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Hydrogeological and Geochemical Aspects of Lakes Forming in Abandoned Open Pit Mines

G. D. Vandersluis, V. Straskraba, and S. A. Effner

Hydro-Geo Consultants, Inc.
165 South Union Boulevard, Suite 400, Lakewood, Colorado 80228

ABSTRACT

The formation of lakes in abandoned open pit mines has become an increasingly important topic to mine owners, environmental groups, and regulatory agencies. Questions about potential water quality and the elevation to which pit lakes will fill often need to be addressed in the planning or in the early stages of mine development. In response to this concern, a method for estimating the rate of pit lake formation and the potential quality of water in the lake is presented in this paper.

The rate of pit lake formation and the equilibrium level to which pit lakes will rise can be estimated using simple analytical methods and a spread sheet program. At equilibrium, the level of pit lakes will fluctuate with seasonal variations in precipitation, evaporation, and runoff. This fluctuation can be estimated using water balance calculations. Water quality in pit lakes is influenced by several factors including lake morphology, the quality and quantity of water flowing into the pit (ground and surface waters), evaporative concentration of solutes in the lake, residence time of lake water, the availability of reactive mineral species, and biological processes. Geochemical modeling based on physical parameters and water-rock interactions can be used to estimate the future water quality of lakes forming in abandoned open pit mines. Hydrogeological, limnological, geochemical, and biological aspects of pit lake formation are included in the discussion as well as a case study of an open pit in the western United States which has already begun to fill with water.

INTRODUCTION

Within the next 20 to 30 years almost 50 open pit mines which intercept the ground water table will be completed in the United States. In Nevada alone, the closure of open pit gold mines during the next 20 years is expected to result in the formation of approximately 40 lakes (Lyons et al., 1993). Because of the potential for poor quality water in these lakes, there is acute interest in being able to predict the rate of formation and the potential environmental consequences of these systems. Many models are currently being developed to predict pit lake formation and water quality in these lakes, but at present, no standardized method exists. Rigorous attempts have been made to predict the geochemistry of pit lakes, but in most cases, available data are insufficient to support this type of analysis. Given the complexity of hydrogeologic and biogeochemical systems, predictions from even the most rigorous models which incorporate enormous amounts of geologic, hydrologic, and geochemical data, involve some degree of uncertainty. In many cases, a simple approach which uses available data or requires a minimum of additional data will yield answers which are sufficiently accurate for mine planning or closure requirements. In the following sections, a method for modeling the rate of pit lake formation and the potential quality of water in the lake is presented which can be adapted to site specific requirements. Included, are discussions about the physical aspects of pit filling, the limnology of pit lakes, the chemistry of water-rock interactions, and biogeochemical processes which operate in pit lakes.

PHYSICAL ASPECTS OF PIT LAKE FORMATION

There are several different approaches to modeling the formation of pit lakes. Although the approach used may vary from site to site, in general, there are six major components or steps required to complete a pit-filling study. These components include analysis of the available data (geologic, climatic, hydrologic, and hydrogeologic), determination of the physical pit parameters, estimation of the pre-mining potentiometric surface, calculation of the rate of pit-lake formation, determination of the average seasonal lake level fluctuations, and the geochemical modeling of the long-term water quality and chemistry of the pit lake.

Analysis of Available Data

Analysis of the geologic data includes, but is not limited to, a review of the regional geologic setting and site specific geology. Site specific geology should include structural information about faults and joint patterns which affect ground water flow in the pit area, information regarding mineralogy and hydrothermal alteration of ore, waste, and unaltered host rocks exposed in the pit, and stratigraphic or lithologic information obtained from exploration drilling. Acid-base accounting (ABA) and humidity cell data for ore and waste rock are often available early in the mine planning process. If available, these data should be incorporated into the conceptual model. Climatic information should include regional and site-specific data regarding seasonal variations in temperature and precipitation, including the type, amount, frequency, and duration of precipitation on a monthly basis. Snowfall and snowmelt information are important in colder climates, and monthly pan or lake evaporation data are necessary to perform water balance calculations. Hydrologic data should include the effective size of the run-off area, the directions and amounts of surface flows entering the pit, the estimated runoff coefficient for the catchment area, and the types and amounts of vegetation and soils surrounding the pit. Hydrogeologic information should include the effective hydraulic conductivity for each of the stratigraphic units or rock types exposed in the pit, as well as data regarding water quality, hydrostatic head and direction of flow for each water-bearing unit.

