Geochemical Ensemble Modeling for Bracketing Uncertainty in Pit Lake Water Quality Predictions

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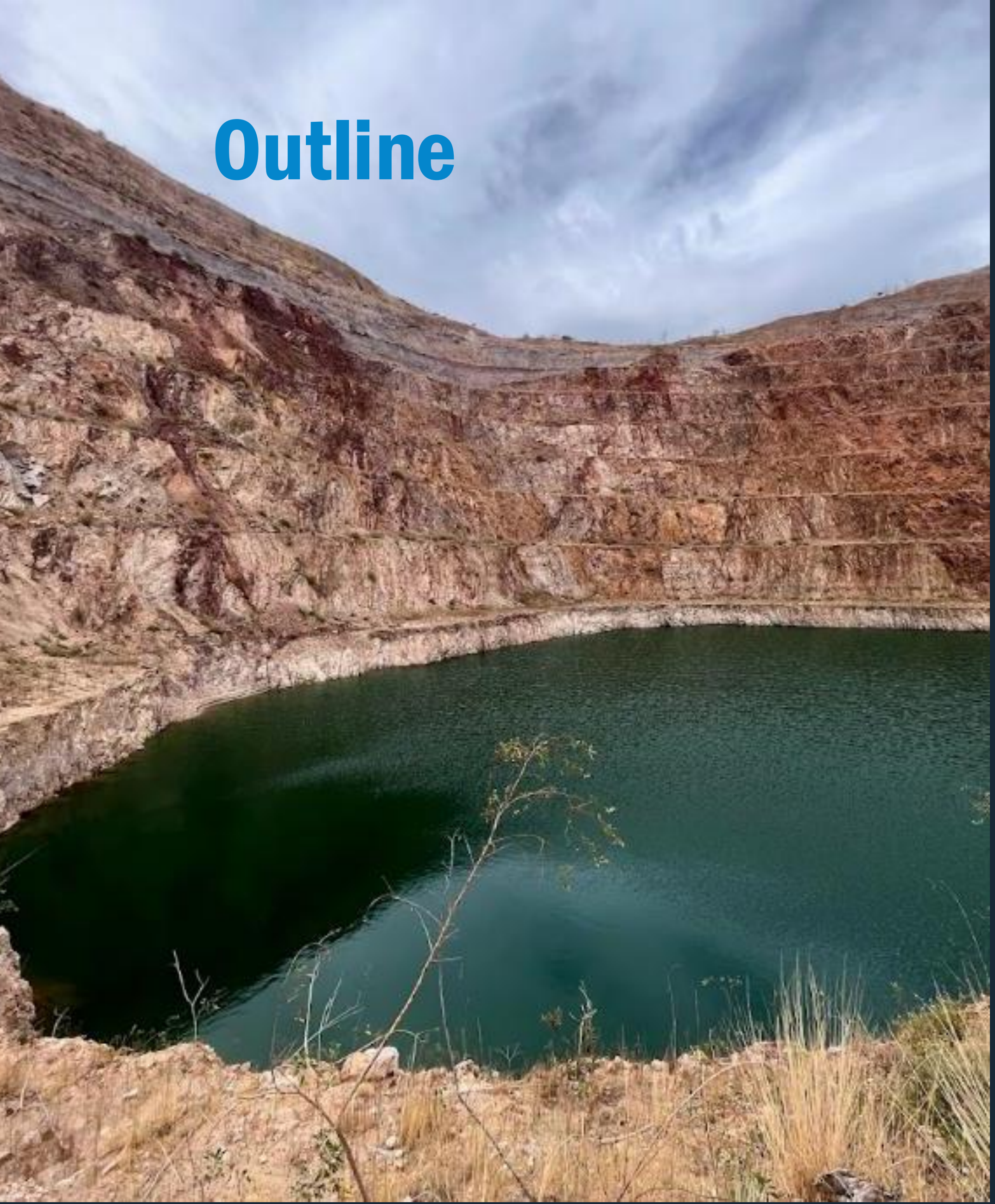


