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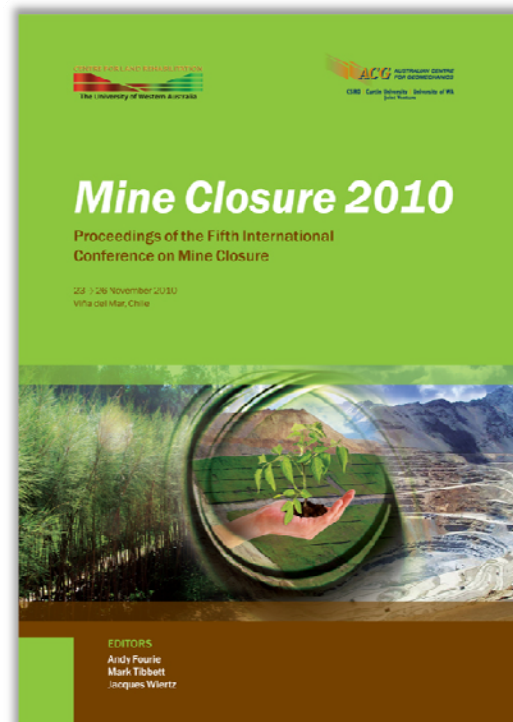
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Integrated water balance and water quality modelling for mine closure planning at Antamina

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Abstract

Post-closure water management is a key challenge in mine water management and planning. A fully integrated closure water balance and water quality model, using the GoldSim modelling platform, has been developed to support closure planning at the Antamina Cu-Zn-Mo mine. The mine is located in the rugged Andes of Peru, 4,200 metres above sea level. As part of closure planning, to minimise the impact to the environment water management requires the consideration of both flows and concentrations.

The developed model links aqueous chemistry to the physical system of the site-wide water balance. The geochemical mechanisms included have been determined from detailed interpretation of extensive static and kinetic testing undertaken since mine inception; and, on-site water quality and flow monitoring. Geochemical modelling using PHREEQC and Geochemists Workbench identifies the most important geochemical processes to be included in the model. Hydraulic components of water balance include seasonal flow variability, waste rock dump storage and lag discharge mechanisms, runoff variability and pit recovery scheduling.

The model allows several water and waste management scenarios to be evaluated. User variable inputs allow updating parameters such as loading and infiltration rates. User defined input parameters also allow for the accommodation of improved understanding of the mine from on-site research programmes. In this way, the model can be used as an effective tool in closure planning.

1 Introduction

Post-closure water management is a significant concern for mining operators. In Peru, regulations require that water discharge from mine sites comply with stringent criteria depending on downstream usage. Maintaining discharge criteria compliance often carries a financial burden and may require years of post-closure water management. Compañía Minera Antamina (CMA) incorporates elements of closure planning as part of the mine operational and management plans, and minimisation of post-closure mine water impacts forms part of these plans.

1.1 Project setting

The Antamina Mine is situated in the central Andes of Peru, approximately 4,200 metres above sea level and 280 km northeast of Lima. Copper, zinc and molybdenum ore is extracted from the Antamina Mine using open pit mining techniques. The ore is processed to produce a metal concentrate that is piped to the Peruvian coast for shipping overseas. Waste material generated by the mining process is deposited in a number of waste rock dumps (WRD) and a tailings storage facility (TSF). Predominantly, land adjacent to the mine site is used for subsistence farming by the local communities.

As with most mining operations, some impacts on the environment have been identified. CMA has, however, made significant and diligent efforts to provide infrastructure to manage impacts associated with water, including: clean water diversions; adequate routing systems to dilute contaminated flows; capture and pump-back downstream flows that do not meet compliance criteria; and, installation of treatment systems/mechanisms for potential discharge water (e.g. wetlands, flocculant treatment). Regular monitoring of water quality and flows

across the mine site have been undertaken; and coupled with the results of the geochemical testing programme an integrated mine closure water balance and water quality model can be developed.

Working with CMA, Klohn Crippen Berger Ltd (KCB) developed a predictive closure water quality model, incorporating the water quality contributing to mine infrastructures. These infrastructures include the open pit, two WRDs (east waste rock dump – EWRD, Tucush waste rock dump – TWRD) and the tailings storage facility (TSF) are presented in Figure 1. The model was developed based on fundamental geochemical principals and, most importantly, available site data. The main capability of the model is to allow the user to simulate various water management scenarios that may cause a change to either flow volumes or water quality. These scenarios, based on anticipated closures strategies, include waste rock cover systems, treating discharge water, discharging without treatment and various discharge pump-back options. The model also incorporates stochastic rainfall and dry periods to allow the simulation of extreme weather conditions.

