

A METHOD TO PREDICT EVOLVING POST-CLOSURE PIT LAKE CHEMISTRY

by

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Abstract: There are currently over 50 active open pit mines in Nevada, at least 30 of which may be inundated by ground water upon pit closure, forming lakes as deep as 200 m when the pumps dewatering the excavation are turned off. With the growing awareness of environmental issues related to mining, prediction of future pit-lake chemistry has become mandatory during permitting, to determine both potential ecological risk, and long-term impacts on downgradient groundwater quality. This paper outline a methodology that couples a groundwater model (MODFLOW) with the rate of solute leaching from pit wall rocks (derived from field experiments and the FND pyrite oxidation model), and the geochemical reactions occurring in the pit lake water column (using PHREEQC). The model would predict pit lake water quality (chemogenesis) from the juvenile infilling condition through a mature, hydrogeologically steady-state condition.

Introduction

The predicted pit lake water quality following the closure of mining facilities is receiving close scrutiny from the regulatory community, due primarily to perceived evapoconcentration effects, potential downgradient impacts on surface and ground water quality, and the possible ingestion of metal-bearing epilimnion waters by water fowl. The chemical composition of a pit lake depends on both hydrological and geochemical processes that may change over time as the pit initially fills after mine closure, eventually reaching an approximate steady-state depth after some period. Hydrological processes are important because the water in the pit lake will be derived from a number of different pathways that include, 1) lateral inflow of groundwater through perimeter wall-rocks, 2) sheetwash and throughfall of precipitation along the pit walls, 3) artificial diversion of surface runoff into the pit lake, and 4) direct precipitation to the pit lake.

The chemical composition of the pit lake is a function of the flux and chemistry of these inflows, on which is superimposed the geochemical processes that occur in the pit wall rock perimeter (the ultimate pit surface; UPS). At this interface, subsurface rocks that are generally reducing and often sulfidic in character

in mineralized zones react with air and oxygenated surface waters to produce solution compositions that are a function of 1) the oxidizable sulfide content of the wall-rock, 2) the alkalinity of the infiltrating groundwater, 3) the buffering capacity (i.e., lithology) of the wall-rock, 4) the extent of formation of amorphous ferric hydroxide (AFH) [Fe(OH)₃(am)], 5) site-specific variables, such as moisture content, temperature, and diffusion rate of oxygen into the wall-rock, that affect sulfide oxidation kinetics, and 6) the seasonal rate of lake-overturn and maintenance of oxygenation at depth.

The contribution of these various hydrological and geochemical processes to the ultimate pit lake chemistry may change over time as the pit lake fills. For example, as alkaline ground water discharges into the pit, acidity and iron may be flushed from the wall rock, facilitating precipitation of AFH in the pit lake water column. AFH sequesters metals in solution, either by sorption or coprecipitation, forming a metal rich, basal sludge as it settles through the water column (Figure 1).

Additionally, the regional hydrologic regime surrounding the pit lake constrains chemogenesis by controlling the rate of infiltration and exfiltration of solutes. Pit lakes located on regionally sloping water tables may be partially recharged with groundwater from upgradient sources, with outflow recharging down gradient groundwater. However, solute transport will be mitigated by sorption of solutes to AFH in the downgradient face of the UPS.