Physical Pit Parameters

The size and shape of the pit will influence both physical and geochemical aspects of pit lake formation. To calculate the rate at which the pit will fill and the level to which it will ultimately rise, the extent and volume of the pit must be calculated for each individual mining level below the pre-mining potentiometric surface. In many cases, depending on the accuracy desired, it is possible to combine two or more levels for this calculation by using the total thickness and the average estimated circumference of the combined intervals. Information regarding the areal extent and volume of the pit can be obtained from topographic maps, bench-level maps, or mine plan maps using a digitizer and computer aided drafting system to calculate areas and volumes, or by measuring areas by planimeter. Most mining operations have detailed planning maps showing the projected extent of the open pit during and after the completion of mining. These maps can be used for pit-filling studies that are conducted before mining commences.

Estimation of the Pre-mining Potentiometric Surface

Accurate estimation of the pre-mining potentiometric surface is essential for pit filling calculations. In the best scenario, information about pre-mining ground water levels can be obtained from hydrogeologic studies which were conducted before mining commenced. Most recent mining operations have a wealth of data which can be obtained from dewatering wells, monitoring wells, or hydrogeologic studies completed before the start of mining or dewatering operations. In this case, it is relatively easy to construct a potentiometric surface map of pre-mining conditions. In areas where hydrogeologic investigations were not completed prior to mining, the task is more difficult, and other sources of data for the pre-mining ground water level become important. Information from exploration or grade-control boreholes can be used if the driller or geologist has noted where water was first encountered in the boreholes, and the approximate volume of ground water flow into the boreholes during drilling. Caution must be used to avoid using perched water tables as the original potentiometric surface for inflow calculations. The converse situation, choosing a water level below the pre-mining potentiometric surface, must be avoided in areas where hydraulic conductivity is very low, and water in the borehole is not be noted until the drill penetrated several meters below the potentiometric surface. Additional information may also be obtained from mining records which note when and where water was first encountered during the pit excavation.

Estimating Pit Inflows and Outflows

To estimate the rate of pit lake formation, it is necessary to define the major sources of water inflow and outflow. The most important sources of water inflow are direct precipitation on the lake surface, surficial runoff of water from the pit watershed, and horizontal or vertical inflow of ground water from bedrock or alluvium. The contribution from each of these sources is dependent upon site specific conditions. The two most important sources of water discharge from pit lakes are evaporation and seepage. As before, the loss from each of these sources will depend on site specific characteristics. It is important to note that the contribution or loss from any of the sources listed above will not remain fixed as the pit fills with water. In general, as the pit fills, the difference in elevation between the pre-mining potentiometric surface and the lake surface will decrease. This reduction in hydraulic head will cause the rate of ground water inflow to the pit to decrease over time. The size of the runoff area on the pit walls and the contribution from surface runoff will also decrease. Evaporative losses from the lake surface will increase as the pit fills, and an increasingly larger proportion of water inflow will occur by direct precipitation on the lake surface.

For mining operations in arid and semi-arid regions where precipitation is limited, inflow to the pit will be primarily by horizontal ground water inflow. Ground water inflow will be greatest from geologic units with the highest effective permeability and hydraulic head. Horizontal ground water inflow to a specific pit level can be calculated using large well equations based on Dupuit assumptions for radial steady state flow to wells fully penetrating an aquifer. The following equation is for flow in an unconfined aquifer (Maximov, 1967).

$$Q=\frac{1.366K(2H-s)s}{Log(R+r_0)-Logr_0}$$

Where:

Q = ground water inflow to an open pit (m^3/day);
K = hydraulic conductivity (m/day);
H = potentiometric surface (m);
s = drawdown in the aquifer (m);
R = radius of influence (m); and,
r_0 = reduced radius of the open pit by level (m).

The radius of influence (R) can be calculated using the Kusakin equation (Dobrzanski, 1956):

$$R=575s\sqrt{HK}$$

Where: R = radius of influence (m);
s = maximal drawdown (m);
K = hydraulic conductivity (m/sec);
H = potentiometric surface (m); and,
r_0 = reduced radius of the open pit by level (m^2).

