

# PIT LAKE WATER QUALITY MODELING CALIBRATION OF THE MAIN PIT, TYRONE MINE, NEW MEXICO, USA<sup>1</sup>

Walder<sup>2</sup>, I.F., <sup>3</sup> Blandford, N., and Shelly Jr, T.

**Abstract.** A major difficulty facing many open pit mines where sulfides are present is the pit lake water quality after closure. A reliable prediction of future water quality within an open pit mine, excavated below the water table, requires a large amount of information and predictions for maybe hundreds of years into the future. These long-term predictions can only be useful with thorough understanding of geochemical and hydrological processes of pit walls and surface water and groundwater discharging into the pit during mining and at closure.

Tyrone Mine initiated a pit-lake water quality evaluation as part of a closure evaluation. This involved characterization of waste rocks near the mine pit; determination of groundwater discharge and recharge into and from the pit using numerous wells drilled in the vicinity and monitored over many years; analysis of existing pit lake water quality over many years including a period of seven months with no pumping; water quality data from monitoring wells; local climate measurements; simulated rainfall leaching tests; and waste rock discharge water analysis.

A modeling scenario was set up dividing the groundwater recharge/discharge into 5 zones based on groundwater flow and geochemistry. The hydrogeological model was calibrated based on the monitoring data where recharge or discharge volumes for each of the zones were calculated. Surface runoff water quality was based on three different mineralogical zones that had a distinctly different leaching potential: an oxide zone with neutral pH and low total dissolved solids; a Chalcantite zone with weakly acidic and very high TDS (in particular sulfate and copper); and a sulfide zone with low pH and high sulfate.

Pit lake modeling was performed to simulate the water quality observed during a seven-month period when there was no pumping taking place in the Main Pit. The model was calibrated with surface runoff and mineral precipitations. This modeling indicated that pit wall runoff was the most important control on water quality, and that the runoff water quality could be well represented by using in-field rainfall simulated leach tests.

**Additional Key Words:** weathering tests, porphyry copper deposit, Tyrone Mine, pit walls

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<sup>2</sup>Ingar F. Walder, Principal Geochemist, SARB Consulting Inc. 8400 Menaul Blvd. Albuquerque NM, 87112, (sarb4you@aol.com), <sup>3</sup>Neil Blandford, Vice President, Daniel B. Stephens and Associates, Albuquerque, NM, Tom Shelly, Jr., Environmental Manager, Phelps Dodge New Mexico, Tyrone, New Mexico.

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## Introduction

The water quality of the Main Pit at Tyrone Mine was investigated in order to evaluate closure options for the open pit. The open pit mining began in the late 1960's and has still reserves left for several years of operation. This investigation is reporting on the modeling and calibration of the water quality sources for a pit lake formation.

Large-scale mining of low-grade ore has been common for many years in all parts of the world. This type of mining commonly results in large open pits with major waste rock piles in the near vicinity of the pit. This is typical for porphyry copper and porphyry molybdenum mines and certain large-scale Au mines. Many of the open pit mines have been excavated far below the water table and will, when the mining operation and dewatering ceases, result in a pit lake, e.g. Berkeley Pit, Butte, Montana (Miller et al., 1996), and McLaughlin Gold Mine Pit (Rytuba et al., 2000). Many of these pits will have poor water quality (Davis and Eary, 1997; Miller et al., 1996). A critical component in the pit lake water quality modeling is an understanding of the nature of the rocks/mineral types exposed to weathering in the pit walls (Walder and Schuster, 1998).

Closure of large-scale open pit mines is problematic when sulfide minerals are associated with low-grade, un-mineable wall rocks. It is necessary to predict the future quality of water accumulating within the open pit, in order to evaluate closure options and to estimate closure costs. However, the input sources are the most critical components of pit lake water quality prediction and require careful evaluation before future pit lake water quality predictions can be made. Phelps Dodge Tyrone Mine (Tyrone) initiated a pit lake water quality investigation to evaluate the future pit lake water quality after closure, of a pit lake that is kept to a shallow depth during operation. As an initial step in predicting the future water quality in the Main Pit at Tyrone, the water quality was modeled during a seven-month period in which pumping was ceased. The focus of this paper is on the input data, the modeling approach and calibration of the modeling during this seven-month period. This paper is primarily based on a hydrology report (DBS&A, 1999) and a geochemistry report (SARB, 2000) prepared for Tyrone Mine. The Closure Plan for the Main Pit calls for permanently pumping and treating the water that enters the pit.

### Tyrone Mine Geology

Open pit mining began in May 1967 at the Tyrone porphyry copper deposit, located 10 miles (16 km) south of Silver City, New Mexico (Fig. 1). There are numerous mining areas and open pits; however, the Main Pit is by far the most extensive area of excavation.

The Tyrone Mine currently produces Cu, the only recorded product, from stockpile leaching. In the past, Cu concentrate was produced by froth flotation. There are fluorite deposits situated north and northwest of the Tyrone ore deposit (Gillerman, 1964). Fluorite, U, Ra, Au, Cu, Ag, Pb, Bi, turquoise, and garnets have, at various times, been produced from the White Signal District located 5-6 miles (10 km) southeast of the Tyrone Mine.

The Cu mineralization at the Tyrone Mine is hosted within Precambrian granitic rocks and the Paleocene Tyrone stock (granodiorite and monzonite intrusions). These rocks are overlain by Tertiary volcanic and sedimentary rocks (Gila Conglomerate and Quaternary alluvium). A

quartz monzonite porphyry dominates the southern half of the ore body, while the ore body is hosted by Precambrian granites in the northern half of the Tyrone deposit (Kolessar, 1982).

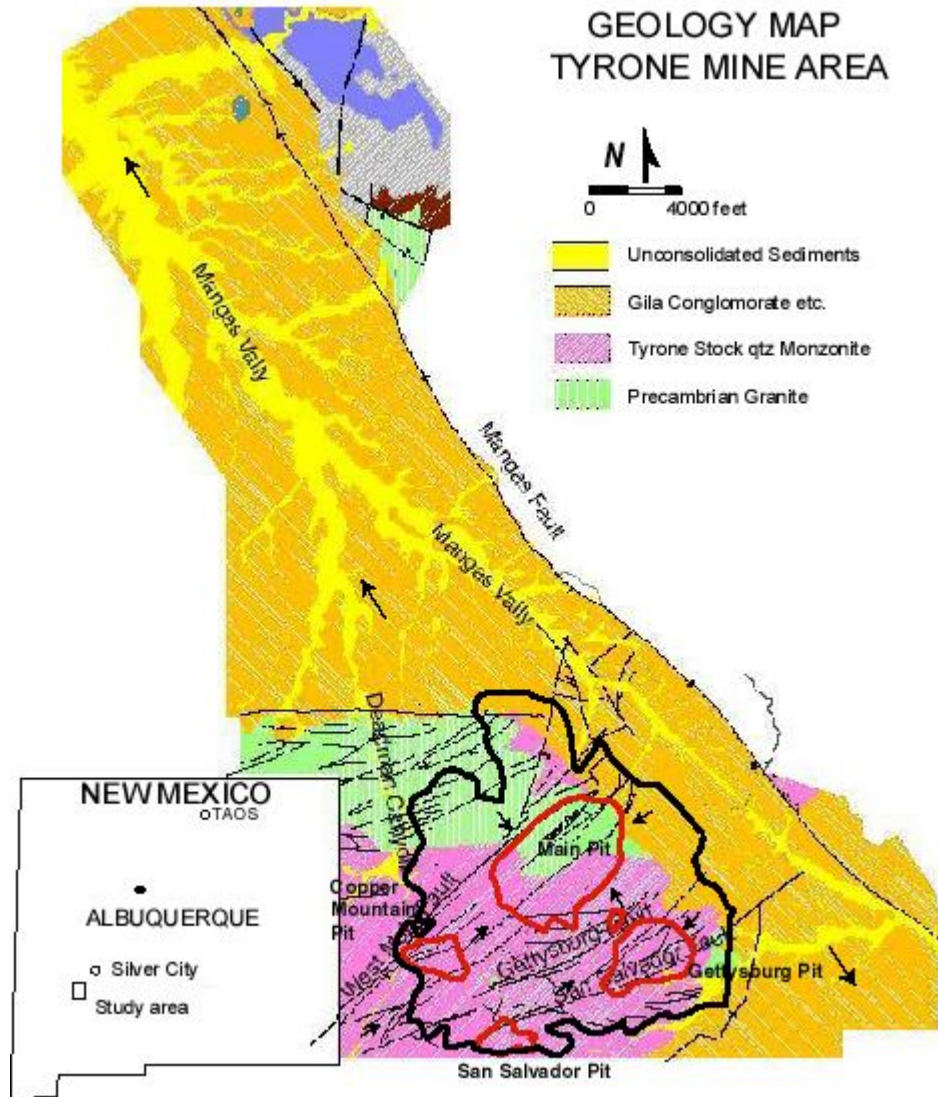


Figure 1. Map of the Tyrone Mine area. The Copper Mountain Pit and the southern-most pit, the San Salvador Pit are above the groundwater table. The black line is the mine area. Arrows indicate groundwater flow directions. The bottom of the Copper Mountain Pit intersects the water table. There are depression cones around the Gettysburg and the Main Pits.

