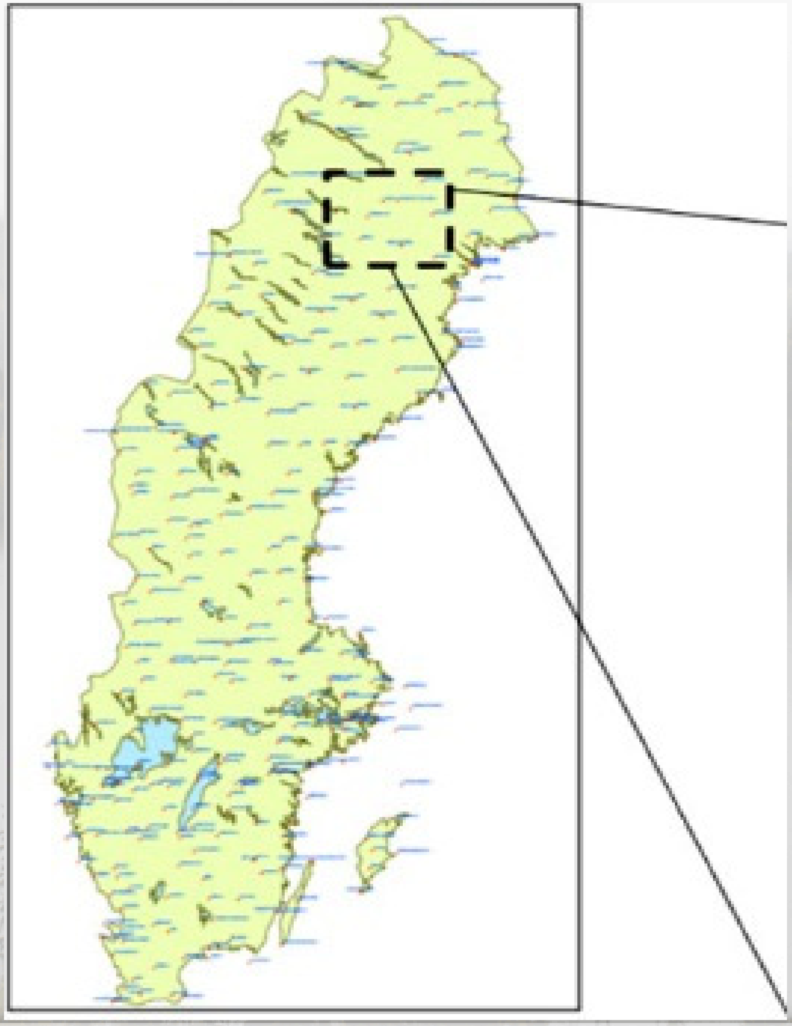
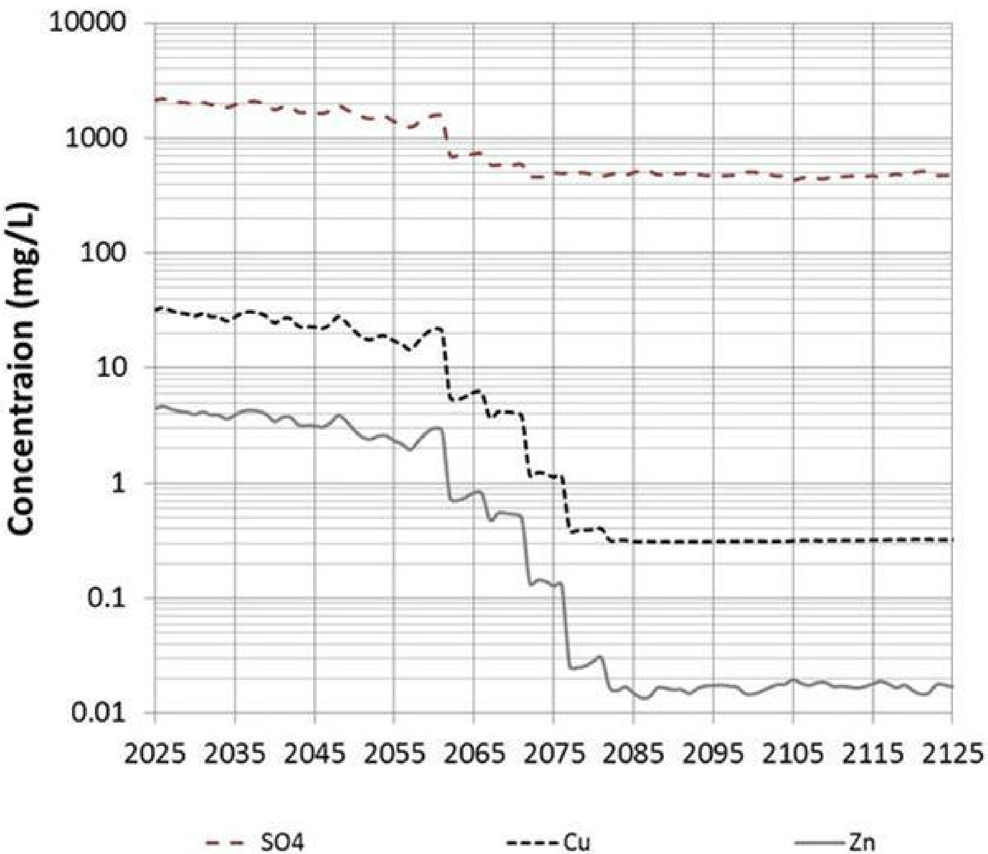


