

Pit Lake Water Quality Modelling at Century Mine

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This paper was first presented at the 9th Australian Workshop on Acid and Metalliferous Drainage on 20-23 November 2017.

Abstract

The Century open cut zinc mine at Lawn Hill recently changed ownership from MMG Limited (MMG) to New Century Resources (NCR). Closure planning for the site was initiated by Zinifex, developed further by MMG, and is continuing under the new ownership. The waste rock dumps will be covered with a store and release cover system to meet closure objectives. However, the open pit, which is partially backfilled with waste rock, is expected to fill with water post closure to form a pit lake. As part of developing the site closure strategy, the final pit lake level (i.e. risk of discharge), and water quality that may develop within the lake post closure, were identified as potential risks to meeting downgradient water quality objectives. To evaluate this risk, a pit lake model has been developed that integrates outputs from geochemical characterisation programmes, water balance studies and hydrogeological modelling. The model quantifies solute production from pit walls and mineralised wastes located within the pit, and accounts for potential influence from out-of-pit waste dumps. Pit lake water quality is calculated over time, allowing assessment of potential impacts to surface and groundwater, and third party receptors. Using the predictions from the model, it has been possible to compare potential environmental outcomes for different closure strategies and assumptions, thus allowing prioritisation of forward works and informed selection of optimal closure measures.

1. Introduction

Figure 1 shows the layout of Century mine site, and the mine setting with respect to local surface watercourses. Page Creek, the most proximal creek to the pit, has undergone a number of phases of diversion and realignment (1997-2014) to re-route streamflow around the western margin of the pit.

The Century pit is approximately 330m deep, with a circumference of 6,800 m. The pit wall rock comprises predominantly siltstone and shales near the base (including mineralised zones). The intermediate portion of the walls are sandstone, and the topmost portions are Thornton limestone.

Three external waste rock dumps are located around the edge of the pit, and a fourth dump is located within the confines of the pit (the in-pit dump). The in-pit dump occupies a significant volume, and contains highly reactive sulfide minerals as evidenced by elevated temperatures (up to 300°C) and periodic gaseous emissions (SO₂, steam and smoke) from the dump surface.

A tailings storage facility (TSF) and an evaporation dam are located to the south east of the pit. Due to mounding of the local groundwater table beneath these facilities during operations, the TSF and evaporation pond have been linked to surface expressions of localised seepage and minor ephemeral impacts within the surface water regime. Closure options for the TSF include

- (i) leaving the existing facility in place and emplacing a cover, or
- (ii) deposition of the tailings in the pit, either with or without re-processing to recover metals. The evaporation dam would be dewatered and the embankment removed.