The reduced radius of the open pit (r_0) is equal to:

$$r_0=\sqrt{\frac{A}{\pi}}$$

Where: A = circular area of the open pit by level (m).

This method of calculating ground water inflow to an open pit has been used by the authors on many mining projects, and has proven to be quite accurate given reasonably correct values of aquifer hydraulic parameters. Hydraulic parameters needed for this analysis include the effective hydraulic conductivity of each bedrock unit and the hydrostatic head for each contributing aquifer. This information is often available from packer permeability testing of boreholes, slug tests which have been performed in monitor wells (rising or falling head tests), or aquifer pumping tests for mine water supply or dewatering operations.

Precipitation can also be an important component of pit filling. Direct precipitation can contribute several hundred cubic feet of water per day to the lake. The volume of water contributed by direct precipitation is calculated by multiplying the amount of precipitation by the area of the pit lake surface. Data for this contribution are usually taken from monthly and annual records.

Inflow from runoff can be important in several situations. Runoff can contribute significant volumes of water to pits with large drainage areas or pits with drainage areas that are particularly steep. Runoff can also be important in rocky areas where there is little topsoil or vegetation to retard surface runoff into the pit. The contribution from runoff is calculated by multiplying the area of the pit drainage basin by the monthly or annual precipitation and by a runoff coefficient which is derived for a particular situation.

Evaporation, especially in arid regions, is often the greatest source of discharge. In many areas, the annual evaporation from pit lake surfaces is large enough to draw down the premining potentiometric surface by several hundred feet around the lake. Evaporation from the pit lake is calculated by multiplying the area of the lake surface by the monthly or average annual pan or lake evaporation.

Seepage through the downgradient face of the pit in areas with steep topography and/or steep ground water gradients can also account for significant discharge. In some areas post-mining topography is radically different from the pre-mining topography and pit lakes can discharge to surface waters. Seepage from the pit is generally becomes important as the lake approaches its equilibrium level.

Calculation of the Rate of Pit Lake Formation and Equilibrium Surface Level

The rate of pit filling and the time required for a pit lake to reach its equilibrium level can be calculated using a simple spread sheet computer program. Changes in inflow and outflow as well as the level of the pit lake surface are calculated over time using an iterative approach to converge on a solution. Input to the program consists of the calculated pit areas by level, the incremental pit volumes, the average daily precipitation, the average daily evaporation, the initial runoff area of the pit watershed, and the average rate of ground water inflow by level. The program calculates the net inflow from precipitation, runoff, and horizontal inflow from bedrock, minus the outflow by seepage and evaporation on a daily basis until equilibrium between inflow and outflow is achieved. Output from the program consists of the net rate of inflow to the pit, the time required for the lake to rise to individual levels or elevations within the pit, and the time required for the lake to reach its equilibrium level. After the pit lake reaches its equilibrium level, the surface will fluctuate during the year and between years because of the variation in precipitation, runoff, and evaporation. A simple calculation can be made to determine the monthly fluctuation for a typical year using precipitation and evaporation data. In many situations, lakes begin forming before pit-filling studies are initiated. In this case, it is possible to use actual pit-filling data to calibrate the model and more accurately determine the rate of inflow.

GEOCHEMICAL MODELING OF PIT LAKE WATER QUALITY IN PYRITE OXIDIZING ENVIRONMENTS

Equilibrium geochemical modeling of water-wallrock interactions can be used to predict the chemistry of lake water and evaluate the potential for acidification of pit lakes. Although equilibrium conditions seldom exist in nature, this type of modeling yields results which are sufficiently accurate to be used for mine planning or closure. Several computer models exist to perform calculations for complex chemical equilibrium in dilute aqueous solutions. Two of the most widely accepted are the programs PHREEQE (Parkhurst et al.1983) and MINTEQA2 (USEPA, 1991). A detailed discussion of equilibrium geochemical calculations is beyond the scope of this paper and the reader is referred to Drever (1988), or Garrels and Christ (1965). Depending on the type, quality, and quantity of geochemical data available, the expected water quality of pit lakes can be modeled using either a mass balance or kinetic approach. Several factors will influence the long term quality of water in the pit lake. These factors include: the initial quality and quantity of water flowing into the pit (ground and surface waters); concentration of solutes in the pit lake by evaporation; residence time for water in the pit; the availability of reactive mineral species in the wall rocks; biological processes active in the pit lake; and the ratio of lake surface area to depth.