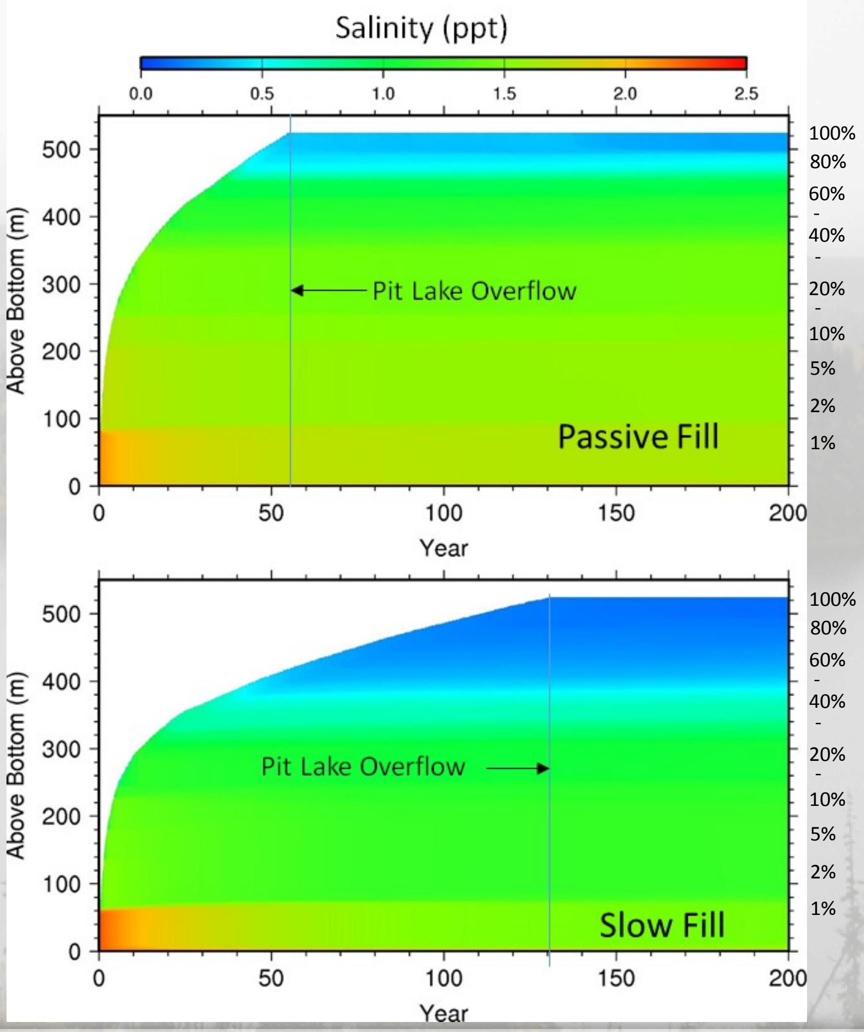
- 67° N (sub-arctic climate, $T_{avg}$ = -1°C)
- Pit lake:
  - 279 ha
  - 525 m deep
  - 579 M $m^3$
  - $Z_r$ = 28%
- Main inputs:
  - TSF runoff/seepage
  - Waste rock runoff/seepage
  - Natural runoff
  - Pit wall runoff
  - Direct precipitation to pit lake surface.
- Fill scenarios modelled:
  - Passive Fill
  - Slow fill – delayed pit lake overflow to realize water quality improvement of waste rock seepage

# Aitik Pit – Waste Rock Seepage Quality




- 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.

