Predictive Site-wide Water Quality Modelling as a Tool for Mine Planning and Permitting: A Recent Canadian Example

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Abstract

An integrated and dynamic water balance and water quality model for a proposed base metal mine has been created using the GoldSim™ software package. The model was initially developed to address the water quality of the Tailings Management Facility pond and how pond discharge would potentially affect downstream water quality. However due to changing project objectives, the modeling has expanded over time through an iterative process to encompass the full mine site and all receiving environment water quality. The model results have been used as part of the mine planning/design process but are also intended to be used for the environmental impact assessment and permitting process. The model results serve as a prediction of water quality and the potential project impacts to the receiving environment water quality. This paper presents the process by which data from a wide variety of sources was used to construct the model and how the model results were used to guide development of a conceptual water management plan. In addition, the role of the model in establishing proposed discharge criteria will be highlighted. The model has been delivered as a fully functional application and the development of this aspect shall also be covered. The intent is that the end-user can be other than the modeller.

Key Words: GoldSim™, base metal mine, water management, case study

Introduction

A key aspect of the environmental impact assessment and permitting for a future mine project is an assessment of the potential impacts that the project may have on the receiving environment. A key input to this impact assessment is the prediction of potential changes to water quality in the receiving environment as influenced by the mine site and associated activities. This can only be predicted through a process of modelling that is not always transparent to the end-users of the model results. Therefore the validity and applicability of the results cannot always be easily ascertained. These end-users include the mine developers, regulators and the general public.

A proposed Canadian base metal mine development has presented an opportunity to develop an integrated water balance and quality model to meet the inherent goals of water quality prediction and to produce a model that can be used and understood by the end-user of the model results.

The resulting site-wide water quality model was developed with the goal of predicting the potential impacts of mining activities on the receiving environment and identifying water management strategies to mitigate any potential impacts.

The model was built using the GoldSim™ software package (GoldSim, 2011) and was primarily based on mass and volume balance modeling with limited application of semi-dynamic geochemical constraints derived from external thermodynamic modelling. The model was built to address two specific potential water quality impacts and also to provide general prediction of site water quality. The two specific impacts to be assessed were:

- the potential impacts from water treatment plant effluent discharge to downstream receiving environment water quality(and the development of water treatment plant polishing pond discharge criteria for permitting), and
- the potential impacts of Tailings Management Facility (TMF) seepage to downstream receiving environment water quality (and the definition of design criteria for TMF seepage rate).

In addition, as a consequence of the need to track the water volumes and flows within the model for water quality prediction, the model also generates the required storage capacities for the various reservoirs and the required staging for the TMF dam construction.

The model was delivered as a self-contained GoldSim^{TM} Player file which is operable by the freely distributable GoldSim^{TM} Player executable. The intention of the player file is to be intuitive for the end-user, report needed results and to allow for any anticipated changes in numerical input terms. A limited number of options are provided that reflect different water management strategies, but not all real-world possibilities can be incorporated in these options without the quantitative definition of the management options.

Rather than give a full description of the model and the mechanisms used within it, this paper describes the model in conceptual terms as well as the iterative process by which the model was developed and how it has influenced the conceptual mine design and the detailed mine plan .

Current Mine Project Description

The proposed mine project exploits two geographically separate base metal ore bodies. Ore from two mines (MINE 1, MINE 2) will be processed to produce two base metal concentrates in an onsite mill and concentrator (MILL). The tailings will be deposited subaqueously to an engineered TMF. The waste rock will be returned underground as backfill. The relative locations of the main water quality model components are shown in Figure 1.

The mines and the mill are located in a stream valley (STREAM 1) with the mines located both upstream and downstream from the mill. The TMF lies in a separate stream valley (STREAM 2). STREAM 2 flows into STREAM 1 that subsequently flows downstream approximately 13 to a confluence with a larger river (RIVER 1) approximately 13 km.

Water Management Strategy

The water management strategy explained here is the end result of the iterative process of the model results influencing the mine plan. The evolution of the water management strategy is given in the Model-Plan Iterative Process section below.

The water management strategy changes from the development phase through to the closure phase. The development (1 year) and transition phases (~1.5 years) are brief in length and water management is highly reactive in these periods.

Figure 1 shows the spatial arrangement of the mine and receiving environment locations discussed below.

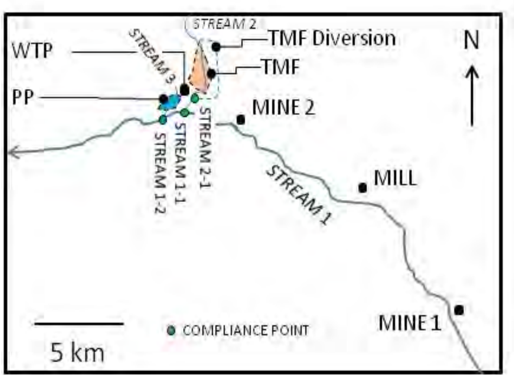


Figure 1 Spatial arrangement of project and receiving site components and representation in model. Not shown; RIVER 1 and compliance point RIVER 1-1(approximately 13 km downstream of STREAM 1-1)

During the development phase, streamflows are diverted from STREAM 2 and its catchment around the TMF by means of diversion ditches to a discharge point in the original STREAM 2 below the TMF. The mine water of MINE 1 reports to STREAM 1 via a temporary water treatment plant (WTP) while MINE 2 reports to the TMF pond. Seepage from the TMF will be partially captured by a seepage pond that will then be returned to the TMF pond. Surplus TMF water is treated via the permanent lime WTP at the maximum available treatment rate and discharged to a polishing pond (PP) located in the valley of a 3rd stream (STREAM 3). The PP releases water seasonally at a rate controlled by the receiving flow to a maintain a fixed dilution ratio at the discharge point in RIVER 1 below the confluence of STEAM 1 and RIVER 1. The release of PP water is also dependent on meeting the designated water quality discharge criteria.