Outline

Project Context & Site Setting

Conceptual Model

Data Sets and Approach

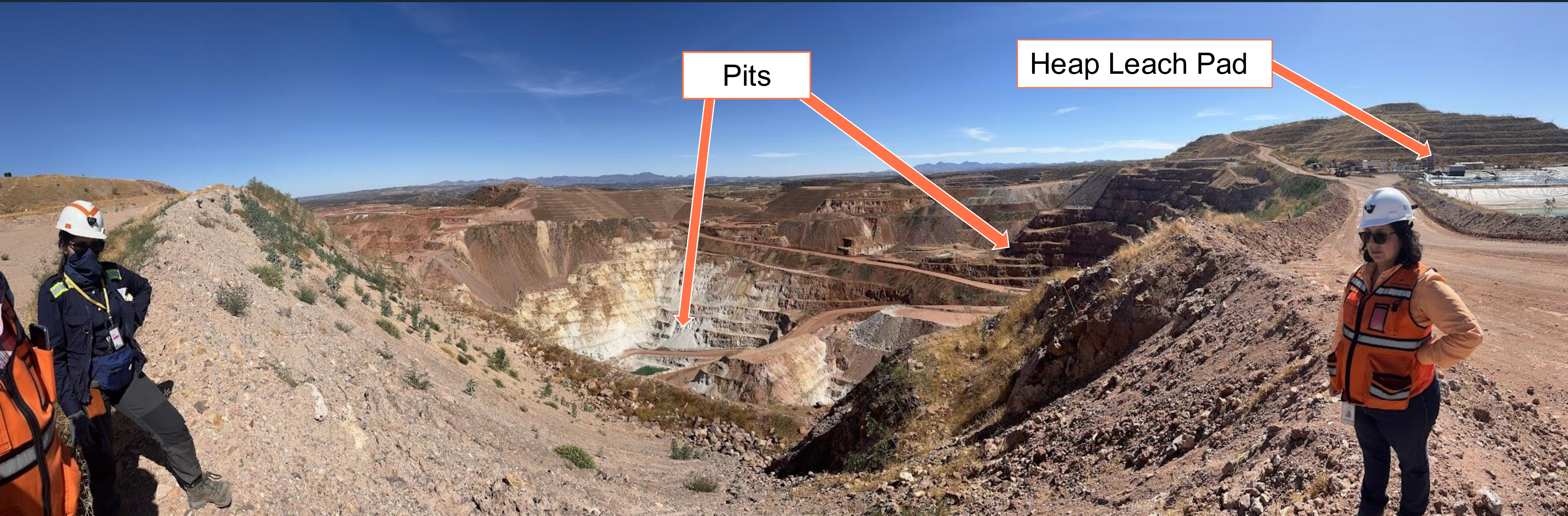
End-Member and Scenario Identification

Model Setup and Ensemble Results

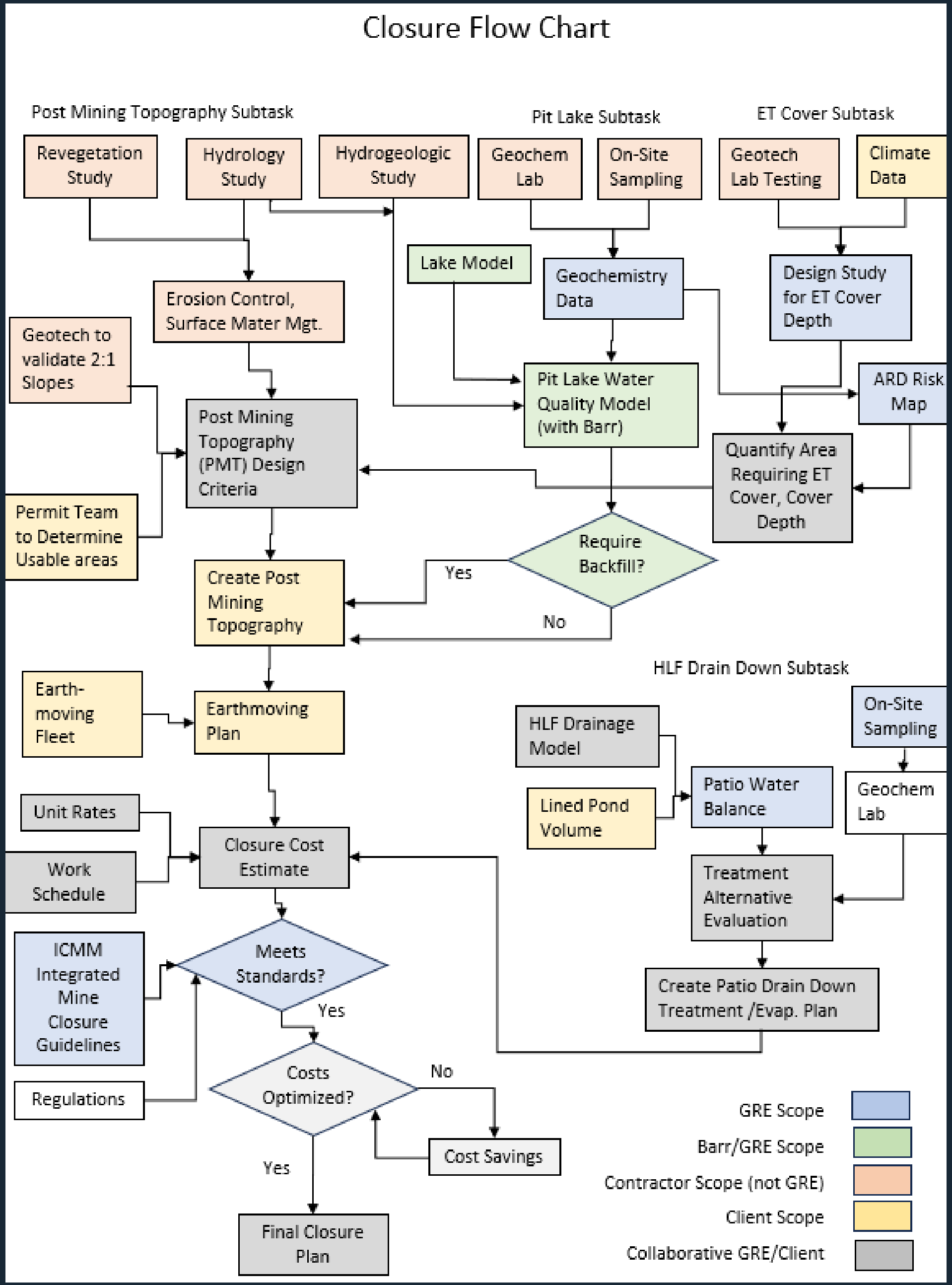
Contributions

Project context

- Mine closure planning, consulting, and support
- Open-pit, heap-leach gold project, located in an arid region



The plan: multi-year closure project funded by operating mine



Reality

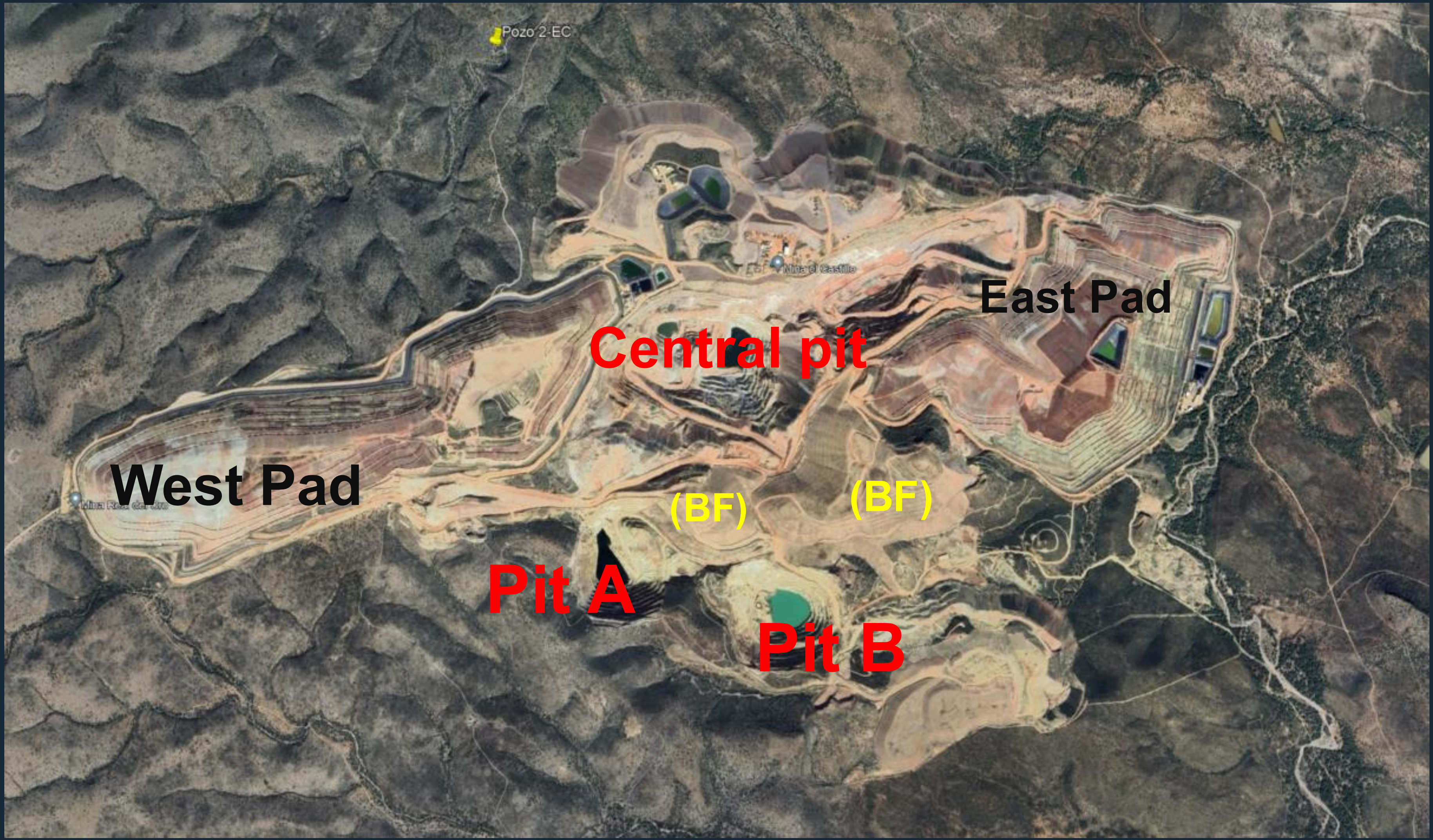
- Massive cost overruns in new mine drove client into near-bankruptcy
- Sale of assets
- Need for a “right now” assessment of project liabilities
- Pit lake risk assessment with little data
- What to do?

The new plan: assess conditions using the best available information.
This is what happens in the world of junior mining

Regional Setting

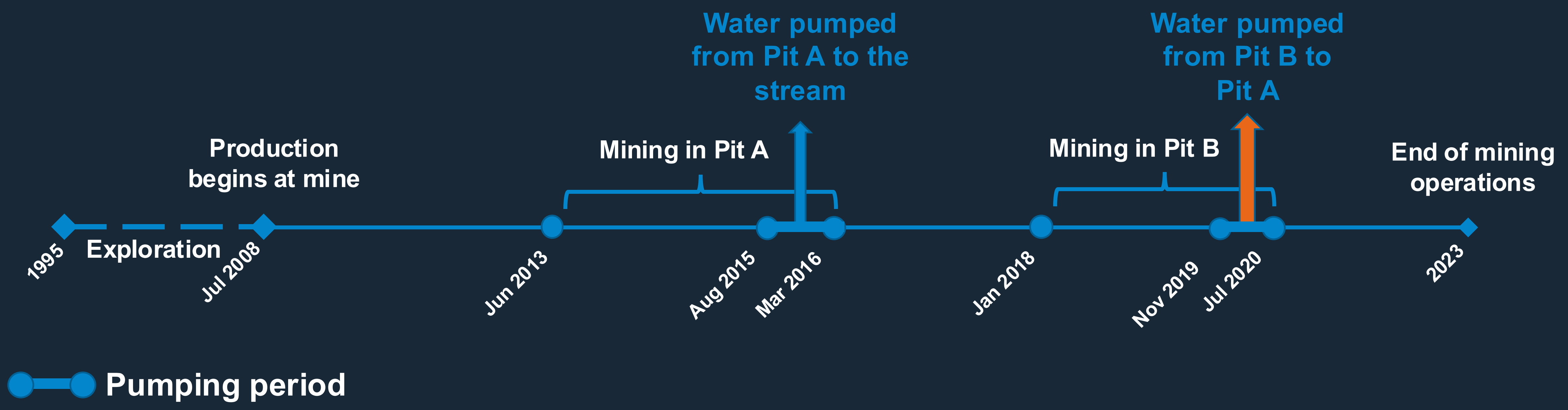
- Arid region in southern North America
- Pit lakes may be terminal sink, or flow through (mine is on a plateau)
- Abundant use of irrigation for local agriculture
- Pit lakes promised to locals as a recreational, water resource