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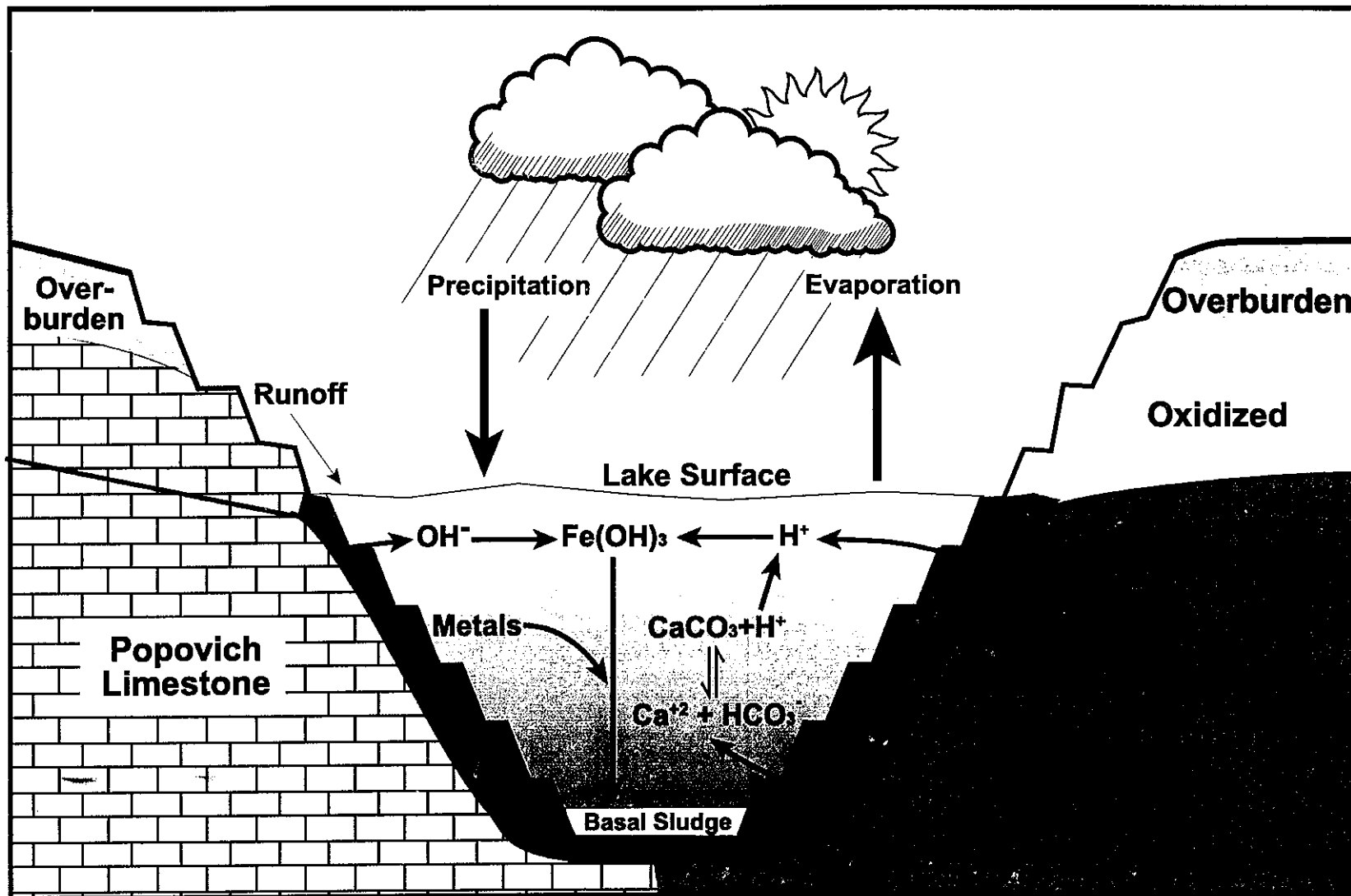


Figure 1

In contrast, pit lakes located in topographic depressions, i.e., those in the arid Great Basin of the Western U.S., are self-contained and lose water volume primarily by evaporation. These pit lakes will undergo evapoconcentration, leading to a gradual temporal increase in total dissolved solids concentrations. This paper describes the computer model PITQUAL which couples a groundwater model (MODFLOW) with the rate of solute leaching from the pit wall rocks (derived from field experiments and the FND pyrite oxidation model), and the geochemical reactions occurring in the pit lake water column (using PHREEQC). The PITQUAL output predicts pit lake water quality (chemogenesis) from the juvenile infilling condition through a mature, hydrogeologically steady-state condition (Geomega 1997a, 1997b).

Overview of the Technical Approach

The steps involved in modeling pit lake chemogenesis are depicted in Figure 2. Baseline hydrogeologic data provides the input to quantify the regional groundwater flow directions (Task 1). These data are used to develop a site-specific groundwater model (Task 2). The flow field output from the groundwater model is used as input to the pit lake model that uses the acid-base characteristics of the UPS wallrock obtained from the Geologic Block Model. Hence it is necessary to couple the groundwater model grid with that of the Geologic Block Model (Task 3).