Physical Limnology of Pit Lakes

With exception of volcanic crater lakes, no natural analogs exist with morphological characteristics similar to lakes forming in abandoned open-pit mines. The steep-sided profile of these lakes will profoundly influence the geochemical and biogeochemical characteristics of these systems by affecting the redox state of the lake water, the residence time of the water rock contact and the type of biological community the lake will support (Lyons et al., 1993). The redox state of the pit lake and the residence time of the water rock contact will be influenced to a large degree by whether or not the lake overturns seasonally. If density stratification of the lake occurs and there is no mechanism to remove it, water at the bottom of the pit lake may become reduced and its residence time could be very long. This will affect the solubility of iron and manganese species as well as the mobility of toxic metals associated with these species. A scaling parameter can be used which compares the lake's surface area to its depth to evaluate whether or not a pit lake will seasonally overturn (Lyons et al., 1993). This parameter is called the Peterson Scaling Parameter (PSP). The Peterson Scaling Parameter is calculated by dividing the surface area of the lake in square kilometers by its mean depth in kilometers. The resulting number can then be compared to other lakes of similar size in similar climates to predict whether the lake will overturn or stratify. Peterson Scaling Parameters for selected lakes are presented in Table 1.

The geometry of the pit lakes will also affect biogeochemical processes operating in the littoral zone. Pit lakes have steep banks with virtually no shoreline or shallow water area. It is expected that there will be limited or no development of a submerged, rooted biological community, and that biological processes will occur predominately in the pelagic zone. The geochemical ramifications of this are that carbon, nutrient, and trace metal uptake and removal will be focused in the deepest portions of the lake. If the biological productivity of the pelagic zone is great, the lake may become chemically stratified, but if the lake is density stratified, nutrients will be rapidly lost from the system and biological productivity will decrease to very low levels (Lyons, 1993).

Redox Conditions

The first step in the modeling process is to establish a rationale for the redox state of water in the pit lake. Many attempts have been made to estimate the Eh conditions of natural waters based on the presence of a master redox couple (i.e. Fe III/Fe II). These attempts have met with varying amounts of success. In general, the Eh values observed in natural waters are measures of mixed potentials, and the use of a single master redox couple to compute Eh may not yield completely accurate results (Lindberg et al., 1984). Because of this, care must be taken to assess the redox sensitivity of the system. In most natural waters, ferrous iron (Fe^{2+})

is the dominant specie of iron at near neutral pH. Under oxidizing conditions Fe^{2+} is rapidly oxidized to Fe^{3+} which precipitates as amorphous ferric hydroxide.

TABLE 1
Peterson Scaling Parameters for Selected Lakes

Name	Location	Lake Type	Stratification State	Surface Area (km²)	Mean Depth (km)	Peterson Scaling Parameter (km)
Pyramid(1)	Nevada	Closed Basin	Seasonally Stratified	438	0.058	7.5×10^3
Walker(1)	Nevada	Closed Basin	Seasonally Stratified	132	0.020	6.6×10^3
Tahoe(1)	California	Tectonic	Well Mixed	500	0.249	2.0×10^3
Big Soda(1)	Nevada	Volcanic Crater	Permanently Stratified	1.6	0.026	6.1×10^1
Blue(1)	Australia	Volcanic Crater	Well Mixed	0.6	0.070	0.9×10^1
Caliente(1)	Nevada	Volcanic Crater	Well Mixed	0.05	0.020	0.2×10^1
Berkeley(2)	Montana	Pit Lake	Permanently Stratified	2.5	0.242	1.0×10^1
Betzy(1)	Nevada	Pit Lake	?	1.4	0.169	0.8×10^1
Case Study	Western U.S.	Pit Lake	Well Mixed	0.03	0.04	0.8×10^0
-	Western U.S.	Pit Lake	Well Mixed	0.01	0.04	0.3×10^0

1. Lyons et al., 1993
2. Davis et al., 1993

The half time of this reaction is approximately 18 minutes (Hem, 1992). Oxidation and reduction processes that involve sulfur species are inclined to be slow unless mediated by microorganisms. The rapid rate of the $Fe^{2+} \rightarrow Fe(OH)_3$ reaction suggests that the FeII/FeIII will be the master redox couple in the pit water and that redox equilibria will be controlled by the precipitation of ferric hydroxide $Fe(OH)_3$ and not by the oxidation of pyrite which is kinetically limited. Because of the uncertainty associated with redox equilibria, it is recommended that a range of possible Eh values be used to assess the sensitivity of the system, and that model results be reported as a range of possible values unless site specific data are available.

