Pit Lake Prediction Case Study: Managing Insecurity in the Dataset using Bracketed Inputs

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Abstract

Two pit lakes formed in mine pits in an arid region. To estimate potential future pit lake water quality composition, and given uncertainties and data gaps in the dataset, eight scenarios were modelled for each pit lake using end-member input for the most-sensitive and least-understood input parameters. Key inputs were the hydraulic conductivity of the aquifer, and the acidity of pit wall runoff. In all but one scenario, both pit lakes remained circumneutral, but water quality is unlikely to meet water quality standards in any scenario because arsenic exceeds the agricultural use standard. The estimates were used to prioritize field programs to reduce uncertainty.

Keywords: Pit lake model, uncertainty, water quality

Introduction

Decisions about the management of pit lakes often must be made prior to the acquisition of robust datasets such as aquifer test results. In this case, closure and management decisions had to be made on two pit lakes due to a property transaction. This study describes methods for decision-making and analysis when data gaps exist.

Mining in Pit A began in 2013. Dewatering the pit began in late 2015 by discharging pumped water to a nearby stream. Mining ceased in March, 2016. Mining in Pit B began in 2018 and dewatering water was pumped and discharged into Pit A. Mining in Pit B ceased in 2020 and the pit lake elevations continue to equilibrate (Fig. 1). The future water surface elevations and groundwater flow rates under equilibrium conditions are unknown.

The adjacent mine pit lakes have relatively small watershed areas (0.42 km2 and 0.66 km2, respectively), which consist of natural areas, disturbed mine areas, pit walls and open water areas. Runoff from the watershed areas contacts the pit walls prior to running into the pit lakes. The mine site is located in an area with a semi-arid climate, with annual average rainfall, potential evaporation, and temperature of 490 mm, 1,990 mm, and 17.5 °C, respectively. Groundwater monitoring wells provide little information about the groundwater levels because they were specifically designed for monitoring heap leach pads and are too shallow to provide reliable information regarding the water quality or hydraulic conductivity of the deeper aquifer that the pit lakes intersect.

Seasonally-collected, depth-correlated field observations of temperature, conductivity, oxidation-reduction potential and pH suggest well-mixed conditions in both pits. With no obvious chemocline or thermocline, they classify as warm polymictic lakes.

Methods

The overall objective of pit lake water quality modeling was to forecast water chemistry in the two pit lakes and to compare these predictions to water quality standards. Specific uncertainties included:

- long-term water elevations in the pits;
- the amount of groundwater flow into and out of the pits that will occur once the pits have reached hydrologic equilibrium;
- inadequate data from kinetic cell tests to determine the amount of acidity and dissolved solutes that will be contributed to the mine pit lakes from pit wall runoff.

Figure 1 Photograph of flooded Pit B.

Therefore, the modeling simulates hydrologic steady-state conditions using upper and lower bounds on the anticipated future pit inflow and outflow conditions, the future equilibrium water surface elevations, and the contribution of acidity from pit wall runoff. Despite limitations, existing datasets were successfully used to provide a conceptual model and a transient water balance that accounts for inflow and outflow to the pits, and water quality simulations.

Conceptual Model

The quality of pit lake water is determined by mixed sources of inflow, evaporative concentration, and thermodynamic equilibrium reactions based on interaction with with solid- and gas-phases (Fig. 2). Because the pits are well-mixed, hydrodynamic modeling was not performed.

Preliminary speciation modeling of the existing water quality in the pit lakes at both Pit A and Pit B was conducted in the aqueous equilibrium geochemical modeling program PHREEQC with the MINTEQ.v4 database (Parkhurst and Appelo 2013). The modeling indicates that calcite is at saturation. Therefore, the mixing model of the pit lake includes calcite in the wall rock that is available to neutralize acidity from runoff.

Transient Water Balance

The present hydrologic water balance for the pit lakes was simulated for the weekly surface water elevations using climate data from on-site monitoring, evaporation calculated using the Meyer equation (Meyer 1942) and surface runoff modelling in PCSWMM (James *et al.* 2010; Fig. 3).