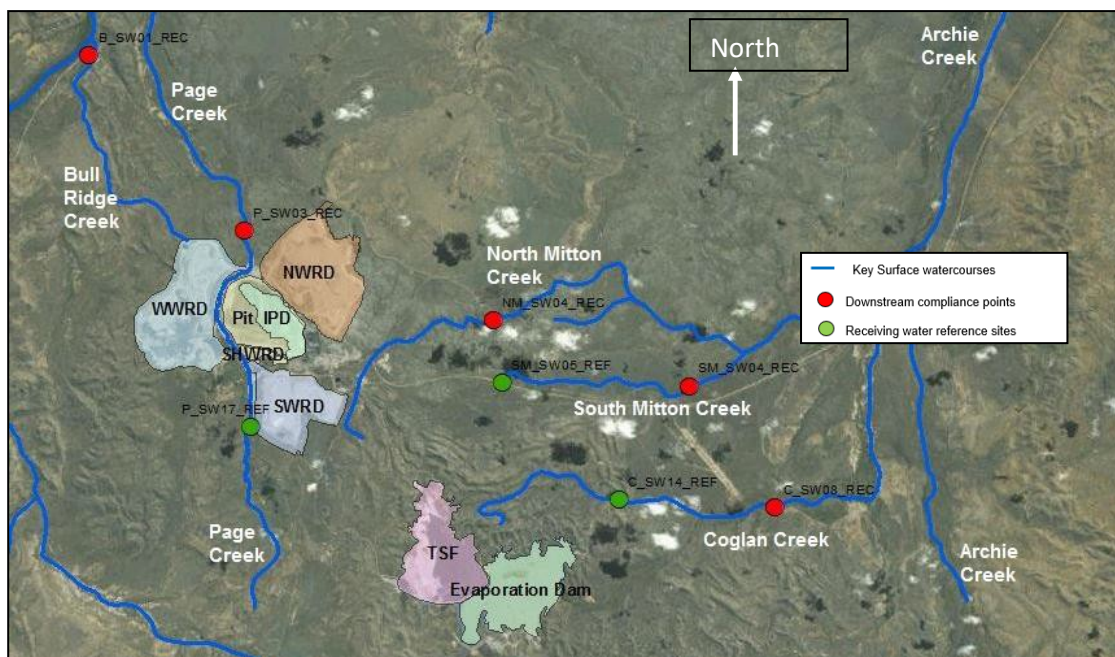


Fig. 1. Schematic of Century Mine and surrounds

Post-closure, a lake will develop within the pit. This paper describes modelling of pit lake water chemistry, accounting for the influence of solute production from exposed pit walls, external and internal waste rock dumps, and the tailings. Three primary closure scenarios were assessed for the tailings as summarised in Table 1.

Table 1. Summary of assessment scenarios

Scenario	Description
1	No tailings in pit
2	Tailings deposited in-pit (not re-processed) based on the two hydraulic mining rates: 650 tonnes per hour (tph) and 2,000 tph.
3	Tailings deposited in-pit (re-processed for metal recovery) based on the two hydraulic mining rates: 650 tph and 2,000 tph.

2. Long-Term Pit Hydrogeology and Water Balance

The most recent hydrogeological model for the Century site was developed on behalf of MMG by others, and implemented using a FEFLOW modelling platform. This included modelling to support the current assessment. Based on the groundwater inflow modelling, a pit water balance model was also developed on behalf of MMG (using GoldSim). The Goldsim model was modified to calculate pit water balances for the transfer of tailings from the existing TSE and the modified model was made available to SRK for the current assessment.

If current creek and catchment diversions remain in place, surface catchment inflows are minimized and pit lake elevations are expected to remain low. The pit would become a long-term groundwater sink (Figure 2).

For this outcome:

- Water rebound times were of order 130 to 170 years.
- Water elevations in pit would remain approximately 30 to 40 m below the pit crest, and would remain below the pre-mining groundwater table.
- A groundwater drawdown cone could extend many kilometres from the pit, particularly to the north where the main aquifer host is the more permeable Thornton Limestone.
- External waste rock dumps footprints would fall within the drawdown zone for the pit.

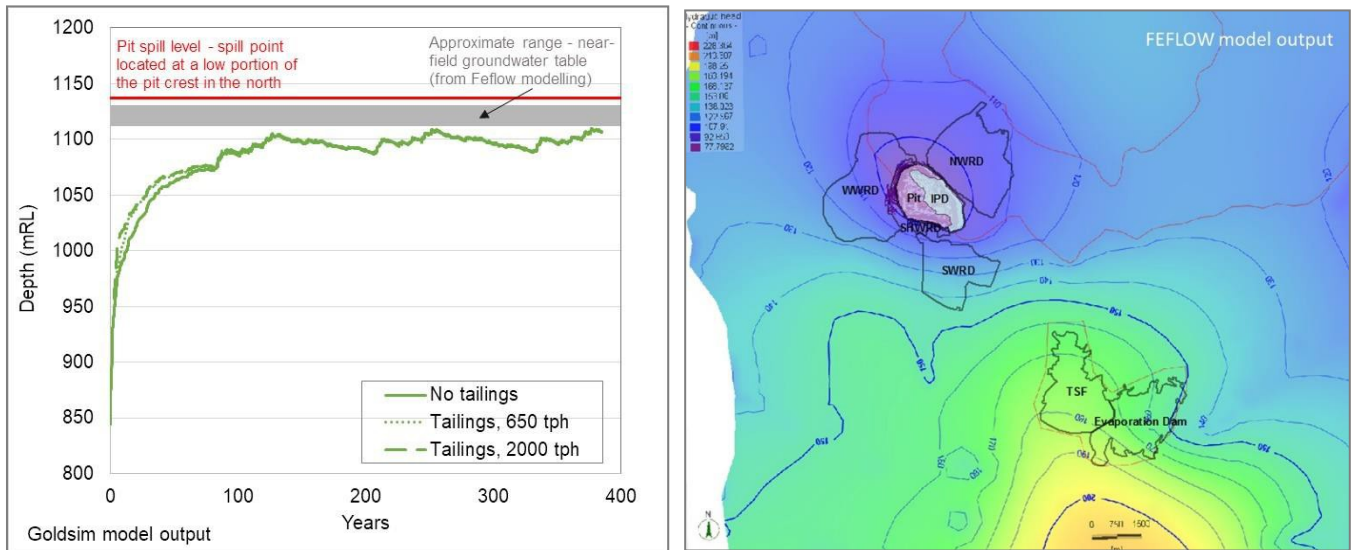


Fig. 2. Lake elevations and groundwater contours around the pit, for a permanent sink case

