

Assessing the Robustness of Antamina's Site Wide Water Balance/Water Quality Model over 5 Years of Implementation

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ABSTRACT

Predicting water chemistry resulting from mining activities is arguably one of the most important aspects of environmental management at mines. The water quality within waste storage facilities presents an especially important consideration in mine planning and the ability to accurately simulate the chemical evolution within such facilities is a major goal for environmental planning.

To illustrate the concepts in development of a predictive model, a water quality model for the tailings storage facility (TSF) at the Antamina mine in Peru is presented. The model is based on fundamental mineralogical and thermodynamic controls and monitoring data from the mine's regular monitoring and field research programs.

The model has developed as a collaborative effort between KCB and Antamina. The geochemical controls and water balance mechanisms simulate the interaction in the TSF and these are continually calibrated against observed data. This iterative process has resulted in the construction of a robust model that can predict, with confidence, water quality originating from the facility for the life of mine and after closure.

Here we outline the main control mechanisms built into the model and compare these to the observations of the tailings storage facility at Antamina. By introducing 'stresses', such as erroneous water flows or large inputs of sulfate, we can demonstrate that the model is robust and able to handle a variety of alternative scenarios. We also use established geochemical modelling software, such as PHREEQC and GWB, to cross-check predicted mineral and geochemical controls and compare the equilibria predicted in these models to those that have been constructed in the Antamina water quality model. The results show that that model's mechanisms and simulation algorithms are robust and versatile and may be utilised successfully at this mine site but also in a variety of mining waste rock dumps, tailings storage facilities and water catchments.

Keywords: GoldSim, modeling, geochemistry

INTRODUCTION

The Antamina mine is a polymetallic skarn deposit situated in the Peruvian Andes, approximately 270 km northeast of Lima. The mine produces copper, zinc and molybdenum concentrates. Waste material generated by the mining process is deposited in two waste rock dumps (WRD) and a tailings storage facility (TSF).

Due to the distinct wet and dry season climate (Harrison *et al.*, 2012), Compañía Minera Antamina (Antamina) manages water using infrastructure such as: diversion channels; passive treatment wetlands; capture and pump-back and operational controls such as flocculation and neutralization. Antamina conducts regular monitoring of water quality and flows across the mine site and compliments this information with a comprehensive geochemical testing program. The program includes static testing (acid-base accounting, whole rock analysis, mineralogy and leachate testing) and kinetic testing through laboratory and field testing methods (*e.g.* field cells and instrumented waste rock piles).

KCB uses the geochemical testing data, site water quality and flows to understand site interactions, construct feasible conceptual models for each of the major mine site components, calibrate and test the operation of the model. This collaborative effort has resulted in a mine site-wide integrated water balance and water quality model (IWBWQM).

The IWBWQM has been built using the GoldSim Pro software developed initially in partnership with Golder Associates and the United States Department of Energy for water balance purposes. The Antamina IWBWQM is a coupled water balance and water quality model built to simulate a variety of different scenarios including: predicting water levels, flows, seepage, pumping needs, and water quality as a solution of up to 42 water quality parameters at a variety of locations throughout the system. GoldSim was considered an appropriate choice for Antamina due to its capacity for complex modelling in terms of handling of data arrays, measurement unit continuity, error checking and user interface. GoldSim simulation software is capable of deterministic and probabilistic modelling as well as providing sensitivity analyses. Specific to this project, multiple realizations of the water balance can be achieved and the sensitivity of different input parameters or processes can be determined. The GoldSim model construction means the model is flexible enough to make impact assessments even given a broad range of potential future water management scenarios.

The Antamina IWBWQM encompasses the entire project area. Here, we focus on the construction and development of the modelled TSF facility. In this paper we demonstrate the fundamental concepts that form the underlying infrastructure of the TSF model, the integration of this framework with data provided by Antamina and comparisons between the predicted evolution of the TSF with historical data. Finally, we demonstrate that the principles in the TSF model construction can be applied to other components of the mine site and that the Antamina mine provides the ideal setting to test this.