The Tyrone stock is a multiple phase pluton. Four stages of intrusive rocks are recognized at Tyrone of which stage 2, a biotite granodiorite-tonalite quartz porphyry, hosts the mineralization (DuHamel et al, 1996).

The Miocene Gila (Mangas) Conglomerate crops out in the northeastern part of the Tyrone deposit. The unit dips 15 to 20 degrees to the northeast. The Gila in this area consists mostly of conglomerate which contains locally derived boulders, cobbles, and pebbles of igneous rock set in a matrix of coarse sand, grit, and gravel. Caliche formation is common, and carbonate may be

found in the matrix and in the conglomerates clasts. The base of the conglomerate is locally cemented by silica and Fe oxides which host irregularly developed exotic Cu mineralization. Concentrations greater than 0.2% are common, and scattered bodies containing greater than 1% Cu are known (DuHamel et al, 1996) .

The mineralized zone has a strong southwest-northeast fabric of veins, joints and faults. Ore occurs a few feet below the surface near the Copper Mountain Pit area, while it is 500-600 feet below the surface in the northeast portion of the Main Pit area.

The mineral assemblages within the Tyrone Mine are as follows:

- The hypogene mineralization contains the original mineralization with the primary sulfides (pyrite, chalcopyrite, bornite and minor galena, sphalerite, and molybdenite) making up a large portion of the lower part of the pit walls and the bottom of the pit.
- The lower enrichment zone contains a mix of the original mineralization and secondary copper sulfide minerals (chalcocite, covellite, and digenite).
- The higher enrichment zone contains a mixture of secondary copper sulfide minerals and copper oxide minerals. This zone makes up a small portion of the pit walls.
- The oxide zone contains no sulfide minerals. These have been replaced by either chrysocolla, copper carbonate, copper oxide, or iron oxides.
- The leach cap contains no sulfide minerals or copper minerals. This zone makes up a large portion of the pit walls.

#### Site Hydrology

According to the Tyrone Pit Lake Modeling Formation Report, (Blandford et al., 2004; DBS&A 1999a), the Precambrian Burro Mountain Granite, the Quartz Monzonite, the Gila Conglomerate, and the Quaternary alluvium are the primary water-bearing units at the Tyrone Mine. A very complex flow system was interpreted based on water levels measured in June and July 1998. The systems of extensive fractures and faults in the igneous rock units are a main contributor to the complexity of the local groundwater flow regime within the regional aquifer (Blandford et al. 2004).

According to conceptual models presented in DBS&A (1997; 1999), the regional aquifer can be separated into four general areas of flow: the Gila-San Francisco underground basin with a general flow direction to the northwest; the Mimbres Valley underground basin with a flow direction to the east; and the Main Pit and the Gettysburg Pit capture zones where flow direction is towards the hydrostatic depression created by the dewatering systems in each pit (Fig. 1). Based on the 1997 and 1998 water level maps, the regional flow regime appears to be in a quasi-steady state condition (DBS&A, 1999d) using MODFLOW (McDonald & Harbaugh, 1984).

The Main Pit, which is by far the largest of the pits at Tyrone, is approximately 5000 feet (1.7 km) in length and 4000 feet (1.3 km) wide. The pit is approximately 900 feet (300 m) deep.

#### Methods

Temperature, total dissolved solids and pH were measured in the field of all surface water and groundwater samples. Samples were split, and one split was filtered using a 0.45-micron filter

and acidified. The element analyses were performed by SVL Laboratories, Kellogg, Idaho, using ICP following US Environmental Protection Agency procedures.

Field rainfall simulated leach tests were performed at two selected sites from each of the geological units exposed in the pit walls: oxide zone (the leach cap material); chalcantinite zone (upper enrichment zone with chalcantinite); and sulfide zone (lower enrichment zone and hypogene mineralization). The area of each site was approximately 10 ft<sup>2</sup> (1 m<sup>2</sup>). Half a gallon (1 1/2 liters) of distilled water was sprayed evenly on the selected pit wall areas, and runoff water was collected at the base of the areas. This represented a rainfall of approximately 1/2 inch (15 mm). The collected water was handled and analyzed as the water samples described above.

## Results

In order to evaluate the groundwater and surface water entering the Main Pit, surface water runoff and groundwater discharge volumes were measured; surface water and groundwater were sampled, analyzed and evaluated together with seeps from the pit walls. Pit wall mineral reactions and leaching were also evaluated. The groundwater discharge and the seeps were divided into five flow zones around the Main Pit (Fig. 2). In addition, the pit lake in the Main Pit was sampled and evaluated during a seven-month period, during which pumping had stopped. The results of these measurements and calculations are described in the following sections.

### Hydrology

A pit lake formation model was developed for the Tyrone deposit in order to:

- Develop a comprehensive simulation tool for conducting groundwater computations within the Tyrone Mine/Stockpile Unit; and
- Evaluate the formation of pit lakes and groundwater flow directions under long-term post-closure conditions.

A variation of the U.S. Geological Survey (USGS) code MODFLOW (McDonald & Harbaugh, 1984), MODFLOW-SURFACT (HydroGeoLogic, Inc, 1999) was selected for developing a numerical groundwater flow model for the Mine/Stockpile Unit and simulating the rise of the water table in the pits.

A three-layer flow model was developed for the Tyrone Mine area. The top model layer intersected the bottom of the Gettysburg Pit at 5,600 feet above mean sea level (ft msl), since the bottom of this pit intercepts the groundwater table. The top and mid layers were assigned a thickness of approximately 300 feet each, with the bottom of the mid layer being set at 5,000 ft msl, which approximately corresponds to the base of the Main Pit. Assigned values of evaporation, precipitation, and runoff into the pit were variable for each model layer. The recharge sources included groundwater inflow and seepage from stockpiles and other facilities.

The groundwater flow was then divided into five zones based on similar geochemistry, flow direction and stockpile location. The groundwater discharge into the pit from each of these zones was calculated (Table 1).

The groundwater flow model was calibrated to the groundwater flow regime at Tyrone at the time of the modeling, including the Mangas Valley north of the Tyrone Mine area, the Burro Mountains southwest of the mine area, and the Gila San Francisco basin east of the mine area.



The simulated rate of groundwater inflow to the Main Pit, without an initial pit lake at the bottom, was 1,797 gallons per minute (gpm). The initial groundwater inflow rate to the Main Pit, with an initial lake elevation of 5,200 ft msl (65 meters above the pit floor) was simulated to be 1,279 gpm.

Table 1. Surface runoff was based on the runoff area  $30.3 \times 10^6 \text{ ft}^2$  multiplied by the precipitation, 15 inches/year (in/yr, 45 cm/year) assuming approx. 50 percent evaporation loss for the area outside the pit perimeter and no evaporation for the area within the pit perimeter; and subtracting the direct lake precipitation. The Roman numerals correspond to the five flow zones.

Year\ Zone	I	II	III	IV	V	Pit Lake Level	Lake Surface Area	Lake volume	Surface runoff Outside	Surface runoff Inside	Rainfall	Evaporation.
Present (6/98)	$83 \times 10^3$	$38 \times 10^3$	30,025	$105 \times 10^3$	$86 \times 10^3$	$5.1 \times 10^3$	$654 \times 10^3$	$23.7 \times 10^6$	$32 \times 10^3$	$45.9 \times 10^3$	$3.63 \times 10^{-3}$	$1.45 \times 10^{-2}$