The site

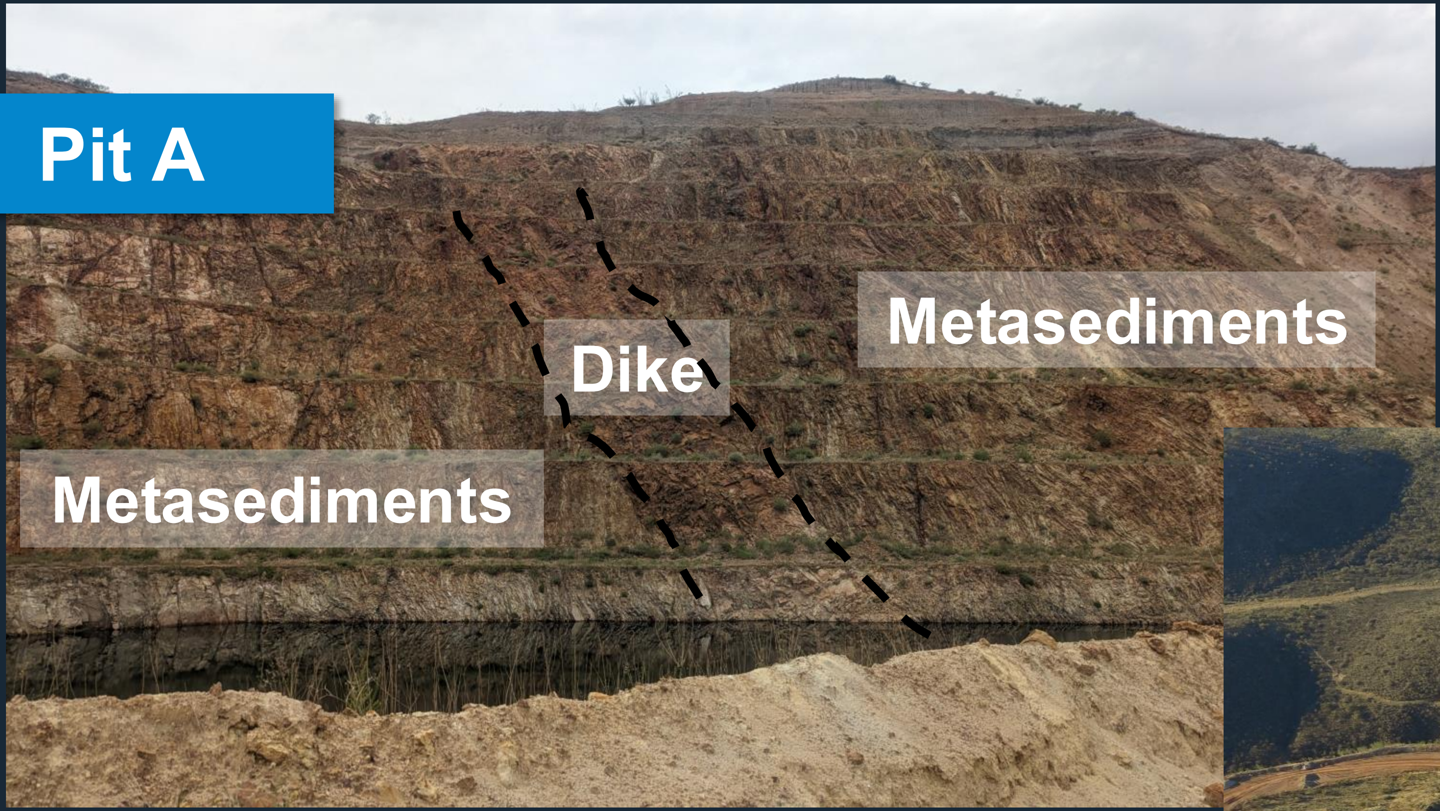


Pit lakes A and B

Timeline for Pit A and Pit B



Pit A



- Highwall is metasediments and granodiorite porphyry sills porphyry w/ a prominent cross cutting dacite dike

