A Rational Approach to Pit Lake Chemistry Modeling

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Abstract Pit lake modeling can be complex due to the need to consider the water/rock interactions with the lithology exposed on the final pit walls and with any backfill material. Taking a systematic and iterative approach to pit lake modeling will ensure the proper level of detail and more accurate predictive results are generated. Developing a pit lake model in a stepwise method (conceptual model to "general" system representation to a detailed spatially representative statistically based model) allows for the model to be aligned with the level of detail of the data and the complexity of the scenario.

Keywords Pit Lake, PHREEQC, Geochemistry, POSTGRES, Groundwater, Mine Closure

Introduction

Several approaches to pit lake modeling have been utilized, that while yielding generally grossly comparative results, can result in subtle differences in the final pit lake chemistry. These differences are due either to considering or ignoring spatial chemical variability in wall rock materials, runoff solutions, groundwater solutions, and pit lake waters. For a sound, representative model water chemistries, pit wall, and backfill material need to be consider material type, spatial parameters, and overall chemical (particularly ARD/ML) parameters. These are used to develop the probable pit lake chemical behavior and composition from inception through post-closure, as well as provide source term inputs for numerical models. For many projects, the quantity and quality of data available may be such that the model of the pit lake cannot be developed beyond the conceptual model phase. Even at this stage, the model can provide some information about the potential for geochemical risk. Whenever possible, the GIS component should be applied and averaging, or lumping parameters should be avoided.

Developing a sound pit lake model requires significant amounts of data, often more than what most investigators utilize. In most cases, the model only utilizes the "average or generalized" groundwater chemistry and the zonal leachate chemistry of each rock type, along with the effective area (volume) of rock exposed on the pit wall as well as backfill within the pit. Such aqueous calculations are carried out using geochemical modeling packages such as the United States Geological Survey (USGS) PHREEQC software (Parkhurst and Appelo 1999). This type of model results in a simplified pit lake chemistry that can be a good approximation of the system, especially where limited data exists. For many projects, such a model will provide enough detail to develop water management and permitting strategies. However, the complex nature of these systems may require additional detail to fully characterize the long-term behavior of a pit lake. Using detailed spatial information to model groundwater/wall rock interactions, along with localized differences in the chemistry of the wall rock and backfill materials, results in a more detailed picture. Additionally, by taking into account chemical processes such as dissolution, precipitation, and colloidal formation, as well as utilizing a statistical representative number of static and kinetic samples that also spatially representative, a more defensible and accurate pit lake model will ensue. Application of GIS then becomes a preferred and necessary step in fine tuning the overall model.

Conceptual Model Method

Regardless of the complexity of the system and the data available, the first step in understanding the long-term behavior of a post closure pit lake is the development of a conceptual model of the system, including all water and chemistry inputs and outputs. Prior to mining, groundwater is generally in equilibrium with the country rock. As the groundwater passes through the ore body, natural concentration gradients might exist in the pre-mining stage. Once mining commences, the normal flow of groundwater is disrupted often resulting in changes in flow dynamics. After the completion of mining and cessation of dewatering the rate of pit filling and stage of the pit lake will be controlled by the post-closure water balance. Conceptually, the post-closure water balance can be expressed as:

$$\Delta_{\text{pit lake volume}} = I_{\text{precip}} + I_{\text{run-off}} + I_{\text{pit run-off}} + \text{GW}_{\text{inflo}} - E_{\text{pit}} - \text{GW}_{\text{outflow}} - \text{SW}_{\text{outflow}}$$

Where:

I_{precip} inflow from direct precipitation falling on the lake surface;

$I_{\text{run-off}}$ inflow from run-off from up-gradient drainages;

$I_{\text{pit run-off}}$ inflow from pit wall run-off (the fraction of precipitation falling on the pit walls that ultimately reaches the pit lake);

$\text{GW}_{\text{inflow}}$ groundwater inflow to the pit lake;

E_{pit} open water evaporation from the pit lake surface based on a pan or estimated evaporation rate;

$\text{GW}_{\text{outflow}}$ outflow of groundwater from the pit lake; and

$\text{SW}_{\text{outflow}}$ outflow from surface water from the pit lake.

The interaction between these parameters is presented schematically in Fig. 1.