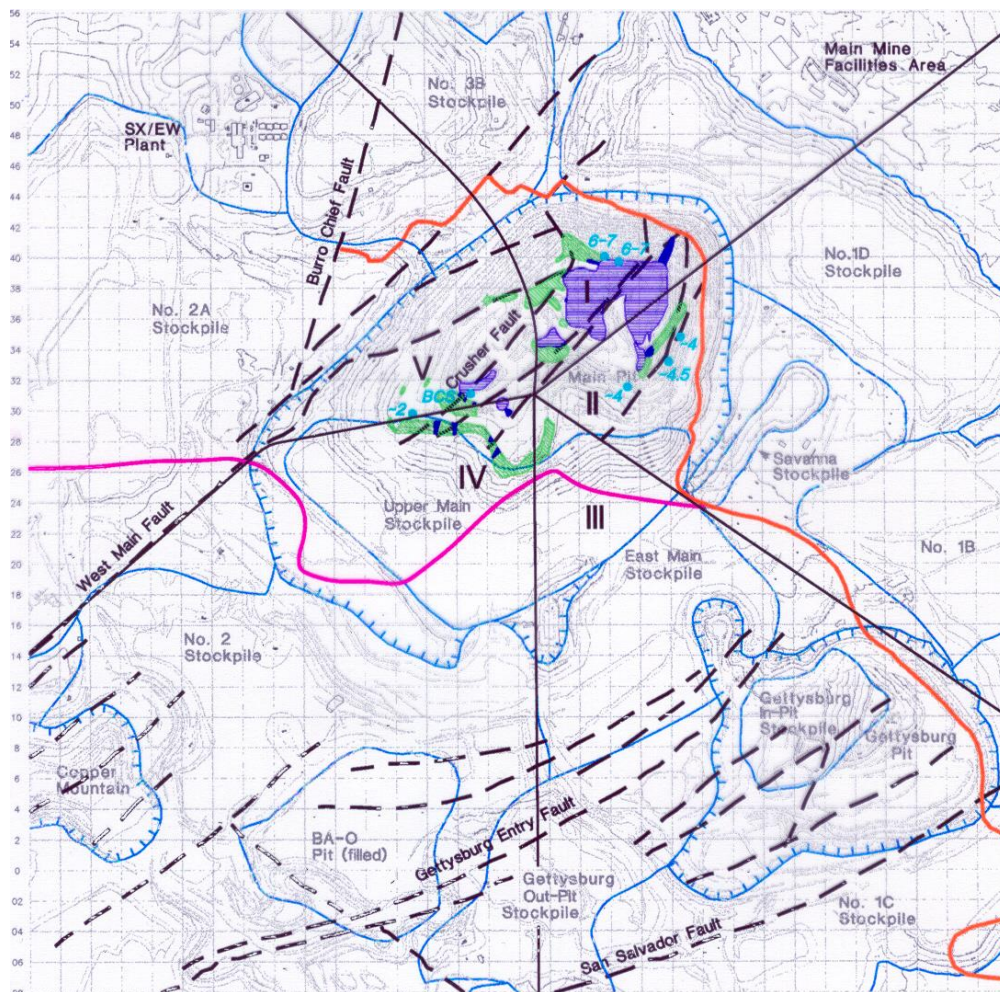


Figure 2. Topography map of the Main Pit divided into the five pit lake recharge zones (Roman numerals) including the location of an in-pit stockpile (Upper Main Stockpile) and

current pit lake (purple); wet areas (green) and fractures with groundwater discharge (dark blue). The pink line indicates a pre-mining groundwater divide.

The pan evaporation measured at Tyrone Mine was approximately 90 in/year (270 cm/year) (DBS&A, 1997). This corresponds to approximately 65 in/year (190 cm/year) for lake evaporation, using a pan coefficient of 0.7. This pan coefficient was used in the pit lake formation modeling.

The yearly precipitation rate was 15 in/year (45 cm/year) based on monitoring data at Tyrone Mine (DBS&A, 1997). The volume of rainfall entering the pit as surface runoff was based on the surface area of the pit perimeter minus the surface area of the pit lake. As the pit lake increased, the volume of the rainfall entering the pit as surface runoff decreased. At the start of the modeling the volume of runoff water entering the pit was approximately  $75 \times 10^3$  ft<sup>3</sup>/day (Table 1). At the start of the water quality modeling the volume of direct precipitation was approximately  $2.3 \times 10^3$  ft<sup>3</sup>/day.

### Geochemistry

The groundwater had been sampled from numerous wells since the 1970's, while surface water had been sampled from the early 1990's. Data from this earlier sampling together with data collected during this investigation were geochemically evaluated and are described below. Figure 3 shows a conceptual model of the sources entering the pit.

**Seepage.** Water was discharging from three fractures in the Main Pit walls. The volume of these seeps was calculated based on collecting the seeps into a 10-liter bucket and measuring the filling time. Water samples were collected from these seeps. Results are summarized in Table 2. The water quality and volume from these seeps were included in the groundwater discharge, in the groundwater flow zones corresponding to their locations. The seeps are above the estimated groundwater table (Fig. 3).

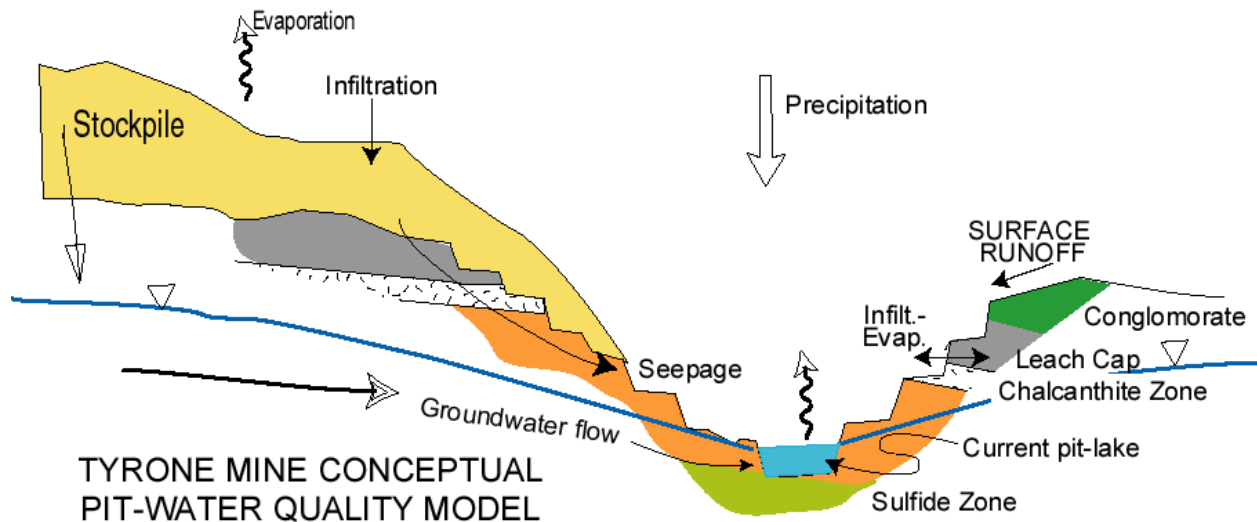


Figure 3. Conceptual model of the pit lake recharge sources showing: rainfall (precipitation) and evaporation; infiltration through stockpiles and seepage through fractures and groundwater recharge; groundwater discharging into the pit; surface runoff flushing secondary products along the pit walls; infiltration-evaporation in the pit walls; the

different rock types (simplified) exposed in the pit walls; and groundwater depression due to the mining activity with a smaller pit lake at the bottom.

Table 2. Analysis of fracture seep samples. Concentrations are reported in mg/L and conductivities in  $\mu\text{mhos/cm}$ . The “<” indicates a concentration below detection limit, the number being the detection limit. Three wall rock seeps (MPS) were sampled.

Sample_ID	MPS-1	MPB-2S	MPB-3S
Al	1,880	8.07	21.5
As	0.02	<0.005	<0.005
B	9.68	<0.05	0.07
Ca	542	103	152
Cd	9.48	0.05	0.07
Cl	195	7	7
Co	9.52	0.11	0.1
Cr	<0.01	<0.01	<0.01
Cu	707	3.77	11.4
F	1.57	10.5	17.5
Fe	1,290	7.22	22.2
K	2.3	10.1	10.5
Mg	1,060	19	28.9
Mo	0.05	<0.01	<0.01
Mn	549	5.9	6.8
Na	42.2	37.6	28.9
Ni	2.32	0.02	0.03
Pb	<0.05	<0.05	<0.05
SO <sub>4</sub>	21,000	562	859
Zn	1,160	13.7	13.9
CO <sub>3</sub>	<1	<1	<1
HCO <sub>3</sub>	<1	<1	<1
TDS	32,500	3,740	5,490
Spec. Cond.	15,000	970	1,320
Field pH	2.6	4	3.5

Pit Water. The Main Pit surface water had been routinely sampled and analyzed after mining ended in the deeper part of the pit (1992-1999) (Fig. 4). In 2000, lower parts of the Main Pit were again being excavated and the lake pumped. There were large concentration variations for most of the analyzed elements during this time period. The largest increase in trace elements concentrations were seen from mid 1995 to early 1996 with a distinct drop in pH (5 to 3). Magnesium increased one order of magnitude during this time period, while others, K and Na,



increased only ½ order of magnitude or less. According to Tyrone staff, water was pumped from the Gettysburg Pit (receiving leach solution) to the Main Pit during this time frame.