- Metasediments contain clastic carbonates as thin-bedded limestone

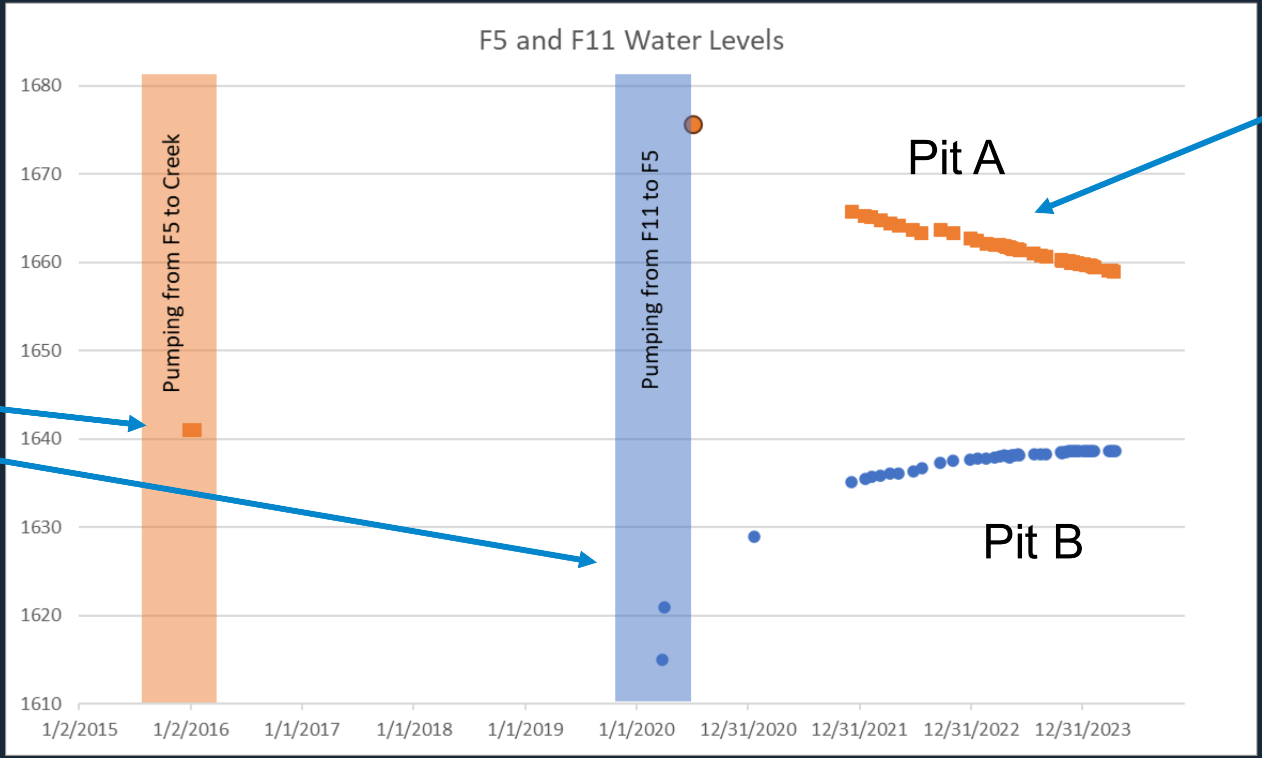
View ~southwest

Pit A in the background at maximum extent of mining

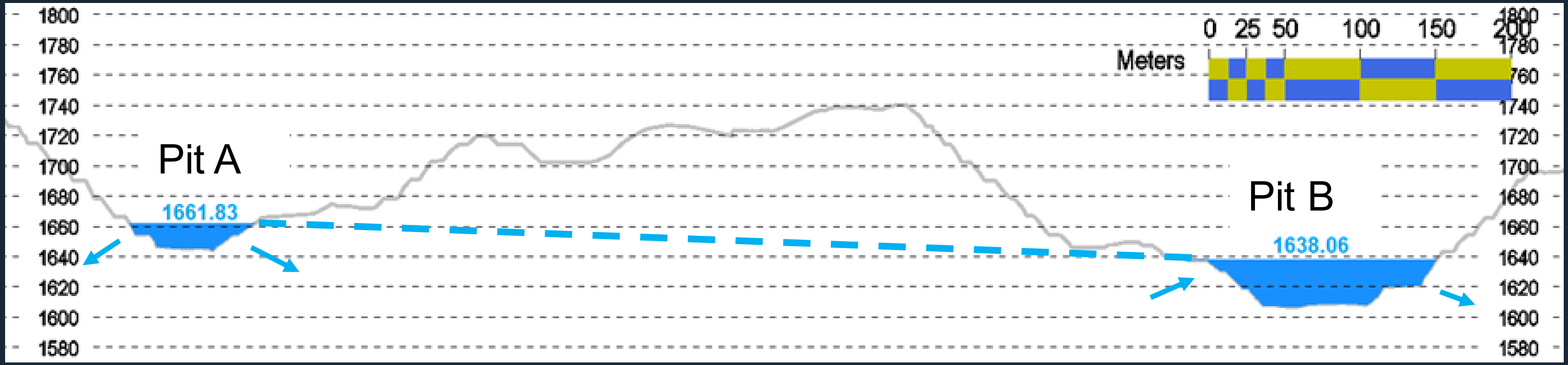
Backfilling in the foreground

Water Level History

Estimates from mine air photos



Weekly water level monitoring



Lake characterization

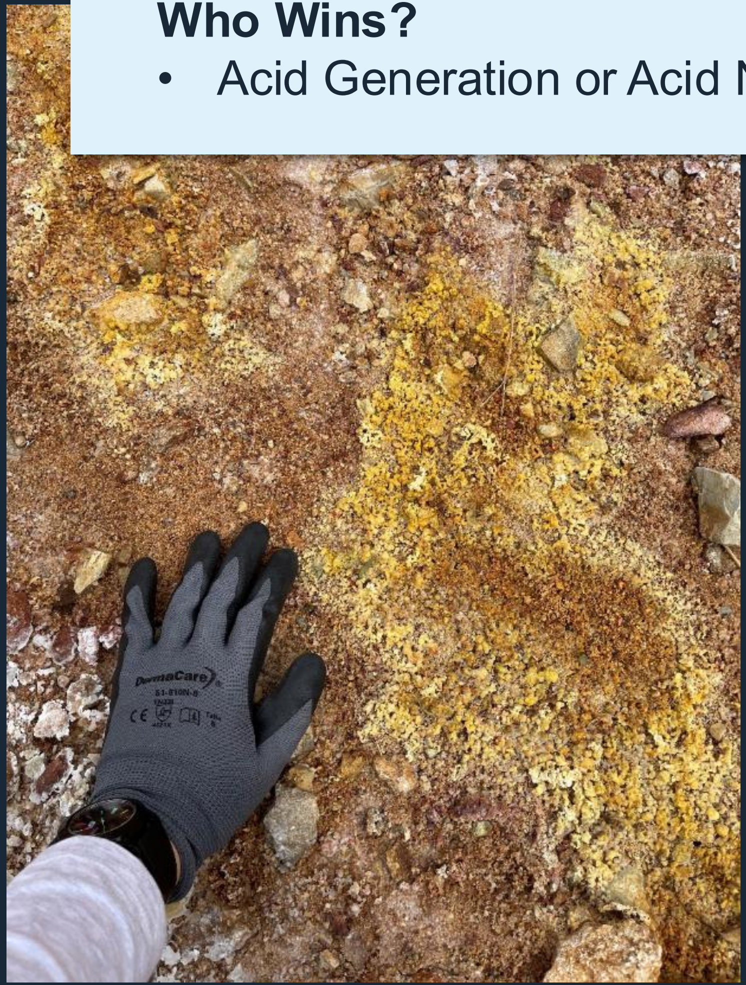
- Water samples (with depth)
- Pit wall samples
- Flow rates between adjacent pits

La Lucha

Carbonate-Rich System

Who Wins?

- Acid Generation or Acid Neutralization?



Acid Loading in Pit B

The challenge

Limited hydrogeologic data

- No routine gw monitoring
- No aquifer tests

Limited geochemistry data

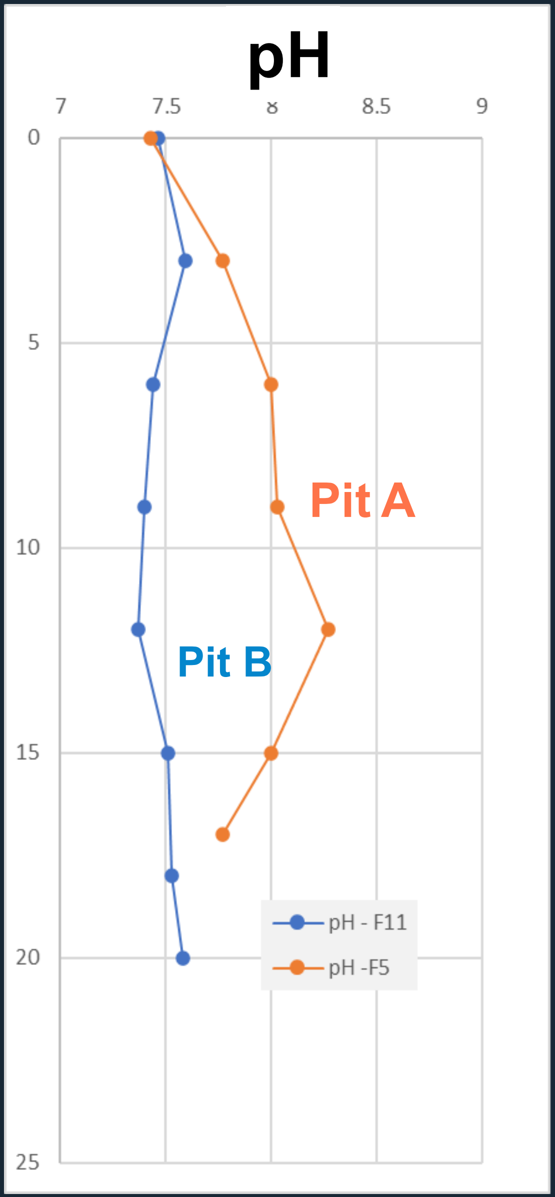
- On-site field kinetic cells were too dilute to measure effects
- Good rock composition/assay data including sulfur/carbonate

