FEFLOW Model of a Copper Mine, Arizona, USA

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ABSTRACT: A three-dimensional, transient, groundwater flow model has been developed using FEFLOW 6 to predict current and future groundwater conditions that may result from ongoing and proposed open-pit mining of three copper ore bodies. The FEFLOW model simulates a region of 570 square miles (1,476 km^2) within the Basin and Range Province in the southwestern United States. The model, which is based on a previously developed MODFLOW-96 model and on new data, simulates four groundwater systems: Holocene fill, deeper Tertiary (Paleogene and Neogene) basin fill, bedrock (fractured volcanics of Tertiary to Cretaceous age) of generally small permeability, and moderate-sized pockets of bedrock having relatively larger permeability. Dewatering of two existing pits and one proposed pit were simulated using transient boundary conditions and material properties. The model also simulates numerous groundwater production wells, which supply the mine for processing ore and other needs. The calibration of the model has been updated for pre-mining and during-mining based on an extensive database of measured groundwater levels gathered since the MODLFOW-96 model was completed. After the ultimate depth of the pits is reached (approximately 42 years of mining), the model predicts the formation of pit lakes over a span of 1,200 years using a unique and simple IFM. The updated model was used to predict the potential impact of mining on groundwater flows in areas as far away from the mine as 15 miles (24 km). The modeled water-balance is evaluated, and the potential impacts are assessed using pressure-head decline maps and by calculating the change in flows at external boundaries.

MODEL DESCRIPTION

The modeling project involved updating a previously developed MODFLOW-96 model based on new information and simulation technology. The model is intended to predict the hydraulic influence on both groundwater and surface water that may arise due to excavation of three bedrock open pits and due to pumping of groundwater for mine operations (Figure 1). Groundwater for mining operations will be pumped from up to eleven wells completed in bedrock or from up to seven wells completed in old, deep basin fill (Figure 1).

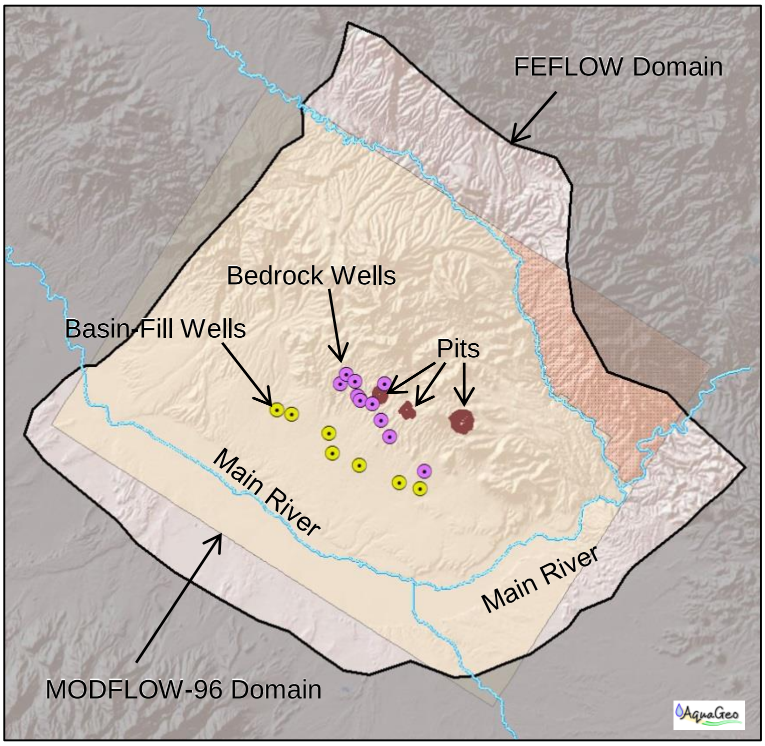

Figure 1: FEFLOW and MODFLOW-96 domains, and mine wells and pits

The three-dimensional model (Figure 2) covers approximately 570 square miles of an arid basin in the Basin and Range Physiographic Province characterized by heavily eroded, northwest-trending, elongated mountain ranges separated by broad valleys. The mountains are typically tilted blocks of structurally deformed bedrock bounded by faults with intermontane valleys that have been filled to great depths (more than 7,000 feet) by sediments eroded from the adjacent mountain ranges. The model simulates three main groundwater systems (Figure 2): a shallow aquifer hosted in Holocene basin fill, a deep aquifer hosted in basin fill of Pliocene to Miocene age, and a bedrock system in crystalline rock of Cretaceous and older age. The bedrock is generally not very permeable except for relatively small pockets of densely fractured rock that host producible quantities of groundwater (these pockets comprise the fourth system referred to in the abstract). A very thick sequence of very-fine grained (predominantly clay) sedimentary deposits separates the shallow aquifer from the older, deeper basin-fill aquifer and the bedrock unit.