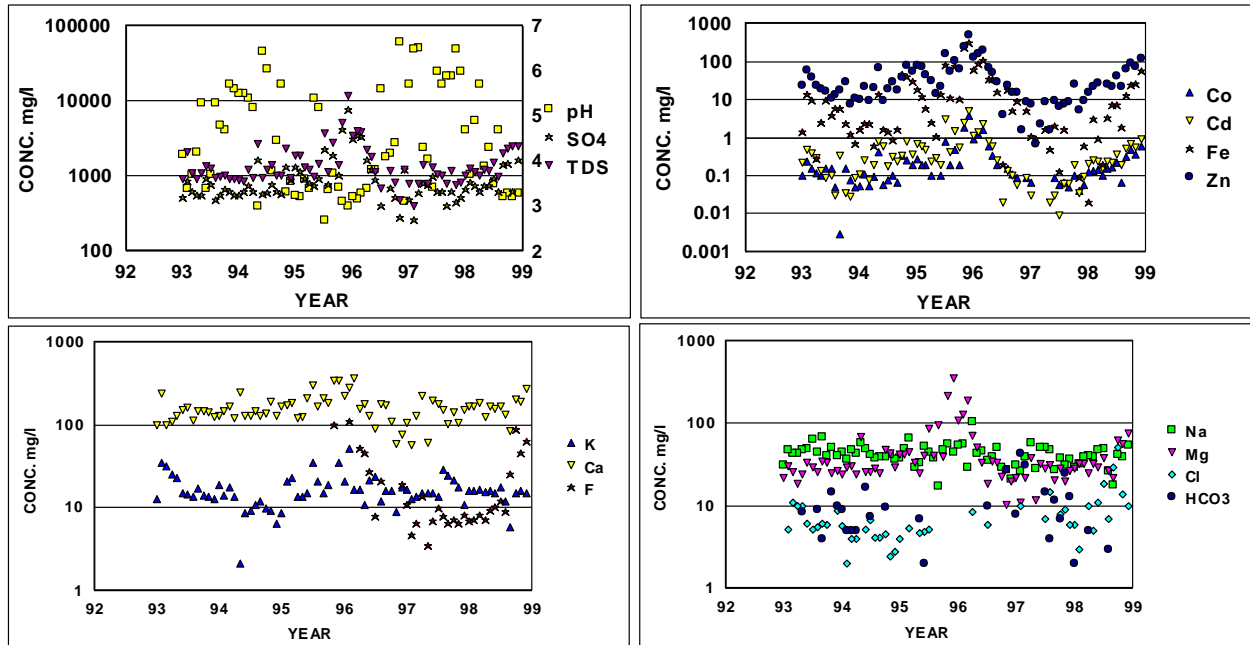


Figure 4. Plots of element concentrations (mg/L) versus time of sampling (years) for the Main Pit water samples for most of the analyzed constituents. Log scale has been used for many of the constituents because of the large concentration variation. The measured pH is used for plotting.

The surface water temperature in the Main Pit was measured with every water sample collected. Depending on the time of the year, samples were collected with temperatures ranging between 5 and 32 °C (Fig. 3). The data collected showed no correlation between the temperature of the lake and its water quality.

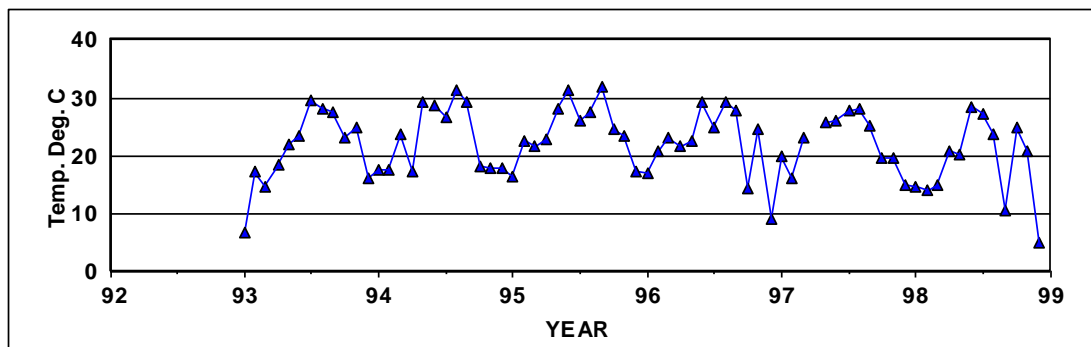


Figure 5. Plot of temperature, in degree C, versus sampling time for the Main Pit water samples collected during the years 1993 through 1998. The lowest recorded temperature was 5 degree C, while the highest was approximately 32 degree C.

Pregnant Leach Solution. Pregnant Leach Solution (PLS) is the Cu-enriched solution resulting from leaching Cu from the stockpiles. The PLS has a pH around  $2 \pm 0.6$  with moderate to very high metal and  $\text{SO}_4^{-2}$  concentrations. The PLS collected in the Gettysburg Pit has been analyzed (Table 3).

Table 3. The table gives the mean analyzed values of PLS from the Gettysburg Pit. Concentrations are in milligrams/liter (mg/L). Specific conductance is in  $\mu\text{mhos/cm}$  and temperatures in degrees C ( $^{\circ}\text{C}$ ). The calculated mean is based on the analyses that had concentrations above detection limit.

Element	Mean	Element	Mean
Al (mg/l)	673	Mn (mg/l)	269
As (mg/l)	0.11	Na (mg/l)	14.7
Ca (mg/l)	340	Ni (mg/l)	1.4
Cd (mg/l)	2.24	SO4 (mg/l)	9,760
Cl (mg/l)	106	Zn (mg/l)	220
Co (mg/l)	3.84	HCO3 (mg/l)	nd
Cr (mg/l)	0.21	pH	2.6
Cu (mg/l)	264	TDS (mg/l)	13,665
F (mg/l)	59.3	Field Cond. ( $\mu\text{mhos/cm}$ )	7,000
Fe (mg/l)	525	Temp. (dC)	20.66
K (mg/l)	50.5	Field pH	2.51
Mg (mg/l)	374		

Groundwater. In order to evaluate the water quality that will flow into the Main Pit over time, the area around the Main Pit was divided into five zones. These five zones were selected on the basis of the water quality data, preliminary flow information, and geological setting. Two of these zones (I and II) contained major fractures where visible water entered the pit. All the wells surrounding the Copper Mountain, Gettysburg and the Main Pits were evaluated as possible point sources for the pit water quality modeling. A smaller group of wells was selected from these wells based on their location relative to the capture zone of the pit.

There are many wells around the Main Pit. These wells were sampled frequently for water table elevations in order to evaluate the flow system and less frequently for water quality analysis. Wells were selected from each of these zones based on available water quality data. The arithmetic means of the element concentrations from the wells from each of the zones were used as the initial input water quality for the different zones.

Groundwater was analyzed from well samples for at least Al, As, B, Cd, Ca, Mg, Mn, Cu, Fe, Cr, Co,  $\text{F}^-$ , K, Na,  $\text{Cl}^-$ , Zn, Ni,  $\text{HCO}_3^-$ ,  $\text{SO}_4^{-2}$ , and total dissolved solids (Appendix I). Field and laboratory pH measurements were also taken. Some samples were also analyzed for Hg, Se (one sample contained 0.0008 mg/L), Ag (one sample with 0.002 mg/L),  $\text{NO}_3^-$  (samples with 1.3-0.3 mg/L as N), and CN (four samples with 0.31-0.004 mg/L). Some of the wells that were located

within the pit drawdown down-gradient from the leach pile increased in element concentration with time.

**Runoff Water Quality.** Six field leach tests designed to simulate a ½-inch rainfall event were performed on the walls within the Main Pit. The results of the leach tests are given in Table 4. The leach from the oxide zone showed relatively low concentrations of most elements compared with the sulfide zone and chalcantinite zone leaches. The leach, however, was acidic with a pH of 3.6 and 4.8. The chalcantinite zone leach was by far the highest concentrations of Cu and SO<sub>4</sub><sup>-2</sup>. The sulfide zone leach had the lowest pH (2.8 and 2.9) and the highest Fe content.

Table 4. Rainfall simulated leach tests results for the six tests performed on the mine walls of the Main Pit (Main Pit leach Water – MPLW). Mean values of three geological zones are also listed, nd - not detected.