METHODOLOGY

The conceptual design and construction of the IWBWQM have been detailed by Strand *et al.* (2010). This study focuses on the design, construction and subsequent testing of the TSF.

The TSF is the most interconnected facility to simulate in the model, with contributions from over 20 inflows and 10 outflows, geometric calculations and area balances. TSF inputs and outputs are based on processes and controls operating at Antamina. The transport of reaction products is taken into account primarily from the dissolved flows and tailings reactivity. Geochemical systems are simulated in both the pond and the tailings pore space as separate systems, with mass transfers between the pond and the tailings as a function of flows and diffusion. Use was made of PHREEQC (Parkhurst and Appelo, 1999) and Geochemist’s Workbench (Bethke, 2008) in both the pond and pore space. Mine infrastructure plans, waste schedules and static geochemical test results are used to define the mass of reactants available. Field kinetic cells are used to define the expected reaction sequence and kinetic loading rates under oxidizing (beach surface) and reducing (beach pores and base pores) conditions. The site’s water quality monitoring record is used to define the expected behaviour, provide reasons for observations and deviations from expected flows or concentrations. The approach is summarised schematically in Figure 1.

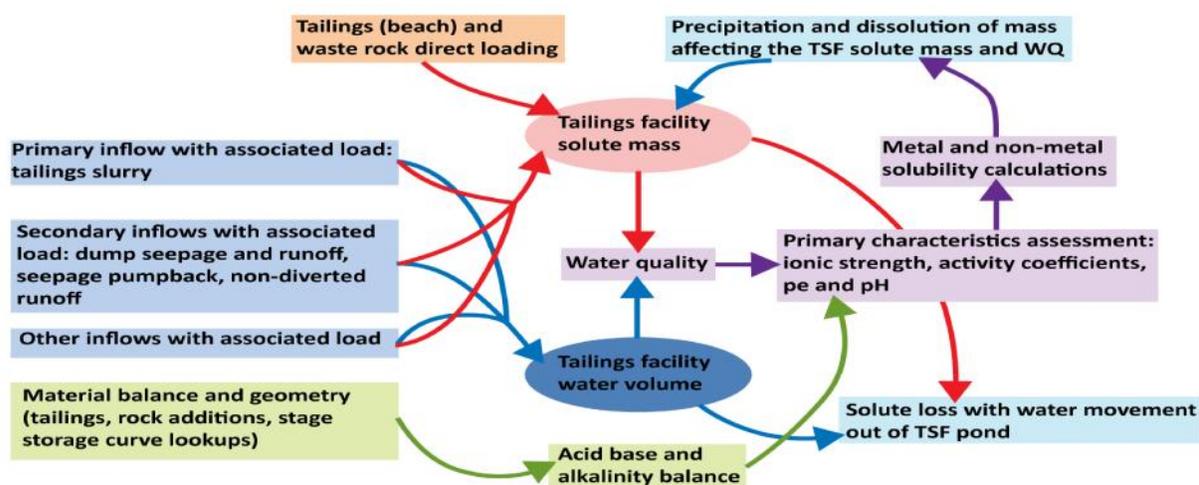


Figure 1 TSF model conceptual components

The TSF pond is the central reservoir and is affected by all of the water inflows and outflows of this section of the model. The most significant inflow to the system is the tailings slurry, which regulates the chemistry in the TSF pond by constant addition of dissolved load and high pH water. Secondary inflows from the waste dumps are the greatest contributors of dissolved metals. These flows include direct precipitation, runoff and contact flows from the waste rock dump or water inflows from non-contact sources. Direct loading from the tailings beach and waste rock also provides a significant contribution. Solute loss is controlled through the precipitation of minerals within the pond, or loss associated with water movement out of the TSF via dam seepage to the seepage pumpback system.

Time and mass dependent loading rates are calculated by multiplying the effluent concentrations by the effluent volume and dividing by the sample mass and the sample interval to produce a mg/kg/week value, Equation 1.

$$\text{Loading Rate} = \frac{[X]v}{m} \quad (1)$$

where X is the concentration in the effluent, v is the effluent volume, m is the mass of the source term used (rock mass) and t is the time interval between measurements.