For the water balance, groundwater flux was the unknown term. Without information about the quantity of groundwater inflow to or out of the pits, the groundwater flow values in the water balance for each pit remain “net” groundwater flow estimates. To estimate the future equilibrium hydrologic conditions, a reasonable envelope for the future equilibrium water surface elevations was used and the groundwater inflow rates were bracketed (high and low). The transient water balances for the pit lakes were used to estimate two steady-state scenarios once final equilibrium water surface elevations are reached: 1) a “flow-through” lake condition,

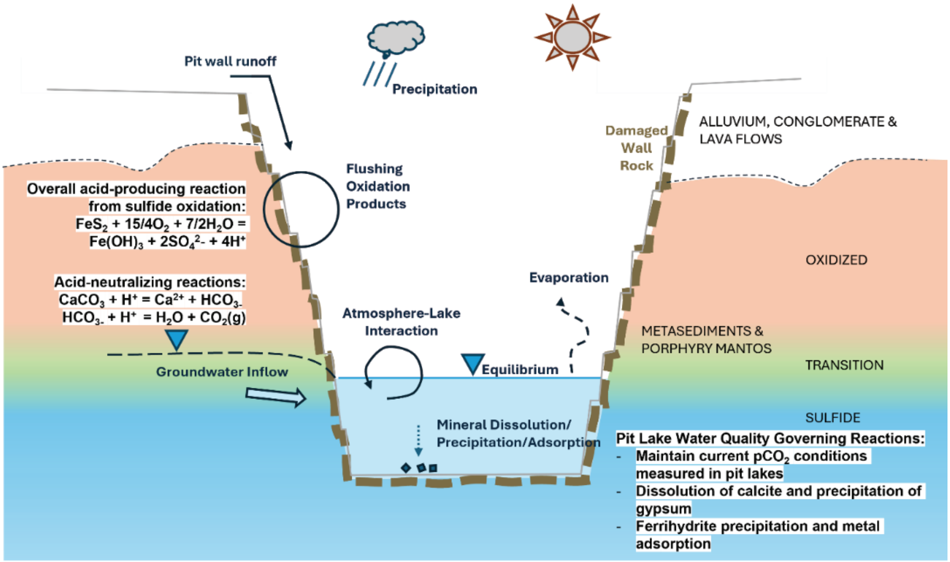


Figure 2 *Conceptual model of geochemical reactions included in pit lake simulations.*

estimated as the maximum groundwater flux needed to solve the balance during pit-filling; and 2) a terminal lake condition, where inflowing groundwater and runoff are balanced by evaporation, which is also a minimum groundwater flux condition.

For the maximum groundwater flux scenario, the inflows are balanced by outflow from evaporation and groundwater outflow. For the terminal lake scenario, inflows are balanced only by evaporation. The high and low surface water elevations bracket reasonable elevations for the anticipated final equilibrium water surfaces in each pit based on the recent monitoring. Fig. 4 shows lake elevations, groundwater flux, exchange between lakes, and evaporation totals at high and low bracketed scenarios. These flow values are used in the pit lake water quality model to specify the volumes contributed by each source.

Geochemical Model

The aqueous equilibrium geochemical modeling program PHREEQC with the MINTEQ.v4 database (Parkhurst and Appelo 2013) was used to simulate the processes of mixing the inflows and outflows for each time step and equilibrate the resulting chemistry with mineral and gas phases. The concentration of carbon dioxide gas (CO2) was constrained by the partial pressure of