A knowledge of the leachate quality from the wallrock in each grid cell, together with the groundwater flow through each cell results in a temporally variant mass contribution to the developing pit lake. As groundwater continues to flow through each cell, the wall rock solute concentrations entering the pit through that cell decrease, becoming asymptotic with the ambient groundwater chemistry. The wall rock solute leaching characteristics are obtained from humidity cell or field oxidation tests that result in temporally varying chemical release functions (Task 4). The CRFs are coupled with the calculated thickness of the oxidized rind in the UPS in each cell (Task 5), then integration of solute concentrations over time through each cell results in a prediction of the evolving bulk pit lake chemistry (Task 6).

Reactions in the water column remove metals from solution by precipitation of solid phases e.g., amorphous ferric hydroxide (AFH), and sorption to the AFH floc (Task 7). The floc settles to the base of the

pit lake where it forms a metal-rich basal sediment. Determination of the oxygen status of the pit lake water column throughout the year is necessary (Task 8) to determine the stability of the AFH because under the reducing conditions that may prevail in an anoxic environment, the potential exists for reductive dissolution of the floc, with concomitant release of metals back into the hypolimnetic region of the water column.

Finally, the potential exists for ground subsidence as waters are abstracted from the vicinity of the pit (Task 9), and depending on the flow regime in the pit lake, degradation of ground waters of the State can occur (Task 10). The results of these analyses present a holistic perspective of the potential environmental effects resulting from installation of an open pit mine and provide information integral to preparation of an Environmental Impact Statement for the proposed facility.

Task 1: Baseline Hydrogeologic Characterization

Specific information necessary for the baseline hydrogeologic characterization includes:

- results of geophysical surveys,
- geologic maps and cross-sections,
- well logs and water level data,
- data concerning the fluxes and water levels of surface water bodies,
- water quality data,
- climatological records, and
- the results of aquifer tests and other system stresses.

Task 2: Groundwater Flow Modeling

Numerical modeling of the groundwater flow system is necessary to evaluate:

- the influence of mine dewatering on the regional water table,
- the effects of infiltration on groundwater quantity and quality,
- potential hydraulic impacts to surface waters due to dewatering and infiltration,
- the fluxes of water entering the pit upon cessation of dewatering,
- the potential degradation of State waters due to groundwater throughflow after the pit lake has filled, and