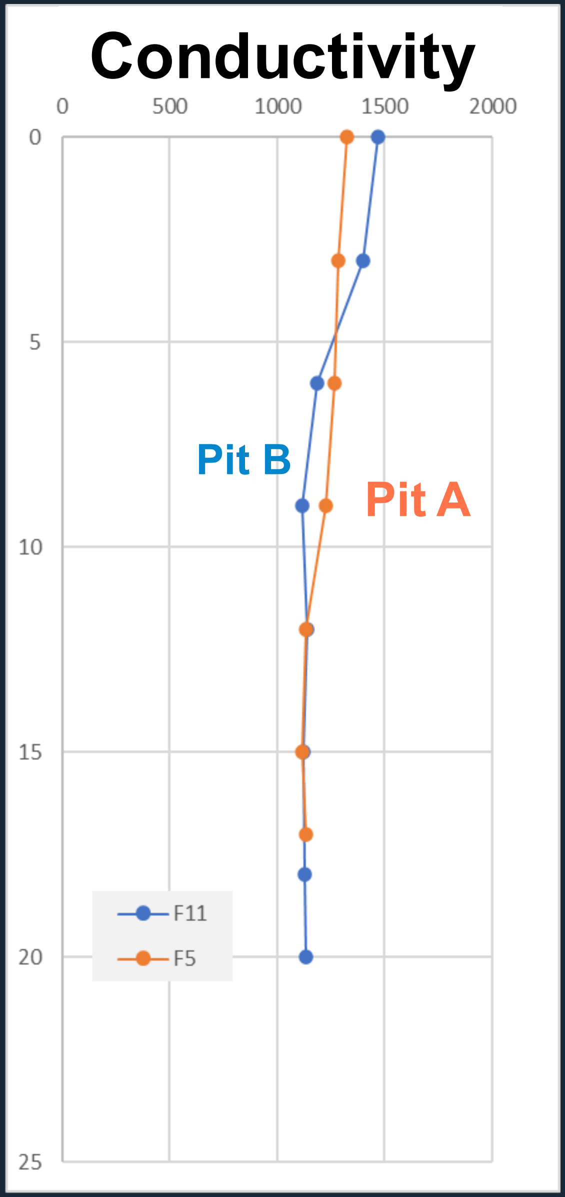
The solution

Develop a conceptual model to prioritize what to include in numerical model and bracket potential scenarios

Conceptual model development

- Pit lakes well-mixed, circumneutral
- Large areas of exposed pit walls
  - Oxide, transition, sulfide alteration
- Acidic drainage from some KC samples
- Calcite and gypsum saturated in pit waters
- Lake solutes are sum of:
  - Existing lake water quality, pit wall runoff, direct precipitation, removal of water through evaporation, sequestration in precipitated minerals
- Alkalinity sources:
  - Dissolved in groundwater, dissolved in pit wall runoff, dissolution of calcite





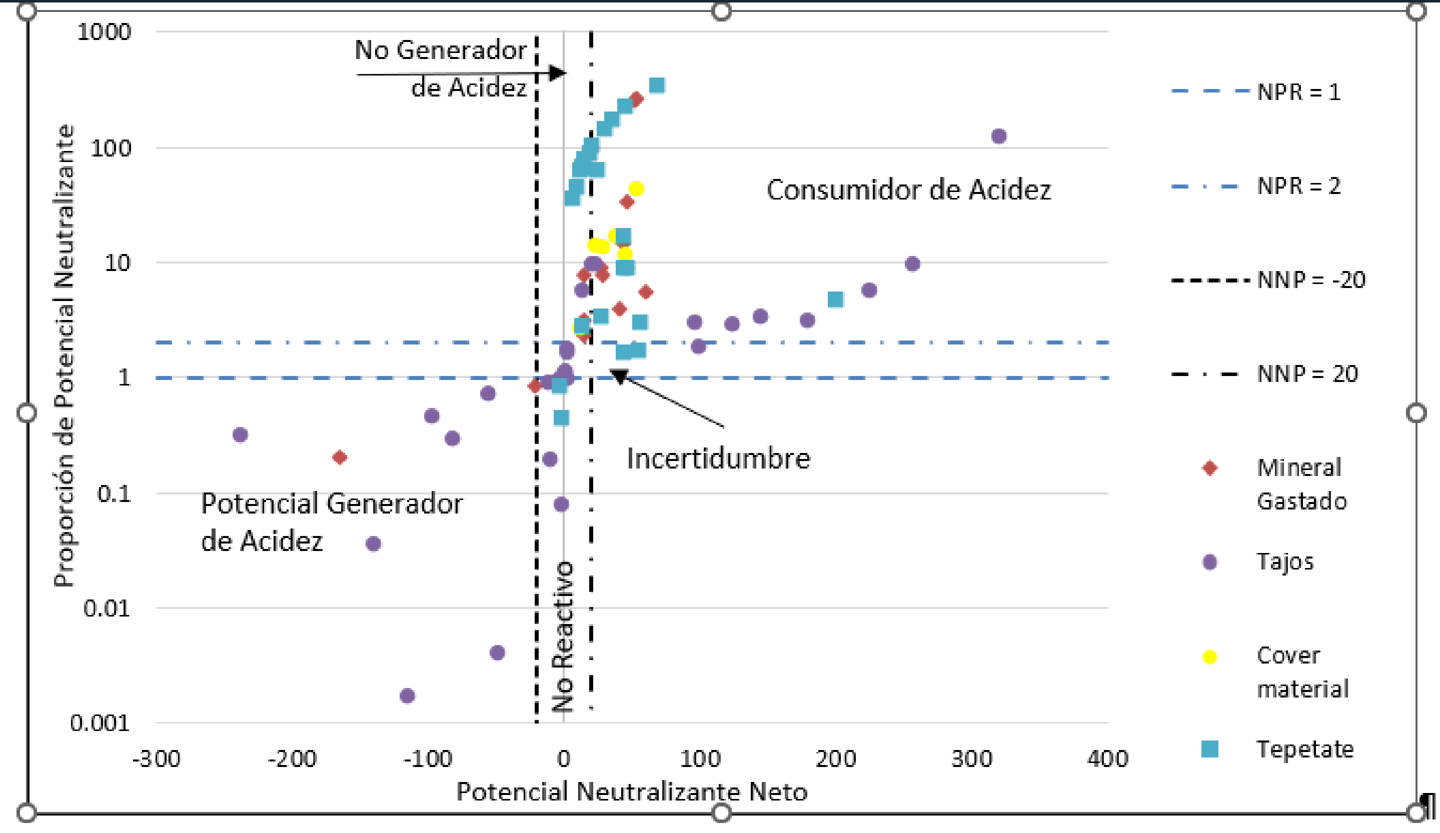
Conceptual model development

Three stratigraphic units of significance:

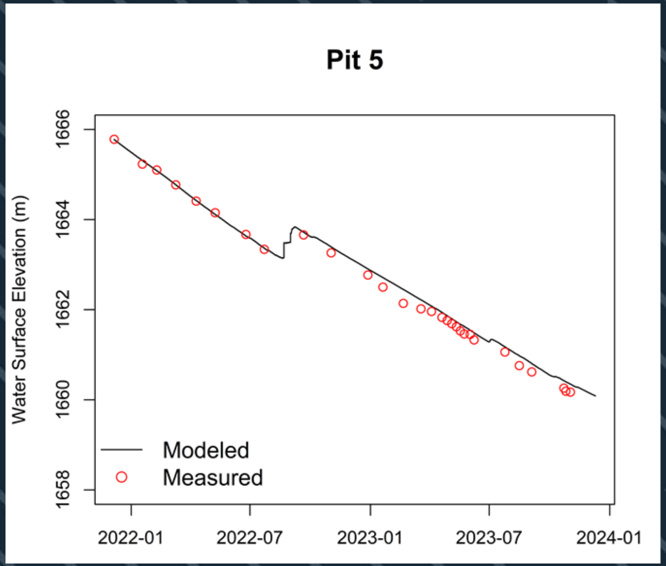
- Overburden (net acid consuming)
- Oxide zone (largely inert)
- Sulfide zone (acid generating)

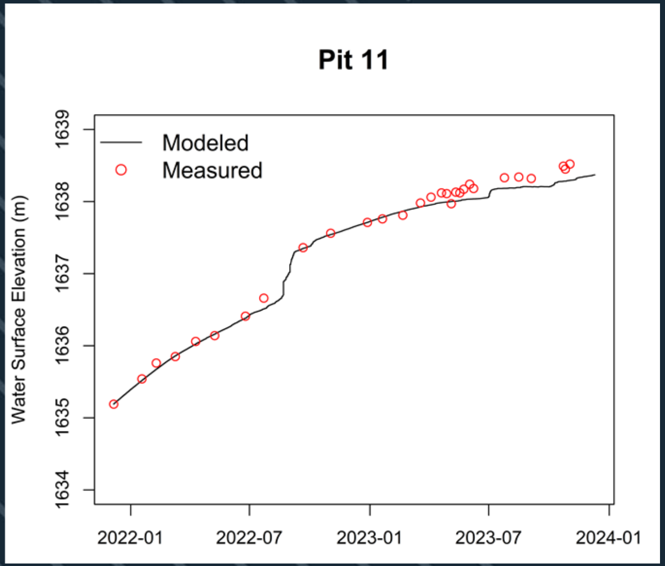
In mine waste:

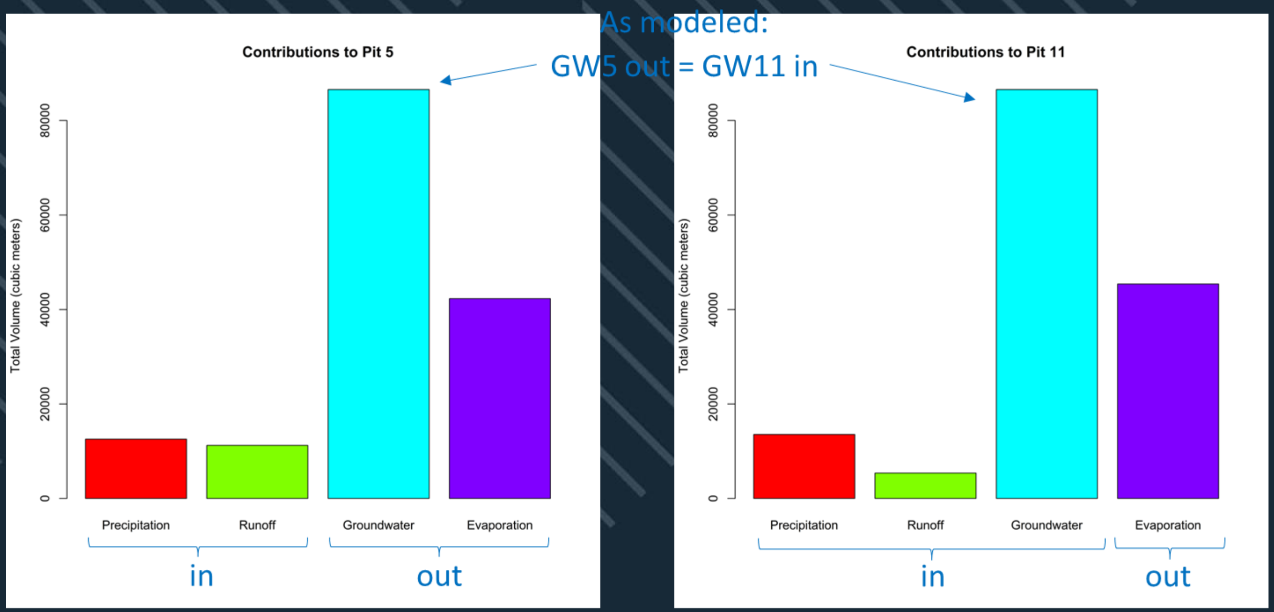
- Oxide spent heap inert
- Sulfide spent heap acid generating
- Shallow overburden acid consuming
- Deep exposed sulfides acid producing



Preliminary Water Balance in R







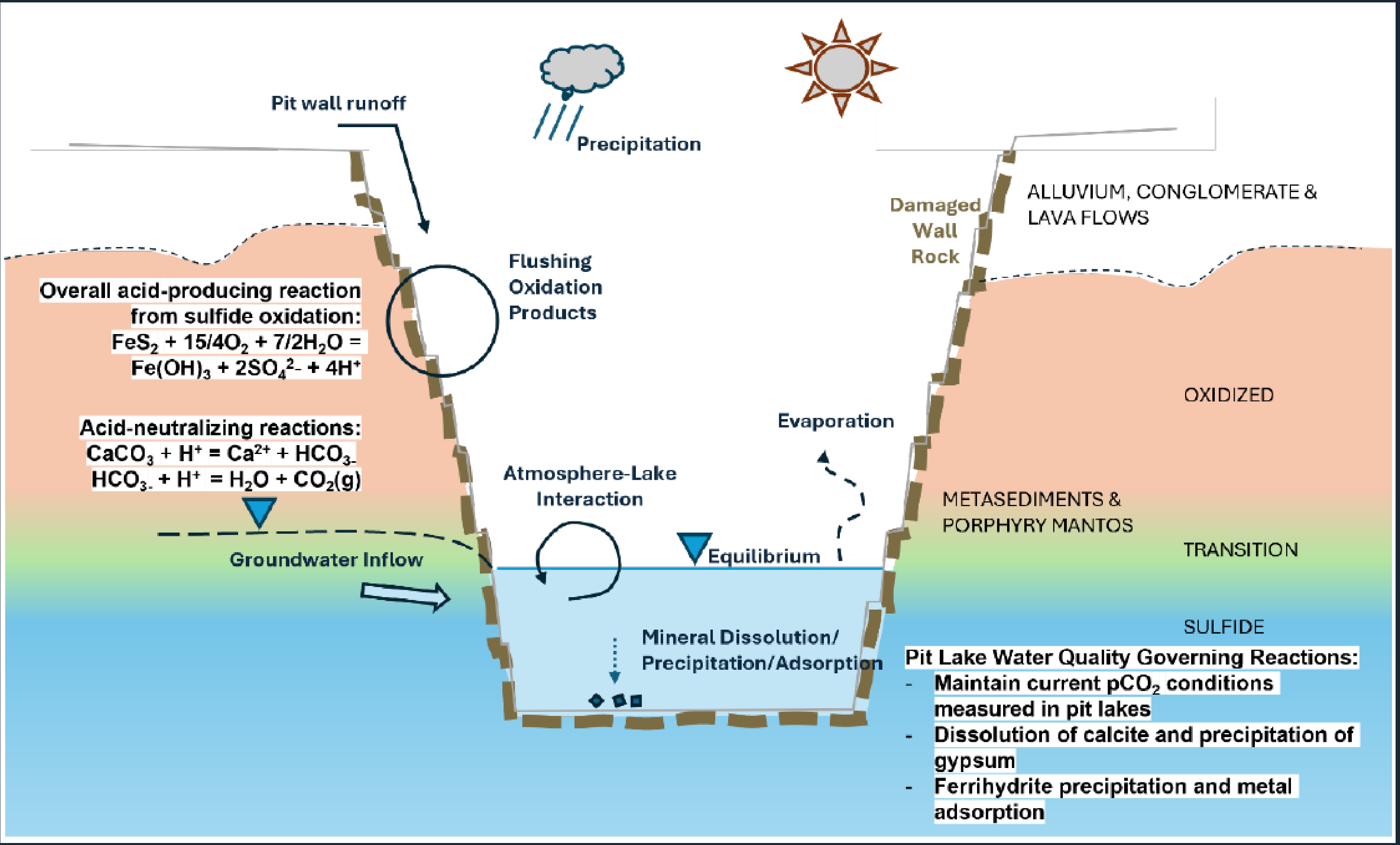
Conceptual Model Development

- Arid climate, high evap, small amount of runoff compared to groundwater
- Pit lakes responding to pumping and flooding from pumped water
- Water balance dominated by groundwater

Need better understanding of gw flow and chemistry

Conceptual model development

- Major processes identified
  - Mixing (direct precipitation, runoff, groundwater inflow/outflow, evaporation)
  - Mineral dissolution and precipitation
- Use PHREEQC to simulate mixing and equilibration with mineral and gas phases
  - Annual time step for 100 year



Changes to anticipated numerical water quality modeling approach

Water Balance

- Solve equilibrium level and flows
- GoldSim or CE-QUAL

Simplify: "bounding" assumptions about groundwater inflow and equilibrium water levels

Hydrodynamic Model

- Determine mixing conditions based on climate data
- CE-QUAL

Simplify: well-mixed pit

Mass Balance

- Assigns dissolved concentrations to flows in water balance
- CT Module in GoldSim

Simplify by using acidic inflow end-members, and accounting for sources of solutes (calcite available)