Should diversions fail (e.g. breaching of diversions close to the pit crest due to pit wall failure or flows greater than the design flood), then the water balance would change and lake levels would rise. For such a case, intermittent pit discharges are predicted to occur in the long term (Figure 3). These could comprise both groundwater (through-flow) and surface water discharges.

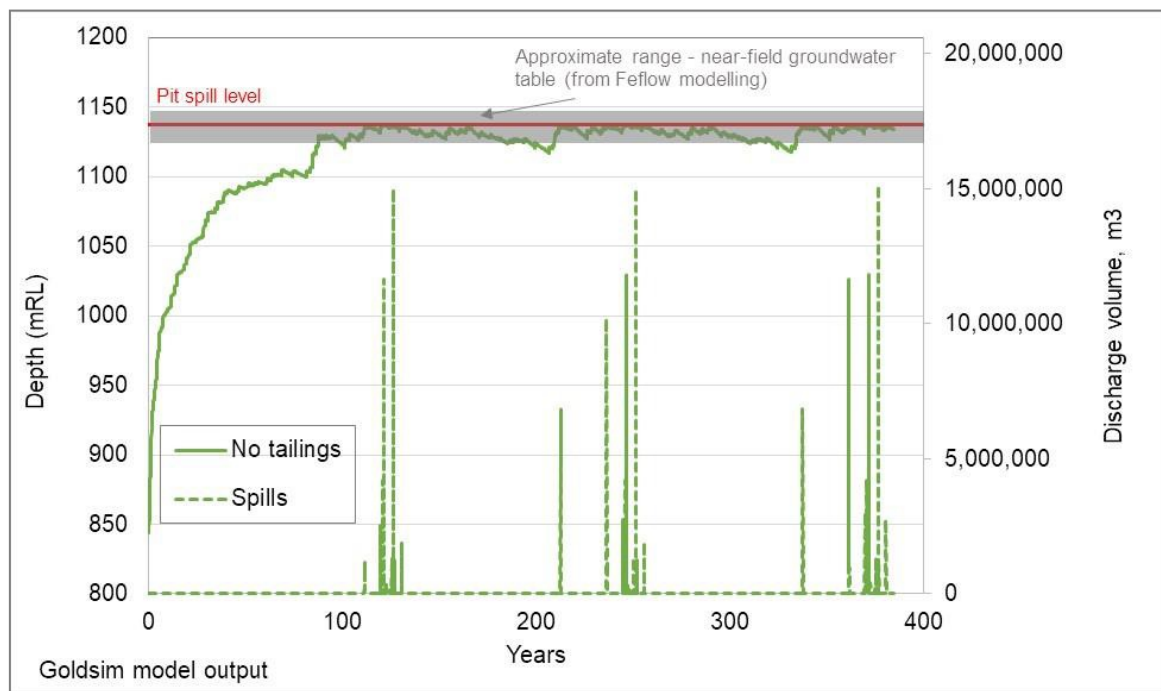


Fig. 3. Pit lake elevation as a function of time (intermittent pit discharge)

3. Solute Sources

Figure 4 shows a schematic representation of pit lake solute sources, which include:

- Inflowing groundwater (groundwater in the area can be saline; total dissolved solid content up to 1000 mg/L);
- Pit wall runoff (e.g. soluble salts that form on exposed walls, or within rubble (talus) that has accumulated along benches);
- Percolate and runoff from mineralised wastes placed within the pit (i.e. the in-pit dump, and possibly tailings); and

- Percolate and runoff from external waste rock dumps located within the pit catchment and groundwater drawdown zone.