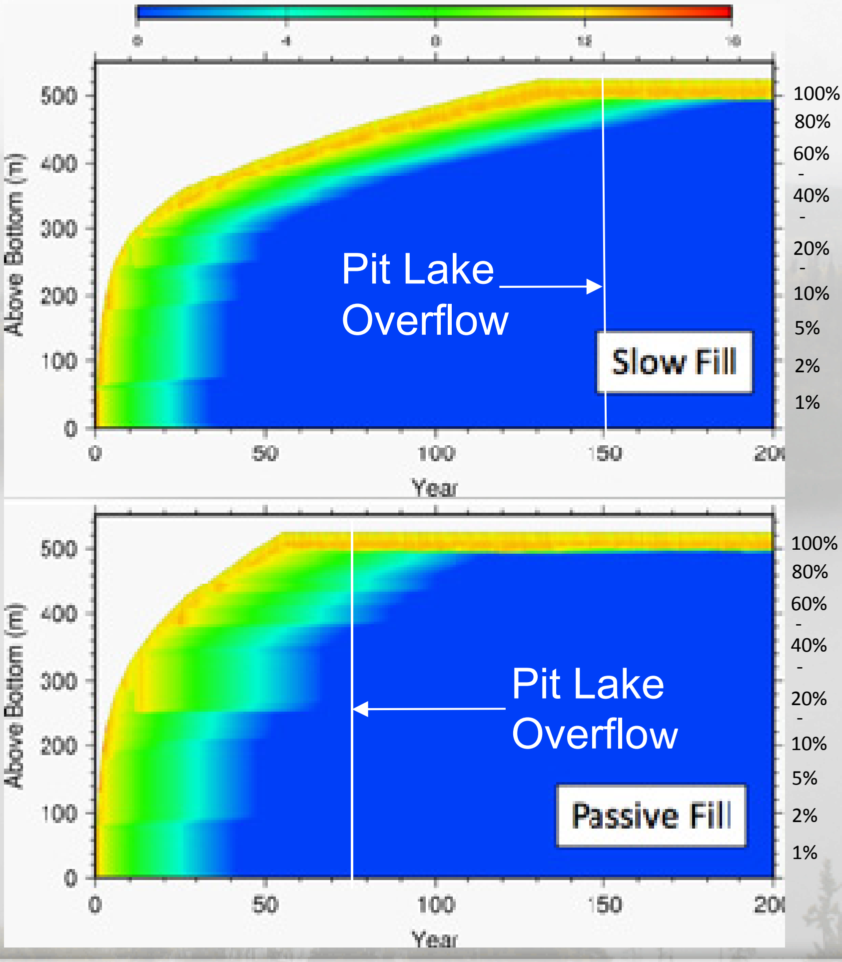
# Aitik Pit – Model Results: Salinity (TDS)




- 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.