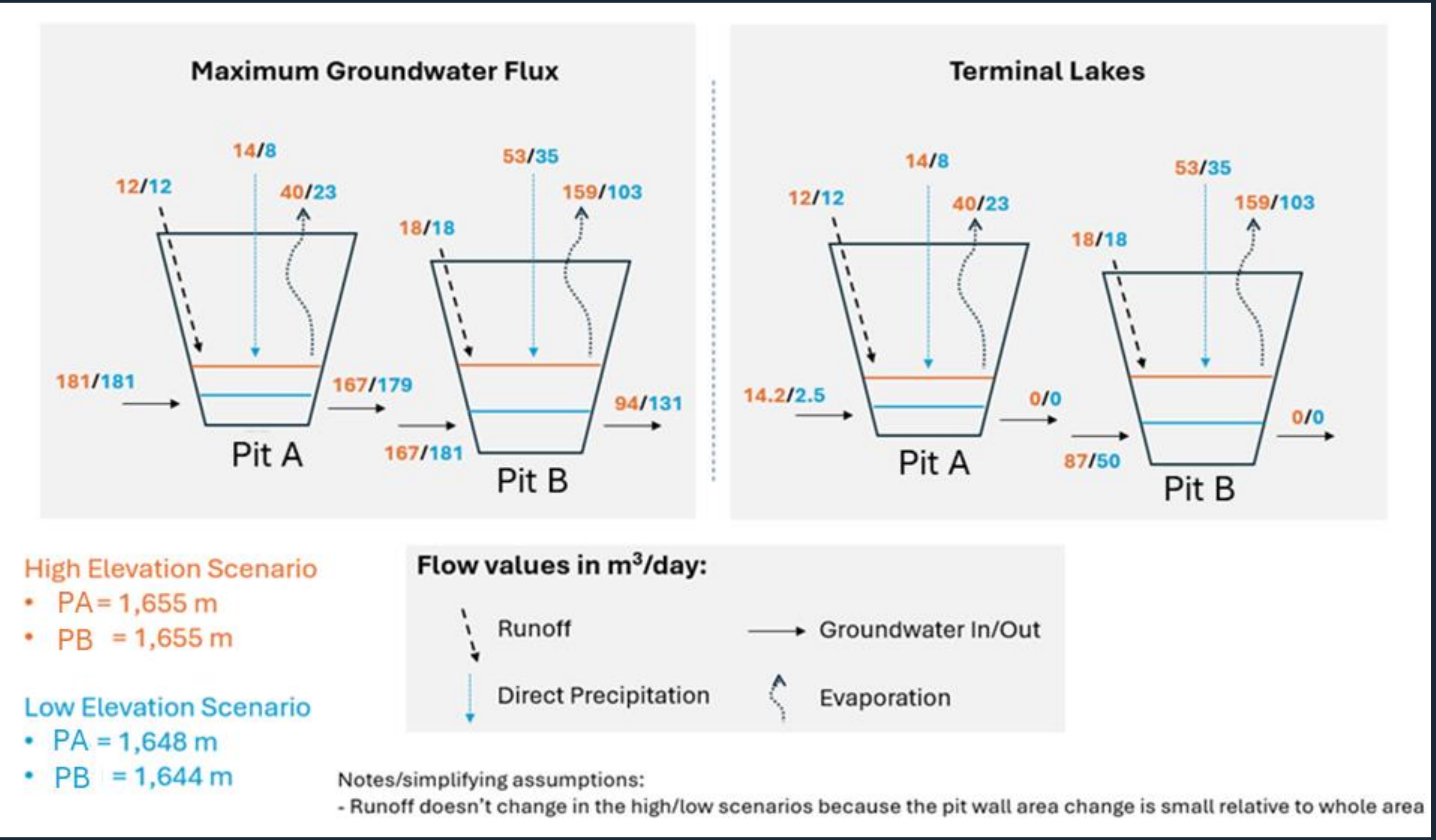
Thermodynamic Equilibrium Model

- Simulates gas-phase and solid-phase reactions in the pit water column based on hydrodynamics
- PHREEQC or Geochmists' Workbench

Simplify to account for pyrite oxidation, iron cycling, and calcite precipitation and dissolution

Create end-member equilibrium scenarios to run multiple simulations

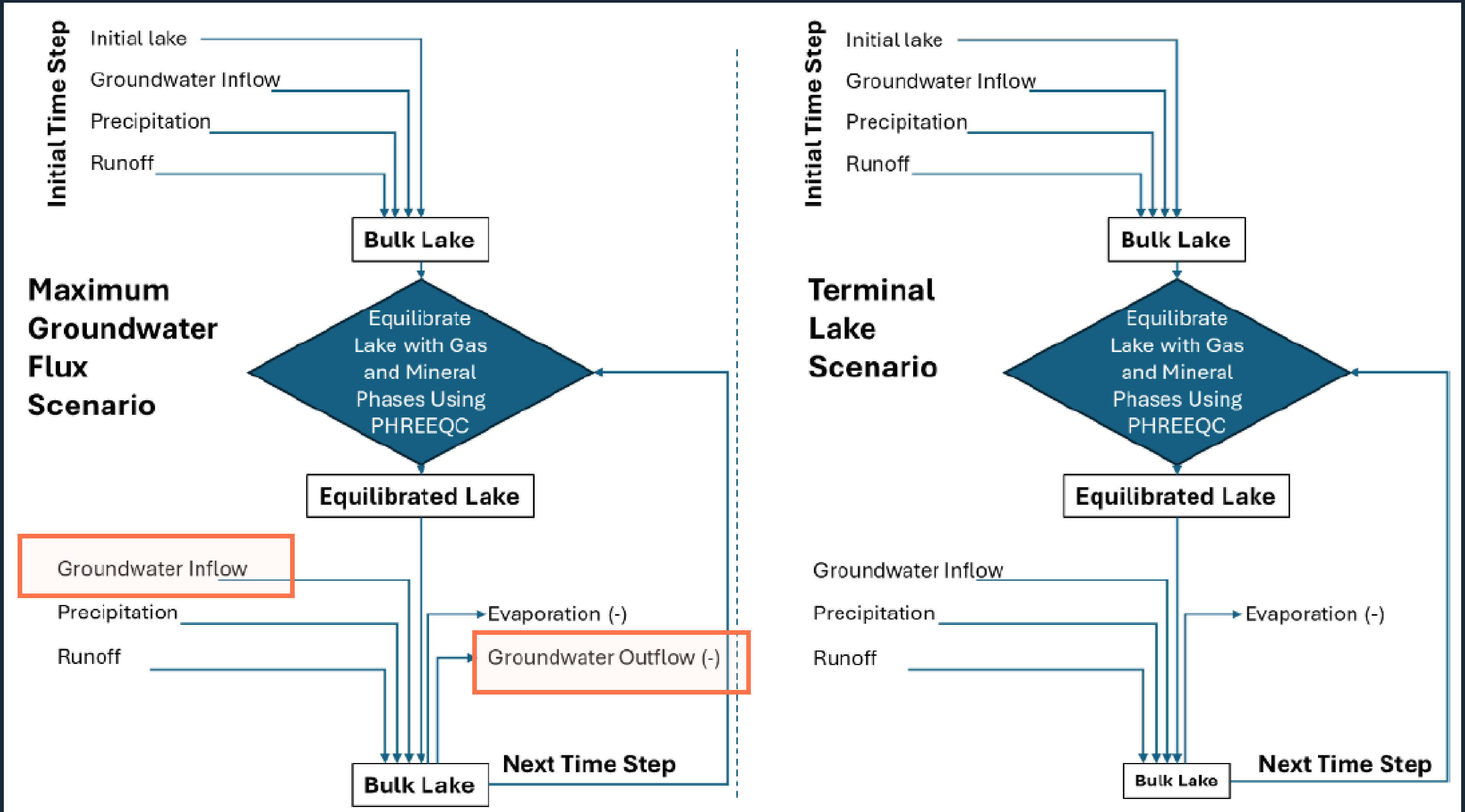
1. Flow-Through Lake: Maximum groundwater estimated from transient water balance
2. Terminal Lake: Inflows balanced by evaporation
3. Create reasonable bounds on equilibrium water surface elevation "high" and "low" based on field data, surrounding water table elevations, and water balance
4. Bracket acidic drainage input – where 5% - 20% of runoff is acidic