Inorganic Geochemical Processes and Acidification of Pit Lakes

Acidification of pit lakes and the resulting increases in heavy metal concentrations have been demonstrated to be the result of pyrite oxidation (Nicholson, 1988, and Bierens de Haan, 1991). Pyrite oxidation is a complex process which involves a number of reactants and products. In alkaline waters, the complete oxidation of iron and sulfur is described by the following simplified reaction:

$$FeS_2(s) + 15/4O_2 + 7/2H_2O \rightarrow Fe(OH)_3(s) + 2SO_4^{2-} + 4H^+$$

In buffered waters where carbonate is present in sufficient quantities to maintain near neutral pH, the overall oxidation reaction can be represented by:

$$FeS_2(s) + 15/4O_2 + 7/2H_2O + 4CO_3^{2-} \rightarrow Fe(OH)_3(s) + 2SO_4^{2-} + 4HCO_3^-$$

In this case, acid generation is balanced by acid consumption and the pH remains near neutral. The net products of this reaction are bicarbonate, sulphate, and ferric hydroxide precipitate (Nicholson et al., 1988). The partial pressure of atmospheric carbon dioxide will also affect the solubility of calcium carbonate in the pit-lake and the various waters contributing to the lake. This must be considered in the geochemical model.

Pyrite oxidation and acid generation in the pit lake will be affected by several factors which will determine the rate and completeness of this reaction. It is generally accepted that bacterial catalysis is responsible for the rapid acidification of natural waters in pyrite oxidizing environments, and that oxidation proceeds relatively slowly in the absence of a biological mediator (Nicholson et al., 1988). The rate of pyrite oxidation will be affected by the presence of carbonate minerals contained in the wall rocks which will buffer the pH of the pit water. Studies indicate that abiotic, and neutral pH, biologically mediated rates of oxidation are much slower than rates produced by acidophilic bacterial catalysis at low pH (Nicholson et al., 1988). Accumulation of sediments on the pit floor will decrease the rate of pyrite oxidation by limiting the availability of sulfide minerals to oxidized water. The rate of pyrite oxidation and acid production is expected to decrease significantly with time by the formation of oxide coatings on pyrite grains which will reduce the amount of available reactive surface area (Nicholson et al., 1988 and 1990, and Bierens de Haan, 1991).

Model Inputs

The second step in the modeling process is to determine the quantities and geochemical characteristics of the various sources of water entering or leaving the pit. As discussed earlier, inflow to a pit lake will be by surface water runoff, ground water seepage, and direct precipitation on the lake surface. Outflow from the pit will occur by evaporation and seepage. The volumes and percentages for each source of inflow and outflow can be obtained directly from the pit filling calculations.

Ground water quality for each lithology contributing water to the pit should be obtained from monitor wells located as close to the pit as possible. For most models, the average analyses for dissolved constituents in ground water from each rock type are used as starting input. In many cases, analyses for trace metals in ground water samples are below the detection limit. These analyses should be assigned a value equal to ½ of the detection limit. Surface water runoff is usually of poorer quality than ground water. Pyrite exposed on the pit wall is subject to rapid oxidation and intermittent surface flows will flush oxidation products into the pit lake. Water quality for surface runoff can be approximated using humidity cell data, or if humidity cell data for wallrocks is not available, surface runoff can be approximated by degrading the average composition of the ground water by two standard deviations and using this as input to the geochemical model. Direct precipitation falling on the lake surface is generally of good quality. Pure water in equilibrium with atmospheric CO_2 can be used to simulate the contribution to the lake from this source.

Outflow from a pit lake will occur by evaporation and seepage. Evaporative concentration of the lake can be modeled by removing pure water from the reacting solution and replacing it with inflowing waters in the correct proportions. Outflow by seepage can be modeled in much the same way by removing the appropriate amount of reacting solution and replacing it with the correct proportions of inflowing waters. The addition, subtraction, and mixing of waters for the pit lake geochemical simulation can be accomplished using the computer program PHREEQE (Parkhurst et al.1983).

