Hydrogeologic and Geochemical Prediction of Rosemont Pit Lake Using Three Different Modeling Programs

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Abstract
The Rosemont Copper Project involves developing an open pit mine over approximately22 year mine life on the east side of the Santa Rita Mountains in southern Arizona. Due to the complexity of the system, three different modeling packages were used to assess the hydrogeology and geochemistry of the post closure pit lake. Groundwater flow modeling results from MODFLOW-SURFACT showed a pit lake is expected to form in the open pit.Based on the expected inflows to the pit lake in relation to the annual evaporation from the pit lake surface, the pit lake will be a hydraulic sink. A dynamic systems model (DSM) was developed in GoldSim to simulate the Rosemont pit lake hydrologic water balance and the mixing of the chemical loads from groundwater inflow, pit wall runoff, and precipitation. Outputs from the GoldSim predictive simulations were used as inputs for geochemical modeling. The geochemical modeling results show the pit lake water quality was only slightly changed from local groundwater after 200 years of model simulation. This multiple modeling program approach allowed for the characterization of the primaryphysical and chemical processes in the pit-lake system.

Key Words: groundwater, dewatering, MODFLOW, SURFACT, GoldSim, PHREEQC

Introduction
Rosemont Copper Company (Rosemont) is planning the development of an open-pit mining and mineral processing operation known as the Rosemont Copper Project (project) located on the east side of the Santa Rita Mountains, approximately 48 km (30 miles) southeast of Tucson, Arizona in Pima County. Operations will occur for approximately 22 years, during which time the open pit will be incrementally expanded and dewatered. Because thepit will require dewatering and a pit lake is expected to form, groundwater flow, dynamic system, and geochemical models were developed to estimate potential impacts to water resources within the regional groundwater system, simulate the pit water balance and chemical loading/mixing, and water quality, respectively.

Regional and Open Pit Geologic Settings
The regional, local, and property geology of the Rosemont deposit has been described in Anzalone (1995), Mosher et al. (2005), and Rose (2007). An early to middle Proterozoic batholith (Continental Granodiorite) with minor remnants of metasediments (Pinal Schist) form the basement beneath a thin sequence of Paleozoic sediments in the northern Santa Rita Mountains. The Paleozoic section is characterized by a basal quartzite, overlain by a sequence dominated by carbonate lithologies with lesser amounts of sandstone, siltstone, and shale. Sedimentary deposition ceased for a time during uplift and development of a widespread unconformity during the early Mesozoic time. Sedimentation resumed during the late Jurassic period with the deposition of continental and shallow marine sediments of the Bisbee Group. Subsequent granitic intrusive and felsic volcanic activity dominated the late Cretaceous and early Eocene period, corresponding to the Laramide Orogeny. Most of the porphyry copper deposits

of this region were formed at this time. Compressional tectonics during the Laramide Orogeny created low-angle thrust faults and high-angle strike-slip faults, as well as extensive development of folds. Extensional Basin and Range type deformation followed the Laramide Orogeny. It was accompanied by voluminous felsic volcanic eruptions and resulted in large-scale block faulting that produced the present Basin and Range Province.

The Rosemont depositcan be classified as a skarn system. Within this class of copper deposits, the ores are primarily contained within carbonate sedimentary rocks and/or volcanic hosts. The Paleozoic section at Rosemont generally strikes N-S and dips roughly 55 to 65 degrees east. A major, east dipping, low angle fault zone separates the Paleozoic section in its western footwall from the Concha Limestone, Glance Conglomerate, and Willow Canyon Formation, which occupy its eastern hanging wall. Strata within the upper plate of this low angle structural zone have been folded into a moderately to steeply southeast plunging anticline. The preliminary open pit design transects the entire geologic section from the Cambrian Bolsa Quartzite in the northwestern high wall to an easterly thickening sequence of early Cretaceous Willow Canyon Formation and Miocene to Pliocene Gila Conglomerate in the eastern and southeastern walls of the open pit. Compared to other southwest porphyry copper systems, the total sulfide content of the Paleozoic hosts at Rosemont is generally quite low (<3%). Thus, while sulfide mineralization is present at the Rosemont site, acid neutralizing limestone and marble (calcium carbonate) are abundant.

Groundwater Flow Modeling

Numerical groundwater flow modeling was preceded by first developing conceptual and hydrogeologic framework models of the study area. The basis for these models was existing data and analyses completed for the Rosemont Project and from other independent studies. Additionally, the model domain was constrained to the area previously delineated by Montgomery & Associates for their groundwater flow model simulations (M&A, 2009). The hydrogeologic framework model, which formed the foundation for the groundwater flow modeling simulations, was also based on existing horizontal hydrogeologic slices developed for the Montgomery & Associates flow model domain (M&A, 2009).