Understanding the geochemical reactions of mined rock and water interactions is critical in assessing the potential for mining projects to adversely affect the quality of the surrounding environment. There are two different classes of mine drainage that might impact water quality:

- Alkaline drainage (basic pH water that may contain elevated total dissolved solids (TDS), oxy-anions such as arsenic and selenium);
- Neutral pH (that may contain elevated TDS and metals that remain soluble at neutral pH such as zinc, nickel, and sometimes copper); and

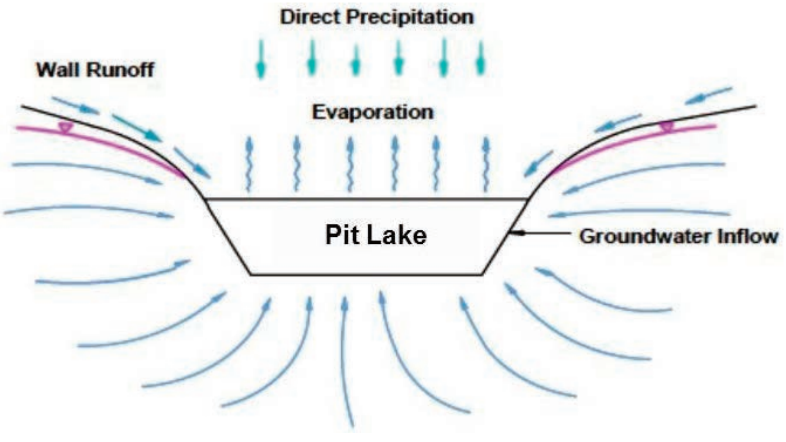


Fig. 1 *Post Closure Pit Lake Water Balance.*

- Acid drainage (acidic pH water that usually contains elevated aluminum, iron, manganese, copper, and other metals).

During the mining stage atmospheric oxygen, humid air, run-off, and precipitation can impinge on the wall rock and produce local zones of ARD/ML allowing for the buildup of metal salts on and in the wall rock surfaces. As the pores within the wall rock are resaturated they can react with the pit wall runoff or lake water at alter the chemistry. The hydration of stored salts and acids in the pore rock can be significant, with near instant additions of acidity as well as metals to groundwater as well as pit lake waters. Similarly carbonate dissolution with an increase in alkalinity may occur depending upon the particular litho-chemical environment.

Simple Numeric Modeling Method

Numeric modeling can act as a useful tool in addressing potential future impacts of mining facilities (Zhu and Anderson 2002). The use of computer modeling codes provides a way to quickly test a variety of scenarios for a particular system. The results are a quantitative estimate of the system that can be used to identify key parameters and understanding of the system.

Mining facilities are complex systems that need to be addressed with a multidisciplinary approach. Therefore, numerical modeling of a post closure pit lake development can require multiple modeling platforms and methods to be utilized. Hydrologic modeling can be used to establish a water balance of this system, which provides information about the quantities, as well as the interactions, of the water inflows and outflows in the affected areas. Hydrogeologic models can be applied to simulate dewatering systems, pit filling, facility/groundwater interactions, and fate and transport of any impacts to the groundwater. Limnological modeling can be a key component in a predictive modeling study to define the lake's physical behavior or temporal. Finally, the geochemical modeling is used to determine the overall water chemistry of the pit lake's life.

By integrating different modeling disciplines into a site-wide model, the system can be tuned to generate a more realistic characterization. This type of a modeling approach by its nature is extremely data intensive and one often resorts to some simplifying assumptions and data averages.

Such simplification should be avoided if at all possible as the use of a highly integrated approach can provide a complete understanding of the pit lake system over time as well as better predict potential environmental issues that may arise.

Spatially Distributed Data Modeling Method

In larger mining projects and more complex systems modelers may have access to large quantities of data, which if spatially distributed, results in a more detailed model. As with the previous numerical modeling discussed, spatially distributed data modeling relies on multiple disciplines to provide a more detailed pit lake model. For this type of modeling, several components are required. First, an accurate mapping of differences and character of groundwater chemistry spatially around the pit is paramount. As mining ceases, the cone of depression that was generated during dewatering around the pit will rebound. Initially, at least, this water will encroach on the pit from all directions. Fig. 2 illustrates two of the many possible variations that may be encountered in the geologic settings and thus the groundwater chemistry near an ore body. By utilizing the models such as those shown in Fig. 2, it can be seen that infilling water may exhibit differing chemistries depending on whether it is migrating from upgradient or down gradient areas.