2 Background site information and model input data

2.1 Mine infrastructure

The project extent of the Antamina Mine is located across two surface water catchments: the Quebrada Antamina catchment and the Rio Ayash catchment. Quebrada Antamina generally flows towards the west, discharging into the Pampa Moruna River. At mine closure it will include discharge from the open pit and runoff from a small proportion of the TWRD and a small proportion of the EWRD. The confluence between the Quebrada Antamina and Pampa Moruna is a water quality compliance location for the Antamina Mine. The Rio Ayash catchment underlying the mine footprint can be divided into two sub-catchments, Quebrada Tucush and Quebrada Yanacancha; Quebrada Tucush hosts the valley-filled TWRD, while Quebrada Yanacancha hosts the EWRD and TSF. Runoff and seepage from the EWRD is directed into the TSF, which ultimately flows into Rio Ayash; Quebrada Tucush discharge flows into Rio Ayash downstream of the TSF toe. A compliance monitoring point is located on the Rio Ayash downstream of the confluence with Quebrada Tucush.

Mine waste segregation, based on waste rock reactivity, is practised at the Antamina Mine. More reactive waste is deposited in the EWRD and less reactive material deposited in the TWRD.

At closure, dewatering activities within the open pit will cease and a pit lake will gradually develop with time. The pit lake will continue to fill until the spill elevation of the Quebrada Antamina is reached. After this, a continued flow into the Quebrada Antamina is expected to be sustained.

2.2 Geochemical and water monitoring data

A rigorous geochemical testing regime of mine waste at Antamina has been undertaken by CMA. This testing includes static testing (acid-base accounting, whole rock analysis, mineralogy and leachate testing) and kinetic testing through laboratory and field testing methods. Field testing techniques comprised field cells for waste rock and tailings leachate tests; and, instrumented waste rock piles that measure leachate chemistry, water balance, temperature and oxygen. These field testing infrastructures form a major part of the ongoing geochemical characterisation undertaken by CMA through collaboration with consultants and the University of British Columbia (Aranda, 2009; Bay, 2009).

Geochemical testing at Antamina focuses on the various mined rock classifications. Generally, these classifications broadly comprise ore and waste rock. A summary of geochemical testing completed for these classifications is presented in Table 1.

Table 1 Summary of geochemical characterisation tests

Material Type	Metal Analysis	Total Sulphur	Acid Base Accounting	Static Leaching	Field Cells
Ore/LGO/marginal grade ore	10	22	18	14	8
Waste rock	307	554	463	92	63
Tailings and lake sediments	19	17	17	14	18

In addition, five instrumented waste rock piles provide a greater understanding of the water quality and hydrology of the waste material.