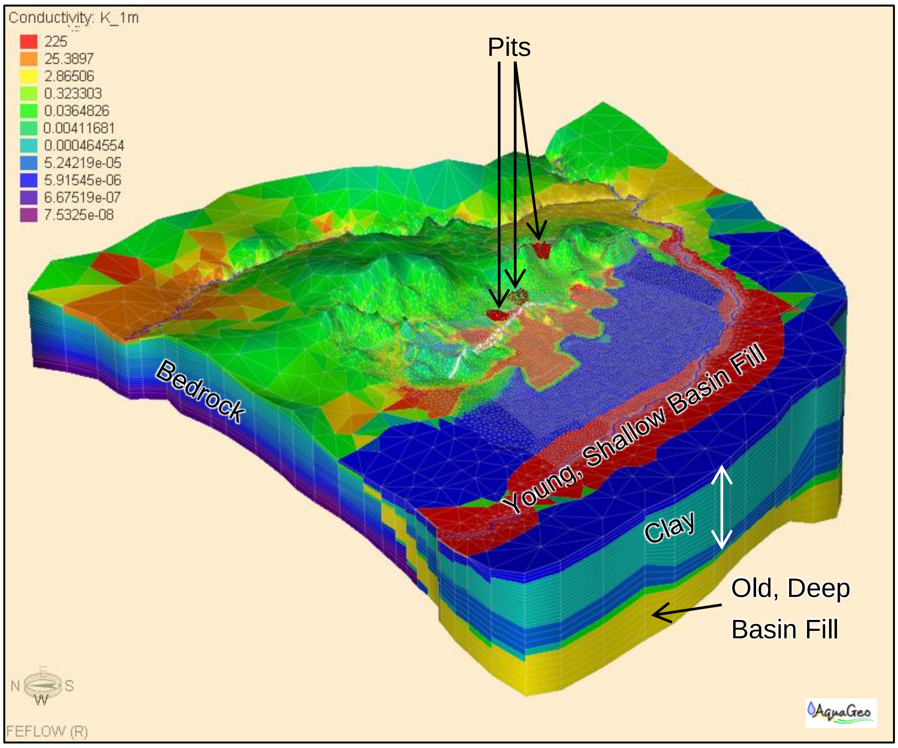

Figure 2: 3D view of hydraulic conductivity and hydrogeologic units

A "transitional approach" was used in the model layering which accommodates sedimentary basin-fill and crystalline bedrock units (Figure 3). Material properties were computed based on the percentage of each geologic unit (e.g. clay, young or old basin fill, bedrock, etc.) in an element. Sedimentary basin-fill deposits are up to 7,000 feet thick and bedrock thickness ranges up to 4,000 ft. The model simulates the rise and fall of the water table using the approach discussed by Sinton (2013) and Sinton and Moreno (2012).

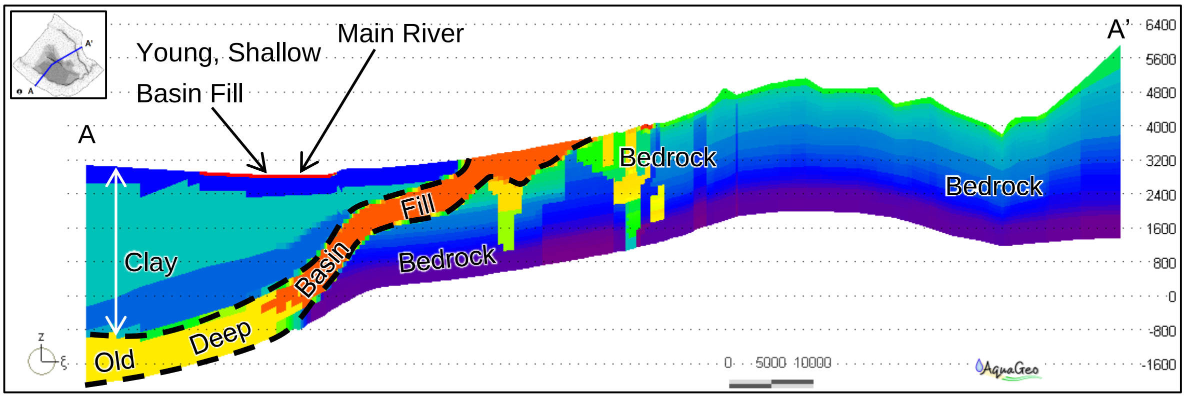

Figure 3: Cross section (elevation in feet above mean sea level; 5x vertical exaggeration)

The groundwater systems are fed by infiltration of precipitation, which is limited by the arid climate. Groundwater flows from highland areas where recharge occurs towards low areas. Groundwater also flows into the model domain along the southwest and southeast borders into relatively more permeable basin fill (Figure 4).