Three (3) numerical flow models were developed to simulate the different stages of the project: pre-mining, operations, and post-mining (post-closure). The pre-mining model was calibrated based on historicalwater-level measurements and stream flows. Results of the calibrated pre-mining model were subsequently used as the start of the operation-phase model. Conditions simulated at the end of the operation-phase model were used as the input to the post-closure model. All models used the finite-difference model code MODFLOW-SURFACT (HydroGeoLogic, 2010).

Pre-mining model development

Geologic controls and hydrogeologic units were incorporated into the numerical models as appropriate. Due to the large model domainof 1,183 km^2(457 sq miles), the 61 m (200 ft) to 244 m (800 ft) grid spacing within the numerical models limited the resolution of the smaller geologic features, but incorporated geologic features that control regional groundwater flow. Additionally, modeling was performed using an equivalent porous media assumption, which is inherent in MODFLOW. Although the groundwater flow system includes fractured geologic formations, at the regional scale it was assumed that the aquifers were simulated as a low conductivity porous media within MODFLOW.

Pre-mining groundwater model calibration

The objectives of the pre-mining model calibration were to: 1) obtain appropriate model parameters that were representative of the hydrogeologic conditions; and 2) simulate current, observed water levels and stream flows. The calibration approach consisted of iteratively using automated parameter estimation methods and manual calibration to achieve the calibration objectives and the best possible model fit. The model calibration showed slightly more points below the 1:1 line on the observed versus simulated groundwater level plot, indicatinga small negative model bias due to simulated water levels being below the observed water levels. This bias was evident near the pit area where the model tended to under predict water levels comparedto the measured water levels near or above land surface. Other calibration measures such asthe residual standard deviation divided by the range(<5%) and a random pattern of observed water levels versus unweighted residuals indicate a good model calibration.

Operation-phasemodel

Dewatering of the proposed open pit will result in groundwater levels being lowered to approximately 920.5 m (3,020 ft) above mean sea level (amsl), which is a decrease of670.5 m (2,200 ft)from pre-mining water level in the immediate project area. The projected bottom of the pit is 929.6 m (3,050 ft) amsl. Inflows to the pit during dewatering were estimated to be up to 1,892 litres per minute (500 gallons per minute). Dewatering the pit will create drawdown in the regional groundwater system, propagating outward. Drawdown will be most dramatic in the vicinity of the open pit, and the drawdown effects will decrease with increased distance from the pit.

Post-closure model

Following the cessation of dewatering, groundwater levels will rebound causing the pit tonaturally refill with water. The post-closure groundwater flow model predicts the refilling process will take 700 to 1,000 years to reach an equilibrium or steady-state condition (Figure 1). After 1,000 years, the equilibrium lake stage is predicted to be 1,304.2 m (4,279 feet) amsl. Due to the high evaporation rate in the Rosemont area 127 cm/yr (50.1 in/yr), the pitlake is predicted to be a hydraulic sink. A capture zone will exist around the open pit, perpetually drawing groundwater into the pit or pit-lake.Flow-through conditions, or a non-terminal pitlake, would exist should the lake stage reach the groundwater-divideelevation of 1,426.5 m (4,680 feet) amsl.