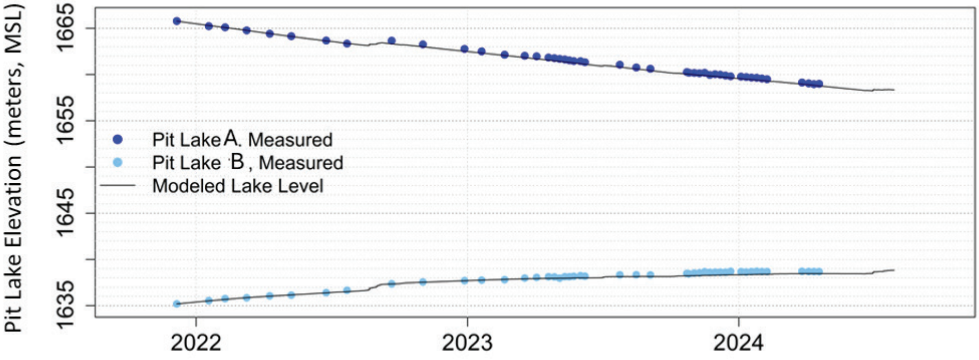
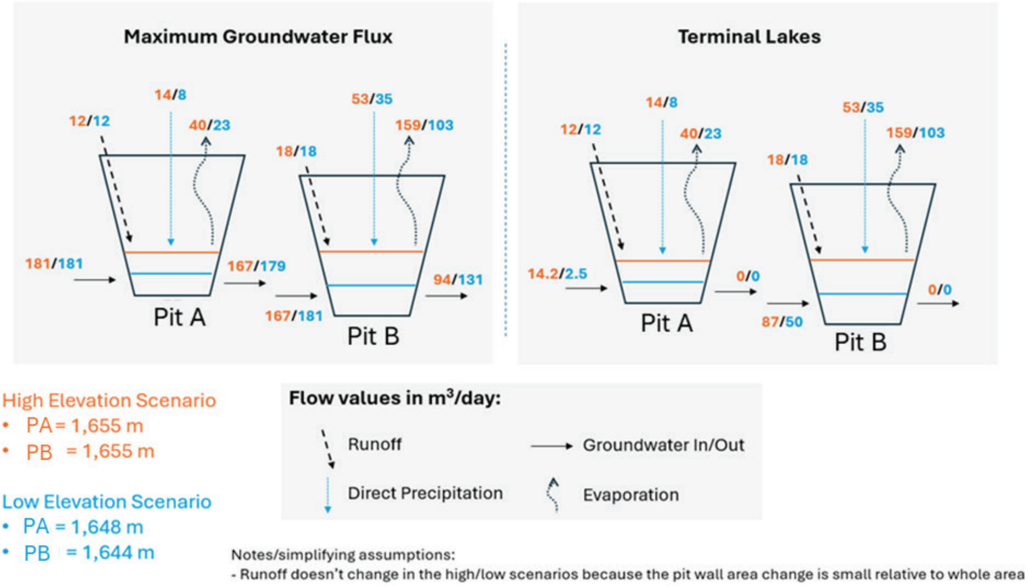


Figure 3 *Transient water balance model results.*



Notes/simplifying assumptions:
- Runoff doesn't change in the high/low scenarios because the pit wall area change is small relative to whole area

Figure 4 *End-member hydrologic scenarios for the two mine pits.*

CO2 (pCO2) calculated in the 2023 surface samples (pCO2 10–2.5) by setting the SI of CO2 to –2.5. An annual time step was used. Simulations were carried out to estimate the mixed bulk lake water quality, year-on-year, for 100 years

The future water quality was modeled by mixing inflow and outflow terms that undergo chemical reaction due to gas exchange, evaporation, mineral dissolution and precipitation, and adsorption of trace metals. The concentrations of mass assigned to each inflow and outflow term in the model are derived from site-specific water quality measurements, analyses of effluent samples from the kinetic cells, or from regional measurements. Evaporation was applied by removing the annual average volume fraction of pure deionized water.

PHREEQC was used to evaluate the speciation and saturation indexes (SIs) of relevant mineral and gas phases. The calculated SIs of carbon dioxide, calcite, gypsum, ferrihydrite, manganese carbonate, and aluminum hydroxide are used to inform the equilibration conditions specified in the future pit model. These mineral phases are those commonly known to control reactions in pit lakes associated with neutralization of acid rock drainage (ARD; Davis *et al.* 2024; Castendyk *et al.* 2015).

Insufficient laboratory analyses from the kinetic cells precluded calculation of solute release rates from wall rock or an estimate of sulfide oxidation rate. Therefore, an important assumption in the model is the proportions of runoff that are acidic and non-acidic. One of 23 kinetic cell tests of pit wall rock is characteristically acidic with a pH between 1 and 3 and high concentrations of solutes, with the rest pH neutral with moderate alkalinity. The acidic sample came from a fault zone between dacitic intrusive rock and hornfels metasediments. Available data and lithological mapping are indeterminate about the frequency of similar sulfide-rich fault zones. Therefore, a range of 5 to 20 percent ARD was selected for the model. This range was considered reasonable, with the high end of 20 percent setting a conservative upper end.

In the simulations, calcite dissolves as needed to neutralize the acidity from ARD while maintaining calcite equilibrium and the fixed pCO2. Iron, manganese, and aluminum, introduced primarily from the pit wall runoff, precipitate to maintain the designated SIs for ferrihydrite, rhodochrosite, and aluminum hydroxide, respectively.

The model includes adsorption of arsenic and cadmium onto the precipitated ferrihydrite according to the diffuse double layer model provided by Dzombak and Morel (1990) with the inclusion of a correction factor for inefficiency. The amount of ferrihydrite available for adsorption is conservatively assumed to be approximately 50 percent of the mass calculated as the acidity of the ARD is neutralized and iron precipitates.

