Selecting Pit Lake Model Approaches Based on Data Availability

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ABSTRACT

Information on costs and environmental management strategies related to the closure of open pit mines requires results from comprehensive numerical hydrogeological and hydrochemistry models. Ideally, each model input parameter is defined by comprehensive field or laboratory tests.

Since closure assessments are now carried out earlier in the lifetime of a mine, it is rare that each input parameter can be accurately quantified prior to modelling. To compensate for data limitations, pit lake models increasingly incorporate additional, theoretical assumptions which are subsequently evaluated using sensitivity analyses.

Based on a study in equatorial Africa of three existing pit lakes (gold mines), we compare the water quality results of the initial water mixing models with the results of the more complex pit wall interaction models. The initial models only used water quality samples collected in the field while the more advanced models incorporated the results of the static and the kinetic leach tests for solids.

The differences between the model results are partially reduced by incorporating more laboratory data and by increasing the level of model complexity. But, additionally, for large operations where pits are in various stages of development, basic field sampling data facilitates a "calibration" to known conditions.

We recommend designing models based primarily on water balance components and available water quality data supported by the mineralogical and leaching characteristics of the wall rock. In circumstances where specific inflows dominate the water balance, simplified mixing models can provide defensible initial estimates with regard to the long term trends of the pit lake water quality.

Keywords: pit lake model, hydrogeology, hydrochemistry

INTRODUCTION

Financial, social and environmental obligations need to be met after the closure of a mining operation. As a result, the project developer, even at the earliest stages of an ore body's assessment, aims to incorporate the final closure conditions and determine their eventual impact on the planned development.

Due to the limited amount of data available at such early stages of a project, we increasingly rely on theoretical models to predict the future closure conditions. Specifically for pit lake studies, we use numerical hydrogeological and hydrochemistry models to simulate the pit lake rebound behavior and the pit lake quality, well before any excavation has taken place. In order to do so, ever more complex theoretical assumptions are made, which are then subjected to numerous sensitivity analyses.

In this paper, we compare the results of simple water mixing models with subsequent, more complex, mineral / water interaction models. We evaluate whether the increase in laboratory data and model complexity leads to a better understanding of the final closure conditions.

METHODOLOGY

The chemistry of pit lakes varies widely, ranging from circum-neutral or alkaline type waters with a low metal concentration to highly acidic waters with elevated metal concentrations. The type of lake chemistry is the result of physical and chemical interactions, namely (Bowell, 2002):

1. Geological controls: The composition of the host rock and the ore body determine the extent to which any geochemical reaction may occur (i.e. the source);

2. Geochemical controls: The types of minerals, the chemistry of the reactive water and the physical and chemical conditions determine the release and attenuation mechanisms;

3. Hydrological and hydrogeological conditions: The flow of water which, upon contact with the minerals, mobilizes the metals and mixes the different effluents; and

4. Limnological processes: Temperature and density variations related to the lake geometry influence the circulation and the stratification of the water inside the pit.

This paper focusses on the water balance calculations, the mixing of the different water qualities and the chemical reactions along the exposed pit wall. Many of the factors discussed by Castendyk et al. (in press) are included in the construction of the models. We compare these theoretical predictions with the actual lake rebound and water quality trends observed in three existing pit lakes.

Field sampling and laboratory tests

Since starting operations in 2000, the mine has collected and analysed approximately 1750 water samples, including surface water, groundwater, waste rock seepage and pit lake samples. The samples are collected quarterly in accordance with the environmental monitoring practices described by the US Geological Survey National Field Manual (USGS 2003) and the Standards Association of Australia (1998). The laboratory analyses are carried out in an accredited laboratory using standard techniques and protocols.

Mine safety regulations prohibited the collection of pit wall rock samples from the three closed open pits, "K", "M" and "L". Instead, 40 rock samples were collected from stockpiled materials on

site. The rock samples were subjected to a shake flask extraction (SFE) leachate test and a single addition net acid generation (NAG) test. These tests measure the composition of the contact water after the reagent (either distilled water for the SFE, or hydrogen peroxide for the NAG) has been in contact with the rock samples. The laboratory procedures recommended in the Acid Rock Drainage Prediction Manual (Coastech Research, 2008) and the ARD Test Handbook (AMIRA International, 2002) for these types of tests were followed.