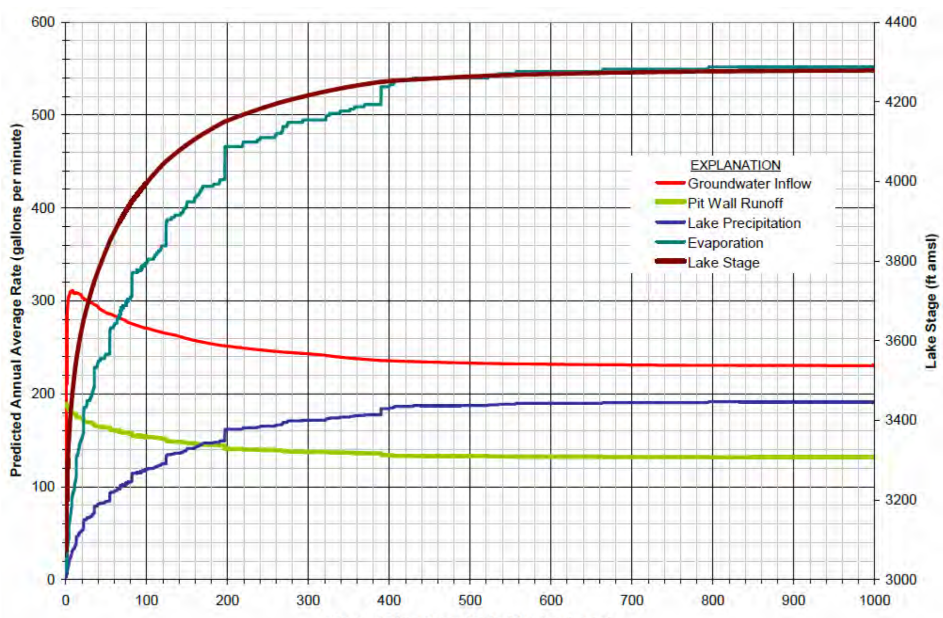

Figure 1.Simulated pit-lake water balance from groundwater flow model

The estimated groundwater-level drawdown associated with the dewatered pit and thepitlake 1,000 years into the post-closure period is shown on Figure 2. Historically, observed water-level fluctuations greater than 1.5 m (5 ft) have been recorded within 8 km (5 miles) of the open pit. After 1,000 years post closure, the steady-state groundwater inflow to the pit is anticipated to be 870 litres per minute (230 gallons per minute).

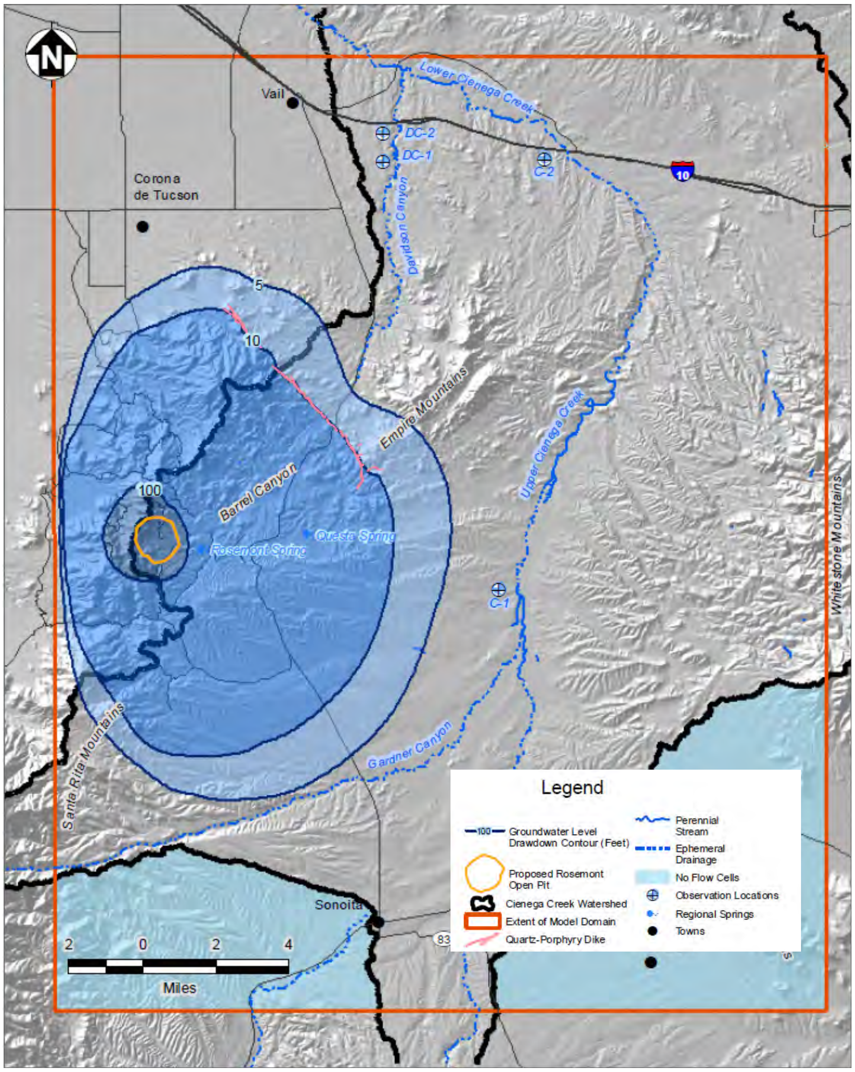

Figure 2. Predicted water level drawdown 1,000 years after end of mine operations

Predicted impacts to base flows in Davidson Canyon and Cienega Creek during operations were negligible and indiscernible compared to the accuracy of the model. Predicted impacts to springs were dependent on the distance from the open pit and whether the spring is hydraulically connected to the regional groundwater flow system. Rosemont Spring will be covered by the Waste Rock Storage Area and is located within the simulated capture zone of the pit or pitlake. Therefore, terminated flows are anticipated at this spring. Impacts to Questa and Helvetia Spring are not anticipated during the mining-phase, but will likely have reduced or terminated flows in the post-closure period.