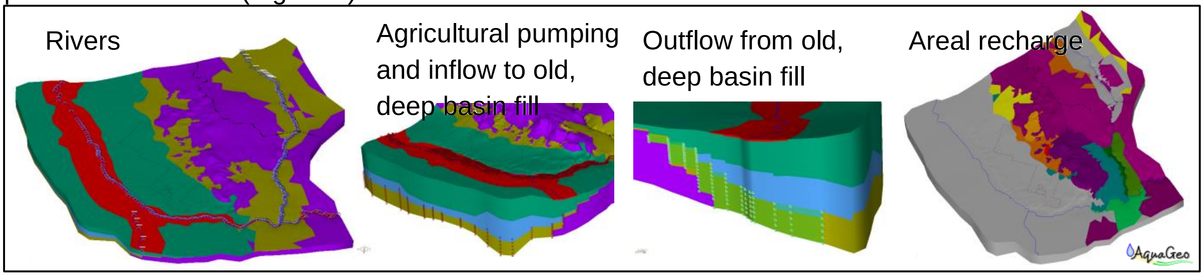

Figure 4: Boundary conditions (excluding pumping for mine operations).

Discharge occurs along streams and rivers, as outflow from the old deep basin-fill system, due to pumping for agricultural and mining uses, and due to dewatering of mine pits. Agricultural pumping is from the groundwater system in the young and shallow basin fill that occurs along the main river flowing through the area (Figure 4). Discharge from the old, deep basin-fill sediments also occurs along the northwest border (Figure 4). The model simulates transient dewatering of the mine pits using constrained specified-head nodes that activate as the pits are deepened (Figure 5). Hydraulic conductivity and storage properties in the pits also increase to large values as mining proceeds to allow simulation of potential pit lakes. Actual and planned groundwater pumping for the mine is shown in Figure 6 (see Figure 1 for locations). After mining ceases, the rate of filling and ultimate level of pit lakes is predicted using an IFM plugin (Wingle and Sinton, 2015).