Subaqueous deposition is associated with considerably slower kinetic rates than aerated deposition. Reaction rates are derived from the kinetic geochemical testing program. The kinetic rates are obtained from the humidity cell data and subsequent field cells operated by Antamina; there are cells currently in operation which continue to provide data for model population.

The model uses a mass balance approach combined with an acid-base accounting and alkalinity balance system and subsequent pH modelling to assess the net load of acid or alkalinity entering the TSF pond via loading at each time step. The TSF load, (the result of water concentration and flow) entering the TSF is a function of all sources considered. Therefore, because those sources vary rapidly, it is assumed that incoming acidic loads only neutralise according to the total concentration of alkalinity present in aqueous solution; thereafter neutralisation is due to the tailings material itself.

The total mass of dissolved solute present in the pond is simulated. All dissolved solute is added to this “reservoir”, and all precipitation or physical removal via outflow is removed directly from this element. Dissolved loads that are associated with inflows and dissolution of secondary precipitates also contribute. The solute mass is a primary input for the tailings pond free water quality.

Since the TSF is a mixing pond of several different water flows, preliminary acid base accounting is undertaken through a series of algorithms prior to depleting neutralizing potential (NP) in the TSF. If a water flow is assumed to be acid, then the acidity from that inflow is allowed to deplete the dissolved alkalinity load reporting to the TSF. The net addition of alkalinity and acidity to the pond is the difference between the various alkalinity and acidity contributors. Excess acidity is simulated to then consume the available NP in the tailings, which is present as calcite and small amounts of dolomite in the tailings solids. This differs from other facilities, which consider pyrite oxidation (based on conservative estimates) as the primary driver for the source term systems with acidity generation through sulfide oxidation and subsequent neutralization of acidity by carbonate minerals. From this point, however, acidity as a driver is handled much the same as in source term facilities. Excess acidity consumes minerals contributing to neutralization potential of the tailings.

The TSF pond is modelled using the established carbonate-bicarbonate-CO₂ equilibrium detailed in Strand *et al.* (2010). In the model, the ‘central pillar’ is considered to be the alkalinity within the TSF pond, which can be estimated as the molar concentration of bicarbonate (HCO₃⁻). A certain amount of alkalinity is present in the pond; this is based on measurements provided by Antamina. When the model is operated, any acidity added to the pond (e.g., from the mill) consumes alkalinity. This in turn shifts the equilibrium so that the net effect is to dissolve calcite (CaCO₃) to produce more bicarbonate (Strand *et al.*, 2010). The shift in equilibrium results in the dissolution of CO₂, which is assumed to be in equilibrium with the atmosphere (Strand *et al.*, 2010). The model thus combines calcite dissolution/precipitation and CO₂ dissolution/degassing to buffer acidity additions to the TSF pond, provided solid calcite remains in the system (atmospheric CO₂ is considered to be constantly replenished). Alkalinity is also added to the pond from the various additions (e.g., from the mill slurry), which are simulated in the model based on data provided by Antamina.

Calcite provides the major buffering mechanism in the TSF, but bicarbonate is stable within a pH range of ~ 6 – 9. At lower pH levels, other mineral buffering systems are more appropriate and

these have been built into the model. Minerals and secondary precipitates that neutralize acid and buffer pH, using similar principles to the calcite system, have been assigned the pH ranges in the model as follows, after Blowes & Ptacek (1994):

1. Calcite and /or dolomite (6.3 pH – 9 pH)
2. Siderite (4.8 pH – 6.3 pH)
3. Aluminosilicates and gibbsite (pH 4.0 – 4.5)
4. Iron Oxides Ferrihydrite and/or Goethite (2.5 pH – 3.5 pH)
5. Jarosite (1.8 pH – 2.0 pH)