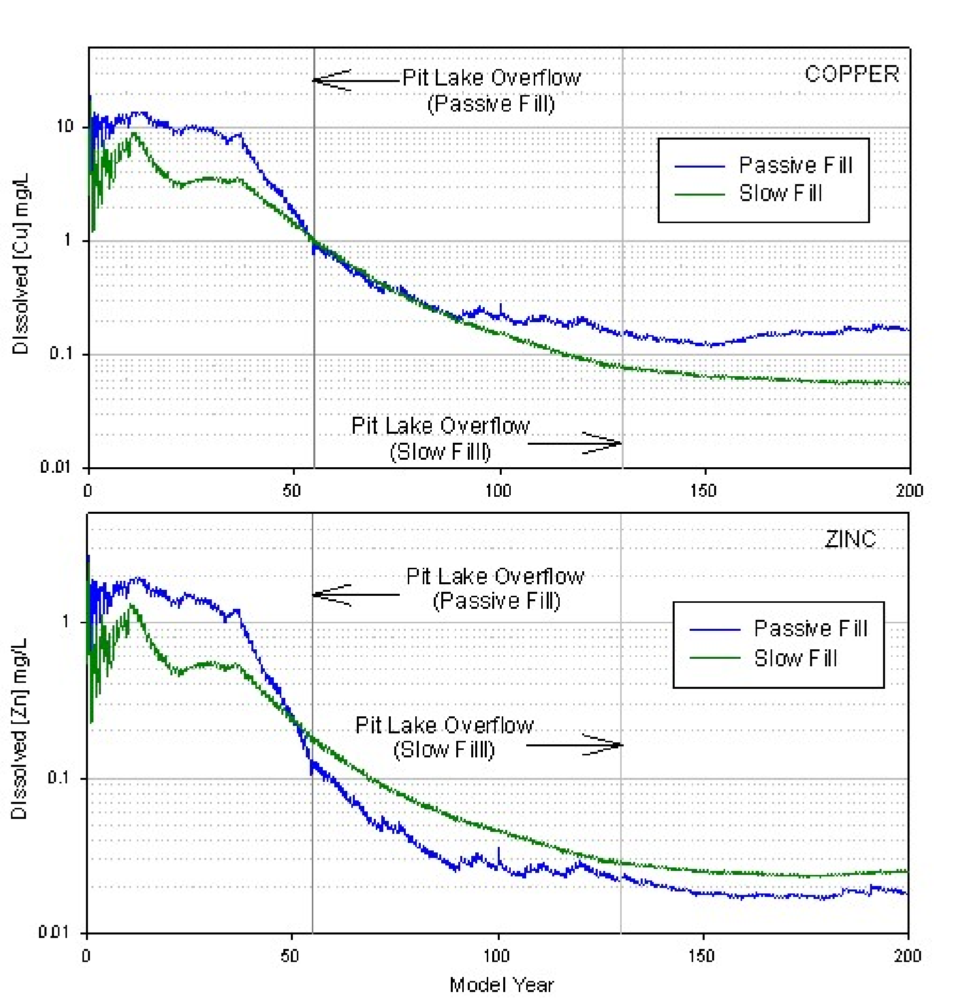
# Aitik Pit – Model Results: Dissolved Oxygen

Dissolved [$O_2$] mg/L




- $O_2$ 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 $H_2S$
  - 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

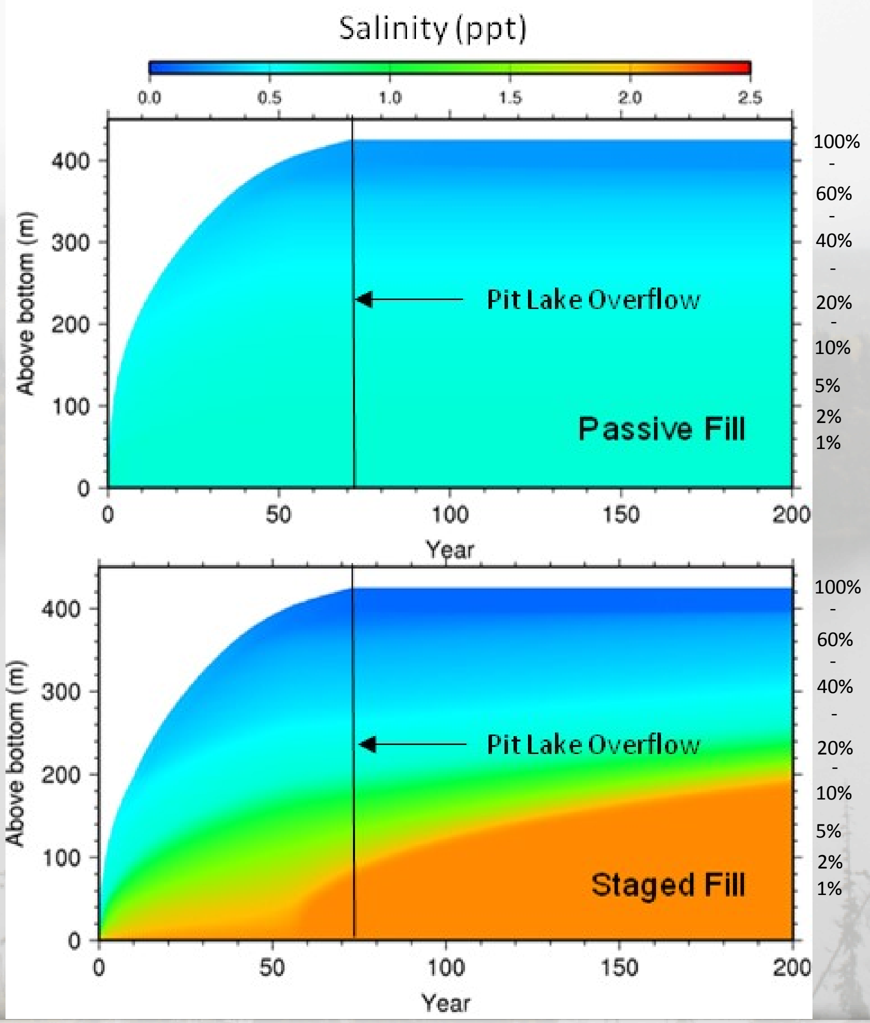
- Anonymous mine in the interior of eastern Canada
- Climate:
  - Cold-interior continental climate
  - Mean annual temperature: 3˚C
  - Mean annual precipitation: ~700 mm.
- Pit Lake:
  - 425 m depth
  - 208 ha
  - 253 M $m^3$
  - $Z_r$ = 26%
- Main inputs:
  - Waste rock seepage/runoff
  - Natural 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)