Constituent	Oxide Zone			Sulfide Zone			Chalcantinite Zone		
	MPLW-1	MPLW-6	Mean	MPLW-3	MPLW-5	Mean	MPLW-2	MPLW-4	Mean
Al (mg/l)	149	22.5	85.75	1,140	45.6	592.8	130	210	170
B (mg/l)	0.18	0.09	0.14	nd	0.34	0.17	nd	nd	nd
Ca (mg/l)	204	35	119.5	53.4	23.7	38.55	448	471	459.5
Cd (mg/l)	0.5	0.02	0.26	0.57	0.05	0.31	nd	2.42	1.21
Cl (mg/l)	12	4	8	136	273	204.5	632	226	429
Co (mg/l)	1.7	0.07	0.89	2.8	0.39	1.6	3.7	9.4	6.55
Cr (mg/l)	nd	0.01	nd	nd	0.24	0.12	nd	nd	nd
Cu (mg/l)	176	9.98	92.99	321	566	443.5	25,500	32,000	28,750
F (mg/l)	67.7	1.04	34.37	9.26	4.27	6.76	0.42	73.9	37.16
Fe(mg/l)	nd	46.4	23.2	2,470	271	1,370.5	15	74	44.5
K (mg/l)	58.9	12	35.45	nd	nd	nd	9	1.7	5.35
Mg (mg/l)	185	11.7	98.35	61	13.6	37.3	106	309	207.5
Mo (mg/l)	nd	nd	nd	nd	0.08	0.04	nd	nd	nd
Mn (mg/l)	52.7	0.44	26.57	13.5	3.25	8.38	34.2	80	57.1
Na (mg/l)	91.1	7.5	49.3	3.6	3.1	3.35	8.4	3	5.7
Pb (mg/l)	nd	nd	nd	nd	0.4	0.2	nd	nd	nd
SO <sub>4</sub> (mg/l)	2,510	372	1,441	11,800	1,960	6,880	40,800	50,500	45,650
Zn (mg/l)	78.9	4.26	41.58	181	16.3	98.65	23.2	209	116.1
CO <sub>3</sub> (mg/l)	nd	nd	nd	nd	nd	nd	nd	nd	nd
HCO <sub>3</sub> (mg/l)	nd	nd	nd	nd	nd	nd	nd	nd	nd
Lab pH	3.8	3.2	3.4	2.7	2.8	2.75	3.8	3.7	3.75
TDS (mg/l)	3,870	490	2,180	18,600	3,130	10,865	74,800	92,400	83,600
COND	3,100	450	1,775	7,000	2,190	4,595	20,000	25,000	22,500
TEMP (d. C)	29.8	32	30.9	30	35	32.5	35	25	30
FIELD pH	3.58	4.83	3.86	2.89	2.72	2.8	3.63	3.45	3.53

## Discussion

Past pit water quality data collected can give an indication of future water quality; therefore, pit water quality data collected during the period 1992-1999 was evaluated and incorporated in the modeling for the starting point water quality conditions. In addition, the input water quality

modeling of the Main Pit at Tyrone Mine involved the evaluation of various input sources. These sources included seepage, pit water, evaporation, precipitation, runoff, and groundwater.

Prediction of long-term acid rock drainage is difficult. One way of estimating the drainage is using Ritchie-Davis equations (Davis and Ritchie, 1986), based on a propagating oxidation front into the walls of the pit. Water quality of the drainage is provided from kinetic tests performed on the material. However, this method does not take into account the oxidation that may be taking place within the whole dewatered area, where oxygen is entering the sulfide rocks through fractures in the pit walls and may, therefore, underestimate the severity of the drainage water quality. To circumvent this, the rainfall simulated field tests were used to estimate the runoff water quality. These tests took into account the element transport to the surface by groundwater flow, capillary forces, and evaporation. These tests were only performed once on each of the selected spots. Further refinement of this method to predict long-term surface water runoff quality by performing tests on the same areas several times, would be appropriate.

As a way of evaluating the chemical differences seen in the Main Pit water quality, the element concentrations vs. lab pH are plotted in Fig. 6. In general, all solutes increase in concentration with decrease in pH. Plots of solute ratios can sometimes be diagnostic of mixing trends. For example, Al/Na has been plotted against  $\text{SO}_4^{2-}/\text{Na}$  in Fig. 7. This linear trend indicates two sources mixing. One endpoint is likely the background water quality with a neutral pH and, in general, low metal concentrations. The other endpoint of this mixing may be acid rock drainage and/or PLS.

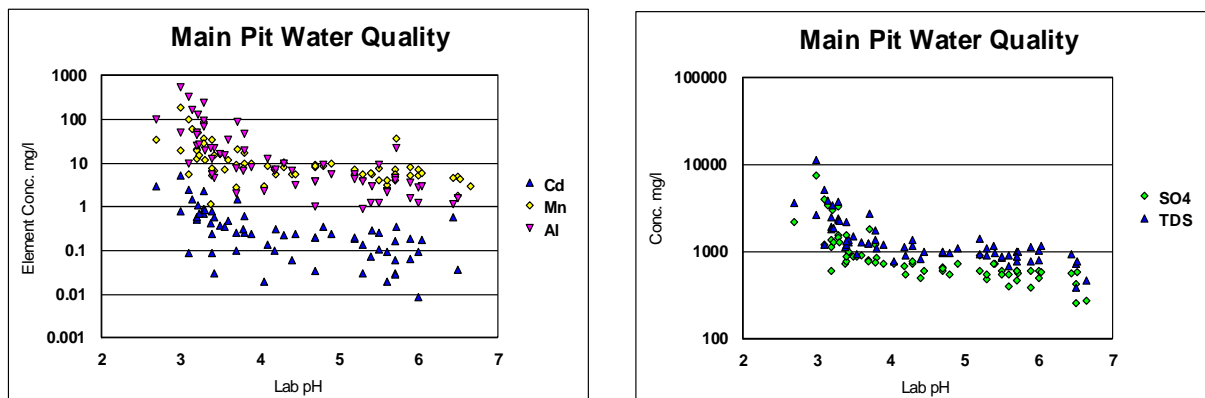


Figure 6. Concentrations vs. lab pH for the pit lake water.

### Runoff Water Quantities

The runoff water volume given in Table 5 includes the surface runoff outside and inside the pit perimeter, however, this estimate excludes the areas covered by the stockpiles. The Tyrone groundwater study indicated that there was no runoff from the stockpiles directly into the Main Pit (DBS&A, 1997). Rainwater that hits the stockpiles will infiltrate and partly evaporate (85 percent according to Walder et al., 2006). The infiltrating rainwater will partly be stored in the stockpile and eventually recharge the groundwater. The active runoff drainage area for the Main Pit was, therefore, divided into two areas: 1) areas within the pit perimeter, and 2) areas outside the pit perimeter that have a positive drainage to the pit (Table 5).

The groundwater modeling assumes that 100 percent of the rainwater that falls within the pit boundary drains into the pit lake, while evapotranspiration depletes approximately 50 percent of the rainwater that falls outside of the pit (DBS&A, 1997).

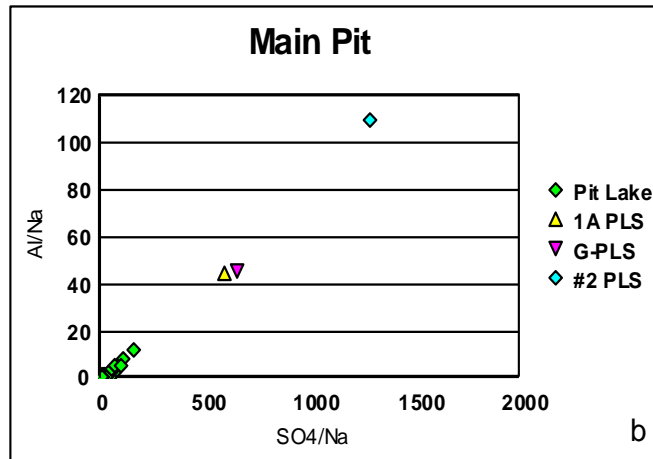


Figure 7. Plots of Al/Na versus SO<sub>4</sub><sup>-2</sup>/Na (in mg/l) for the Main Pit water samples and the average concentrations of the Gettysburg PLS ponds (G-PLS), and two additional PLS collection ponds

Table 5. The table lists the surface areas in square footage that have drainage direction into the pit. The Main Pit area includes the lake surface. The stockpiles are assumed not to have a direct runoff into the pit due to the coarseness of the material and lack of seeps at the toes directed towards the pit. The data are from (DBS&A, 1997).

LOCATION	SURFACE AREA (ft <sup>2</sup> )
No 3B Stockpile	2.5 x 10 <sup>6</sup>
No 2A Stockpile	5.8 x 10 <sup>6</sup>
No 1D Stockpile	1.3 x 10 <sup>6</sup>
EMP Stockpile	3.2 x 10 <sup>6</sup>
Main Pit	13.3 x 10 <sup>6</sup>
Outside Pit Perimeters	17.0 x 10 <sup>6</sup>
Total	43.1 x 10 <sup>6</sup>

In order to estimate the volumes of different water qualities of the runoff, water in the Main Pit area was divided into three geological zones corresponding to the rainwater runoff simulation tests: 1) oxide zone; 2) sulfide zone; and 3) chalcantinite transition zone. As the pit-lake water level rises, parts of these zones will be under water, and eventually the oxide zone will become the dominant zone above the lake surface. For verifying the input sources with analyzed pit lake water quality two surface area scenarios were chosen based on area estimations (Table 6).