Modeling Approach

Based on pyrite oxidation reactions and carbonate equilibria, a model for the potential evolution of pit lake water quality can be developed. One of two modeling approaches is recommended depending on the type of data available and the purpose of the model. The first approach is mass balance based, and uses acid-base accounting data to estimate the potential degradation of water in the pit as pyrite contained in the pit wall is oxidized. For this approach, the total volume of pyrite contained in a shell of wallrock in contact with the pit lake is allowed to react with lake water. The thickness of the reactive shell will vary depending on fracture spacing, rock type, and blasting techniques; but in general, it is proposed that allowing all of the pyrite contained in a one to three-foot-thick shell of wallrock to react with the lake will provide a conservative estimate of the potential degradation of water quality which could occur by this process. In reality, the oxidation front for pyrite could extend as far as 15 feet into the wall rock (PTI, 1993), but for the most part, oxidation will occur mostly along fractures and exposed surfaces, and will be incomplete in the majority of the rock. Given this scenario, reacting all of the pyrite contained in a one to three-foot-thick shell of wallrock is a conservative assumption. All buffering capacity of the wallrock is attributed to calcium carbonate (calcite), and calcite in the model is allowed to equilibrate with the impounded water in an amount not to exceed that contained in the reactive shell.

The second modeling approach is based on kinetic testing. This method uses the leachate composition from humidity cell tests to simulate the quality of runoff and ground water entering the pit. Geochemical modeling based on kinetic data can provide a more realistic approximation of the expected water quality in the pit, but in general, this approach is more costly than the mass balance technique, and still involves a large degree of uncertainty because of the nature of interpreting humidity cell data. The basic assumptions and procedures for this approach are the same as those for the mass balance approach except that pyrite and calcium carbonate contained in the wallrocks are not allowed to react with the lake water.

After mixing, speciating, and allowing the input waters to react with pyrite, calcium carbonate, and atmospheric CO_2, the resultant solution is inspected for oversaturated mineral phases (or undersaturated phases contained in the reactive shell) and geologically reasonable minerals are allowed to precipitate or dissolve. In many cases this is an iterative process because of the interdependence of mineral phases in complex equilibrium. Water-rock interaction can be modeled using either PHREEQE (Parkhurst et al. 1983) or MINTEQA2 (U.S. EPA, 1991). Mixing of waters is easily accomplished in PHREEQE, but, in many cases it is desirable to use MINTEQA2 for the final equilibrium calculations because of its extensive metals database and sophisticated options for sorbing trace metals onto precipitating iron and manganese oxy-hydroxides.

CASE STUDY: FORMATION OF A LAKE IN AN ABANDONED OPEN PIT GOLD MINE IN THE WESTERN UNITED STATES

The study area is located in a semi-arid environment at an elevation of approximately 7150 feet on the northeast flank of a fault-block mountain range in the western United States. The geologic column at the site consists of Mesozoic and younger sedimentary rocks which have been intruded by tertiary dikes, sills and laccoliths of monzonitic composition. Locally these rocks are overlain by felsic volcanics. Gold-ore at the mine was hosted in a hydrothermally altered collapse breccia related to Tertiary plutonism, and was mined by conventional open pit methods. Deposit mineralogy consisted of silicic and argillic hydrothermal assemblages which contained free gold, silver, pyrite, magnetite, hematite, scheelite, and calcite, with minor amounts of chalcopyrite, pyrrhotite and galena. The original orebody cropped out at a elevation of 7,200 feet and extended 535 feet below the ground surface to an elevation of 6,665 feet. The upper portion of the ore zone was variably oxidized to a depth of 140 feet. Below this level the ore and waste rock were sulfidic.

Mining at the site ceased in the mid-1980's. Currently, the open pit forms a circular enclosed depression 1,250 feet across, which penetrates bedrock to a depth of approximately 235 feet below the pre-mining water table. The original potentiometric surface near the center of the pit occurred at 6,900 feet elevation, and sloped to the northeast with a hydraulic gradient of 0.024 ft/ft. Bedrock surrounding the deposit was dewatered in advance of mining using extraction wells. Pumping from the wells ceased at the end of mining and since that time, the pit has been slowly filling with water. Data regarding the rate of filling, and water quality of the pit lake have been collected sporadically since the pit began to fill.