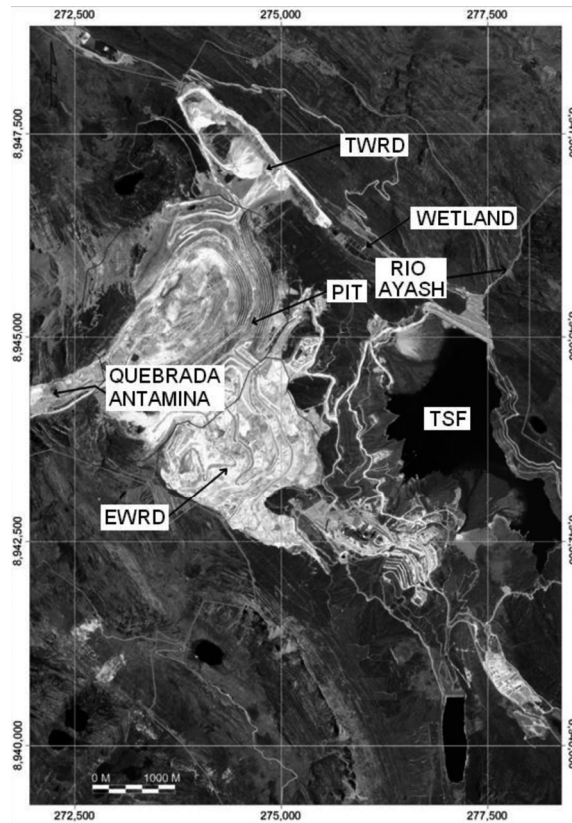


Figure 1 Aerial photograph of the Antamina Mine in 2009

Routine surface water sampling is undertaken at various locations across the Antamina Mine area, including downstream of the mine waste storage infrastructures and at the mine discharge compliance locations. As a minimum, monitoring is conducted on a quarterly frequency for flow rates and water quality parameters. This provides information on seasonal variability for the site. These monitoring records are critical for the establishment of the water balance/water quality model, as they provide an understanding of current and historical loading rates from the current waste facility configurations.

Rigorous analysis on the data was first necessary in order to determine the general response of the waste material. This preliminary data analysis provided the loading rates and solid compositions of waste components. Interpretation of site water quality data was undertaken using PHREEQC (Parkhurst and Appelo, 1999) and Geochemists Workbench (Bethke, 2008) to determine mineral saturation and potential geochemical controls. This compared theoretical fundamental reactions and responses to pH changes using these geochemical models.

The values obtained were used to populate solubility lookup tables and to help determine the active alkalinity in water sources for the acid-base account for each facility. Total sulphur and other Acid-Base Accounting (ABA) testing provided the data to populate the initial geochemical characteristics of the model.

2.3 Other data required to populate the model

Although the focus of the model is on water quality aspects, several other important data sets are required to establish the conceptual model, and as input to the model. Most of these data are readily available from different

sources at mines such as Antamina. The most important supporting data (for use in the model) includes rainfall and climate; timing and expected performance of waste rock dump covers; underlying geology and associated hydrogeological characteristics; and, final infrastructure operation at closure (especially for piping, capture and pumping of discharges). Tonnages of the mine waste facilities at closure are:

- EWRD – 1,410 Million tonnes (Mt).
- TWRD – 1,010 Mt.
- TSF – 700 Mt.

3 System conceptualisation and model development

3.1 System conceptualisation

Developing a feasible conceptual model of the Antamina Mine is the first and most important step of the modelling process. The purpose of this step is to establish a conceptual framework which can explain hydrogeochemical behaviour at each mine component from existing information (LeGrand and Rosen, 2000).

The conceptual model was developed to allow transferability into the analytical modelling platform, such that climate scenarios and seasonal variability could be simulated.

3.2 Water balance considerations

The second step of model development was the construction of a closure water balance. The closure water balance was built to assess water balance for each mining component, and the site as a whole, based on known water flows on site and the proposed site closure water management strategy. Water balance incorporates stochastic rainfall, evaporation, routing of water, cover systems, infiltration/runoff coefficients, and contributions to or from groundwater.

3.4 Deriving the fundamental geochemistry

The third step to model development is the establishment of the conceptual geochemistry model and the inclusion of fundamental geochemical reactions in the model. These reactions were derived by detailed interpretation of the site monitoring data, determining kinetic loading rates for different waste types from on site kinetic cells and the supporting mineralogy and static test data (Aranda, 2009). Through the use of this data and PHREEQC and Geochemists Workbench (GWB) modelling, the expected geochemical reactions were identified. From these analyses water quality concentrations were shown to be controlled by: kinetic reaction rates; equilibrium controls on saturation; and the quality and associated water volumes for each mining component over time.

In many of the mine components the major mineral assemblage is dominated by calcium containing carbonates. This results in pH levels being largely controlled by the presence of carbonates, the carbonate mineral composition (i.e. the range of calcitic to dolomitic carbonate present), the threshold concentrations of these carbonates below which they can no longer buffer acidity and the factors that control carbonate solubility and equilibrium (see Figure 2). These factors include the fugacity of CO₂, (confirmed by on site research by Bay, 2009) the overall salinity of the water, temperature and the effect of other processes which consume alkalinity or impact Ca or Mg concentrations.