# Mine B – Model Results: Salinity (TDS)

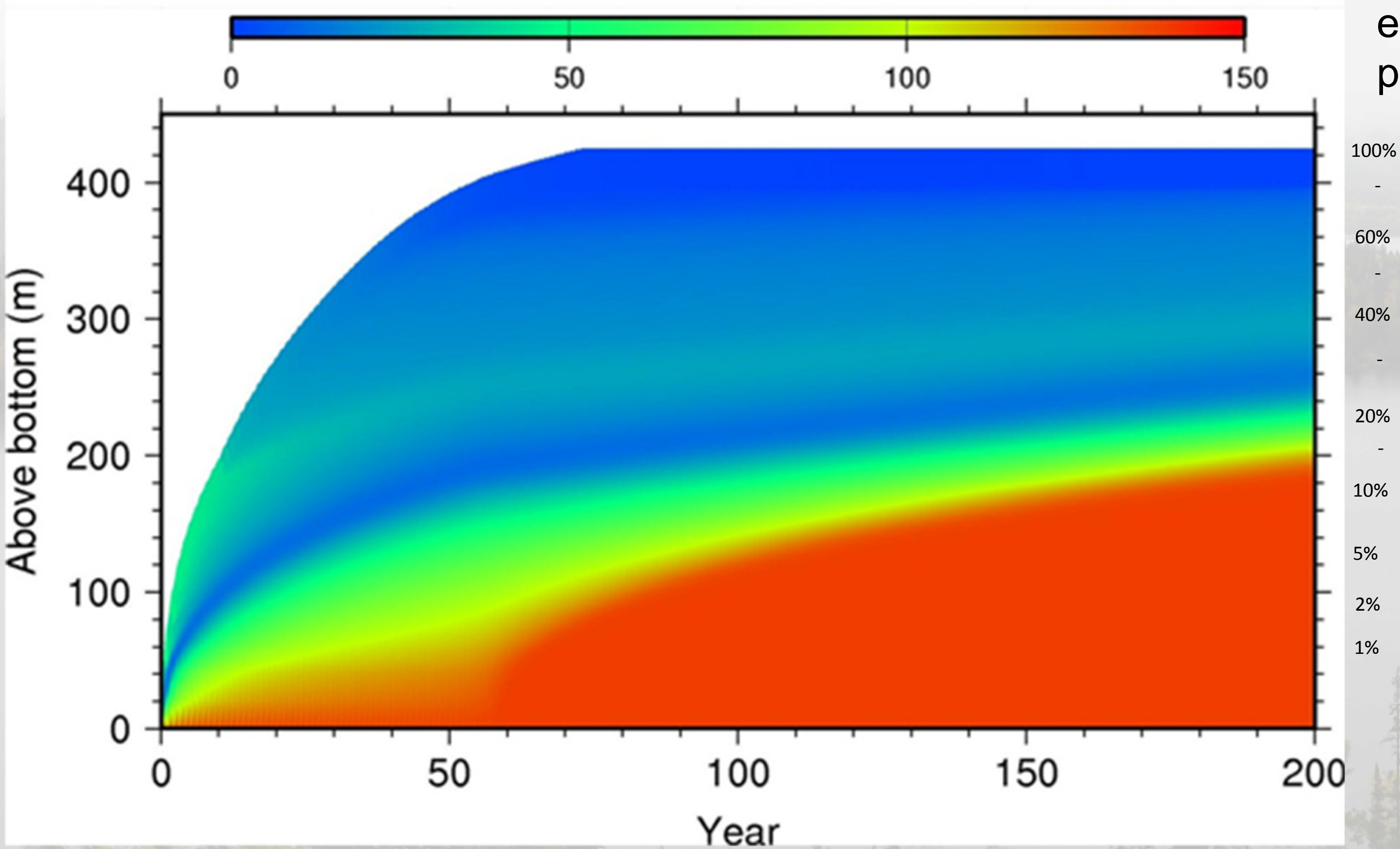



Staged fill:

- 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

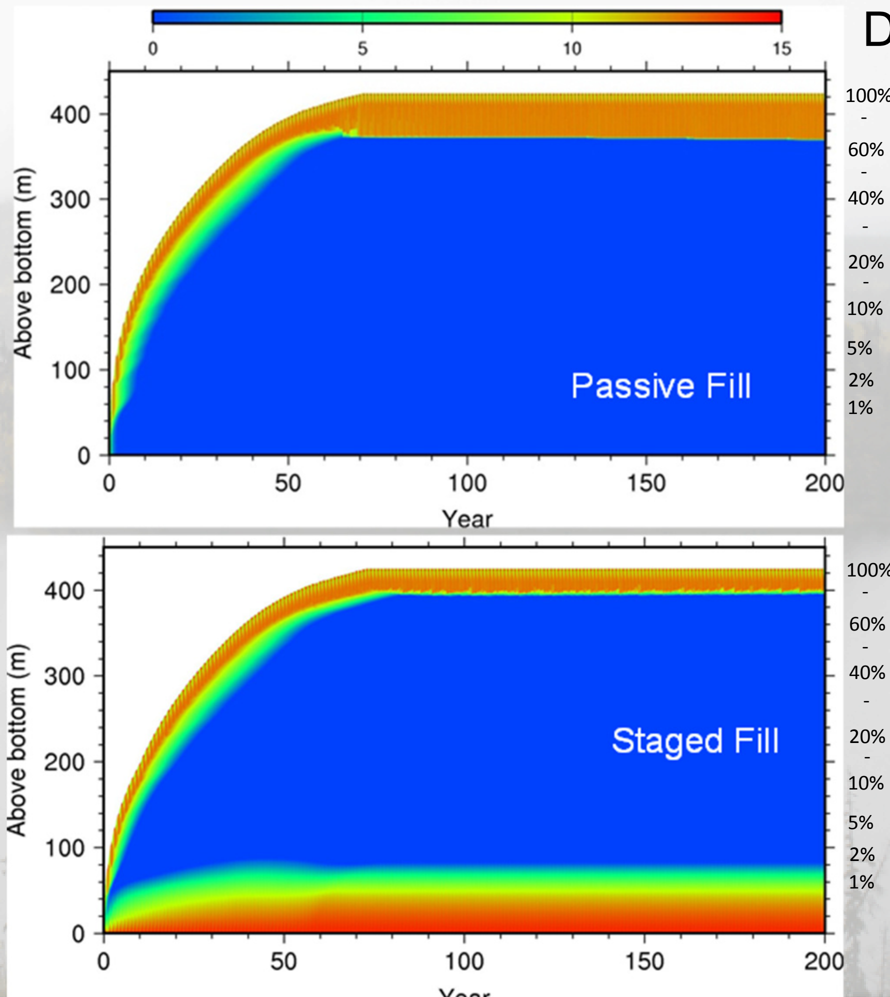
Dissolved [Cu] ppb




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

# Mine B – Model Results: Dissolved $O_2$

Dissolved $[O_2]$ mg/L




- Strongly stratified water columns in both cases
- Passive fill: thicker surface mixed layer
- Staged fill: $O_2$ enrichment in bottom 1.5% caused by the input of oxygenated PAG seepage