Geochemical processes controlling water quality at Antamina

TSF concentrations are governed by kinetic reaction rates, equilibrium controls on saturation and associated water volumes. The major mineral assemblages are dominated by calcium containing carbonates (Strand *et al.*, 2010). Water quality variation appears to be most strongly affected by the oxidation of sulfide minerals, which drives the increase in salinity, sulfate and the acidity. Neutralization of the acidity may occur through the water's natural alkalinity, but occurs principally through the dissolution of Ca-containing carbonates. Sulfide oxidation and concurrent buffering increases salinity and releases the associated metal in the sulfide (*e.g.*, Fe, Cu, Zn or Pb). The resultant increased sulfate and calcium culminates in gypsum (CaSO₄) precipitation (Fig. 2). The continued presence of carbonates maintains neutral to alkaline conditions, which limits mobilization of many of the metals, apart from neutral drainage species, such as As and Mo.

Using the sulfate generation rate allows 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 sulfide oxidation). The site observations confirm that the concentrations of the majority of metals are a function of the pH conditions, overall salinity and mineral solubility constraints. From these observations the required geochemical mechanisms including pH determination, acid generation and neutralization, salinity calculation and solubility constraints have been built into the model (Strand *et al.*, 2010).

TSF solution chemistry was analyzed using PHREEQC to assess the precipitate phases most likely to govern solution chemistry and GWB to observe the potential speciation and the relationships between solubility, concentration and pH. Since the purpose of the IWBWQM is to simulate dynamic conditions, algorithms are used to assess how far the system is from the equilibrium condition. This is achieved by calculating the solubility product, K_{sp} , for a particular mineral at supersaturation and undersaturation. Equations 2 and 3 are examples, for gypsum, of the basis of the quantification of these non-equilibrium conditions:

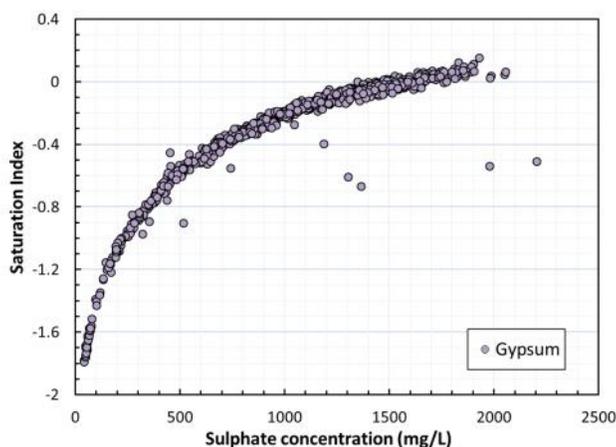


Figure 2 Saturation state of gypsum with increasing sulfate concentrations at the Antamina east waste rock dump

$$\text{Undersaturated: } ([Ca^{2+}] + \delta[Ca^{2+}]) \cdot ([SO_4^{2-}] + \delta[SO_4^{2-}]) = K_{sp(\text{gypsum})} \quad (2)$$

and

$$\text{Supersaturated: } ([Ca^{2+}] - \delta[Ca^{2+}]) \cdot ([SO_4^{2-}] - \delta[SO_4^{2-}]) = K_{sp(\text{gypsum})} \quad (3)$$

These calculate the change in the molar concentration (δ) that is required to bring the solution back to equilibrium. A series of these relationships is included in the model to move sensitive parameters in and out of solution as the pH and other variables change; those used in the TSF are shown in Table 1.

Table 1 Primary mineral controls used in the TSF section of the IWBWQM

Mineral	Formula	Mineral	Formula	Mineral	Formula	Mineral	Formula
Calcite	CaCO ₃	Gypsum	CaSO ₄		Cr ₂ O ₃	Otavite	CdCO ₃
Dolomite	CaMg(CO ₃) ₂	Anglesite	PbSO ₄	Malachite	Cu ₂ CO ₃ (OH) ₂		Pb(OH) ₂
Siderite	FeCO ₃	Brucite	MgCO ₃	Manganite	MnO(OH)	Rhodochrosite	MnCO ₃
Gibbsite	Al(OH) ₃	Cerrusite	PbCO ₃	Molybdate	Ca/Cu/Pb /ZnMoO ₄	Smithsonite	ZnCO ₃
Goethite	FeO(OH)						