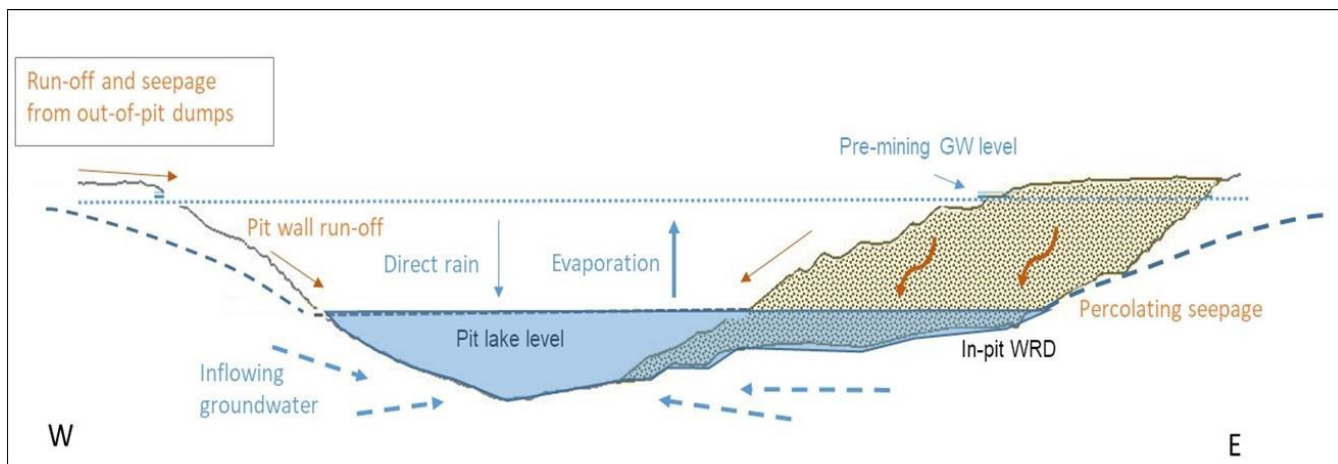


Fig. 4. Schematic showing potential pit lake solute sources

Geochemical characterisation of Century materials included kinetic (column) testing of waste rock and tailings. Results from these tests were used to develop an understanding of key controls on solute production from pit walls and internal/external waste rock dumps, and indicated:

- Sulfate release rates did not correlate well with total sulfur content – probably reflecting complex sulfide mineralogy within the samples. Abundant sulfides included pyrite, galena and sphalerite. Oxidation rates determined from sulfate generation rates were influenced by sulfate storage in the columns (e.g. galena-rich samples likely were influenced by lead sulfate formation).
- Non acid forming (NAF) classed samples generated near neutral pH leachates with molar ratios of Ca (or Mg) to SO₄ that were consistent with neutralisation by Ca- or Mg- carbonates.
- Acidic leachates contained relatively high concentrations of elements such as Al, Co, Fe, Mn, Ni and Zn.
- The highest sulfate and metal release rates were observed for samples believed to have been affected by high temperature alteration (considered evidence of high oxidation rates). Such samples are expected to contain high quantities of soluble oxidation products.

From the kinetic test results, ‘average’ solute release rates were calculated for NAF and PAF-classed materials (Table 2). These laboratory-derived release rates were scaled to the field conditions to account for particle size distributions, water-rock contact, temperature, and the availability of oxygen. Whilst not expected to be limiting under laboratory operating conditions, oxygen availability would constrain reaction rates in the field. Elevated temperatures – such as those observed within the in-pit dump – would be expected to result in increases to solute production rates. The scaling factors adopted were modified according to the regime: intact pit walls, talus on benches, in-pit dump material or out-of-pit dumps.

Table 2. Laboratory-derived solute production rates and scaling factors[1]

Parameter	Average release rate, mg/kg/week		Scaling factors ^[2]	Regim			
	Acid conditions	Neutral conditions		Talus on benches	Intact wall rock	In-pit dump	Ex-pit
SO ₄	500	76	Surface area correction	0.2	0.01	0.2	0.2
Ca	15	7.8					
Mg	57	13					
K	30	0.62	Fraction flushed by contact water 0.9	0.3	0.3	0.3	0.3
As	0.0025	0.000074					
Cd	0.06	0.00095					
Co	0.39	0.0024					
Cu	0.1	0.00013					

Parameter	Average release rate, mg/kg/week		Scaling factors ^[2]	Regime			
	Acid conditions	Neutral conditions		Talus on benches	Intact wall rock	In-pit dump	Ex-pit dump
Fe	1.8	0.003	Temperature correction	1	1	10	2
Mn	43	0.28					
Ni	0.58	0.0012					
Pb	0.0036	0.066	Oxygen availability	1	1	1	0.1
Se	0.0028	0.00088					
Zn	31	0.5					

Note:

[1] Laboratory rates are multiplied by the scaling factors to derive release rates applicable to field conditions

[2] Scaling factor values are assigned based on theoretical considerations (e.g. surface area as a function of particle size, Arrhenius equation for the temperature dependence of reaction rates) and professional experience.