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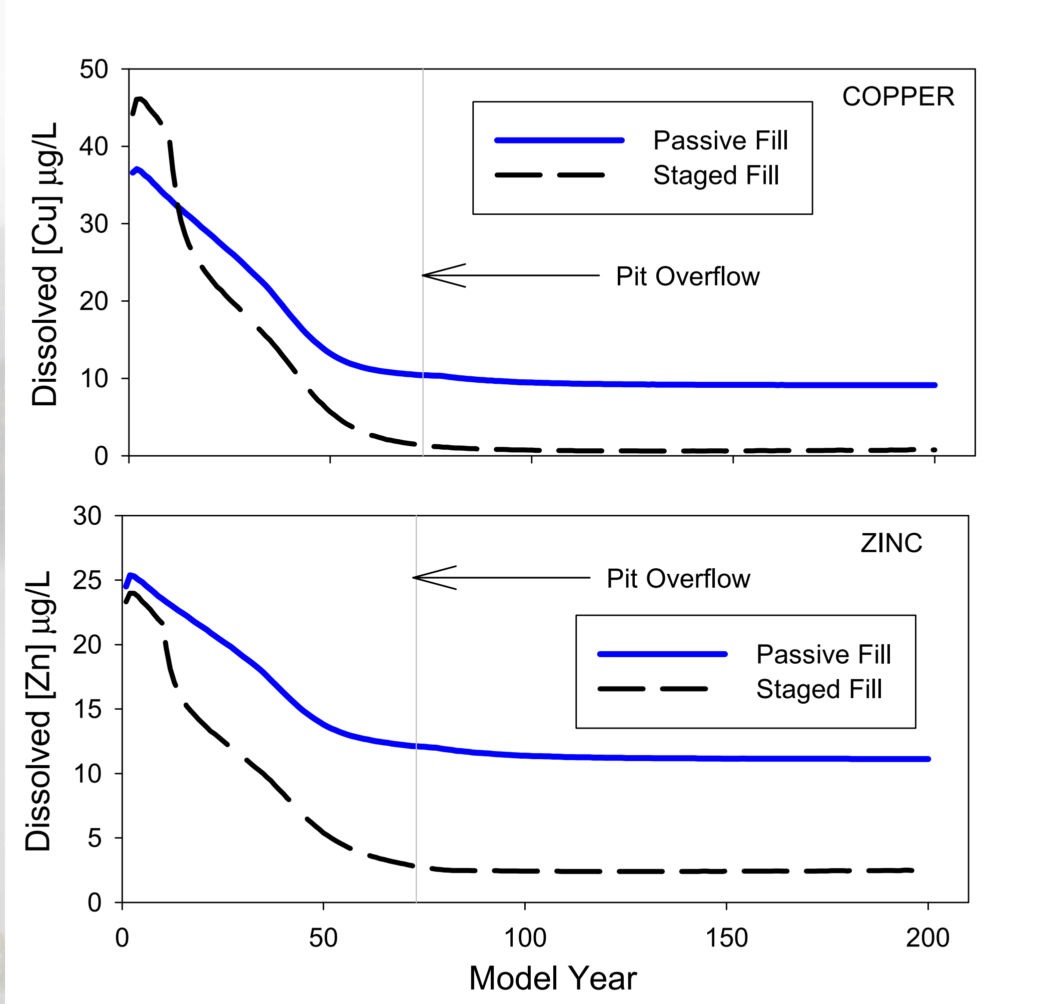
# Mine B – Model Results: Cu and Zn in Surface (<10 m)




- 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

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# 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!


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- Dunbar, D. (2013) Modelling of Pit Lakes, In *Acidic Pit Lakes - The Legacy of Coal and Metal Surface Mines. (Geller, W., Schultze, M., Kleinmann, R., and Wolkersdorfer, C., Eds.), pp 186-224, Springer-Verlag Berlin Heidelberg.*

- Dunbar, D., R. Pieters, and J. McNee. (2004) Modeling a Negatively Buoyant Plume and Related Surface Dissolved Metal Removal in the Equity MainZone Pit Lake, In *Pit Lakes 2004. United States Environmental Protection Agency. Reno, Nevada, November 16-18, 2004.*