

# POST-BETZE PIT LAKE WATER QUALITY PREDICTION, NEVADA<sup>1</sup>

William M. Schafer<sup>2</sup>, Mark Logsdon, Guosheng Zhan, and Ron Espell

**Abstract** - The Barrick Goldstrike Mine is located in the Carlin Trend, about 20 miles northwest of Carlin, Nevada. The majority of the ore mined at Goldstrike is from the Post-Betze open pit, the largest open pit operation in Nevada. Nevada law requires that the water quality of temporary or permanent reservoirs that may develop in open pits be periodically tested. Pit water quality prediction is conducted to monitor water quality and the possible impact that it may have on human, terrestrial, or avian life.

Water quality in the open pit at Goldstrike has been analyzed in three previous studies (BGMI 1991, Radian-Baker 1997, TRC 2000). The most recent analysis of the pit lake water quality model is discussed in this presentation. The effects of placing 516 million t of backfill waste rock into the open pit were also examined. This evaluation of pit lake water quality (Schafer and Logsdon 2003) differs from previous studies in that it utilized laboratory studies where natural groundwater from the site was mixed with water that had contacted weathered mine rock as a means of simulating the pit lake geochemical reaction path. Calibration of PHREEQC using batch test results enabled refinement of solubility data obtained from the thermodynamic mineral equilibrium database employed by PHREEQC. The prediction of pit lake hydrology and water quality involved six key elements including 1) summarizing the mine plan, and geochemistry of exposed rocks and backfill, 2) evaluating mine filling using a regional groundwater flow model, 3) conducting eight large-diameter column studies to generate representative rock contact waters, 4) performing batch mixing tests to simulate final pit water quality at various stages of filling, 5) calibrating a geochemical model based on the batch tests, and 6) using the calibrated model to predict water quality at various stages of pit lake recharge.

The uncalibrated PHREEQC model accurately predicted the common ion concentrations and pH of the batch tests, and correctly simulated the precipitation of large amounts of calcite when a mixture of various mine waters, groundwater and meteoric water was evaporated (although aragonite was actually the dominant solid that formed). Agreement between the model and batch tests was poorer for some metals, however. The PHREEQC model over-predicted zinc, nickel and antimony concentrations in the pit lake while under-predicting concentrations of barium, copper and arsenic. Calibration of PHREEQC enabled accurate prediction of trace element concentrations in batch tests, therefore improving its reliability for pit water quality prediction.

<sup>1</sup> Paper presented at the 7<sup>th</sup> International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel (ed.) Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502

<sup>2</sup> Principal of Schafer Limited LLC, 3018 Colter Ave, Bozeman, MT, USA 59715; Principal of Geochimica, Ojai, CA; Senior Corporate Hydrologist, Barrick Management Corporation, Salt Lake City, UT; and Environmental Manager, Barrick-Australia, Perth.

7<sup>th</sup> International Conference on Acid Rock Drainage, 2006 pp 1863-1886

DOI: 10.21000/JASMR06021863

<https://doi.org/10.21000/JASMR06021863>

## Introduction

Barrick Goldstrike Mining Company (BGMI) operates the Goldstrike Mine, which is located near Elko in north central Nevada, USA. Goldstrike is a large open pit and underground gold mining operation located in the Carlin Trend. The mine consists of the Post-Betze Pit, the Bazza waste rock facility, the AA Leach Pad (reclaimed), the North Block Tailings Facility, the Rodeo and Meikle Underground Mines, a Roaster and an Autoclave Facility (Fig. 1). Closure planning at BGMI is a continuous process of concept development, design, construction, performance monitoring, evaluation and refinement. The closure concepts involved in operation and closure of the Betze open pit evaluated in this study include optimizing the placement of waste rock as pit backfill to cover potentially acid generating (PAG) highwall zones and to reduce the long-term exposure of oxygen to backfilled PAG waste rock.

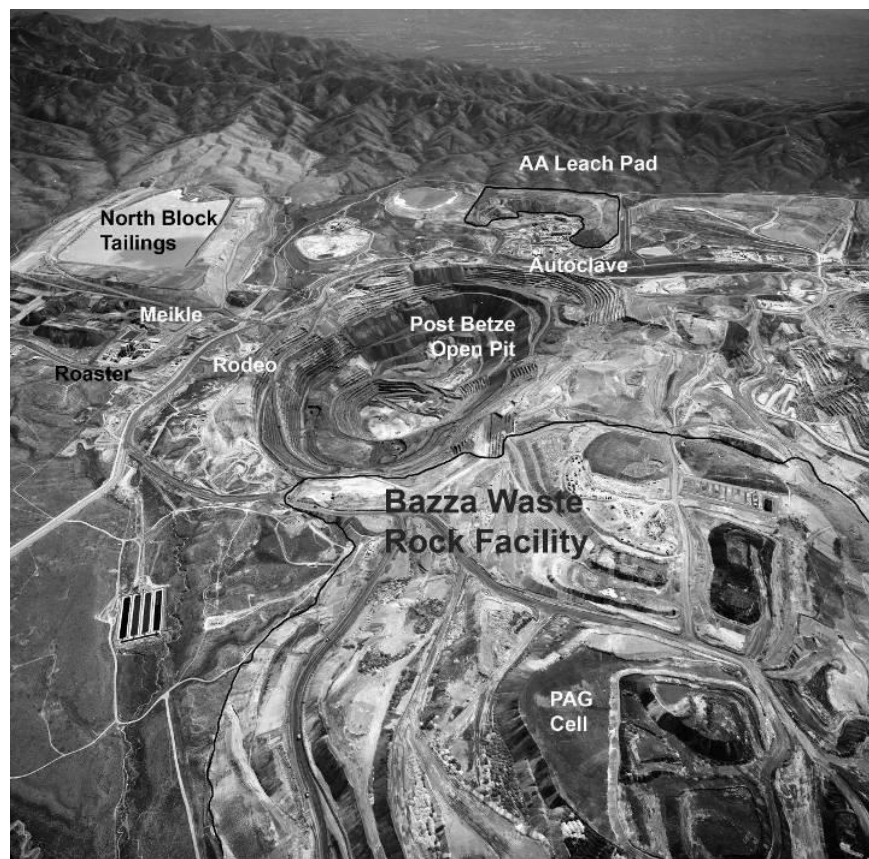


Figure 1. Aerial photo of the Barrick Goldstrike Mine looking east.

The conceptual model of water quality in the Post-Betze pit lake (Fig. 2) corresponds to many previous pit lake water quality studies (BGMI 1991, Radian-Baker 1997, TRC 2000). Water quality in the pit will be determined by the proportional amount and chemistry of each type of water that flows into the pit lake. Changes in the proportional contribution of water sources and cumulative evaporation through time will cause transient water quality trends. Influent waters include precipitation, highwall runoff, groundwater flowing through the weathered highwall, and groundwater flowing through backfill. Evaporation will tend to

increase the concentration of constituents in the pit lake. Chemical conditions at various depths in the pit lake will be controlled by limnological processes that will ultimately dictate the levels of dissolved O<sub>2</sub>, CO<sub>2</sub>, and the amount of organic C available for decomposition. Based on the conceptual model, the proportional amount and chemistry of the influent waters are critical elements that affect water quality.

## Pit Lake Water Quality Conceptual Model

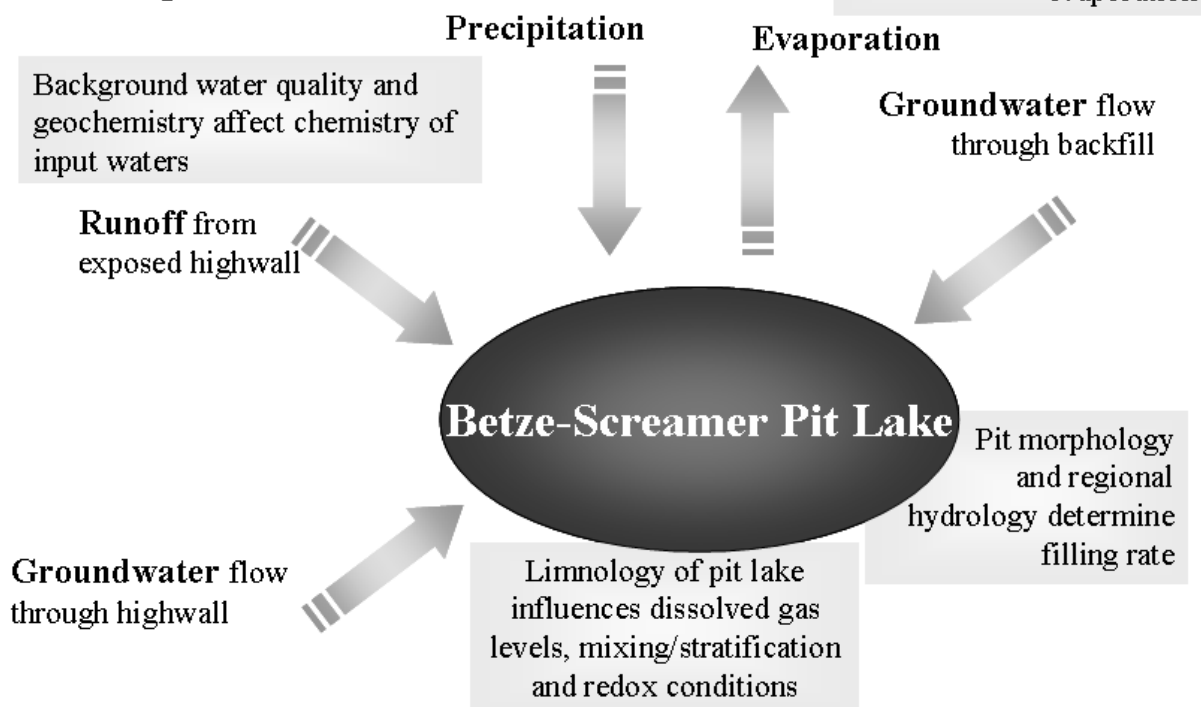


Figure 2. Conceptual model of the Post-Betze pit lake.

The purpose of this study is to predict water quality evolution in the Post-Betze pit lake. Prediction of pit lake hydrology and water quality involved six key elements including 1) summarizing the mine plan, and geochemistry of exposed rocks and backfill, 2) evaluating mine filling using a regional groundwater flow model, 3) conducting eight large-diameter column studies to generate representative rock contact waters, 4) performing batch mixing tests to simulate final pit water quality at various stages of filling, 5) calibrating PHREEQC based on the batch tests, and 6) using the calibrated model to predict water quality at various stages of pit lake recharge.