Pit lake water balance

Open pit operations form depressions in the ground that collect rainfall, surface water run-off and groundwater (if the pit extends below the original groundwater table). The water body collecting inside the pit is also affected by losses, such as evaporation, pit rim overflow and seepage.

Therefore, a pit lake rebound calculation is essentially a water balance calculation to a terminal recipient (i.e. sink) or a through flow recipient (if overflow or seepage of lake water occurs). At specific time intervals (e.g. monthly or annually), the sum of the outflows is subtracted from the sum of the inflows to calculate the net gain or loss from the pit. The cumulative volume is then converted to the equivalent stage height and lake surface area using the pit geometry curves.

The following mathematical equations summarize the water balance calculation:

$$V_{tot}(t) = V_{tot}(t_0) + \int_{t_0}^{t} F_{in}(\tau).d\tau - \int_{t_0}^{t} F_{out}(\tau).d\tau \tag{1}$$

$$F_{in}(\tau) = F_{rain}(\tau) + F_{runoff}(\tau) + F_{runoff\_wall}(\tau) + F_{GWin}(\tau) \tag{2}$$

$$F_{out}(\tau) = F_{GWout}(\tau) + F_{evap}(\tau) + F_{discharge}(\tau) \tag{3}$$

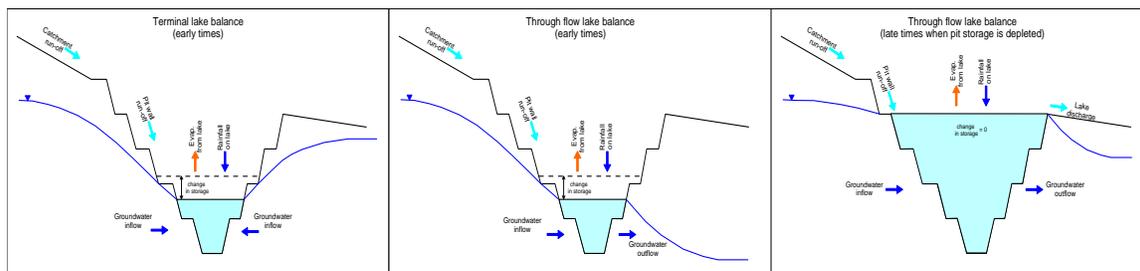The flow concepts are graphically shown in Figure 1.

Figure 1. The dominant flow mechanisms during different stages of pit lake filling.

Pit lake chemistry

The pit lake geochemical model is a PHREEQCI Version 3 (Parkhurst and Appelo, 2013) model that represents a leaking beaker exposed to the atmosphere. The water inside the beaker is well mixed and is not stratified. Figure 2 shows the basic aspects of the two different models, including:

- Inflow of different water quality sources (such as rainfall, run-off and groundwater);
- Mineral / water interaction reproduced by an empirical formula. The incorporation or absence of this formula constitutes the main difference between the simple mixing model (A) and the more complex pit wall interaction model (B);

- The evaporation rate increases proportional to the expansion of the lake surface area, producing an evapo-concentration effect in the solution. At this site, the annual lake evaporation rate was approximately 1.3 times higher than the mean annual precipitation rate.
- Discharge is allowed via the seepage to the groundwater and/or discharge across the pit rim (the latter only occurring when the pit storage has been depleted);
- The model steps include the equilibration between carbon dioxide gas (CO_2) and oxygen gas (O_2). For the CO_2 gas, the partial pressure has been increased to $10^{-3.0}$ atmospheres to reflect the roll of biological activity in the lake (Cole et al., 1994);
- Finally, mineral precipitation and dissolution reactions may also take place inside the pit lake in accordance with a continuously stirred batch reactor.