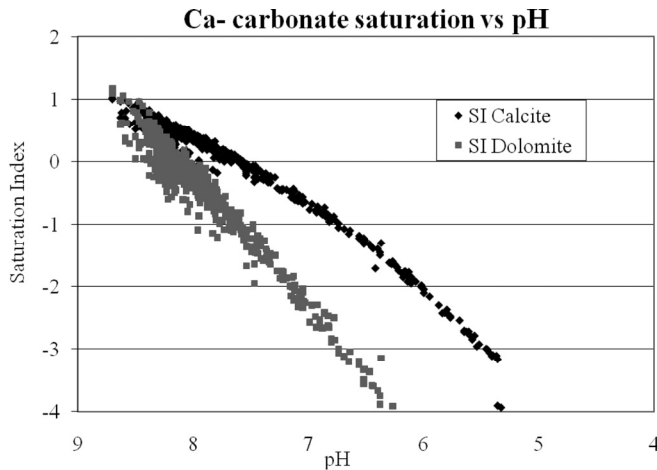


Figure 2 Saturation state of calcite and dolomite as a function of pH in the EWRD

The key process for water quality deterioration is the oxidation of sulphide minerals. Sulphide oxidation drives the increase in salinity, sulphate and the acidity. Neutralisation of the acidity may occur through the water's natural alkalinity, but principally through the dissolution of Ca-containing carbonates.

The process of sulphide oxidation with concurrent buffering increases salinity and releases the associated metal in the sulphide (i.e. Fe, Cu, Zn or Pb). Increased sulphate and calcium concentrations can result in gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) precipitation. The continued presence of carbonates maintains neutral to alkaline conditions which limits mobilisation of many of the metals, apart from neutral drainage species such as As and Mo. Where the carbonates persist, pH remains neutral (Figure 2).

Using the sulphate generation rate allows for an estimation of the amount of acidity and the amount of carbonate needed to buffer this acidity (i.e. depletion of calcite/dolomite as a result of sulphide oxidation).

Site observations confirm that the concentrations of the majority of metals are a function of pH conditions, overall salinity and mineral solubility constraints.

From these observations the required geochemical mechanisms including pH determination, acid generation and neutralisation, salinity calculation and solubility constraints have been built into the model.

3.5 Closure water management scenarios

The fourth step of model development is the inclusion of closure water management options. The water quality model is predictive, and has been developed to assess one of four water management scenarios. The four scenarios modelled are:

- Treatment of all water from the dumps and tailings using a treatment plant.
- Pumping of all water from the TSF seepage collection pond back to the TSF.
- Pumping of water to the TSF from the TSF seepage collection pond only during the dry season.
- Discharge of all water.

Figure 3 shows the model input screen with pre-selected scenarios and other input variables.

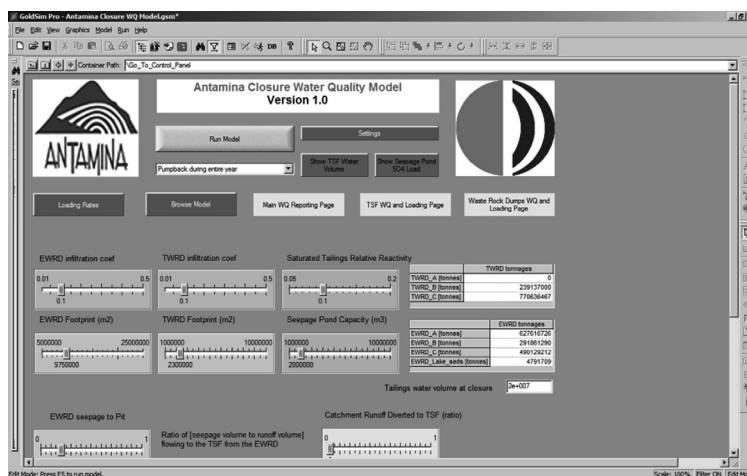


Figure 3 Data and scenario selection screen

3.5.1 Treatment of all water

Water treatment requires the routing of all contaminated water flows from the EWRD and TSF through a treatment plant while maintaining riparian flows from diverted water and compliant discharge water. The riparian flow requirements form part of the mine's commitment to minimise downstream impacts.

3.5.2 Pump back all water

Pumping back all water collected in the TSF seepage pond for an indefinite period of time is not an ideal solution, however, system capacities can be simulated through this water management option to determine the post-closure period available, or institute remedial, or other water management measures, to implement prior to closure.