Pit lake characteristics under various scenarios

	Pit A		Pit B	
Lake Characteristic	**Low Elevation Scenario**	**High Elevation Scenario**	**Low Elevation Scenario**	**High Elevation Scenario**
Lake Elevation (m):	**1,648**	**1,655**	**1,644**	**1,655**
Mean depth (m)	6.3	8.3	14.2	17.9
Max depth (m)	10	17	37	48
Lake surface area (km2)	0.007	0.013	0.032	0.050
Max length (km)	0.14	0.23	0.25	0.28
Max width (km)	0.08	0.13	0.19	0.27
Volume (m3)	40,760	104,604	448,306	893,056
Hydraulic residence time - Maximum groundwater (yr)	0.6	1.4	5.3	9.8
Hydraulic residence time - Terminal lake (yr)	3.8	7.2	12.1	15.7

Model inputs and mixing – GW inflow and outflow in max GW scenarios



Results examples

- Example results from Pit B under a terminal lake scenario

Low elev, High ARD

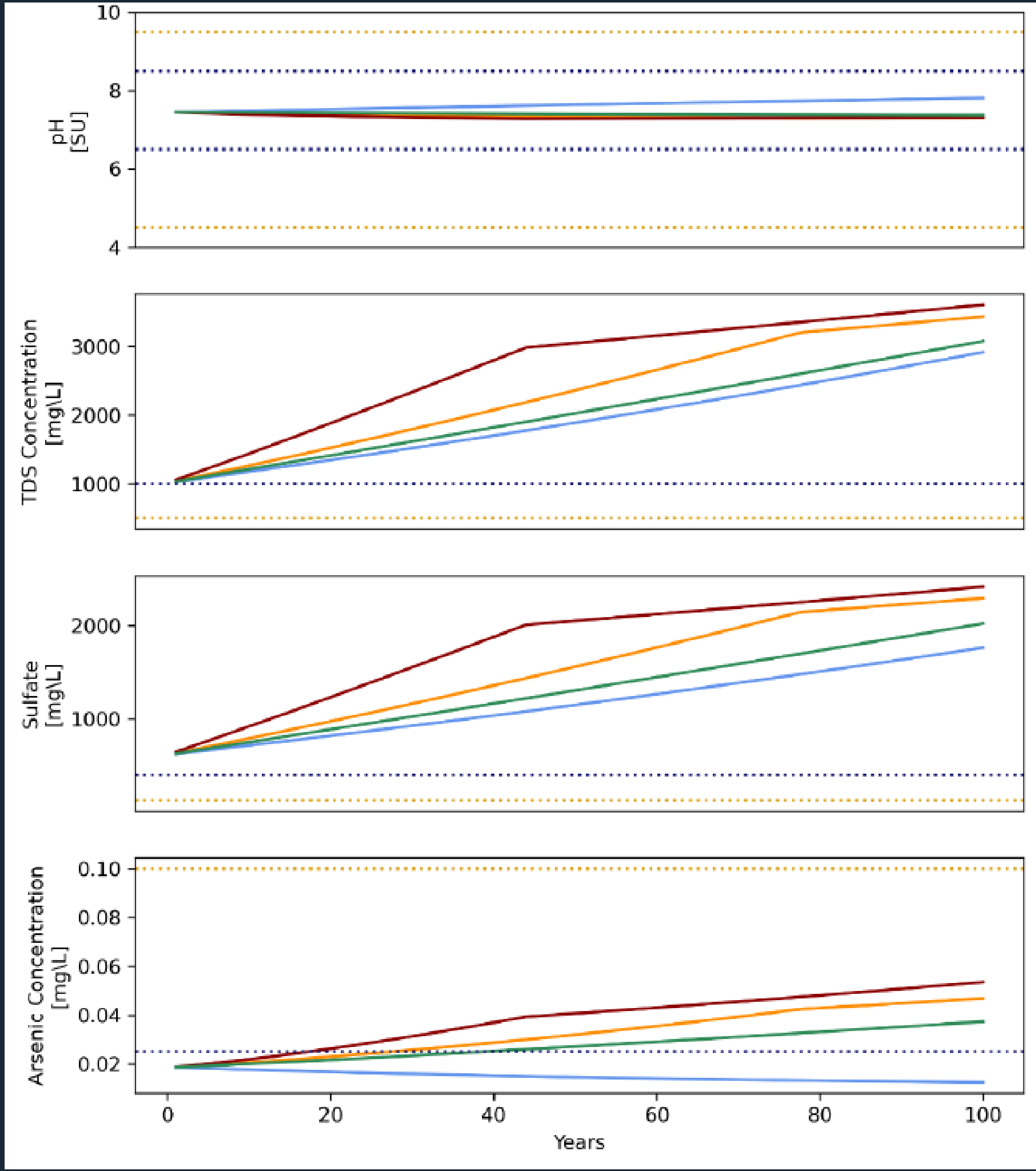
High elev, High ARD

Low elev, Low ARD

High elev, Low ARD

Human Use and Consumption Standards

Agricultural Contact Standards



Results array for multiple scenarios – Pit A

Hydrologic Condition	Final Equilibrium Water Elevation	National Water Quality Standard	ARD %	pH	TDS*	Sulfate*	Arsenic*
Max GW Flux	1,655 - High	Human Use/Consumption	5	Meet	Meet	Meet	Exceed
			20	Meet	Meet	Meet	Exceed
		Agriculture	5	Meet	Exceed	Exceed	Meet
			20	Meet	Exceed	Exceed	Exceed
	1,648 - Low	Human Use/Consumption	5	Meet	Meet	Meet	Exceed
			20	Meet	Meet	Meet	Exceed
		Agriculture	5	Meet	Exceed	Exceed	Meet
			20	Meet	Exceed	Exceed	Exceed
Terminal Lake	1,655 - High	Human Use/Consumption	5	Meet	Exceed	Exceed	Exceed
			20	Meet	Exceed	Exceed	Exceed
		Agriculture	5	Meet	Exceed	Exceed	Exceed
			20	Meet	Exceed	Exceed	Exceed
	1,648 - Low	Human Use/Consumption	5	Meet	Exceed	Exceed	Exceed
			20	Exceed	Exceed	Exceed	Exceed
		Agriculture	5	Meet	Exceed	Exceed	Exceed
			20	Meet	Exceed	Exceed	Exceed

* Indicates current pit lake water quality exceeds maximum permissible limits

Results array for multiple scenarios – Pit B

Hydrologic Condition	Final Equilibrium Water Elevation	National Water Quality Standard	ARD %	pH	TDS*	Sulfate*	Arsenic*
Max GW Flux	1,655 - High	Human Use/Consumption	5	Meet	Exceed	Exceed	Meet
			20	Meet	Exceed	Exceed	Meet
		Agriculture	5	Meet	Exceed	Exceed	Meet
			20	Meet	Exceed	Exceed	Meet
	1,644 - Low	Human Use/Consumption	5	Meet	Meet	Meet	Meet
			20	Meet	Meet	Exceed	Meet
		Agriculture	5	Meet	Exceed	Exceed	Meet
			20	Meet	Exceed	Exceed	Meet
Terminal Lake	1,655 - High	Human Use/Consumption	5	Meet	Exceed	Exceed	Meet
			20	Meet	Exceed	Exceed	Exceed
		Agriculture	5	Meet	Exceed	Exceed	Meet
			20	Meet	Exceed	Exceed	Meet
	1,644 - Low	Human Use/Consumption	5	Meet	Exceed	Exceed	Exceed
			20	Meet	Exceed	Exceed	Exceed
		Agriculture	5	Meet	Exceed	Exceed	Meet
			20	Meet	Exceed	Exceed	Meet

* Indicates current pit lake water quality exceeds maximum permissible limits

Contributions

- These two lakes appear to:
  - Be too low in quality to be used as a water resource
  - Are unlikely to be a regional source of contaminants
- Never offer a pit lake as a community resource before you know if it's going to be an acidic or full of toxic metals
- If you lack data, you can still say something, but it must include the uncertainty in the response
- Preliminary work like this can help focus future characterization

Thank you!

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