Sensitivity analyses
Sensitivity analyses were run on various pre-mining, operation-phase, and post-closure model scenarios and model input parameters, such as changes in the evaporation rate and in groundwater recharge contributions from meteoric precipitation. Post-closure simulation results were most sensitive to decreases in pit-lake evaporation and changes in recharge in the pit area due to stormwater infiltration.None of the sensitivity model runs, however, caused the lake stage to reach the groundwater divide elevation.

Due to the proximity of the western model boundary to the Open Pit (Figure 2), sensitivity simulations were also conducted to determine this boundary's impact on the simulation results. These sensitivity simulations indicated that drawdown propagation to the east and outflows to the west were not sensitive to whether the western boundary was simulated as a constant-head or a general head boundary.

Discharge impact analysis

Based on pit dewatering and the formation of a terminal sink pitlake during the post-closure period, the pit capture zone will extend underneath most of the project facilities. Particle tracking simulations indicate that any seepage from facilities within the capture zone will flow back to the pit. Seepage that was not captured by the pit lake was of acceptable quality and was not predicted to degrade the water quality of the down-gradient regional aquifer.

Dynamic Systems Model (DSM)

A DSM for the anticipated Rosemont mine pit lake was developed in GoldSim™ (GoldSim Technology Group, 2005) to simulate the hydrologic water balance and the mixing of the chemical loads from the various hydrologic processes (e.g., groundwater inflow, pit wall runoff, and precipitation). The DSM outputs from the predictive simulations were used as inputs to a final simulation model using PHREEQC, which simulated the equilibrium geochemical condition of the pit lake.

The DSM includes both stochastic (variable) and deterministic (fixed) parameters. The stochastic parameters are used to assess the uncertainty in the predictions due to the data and analytical constraints and natural variability in the input parameters. This was accomplished by utilizing GoldSim in the Monte Carlo simulation mode. The model was allowed to run for a 1,000-year period using MonteCarlo sampling (for the stochastic parameters) with 1,000 realizations. The 1,000-year period of simulation was based on the groundwater flow modeling results which indicated that the system would require approximately1,000 years to reach ahydrologic steady-state condition.

DSM structure and formulation

Each element of the conceptual groundwater flow model (Tetra Tech, 2010b) wereincorporated into the DSM. These elements were organized into modules or containers of related elements. The DSM contains five (5) organizational modules: pit geometry, meteorology, hydrology, geochemistry (chemical mass loading), and results.

The uncertainty associated with hydrologic parameters in the DSM was addressed by varying the hydrologic inputs over a range of values (Table 1). Changes to the hydraulic parameters in the DSM were consistent with those used in the sensitivity analysis of the groundwater flow model (Tetra Tech, 2010b). The range of groundwater inflows used in the DSM (i.e., 85 to 107 percent) was based on the lake stage-groundwater inflow relationship from the base case regional groundwater flow model (Figure 1). A uniform probability distribution function (PDF) was used for the stochastic water balance components: groundwater inflow, pit wall runoff, precipitation, and evaporation coefficient. This approach provides a more rigorous assessment of the potential upper and lower bounds on pit lake elevation and chemistry than is possible using a reasonable number of deterministic model runs. Furthermore, this approach permits an assessment of the cumulative uncertainties with multiple parameter estimates.

Table 1. Range of values for DSM stochastic variables

Parameter	Range (Low)	Range (High)
Precipitation	80 percent	120 percent
Evaporation	80 percent	120 percent
Lake Evaporation Coefficient	65	70
Pit Wall and Catchment Runoff	20 percent	40 percent
Groundwater Inflow	85 percent of base case flowmodel	107 percent of base case flow model

Interdependent physical processes are not explicitly coupled when multiple parameters are simultaneously varied using PDFs. For example, a single groundwater inflow function from the base flow model was used for all sensitivity simulations. However, if evaporation is lower and precipitation is higher than was simulated in the base flow model, these conditions would result in a higher DSM lake stage than would be predicted if the same evaporation and precipitation values were simulated in the flow model. The higher simulated DSM lake stage occurs because the DSM does not account for lower groundwater inflows that would result from the higher lake stage. Due to the inherent uncertainty in groundwater inflow predictions, this is an acceptable limitation. The insights gained through predicting a range of future pit water qualities based on the uncertainty in multiple parameter estimates is essential for bounding the potential future conditions.

Chemical mass loading

Each contributing hydrologic component to the Rosemont pit lake (groundwater, precipitation, and pit wall runoff) has an associated mass loading component that can be directly measured or estimated through geochemical testing. The total mass of all constituents delivered to the pit lake combine with the hydrologic water balance to produce specific bulk pit lake compositions at various stages of pit filling.