This general approach has been used in other locations in Africa (Duthe et al., 2011) where it was originally set up for the removal of reactant phases. As minerals precipitate, the components are removed from the solution and the subsequent calculations, preventing the re-dissolution of the solids.
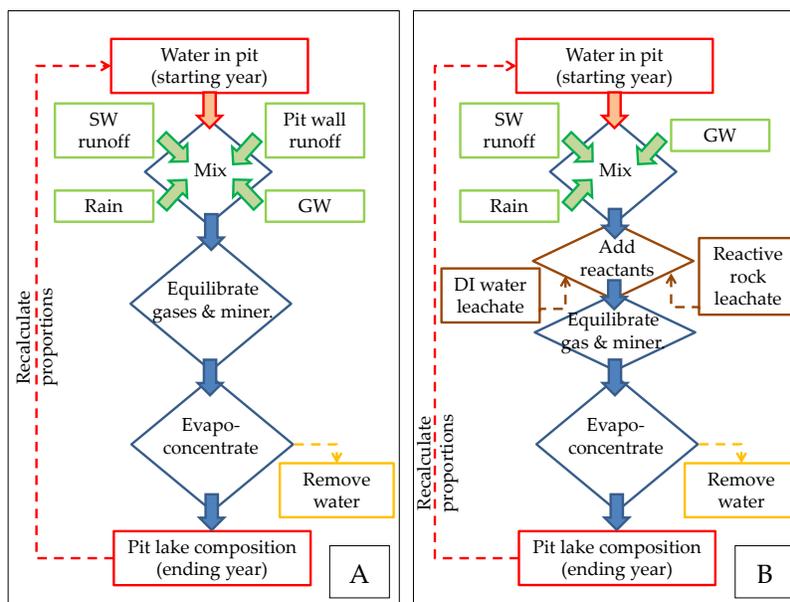

Figure 2. The PHREEQC water mixing model (A) and the pit wall interaction model (B).

RESULTS AND DISCUSSION

Water quality monitoring versus laboratory results

Figure 3 compares the results of 10 years of water quality monitoring at an acidic waste rock seep with the laboratory leach test results for 7 rock samples taken at the same acid forming waste rock dump. In contrast, Figure 4 compares the water quality monitoring data from a benign waste rock seep with the leach tests carried out on 3 rock samples taken from the same non-acid forming waste rock dump.

Based on a select number of signature parameters (such as pH, TDS, SO_4, Al, Mn and Fe), it is shown that the leach tests do not consistently identify the acid generation potential of the waste materials. For the acid forming materials, the laboratory tests overestimate the pH value and underestimate the sulphate and metal leaching effect. This is commonly observed when the rate of release of acidity and/or alkalinity is slower than the actual duration of the test.

Meanwhile, leach tests performed on the non-acid forming materials are generally similar to the water quality observed in the field.
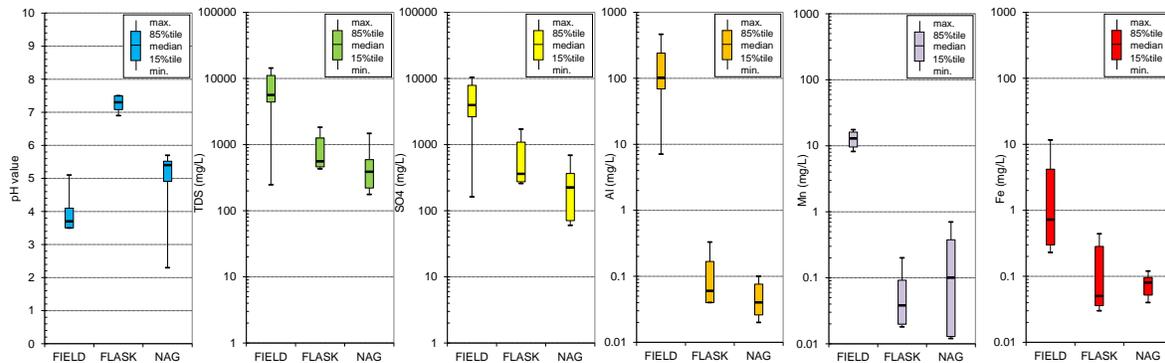

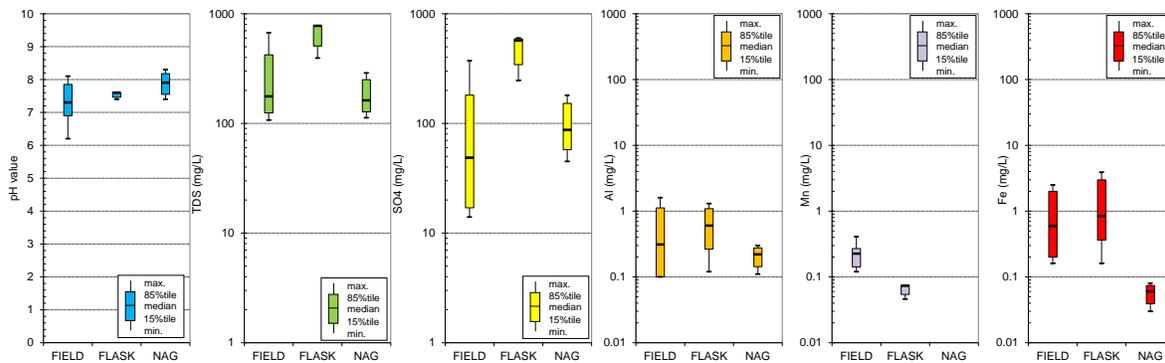**Figure 3.** ARDML water quality field samples compared with leach test results for PAF materials.