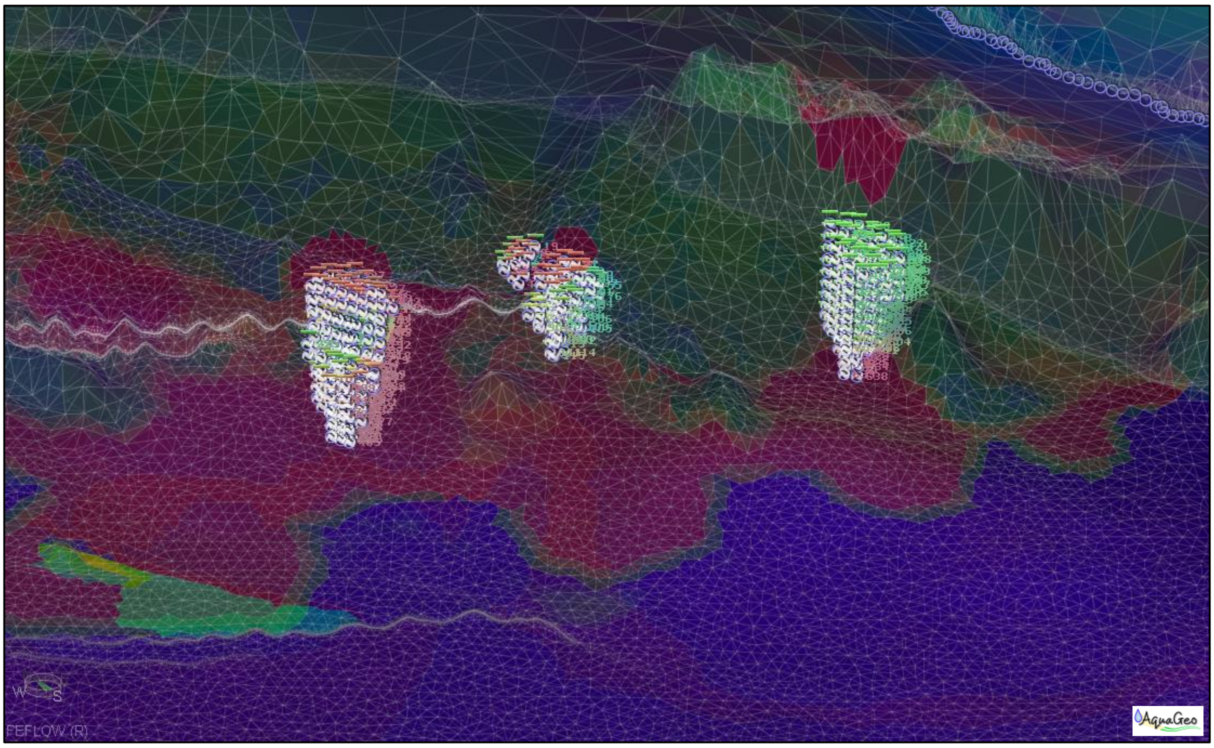

Figure 5: Pit dewatering nodes

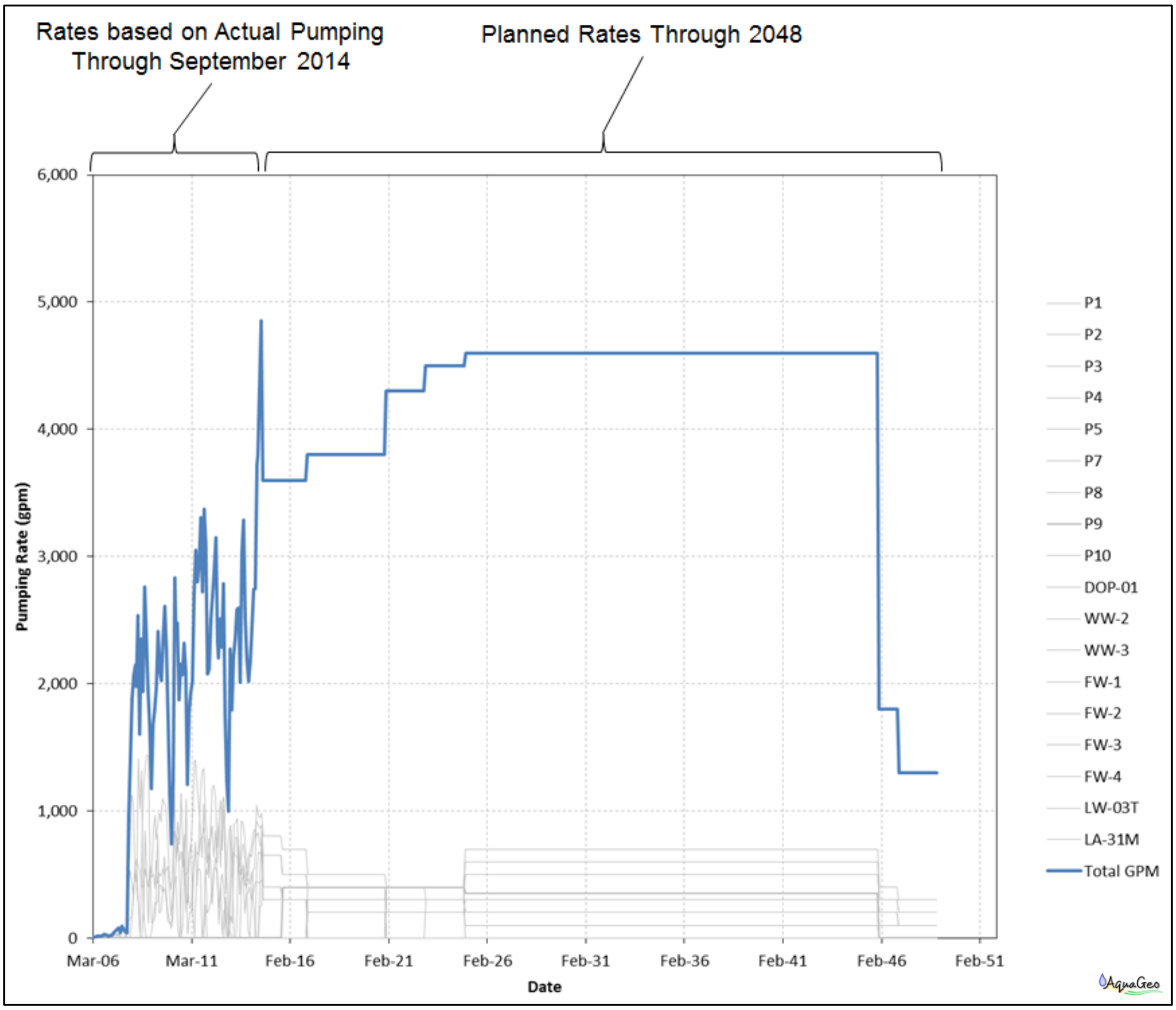

Figure 6: Actual and planned pumping of groundwater for the mine

In addition to the pit-lake plugin, a plugin was developed that allows the user to save the following simulation results to binary or ASCII files:

- Elevation and layer of the water table,
- Effective hydraulic conductivity based on pressure head and degree of saturation, and
- Volumes of water stored in pores and stored in compression

The material properties and boundary conditions of the new FEFLOW model are similar to those of the previous MODFLOW-96 model, with four primary exceptions:

1. The permeability of the old, deep basin-fill aquifer near the site is approximately five times greater based on new pumping-test results,
2. The permeability of the upper 500 feet of the clay beds of the upper basin-fill is approximately 1,000 times smaller based on new information,
3. Pumping of groundwater from the old, deep basin-fill system is planned and simulated, and
4. An additional mine pit is simulated (total of three pits).

CALIBRATION

The model was re-calibrated to pre-mining (steady-state) and during-mining (transient) conditions based on information gathered after the previous MODFLOW-96 model was completed. The re-calibration of the model focused primarily on matching transient conditions arising during actual pumping of groundwater for mine operations. The calibration, which was periodically reviewed and evaluated by a small team of experts, was improved by making focused adjustments to the conceptual model of hydrogeology. Examples of model fit at two locations are provided in Figure 7.

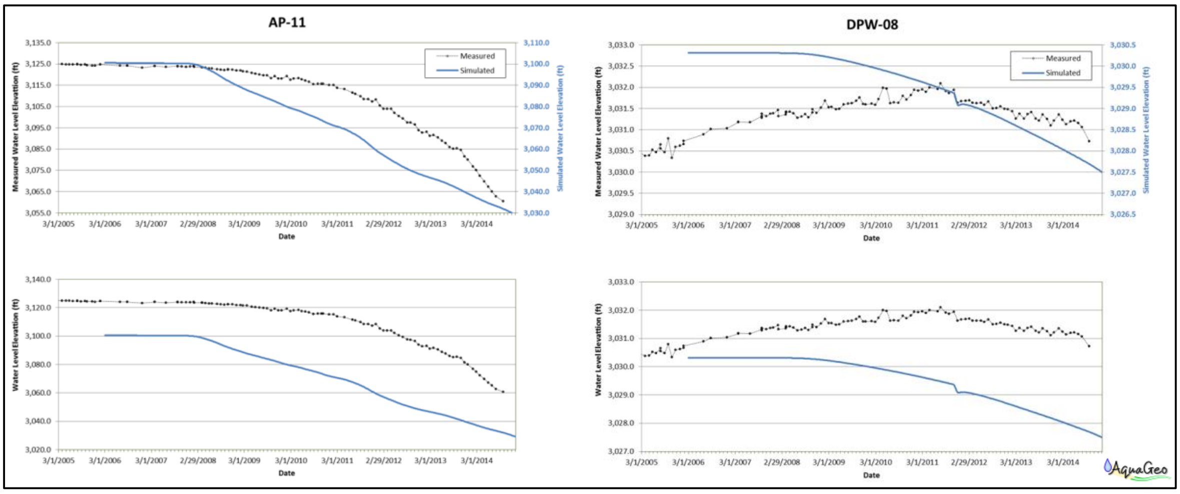

Figure 7: Example calibration data. AP-11 is relatively near where groundwater is pumped for mine operations, and DPW-08 is a few miles from that pumping

PREDICTIONS

Predictions were performed using the calibrated model included transient simulation of 42 years of mine operation followed by 1,200 years of groundwater system recovery. For this project, the hydraulic influence of mining was evaluated as drawdown (Figure 8) or as reductions in the amount of groundwater discharging to rivers, the peak effects of which are predicted to be 58 acre-feet per year, occurring after 82 years (Figure 9). The predicted decline of the water table is limited to areas near the mine; no decline is predicted in the young, shallow basin fill along the main river or in bedrock beyond the crest of the mountains adjacent to the mine.