Antamina site monitoring data and field kinetic testing suggests that sorption has an important control on metal concentrations at the TSF. This is taken into account in the model by calculating sorption of metal species to Fe-precipitates. The model assumes that the total iron in the TSF is the amount produced by pyrite oxidation; the dissolved iron is governed by solubility calculations. The iron precipitated at each time-step results from the total iron minus the dissolved iron. At a given pH and provided enough precipitated iron is present, the proportion of As, Mo and Se adsorbed to the precipitate is based on PHREEQC determined adsorption ratios. Although metals are typically

desorbed from other minerals present as pH decreases, this is not always the case. Figure 3 shows how the fraction of MoO_4^{2-} sorbed to a surface decreases as pH increases. In contrast, other Mo species, such as H_2MoO_4 , remain sorbed at high pH.

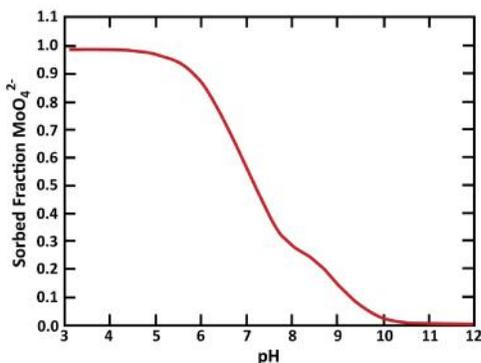


Figure 3 Sorption of MoO_4^{2-} with pH

Once the mass loss and gain and its effect on the TSF pond water dissolved solute has been determined in each time step, the dissolved solute mass for each parameter controlled by minerals/pH is assumed to be 'near' equilibrium in the pond. The concentration of solutes in the pond water is assumed to be the water quality in the pond for that time step. Any outflows from the system (barge pumped, seepage through the tailings-water interface, or other) are assigned this water quality.

RESULTS AND DISCUSSION

TSF IWBWQM model output was compared to TSF monitoring data provided by Antamina. Figure 4 shows the simulated output normalized to the site monitored data and expressed as a percentage above and below the monitored concentrations (set at 1). Simulated sulfate and chloride concentrations are within 20 % of the monitored values for the majority of the five year simulation period: this error is comparable to the analytical error associated with the monitoring data.

Figure 5 shows simulated pH levels normalized to those monitored at the TSF and expressed as percentages above and below the real values. For the majority of the simulated period, pH values are within 20 % of the real values (often within 10 %). This is comparable to analytical error. Figure 5 also shows the simulated TSF pond water volume normalized to water balance data provided by Antamina. The TSF IWBWQM produces a close calibration with the real water balance and is within 10 % of monitored values for the majority of the simulated period. In addition, Figure 5 shows the effect of deliberately 'stressing' the water balance; in this case adding an erroneous water flow of 50 L/s to the TSF pond. In this scenario the model rapidly loses the close calibration to the real data, indicating that the TSF IWBWQM is performing in close agreement to the observed water balance.