### Methods of Analysis

#### Mine Pit Morphology and Geology

One of the purposes of periodically updating the water quality model is to account for changes in mine plans, and to incorporate recent geological and geochemical data. The mine

plan has been revised since the last water quality study, and extensive additional geochemical information has been collected. Additionally, the hydrologic model was also re-run to account for changes in the mine geometry. Mining in the Post-Betze pit lake is expected to continue through at least 2021. At closure the pit will be oblong with a length (east to west) of 2.9 km and width (north to south) of 1.8 km. When full, the pit lake will be 345 m deep and will contain 456,000 m<sup>3</sup> of water. The pit lake will have a drainage basin area of 874 ha, of which the pit lake will cover 320 ha. The remaining basin will consist of the mine highwall (140 ha), backfill (163 ha), and a portion of the Bazza waste rock facility (251 ha).

#### Hydrologic Flow Model Update

The regional groundwater system and its depression through the dewatering program have been modeled with a 3-d MODFLOW groundwater flow model. The calibrated MODFLOW model has also been used to simulate the rate of recovery of the water level in the pit lake and to determine the flow contributions from various sources including groundwater, rainfall, runoff and evaporation. The proportions of groundwater that flow through the weathered highwall and through the backfill is also determined using the MODFLOW model.

#### Geochemistry of Exposed Highwall and Backfill

Sources of information analyzed for this study included the exploration sample database (Fig. 3) consisting of more than 30,000 geochemical determinations of pyritic sulfur and carbonate levels (Sobek et al., 1978) from various rock types found in the pit, and queries of a mine block model (based on more than 500,000 analyses of acid neutralizing and acid generating potential by a modified Sobek Method) to determine the characteristics of the backfill and the exposed highwalls.

Statistical analyses of the exploration samples were used to assess the general geochemical nature of each rock type mined. The exploration data contained bias because of closer borehole spacing in mineralized areas and the greater sample density in the eastern part of the pit, which had lower carbonate levels. Consequently, the Post-Betze block model was used to develop unbiased estimates of overall geochemistry.

Block Model Estimates of Backfill and Highwall Characteristics: The mine block model consists of 15.2 by 15.2 by 6.1 m cells in the proximity of the mine pit for which the lithology, grade, and geochemical characteristics have been modeled using a block Kriging routine. The block model was used in conjunction with the planned mining sequence to summarize the tonnage and characteristics of backfill that will be placed in the mine pit. This information was used to assess the overall acid generation risk in the backfill and to predict chemical interaction between groundwater flowing into the pit and the backfill material. The mine block model (Fig. 4) was also queried to assess the characteristics of the final exposed pit floors and highwall. Areas covered by backfill in the eastern and southeastern portions of the pit were excluded from this analysis. The average acid generating potential (AGP) of exposed highwall is 33.8 kg/t, while the acid neutralizing potential (ANP) was 175.4 and the net neutralization potential (NNP) was 141.9 kg/t. About 10 to 15 % of the highwall had rocks with NNP values less than 0.

Barrick Post-Betze Pit  
Exploration Geochemistry Samples

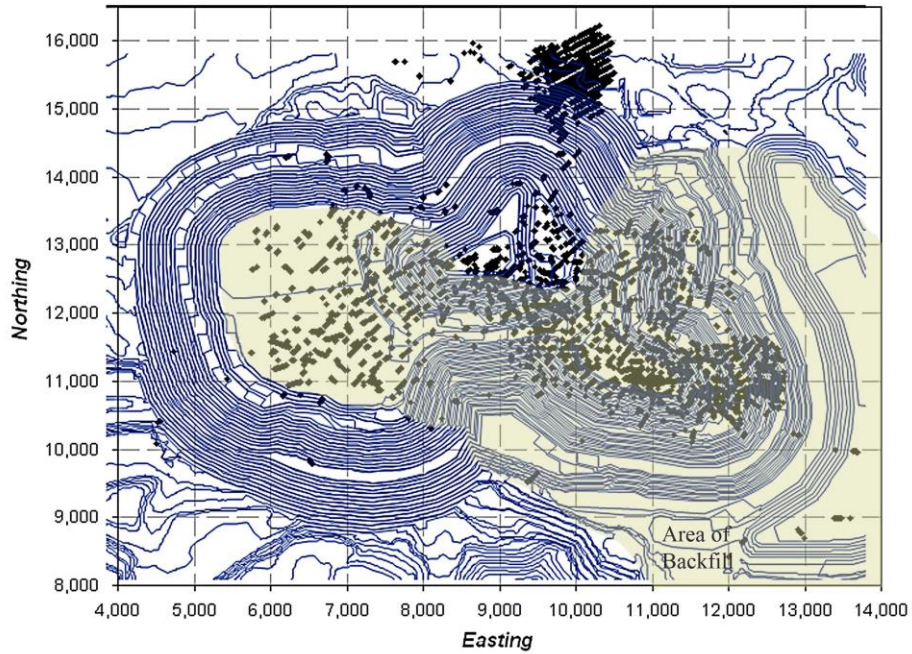


Figure 3. Location of exploration samples for which static test data are available projected onto surface of final backfilled pit.

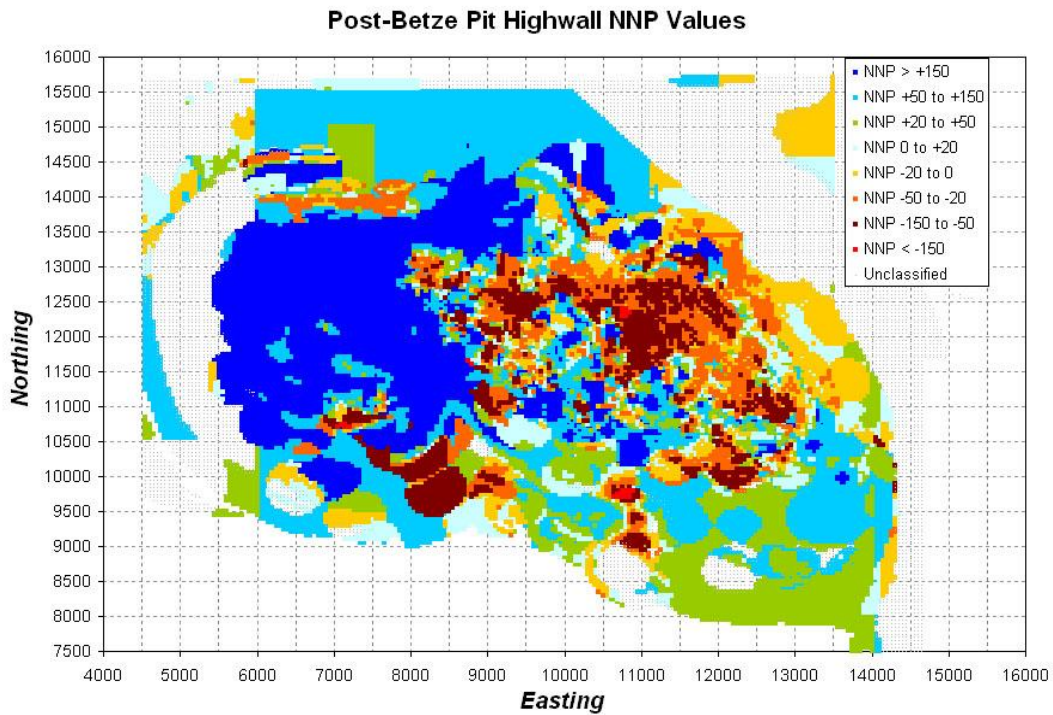


Figure 4. Net neutralization potential values of the final mine highwall.

The proposed mining sequence includes placement of 516 million t of backfill in the open pit. A block model was used to construct estimates of the composition of the backfill by rock type and NNP (Table 1). The average NNP of backfilled rocks (+111 kg/t) was slightly less than the average NNP in the highwall. The NNP values varied slightly by elevation within the backfill but all zones contained average NNP that were appreciably greater than 0. The uppermost backfill zone, which will remain above the final water table, had a higher NNP than the zones just below the water table because of the selective handling plan which precludes placement of PAG material near the final water table.

Table 1. Geochemical characteristics of backfill within elevation zones.

Elevation Zone (m)	Metric Tons (x1,000)	Sulfide (%)	Carbonate (%)	Calculated (t/1000 t)		
				AGP	ANP	NNP
>1575	151,300	0.9	7.8	28.4	128.6	100.1
1508-1575	76,700	1.2	5.0	36.3	81.8	45.5
1400-1508	115,100	1.6	8.6	50.4	141.8	91.4
1097-1400	173,000	1.1	12.1	35.7	197.9	162.2
Total	516,100	1.2	9.0	36.9	147.8	110.9

#### Large Diameter Column Studies

The effect of backfilling on post-closure pit water quality was evaluated using large-scale column tests. The columns consisted of 30 cm diameter PVC pipe in which a 150 cm charge of weathered rock was placed. Two types of column tests were constructed including saturated and trickle leach (unsaturated). Four saturated columns were used to simulate groundwater seepage through the saturated backfill. Four unsaturated columns simulated seepage through subaerial backfill and runoff from the highwall.

The saturated columns were constructed, charged and operated to simulate the water-rock interactions that will occur within the backfill zone. The uncrushed waste rock samples were screened to less than 2 inch nominal diameter prior to placement in the columns. The four saturated columns consisted of varying proportions of waste rock, which corresponded to a representative range of NNP values. Each week, 24 L of groundwater was added to the columns in 3 equal daily aliquots. The weekly volume of groundwater was equivalent to about 54 % of the sample pore space in the 0.11 m<sup>3</sup> sample. Saturated columns were rinsed with at least 5 pore volumes of groundwater from the dewatering wells over the course of the 12 week saturated column tests.

The unsaturated columns were the same size as the saturated columns but were charged with rock samples that were representative of a range in NNP values found in the ultimate pit shell. The columns were rinsed with 6 L of solution, added in 3 daily 2 L aliquots, each week. The weekly solution quantity averaged about 14 % of the volume within the 0.11 m<sup>3</sup> sample charge, which had about 40 % porosity. The distilled water added to the columns, which represented the infiltration of precipitation, was added to the columns slowly to create pulses of water while maintaining unsaturated conditions. Over the course of the 8 week unsaturated column study, 2 to 3.5 pore volumes of water were added to the unsaturated columns.

Experience with large diameter column tests conducted at numerous mine sites indicated that the fully saturated tests would rapidly approach near steady-state conditions, and therefore need not be pursued for very extensive periods. The variably saturated tests, on the other hand, are inherently transient both physically and chemically. It is very difficult to predict *a priori* how long it will be necessary to run such tests. In both the saturated and unsaturated columns, the chemical characteristics of the “first flush” of solution were used to represent the long-term geochemical processes in the pit lake by conducting batch tests.