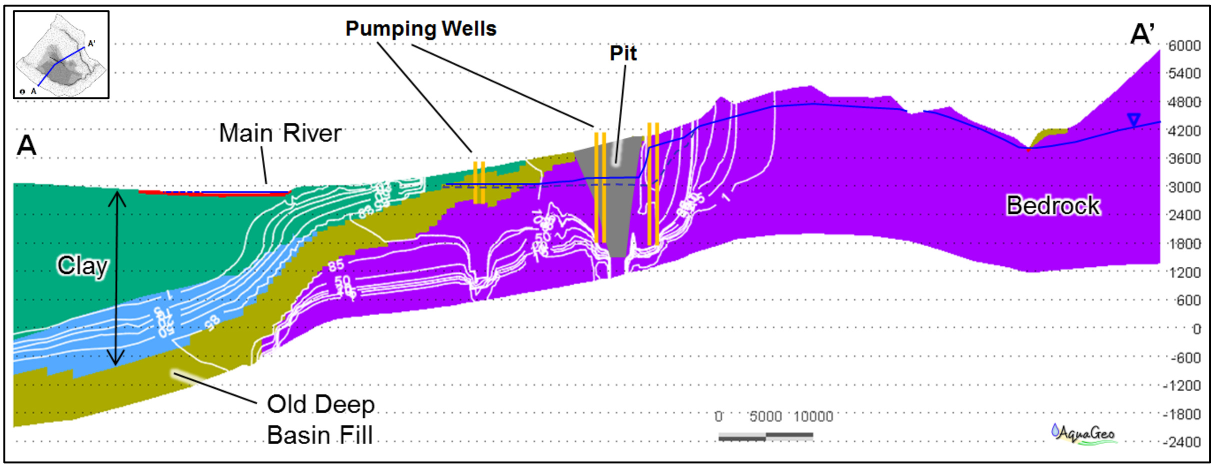

Figure 8: Predicted results. Pre-mining water table (blue line), post-mining water table (blue dashed line), and drawdown of total hydraulic head (white contour lines). Elevation in feet above mean sea level; 5x vertical exaggeration.