Figure 4. Benign water quality field samples compared with leach test results for NAF materials.

Pit lake water balance predictions

The mean annual precipitation (MAP) at the mine is in the order of 1000 mm/year and occurs mostly between November and April. The evaporation across open water bodies amounts to approximately 1300 mm/year. The surface water run-off and the groundwater infiltration rate are equal to 5% and 3% of MAP, respectively. The run-off from the exposed pit walls was set at 55% MAP after a calibration.

Figure 5 compares the predicted with the measured lake level rebound for the existing pit lakes "K", "M" and "L" during the 6 year monitoring period. The water balance conditions were

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subsequently extrapolated using a statistical sequence based on 14 years of measured rainfall and evaporation records. The results are shown in Figure 6, indicating:

- A gradual filling of pit lake "K", eventually leading to overflow and groundwater seepage;

- A stabilizing condition at pit lake "M", maintaining a long term evaporative "sink"; and

- A relatively rapid rebound and overflow of pit lake "L", mainly due to a groundwater inflow contribution absent at "K" and "M".
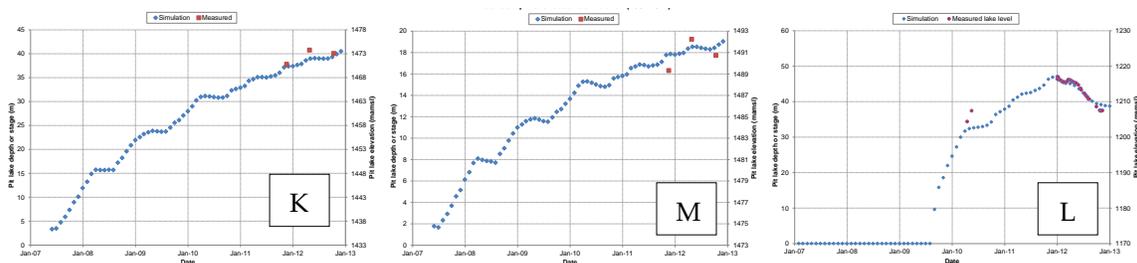

Figure 5. Predicted versus measured pit lake rebound behaviour at "K", "M" and "L".
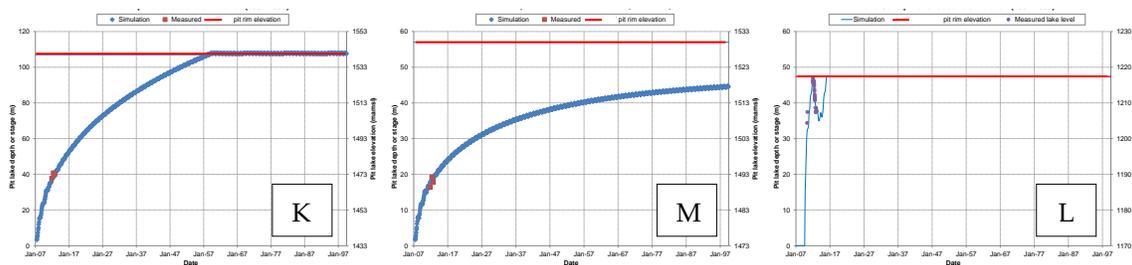

Figure 6. Long term predicted lake level rebound at "K", "M" and "L".

Pit lake chemistry predictions: water mixing models

The field samples of the "M" pit lake display a slight but apparently continuous improvement in water quality for indicators such as pH (increasing from 2.5 to 3.4), TDS (trending down to 400 mg/L) and sulphate (decreasing from 1800 to 200 mg/L).