#### Empirical Batch Mixing Experiments

In order to identify transient water quality, empirical mixing studies were used to simulate water quality during interim periods of filling, including partial filling after 45 and 150 years, and after attainment of equilibrium water levels (in approximately 400 years). In most pit water studies, the composition of the water in pit lakes is predicted using a geochemical equilibrium model such as MINTEQA2 or PHREEQC. Unfortunately, these models are seldom calibrated since the pit lake does not yet exist. Consequently, the results of geochemical models may differ from future lake chemistry because thermodynamic data are often lacking or are incorrect for the various secondary minerals and complex mixtures of sorbed ions that form in low temperature settings. Consequently, in this study the pit lake chemistry was simulated by mixing water samples that were collected from the field or created in the laboratory, which simulated the different types of water that will combine after closure to form the pit lake.

Representative waters (Table 2) were mixed in the proportions specified by hydrologic modeling of pit refilling. The combined solution was allowed to equilibrate in a continuously stirred glass beaker for 24 hours prior to initiating the evaporation cycle. The bulk mixture was maintained at atmospheric oxygen and carbon dioxide levels to approximate conditions found in the pit lake epilimnion. Evaporation was conducted near room temperature and continued for up to 7 days until the volume reduction predicted by the hydrologic model was achieved. The extent and nature of solids formed during the mixing tests were evaluated using mineralogical analysis by x-ray diffraction and scanning electron microscopy. This technique enabled verification of important solid phases like calcite or ferrihydrite to confirm interpretations of the controlling geochemical reactions.

Precipitation: Precipitation that falls on the surface of the pit lake was simulated with distilled water. For the geochemical modeling of the pit lake, average precipitation chemistry was derived for the Saval Ranch meteorological station located in Elko County, Nevada. The period of record for the Saval Ranch station (NADP 2005) is from July 1984 to March 1997 and approximately 300 measurements of rainfall chemistry have been conducted.

Evaporation: The representative mixture of waters was reduced in volume by an appropriate amount corresponding to the cumulative evaporation predicted by the hydrologic model.

Runoff: Precipitation that falls on the highwall will either runoff into the pit lake, evaporate, or infiltrate into the highwall. Runoff was simulated with outflow from the unsaturated columns.

Groundwater Flow through Weathered Highwall: As groundwater flows through the weathered highwall, the secondary minerals that have accumulated as a result of weathering of sulfide minerals will be rinsed from the rock, and will increase the concentration of some constituents (especially sulfate salts and some metals). In earlier pit lake water quality studies; this gradual process of mineral removal was simulated with long-duration column tests. Results of these



rinse-out tests are often fit to empirical curves (Fig. 5) such as an equation of the form in [1] where the concentration after any number of pore volumes ( $C_{PV}$ ) of displacement can be estimated from the initial or “first flush” chemistry ( $C_0$ ) and the chemistry of the solution being used to rinse the columns, in this case groundwater ( $C_{GW}$ ). A pore volume is the quantity of water contained within the pore space within a granular sample.

$$C_{PV} = C_0 \text{ for } PV \leq 1, C_{PV} = C_{GW} + (C_0 - C_{GW}) * PV^{-1}, \text{ for } PV > 1 \quad [1]$$

Table 2. Representative waters for pit lake water quality prediction.

Source	Description	Representative Waters
Precipitation	Natural rainfall that falls directly into the pit lake	Distilled de-ionized water
Evaporation	Evaporation of water from the pit lake surface, without any attendant chemical flux	Volume reduction of mixture of representative waters
Runoff from exposed highwall	Meteoric water that runs off of the highwall	Water samples derived from the early stages of leaching the unsaturated columns mixed with distilled water according to [1].
Groundwater flow through highwall	Groundwater, predominantly from the carbonate system, that flows through weathered rock in the exposed highwall	A combination of groundwater from the dewatering system and samples from the first flush of water through the saturated columns derived from equation [1]
Groundwater flow through backfill	Groundwater, predominantly from the carbonate system, that flows through backfill, and then into the pit lake	A combination of groundwater from the dewatering system and samples from the first flush of water through the saturated columns derived from [1]
Groundwater outflow	Groundwater seepage out of the pit lake (if any occurs)	As in prior pit lake studies, no outflow was predicted as was the case for this model.

The early stages of rinse-out from the column tests were used to represent the first-flush solutions described as  $C_0$  in Fig. 5. For this study, it was not necessary to perform long-term column tests because any stage in the rinse-out curve can be simulated by mixing first-flush solution with groundwater in appropriate proportions as predicted in [1]. Additionally, the cumulative contribution of solution displaced through the highwall or backfill up to any pore volume on the leaching curve can also be simulated with a combination of first-flush and groundwater. By using [1] to predict the transient change in ion concentration leached from the highwall, concentrations in groundwater through time can be simulated by determining the number of pore volumes rinsed at each time stage. The cumulative pore volumes of groundwater that flowed through the highwall and backfill corresponding to different temporal stages of pit lake filling were derived using data from the groundwater flow model. The cumulative groundwater flux from MODFLOW was converted to pore volumes by determining the porosity of the fractured highwall, and the thickness of the weathered highwall. The weathered highwall thickness was based on an analysis of  $O_2$  diffusion using the Approximate Analytical Solution to



the Davis-Ritchie equation (Davis et al. 1986). The oxidation model, which was calibrated with kinetic test data to estimate the inter-particle diffusion rate, yielded fully weathered highwall thickness varying from 1.25 to 3 m after 50 years to 2.5 to 5 m after 400 years. Highwall porosity was assumed to be 2 %. Weathered zone thickness was greater in lower sulfide rock material than in high sulfide rock. The weathered zone thickness was used to determine the volume of weathered rock used to predict chemical mass transfers into the pit lake.

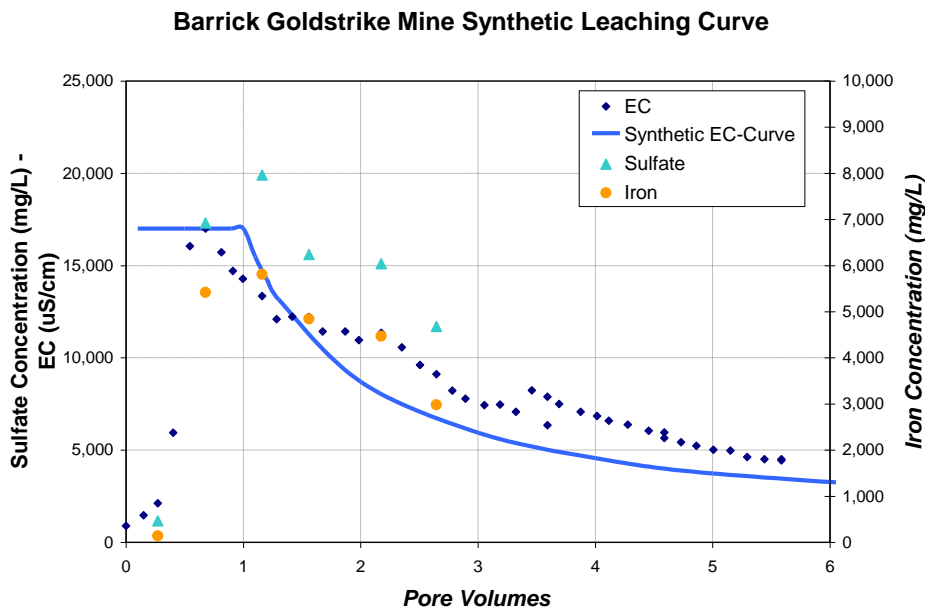


Figure 5. Observed changes in sulfate, electrical conductivity, and iron as a function of displaced pore volumes. Synthetic rinse-out curve for EC shown for comparison.

Groundwater Flow Through Backfill: Inflow through backfilled waste rock, which was assumed to have 40 % porosity, was simulated in a similar fashion to that used for the highwall. Since the backfill has a much greater porosity and thickness than the weathered highwall, far fewer pore volumes of leaching occurred at a comparable time stage of pit filling.

#### Equilibrium Modeling

A geochemical model, PHREEQC (Parkhurst and Appelo, 1999) was used to simulate the chemical reactions that occur in the mixing tests. Actual batch test results were compared to the modeled results so that necessary adjustments could be made in the model assumptions and inputs to improve agreement. In this way, the model was calibrated to the actual chemical processes such as precipitation of calcite and ferrihydrite and sorption of trace metals that occur when the source waters are mixed. The calibrated model was then be used to perform forward modeling of pit lake water quality for critical time periods including 50, 145, 400 and 3,000 years. Additionally, effects of differing dissolved oxygen, carbon dioxide, and redox levels were also evaluated.

## **Results and Discussion**

### Climate

The climate of the Post-Betze pit affects each of the sources of water that flow into the pit lake. These include direct rainfall, evaporation, groundwater inputs, and surface runoff from the pit lake catchment area. The annual precipitation at Barrick is 260 mm based on a summary of on-site climatic data collected between 1990 and 2002. The average annual pan evaporation recorded for a portion of the year (April to October) with highest evaporation was 1330 mm. Average annual temperature was 9.0 C.

### Groundwater Hydrology

Mining in the Post-Betze open pit required a dewatering program with peak pumping rates of 264 m<sup>3</sup>/min. The regional groundwater system was modeled (BGMI, 1991) to understand the behavior of water levels to pumping, storage and utilization of pumped water in the Boulder Valley (McDonald Morrissey Associates, 1998). MODFLOW (McDonald and Harbaugh, 1988) with special extensions to account for cell resaturation (BCF2), recharge from river channels (RIV2), and well pumping (WEL1 and DRN1) was used to simulate groundwater flow.

The natural groundwater flow direction prior to pumping from the Betze-Screamer pit was mainly from northeast to southwest. Recharge occurred in the Tuscarora Mountains and discharge occurred in the evaporative sink in the lower Boulder Valley. By 1998, more than 450 m of drawdown was induced in the vicinity of the pit by dewatering. The zone of maximum drawdown extended to the northwest of the pit in a prominent zone of permeable carbonate rocks.

The regional groundwater flow model was modified to account for changes in pit geometry in the new mine plan, including placement of backfill, and to predict the rate of recovery of the water level in the pit lake. In this simulation, the runoff coefficients for reclaimed areas and the highwall were derived using a runoff curve number approach. Two long-term water management scenarios were modeled. In the base case the pit lake was allowed to fill without any removal of water for irrigation (Fig. 6). In the pumping case, irrigation water was withdrawn from April through September at a rate of 0.14 m<sup>3</sup>/min to support alfalfa production in the Boulder Valley. Pumping was initiated when the pit lake recovered to within 33 m of its equilibrium elevation (e.g. 1,534 m amsl).