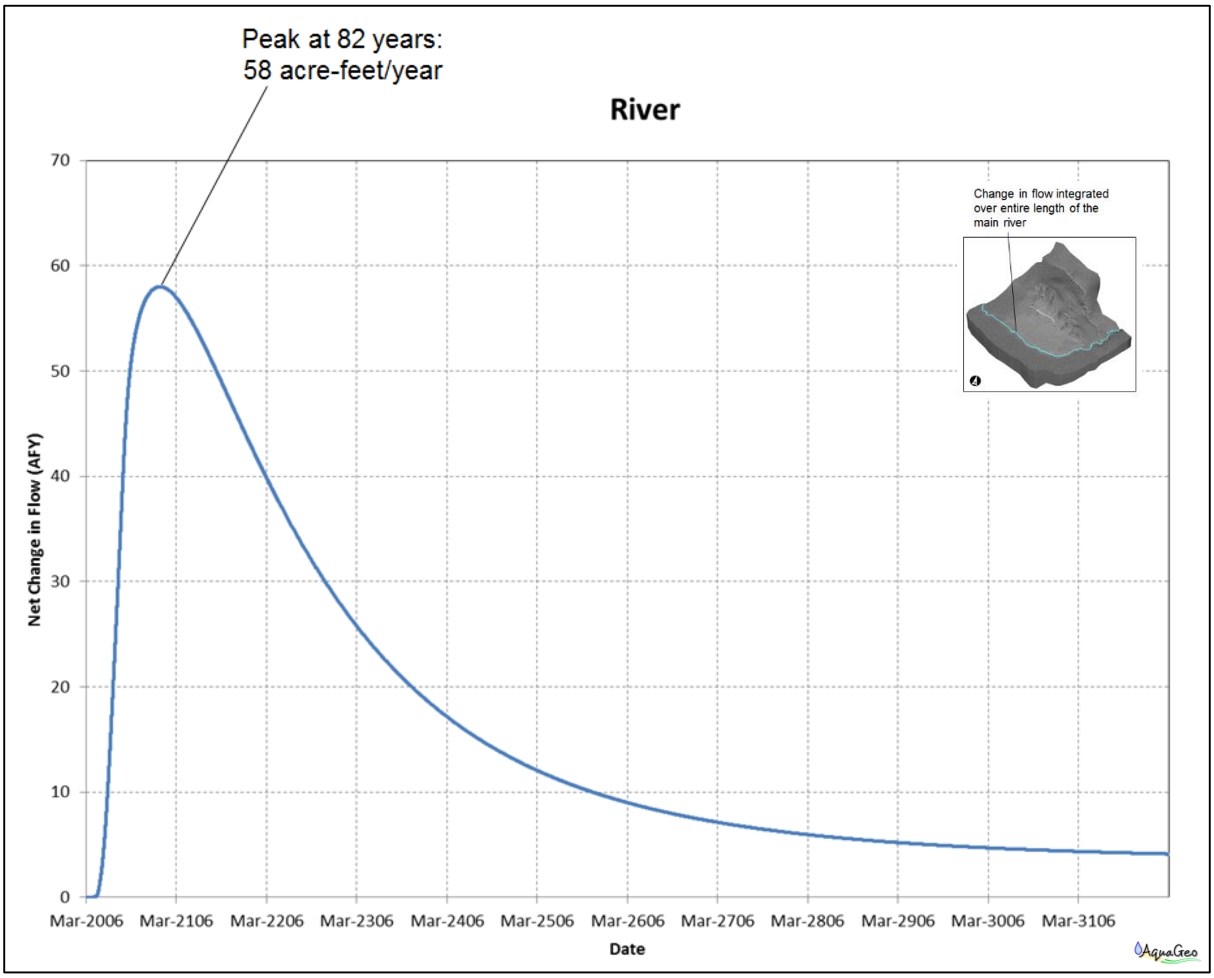

Figure 9: Reduction in groundwater component of flow along the main river

An additional predictive simulation was prepared that starts at the end of excavation of the mine pits. The formation of pit lakes was then simulated assuming the following:

- An average precipitation rate of 9.8 inches per year based on local climate data;
- An adjusted pan evaporation rate of 62 inches per year using a pan coefficient of approximately 0.64 (based in part on local climate data);
- An average pit-wall runoff contribution to the lake of 20% (percentage of precipitation that flows into the pit lake from the pit walls above the lake). This is based on work at other mine sites; and
- The pits are dry at the end of mining (water levels at nodes were set to the elevation of the bottom of the pits when mining ceases).

The predictions for one of the pit lakes 1,200 years after mine pumping ceases are as follows:

- The level of the pit lake will equilibrate at approximately 3,000 ft above mean sea level (300 feet deep), which will be achieved approximately 260 years after mining of the pit ceases (Figure 10);
- The rate of groundwater inflow to the pit lake will be approximately 16 acre-feet/year (10 gallons per minute) (Figure 11). As the lake level reaches equilibrium, the inflow of groundwater fluctuates due to small fluctuations in the area of the lake. These fluctuations arise from the spatial and temporal discretization; and
- The model predicts that the pit lake will form a permanent hydraulic sink for local groundwater, suggesting there will be no long-term loss of pit-lake water to groundwater (Figure 10).

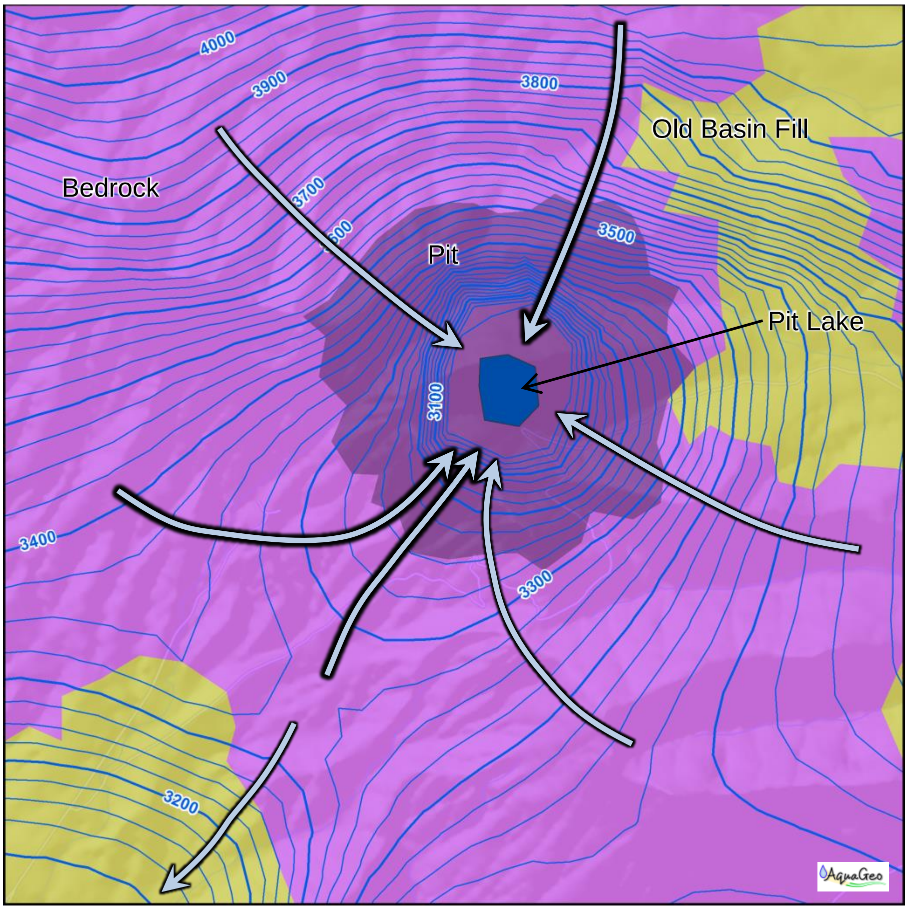

Figure 10: Predicted pit lake at equilibrium. Contours (blue) represent the elevation of the predicted water table.