Using this 6 year trend, an appropriate pit wall run-off composition was achieved by mixing 97% rainwater with 3% acid rock drainage / metal leaching (ARDML) type field water samples. The precipitation of minerals was allowed using the "Equilibrium_Phases"[1] option for calcite, alunite, jarositeK, malachite, ferrihydrite, gibbsite, magnesite and gypsum. If oversaturated, they precipitate and remove some concentrations of Al, Fe and SO_4 from the solution. This effectively meant that, upon precipitation along the pit floor, the solids became unavailable for further reactions.

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[1] JarositeK formed in preference to ferrihydrite. So, although the model allowed for surface complexation onto the hydrous ferric oxide (HFO) surface, it did not take place due to the absence of ferrihydrite.

In particular the alunite and jarositeK phases had a slight, but not significant, effect on the modelled pH and SO_4 values. There was no significant impact on the trace metals concentrations due to the absence of hydrous ferric oxide (HFO) surfaces under these high SO_4 and low pH conditions.

The calibration and forward prediction results are shown in Figure 7, presenting an acceptable match between the modelled and measured signature parameters and trace metals, respectively.
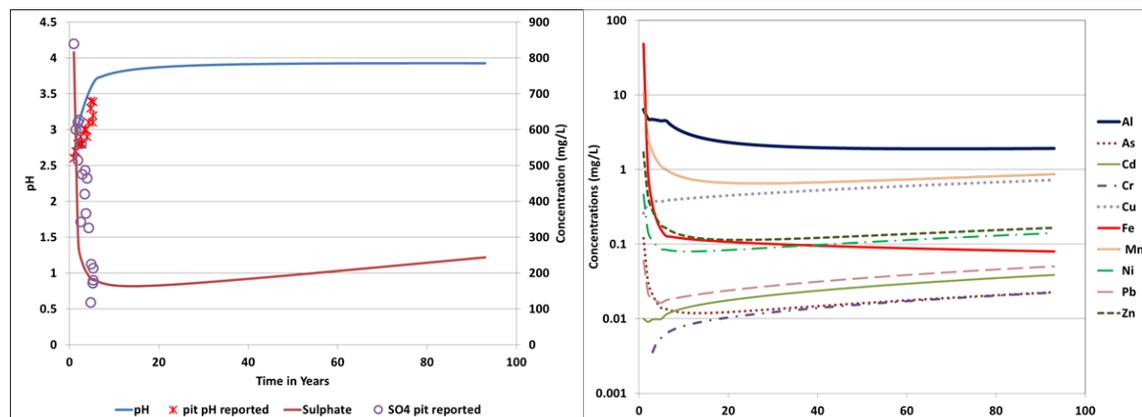

Figure 7. Long term predicted water quality at pit lake "M".

At pit lake "K" the 6 year field record indicated a downward trend from 1000 to 600 mg/L in SO_4, while the pH remained relatively constant at 2.71. Conventionally, when the pH of a pit lake remains relatively constant, the SO_4 is expected to increase or remain constant. The apparent contradictory behaviour of the measured pH and SO_4 complicated the calibration for the "K" pit lake.

The most representative wall rock runoff composition was achieved by mixing 70% rainwater with 30% ARDML type field water samples. It produced a reasonable fit to the SO_4 data, but the match with the pH data is poorer (even when considering the precipitation of jarositeK and alunite). The low pH values and the formation of jarosite phases will suppress the precipitation of ferrihydrite and, hence, prevent surface complexation and the sorption of trace metals.

