

Pit lake geochemical modelling methods for closure

MK Herrell *SRK Consulting, Canada*

AL Prestia *SRK Consulting, USA*

R Howell *SRK Consulting, UK*

G Bosley *Perpetua Resources, USA*

Abstract

Open pit mining can result in the formation of pit lakes at closure for projects that extend below the water table and have a positive water balance. The water quality of the pit lake has important implications for closure, rehabilitation and long-term management of mining projects, both financial and environmental. A prediction of future pit lake water quality is therefore necessary so appropriate mitigation strategies can be developed and implemented if required. In addition, in many environments the lake can represent a potential long-term benefit dependent on water quality.

An understanding of pit lake water quality is evaluated through the application of predictive geochemical and hydrogeological models that rely on real world inputs to define the overall system. The water quality of the pit lake is dependent on several factors, including: the quality of the groundwater and surface water entering the pit; the contribution of chemical load from the exposed talus on benches and surfaces in the highwall above the pit lake; the prevailing climate conditions and hydrodynamics of the pit lake; and pit lake water management activities. In the absence of a present day analogue, accurate prediction of future pit lake water quality can be challenging, even when industry best practices are followed.

This paper presents a case study of a pit lake geochemical model focusing on the approach and lessons learned. Generalised guidance for updating pit lake modelling best practices is also provided.

Keywords: *pit lakes, geochemical modelling*

1 Introduction

Depending on site conditions, lakes can form in mined out open pits at closure (Castendyk & Early 2009). The quality of the pit lake is a function of several factors, including: the mine plan, the hydrological conditions of the pit lake (e.g. groundwater inflow volumes), the pit refilling strategy, the composition of the pit walls, depth and density of fractures in the pit wall, the reactivity of the pit walls, pit lake hydrodynamics and in-pit chemical processes (e.g. reductive dissolution) amongst others (Howell 2002; Castendyk & Early 2009). An evaluation of the long-term pit lake water quality is needed to develop a closure plan that is environmentally protective and to develop mitigation strategies should they be needed (Howell & Parshley, 2005). How the pit is closed and any associated mitigation strategies (e.g. water treatment) that are required to close the pit lake in an environmentally protective manner have a direct bearing on project closure costs. Therefore, a detailed understanding of long-term pit lake water quality is an integral component of the mine closure process.

Long-term pit lake water quality is generally evaluated through the use of geochemical and/or hydrodynamic models by similar mechanisms to other mine site predictive models (Nordstrom & Nicholson 2017). These models rely on several inputs, which include their own inherent uncertainty and variability. Due to the importance of pit lake water quality models in the closure planning process, sufficient data is therefore required to develop a sufficiently robust model with representative source terms that produce useable predictions that are reasonable, defensible and that can be relied upon as part of the closure planning process.

A key component of the modelling process is the development of a conceptual model (Castendyk & Eary, 2009). The conceptual model describes the pertinent processes that can influence pit lake water quality. These mechanisms are subsequently incorporated into the model through the development of source terms (e.g. input water chemistries) and other assumptions (pit wall fracture depth, etc.). The conceptual model can also be used to identify data gaps where additional information needs to be collected to develop a reliable numerical model.

Source terms and assumptions are subsequently developed to account for the processes influencing pit lake water quality identified in the conceptual model (Bird & Mahoney 1994). Typical source terms include: precipitation chemistry, groundwater inflow water chemistry, pit wall runoff, chemistry of other inflows to the pit lake (e.g. active filling sources). Other assumptions built into pit lake models include: pit wall surface areas and composition, pit wall fracture depth and density, pit wall reaction rates, reactive mineral species and the associated thermodynamic database for these mineral species. A key challenge in pit lake geochemical modelling is the inherent uncertainty in each of the source terms and assumptions, which can be compounded and increase the uncertainty in the model outputs (Eary 1998).

Pit lake geochemical models are generally run deterministically. Uncertainty can be addressed through the use of conservative inputs. However, this approach can result in overly conservative outputs that may not be reasonable for use in mine planning. An alternative to addressing uncertainty is to complete a sensitivity analysis by varying the model inputs to determine which inputs the model results are most influenced by. Regardless of the approach that is selected, uncertainty in model predictions is used to identify project risks and to focus the collection of additional information, should it be required (Castendyk & Eary 2009).

Perpetua Resources Idaho, Inc. has developed a mine plan to produce gold, antimony, and silver from three open pits and legacy tailings at the Stibnite gold project (project). Two of the open pits will be backfilled and a pit lake will form in the third (West End pit). Detailed predictive geochemical modelling was completed for the project by SRK Consulting (SRK 2021a; SRK 2021b; Brown & Caldwell 2021) for each of the site facilities and downstream receptors as part of the US National Environmental Policy Act (NEPA) process. The project provides an example of the detailed modelling approach required for pit lakes at closure. This paper presents the modelling approach for the West End pit lake, including the conceptual model development and how uncertainty was addressed through model sensitivity analysis. The modelling included in this case study was developed in consultation with and reviewed by the US Forest Service (USFS), Idaho Department of Environmental Quality (IDEQ) and the US Environmental Protection Agency (EPA) and is therefore a modelling approach that is considered reasonable for evaluating pit lake water quality.