Pit Filling Calculations

Pit filling calculations for the case study were performed as follows. The areal extent of the pit was measured on 25 foot levels starting at the bottom of the pit (6,665 feet elevation) and moving upward to the 6,975 foot level using the final as-built mine map and a digitizer to calculate the surface area. Each level was digitized a total of three times and the resulting values were averaged together to calculate the surface area for each level. Volumes for the pit were obtained by multiplying the average area between two levels by the difference in elevation between the two levels (25 feet).

Inflow to the lake occurs by direct precipitation on the lake surface, surface runoff from the pit watershed, and horizontal ground water inflow from bedrock. The contribution by direct precipitation was calculated on a daily basis using the average annual precipitation of 15.88 inches falling on the pit lake as the lake increased in size with time. Inflow from surface runoff was estimated using a runoff area of 56.74 acres and a runoff coefficient of 99 percent. Horizontal ground water inflow to the pit was calculated using the "Large Well" method presented earlier in this paper. Hydraulic parameters for the geologic units contributing ground water to the pit were taken from previous hydrogeologic studies performed in the area.

Outflow from the lake occurs by evaporation during the spring, summer, and fall months. During the months of December, January and February the lake surface is frozen limiting outflow by evaporation in the winter. Average annual evaporation from the lake was estimated to be 32.86 inches. Calculations indicate that the pit lake will not rise to the pre-mining potentiometric surface. Outflow from the pit by seepage is expected to be minimal, and will only occur when the pit lake surface level approaches its equilibrium surface level. Fluctuation of the pit lake surface during a typical year after reaching equilibrium is presented graphically in Figure 1. Results of pit filling calculations are presented in Table 2.

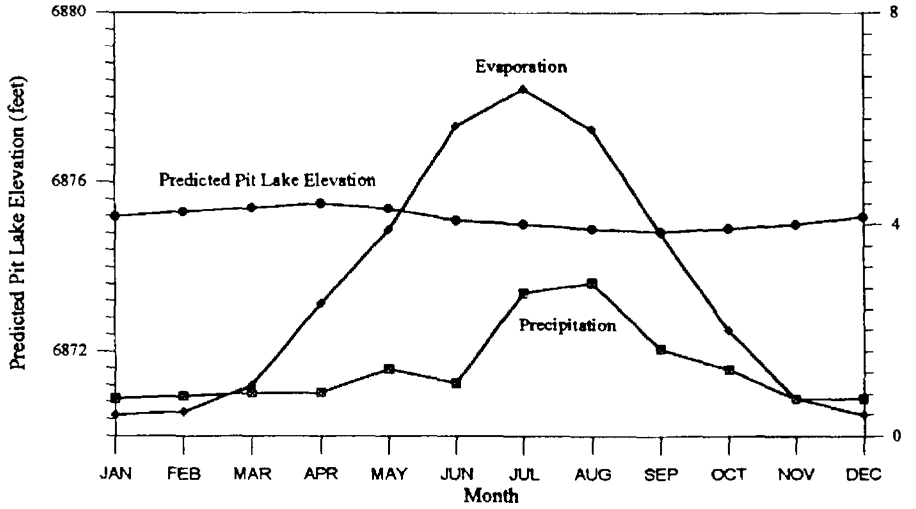

FIGURE 1. Fluctuation of pit lake surface level with monthly precipitation and evaporation overlays.

TABLE 2
Pit Filling Calculations for Case Study

Time to Reach the Top of the Level from the Start of Filling (years)	Level Elevation (feet)	Level Volume (Feet^3)	Daily Inflow by Precipitation (Feet^3)	Daily Inflow by Runoff (Feet^3)	Daily Inflow by Ground Water (Feet^3)	Daily Outflow by Seepage (Feet^3)	Daily Outflow by Evaporation (Feet^3)	Net Inflow (gpm)
0.07	6,675	9,3525	79	5.4	4,011	0.0	3,931	20.4
0.65	6,700	775,200	145	5.4	3,793	0.0	3,643	18.9
1.74	6,725	1,290,262	228	5.3	3,487	0.0	3,247	16.9
3.54	6,750	1,791,363	290	5.3	3,033	0.0	2,726	14.2
6.38	6,775	2,300,300	375	5.2	2,615	0.0	2,216	11.5
11.20	6,800	2,994,900	491	5.2	2,225	0.0	1,702	8.8
20.15	6,825	3,812,300	612	5.1	1,821	0.0	1,168	6.1
41.42	6,850	4,742,012	760	5.0	1,432	0.0	611	3.2
160.52	6,875	5,713,350	983	4.9	966	0.7	10	<0.1