The MODFLOW model was also used to calculate the contribution of water from various sources including groundwater, surface water and precipitation (Fig. 7). Groundwater is the primary source of inflow to the pit lake with roughly 50% of the groundwater flowing through the weathered highwall and the remainder flowing through the backfill. Of the total groundwater flow, about 80% comes from the carbonate system increasing to 85 % in later stages of filling. The remaining groundwater that flows into the pit lake is from the Carlin Formation. Surface water provides a smaller contribution to the pit lake in the form of direct precipitation, runoff from the highwall, and runoff from reclaimed areas.

Losses of inflow to the pit lake, also determined using the MODFLOW model, included evaporation and changes in storage for the base case. Removal of water by pumping occurred in the pumping case. For the Base Case, when the pit lake approaches its equilibrium level at a stage of 1,567 m, the annual change in lake storage approaches zero. After 400 years the only loss of water is from evaporation at rate approaching 7 m<sup>3</sup>/min. For the pumped case the

equilibrium water level was roughly 33 m lower and equilibrium evaporation was 6.1 m<sup>3</sup>/min (slightly less than the base case because of the smaller pit lake area).

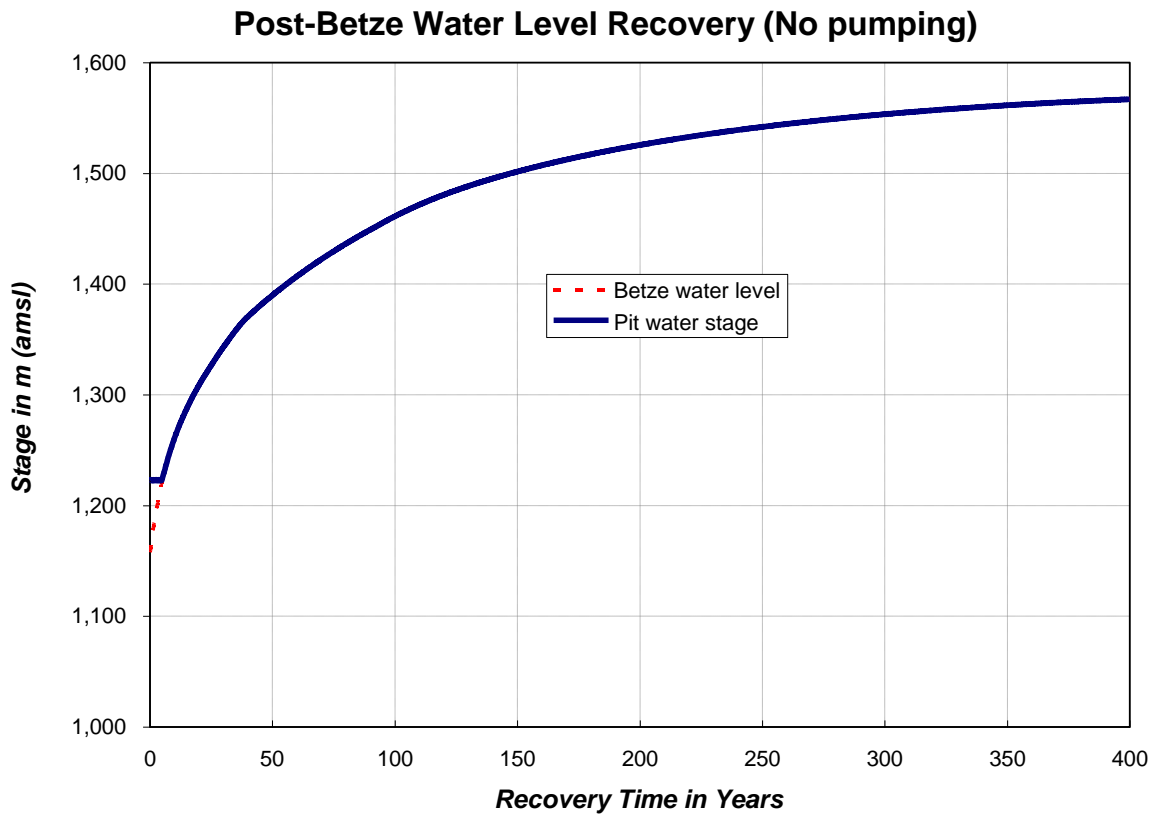


Figure 6. Predicted rate of recovery of the Post-Betze pit lake without withdrawal for irrigation.

### Column Studies

Using the available bulk samples, combinations of material were selected that would provide NNP values that approximated 5%, 25%, 50% and 75% of the frequency distribution of backfilled rock for use in the saturated columns. Additionally, materials used in the unsaturated columns were selected approximating 5%, 25%, 50% and 75% of the NNP frequency distribution for the exposed highwall. Additionally, efforts were made to use an amount of each geologic formation in approximately the same proportions as they were found in the backfill or highwall.

Samples from the saturated and unsaturated columns were collected and analyzed for common ions (pH, EC, acidity if pH below 7 and alkalinity if pH above 4.5, Ca, Mg, Na, K, SO<sub>4</sub><sup>-2</sup>, Cl<sup>-</sup>, silicate, and bicarbonate) trace metals (Al, Ag, As, Sb, Ba, B, Cu, Cd, Cr, F, Fe, Pb, Mn, Mo, Ni, Tl, and Zn). Complete results may be found in Schafer and Logsdon 2003). Selected results for pH, Ca, Mg, Na, SO<sub>4</sub><sup>-2</sup>, As, Sb, Ba, Fe, Ni and Zn are discussed in the remainder of this paper.

Concentrations of common ions generally decreased with increasing pore volumes of displacement (Fig. 8). The first sample collected from the columns was diluted by the distilled

water added to the bedding layer beneath the sample charge and was not representative of the “first flush” chemistry. Consequently, the second or third sample composite was used to represent the most concentrated first flush from the columns. These leachate samples were used in subsequent batch tests in combination with groundwater and other water sources to simulate pit water quality.

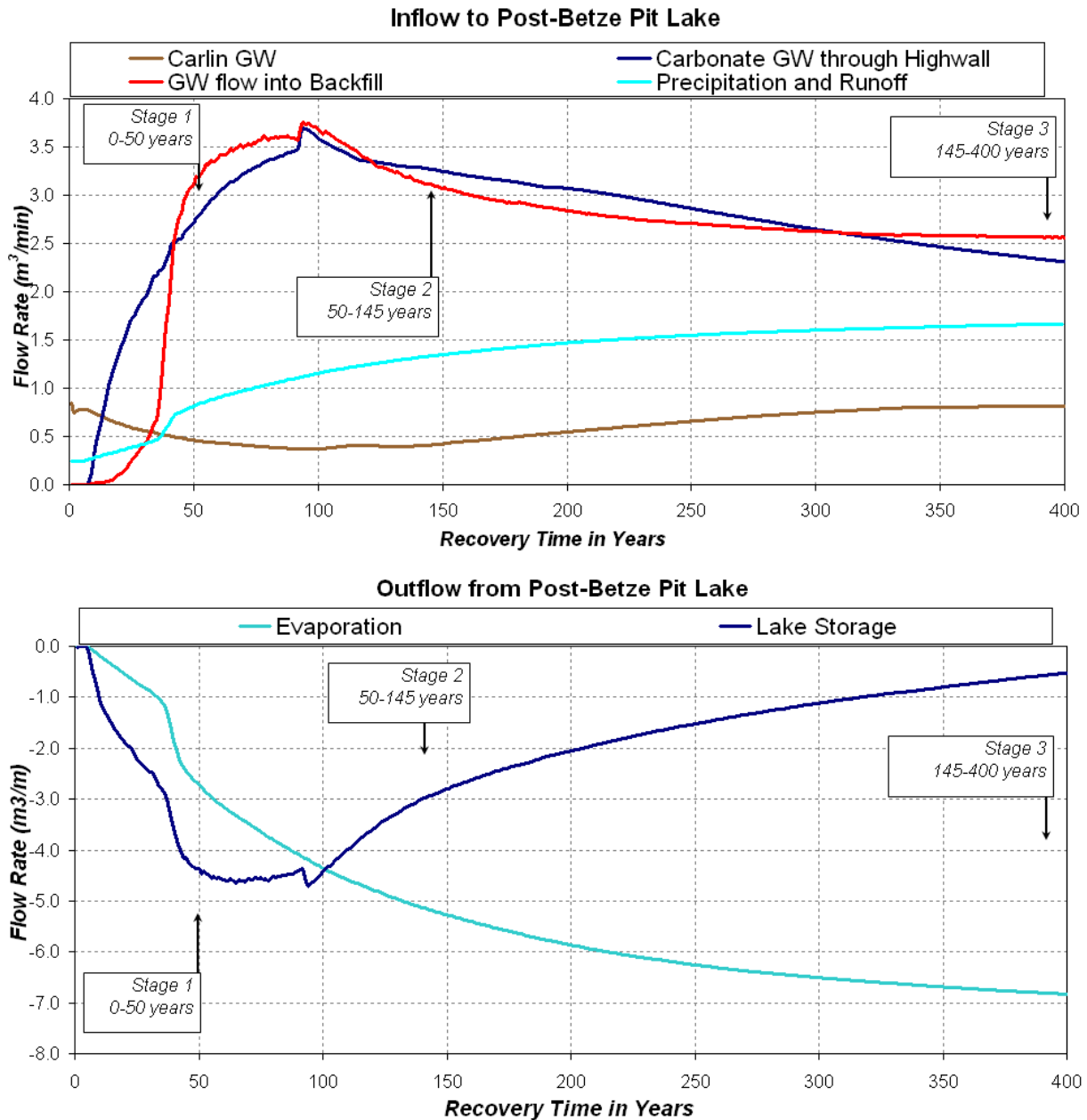


Figure 7. Variations in the primary components of inflow and outflow from the pit lake through time. Outflow is shown as a negative quantity to differentiate it from inflow.