3.5.3 Pump back TSF seepage pond water during dry season

The pump back TSF seepage pond water during dry season scenario was designed to predict the water quality of TSF seepage discharge which would be diluted by other flows from surrounding catchments during the wet season. In the dry season, the dilution is not sufficient to meet discharge criteria; therefore, water pump back into the TSF pond is required.

3.5.4 Discharge all water

In the fourth scenario, all water is discharged regardless of water quality. This was seen as the base line scenario, to which the other scenarios would be compared.

3.5.5 Other situational options included in the model

From the data and scenario selection screen in the model (Figure 3), other situational changes can be made to model certain mine components specifically. For example, some of the other options are as follows:

- Covers can be placed on the dumps over different intervals and with different infiltration efficiencies.
- The amount of water which is diverted around the base of the dump can be changed to influence the ratio of dilution to loading.
- The option to vary other factors which appear to have significant sensitivity to discharge (seepage pond size for dilution, proportion of rock type in each dump, and other factors).

All of the above factors are defined by the user, but, are set as defaults in accordance with data available at the time of model development.

3.6 Selected modelling platform

GoldSim was used as the modelling platform as it allowed integration of multiple data types and the integration of water quality and water balance. GoldSim allows a hierarchical approach to model development which meant that the required algorithms for both water flows and the geochemical reactions for different mining components could be written into individual components or containers, as they are called in GoldSim (Figure 4). The common data, such as rainfall and geochemical mechanisms, and constants can be linked to the different components.

All of the required equations describing water flow and all geochemical and mass transfer interactions were compiled and written into the GoldSim model. As a final product, CMA is provided with a GoldSim player file which is interactive and allows selection of different scenarios and input parameters. This allows the post-closure impact of different water and waste management options to be easily evaluated by mine staff.

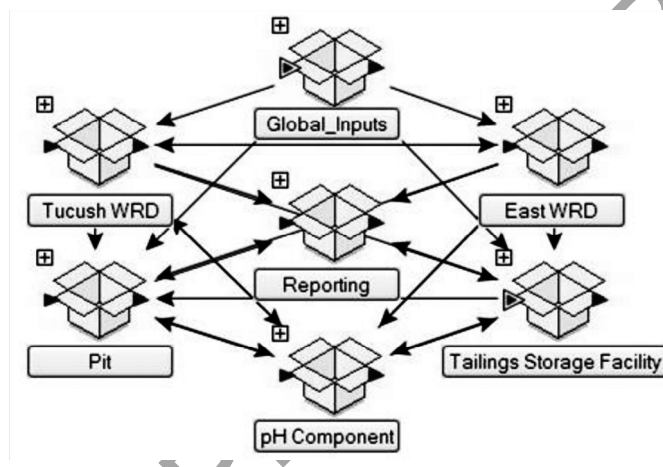


Figure 4 GoldSim model overview and containers

4 Model detail

4.1 Solute mass balance and geochemical processes

The solute mass balance is linked intrinsically to the water mass balance. Each water flow within the model therefore has an assigned or calculated water quality.

4.2 Processes

The model calculates the most important interactions at major mining components. The calculations which are used at these locations comprise the following, generally in the same order: water influx, increase in reaction products, determination of dilution, acid generation and neutralisation, pH calculation, solubility calculations, secondary precipitate gains or losses and finally water and mass transfer from each component.

Using the dumps as example, the sequence of mathematical calculations in the developed Goldsim model is as follows: a proportion of rain falling on the dump surface infiltrates into the dump. Chemical load, as determined by the geochemical testing and the quantity of reactive rock present, is added to the water within the dump. Mass balance dilution is applied to provide the water quality prior to geochemical corrections (PGC). The model calculates the reduction of available neutralisation as a result of acidity generated in each time step. This calculation is used to determine the pH. Water quality (PGC) is compared against solubility curves for a suite of parameters (mostly metals) which have variable solubility as a function of pH. As an

example of solubility processes, sulphate and calcium concentrations (PGC) are compared against gypsum solubility to identify the expected amount of gypsum that will precipitate in the time step. Adsorption processes are simulated for parameters such as arsenic, molybdenum and selenium concentrations (PGC) by computing the mass of precipitated iron in the system to assess adsorption capacity. The theoretical sorption, as a function of pH, is used to determine the expected sorption of each of these parameters. The losses to complexation, precipitation and adsorption are calculated and subtracted from the (PGC) water quality to find the equilibrium water quality. This equilibrium water quality is assigned to dump drainage water, which is apportioned to groundwater infiltration and dump toe seepage.