Groundwater and precipitation chemistry

The chemical composition of groundwater flowing to the pit was represented as the average measured concentrations from eight (8) monitoring wells (PC-1 through PC-8) in the vicinity of the proposed pit (M&A, 2009). The average composition of this groundwater is a calcium-sulfate type water with moderate total dissolved solids (TDS) (700 mg/L), neutral pH (7 to 8), and trace element concentrations below the primary Aquifer Water Quality Standards for drinking water in Arizona. Mean monthly precipitation chemistry (depth-weighted) was calculated using data from 1980 to 2006 collected from the nearest station (NADP, 2008). The regional precipitation contained low TDS concentrations (<10 mg/L) with a pH ranging from approximately 5 to 6.

Pit wall runoff chemistry

Chemical loading from pit walls occurs when precipitation intercepts the pit wall surface and dissolves chemical mass, which is transported to the lake by means of runoff. Both the quantity and quality of the wall runoff will be proportional to the exposed areas of the various rock types in the pit wall. The contribution of chemical loading from wall runoff will decrease with time, as pit filling progresses and less wall rock area is exposed. The exposed Rosemont pit wall lithology is expected to be dominated by arkosic rocks of the Willow Canyon Formation, the Horquilla Limestone, and the Bolsa Quartzite, with less exposure to other limestone units, quartz monzonite porphyry, and andesite (Tetra Tech, 2007). Most of the primary sulfide mineralization is hosted by the Horquilla, Colina, and Epitaph Limestones, although the total sulfide content of these rocks is generally low. Estimates of the magnitude of chemical release from wall rocks were developed through geochemical testing of representative samples.

Testing of representative future pit wall rocks by acid-base accounting (ABA) methods indicate the rocks have excess acid neutralization capacity and are unlikely to generate acidity upon weathering. Because ABA characteristics reflect the dominant reactive mineralogy of the rock, the ABA results were used in a detailed evaluation of sampling adequacy. The results indicated that a sufficient number of samples have been collected to adequately represent the ABA characteristics of the wall rocks, and that each sample used in subsequent leach testing were representative of their respective rock type (Tetra Tech, 2007; 2010a).

Short-term leaching tests (STLTs) were subsequently conducted to quantify release of various constituents from the different rock types to develop source terms for pit wall runoff. The STLTs included both the Synthetic Precipitation Leaching Procedure (SPLP) and the Meteoric Water Mobility Procedure

(USEPA, 1986; ASTM, 2003). A comparative evaluation of HCT data from waste rock samples (Tetra Tech, 2007) to more recent STLT data indicate that SPLP results are appropriate to represent pit wall runoff chemistry for most rock types (Tetra Tech, 2010a) because they produced extracts with chemistry similar to HCT leachates. At Rosemont, the limited occurrence of sulfide minerals in non-ore rock, combined with the abundance of carbonate minerals, eliminates the usual advantage of using HCT for mine rock characterization. The Bolsa Quartzite is the only rock type that contained enough sulfide to generate measurable amounts of acidity in HCTs, although the total acidity was low.

The HCT procedure is primarily used for characterizing the long-term rate of oxidation of sulfide minerals. The SPLP, however, addresses relatively short-term contact between water and a given solid. Therefore a detailed statistical analysis was used to produce a range of SPLP results to represent a range of potential chemical loading to the pit lake (Tetra Tech, 2010a). This approach considers the natural variation in geologic materials and the inherent uncertainties associated with water quality predictions to produce a sensitivity analysis.

Two key elements were important in selecting the SPLP test results for use in the model: (1) incorporating a range of input values based on a probability distribution of measured values, and (2) using actual sample data rather than synthetic data sets derived from the probability distribution. Three model scenarios were developed based on a low (-2 standard deviations, σ), an average (50th percentile), and an elevated scenario (+2σ) corresponding to low, average, and elevated pit loading. A fourth simulation modeled the contribution of acidity from the Bolsa Quartzite using the same hydrologic and chemical inputs as the 50th percentile simulationcell.

DSM results

Based on the 1,000-year simulation period, model results were generated for all components of the hydrologic water balance and various chemical loads. Four (4) chemical loading scenarios were simulated, correlating to the four (4) pit wall rock runoff scenarios outlined above. The data from each of the four chemical loading scenarios was extracted using the mean results for hydrology.

Water balance and lake formation

In all cases, the DSM confirmed that a lake will form in the open pit upon cessation of mining activities. The predicted rate of pit lake filling and the ultimate depth of the pit lake varied between model runs since the output results are dependent on the variability of the stochastic elements. The average, 25th percentile, 75th percentile, and upper and lower bound estimates (as defined by the 5th and 95th percentiles) for the pit lake elevation for the final time step (1,000-year period of simulation) from 1,000 realizations are shown in Table 2.