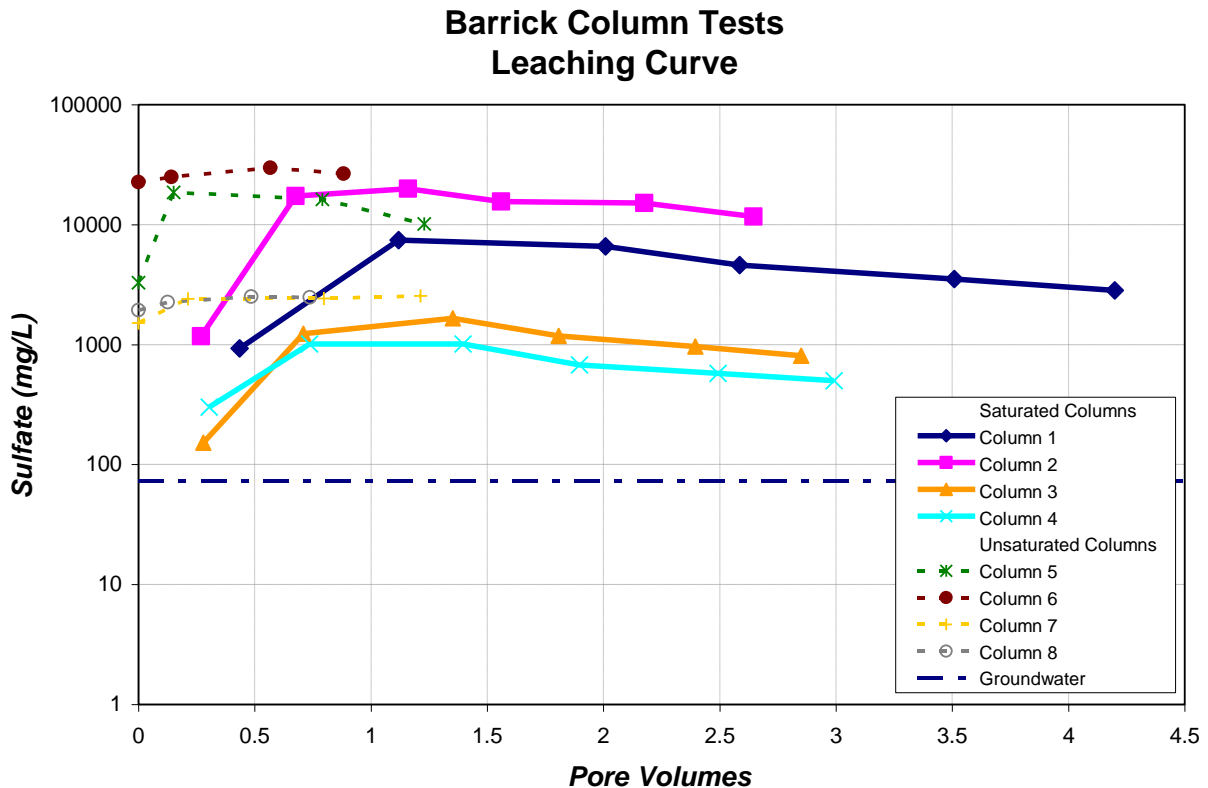


Figure 8. Changes in  $\text{SO}_4^{-2}$  concentration as a function of pore volumes displaced in the saturated and unsaturated columns

Solutions derived from columns with strongly negative NNP values were acidic while neutral pH was observed in column samples with positive NNP values. Lower pH samples tended to have higher common ion levels and electrical conductivity (EC) than neutral pH samples. The elevated sulfate and EC levels indicates that the large diameter columns, consisting of weathered samples, provided representative solutions for predicting the interaction between weathered rock and contact water, which is vital to the prediction of pit water quality (Fig. 9).

#### Batch Studies

The purpose of the batch tests was to simulate the chemistry of water that will exist in the pit lake at various times during filling. A spreadsheet model was developed to calculate the correct quantities of representative solutions required to simulate the water quality. The required proportions of different water samples (Table 3) were based on the cumulative water from the MODFLOW model.

The cumulative water balance was derived by adding together the incremental flows of water for each year of filling. The resultant quantity of water was divided by the total inflow to find the proportion from each source. The groundwater inflow includes the contribution from both the Carlin and the carbonate aquifers. Additionally, the precipitation and runoff term is composed of direct rainfall into the pit lake and runoff from the highwall, the reclaimed backfill and the reclaimed waste rock pile. The inflows in Table 3 add to 100% and the outflows add to -

100%. The pit lake water quality prediction for the pumped case accounts for the fact that some chemical mass is removed from the pit lake when pumping occurs. The 3,000 year pumped case represents the chemical equilibrium that will be reached if water is pumped from the pit lake in perpetuity for irrigation. The water balance for the 3,000 year case was developed by assuming that the annual flow volumes determined for year 400 (in the pumped case) remained the same indefinitely. This is a reasonable approach since the pit lake is near its hydrologic equilibrium by year 400.

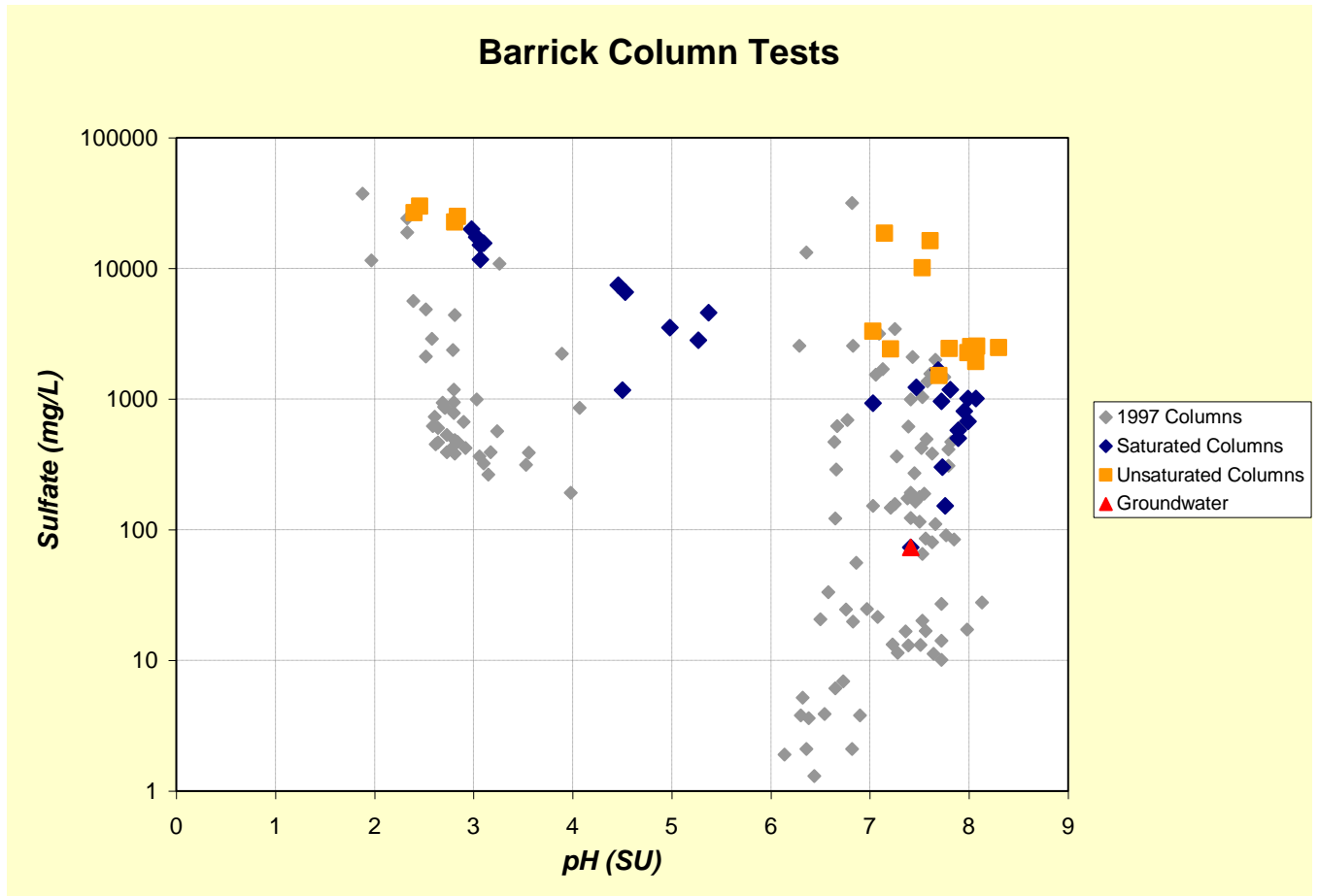


Figure 9. Relationship of solution pH and  $\text{SO}_4^{-2}$  for all samples collected from columns in 1997 and 2002.

Table 3. Pit filling proportional water balance.

Year	Stage	Gains			Losses		
		GW through Highwall	GW through Backfill	Rainfall & runoff	Water stored in pit lake	Evaporation	Pumping
No pumping							
50	4,560	61.6%	24.5%	13.8%	-69.8%	-30.2%	
143	4,929	47.9%	38.6%	13.6%	-53.0%	-47.0%	
400	5,141	45.7%	36.3%	18.0%	-29.8%	-70.2%	
Pumping at 0.14 m <sup>3</sup> /min for growing season							
400	5,050	47.8%	37.2%	15.0%	-20.7%	-58.0%	-21.2%
3,000	5,050	48.7%	36.7%	14.6%	-1.37%	-59.2%	-39.4%

*Note- Direct rainfall, highwall runoff and reclaimed area runoff equal the total inflow from precipitation and runoff.*

The empirical batch tests, which were conducted to simulate the 400 year cases with and without pumping and the 3,000 year case yielded, results that were generally similar to prior pit lake evaluations (Table 4). Water quality for the 400 year pit lake simulation had a basic pH, high alkalinity, contained elevated sulfate, and low metal levels. Both the batch tests that simulated post-closure management involving withdrawing water for a beneficial use showed slightly lower salinity than the 400 year case. Minor differences in trace element levels between the batch tests could be attributed to either gradual depletion of metals from the weathered highwall and backfill zones, or due to differences in equilibrium pH. Evaporation of the mixture of waters that form the pit lake caused formation of a variety of solids. Some constituents such as sulfate and sodium tended to remain in solution during evaporation. Among the metals, B and Se also tended to remain in solution despite evaporation. Many common ions and metals were partially removed from solution when solids formed. These included Ca, Mg, HCO<sub>3</sub><sup>-</sup>, Al, As, Sb, Ba, Cu, Fe, Mn, Ni, and Zn.

Analysis of Solids Formed in Batch Tests: Representative samples of precipitated solids from the batch tests were analyzed by X-ray diffraction (XRD) for bulk mineralogy, and scanning electron microscopy (SEM) was used to characterize grain morphology and to determine the trace composition of specific mineral grains.

Solids that precipitated from the batch tests were comprised of a mixture of crystalline and amorphous material. Crystalline material in samples was principally aragonite (70 to 90 %) and calcite (10 to 30 %), with minor amounts of quartz (<1%). Detailed grain analysis by SEM determined that the solids consisted of predominantly acicular aragonite crystals, with lesser amounts of stubby equant calcite containing variable but generally minor amounts of Fe, Mg and Mn, small quartz grains, and occasional grains of barite. These samples also contained amorphous material consisting of complex (hydrated) Fe<sub>2</sub>O<sub>3</sub> with variable amounts of C, Ca, and silica. Magnesium, Mn, Zn, Al and K were more rarely identified within the amorphous ferrihydrite masses.