4.2.1 Water influx

Inflows include any flow such as direct precipitation, runoff, contaminated flows from a waste rock dump or clean water inflows.

4.2.2 Increase in reaction products

The increase in reaction products is largely from loads emanating from tailings or waste rocks which have been derived from the kinetic test results. Dissolved loads which are associated with inflows and dissolution of secondary precipitates also contribute. The mass accumulated in each time step is added to the mass of elements already present in the reservoir.

4.2.3 Calculation of dilution and concentration

The division of the total mass of solutes present in a reservoir in a single time-step by the volume of water present in the reservoir at that same time-step provides the dilution factor and initial concentration calculation. Calculations of ionic strength of water in each component are derived from these calculations.

4.2.4 Acid generation and neutralisation

There are two different types of acidity considered in the model. The first type is the acid produced as a result of sulphide oxidation. The magnitude of this acid generation is derived from the kinetic test results and scaled up to field scale by several factors and assumptions. The second type is latent acidity from influent flows or from stored acidity in reaction products. Both situations occur at Antamina Mine.

These two acidifying agents will react with neutralising materials which buffer pH and consume the neutralising agents. There is often more than one neutralising agent, with calcite being the most common and the most effective buffering mineral at Antamina.

The mineralogical investigations on site have identified five significant neutralising minerals/mineral classes. Calcite neutralises (buffers) acidity at a pH range from about 6.3 to 9. PHREEQC and GWB were used to define the pH ranges which would occur with each subsequent neutralising agent present. In the model, the pH is a function of the relative quantity of calcite (and other neutralising agents) present in the system. As long as there is sufficient calcite (minimum buffering ratio) remaining in the system, the pH will be buffered by calcite. Once that threshold is passed, however, the pH falls into the next buffering pH range.

Calcite is the first carbonate containing mineral to react due to its rapid reaction rates (Blowes et al., 2003). Because of this, calcite has the best efficacy for neutralising acid. When acid comes in contact with calcite, the following reaction occurs:



Similar reactions occur for dolomite. Dolomite ($CaMg(CO_3)_2$) has a slightly wider and lower range of buffering, which may in part be due to its somewhat variable molecular make up; both of these calcium carbonates maintain neutral pH. Siderite has been included based on mineralogical observations despite its temporal buffering capacity. Below pH 5, the aluminosilicates and aluminium hydroxides are taken into consideration, although these have substantially reduced kinetic reaction rates, on the order of 400 times slower than calcite (Jambor, 2003), and thus, while widely prevalent in felsic systems, only provide a relatively low range of pH buffering. Aluminosilicates cannot be discounted though: even though the rate of

neutralisation is substantially slower, systems often will be buffered by very long periods of time due to the large amount of aluminosilicates in the system.

The last modelled component of the acid neutralisation is the iron oxy-hydroxides. Even though the neutralisation capacity of this compound is relatively insignificant, it occurs at a pH range which is highly important to the biological processes of several *Sulfobacillus* type bacteria (Dufresne et al., 1996). At Antamina there is currently no data to indicate that pH will fall to these levels.

4.2.5 pH calculation

pH calculations are a direct result of the determination of the balance between acid generation and neutralisation in each time step. The modelled pH is calculated by the quantity of each buffer present, the buffer pH values and the ambient environmental processes of dilution and evaporation. In addition, where the carbonates are the principle buffer, the expected partial pressure of CO_2 is used to define the pH. This is related to the internal hydrology of the waste rock dumps particularly where seasonal variation in major contributing flow paths (rapid preferential wet season flow and slower matrix release in dry season) provides discharge waters which are equilibrated with atmospheric or increased P_{CO_2} values respectively.

The measured and modelled pH downstream of TWRD is shown on Figure 4.