2 Project background

The project is located in the Stibnite-Yellow Pine Mining District in central Idaho, approximately 160 air kilometres northeast of Boise, Idaho, 60 km east of McCall, Idaho, and 60 kilometres east of Yellow Pine, Idaho (Figure 1). The property is in mountainous terrain at an elevation of approximately 2,000 metres above sea level, in the Salmon River Mountains. The area consists of uplifted rocks of the Idaho Batholith, Palaeozoic and Proterozoic metamorphic rocks and Cenozoic volcanics which are deeply incised by the East Fork of the South Fork of the Salmon River (EFSFSR). The EFSFSR traverses the central portion of the Yellow Pine deposit and is near both the planned West End and Hangar Flats pits.

The district is characterised by historical mining activities on unpatented (federal) and patented (private) land which hosts deposits of gold, silver, tungsten, and antimony. The Stibnite-Yellow Pine Mining District is in the Boise National Forest (BNF) but is administered by the Krassel Ranger District of the Payette National Forest (PNF).

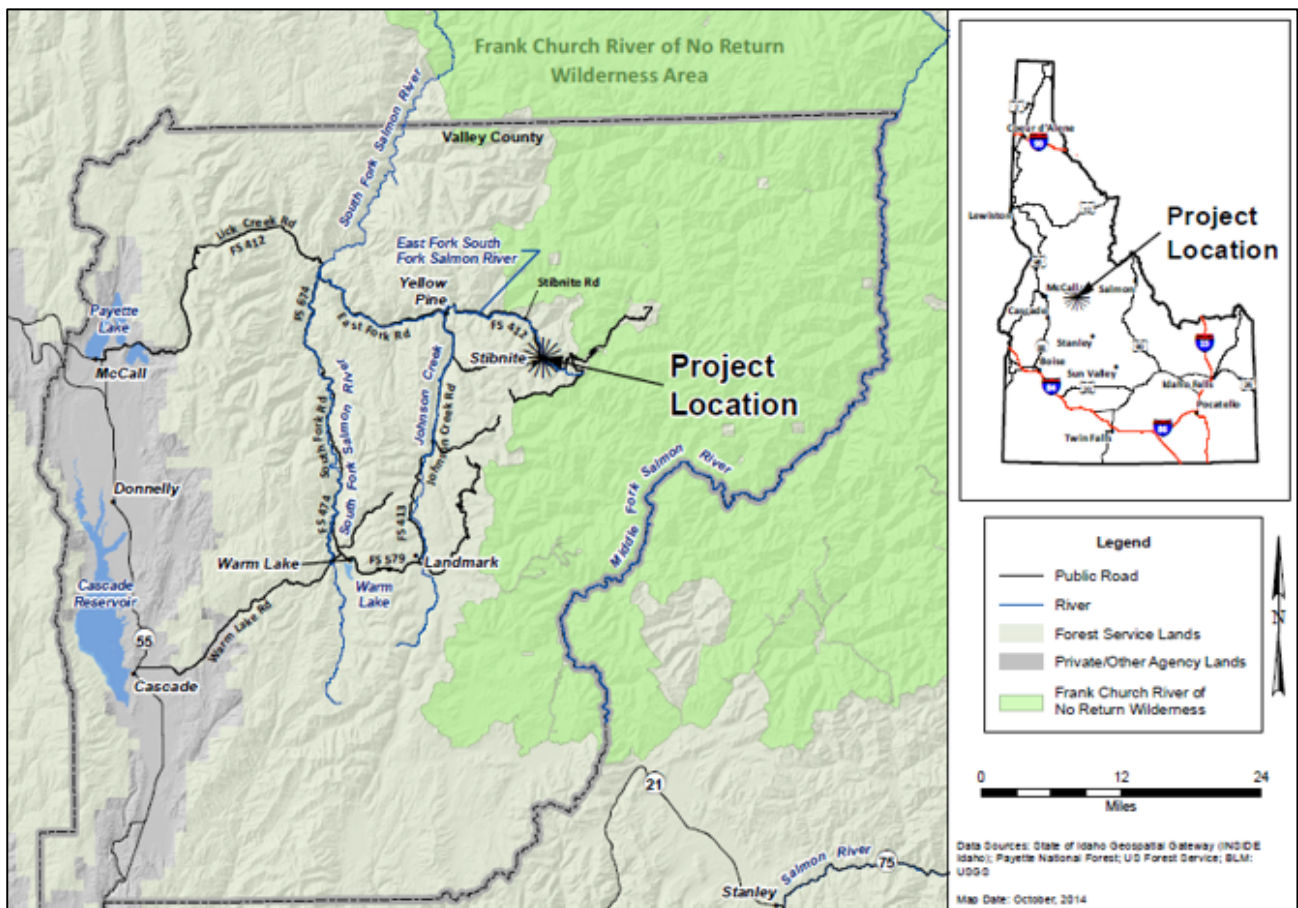


Figure 1 Stibnite gold project vicinity map

Ore will be mined from three open pits: Hangar Flats, Yellow Pine pit and West End. Open pit mining has previously occurred in the Yellow Pine and West End pit, while Hangar Flats pit was the site of underground mining in the 1930s. The Yellow Pine pit will be mined first, followed by the Hangar Flats pit. The West End pit will be mined last and development rock produced from this pit will be used as backfill in the Hangar Flats and Yellow Pine pits. A pit lake is predicted to form in the West End pit at closure (Brown & Caldwell 2021).