Selected carbonate grains and zones of adjacent amorphous material were analyzed to determine elemental composition. Three of the grains had the distinctive diamond/rhomb cross-



sectional shape of aragonite (Fig. 10) while the other 2 carbonate grains were irregularly shaped. Element mapping showed that As was not associated with the amorphous Fe phases but appeared to concentrate in the outer margins of the calcite and aragonite grains. Manganese was slightly more concentrated in the center of calcite grains, while Mg was concentrated along the grain margins. Iron was not present in any of the carbonate grains but was concentrated in the amorphous materials. The scan for Ni showed that the element was evenly distributed through all grains, but the apparent Ni distribution may have been an artifact of interference since it was not detected in point and line scans.

Table 4. Analytical results for batch tests used to simulate pit lake chemistry after 400 years and 3,000 years, with and without pumping.

Common Ions									
Sample ID	PH Method EPA 150_1 (SU)	Electrical Conductivity / Method EPA 2510B (UMHOS/C M)	Alkalinity / Method EPA 2320 (MG/L), MDL is 1	Total Recov.	Total Recov.	Total Recov.	Total Recov.	Total Recov.	Total Recov.
				Calcium / Method EPA 6010B (MG/L)	Magnesium / Method EPA 6010B (MG/L)	Sodium / Method EPA 6010B (MG/L)	Sulfate / Method EPA 300 (MG/L), MDL is 0_3	Chloride / Method EPA 300 (MG/L), MDL is 1	Bicarbonate / Method EPA 2320 (MG/L), MDL is 1
400 Years	9.03	1610	310	10.7	96.3	190	574	42.5	220
400 Years (Pumped)	9.14	1560	372	8.19	86	195	464	42.2	247
3,000 Years (Pumped)	9.33	1320	379	2.44	40.2	202	246	41.1	235

Trace Metals						
Sample ID	Total Recov.	Total Recov.	Total Recov.	Total Recov.	Total Recov.	Total Recov.
	Arsenic / Method EPA 206_2 (MG/L), MDL is 0_001	Barium / Method EPA 6010B (MG/L), MDL is 0_002	Iron / Method EPA 6010B (MG/L), MDL is 0_02	Nickel / Method EPA 6010B (MG/L), MDL is 0_01	Antimony / Method EPA 204_2 (MG/L), MDL is 0_002	Zinc / Method EPA 6010B (MG/L), MDL is 0_005
400 Years	0.016	0.0312	0.02	B	0.065	0.012
400 Years (Pumped)	0.032	0.0302	0.02	B	0.046	0.008
3,000 Years (Pumped)	0.046	0.043	0.02	B	0.01	B

### Model Calibration

Several changes were made in the PHREEQC input files and database to improve the agreement for As, Sb, Ba, Ni, and Zn. The model indicated that most of the As was held in a sorbed form on ferrihydrite. Trace element analysis using SEM indicated that As was associated with carbonate grains, but the thermodynamic data necessary to model this chemical form of As are generally unavailable. Consequently, As solubility was calibrated by decreasing the quantity of strong and weak ferrihydrite sorption sites to 15% of the values used by Dzombak and Morel (1990). Next, the formation constant for sorbed Sb was greatly increased to cause greater sorption in the model. Additionally, the thermodynamic data for barite, and willemite were changed to improve agreement for dissolved Zn and Ba (e.g. the solubility constant was increased for barite and decreased for willemite). Nickel silicate and Ni carbonate species were added to the list of possible solid phases, and the thermodynamic data for Ni silicate were

modified. Finally, a solid solution allowing partial substitution of Zn and Ni for Ca in calcite was created. These changes improved the agreement between the model and actual results.

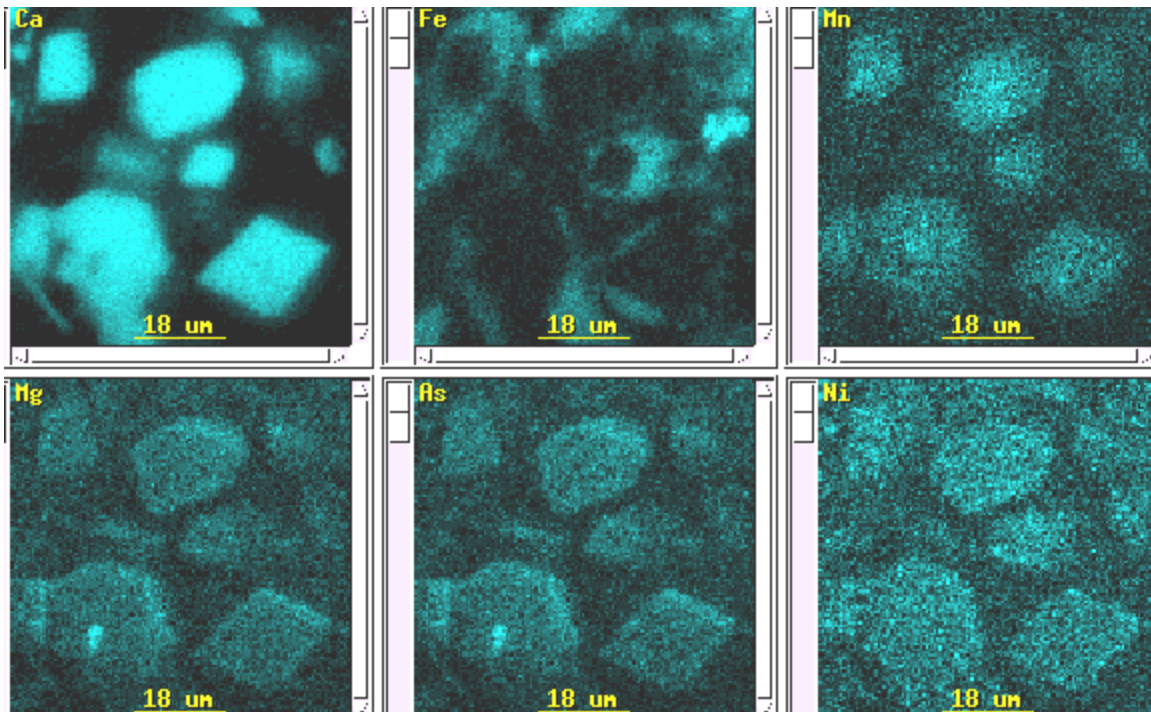
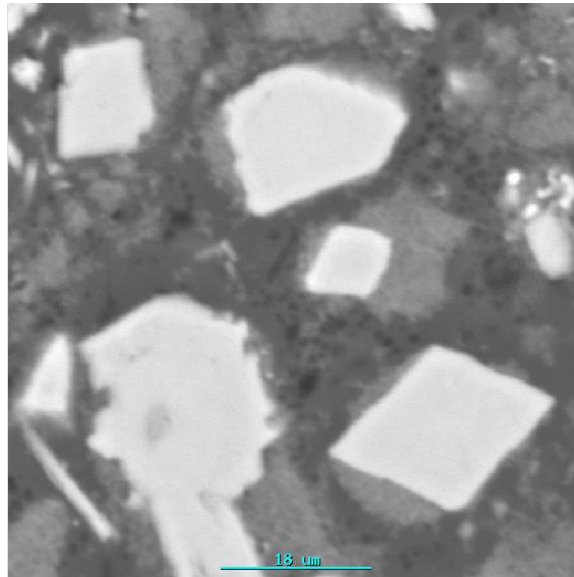


Figure 10. Carbonate grains in sample (02-485-B, evaporated 400 year pumped untreated). Arsenic and Mg showed slight enrichment towards the exterior of the grains, while core regions contained elevated levels of manganese. Iron was not present in any of the carbonate material.

### Transient Changes in Pit Lake Chemistry

Using the calibrated model, expected changes in pit lake chemistry through time were evaluated. In the early stages of filling the pit lake is dominated by Ca and  $\text{SO}_4^{-2}$  ions, and while neutral in pH has lower alkalinity than at later stages (Fig. 11, Table 5). As the pit lake continues to fill, more of the oxidation products are removed from the backfill and highwalls, more of the sulfide-enriched portion of the highwall is inundated, and evaporation has a larger cumulative effect. Consequently,  $\text{SO}_4^{-2}$  decreases from its initial concentration due to decreasing highwall rinse-off, and Ca decreases due to calcite precipitation. These reductions in ion concentration are off-set by increases in alkalinity and  $\text{Na}^+$  ion so that TDS increases slightly from year 50 to year 400. The pH of the lake system increases slightly with time (from 8.1 to 8.9) due to the transition from a calcium-bicarbonate towards a sodium-bicarbonate water. If no water were removed from the pit lake system, ion concentrations would tend to slowly increase through time.

Removal of water for irrigation will, by the year 400, tend to reduce ion concentrations by about 27% relative to the case where no water is pumped because some of the chemical mass is removed by pumping. When water is removed for irrigation, the water chemistry tends to stabilize after 1,000 years or more with a TDS less than 1,000 mg/L, 30 % less than the value reached in 400 years without pumping.

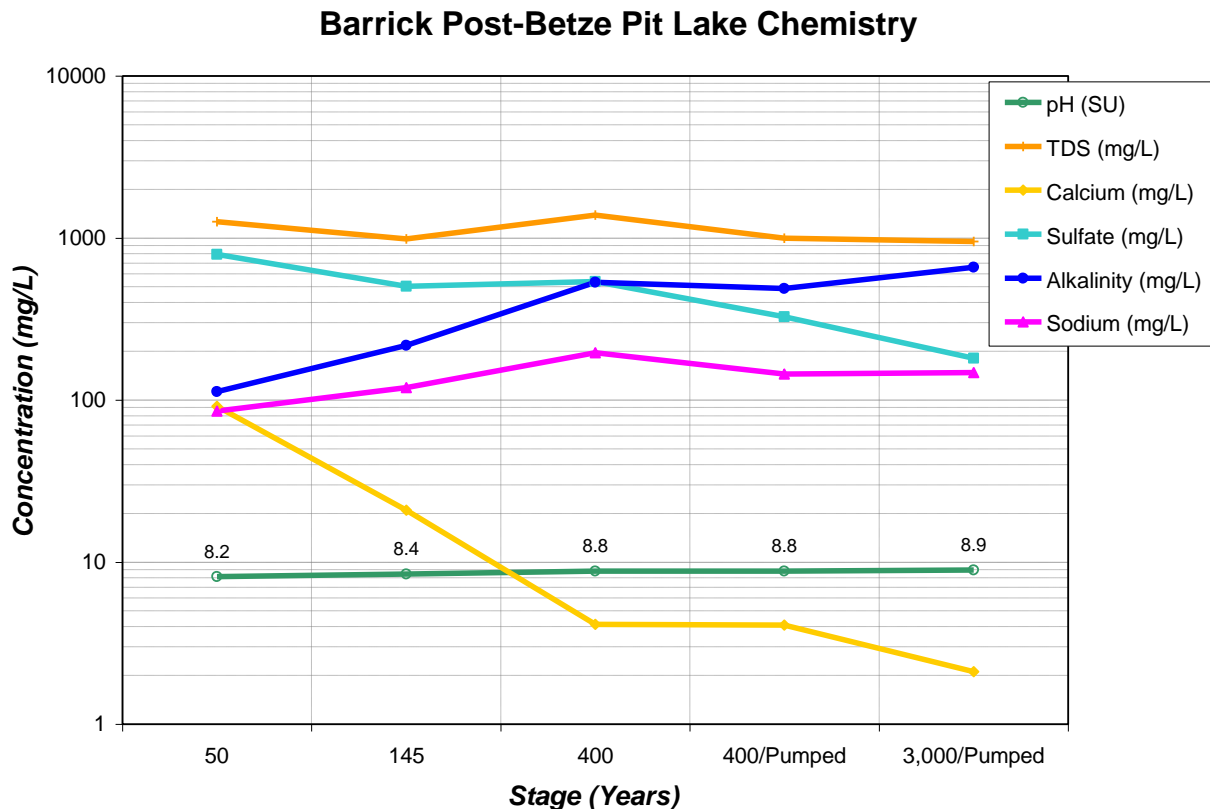


Figure 11. Predicted transient changes in common ion concentrations in the Post-Betze pit lake.