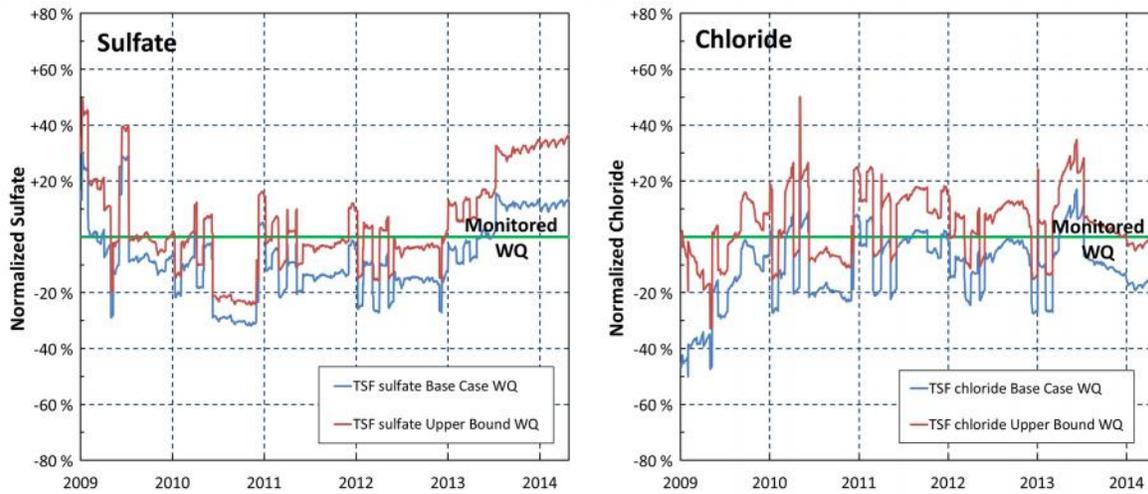


Figure 4 Simulated sulfate and chloride concentrations normalized to monitored concentrations at the TSF

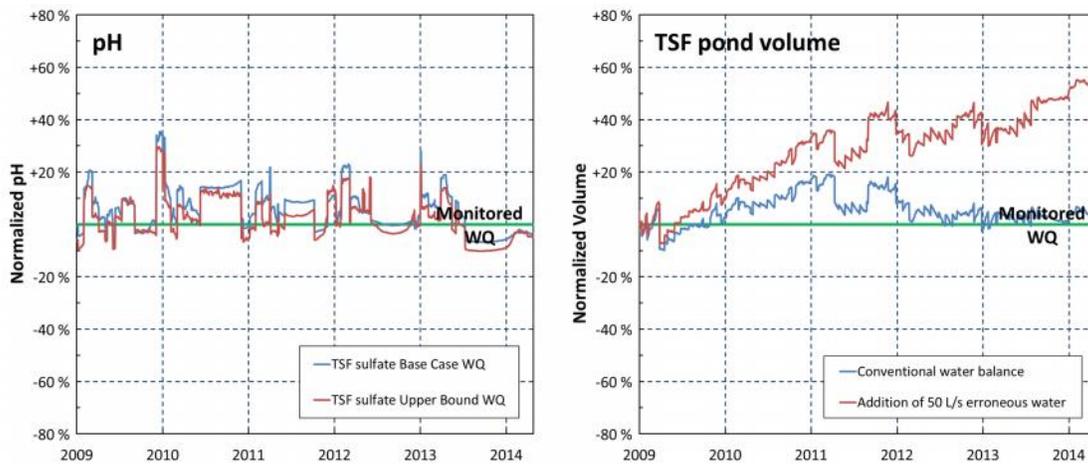


Figure 5 Simulated pH normalized to monitored pH values (LHS) and simulated TSF pond volume normalized to monitored values (RHS)

PHREEQC saturation assessment and the effect of increased sulfate to the TSF

Saturation indices of the IWBWQM mineral controls (Table 1) were calculated using PHREEQC, based on monitored TSF water qualities under the conditions of the mine site. Using PHREEQC in conjunction with the model is an iterative process and allows for continual adjustment of the controls as more data become available. Figure 6 shows that there is generally a good agreement between the TSF IWBWQM expected minerals (which, for equilibrium should be zero) and the saturation indices calculated in PHREEQC.