3 Conceptual model development and methods

3.1 Geochemical conceptual model

A generalised conceptual model for the West End pit lake is presented in Figure 2. Each source that could influence the pit lake chemistry was assigned a source term based on geochemical testing data or water quality monitoring results. The West End pit will be passively filled at closure from the following inflows (Figure 2): runoff from exposed pit walls, groundwater inflows, streamflow from West End Creek, runoff from undisturbed catchment areas uphill of the highwalls, and precipitation directly onto the pit lake surface. Outflows from the pit lake include losses to groundwater and evaporation. There is no surface discharge from the pit lake. Pit lake levels are estimated to require approximately 56 years to reach equilibrium (Brown & Caldwell 2021).

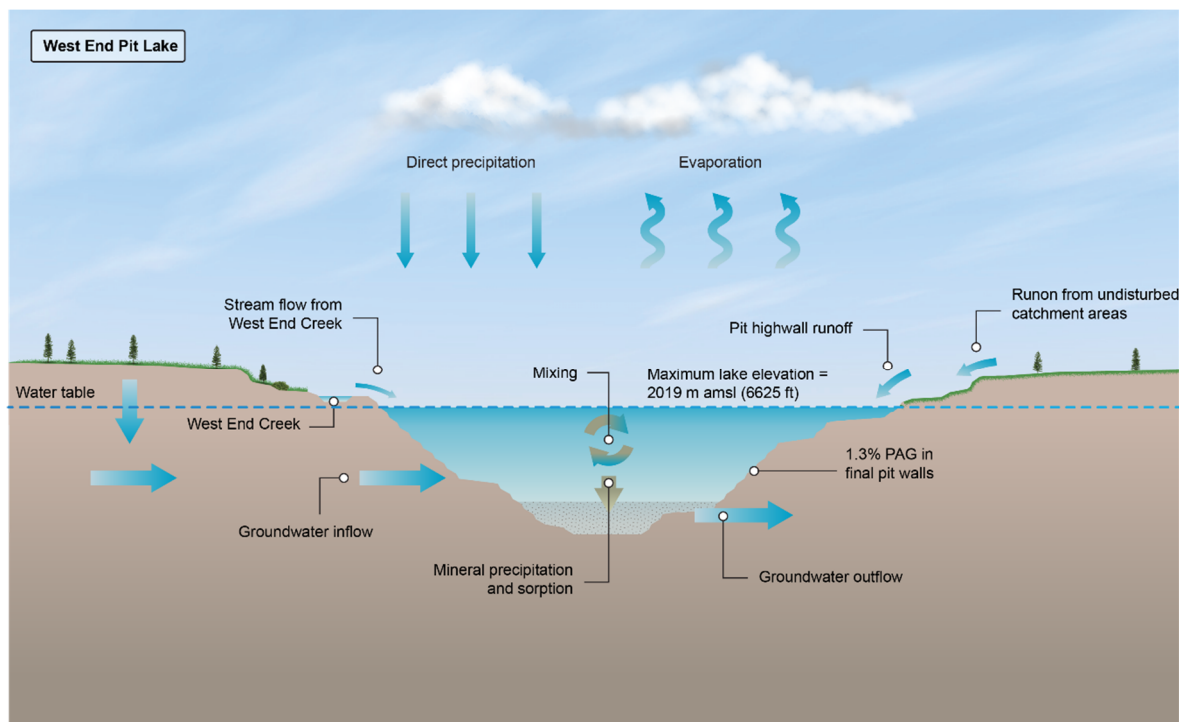


Figure 2 West End pit lake conceptual model

A key component of the conceptual model is how incident precipitation contacting pit walls interacts with exposed surfaces and releases stored oxidation products on these surfaces. Figure 3 presents the conceptual model for pit walls. The amount of mass that is available to react is dependent on the chemical composition of the pit rock (SRK 2021a), fracture depth in pit wall surfaces and the fracture density in the damaged rock zone. Details of the assumptions used for these parameters are discussed in Section 3.2. In addition to the fracture zone described above, mineralogy work carried out by SRK on HCTs for other projects identified that particles generally exhibit water infiltration and products of reactivity up to 0.012 m on the surfaces of similar geological lithology fragments. Mass release from the reactive rim or ‘oxidised rind’ was also included in the geochemical conceptual model.

The pit lake conceptual model assumes flushing of solutes from pit wall fractures by groundwater will only take place in the ‘active’ zone of groundwater inflow (Figure 4), and the flushing of oxidation products will end once the pit walls become submerged. Pit walls were assumed to be non-reactive below the zone of active groundwater inflow and do not contribute load to the pit lake.