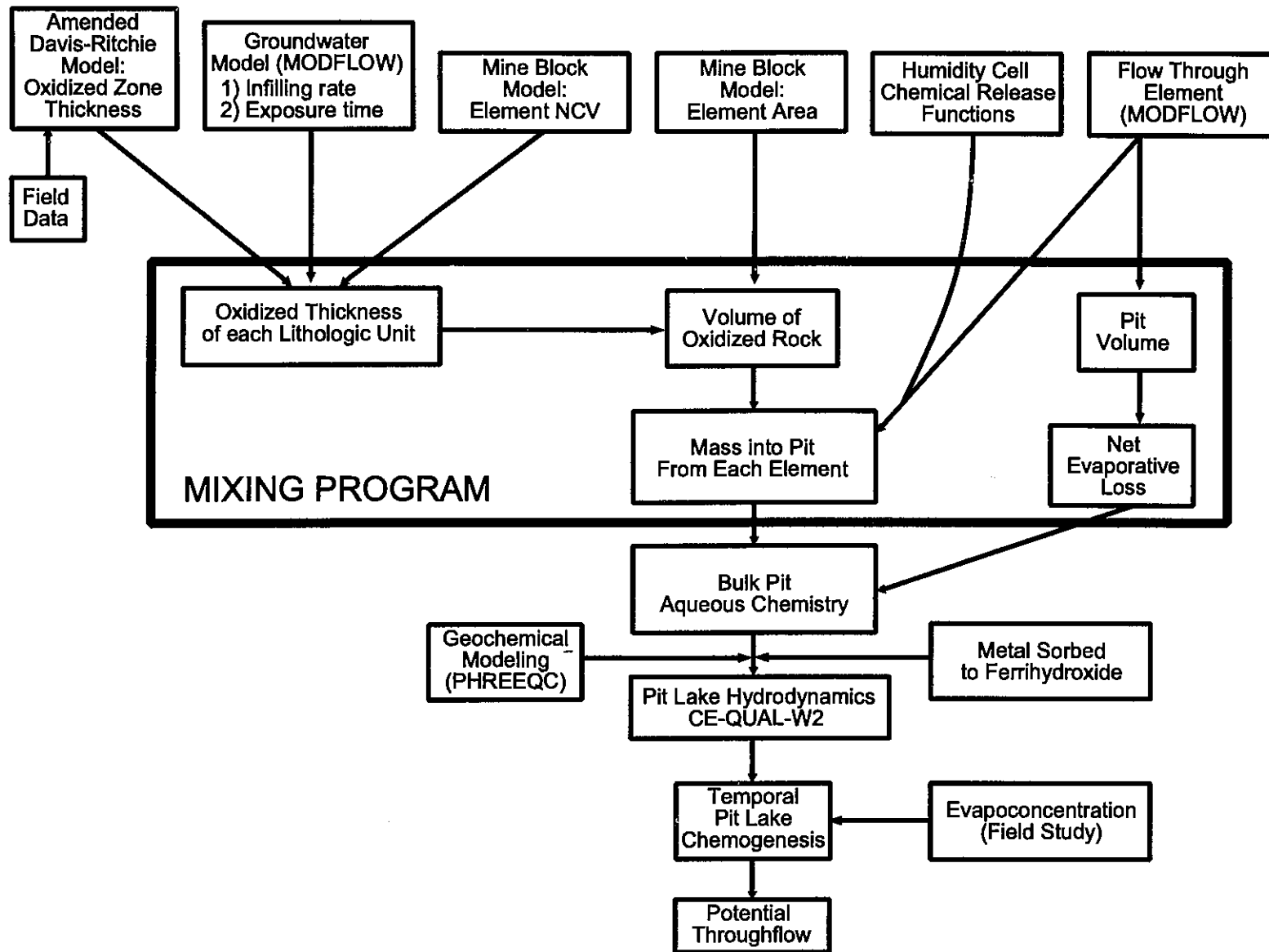


Figure 2

- the possibility of land subsidence due to groundwater withdrawals.

A primary objective is to incorporate into the groundwater model all significant hydrogeologic features of the basin, both natural and anthropogenic. Hence, a finely discretized grid is necessary both laterally and vertically in the vicinity of these features. Specific characteristics derived from the baseline characterization include:

- the spatial variation of bedrock geologic units,
- the hydraulic influence of faults, and
- the hydraulic communication between the alluvial material and the underlying bedrock.

The flow system geometry and boundary conditions are characterized using the information obtained from the Baseline Hydrogeologic Characterization resulting in generation of a conceptual hydrogeologic model that includes:

- definition of boundary conditions,
- identification of hydraulically significant features (faults, etc.),
- identification and assignment of hydro-lithologic units, and
- spatial discretization of the model domain.

The baseline characterization would provide hydrogeologic and hydrologic parameters, including hydraulic conductivity, porosity, specific storage, and/or specific yield (i.e., storage coefficients), flow barrier fault properties, flow conduit fault properties, and recharge and evapotranspiration rates. These parameters represent inputs to the ground water flow model (often MODFLOW; WHS, 1988) that is used to predict groundwater quantity and flow conditions.

Model Calibration and Verification

The model is initially calibrated by matching the predictions to observed historical steady-state groundwater conditions (i.e., prior to start-up of dewatering operations). Calibration targets typically include observed groundwater elevations in wells throughout the area, and estimates of groundwater water fluxes into and out of the model domain. The process continues with transient calibration because predictive simulations of pit dewatering and refilling are time-dependent.

Model Simulations and Predictions

When a calibrated model that accurately represents the groundwater flow conditions has been achieved, predictive simulations including dewatering of the pit during mining and refilling of the pit after mining is complete can be performed. Model runs should conclude a determinant of when approximate steady-state conditions (representing pit lake maturity) have been re-established following the cessation of mining.

Important model results should include, 1) the magnitude and areal extent of the regional water, 2) drawdown at the end of the dewatering period, 3) dewatering rates, 4) impacts to seeps and springs, 5) the water table recovery rate after cessation of pumping, 6) estimates of water fluxes into the pits from different geologic units, and 7) rates of throughflow of groundwater after the pits have filled. The results of the simulations should allow identification of potential impacts due to mining, and analysis of alternatives to eliminate or mitigate these effects. For example, transient simulations would provide time-dependent boundary conditions to test the potential for land subsidence due to dewatering.