Abundant calcite in the pit wall rocks controls the pH in each time step. Calcite dissolves over the 100-year simulation represents a 100-year calcite "demand" required to maintain a buffered pH. This demand ranges from ≈ 0.01 g/L for Pit A under "lowest risk conditions" and ≈ 26 g/L for the Pit A under "highest risk conditions". This calcite present to meet the demand was calculated from calcite availability derived from the net acid neutralizing potential from acid-base accounting tests of pit wall rock and calcium in the assay database to determine if pits remained pH neutral.

Results

In all but one scenario, the available calcite for reaction is greater than the 100-year calcite demand. Results for each pit are summarized below and in Table 1.

Pit A:

- For maximum groundwater flow conditions, due to the large annual influxes of groundwater, total dissolved solids (TDS) and sulfate concentrations decrease in all scenarios and stabilize within the first few years; the water quality in this pit quickly evolves to reflect the chemical composition of groundwater.
- For the terminal lake condition, calcite is not sufficient to maintain circumneutral pH in the scenario in which the equilibrium water surface elevation is low and the ARD proportion is high. The model indicates a decrease in pH after calcite is depleted (after approximately 30 simulated years), to a pH of 5.3 after 100 years. TDS increases in all scenarios, quickly approaching 3,000 mg/L in the first 10–30 years of the simulation, and more gradually after the water chemistry reaches equilibrium with gypsum ($CaSO_4$).
- Arsenic concentrations in Pit A for all scenarios was above agricultural use

	Hydrologic Condition	Final Equilibrium Water Elevation	ARD %	pH	TDS*	Sulfate*	Arsenic*
Pit A	Max GW Flux	High	5	Meets	Meets	Meets	Exceeds
			20	Meets	Meets	Exceeds	Exceeds
		Low	5	Meets	Meets	Meets	Exceeds
			20	Meets	Meets	Exceeds	Exceeds
	Terminal Lake	High	5	Meets	Exceeds	Exceeds	Exceeds
			20	Meets	Exceeds	Exceeds	Exceeds
		Low	5	Meets	Exceeds	Exceeds	Exceeds
			20	Exceeds	Exceeds	Exceeds	Exceeds
Pit B	Max GW Flux	High	5	Meets	Exceeds	Exceeds	Meets
			20	Meets	Exceeds	Exceeds	Meets
		Low	5	Meets	Meets	Meets	Meets
			20	Meets	Exceeds	Exceeds	Meets
	Terminal Lake	High	5	Meets	Exceeds	Exceeds	Exceeds
			20	Meets	Exceeds	Exceeds	Exceeds
		Low	5	Meets	Exceeds	Exceeds	Exceeds
			20	Meets	Exceeds	Exceeds	Exceeds

* Indicates current pit lake water quality exceeds maximum permissible limits

Figure 5 Results of pit lake model scenarios.

standards.

Pit B:

- For maximum groundwater flow conditions, TDS and sulfate increased but reached equilibrium concentrations below water quality standards.
- For the terminal lake condition, evaporation causes TDS and sulfate to increase in all scenarios, with final TDS concentrations ranging from approximately 2,900 to 3,600 mg/L and final sulfate concentrations ranging from approximately 1,800 to 2,400 mg/L. TDS and sulfate concentrations were highest in scenarios with high ARD contribution. In all scenarios, TDS and sulfate exceed human use and agricultural contact standards.

Conclusions

Many projects lack sufficient data to perform a detailed pit lake water quality study, but many times, professionals are called upon to assess risk on a dataset with critical gaps. To assess the water quality risk of two adjacent pit lakes in an arid environment, a series of scenarios bracketing reasonable end members were constructed. The series of forward-simulations for the pit lakes and comparison with wall rock mineralogy generally suggest that pH will be buffered at circumneutral conditions in the short and long term (100 years) by the available calcite in the pit wall rocks. However, the pit lakes are unlikely to meet water quality standards for TDS and sulfate. Arsenic is unlikely to meet water quality standards in Pit A but may meet the standards in Pit B depending upon the equilibrium scenario.

The model is flexible, and run-times are short, meaning that they can be used to simulate various potential future conditions (i.e. pumping water for community use) or used to answer questions related to sensitivity of parameters. In addition, the water quality model can be easily re-run as improved hydrologic data become available to inform the water balance.

This model provided critical guidance to mine owners within a transaction to help determine the risk associated with the long-term management of Pit A and Pit B.

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