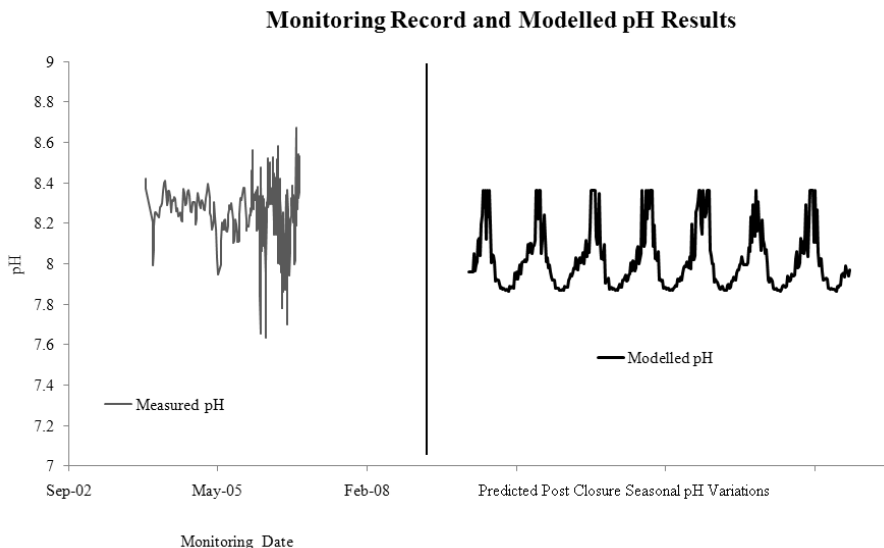


Figure 4 Measured and modelled pH for TWRD contact water showing seasonal variation

4.2.6 Solubility calculations

Many elements will have a solubility concentration which is dependent on two major factors, the solution pH and/or the concentration of another element. The developed model compares a series of mineral solubilities to the respective solubility product or K_{sp} of the ions which make up the mineral. The developed model also determines the overall ionic strength and makes corrections to the concentrations as a function of the non-ideality of the solution. The difference between the K_{sp} and the product of the concentrations determines the amount of secondary mineral precipitated. This is particularly important for salts that are not controlled by pH such as gypsum ($\text{CaSO}_4 \cdot 2 \text{H}_2\text{O}$).

pH dependent solubility is a separate calculation. For pH-based solubility, the model harnesses output from Geochemist Workbench in the form of algorithms which explicitly defines the maximum concentration of an element in solution at a given pH or pH range, based on theoretical and site data.

4.2.7 Secondary precipitates and sorption

To predict how much mineral precipitation will occur, a check is made versus the known solubility limits. If there is a greater concentration in solution than the prescribed solubility, the model removes mass until equilibrium is reached. If at any point the conditions become favourable to the dissolution of secondary minerals, the model allows re-dissolution to meet equilibrium.

Interrogation of the site monitoring data and comparison to field kinetic tests suggest that sorption is another important control on observed concentrations. Sorption is calculated in the model as follows:

- Total iron is assumed to be the amount produced from pyrite oxidation.
- Dissolved iron is calculated according to solubility calculations.
- Precipitated iron in any time-step is given by total iron minus dissolved iron.
- The proportion of As, Mo, Se adsorbed at the pH of the system, is based on adsorption ratios of each element determined from geochemical modelling, provided there is enough precipitated iron present.

4.2.8 Diffusion

Diffusion occurs where a concentration gradient exists. Diffusion calculations have been included to transfer mass between the tailings pore water and the pond after closure. This is calculated according to Fick's laws.

4.2.9 Water and mass loss from each component

Water leaving the reservoir, in all cases except evaporation, includes the concentration of all dissolved elements in the reservoir solution at the time of departure.

5 Functionality and client needs

The functionality of the model is, largely, met by the relative ease of operation of the GoldSim platform. Instructions and self explanatory options provide simple and intuitive operation. The model meets client demands in the ability to model different scenarios and options. Easy to read graphs and indicators provide results in a manner which are accessible via buttons on the 'dashboard' which provide navigation. The model may be run for up to 100 years from the start date, and predict such things as water levels, water qualities, source term depletion, loads, total flows, and reservoir levels (see Figure 5). The model acts as a standalone system for water management for all closure aspects of the mine.