Geochemical Modeling

The computer program PHREEQE (Parkhurst et al., 1986) was used to the assess the potential for acidification of the pit lake as pyrite in the pit wall is oxidized. The pit wall is composed of a hydrothermally altered rind of both silicified and argillically altered rock which is locally calcareous. This surface is available to react chemically with the pit water. The Peterson Scaling Parameter (PSP) for the pit lake was calculated to be 0.8 km. This is similar to the PSP calculated for Caliente Lake in Nevada. Caliente Lake is volcanic crater lake of comparable size, which overturns seasonally and maintains oxidizing conditions throughout its depth (Lyons et. al, 1993). Depth profiles of dissolved oxygen, temperature, pH, and electrical conductivity indicate that this is currently the case in the pit lake.

The average analyses for dissolved constituents in ground waters for each hydrostratigraphic unit contributing water to the pit lake were used as input to the geochemical model. Analyses which were below the detection limit were assigned a value equal to ½ of the detection limit. Data concerning the relative volume of water contributed by each unit were not available, and for simplicity, it was assumed that each lithology contributes water to the lake in equal proportions. This approach is reasonable given that the water quality for each of the hydrostratigraphic units is very similar. Inflow to the pit lake by surface runoff was simulated by degrading the average ground water quality by two standard deviations and adding it to the reacting solution in a proportion similar to that estimated in pit filling calculations. Direct precipitation and evaporation were simulated by adding or subtracting pure water from the solution. The reacting solution was then equilibrated with atmospheric CO_2 and ferric hydroxide over a range of oxidizing Eh conditions to test the system's sensitivity to its redox state.

Modeling results suggests that the water quality of the pit lake is not sensitive to redox conditions over the range of oxidizing Ehs expected (200 to 500 mV). Comparison of model results to existing water quality data for the pit lake indicates that water quality decreases after entering the pit. This decrease in quality is the result of increased sulfate and calcium concentrations. Sulfate and calcium are reaction products of pyrite oxidation in carbonate buffered waters. This supports the hypothesis that pyrite oxidation is responsible for the degradation of the pit lake water.

The potential for continued degradation of water quality in the pit lake was then simulated by allowing the total amount of pyrite contained in a one foot thick shell of wallrock to react with the pit lake water at an Eh of 400 mV. Calcite contained in the reactive shell was allowed to equilibrate with lake water, and geologically reasonable phases were allowed to precipitate. Data regarding pyrite and calcium carbonate content of the wallrocks were obtained from acid-base accounting tests. Model results are presented in Table 3. Laboratory analyses for pit lake water are included for comparison.

TABLE 3
Geochemical Model Results for Case Study

Parameter	Laboratory Analyses for Pit Lake	Model Results for Mixed Inflow Waters	Model Results after Oxidizing Pyrite in the Reactive Shell
pH (s.u.)	7.9	7.7	7.0
Alkalinity (mg HCO_3/l)	153	200	150
Cl	16	17	22
Ca	290	182	385
Mg	69	38	95.33
Na	37	33	48
K	4.5	1.3	5.24
SO_4	907	308	1,191
Fe	<0.025	.023	<0.02
Mn	1.16	1.9	1.9

After pyrite in the reactive shell was oxidized, the predicted pH of the pit lake declined slightly but remained near neutral. Iron oxy-hydroxides and gypsum were strongly oversaturated in the resulting solution and these minerals were allowed to precipitate. Manganese oxy-hydroxides as well as most trace metals remained undersaturated in the final solution. Sorption reactions were not modeled for this pit. It is possible that trace metal concentrations could either increase or decrease as the lake fills, but because the uncertainty associated with the model is greater than the concentrations of trace constituents present in the lake, no attempt was made to predict the final concentrations of these elements.

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