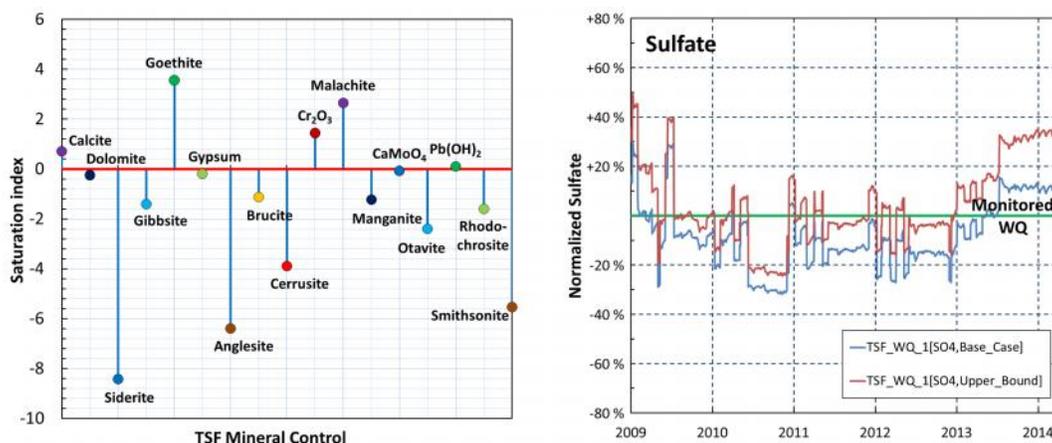


Figure 6 PHREEQC saturation indices using the water quality monitored in the TSF by Antamina (LHS) and normalized TSF sulfate concentrations after a 6-fold sulfate increase at 100 L/s (RHS)

The IWBWQM was tested for its robustness to changes in conditions by simulating an increased sulfate addition to the TSF. Figure 6 shows that, in spite of the increased sulfate input (here this is simulated as a 6-fold sulfate increase at 100 L/s), the TSF sulfate concentrations remain within 20 % of the monitored values (*cf.* Fig. 4) and suggests that the mineral control mechanisms built into the model can adjust to this influx; the IWBWQM moderates the impact of the additional sulphate by allowing oversaturated minerals to precipitate.

The Antamina site is ideal for applying the IWBWQM principles to other mine site facilities. Figure 7 compares the simulated normalized concentrations at the East Waste Rock Dump (EWRD). Although simulated sulfate is consistently lower than shown in the monitoring data, the values are, nonetheless, within 20 % for the majority of the simulation.

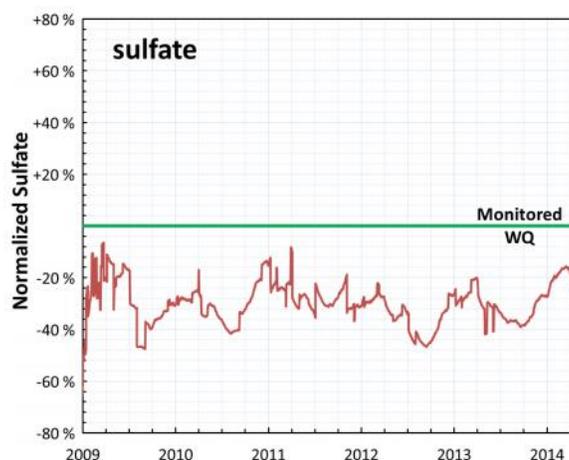


Figure 7 Simulated sulfate concentrations normalized to monitored concentrations at the EWRD, Antamina

CONCLUSIONS

This report outlines the infrastructure of the TSF IWBWQM and testing that has recently been conducted to check the mechanisms and controls within the model. The model is based primarily on site observations and fundamental geochemical principles: monitored water qualities are used provide the provisional model calibration and the water balance and water quality components of the model are continually updated as more information becomes available. Testing of the TSF IWBWQM has shown that the simulated water quality is within 20 % of that monitored at the mine site. The simulated TSF is closely calibrated with water balance data provided by Antamina.

Comparison with hydrogeochemical modelling programs, such as PHREEQC, shows that the TSF IWBWQM is operating as predicted by these programs. Nevertheless, the mechanisms built into the model are continually revised (with the aid of programs such as PHREEQC) to optimise the performance of the model. It is expected that this process will continue.

This paper has focused on the TSF facility at Antamina, but the mine site provides an ideal setting to test the application of the model to other facilities. Here we show examples applied to the East Waste Rock Dump.

ACKNOWLEDGEMENTS

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