Table 2. Predicted pit lake elevation for various DSM outcomes

Average	5th Percentile	25th Percentile	75th Percentile	95th Percentile
1,307 m (4,287 ft)	1,248 m (4,095 ft)	1,282 m (4,209 ft)	1,329 m (4,363 ft)	1,367 m (4,488 ft)

The rate of pit filling is initially controlled by the groundwater inflow rate and later by evaporation and direct precipitation as the surface area of the pit lake increases. Based on the simulated hydrology, the pit lake will fill to 90% of the final lake elevation in 215 years. The steady-state lake elevation is estimated to be achieved in approximately 1,000 years. The mean estimates for lake area and lake volume are 0.88 km^2 (218 acres) and 0.13 km^3 (101,700 acre-feet), respectively.

The lake water balance simulated by both the mean DSM simulation and the regional groundwater flow model (Tetra Tech, 2010b) are nearly identical. The result is that the predicted chemical loading to the pit lake (based on the mean values) is consistent with the regional groundwater flow model. Based on the pre-mining groundwater elevations on the down-gradient side, and those predicted by the regional groundwater flow model, the upper bound predicted lake stage of 1,367 m (4,488 ft) amsl would not create flow through conditions.

The lake water balance is largely controlled by the relationships between lake stage and groundwater inflow and lake stage and evaporation. As the lake elevation and surface area increase, so does the lake evaporation and lake precipitation. In contrast, the groundwater inflow decreases substantially, while the pit wall runoff decreases only slightly due to the cone-shaped geometry of the simulated pit. The simulated annual water balance for the last year of the simulation is presented in Table 3.

Table 3. Simulated water balance in model year 1,000

Inflow*				Outflow		
Groundwater Inflow	**Direct Precipitation**	**Pit Wall Runoff**	**Total In**	**Evaporation**	**Groundwater Outflow**	**Total Out**
823.7 Lpm (217.6 gpm)	748.0 Lpm (197.6 gpm)	523.5 Lpm (138.3 gpm)	2,095 Lpm (553.5 gpm)	2,091 Lpm (552.5 gpm)	0 m^3/yr (0 ac-ft/yr)	2,091 Lpm (552.5 gpm)

* Lpm – litres per minute; gpm – gallons per minute

Chemical loading

The hydrologic system reaches a dynamic equilibrium in the 1,000-year simulation period; however, chemical mass continues to be added to the system past this 1,000-year period. Chemical concentrations will continue to increase even when a dynamic equilibrium is achieved. This is due to continual removal of water by evaporation. The effect of evapo-concentration of the lake water is an important component affecting the chemical concentrations in the system at the end of the 1,000-year simulation period.

Model simulations were conducted to provide not only a sense of the expected case (average or mean) associated with conditions in the pit lake, but also the relative uncertainty of the predictions. Uncertainty in the model is derived from the expected uncertainty in precipitation, lake evaporation, pit wall runoff, and groundwater inflow. Uncertainty is also associated with the range of the observed geochemical leach tests. Taken together, the hydrologic uncertainty, coupled with the uncertainty associated with how the pit wall rocks will weather, were used to generate a range of chemical loads to the pit.

Accordingly, the low chemical loading scenario couples low end leach testing with maximum water accumulation (high runoff, low evaporation) to simulate the best case water quality scenario. The high chemical loading scenario couples high end leach testing results with minimal water accumulation (low runoff, high evaporation) to estimate worst case conditions. These two end members bracket the average case. Overall, the bulk of the chemical mass is found to be contributed from good quality groundwater flowing into the pit (over 95%), with less than 4% of the mass attributed to pit wall runoff and less than 1% of the mass attributable to the first flush of the blast affected rock.

The first flush of water through blast affected rock was simulated by assuming that the higher permeability zone around the pit shell penetrates approximately 2 m (6 ft). The specific yield of this zone was simulated using a stochastic element with a uniform distribution between 3% and 15%. Three (3) pore volumes were assumed to have elevated dissolved chemical mass, which was simulated using the humidity cell test(HCT) results.

Table 4 presents the chemical contributions to the pit lake geochemical model from groundwater, pit wall runoff, and the initial flushing of the pit wall blast zone in the DSM. As shown, about 90% of the major ions(i.e., Ca, Mg, Na, K, SO_4, Cl, and F) are derived from groundwater. Alternatively, the majority of trace chemical constituents are derived from pit wall runoff and flushing of the pit wall blast zone.