Talus will be present on pit benches. Oxidised load from these materials will be flushed by meteoric water, during flooding and when it is stored in the ‘active’ zone of groundwater inflow (Figure 4). Mass release from talus stored on pit benches is a process also considered in the West End pit lake conceptual model. Where prolonged erosion and weathering occurs in the pits, this source can potentially become a significant source of solutes to a pit lake as talus accumulates over time.

Reactions of the water with secondary mineral phases within the pit lake is considered a pertinent process influencing pit lake water quality (Figure 2). Precipitation of secondary mineral phases was also considered in the West End pit conceptual model.

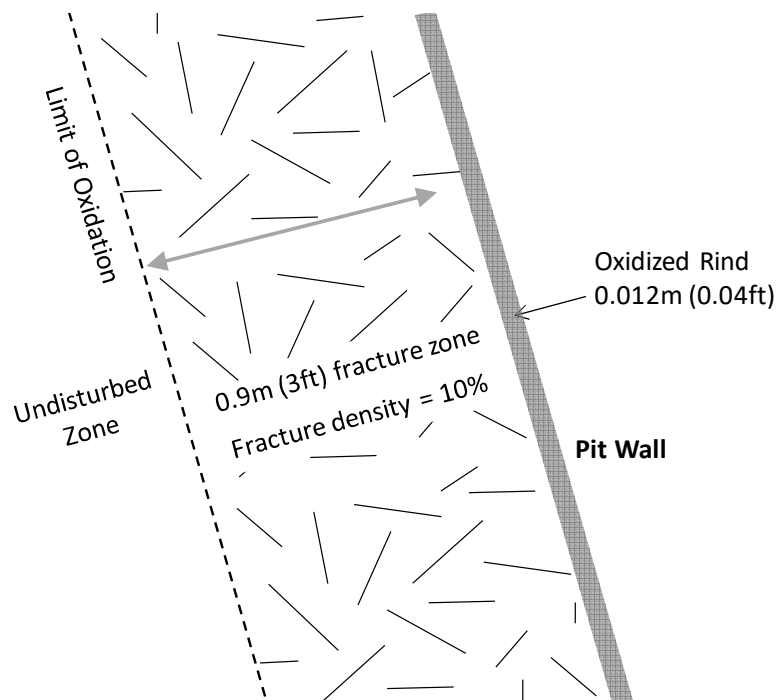


Figure 3 Pit wall conceptual model

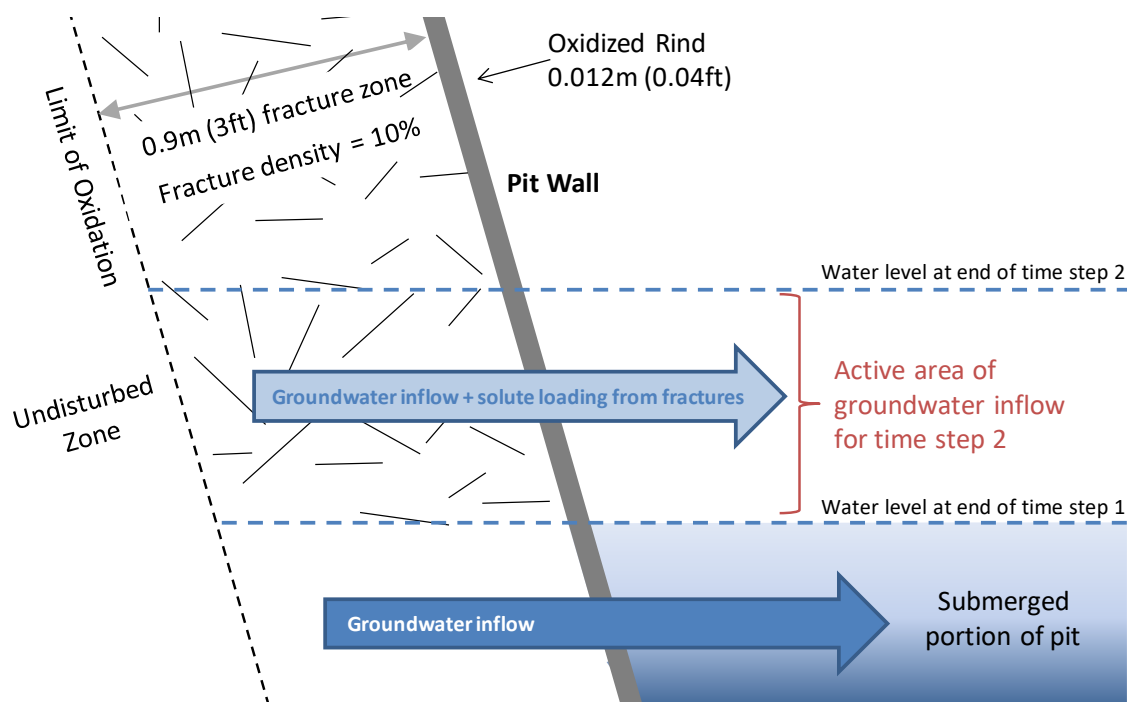


Figure 4 Pit wall conceptual model showing zone of active groundwater inflow

3.2 Numerical model

The geochemical pit lake numerical model was developed using the publicly available speciation and mass transfer code PHREEQC (Parkhurst & Appelo 1999) developed by the United States Geological Survey (USGS). The resultant pit lake geochemical prediction is based on mixing of the inflow sources (e.g. groundwater, pit wall runoff, runoff from undisturbed catchment areas, precipitation and surface water sources) in ratios defined in the refined Modified Plan of Restoration and Operations (ModPRO2) modelling report (Brown & Caldwell 2021).

The mixing step can be described by the following formula:

$$C_{\text{Pit Lake}} = \frac{\sum_{i=1}^n (C_{\text{in}} \times Q_{\text{in}}) - \sum_{i=1}^n (C_{\text{Pit Lake}} \times Q_{\text{out}}^*)}{\sum_{i=1}^n Q_{\text{in}} - \sum_{i=1}^n Q_{\text{out}}} \quad (1)$$

where:

$C_{\text{Pit Lake}}$ = modelled pit lake concentration.

C_{in} = water quality of each source recharging the pit lake.

Q_{in} = volume of each inflow source.

Q_{out} = volume of each outflow source.

*Does not include evaporation.

Direct precipitation, groundwater inflows and West End Creek inflows were assigned average source term water qualities based on monitoring results representative of these sources. The pit wall chemistry was represented by the results of humidity cell tests (HCTs) that are appropriately scaled to reflect the mass release of solutes under field leaching conditions, compared to the laboratory scale tests that are operated at a fixed liquid-to-solid ratio. The HCT data have been scaled from lab to field conditions based on the volume of inflowing water (groundwater or runoff) during each time step as defined by pit lake water balance (Brown & Caldwell 2021) in addition to the reactive mass of material in the pit walls and talus on the horizontal benches. This reactive mass is calculated using assumptions regarding pit wall fracturing, material density, surface areas and likely thickness of talus remaining on the pit benches at closure.

Groundwater flowing into the 'active' zone of groundwater flow is represented by groundwater input chemistry data plus a mass of solute leached from the wall rock and talus in the active inflow zone, derived from the HCT data. Groundwater flowing into the fully submerged portion of the pit is represented by the groundwater source term chemistry input (i.e. no additional load from the pit walls is added).