Concentrations of trace elements (Fig. 12, Table 5) in the pit lake are strongly controlled by pH and by the quantity of Fe available for sorption. As the pH of lake increases from 8.1 to 8.9, and as the total quantity of Fe decreases because of decreasing rinse-out of the weathering products from the highwall, the amount of sorption diminishes between year 50 and year 400. Consequently, predicted concentrations of As and Sb increase slightly, while concentrations of Zn and Ni stay roughly the same because of their apparent solubility control by precipitation and co-precipitation in addition to sorption. Manganese concentrations decrease throughout the life of the pit lake, probably due to decreasing proportional contributions from the highwalls and backfill. If water is removed for irrigation, some trace element concentrations may increase slightly when chemical equilibrium is reached, due in part to a reduction in dissolved silica levels (for Zn and Ni), and due to reductions in iron reaching the pit lake (for As). Predicted increases in trace element levels will not cause any constituents to exceed ecological risk benchmark levels, however.

Table 5. Summary of Post-Betze pit lake water quality monitoring result for the lake epilimnion layer.

Parameter	50 Years	145 Year	400 Years	400 Year (Pumped)	3,000 Year (Pumped)
<b>Common Ions</b>					
EC (uS/cm - est)	1922	1490	2114	1559	1484
pH (SU)	8.1	8.5	8.9	8.8	8.9
pe	4.7	4.3	3.9	5.4	5.3
TDS Calc (mg/L)	1230	954	1353	998	950
Alkalinity	78	178	492	488	663
Calcium (mg/L)	84.7	14.0	2.4	4.1	2.1
Magnesium (mg/L)	115.7	79.3	99.9	66.0	51.6
Sodium (mg/L)	85.7	119.2	196.2	144.8	148.0
Sulfate (mg/L)	795.5	504.1	538.7	326.4	180.9
Bicarbonate (mg/L)	47.4	108.5	300.3	297.5	404.5
Carbonate (mg/L)					
<b>Trace Constituents</b>					
Antimony (mg/L)	0.003	0.005	0.010	0.013	0.003
Arsenic (mg/L)	0.002	0.005	0.019	0.002	0.045
Barium (mg/L)	0.046	0.058	0.061	0.007	0.012
Manganese (mg/L)	1.322	0.217	0.035	0.003	0.002
Nickel (mg/L)	0.015	0.013	0.014	0.165	0.035
Zinc (mg/L)	<0.005	<0.005	<0.005	0.025	<0.005

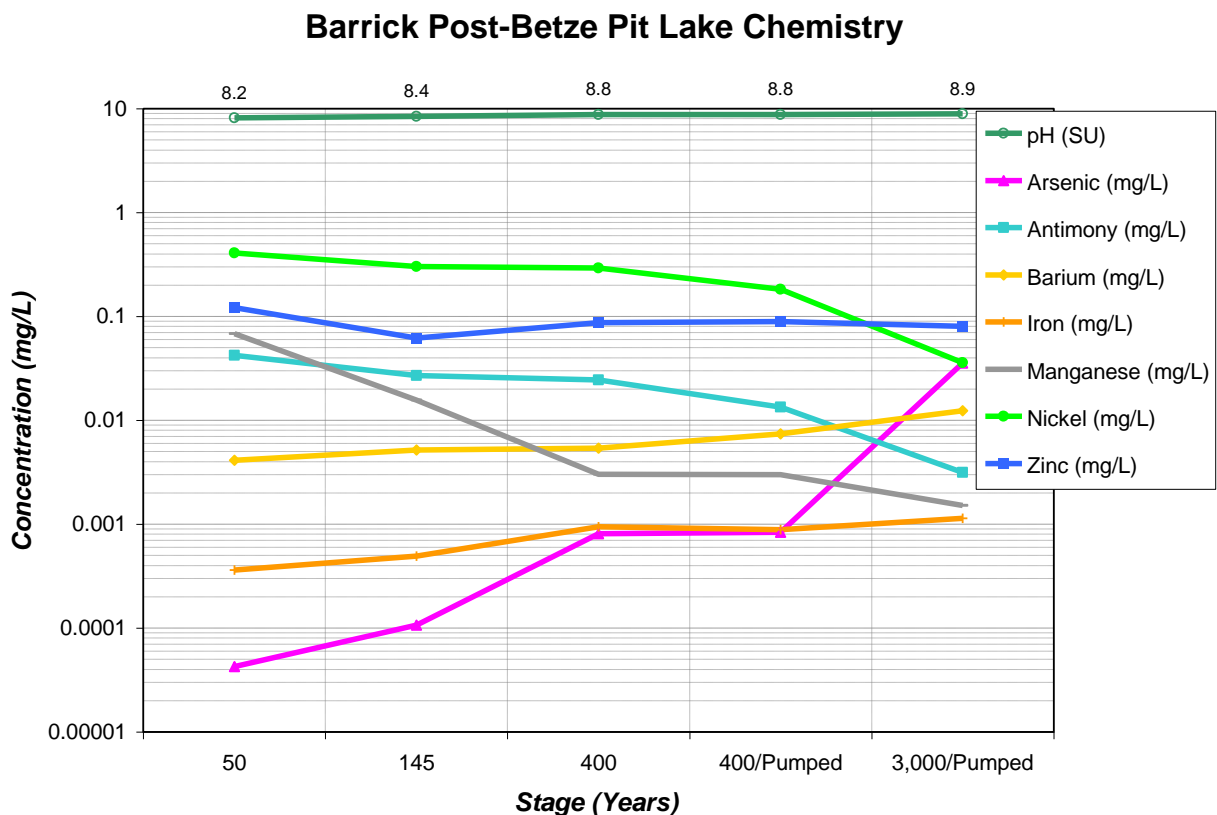


Figure 12. Predicted transient changes in trace element concentrations in the Post-Betze pit lake.

PHREEQC was also used to estimate chemistry in subsurface portions of the pit lake. Redox levels were selected to represent three conditions;

The redox of the seasonal hypolimnion (e.g. the subsurface volume of the pit lake not in direct contact with the atmosphere due to seasonal temperature stratification),

the redox of a permanently stratified lake (e.g. if turnover does not occur as predicted),

and the redox in the sediment layer.

To achieve these redox conditions, the fugacity of oxygen was modified until the resultant target redox levels were achieved (Fig. 13). The dissolved partial pressure of carbon dioxide in subsurface environments was assumed to be 10 times atmospheric levels.

As redox levels decrease, the solubility of most trace elements slightly increased, mostly owing to a decline in equilibrium pH from 8.8 in the simulated epilimnion to less than 8 in subsurface layers (Fig. 14). A large increase in soluble iron was postulated at the lowest probable lake redox levels (-82 mv) that would occur only if subsurface layers remain permanently stratified. Due to the loss of colloidal Fe, the predicted As levels increased to just over 0.1 mg/L. However, the As behavior in PHREEQC was simulated by sorption on Fe, while the SEM data suggests that As solubility is controlled by precipitation with calcite (which was not simulated in PHREEQC). Therefore, actual As levels are expected to be much lower even at low redox levels. At redox levels (-342 mv) that may occur within the sediment layer (if organic

C accumulates), Fe solubility is again reduced because of secondary sulfide formation. Other metals, notably Ni are expected to decrease in concentration in the sediment layer due to formation of sulfides in the organically enriched zone.

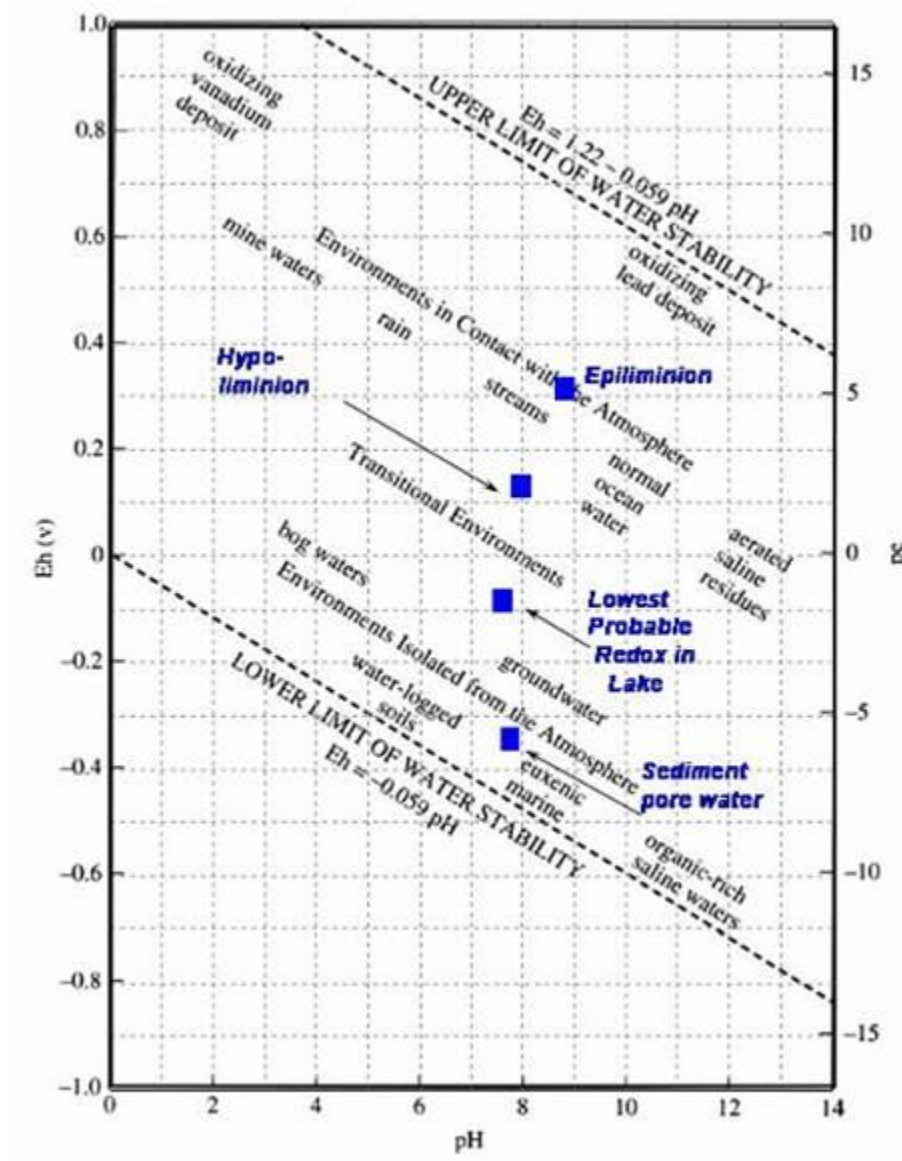


Figure 13. Redox and pH levels used to simulate potential subsurface water chemistry in the Post-Betze pit lake.