Table 6. Estimated percent surface area occupied by the three different geological units used for runoff water leaching for the Main pit. The values used for the chalcantite zone are based on the estimated area ranging from 2 % to 5 % for this relatively small geological zone.

ZONE	SCENARIO I	SCENARIO II
Oxide Zone	30 %	30 %
Sulfide Zone	68 %	65 %
Chalcantite Trans. Zone	2 %	5 %

#### Well data

The arithmetic mean, as opposed to the less conservative geometric mean (Parkhurst, 1998) was calculated for each of the constituent concentration for each of the wells. An arithmetic mean for each of the constituent concentrations for each of the zones was then calculated using those values. The volume-weighted arithmetic means of each of the zones were mixed to obtain a groundwater input concentration relative to the in-flowing volume (Table 1). For example, in Zone I, there are two wells and two seeps. Both of the wells have concentrations below detection limit for Al, Cd, and Fe; while Zn is below detection limit in one of the wells. Concentrations of half the detection limit (as reported by Inter-Mountain Laboratories, Inc., Grants, New Mexico) were included for these elements to avoid having the average concentration of the zone controlled by the elevated fracture seep concentrations. The concentrations used for non-detectable elements are as follows: Al = 0.025 mg/l; Fe = 0.01 mg/l; Zn = 0.012 mg/l; and Cd = 0.0025 mg/l. This average concentration was then mixed with the lake water quality for every month based on a steady groundwater discharge into the pit for a period of six months.

#### Precipitation Data

Direct rainfall onto the lake was included as being in equilibrium with atmospheric CO<sub>2</sub>, which gives a pH of 5.5, and assuming that there were no other species present. Evaporation was treated as an evapo-concentration factor removing water but no dissolved constituents. The runoff water was included in the mixing calculation as described above where each geological zone was weighted relative to the surface area exposed. Figure 8 illustrates the water sources entering the pit lake.

#### Pit Lake

The starting water quality for the pit lake was based on the arithmetic mean of twelve samples collected monthly in the Main Pit Lake in the period May 1997 to May 1998. The first month of in-flowing water was then mixed with this starting pit lake water quality. The second month of influent was mixed with the resulting pit lake water quality of the previous month, and so forth for a period of seven months corresponding to the period of no pumping from the Main pit and no PLS discharge into the Main pit.

#### Mixing Model

The mixing modeling was performed for the two scenarios as described in the section above. The resulting modeled water quality was plotted together with the analysis for the time period May 1998 and December 1998 for the two chalcantite surface areas: Scenario 1 with 2 percent



chalcantite zone exposed; and Scenario 2 with 5 percent chalcantite zone exposed (Fig. 9 and 10, respectively).

There was a good correlation between the modeled concentrations of total dissolved solids (TDS), Mn and  $\text{SO}_4^{-2}$  for both scenarios. The modeling gave approximately 25 percent more sulfate for both scenarios compared to analyzed pit lake water quality. For the first four months, there was good correlation in the increasing trend for Cd and Zn, while the pit lake itself has larger increases of these two elements than those modeled in the latter part of the modeling period (Fig. 9).

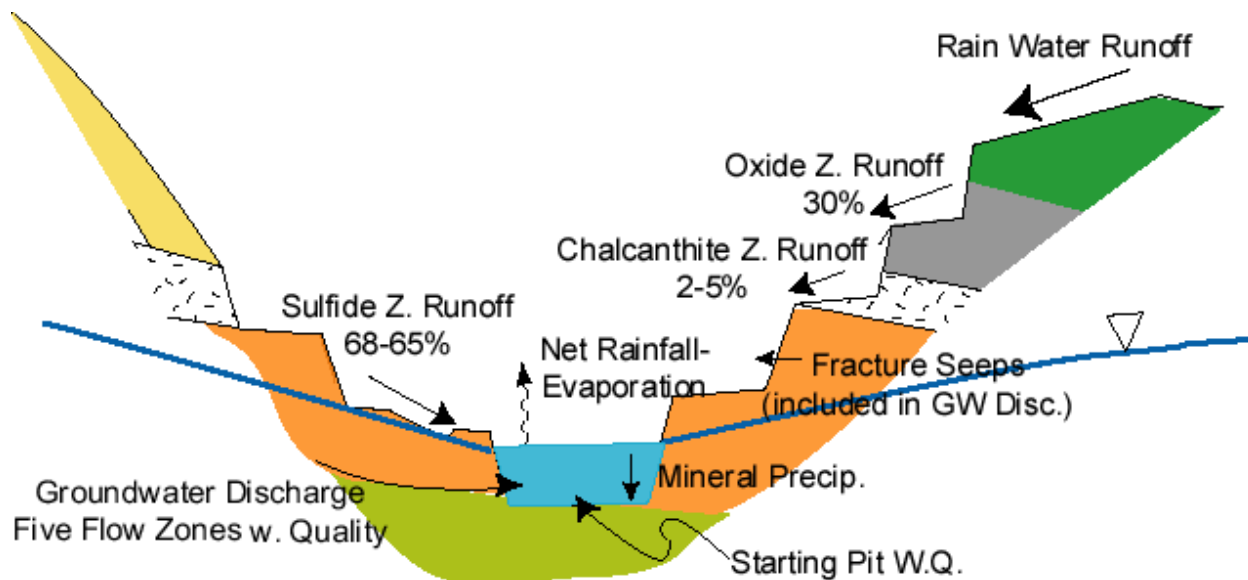


Figure 8. Illustration of the input sources for the lake water modeling evaluation. The water quality from the sampled fractures was included in the groundwater quality discharging to the pit. Runoff water from outside the pit walls was included as pure rainwater. To simulate a sampled period of the lake water, mineral precipitation was also included in addition to mixing the surface and groundwater sources with the starting pit lake water quality.

The concentrations of Mg and Mn in the pit water were reproduced reasonably well. The analyzed concentrations of these elements were more erratic than the modeled concentrations for these latter two elements. The modeled Al concentration was similar for the two input scenarios but approximately 50 percent higher than the analyzed concentrations. The Fe concentration was also similar for the two input scenarios but was 3-5 times higher in the modeled concentrations compared with the analyzed concentrations (Fig. 9).

There was a good correlation between the modeled and analyzed Cu concentration for the scenario with a 2 percent chalcantite zone. When modeling with a 5 percent chalcantite zone, the modeled Cur concentrations was about twice as high as analyzed concentration (Fig. 9).

The modeling was not able to reproduce the erratic variation of Ca. The modeling underestimates the reduction in pH by about 0.3 to 1 pH units for the last three months (Fig. 9). These large systematic errors between measured and modeled pH and Fe, and the smaller erratic

errors for some of the other elements were likely due to the monthly variation in rainfall, while the model assumed constant rainfall, in addition to mineral precipitation.