The pit lake chemistry was first estimated through conservative mixing of each of the inflow sources using Equation 1. Mass was removed via one of the following two pathways: 1) through advective mass transport in pit lake recharge to groundwater and surface water discharge to West End Creek; or, 2) through mineral precipitation of supersaturated secondary mineral phases. Supersaturation of the following secondary mineral phases was evaluated in the model: calcite, $\text{Ba}_3(\text{AsO}_4)_2$, CdMoO_4 , ferrihydrite, fluorite, gibbsite, gypsum, Hg-metal, malachite, MnHPO_4 , pyromorphite, SbO_2 and Smithsonite. Supersaturated mineral phases were allowed to precipitate from solution and sorption to ferrihydrite was considered using the default values of Dzombak & Morel (1990).

The following assumptions were used to calculate the reactive mass in pit wall surfaces and talus stored on the pit benches:

- A fracture depth of 0.9 metres (m) (Kelsall et al. 1984).
- A fracture density of 10% (Siskind & Fumanti 1974; Kelsall et al. 1984).
- A reactive rim or 'oxidised rind' of 0.012 m.
- Site-specific rock densities were used to calculate the reactive mass in the pit walls.
- A talus thickness of 1.6 m composed of a mix of fine and coarse grains.

The pit lake chemistry was predicted annually over a 100-year model duration.

3.3 Sensitivity analysis

The generalised approach described above represents the 'base case' model configuration. As discussed in Section 1, a sensitivity analysis is a necessary component of a robust pit lake geochemical model. One of the

greatest uncertainties in any pit lake model are introduced by the estimates of pit wall fracture depth and density that are used to scale the laboratory data to field conditions. Therefore, a sensitivity analysis was completed to evaluate changes to water quality by decreasing the pit fracture depth to 0.3 m (referred to here as the low reactive mass sensitivity) and increasing the fracture depth to 1.8 m (referred to here as the high reactive mass sensitivity). Chemical release rates were scaled to field conditions. The average annual temperature of 2.8°C was used in the base case. To evaluate the influence of higher temperatures on the pit lake water quality, a sensitivity using a reaction temperature of 12°C was included. This is referred to here as the high temperature sensitivity.

4 Results and discussion

The West End pit lake model was set up to simulate concentrations of multiple constituents in the pit lake during closure. The key constituents for the project are arsenic, antimony and mercury. For brevity, only results for these constituents are presented here, however, a full water quality chemistry suite was included in all numerical simulations and it is essential to do so to account for potential chemical interactions. Predicted concentrations for the base case and the three sensitivity scenarios are presented in Figures 5 to 7. Predicted concentrations are compared to the strictest potentially applicable surface water quality standard for the project, the IDAPA 58.01.11 groundwater quality standard and the average concentration of measured values from a groundwater well installed in the vicinity of the proposed West End pit.