Modeling Pit Lake Chemistry

The predicted water quality of a pit lake is a function of the chemical compositions and proportions of the infilling solutions, chemical reactions between the lake waters and the wall rocks, chemical reactions in the lake water, and the degree of mixing from seasonal overturn of the water column. The relative contribution of each factor to pit lake chemistry changes over time as the pit reaches isostasy. The steps required to model pit lake chemistry (Figure 2) involve, 1) generation of chemical release functions, 2) pyrite oxidation modeling, 3) bulk pit lake chemistry, 4) dissolved pit lake chemistry, 5) hydrodynamic modeling, and 6) analysis of the potential pit lake throughflow into adjacent groundwaters.

Task 3. Coupling of Groundwater Flow and Geologic Block Models

The chemical releases from the UPS wall rock into the pit can be determined from a geologic block model which identifies the quantities, locations, and potential acid generation based on the net carbonate

values (NCV's) of the various rock types. The coupling of the groundwater model and the geochemical model requires discretization of the UPS using a grid consistent with both models, allowing correct representation of the volume and chemistry of groundwater infilling the pit.

Task 4: Determine Chemical Release Functions (CRFs)

The NCV model for the UPS defines the lithologic population from which rock samples should be obtained, and subjected either to humidity cell or field oxidation tests designed to simulate leaching of the wallrock in the UPS. The solute leaching curves (chemical release functions) obtained from these tests are combined with data on the depth of the oxidized zone in the UPS from which discharging groundwater will flush the oxidation products to mathematically describe the temporal accumulation of solutes in the pit lake.

Task 5: Computing Wall Rock Oxidation Thickness

The primary sources of acid result from the oxidation of pyrite in wall rock exposed to the atmosphere during excavation and mining. The contribution of oxidized pyrite on pit lake water quality depends on the oxidation rate, presence of neutralizing minerals (e.g., carbonate), and the alkalinity and discharge rate of groundwater flowing through the oxidized material.

Until recently, the traditional approach to model the rate of pyrite oxidation in wall rock has been the Davis-Ritchie approach (Davis and Ritchie 1986). However the equations incorporate simplifying assumptions that do not accurately represent some systems such as open pit mine wall rock where pyrite is incarcerated within a refractory host, and fractures control oxidation rates.

Our approach (Fennemore, Neller, Davis) relaxes the assumption that particles in the oxidizing medium are of uniform size and that oxidation takes place in an aqueous environment where only oxygen limits the reaction. In addition, our amended approach considers the transport of water through the medium and into individual particles and the effect of water content on oxidation rate. Laboratory experiments have demonstrated that a lack of moisture will diminish the oxidation rate (Borek 1994).

Task 6: Compute Bulk Pit Lake Chemistry

In our approach model, the mass of metal leached from the oxidized perimeter wall rock is divided by the incremental volume of groundwater as it inflows into the pit to provide a temporally variant bulk water composition in the evolving pit lake. Hence the relative mass of solutes from each groundwater type can be combined with the wall rock leachate chemistry. Relevant data necessary to complete this task would include:

- location of local and regional wells,
- chemical analyses from the wells,
- screened intervals of the wells, and
- flow from cells in the UPS based on model.

Task 7: Dissolved Pit Lake Chemistry

Geochemical modeling of bulk pit lake chemistry resulting from the groundwater discharge rates, chemical release functions and oxidized zone thickness needs to be speciated, AFH allowed to precipitate, and metals sorbed to reduce the bulk concentrations to a dissolved form as the AFH sequesters metals and settles to the base of the pit lake.

PHREEQC (Parkhurst 1995), an EPA-supported geochemical equilibrium speciation model can be used to compute equilibria among dissolved, adsorbed, solid, and gas phases, and to calculate the pH of a water when bulk chemistry is known. PHREEQC also accounts for adsorption, using site-specific, experimentally determined input data.