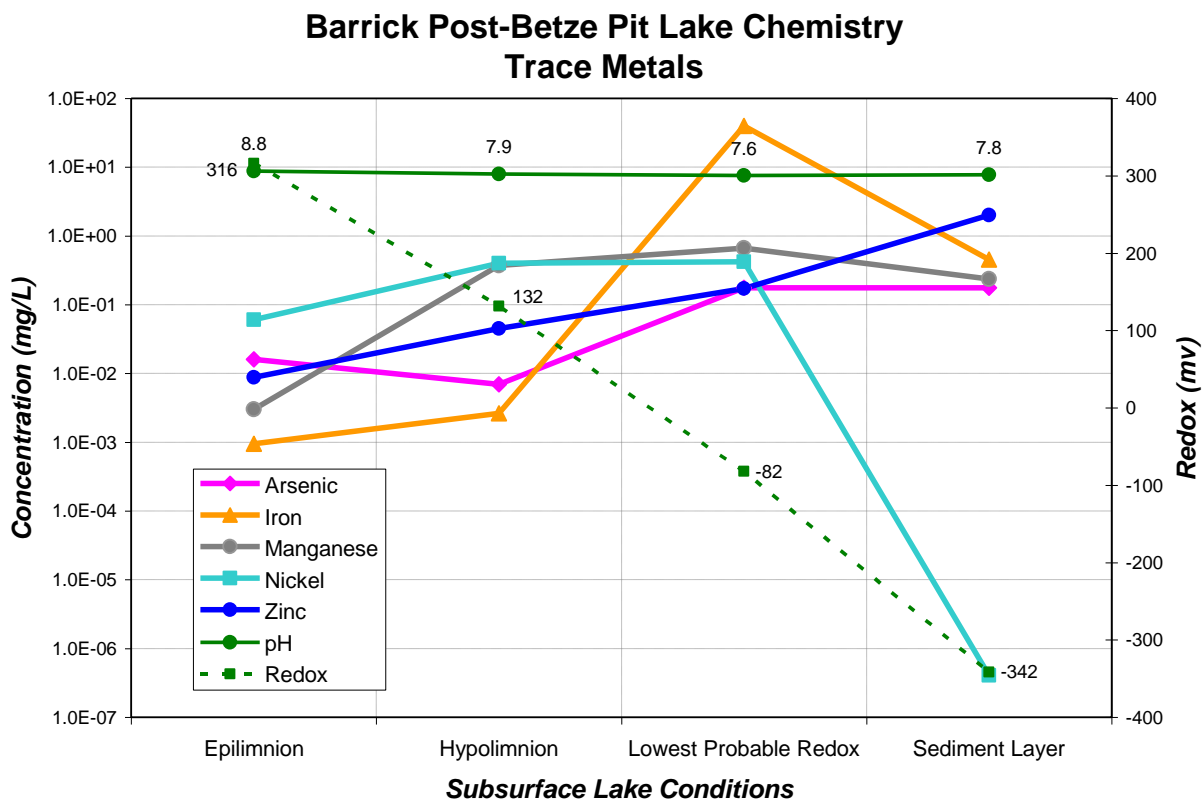


Figure 14. Predicted changes in trace element concentrations in the Post-Betze pit lake due to variations in redox.

#### Conclusions and Evaluation of Predicted Water Quality

The predicted water quality in the Post-Betze pit lake will not degrade waters of the State and is protective of terrestrial, avian and human health. Water contained in the surface of the pit lake will meet all primary drinking water standards except for antimony in year 400. The secondary drinking water standards will be met for all constituents except TDS,  $\text{SO}_4^{-2}$ , and F in early stages of filling. The  $\text{SO}_4^{-2}$  standard may be met in the long term if water is withdrawn for irrigation. The water meets all ecological risk benchmark levels established for Nevada pit lakes. The salinity of the water is suitable for irrigation of alfalfa and the sodium adsorption ratio (SAR) will vary from 1.5 to 4.5, which is suitable for all soils.

The modeling showed that post-closure water management may have a significant effect on long-term water quality in arid environments. Withdrawal of water would control the amount of evaporative concentration that may occur in the pit lake, which would result in lower long-term salinity.

Results of empirical batch tests to simulate pit lake water quality can greatly improve water quality prediction if results are used to calibrate PHREEQC. The model accurately predicted the common ion concentrations and pH of the batch tests, and correctly simulated the precipitation of large amounts of calcite when a mixture of various mine waters, groundwater and meteoric water was evaporated (although aragonite was actually the dominant solid that formed). Agreement between the uncalibrated model and batch tests was poorer for some metals,



however. Prior to calibration, the PHREEQC model over-predicted Zn, Ni, and Sb concentrations in the pit lake while under-predicting concentrations of Ba, Cu and As. Microscopic analysis of precipitated solids facilitates the selection of appropriate solid phase minerals although available thermodynamic data generally do not provide accurate prediction of trace element solubility. After calibration, PHREEQC accurately predicted concentrations of all constituents, improving its reliability for long-term pit lake water quality prediction.

Electron microscopy revealed surprising results, showing that As is strongly associated with calcite and aragonite grains and was not sorbed onto amorphous Fe compounds. In most pit lake studies, very low equilibrium As concentrations are often predicted owing to the strong sorption of As onto ferrihydrite. It appears that the mixed amorphous iron-carbon- calcium-silica phase that actually formed in batch tests had lower As sorption capacity. An additional ramification of this controlling phase is that As solubility may be less than predicted in alkaline pit lakes that are low in Fe and in which calcite forms (such as may occur in later stage of pit lake evolution when less iron may be contributed from the weathered highwall zone). Thermodynamic data for the As-calcite phase are unavailable, and further understanding of this removal mechanism is an appropriate goal of future research.

Previous limnological evaluations (Radian, Baker 1997) indicate that the Post-Betze pit lake will be well mixed. The high temperature (e.g. greater than 40 celsius) of the groundwater tends to weaken the stratification that might otherwise prevent seasonal turnover of such a deep lake. Nonetheless, one potential drawback of the modeling approach is that full mixing is assumed. If the lake does not mix as predicted, PHREEQC indicates that lower subsurface redox levels that may develop in a stratified lake would not significantly change common ion concentrations. Metal concentrations would increase slightly, owing mostly to a slight reduction in equilibrium pH from 8.8 to less than 8.0.

### **Literature Cited**

- BGMI. 1991. Post Mining Geohydrology and pit Closure. Report prepared in support of the Final Environmental Impact Statement, Betze Project.
- Davis, G.B., G. Doherty and A.I.M Ritchie. 1986. A Model of Oxidation in Pyritic Mine Wastes: Part 2: Comparison of Numerical and Approximate Solutions. Appl. Math. Modelling 10:323-329. [http://dx.doi.org/10.1016/0307-904X\(86\)90091-0](http://dx.doi.org/10.1016/0307-904X(86)90091-0).
- Dzombak, D.A., and F.M.M. Morel. 1990. Surface complexation modeling—Hydrous ferric oxide: New York, John Wiley, 393 p.
- Hydrogeologic. 1999. Diffuse-Layer Sorption Reactions for use in MINTEQA2 for HWIR Metals and Metalloids. Report prepared for US EPA - National Exposure Research Laboratory, Ecosystems Research Division, Athens, Georgia
- McDonald, M.G. and A. W. Harbaugh. 1988. A modular three-dimensional finite difference ground-water flow model: U.S. Geological Survey Techniques of Water Resources Investigations, Book 6, Chapter A1, 586 pgs. U.S. Govt. Print. Offc. Wash., D.C.
- McDonald Morrissey Associates. 1998. Regional Hydrologic Model. Report to BGMI dated February 24, 1998. Radian International and Baker Consultants. 1997. Predicted Water Quality in the Betze-Screamer Pit Lake. Final Report submitted to BGMI.

- National Atmospheric Deposition Program. 2005. Station Summary for Monitoring Location NV01 (Saval Ranch), Latitude 41.2853, Longitude -115.8522, Elevation 1872 meters. <http://nadp.sws.uiuc.edu/sites/siteinfo.asp?net=NTN&id=NV01>
- Parkhurst, D. L. and C.A.J. Appelo. 1999. User's Guide To PHREEQC (Version 2)—A Computer Program For Speciation, Batch-Reaction, One-Dimensional Transport, And Inverse Geochemical Calculations. Water-Resources Investigations Report 99-4259. US Geological Survey. US Govt. Print. Offc. Wash., DC.
- Radian International and Baker Consultants. 1997. Pit Lake Water Quality and Limnology of the Barrick Betze Pit Lake. Final Report submitted to BGMI.
- Schafer, W.M. and M. Logsdon. 2003. Barrick Goldstrike Mine - Predicted Water Quality in the Betze-Screamer Pit Lake. Final Report submitted to Barrick Goldstrike Mining Inc.
- Sobek, A.A., W.A. Schuller, J.R. Freeman, and R.M. Smith. 1978. Field and Laboratory Methods Applicable to Overburdens and Minesoils. Report EPA-600/2-78-054, U.S. National Technical Information Report PB-280 495. 403 p.
- TRC. 2000. Pit Lake Water Quality Model Predictions for the Future Partially-Backfilled Betze-Screamer Pit. Final Report submitted to BGMI.