In that the chemistries of the groundwater may be different depending on the local character of country rock adjacent to the pit, using an averaged groundwater composition, as is commonly done in traditional pit lake

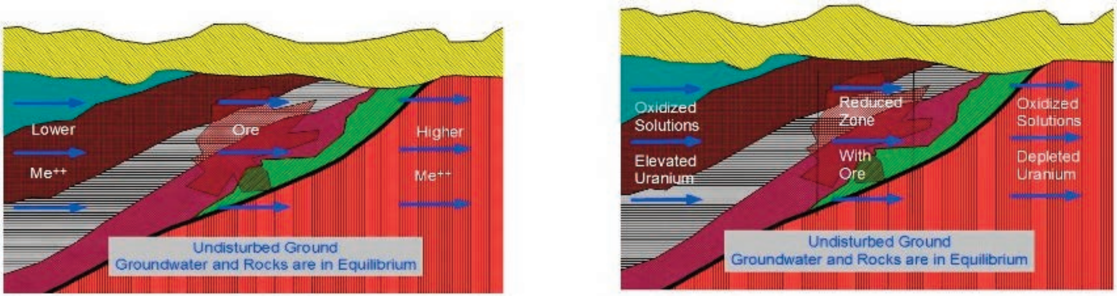
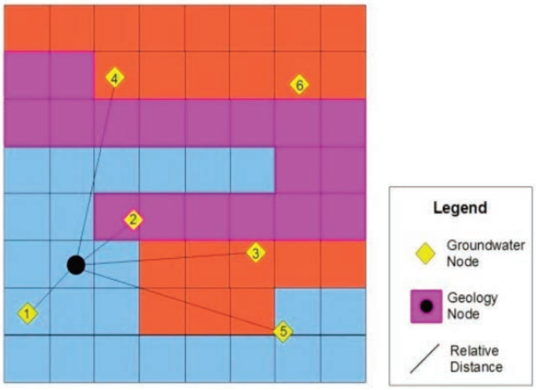


Fig. 2 *Groundwater Character Prior to Mining*

models will result in an inaccurate model. Rather, using spatially distributed modeling methods to define the groundwater chemistry, based on well data and the proximity to those wells to the wall rock (Richers *et al.* 2012a) is a better approach. Utilizing lake filling models such as those derived from the MODFLOW LAK2 or LAK3 packages will allow groundwater nodes to be defined to relate sources of flow relative to wall rock geology. By coupling these models with Geographic Information Systems (GIS) the spatially defined wall rock interactions with the groundwater regime can be utilized (Richers *et al.* 2012b). This flow can then be partitioned among its nearest wall rock cells using some spatial weighing method such as a simple inverse square distance function. In effect, this allows one to assign a measured influence between groundwater nodes and a wall rock geologic cell; those closer would have influence than would more distal groundwater cells (Fig. 3). By defining the chemistry of the groundwater to specific model nodes, spatial differences can be better accounted for and possible localized chemical reactions and processes that otherwise might be overlooked can be included in chemical management considerations.

By carefully integrating the localized groundwater chemistry interaction with the pit walls, reactions that might otherwise be ignored or misrepresented in an averaging approaches to modeling may be realized. Also, depending upon the detail in the groundwater model, areas of localized higher flow, such as along fracture systems or higher porosity zones can be identified. Additionally, areas of preferentially higher chemical reactivity, as well as the inverse, may be identified and exhibit can be simulated to allow prediction of the expected chemical interactions between groundwater and wall rock.

The wall rock composition of the Ultimate Pit Surface (UPS) is also an important data requirement for spatially distributed data models (Moran and Richers 2011). Generally, a geologic block model of the lithology is merged through a GIS application to show the geology on the UPS. This provides a means to ascertain



Weighted Distance (Wi) Is Determined as:

$$W_i = \frac{\left[\frac{R-h_i}{Rh_i}\right]^2}{\sum_{j=1}^{n}\left[\frac{R-h_j}{Rh_j}\right]^2}$$

Fig. 3 *Inverse Square Distance Weighing Example.*

relative proportions of rock types on the UPS and allows for calculating exposed areas of each rock cell. The accurate definition of the spatial extent of the UPS is an essential step in the process and should be made with great care. Generally a slope correction is applied to this surface to adjust the exposed area to represent actual areas of the horizontal or vertical exposures. Similarly, rather than utilizing an average wall rock chemistry, lithologically defined source terms are spatially applied to the UPS. This allows detailed groundwater-wall rock interactions potentially resulting in the dissolution/precipitation of species from the solution to be evaluated spatially throughout the pit. When averaging rock types, these local reactions are often missed resulting in a subtle, but distinctly different chemical outcome of the model, as well as potentially overlooked mitigation strategies.