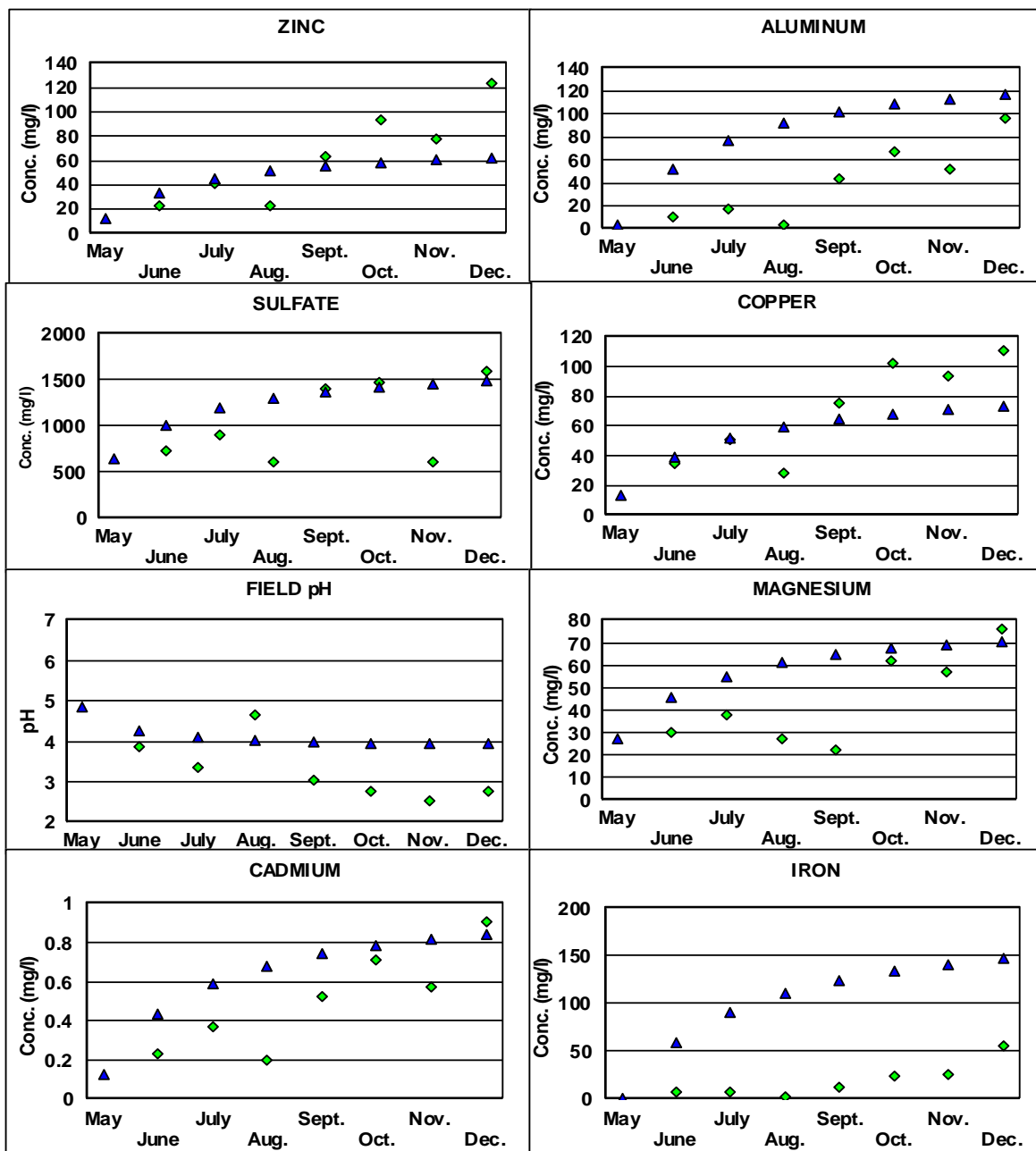


Figure 9. Mixing modeling of the Main Pit lake water quality for Scenario I (30% oxide zone, 68% sulfide zone, and 2% chalcantinite zone). Blue triangles are modeled and green diamonds are analyzed samples from the Main Pit summer –fall 1998.

### Mineral Precipitation

Iron hydroxides (ferrihydrite and goethite) gibbsite, jarosite (H, Na, and K jarosite) and cupricferrite were all supersaturated, using MINTEQA2 (Version 3.11, Allison, et al. 1990) on

the ending solution of the pit lake modeling. If ferrihydrite and H-Jarosite were allowed to precipitate to equilibrium, approximately 99.5 percent of the Fe and 10 percent of the  $\text{SO}_4^{-2}$  were removed, and the pH dropped by approximately 1 unit to  $\text{pH} = 2.7$ . This precipitation also resulted in under-saturation of most of the minerals that were supersaturated prior to mineral precipitation. If only ferrihydrite was allowed to precipitate, 25 percent of the dissolved Fe would be removed and the pH would drop to 3.1.

Comparisons of modeled predictions vs. actual observations indicated that the input data used (volumes and qualities) for the various sources, i.e. fracture seep, groundwater inflow, and runoff/evaporation, and were reasonably well represented, except for pH. Only Cu was highly affected by the size of the chalcantite zone exposure, while the magnitude of runoff water from the sulfide zone areas was a major factor controlling many of the other constituents. If we assumed that there was a 50% evaporation of the rainwater hitting the pit walls and using 5 percent chalcantite exposure, Al, Cu, Mg and  $\text{SO}_4^{-2}$  (Fig. 10) correlated well with the analyzed pit water. With time, as the pit lake covers a larger amount of the sulfide pit walls, the lake water quality would be less controlled by the runoff water and more affected by the groundwater discharge.

By using an average precipitation, the effect of runoff water on the pit lake water quality has evened out the monthly variation. The analyzed water quality could, therefore, be more variable than the modeled water quality, which assumed a constant relationship between the water sources; while the runoff volume was heavily affected by short and heavy rain storms.

### **Conclusions**

Modeling of the Tyrone Main Pit lake using water quality data over a seven month period and calibrating it with surface runoff and mineral precipitation, indicated that the lake water quality was highly controlled by pit wall run off water (unless PLS is discharged into the pit). Dividing the pit walls into three water zones based upon the primary/secondary mineralogy and using rainfall simulated field tests multiplied with average rainfall gave a good representation of the runoff water quality, when mineral precipitation was included. This model setup is, therefore, applicable for predicting future pit lake water qualities, as long as the pit wall surface mineralogy remains constant from year to year.

### **Acknowledgement**

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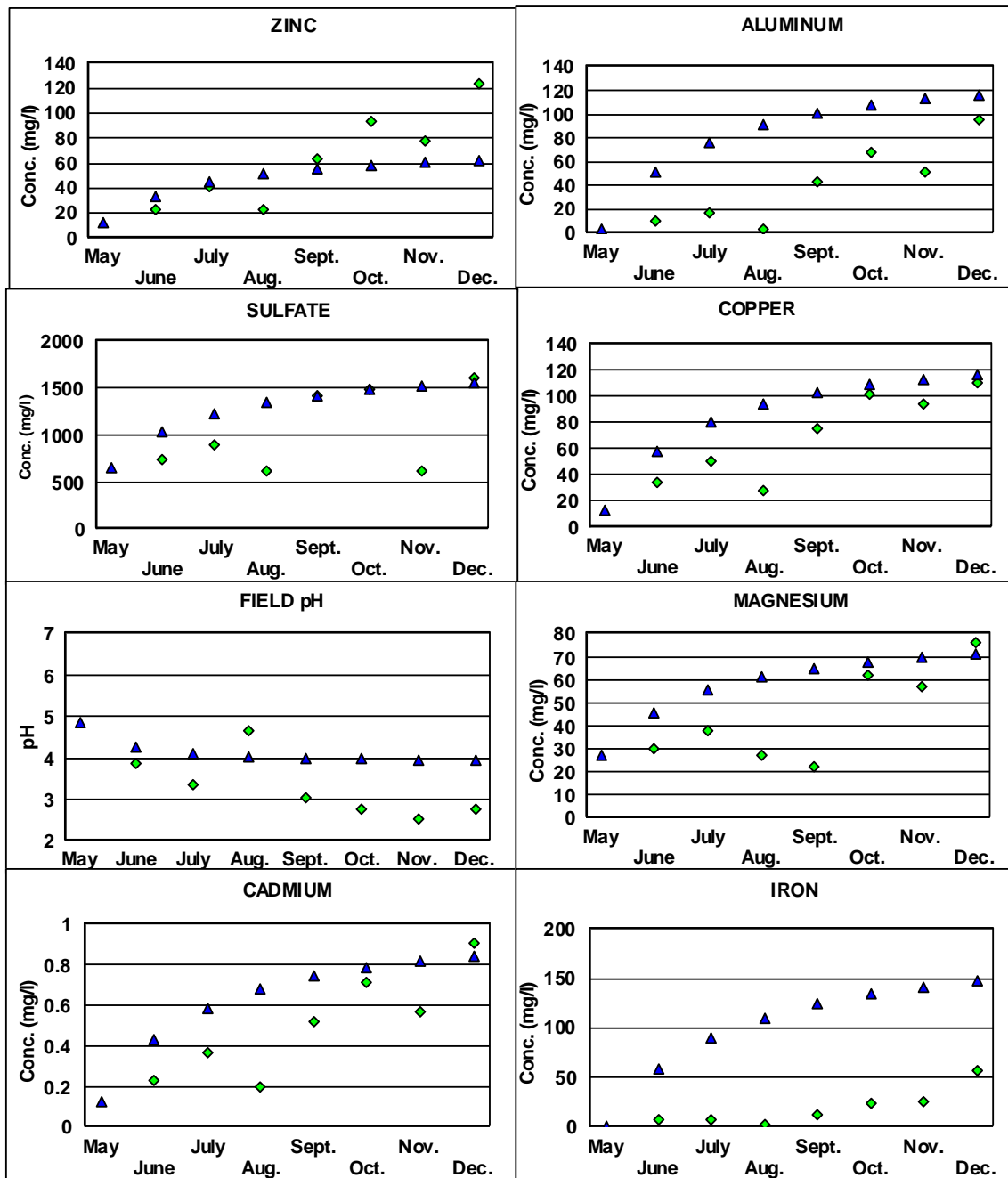


Figure 10. Mixing modeling of the Main Pit lake water quality for Scenarion II (30% oxide zone, 65% sulfide zone, and 5% chalcantite zone). Blue triangles are modeled and green diamonds are analyzed samples from the Main pit summer –fall 1998.