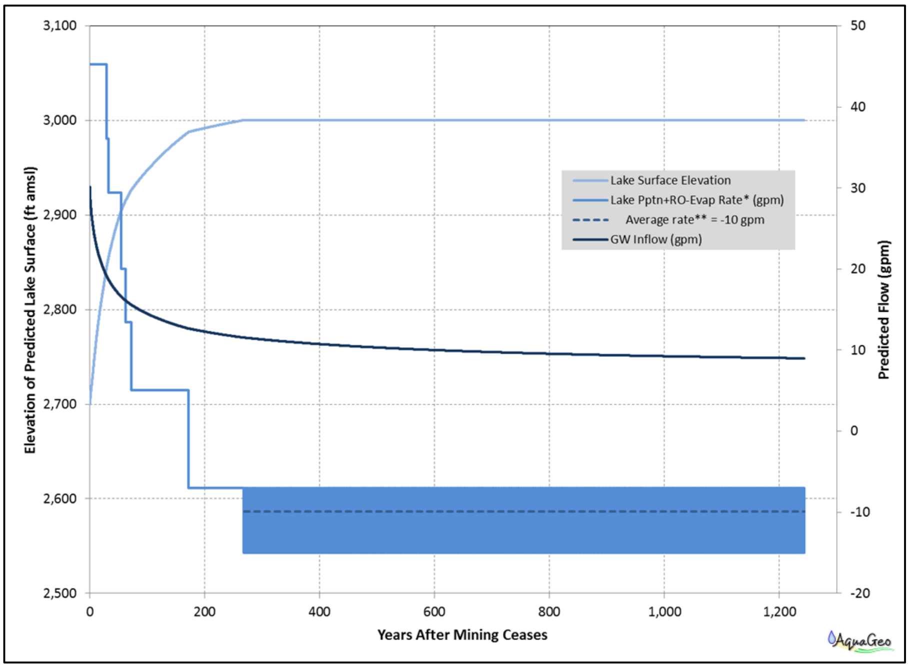

Figure 11: Predicted elevation and flows, in gallons per minute (gpm), to/from the pit lake (see Figure 10). "GW Inflow" is the rate of groundwater inflow to the pit lake. *Net surface water flow to the lake is the sum of precipitation onto the surface of the lake (Pptn) plus runoff from pit walls into the lake (RO) minus evaporation from the surface of the lake (Evap). **The "Average rate" represents the average rate of groundwater inflow after approximately 275 years.

Components of the overall water balance, excluding simulation of pit-lakes, are as follows:

- The total volume of groundwater pumped for operation of the mine is approximately 254,000 acre-feet for the period from March 2006 through the end of 2048;
- The total volume of groundwater that discharges into the open pits from March 2006 through the end of 2048 is predicted to be approximately 5,800 acre-feet (approximately 2% of the volume pumped); and
- The maximum change in the amount of groundwater storage is 246,000 acre-feet which occurs at the time pumping ceases. This indicates that most of the produced groundwater comes from storage in the bedrock and the old, deep basin-fill systems.

At the start of the simulation, the total volume of water in the model is predicted to be approximately 7.7 million acre-feet. At the end of the simulation, 1,200 years after mine pumping ceases and the groundwater system has nearly recovered from groundwater withdrawals (excluding pit lakes), the model predicts that there is approximately 27,000 acre-feet less water in the domain of the model than there was at the start. This suggests that the cumulative discrepancy in the water balance is about 0.4%.

REFERENCES

Sinton, P. O., Comparison of FEFLOW and MODFLOW to Model Mine Sites with Deep Water Tables, MODFLOW and More 2013: Translating Science into Practice, Conference Proceedings, Maxwell, Hill, Zheng & Tonkin (2013), 287-291

Sinton, P. O., and Moreno, J. L., Comparison of Methods Used to Model Mine Sites with Deep Unsaturated Zones Using FEFLOW, Proceedings of the 3rd International FEFLOW Conference, Berlin, Germany, September 3-7, 2012, Number 4

Wingle, W. L., and Sinton, P. O., A Pit-Lake Module for FEFLOW, FEFLOW 2015 Conference, Modelling the World of Groundwater with Mike by DHI, Poster Presentation