Task 8: Hydrodynamic Modeling

CE-QUAL-W2 (Cole and Buchak 1995) can be used to compute the vertical distribution of physico-chemical variables in a pit lake. CE-QUAL-W2 is a two-dimensional, horizontally averaged model, in which the pit lake is conceptualized as a vertical sequence of horizontal layers in each of which thermal energy and materials are uniformly distributed. The model can be used to compute potential anoxia, oxygen profiles, and consequently, the geochemical stability of the AFH floc.

Task 9: Evaluate Possibility of Land Subsidence

The extent of subsidence in a mined area due to dewatering will largely depend on the structural strength of the sediments and rock in the area, and on

the magnitude of the drawdown. Any rearrangement of the skeletal structure of geologic material that may take place due to dewatering will have some lasting effect on aquifer storage properties. Delineation of aquifer compaction due to dewatering can be accomplished using the Interbed-Storage Package in MODFLOW (Leake and Prudic, 1988).

Task 10: Evaluate Potential Degradation of State Waters

In arid climates, where evaporation sometimes exceeds recharge, pit lakes may behave as groundwater sinks. We envision two scenarios for such conditions: 1) groundwater will perpetually recharge the pit lake, precluding throughflow but enhancing evapoconcentration, or 2) throughflow occurs, in which case, constituents in the pit lake may potentially migrate off site.

If groundwater flow modeling suggests that throughflow will occur, groundwater transport modeling may be performed to evaluate potential impacts to off site waters. The numerical code MT3D (Zheng, 1992) is designed to interface with MODFLOW and, therefore, is an appropriate tool for this application. Despite the potential for solute migration in a throughflow condition, the metal concentrations in the pit lake will not be necessarily translate into the surrounding aquifer because, 1) AFH settling on the base and sides of the pit lake may act as a geochemical sponge sequestering metals as water flows from the pit lake into the aquifer, 2) wall rock distal to the immediate pit surface has natural attenuation capacity, and 3) hydrodynamic dispersion acts further to reduce solute concentrations away from the pit lake.

Conclusions

The methodology outlined in this paper provides a brief overview of a proposed strategy for predicting future pit lake chemistry either in fulfillment of the technical requirements for an Environmental Impact Statement, or as part of permitted facility closure. Although the methodology is rather comprehensive, several issues will require further specification. These, include 1) better definition of the constraints on pyrite oxidation in the arid environments and, 2) a more accurate representation of the leachate characteristics in the UPS wallrock. Eventually the predictive models will need to be verified to ensure that they are capable of

simulating the water quality of pit lakes that have reached a steady state in terms of water level and chemistry.

Literature Cited

- Borek, S.L. 1994, Environmental Geochemistry of Sulfide Oxidation, Ch. 3. Effect of Humidity on Pyrite Oxidation, pp. 31-44, American Chemical Society Symposium Series.
- Cole, T. and E. Buchak, 1995, CE_QUAL_W2: A two-dimensional, laterally averaged, hydrodynamic and water quality model, Version 2.0. Instruction Report EL-95, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Davis, G. and A. Ritchie, 1986, A model of oxidation in pyritic mine wastes: Part I, equations and approximate solution. *Applied Math Modeling*, 10:314-322.
[https://doi.org/10.1016/0307-904X\(86\)90090-9](https://doi.org/10.1016/0307-904X(86)90090-9)
- Geomega, 1997a, South Operation Area Project: Gold Quarry Pit Lake Prediction. Prepared for Newmont Gold Company.
- Geomega, 1997b, South Pipeline Project: Pit Lake Water Quality Prediction. Prepared for Cortez Gold Mines.
- Leake, S.A. and D.E. Prudic, 1988, Documentation of a computer program to simulate aquifer-system compaction using the modular finite-difference groundwater flow model. U.S. Geological Survey Open File Report 88-482.
- McDonald, M.G. and A.W. Harbaugh, 1988, A modular three-dimensional finite-difference groundwater flow model, U.S. Geological Survey Techniques of Water-Resources Investigation, Book 6.
- Parkhurst, D.L., 1995, User's guide to PHREEQC - a computer program for speciation, reaction-path, advective transport, and inverse geochemical calculations, U.S. Geological Survey Water Resources Investigation Report, 95-4227.
- Zheng, C. 1992, MT3D: A Modular Three-Dimensional Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems. S.S. Papadopoulos & Associates, Inc.