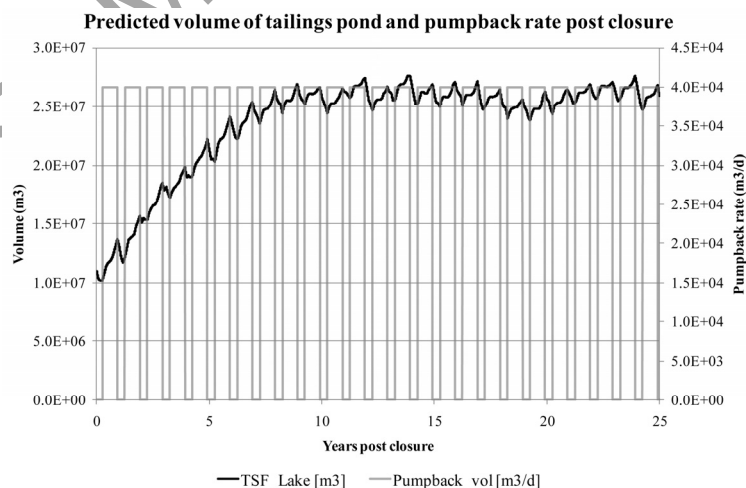


Figure 5 Predicted tailings pond volume and pumpback during dry season scenario

5.1 Considerations and improvements

The model was built with the intent to incorporate any applicable fundamental geochemical process which could be articulated by the software as was feasible given the budget and time constraints. The fundamentals which were able to be incorporated are based on sound chemistry, empirical observation and known processes. There are, however, ambiguities in processes, specific geochemical data limitations, unknowns, and simplifications of known complex processes. There are many assumptions that have user-defined variables instead of single values due to the significant impact that these have on the overall outcomes.

5.2 Model uncertainties

Loading calculations represent a potentially significant source of uncertainty, since there is, in every situation, a loading rate factor applied to convert the lab rates of leachate production to field scale. Sources of uncertainty in this load rate are due to the difference in climate, microbial environment, grain size, the variable agitation each grain undergoes during handling, and other factors such as physical weathering due to freezing, and extreme drying, etc.

Scaling factors are another source of uncertainty. Calibrating is, generally, the comparison to known data, and the adjustment of factors to help match the data. The problem with calibration is that there are essentially unlimited numbers of microscale processes occurring, along with unknowns that may cause significant changes in the environment. Many authors (such as Stromberg and Banwart, 1994; Stromberg et al., 1999; and Banwart and Malstrom, 2001) have attempted to provide site-specific or more general scale up factors from lab to field. No unique scaling factors exist and future work on these aspects will be required at CMA.

There is also a significant source of uncertainty in the hydrologic interpretation of water flows. This is particularly true for the internal hydrology of the dumps where complex unsaturated-saturated flow processes are simplified to provide an indication of the bulk response of the system. Assumptions have been made in the building of the model to simplify some of these processes and provide general scenarios in which flows may not be entirely accurate, but will provide a backdrop against which the character of the water can be modelled effectively.

Another process which comprises several assumptions and a simplified algorithm is that of adsorption of iron precipitates. The adsorption mechanism in nature is intensely dependant towards pH, and depending on the water quality make up, the oxidation levels of the water, and whether the As or Mo was present during the initial precipitation, the amount of material sorbed can vary significantly. These factors are simplified to make the model functional within the bounds of the expected accuracy rather than incorporating all the complexity of the calculations within the model.

5.3 Suggestions and improvements

To better validate the model, and increase its accuracy, ongoing calibration of the model to the current site data will help to identify not only mechanisms of the model which appear to be performing well, but also highlight mechanisms and calculations that require improvement. It is imperative that data for any of the major components continue being collected at regular intervals.

5.4 Current work

Current work in support of this model includes the following:

- Ongoing geochemical testing through the onsite kinetic testing.
- Further geochemical testing of especially identified potentially acid generating materials.
- An extension of the cover testing.
- In-field characterisation of waste rock dumps through drilling.
- Assessment of the metal attenuation mechanisms in the field cells and piles.
- Further geochemical testing of flooded tailings.

Most importantly, CMA has commissioned an extension of the closure water quality model so that the expected water quality changes associated with operational changes and water and waste management can be simulated. KCB is the process of developing this model and continuous comparison to site observations through monitoring will allow improvement of scaling factors, confirmation of attenuation mechanisms and optimisation of the modelling processes. The intention is that this model will be used for operational planning and to guide operational mine water and waste management decisions through to closure.

6 Concluding remarks

This paper has outlined an approach that has proved to be successful for the development of a closure site-wide water quality model at a very large mine site. The work has shown how an extensive geochemical characterisation programme can be used to derive the fundamental geochemical reactions of importance and, from this, develop a user-friendly tool to assist the mine in evaluating the impact of different closure water management options.

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