The tailings, if placed in the pit, would be placed as a slurry; the liquid component of the slurry will be saline and result in an increase in solute loading to the pit. Geochemical properties of the tailings solids, before and after reprocessing to recover metals, are presented in Table 3. The total sulfur, sulfide and associated metal contents of reprocessed tailings would be reduced, compared to the current tailings. A consequent reduction in net acid production potential and metal leachability is indicated for reprocessed tailings.

Once the tailings have been placed in the pit and inundated, little difference to environmental outcomes would result whether the tails are reprocessed or not, since future sulfide oxidation will be precluded (rates of sulfide oxidation are limited by the low solubility of oxygen in water).

Table 3. Geochemistry of tailings, before and after re-processing

Parameter	Current tailings (n=10, unless indicated otherwise)	Re-processed tailings (n=2)
Total sulfur, %	3.4 – 7.3	1.8 – 2.2
Sulfide sulfur, %	2.5 – 5.4 (n=4)	1.6 – 1.7
Acid neutralising capacity, kg H ₂ SO ₄ /t	16 – 40	5 – 17
Net acid production potential, kg H ₂ SO ₄ /t	72 – 206	38 – 61
AMIRA classification	Potentially acid forming (PAF)	Uncertain (PAF)
Fe, %	7.3 – 9.4	9.0 - 9.6
Pb, ppm	2,900 – 8,100	3,500 – 3,700
Zn, ppm	25,200 – 56,300	14,800 – 17,800

4. Estimated Pit Water Quality

The pit lake water is expected to become more saline over time due to solute accumulation combined with evapo-concentrating effects. Figure 5 shows calculated sulfate concentrations as a function of time for two scenarios – permanent sink and intermittent through-flow/over-topping. Similar profiles are calculated for other solutes. Small-scale variability in concentration reflects fluctuation in pit lake volume due to seasonal rainfall and evaporation patterns.