Table 4. Chemical contributions to pit lake geochemical model

Constituent	Ground-water	Pit Wall Runoff	Initial Flush	Constituent	Ground-water	Pit Wall Runoff	Initial Flush
Ca	96.8%	2.9%	0.1%	Cd	66.9%	33.1%	0.0%
Mg	97.0%	2.6%	0.1%	Cr	62.8%	37.2%	0.0%
Na	87.7%	10.2%	0.1%	Cu	28.6%	71.2%	0.2%
K	66.6%	23.1%	0.5%	Fe	95.1%	4.9%	0.0%
SO_4	97.5%	1.7%	0.1%	Pb	7.5%	92.5%	0.0%
Cl	91.3%	5.5%	0.1%	Hg	19.7%	80.3%	0.0%
F	83.4%	16.0%	0.6%	Mn	82.2%	2.7%	0.0%
HCO_3	95.4%	4.2%	0.1%	Mo	98.2%	1.7%	0.1%
Ag	66.9%	33.1%	0.0%	Ni	50.3%	49.7%	0.0%
Al	30.2%	69.6%	0.1%	Se	17.7%	82.3%	0.0%
As	18.1%	81.8%	0.0%	Tl	4.8%	95.2%	0.0%
Sb	57.8%	42.1%	0.1%	U	90.8%	9.2%	0.0%
Ba	94.9%	5.0%	0.1%	Zn	99.6%	0.4%	0.0%
Be	33.6%	66.4%	0.0%				

Pit Lake Geochemical Model

The Rosemont pit lake geochemical model was developed in two stages: (1) geochemical testing to define chemical mass loading for each hydrologic input, and (2) equilibration of the bulk solution generated from GoldSim at selected pit lake model time steps using an equilibrium speciation model (PHREEQC).

Geochemical equilibrium modeling

Output from the DSM model for years100, 200, 500 and 1000 was input into the geochemical speciation model PHREEQC (Parkhurst and Appelo, 1999) used in conjunction with the MINTEQ geochemical database (Allison et al., 1991). The equilibrium modeling step considers potential mineral precipitation/dissolution and adsorption/desorption reactions that may control the concentrations of major ions and trace elements in the pit lake. For example, mineral precipitation removes chemical mass from the pit lake and establishes a limit on the maximum dissolved concentration for the associated components of minerals, such as calcite, gypsum, fluorite, and ferrihydrite, in the geochemical model.

PHREEQC also incorporates the Dzombak and Morel (1990) diffuse double-layer model and a non-electrostatic surface complexation model (Davis and Kent, 1990) to simulate adsorption of various trace elements onto mineral surfaces. Adsorption modeling assumes that the reactive surface is hydrous ferric oxide (HFO), essentially ferrihydrite. The reactive properties of HFO have been well-characterized (Dzombak and Morel, 1990), and the three most important properties of HFO used as model inputs are the: (1) mass of HFO, (2) surface area of HFO, and (3) density of surface adsorption sites. PHREEQC uses the amount of HFO predicted to precipitate in the model simulation to define the mass of HFO available for adsorption.

Pit lake modeling results

Table 5 presents the final equilibrated water quality predictions from PHREEQC using the DSM output for the four Rosemont pit lake simulations in comparison to local groundwater. The model predicts that the water quality of the pit lake will be very similar to that of local groundwater after a 200-year period. The 200-year simulation point was selected to provide a time period that was sufficiently long to provide a sense of scale consistent with several human generations. However, because the pit lake is expected to be a hydraulic sink with water being removed only through evaporation, the concentrations of conservative constituents (e.g., chloride) increase by a factor of about 1.5 times that of local groundwater due to evaporative concentration. Sulfide minerals are largely absent in the limestone wall rocks, while carbonate is abundant, therefore the lake is expected to be slightly alkaline (pH = 8) and acidic conditions are not expected to develop after 200 year model timeframe.

Table 5 Rosemont pit lake water quality predictions compared to local groundwater after 200 years

Parameter*	Ambient Groundwater (mg/L)	Low Chemical Loading (mg/L)	Average Chemical Loading (mg/L)	Elevated Chemical Loading (mg/L)	Average Chemical Loading With Bolsa HCT Data (mg/L)
Ca	131	89.9	99.8	107.7	100.7
Mg	20.5	22.7	25.7	30.1	25.6
Na	26	31.9	35.9	38.6	35.3
K	3.17	5.1	5.7	6.3	5.4
SO_4	300	330.6	374.1	518.5	375.8
Cl	8.36	9.9	11.1	12.5	11.1
F	0.85	1.1	1.2	1.4	1.2
HCO_3	187	37.3	36.2	37.0	36.0
Ag	NA	0.004	0.004	0.005	0.004
Al	<0.03	0.158	0.197	0.260	0.357
As	0.0037	0.004	0.005	<0.001	0.003
Sb	<0.0004	0.003	0.003	0.003	0.003
Cd	<0.0001	0.002	0.002	0.002	0.002
Cr	<0.01	0.004	0.005	0.005	0.005
Cu	<0.01	0.004	0.004	0.005	0.163
Fe	0.554	<0.001	<0.001	<0.001	<0.001
Pb	0.00092	0.004	0.015	0.017	0.015
Hg	<0.0002	0.002	0.001	0.002	<0.001
Mn	0.174	0.229	0.255	0.243	0.254
Mo	0.121	0.137	0.150	0.192	0.154
Ni	<0.01	0.005	0.006	0.007	0.010
Se	0.00212	0.013	0.014	0.016	0.014
U	0.00419	0.005	0.006	0.006	0.006
Zn	0.694	0.745	0.847	0.959	0.862
TDS	581	527	589	751	590
pH	7.6 / 8.2#	8.1	8.0	8.0	8.0