Fig. 4 depicts what a typical groundwater node location map might look like relative to the UPS. Each node is defined over all time steps of the model to determine the flux of the groundwater into (or out of) the pit lake. This will vary over time and will help to define the geochemical inputs and mixing requirements of subsequent geochemical modeling. Geostatistical modeling software is used to derive the geologic input from evaluating many thousands of lithologic data points in 3D space and applying an appropriate 3D Kriging model. The resulting map is then used to correlate the chemical results of representative samples to the static chemical tests, kinetic tests, or both. It should be noted that the assignment of the chemical results of the formation sample that most closely matches the UPS geology node is required. It is not unusual for a given formation to exhibit acid generating character at one location and show a completely different character at another location. Having sufficient geochemical samples to track this reduces the overall uncertainty related to the simulated model predictions.

As with more traditional pit lake modeling approaches, the water chemistry conditions over time are predicted using PHREEQC (Parkhurst and Appelo 1999) or a similar geochemical modeling program. Utilizing software specific to geochemical simulations allows for a robust evaluation of the expected geochemical process, such as dissolution/precipitation adsorption, and speciation, to be applied to the spatially defined water-rock interactions. In that such an approach often is data

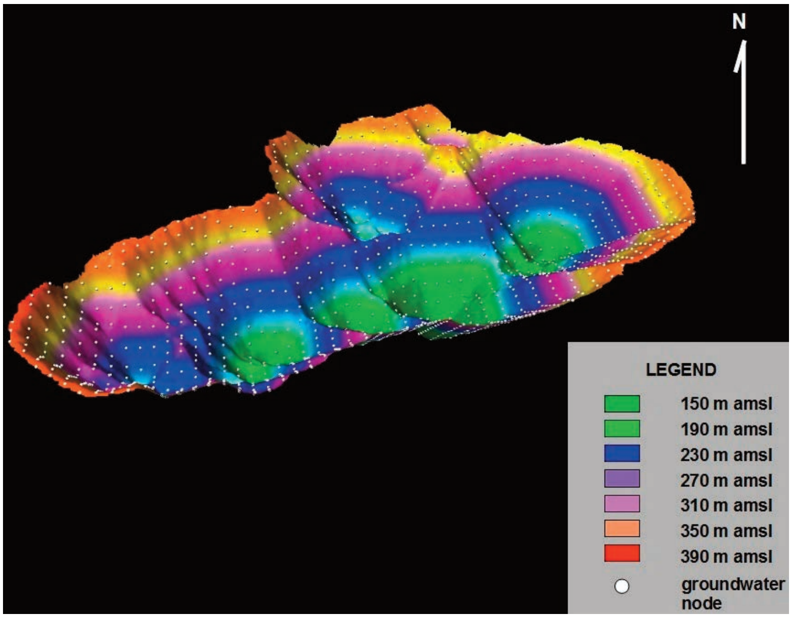


Fig. 4 *Mapping Groundwater Nodes to UPS*

intensive, input and output data from the geochemical modeling program, as well as all pertinent GIS data relationships are stored in a POSTGRES database and extracted utilizing customized scripts. Depending upon the complexity of the groundwater model and the size and nature of individual geologic cells, the model may involve several hundreds of thousands to millions of calculations that are better suited in customized computer programs rather than traditional chemical accounting techniques.

Conclusions

Pit lake systems can have a significant amount of complexity, but understanding the limitations of the quality and quantity of the site data that is available and developing appropriate pit lake models is critical to properly managing these post closure features. Applying a stepwise approach to the modeling allows for the model to be aligned with the level of detail of the data and the complexity of the scenario. For early phase projects and sites with limited data, pit lake modeling may be limited to a conceptual model defining the expected water balance components and general geochemical character of the geologic setting. This can provide a basic understanding of the geochemical risk, but will not allow for development of management strategies.

More traditional numeric models can be powerful tools used to develop and understanding of the level of geochemical risk, as well as to develop mitigation and management solutions. Numerical modeling can be very data intensive, forcing most post closure pit lake models to be based on a limited data set and many simplifying assumptions. However, by carefully integrating the spatial distribution of the information, the pit lake model can be used to evaluate localized, but often important chemical reactions that might otherwise be overlooked. Utilizing geologic block models and integrating the UPS with the geochemical characterization provides for a means to develop a more detailed and spatially distributed model of the long-term conditions of a post closure pit lake.

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