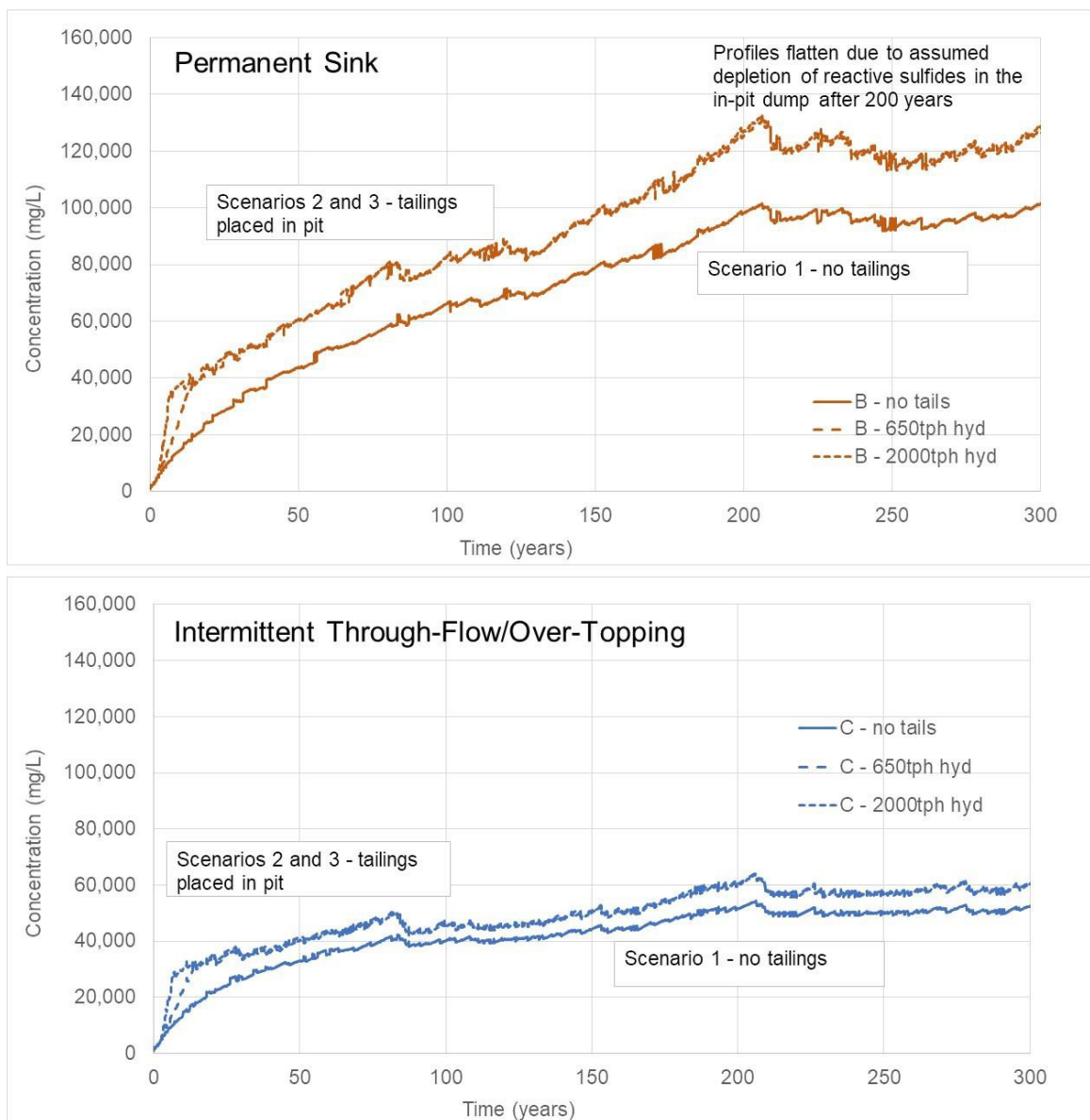


Fig. 5. Sulfate concentration as a function of time – base case input parameters

For the permanent sink case, concentrations are consistently higher than those calculated for the intermittent through-flow/over-topping case due primarily to: i) greater exposure of reactive sulfide on pit walls and unsaturated in-pit dump materials leading to higher net solute loadings; no solutes are removed from the system (i.e. no discharge); and iii) the effects of ongoing evaporation (i.e. evapo-concentration and the pit remaining a net water sink).

In the event that tailings are deposited in the pit, solute loadings are higher due to high solute content in the process water component of the tailings slurry. Calculations were completed based on two tailings deposition rates (650 and 2,000 tph). Comparison of the sulfate profiles for the two cases shows that tailings placement rates influences the rate of change in sulfate concentration in the short-term; however, it has little influence on the long-term outcomes.

Since certain model inputs were based on assumed values, sensitivity analyses were carried out to determine the degree of influence certain key inputs and assumption had on model outcomes. Selected outcomes from these calculations are illustrated in Figure 6. Uncertainty in parameterization of solute production from the in-pit dump was found to have the greatest influence on model outcomes.