Predicted concentrations of arsenic, antimony and mercury decrease during the post-closure period (Figures 5 to 7). This occurs as the pit fills and reduces the exposed wall rock surface area and talus above the water table. The pit elevation decreases after approximately year 75 and arsenic, antimony and mercury concentrations begin to slightly increase in the West End pit lake as a result of additional wall rock surface area being exposed above the water table.

The importance of the chemical load concentration from the wall rock becomes apparent in the sensitivity analysis. As would be expected, predicted concentrations decrease in the low reactive mass sensitivity and increase in the high reactive sensitivity. The model results are most sensitive to the increase in temperature to 12°C and maximum concentrations of arsenic, antimony and mercury are predicted for the high temperature sensitivity.

The sensitivity analysis provides a range of potential concentrations around the base case. The high temperature sensitivity was not considered a realistic scenario for the project since the model is evaluated on an annual timestep. The climate at the project is defined by very distinct cold winters, warmer summers and transitional fall and spring months. Therefore, use of an ambient temperature of 12°C is considered too conservative in the current model configuration (i.e. using an annual timestep). The average annual temperature is considered more reasonable.

Relying on the base case for mine planning purposes was considered reasonable for the project since the other model sensitivities did not change the overall outcomes of the base case. The high reactive mass sensitivity did not result in predicted concentrations being greater than the comparative criteria for which the base case was below these criteria. The exception to this is antimony that was above or near the background groundwater in the base case until mine year 34 but was mainly above the background groundwater concentration for the majority of the model run in sensitivity 2 (Figure 6). If the model sensitivity resulted in different model outcomes, then the sensitivity is identified as being an important control and more effort is needed to determine the importance and likelihood of the sensitivity parameter value being realised.