The calibration and forward prediction results are shown in Figure 8, showing a slight over-prediction of sulphates and pH values. The trace metals are similar in order of magnitude.
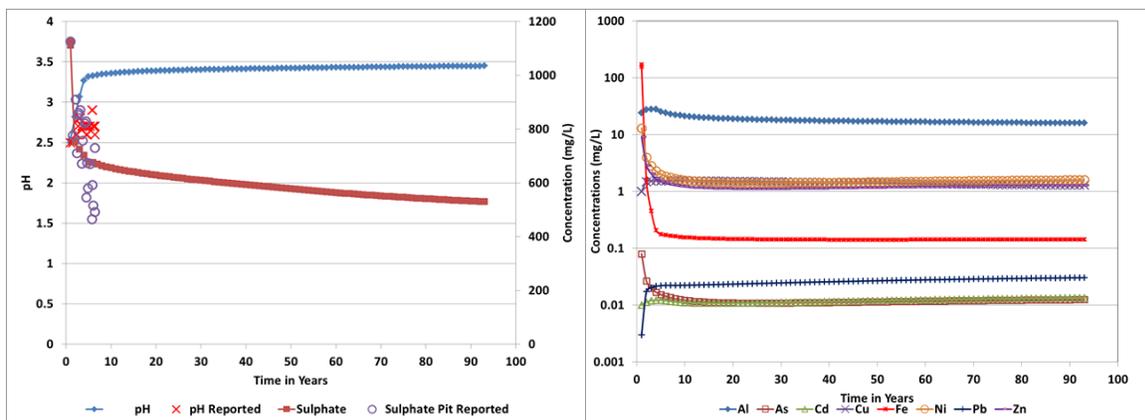
Figure 8. Long term predicted water quality at pit lake "K".

The "L" pit lake refilled quickly due to the storage of drained water from nearby operations, and natural groundwater inflow. The lake has a relatively good water quality with neutral to slightly alkaline pH values (7.3 – 8.1) and slightly elevated SO_4 (approximately 560 mg/L).

The results presented in Figure 9 rely on the inflow of a Ca-Mg / SO_4 type water with an average pH value of 7.7. Rapid filling prevented the generation of acidic pit wall run-off.

The simple mixing model confirms that relatively benign lake water qualities at "L" can be obtained over time if the dominant proportion of inflow is contributed by natural, alkaline groundwater rather than acidic pit wall run-off.
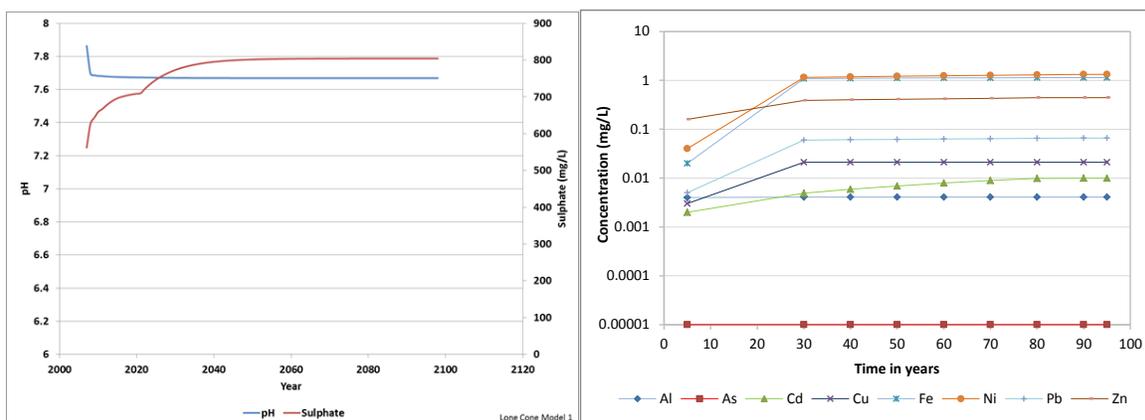
Figure 9. Long term predicted water quality at pit lake "L".

Pit lake chemistry predictions: pit wall interaction models

In the more complex models, rather than mixing two water types to obtain a representative pit wall run-off chemistry, we used the waste rock leach test results to calculate the following mineral / water reaction formula (partial representation):

(F)0.000474(Al2O3)0.000037(BaO)0.000004(CaCO3)0.324351(Fe2O3)0.000018(MgCO3)0.022222 …

$$… (ZnO)0.000015(As2O5)0.000004 PbO)0.000006(SeO3)0.000003(HgO)0.00000006$$

This partial formula represents a reactive leachate from a Banded Iron Formation, a common gold bearing horizon in central and southern Africa. As a check of the models, the formula was applied to reverse calculate the leachate composition of the NAG test for one specific sample, providing a calculated pH of 3.077 versus a measured pH of 2.3[2].

In addition to the reaction formula, the mineral amount that would potentially leach into the pit lake is also required for this type of simulation. We estimated this input parameter by multiplying the pit wall and pit floor surface area by a theoretical wall rock thickness. Based on the "M" and "K" pit lake water samples, the wall rock thickness would range from 5 mm to 20 mm, respectively.