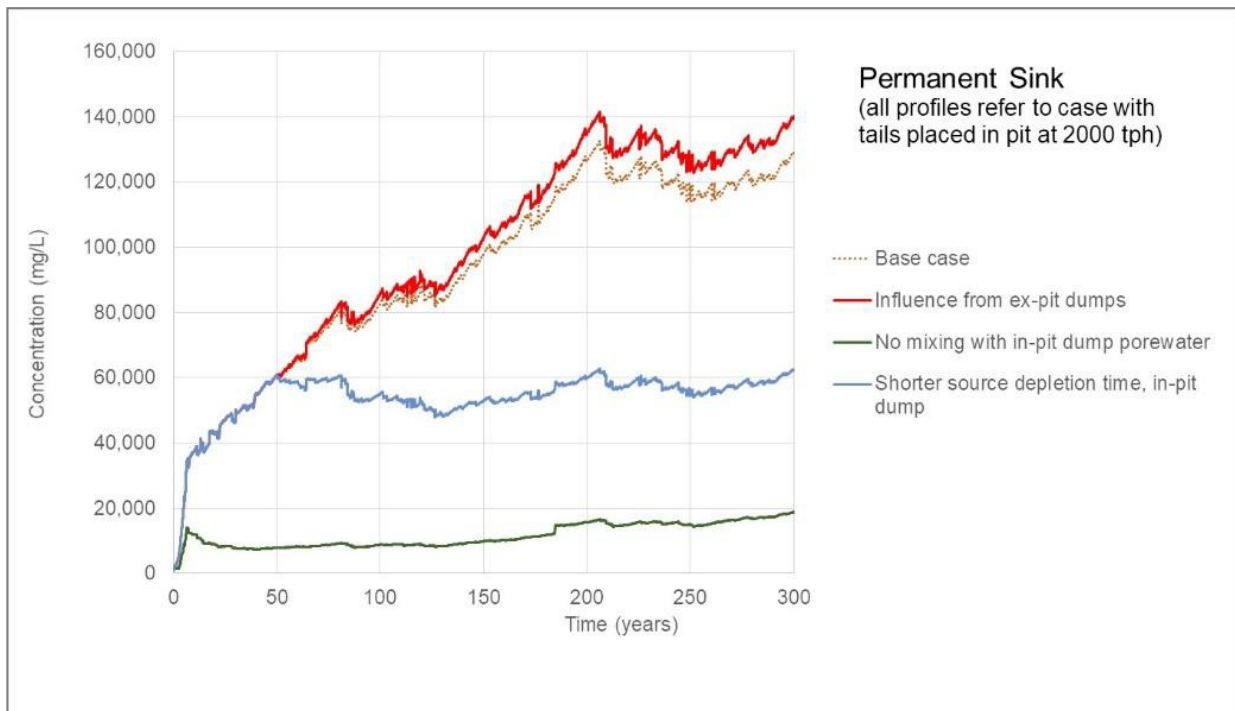


Fig. 6. Sulfate concentration as a function of time – selected outputs from sensitivity calculations

The profiles shown in Figure 5 and Figure 6 do not account for mineral solubility controls. A range of minerals could be expected to form as the pit lake water becomes more concentrated. Precipitation of sulfates, hydroxysulfates and oxides/hydroxides would commonly place upper bounds on the dissolved concentrations of sulfate and many metals. Many of these mineral controls are pH dependent; however, the overall acid-base balance in the lake remains uncertain. Monitoring has demonstrated that conditions in the pit remained pH neutral during operations, and early data for the developing pit lake shows that pH is decreasing (pH ranges from 6 down to a minimum of 4.5, see later). Current predictions indicate that dissolved metal concentrations increase over time, representing a trend of increasing acidity load. Although alkalinity is introduced to the pit via groundwater inflows, for most of the simulations the alkalinity loads are not sufficient to balance accumulated acidity loadings within the pit, suggesting that acidic conditions will develop.

Portions of the pit walls would also provide neutralisation capacity. Limestone – the lithology with the highest neutralization capacity – is exposed at pit wall elevations above 985mRL. If pit lake elevations remain low (e.g. permanent sink conditions), the water may not come into direct contact with the limestone and acidic conditions will develop in the pit lake over time. For the intermittent through-flow/over topping case, contact with the limestone walls will occur, which may offer some degree of neutralization. Conservatively, neutralization by pit walls has not been addressed in the calculations presented in this paper.

The calculated pit lake water quality was assessed using PHREEQC to account for relevant mineral solubility limits. Table 3 includes equilibrated solute concentrations based on precipitation of over-saturated minerals.

Table 3. Calculated pit lake chemistries (long-term, post-closure – permanent sink)

Parameter	No solubility control (mg/L except pH)		Precipitation of Over-Saturated Phases (mg/L except pH)	
	No tails	Tails, 2,000 tph	No tails	Tails, 2,000 tph
pH	0.95	0.85	0.92	0.82
SO ₄	100000	140000	94000	120000
Ca	4400	5900	280	250
Mg	13000	17000	13000	17000
As	0.47	0.6	0.47	0.6
Cd	11	15	11	15
Co	72	93	72	93
Cu	19	24	19	24
Fe	360	460	360	470
Mn	8000	10000	8000	10000
Ni	110	140	110	140
Pb	10	13	2.5	2.3
Se	0.65	0.83	0.65	0.84
Zn	5800	7500	5800	7500
Solubility controls	None		gypsum (CaSO ₄ .2H ₂ O), alunite (KAl ₃ (SO ₄) ₂ (OH) ₆), K-jarosite (KFe ₃ (SO ₄) ₂ (OH) ₆), [2000 tph only], PbSO ₄	

Notes:

- The pit lake was assumed to be well-mixed; no chemical stratification has been represented.
- Redox conditions were assumed to be relatively oxic, and pe was fixed at +10 (-Eh – 590 mV).
- The calculations were performed assuming that the system is open to exchange with CO₂ in the atmosphere, and assuming that the pit water was slightly over-saturated with respect to dissolved CO₂(g) – a common observation in pit waters (Cole et al., 1994). The solutions were equilibrated so that saturation index for CO₂ was -3.