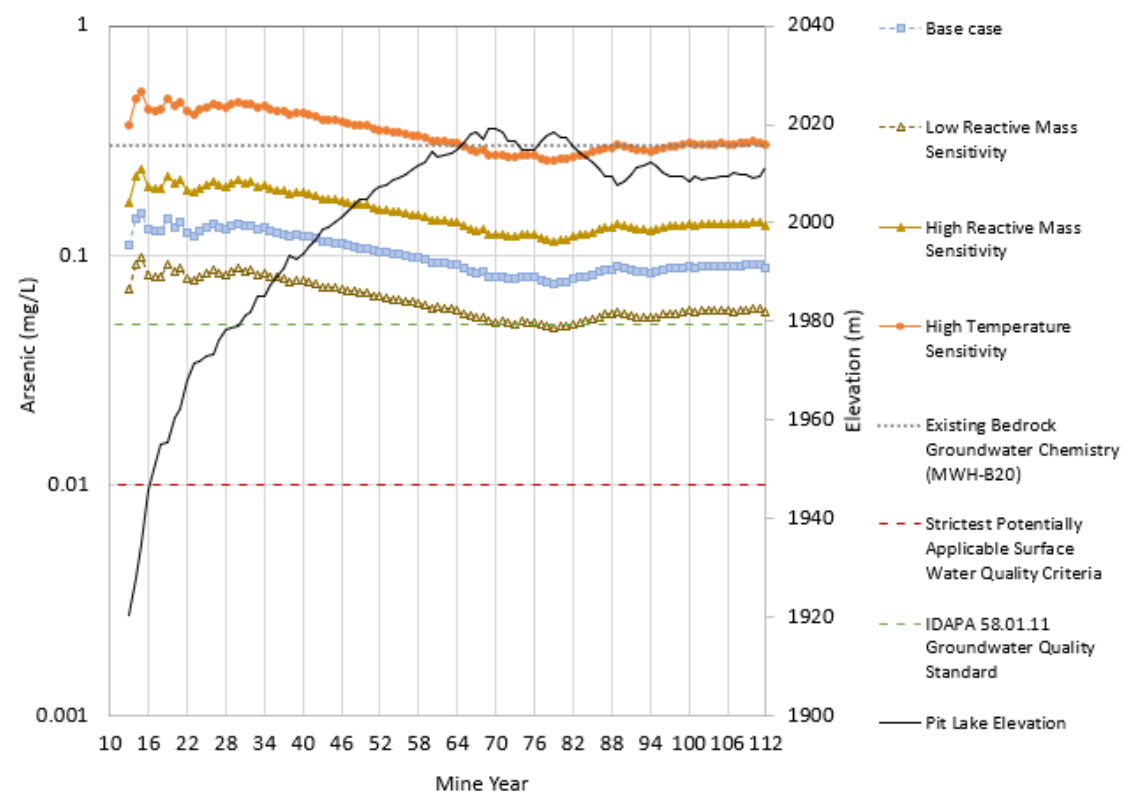


Figure 5 Predicted West End pit lake arsenic concentrations

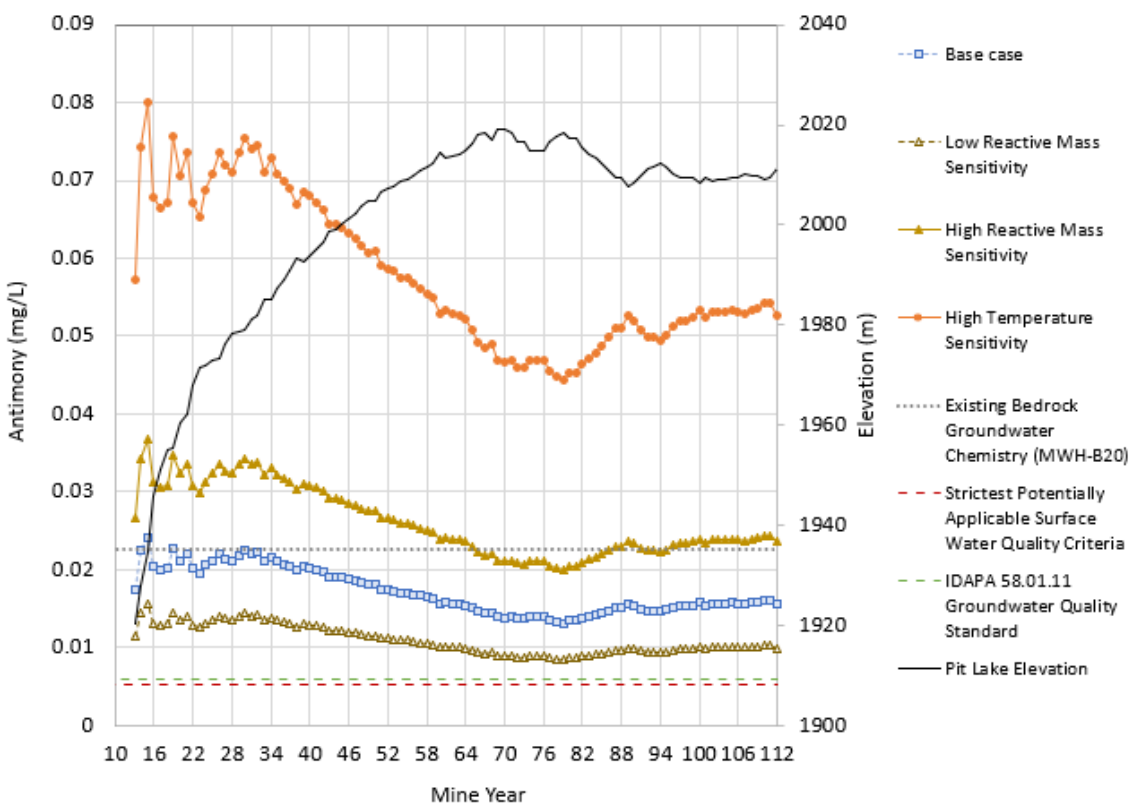


Figure 6 Predicted West End pit lake antimony concentrations

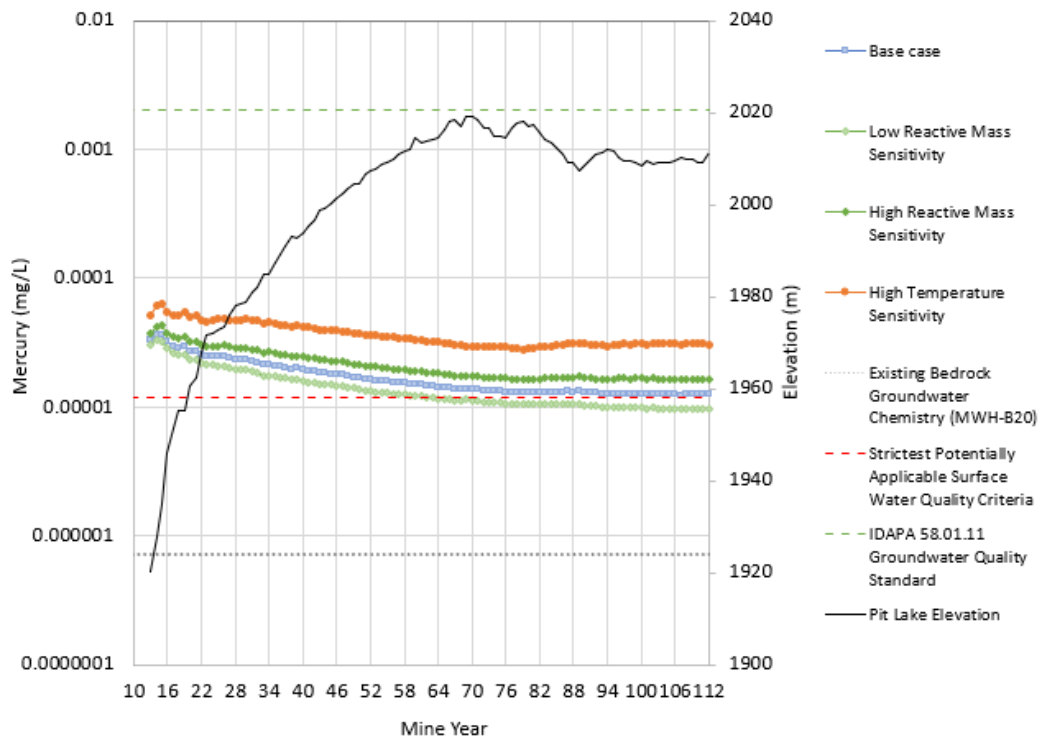


Figure 7 Predicted West End pit lake mercury concentrations

5 Conclusion

Geochemical models provide a tool for predicting the long-term chemistry of pit lakes. The results are used to determine if proposed closure strategies are environmentally protective and to develop mitigation strategies if required. The results of pit lake geochemical models have direct input into mine closure cost estimation and, therefore, the models need to be developed so they produce reasonable and defensible results. This poses a challenge for modellers since a balance between conservatism and realism must be struck. For example, if the model produces an overly conservative model prediction, then closure costs could be overestimated. Conversely, underprediction could result in retroactive management being required which will incur project costs that were unforeseen at the closure design stage.

The first step in pit lake modelling is to develop a comprehensive conceptual geochemical model. The conceptual model is used to identify all the pertinent processes that need to be included in the numerical model. This allows the modeller to determine if sufficient data is available to develop a reliable pit lake model or if additional data collection is required. The conceptual model should not be considered static and needs to be refined and updated as additional information becomes available as projects progress and models are developed.

For projects that do not yet exist, all of the model inputs and assumptions contain uncertainty which needs to be considered and evaluated. One method used to address uncertainty is to be conservative in all of the model inputs. However, this approach often produces unrealistically high concentrations that may not be useful for closure planning. In the case of the West End pit lake, input uncertainty was addressed through model sensitivity analyses on the known drivers of the predicted pit lake water quality in the model. The outcome of this approach was that the overall conclusions of the model did not change even when predicted concentrations increased. This provides confidence that the predicted base case concentrations for the project are reasonable. This statement does not imply that the pit lake model produces absolute concentrations that will be realised in post-closure but only that the predictions are reasonable and can be used for environmental assessment and closure planning purposes. Both the conceptual and numerical models will require regular updates as more site-specific information becomes available as the project progresses through the planning and operational phases.