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Appendix I. Mean, minimum, and maximum constituent concentration for eight wells used in the pit lake water quality modeling including amount of analysis used in the calculation and amount of analysis performed. Nd – not detected. Open space means not analyzed.

Well	4-6				2-9						
	Mean	min	max	Calc count	Tot. Count	Mean	min	max	Calc count	Tot. Count	
Al	mg/l		nd	nd	0	2		nd	nd	0	0
As	mg/l				0	0				0	0
B	mg/l				0	0				0	0
Ca	mg/l	56.7	25.3	122	7	7	329	198	460	2	2
Cd	mg/l		nd	nd	0	2				0	0
Cl	mg/l	21.7	14	51.4	6	6	8.16	7.92	8.4	2	2
Co	mg/l		nd	nd	0	2				0	0
Cr	mg/l		nd	nd	0	2				0	0
Cu	mg/l	0.11	nd	0.2	2	5				0	0
F	mg/l	1.8	0.65	3	2	2		nd	nd	0	1
Fe	mg/l	0.2	0.05	0.45	5	5	83.9	1.8	166	2	2
K	mg/l	5.4	3	8.93	7	7	8	4.29	11.8	2	2
Mg	mg/l	15.1	8.11	28.8	7	7	103	55	151	2	2
Mo	mg/l				0	0	0.01	0.01	0.01	1	1
Mn	mg/l	0.38	0.11	0.75	5	5				0	0
Na	mg/l	20.4	nd	34.5	7	7	31.8	6.1	57.5	2	2
Ni	mg/l		nd	nd	0	2		nd	nd	0	1
Pb	mg/l				0	0				0	0
SO4	mg/l	276	33	1800	9	9	1723	817	2630	2	2
Zn	mg/l	0.01	nd	0.01	1	2	6.02	6.02	6.02	1	1
CO3	mg/l		nd	nd	0	4		nd	nd	0	1
HCO3	mg/l	75.6	nd	201	5	6	0.7	nd	0.7	1	2
TDS	mg/l	569	228	3000	10	10	2817	1310	4324	2	2
Conduct.	umohs	808	308	2390	5	5				0	0
Temp.	deg. C				0	0				0	0
Field pH		5.81	5.36	8.02	6	6	5.23	5.23	5.23	1	1
Ba	mg/l				0	0				0	0

Well	P-8A				EM-1						
	Mean	min	max	count	Mean	min	max	Calc count	Tot. Count		
Al	mg/l		nd	nd	0	3	5.46	nd	30	28	29
As	mg/l		nd	nd	0	3	0.055	nd	0.06	2	7
B	mg/l				0	0				0	0
Ca	mg/l	169	152	195	4	4	58	24.3	160	29	29
Cd	mg/l		nd	nd	0	3	0.11	nd	0.84	24	29
Cl	mg/l	44.2	41.2	47.2	4	4	6.59	nd	20	24	28
Co	mg/l		nd	nd	0	3	0.2	nd	1	26	27
Cr	mg/l		nd	nd	0	3	0.041	nd	0.1	3	26
Cu	mg/l	0.01	0.01	0.01	1	4	1.62	nd	18	27	29
F	mg/l	2.1	nd	2.53	3	4	5.03	nd	10	8	9
Fe	mg/l		nd	nd	0	3	34	nd	180	27	28
K	mg/l	8	8	8	1	1	11.2	nd	39	27	28



Well (cont.)	4-6					2-9				
	Mean	min	max	Calc count	Tot. Count	Mean	min	max	Calc count	Tot. Count
Constituent										
Mg	mg/l	14.5	9	29	4	4	16.6	8.12	38	29
Mo	mg/l	26	24.8	27.6	3	3	0.05	nd	0.05	1
Mn	mg/l	0.38	nd	0.7	2	4	5.5	nd	18	28
Ni	mg/l		nd	nd	0	3	0.077	nd	0.16	5
Pb	mg/l		nd	nd	0	3	0.084	nd	0.15	3
SO4	mg/l	291	272	317	4	4	380	155	1200	28
Zn	mg/l	0.26	nd	0.261	1	4	23.7	nd	110	26
CO3	mg/l		nd	nd	0	3		nd	nd	0
HCO3	mg/l	303	264	394	4	4	24.2	nd	120	10
TDS	mg/l	858	798	938	4	4	623	279	1800	28
Conduct.	umohs				0	0	814	360	1700	27
Temp.	deg. C				0	0				0
Field pH		6.69	6.42	7.1	3	4	4.42	3.18	7.27	27
Ba	mg/l				0	0				0

Well	6-3R					P-4A				
	Mean	min	max	Calc count	Tot. Count	Mean	min	max	Calc count	Tot. Count
Constituent										
Al	mg/l	149	149	149	1	1	3.2	nd	6	2
As	mg/l				0	0		nd	nd	0
B	mg/l				0	0				0
Ca	mg/l	547	493	731	15	15	41	31	53.6	4
Cd	mg/l	0.053	0.053	0.053	1	1		nd	nd	0
Cl	mg/l	7.2	nd	13.9	10	15	17.1	11.2	21	4
Co	mg/l	0.58	0.58	0.58	1	1	0.005	nd	0.005	1
Cr	mg/l				0	0	0.003	nd	0.003	1
Cu	mg/l	0.85	0.85	0.85	1	1	3.5	0.057	14	4
F	mg/l	186	142	269	15	15	1.07	0.43	1.44	4
Fe	mg/l	330	330	330	1	1	0.17	nd	0.297	2
K	mg/l	10	2	16	15	15	5.61	1.8	10	4
Mg	mg/l	200	159	263	15	15	8.91	6.04	16.2	4
Mo	mg/l				0	1				0
Mn	mg/l	98	97.92	97.92	1	1	1.03	0.047	3.7	4
Na	mg/l	84.6	84.6	84.6	1	15	16.5	14.4	21.6	4
Ni	mg/l	95	60	308	15	1	0.005	nd	0.005	1
Pb	mg/l	0.16	0.16	0.16	1	15		nd	nd	0
SO4	mg/l	2932	2470	3750	15	15	26.1	15	32.7	4
Zn	mg/l	51.2	51.2	51.2	1	1	1.31	nd	2.6	3
CO3	mg/l		nd	nd	0	14		nd	nd	0
HCO3	mg/l	15	nd	15	1	15	132	96	209	4
TDS	mg/l	4585	4020	5020	15	15	222	190	260	4
Conduct.	umohs	2624	310	3800	19	19				0
Temp.	deg. C	17.2	14	19.3	18	18				0
Field pH		4.42	3.56	6.94	18	18	6.55	6.04	7.3	4
Ba	mg/l				0	0				0

Well	MB-10					TWS41					
	Constituent	Mean	min	max	Calc count	Tot. Count	Mean	min	max	Calc count	Tot. Count
Al	mg/l	76	10	142	2	2	0.07	0.07	0.07	1	1
As	mg/l				0	0				0	0
B	mg/l				0	0				0	0
Ca	mg/l	210	130	291	2	2				0	0
Cd	mg/l	0.07	nd	0.07	1	2				0	0
Cl	mg/l	15.5	11	20	2	2				0	0
Co	mg/l	0.51	0.22	0.81	2	2				0	0
Cr	mg/l	0.01	nd	0.01	1	2				0	0
Cu	mg/l	83	17	149	2	2	0.025	0.01	0.04	2	2
F	mg/l				0	0				0	0
Fe	mg/l	0.35	0.13	0.57	2	2	0.035	0.03	0.04	2	2
K	mg/l	7.3	7.3	7.3	1	1				0	0
Mg	mg/l	58.6	49	68.2	2	2				0	0
Mo	mg/l	2.8	2.8	2.8	1	1				0	0
Mn	mg/l	54.3	28	80.6	2	2	0.034	0.023	0.047	3	3
Na	mg/l	23.2	20	26.4	2	2				0	0
Ni	mg/l	0.3	nd	0.3	1	2				0	0
Pb	mg/l		nd	nd	0	1				0	0
SO4	mg/l	1420	640	2200	2	2	463	457	470	3	3
Zn	mg/l	20.15	11	29.3	2	2	0.077	0.077	0.077	1	1
CO3	mg/l		nd	nd	0	1				0	0
HCO3	mg/l		nd	nd	0	2				0	0
TDS	mg/l	2700	1100	4300	2	2	826	790	850	3	3
Conduct.	umohs	943	943	943	1	1	1087	1060	1110	3	3
Temp.	deg. C	3.88	3.88	3.88	1	1				0	0
Field pH		19.3	19.3	19.3	1	1				0	0
Ba	mg/l				0	0				0	0