5. Comparisons with Observed Water Quality

Only limited comparisons can be made between the predicted pit lake water chemistry and available water quality data. The majority of the monitoring data represents pit water quality during operations, while dewatering was active. Dewatering activities ceased during February 2015, and therefore only a few of the more recent measurements correspond to early times during the pit water rebound phase, i.e. the time period represented by the modelling calculations.

Monitoring has included sampling of water within the main pit lake (Stage 8) and a perched water body collecting drainage/seepage within the Stage 10 portion of the pit (known as the Stage 10 Sump). The Stage 10 water is believed to represent a combination of pit wall rock runoff and in-pit dump surface runoff and toe seepage. This water is very acidic (pH <3) and saline (electrical conductivity, >5 mS/cm). Water sampled within the main pit area remained near-neutral (pH 6-

7) during operations, but recent results indicate that pH is decreasing (i.e. acidity loadings are exceeding alkalinity loadings from groundwater); the pH measurements between November 2016 and June 2017 have ranged from 4.5 to 5.5.

Table 4 compares measured concentrations with values calculated for the period between 1 and 2 years of simulation. The calculated values lie within the range of the measured values. However, monitoring data for a longer period is required to verify the predictive capabilities of the model.

Table 4. Comparison of measured data and calculated pit lake chemistries

Parameter	Measured data – summary statistics (mg/L, except pH)						Range of values calculated between 1 and 2 years of simulation – base case input assumptions	
	Stage 10 (Acid Sump)			Stage 8 (Main Pit)				
	n	Min	Max	n	Min	Max		
pH	7	2.7	3.2	6	4.5	6.0	2.5	2.4
SO ₄	7	4589	18078	6	2740	4521	2500	3700
Ca	7	388	538	6	345	426	130	170
Mg	7	472	1993	6	385	666	320	480
As	5	0.001	0.12	4	0.0005	0.004	0.011	0.017
Cd	7	0.0084	0.94	6	0.0012	0.12	0.3	0.4
Cu	5	0.0017	0.26	4	0.0005	0.017	0.4	0.7
Fe	5	12	354	4	0.083	2.0	10	14
Mn	5	0.001	1111	4	1.2	115	180	280
Ni	5	0.023	9.3	4	0.0066	0.61	2.5	3.8
Pb	7	0.003	0.41	6	0.001	0.13	0.2	0.4
Se	3	0.0005	0.0005	3	0.0005	0.013	0.01	0.02
Zn	7	765	2973	6	103	221	140	210

6. Conclusions

The size of the catchment reporting to the pit lake will determine whether it remains a permanent sink or transitions to an intermittent flow-through condition. To ensure the pit lake remains a permanent groundwater sink, Page Creek diversions will need to remain in place. Should the diversion be breached, then the creek would flow into the pit, and a flow-through condition would arise.

The water quality in the permanent sink case is expected to become progressively worse due to compounding effects of evapo-concentration and ongoing solute loadings reporting to the pit lake; the pit lake is expected to become acidic, and solute concentrations would increase to very high values.

For the flow-through case, water quality would also become progressively worse prior to discharge, and may or may not be suitable for release when overtopping occurs. However, in the long term, the water quality would not be as acidic or metalliferous as the permanent sink case due to: (i) dilution from increased pit inflows, (ii) potential neutralising capacity that may be contributed by limestone in the pit walls at higher elevations (encountered at elevations above 985 mRL), and, (iii) solute loss from the pit lake in intermittent pit discharges (see Figure 5 which shows time series calculations for sulfate).

Overall, relocating the tailings to the pit would remove the likelihood of ongoing post-closure environmental impacts from the TSF. Post-closure, should the TSF remain in place, the local groundwater mounding would recede and surface expressions of seepage are less likely. However, due to desaturation of the tailings, oxidation and solute production rates would increase leading to long-term impacts on groundwater quality within the footprint of the TSF.

Relocated tailings (re-processed or not), once submerged in the pit lake, would no longer represent an ongoing contaminant source. High solute concentrations in the tailings water would result in an initial increase to the overall solute load in the pit. However, the higher initial loads would not have a material effect on predicted longer-term water quality.

7. Acknowledgements

Scott Weeks (Golder Associates) performed FEFLOW modelling used to support the current assessment. Tony Marszalek (Gilbert and Associates, now HEC) are acknowledged for making the current Goldsim model available for use in the current study. The paper has also benefited from comments by an anonymous reviewer.

8. References

Cole, J.J., Caraco, N.F., Kling, G.W. and Kratz, T.K., 1994. Carbon dioxide supersaturation in the surface waters of lakes, *Science*, **265**, 1568-1570.