* # the reported pH for ambient groundwater includes field measurement average followed by the laboratory measurement average; NA – not applicable.

Concentrations of Ca and $HCO_3$are lower in the pit lake than groundwater in Table 5 due to PHREEQC calculations, which indicated an over-saturated state of composite pit lake water with respect to calcite, which was allowed to precipitate in the calculations. Similarly, the PHREEQC calculations assumed fully oxidizing conditions, which resulted in the oxidation of all iron to ferric iron, subsequently being precipitated as ferrihydrite. The precipitation of ferrihydrite was accompanied by adsorptive scavenging of arsenic from solution. Manganese is higher than in ambient groundwater tabulated.

The above description of precipitation of oversaturated solids is the basis for the reported lower arsenic concentrations in the "elevated loading" scenario as this scenario had a greater loading of iron, which in turn resulted in more efficient scavenging of arsenic. Iron and arsenic loading to the pit lake water body was not directly proportional between the elevated and low loading scenarios.

The pit lake geochemicalmodel indicates the majority of water flowing to the pit lake will originate from groundwater, and hence the model was insensitive to the degree of chemical loading (low, average, or elevated) that was simulated. Even with the elevated loading model scenario, predicted TDS concentrations are similar to the local groundwater, and all constituent concentrations are predicted to be below the Arizona drinking water standards.

Conclusions

A geologically based groundwaterflow model was developed to simulate impacts to the regional groundwater flow system associated with the planned Rosemont Project and the development of an open pit. A pre-mining, steady-state model was developed and calibrated using existing water level and stream flow measurements. The calibrated pre-mining groundwater flow model was used as the starting condition for anoperations-phase model, which modeled the incremental expansion and dewatering of the open pit, including the propagation of drawdown through the regional groundwater flow system. Upon cessation of pit dewatering, a post-closure model was developed to simulate pit refilling and its effect on drawdown propagation.The predicted groundwater level drawdown associated with the project is relatively small, particularly as it relates to distant ecologically sensitive areas in lower Davidson Canyon and Cienega Creek.

Results from the groundwater flow model were input into the DSM to simulate the hydrologic water balance and the mixing of the chemical loads from the various hydrologic processes (e.g., groundwater inflow, pit wall runoff, precipitation). The DSM outputs from the predictive simulations were used as inputs to a final simulation model using PHREEQC.

The conclusions of the predictive geochemical modeling effort performed for the Rosemont Copper Project by Tetra Tech can be summarized as follows:

- Model results indicate that the 95th percentile pit lake stage is lower than down-gradient groundwater divide and thus the pit lake is expected to be a hydraulic sink.
- The majority of the inflow water entering the Open Pit will be from groundwater sources seeping through the pit walls and pit bottom. About 95 percent of the chemical mass contributed to the pit lake will be from groundwater. Direct precipitation, and runoff from the pit walls, will contribute to the pit lake water balance as well. Over time, the contribution from direct precipitation will increase as a percentage of annual inflow as the pit lake surface area increases.
- The range of hydrologic variables used in groundwater modeling sensitivity analysis were simulated in the DSM model as uniform PDFs, which allowed for evaluating cumulative uncertainties.
- After 200 years thesimulated pit lake pH of 8 is similar to the local groundwater, which is slightly alkaline.The pit lake is expected to be a hydraulic sink, with water leaving only through evaporation, and dissolved chemical constituents are expected to concentrate over time. At the 200 year simulation mark, the model showed evapo-concentration of some constituents about 1.5times that of local groundwater.

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Acronyms

amsl – above mean sea level
DSM – dynamic systemsmodel
HCT – humidity cell test
HFO - hydrous ferric oxide
PDF - probability distribution function
STLT - short-term leaching test
SPLP - Synthetic Precipitation Leaching Procedure

TDS – total dissolved solids