Table 1 summarizes the results between the different simulations, indicating only minor differences in the pit lake composition predicted by the simple water mixing model and the more complex pit wall reaction model. The different years after closure are included for reference purposes.

Table 1. Current and predicted pit lake chemistry

Param.	Units	Pit Lake "K"			Pit Lake "M"			Pit Lake "L"	
		Field Chem.	Mixing Model	Reaction Formula	Field Chem.	Mixing Model	Reaction Formula	Field Chem.	Mixing Model
Years after closure		6	90	90	6	90	90	4	90
pH	pH unit	2.71	3.54	3.45	3.19	3.93	4.12	7.90	7.67
pe	pe units	-	17.10	17.16	-	16.68	16.48	-	12.94
Eh	Volts	-	1.01	1.01	-	0.99	0.97	-	0.76
Alk.[(1)]	mg/L	<1.0	-20.0	-24.4	<1.0	-7.4	-4.7	94.9	46.1
Al	mg/L	30.21	9.00	15.94	8.77	1.92	1.02	<0.20	0.0041
As	mg/L	0.03	0.01	0.01	0.032	0.023	0.020	<0.001	0.00001
Ca	mg/L	81	54	66	57	33	35	155	212
Cd	mg/L	0.01	0.03	0.01	<0.002	0.039	0.039	<0.002	0.01
Cl	mg/L	42.1	4.4	8.6	11.7	4.39	4.44	4.9	8.8
Cr	mg/L	0.09	0.01	0.05	<0.03	0.022	0.023	<0.03	0.06
Cu	mg/L	0.62	1.30	1.29	0.08	0.73	0.67	<0.003	0.021
F	mg/L	0.92	0.37	0.55	0.98	0.31	0.32	8.60	1.14
Fe	mg/L	38.45	0.10	0.14	2.43	0.08	0.07	<0.02	0.0015
K	mg/L	8.6	10.0	6.6	5.75	5.52	5.72	15.9	35.3
Mg	mg/L	70	79	89	22.5	39.85	39.39	61	82
Mn	mg/L	13.42	1.07	4.61	9.01	0.867	0.865	0.372	0.00001
Na	mg/L	4.6	6.3	13.9	7.29	6.36	6.34	25.5	55.0
Ni	mg/L	4.07	0.16	1.60	0.39	0.141	0.141	0.04	1.33
Pb	mg/L	<0.01	0.03	0.03	<0.01	0.050	0.048	<0.01	0.066
P	mg/L	<0.5	0.09	0.07		0.129	0.125	<0.005	0.068

[2] The difference is probably due to lower iron concentrations in the laboratory leach sample, whereby some ferric solid, ferrihydrite, $[Fe(OH)_3]$, schwertmannite $[Fe_8O_8(OH)_{4.8}(SO_4)_{1.6}]$ or jarosite formed and released more protons into the solution lowering the pH. It is likely that some acidity had been lost due to reaction with carbonate in the sample.

| SO4 | mg/L | 585 | 508 | 530 | 261 | 243.92 | 240.37 | 562 | 804 |
| Zn | mg/L | 2.18 | 0.15 | 1.27 | 0.42 | 0.166 | 0.157 | 0.16 | 0.44 |

[1] Negative values calculated in PHREEQC

CONCLUSION

We recommend designing models based primarily on water balance components and available water quality data supported by mineralogical and leaching characteristics of the wall rock. Therefore, during the early stages of a mining project, the collection of site specific water monitoring data is as important as the more theoretical laboratory leach tests on solids.

Water mixing models to predict the pit lake chemistry behavior, when calibrated to known conditions measured in the field, can be acceptable substitutes for more complex mineral / water reaction models in circumstances where specific inflows dominate the water balance.

ACKNOWLEDGEMENTS

NOMENCLATURE

V_{tot}: water volume inside pit [m^3] F_{in}: Water inflow rate [m^3/s] τ: time period [s]

F_{out}: Water outflow rate [m^3/s] t_0: starting time [s] t: end time [s]

F_{rain}: rainfall [m^3/s] F_{runoff}: catchment runoff [m^3/s] F_{runoff_wall}: pit wall [m^3/s]

F_{GWin}: groundwater inflow [m^3/s] F_{GWout}: seepage [m^3/s], F_{evap}: evaporation [m^3/s]

$F_{discharge}$: pit rim overflow [m^3/s]

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