6 Acknowledgements

We thank Alan Haslam at Perpetua Resources Idaho, Inc. for allowing us to use Stibnite gold project data in the preparation of this paper. We also thank Claire Linklater from SRK Australia for her support on this project.

References

- Bird, DA & Mahoney, JJ 1994, 'Estimating post mining pit lake geochemistry utilizing geochemical and numerical modelling', *SME Preprint 94-241*, Littleton Colorado.
- Bowell, RJ 2002, 'Hydrogeochemical dynamics of pit lakes', in PL Younger & N Robins (eds), *Mine Water Hydrogeology and Geochemistry*, Geological Society of London Special Publication, pp. 159–187.
- Bowell, RJ & Parshley, JV 2005, 'Controls of pit lake chemistry by secondary minerals, Summer Camp Pit, Nevada', *Chemical Geology*, vol. 215, pp. 373–385.
- Brown & Caldwell 2021, *Draft Stibnite gold project stibnite hydrologic site model refined modified proposed action (ModPRO2) report*.
- Castendyk, DN & Eary, LE (eds) 2009, 'Mine pit lakes: characteristics, predictive modeling and sustainability', SME, Littleton, Colorado, 304 p.
- Dzombak, DA & Morel, FMM 1990, *Surface complexation modeling: hydrous ferric oxide*, John Wiley and Sons, Inc.
- Eary, LE 1998 'Predicting the effects of evapoconcentration on water quality in mine pit lakes', *Journal of Geochemical Exploration*, vol. 64, pp. 223–236.
- Kelsall, PC, Case, JB & Chabannes, CR 1984, 'Evolution of excavation-induced changes in rock permeability', *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, vol. 21, no. 3, pp. 123–135.
- Nordstrom DK & Nicholson, A (eds) 2017, 'Geochemical modelling for mine site characterization and remediation', SME, Littleton.
- Parkhurst, DL & Appelo, CAJ 1999, 'User's guide to PHREEQC (version 2) – A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations', *US Geological Survey Water-Resources Investigations Report 99-4259*, 312 p.
- Siskind, DE & Fumanti, RR 1974, 'Blast-produced fractures in Lithonia granite', US Bureau of Mines, *Report of Investigations 7901*, US Department of the Interior Library.
- SRK 2021a, 'Stibnite gold project ModPRO2 site-wide water chemistry (SWWC) modeling report', SRK Consulting (USA) Inc., prepared for Perpetua Resources Idaho, Inc.
- SRK 2021b, 'Stibnite gold project ModPRO2 site-wide water chemistry (SWWC) sensitivity analysis report', SRK Consulting (USA) Inc., prepared for Perpetua Resources Idaho, Inc.