During operations, the flows of the development phase are mostly maintained but with the following changes. Water from MINE 1 is used as part of feed water for the MILL; the MILL draws on the TMF pond as a process water source while also discharging the water content of tailings to the TMF pond. An additional freshwater source is envisioned for the MILL as water is also lost from the system with the concentrate produced.

The TMF Pond is managed to achieve a minimum 1 m water cover on the deposited tailings. The WTP is operated at a variable rate within its operational range so as to optimize the operational time of the WTP, reagent consumption, and minimize TMF Pond surplus all while minimizing cost.

The transition phase begins with the end of mining and mill operations and ends when the WTP can be shut down. The WTP can be shut down when the release of untreated TMF Pond water via the spillway to STREAM 2 will not cause Water Quality Objective (WQO) exceedances. During the transition phase, the MINE 1 and MINE 2 will cease to be dewatered, removing the mine-water flows, and the MILL and its associated flows will be removed. The WTP will be operated at the maximum available rate with discharge to the PP and operation of the same as during operations.

At closure, the diversions around the TMF will be removed and all of STREAM 2 will pass to the TMF Pond. A spillway at an elevation designed to maintain a designated pond surface area and depth will passively control the TMF volume. An engineered cover designed to minimize infiltration and oxygen ingress will cover the tailings beach. The TMF spillway will discharge to STREAM 2. The WTP and PP will be removed along with the associated discharge pipelines. STREAM 3 will be restored to its previous streambed and report directly to STREAM 1. As the groundwater table rebounds in MINE 1 and MINE 2 and reaches a steady-state, their discharge will report to STREAM 1.

Water Quality Objective compliance points for the receiving environment are below the TMF in STREAM 2 (STREAM 2-1), at the confluence of STREAM 1 and STREAM 2 (STREAM and in RIVER 1 at the discharge point of the polishing pond (RIVER1-1). An additional monitoring point is the TMF Pond.

Model Description

The model is based on the representation of the natural drainage system and future mine components by a series of nodes and pathways. The nodes are intended to represent discrete and separable parts of the minesite and the receiving environment. In this model, nodes are separated primarily on the basis of geography and mining function. The pathways represent flows of primarily water but also in some cases mass. The pathways change as a result of changes in operational phase or as a result of options simulated in the model. The model was constructed to run at a monthly timestep, sufficient for representation of seasonal variation but long enough to eliminate the need to incorporate lag times to represent physical distances or reaction times.

The model follows a general mass balance approach and the following general equations for water flow (Q, Equation 1) and parameter mass flow ($\dot{M}$, Equation 2) apply:

$$Q_{out} = \sum Q_{in} \quad (1)$$

$$\dot{M}_{out} = \sum \dot{M}_{in} \quad \mathbf{(2)}$$

It then follows that a concentration ([X]) can be determined (Equation 3).

$$[X]_{out} = \frac{\dot{M}_{out,X}}{Q_{out}} \quad (3)$$

Model Assumptions and Limitations

As with any model, this model is only as good as the quality of its underlying assumptions and accuracy of input terms. The following is a list of main model assumptions, each of which creates model limitations:

- No snowpack accumulation
- Fixed climatic inputs
- Geographic distances not discretely modelled : long timestep accounts for any lag
- No load source depletion
- Fixed loading rates
- Fixed background water quality with no seasonal variation
- Fixed suspended solid content with no dynamic modeling of changes due to flow differences
- No linkage between the climate and groundwater flows;
- Concentration limits semi-dynamic and imposed at limited locations
- Sorption is not modelled
- Tailings supernatant water quality is fixed.
- TMF simplified to idealized geometry
- Consolidation in TMF to final state is instant
- No temperature effects

In the absence of input data to supply the model, the effort to produce a more sophisticated model is not warranted. In other words, the model complexity should match to the level of available data and the goal of modeling. As a potential minesite, many of the input source terms can only use best judgments on the basis of analog data and observations made at other minesites to validate the model results until the project is approved and the mine is constructed and in operation. Another key aspect was, in the absence of data, to be conservative so as to produce a 'worst-case' scenario.

Model Pathways

The model pathways largely reflect the water management strategies as described in the Water Management Strategy section, with a few additions as described further below. The development and transition phase pathways are not described here due to their short time span. There are additional internal pathways within these models (in particular the TMF) but these details are not covered in this paper. It should be noted that these networks do not explicitly include the climatic inputs (precipitation) and outputs (evaporation) of water.

The pre-existing baseline water flow network is shown as Figure 2. The addition of a groundwater source flowing to Stream 2-1 and Stream 1-1 reflects the overall model requirement to assess the potential impact of TMF seepage. This flow is based on external groundwater flow modelling and has a water quality derived from site groundwater samples. Note that it is only these nodes that receive a groundwater flow.

The operating phase network (Figure 3) incorporates mass flows as well as the water flows. These consist of ore moving from the MINE 1 and MINE 2 to the MILL, tailings moving to the TMF and concentrate leaving the model.

The uncaptured seepage from the TMF is represented as mixing with the existing groundwater and then flowing to STREAM 1 and STREAM 2 below the TMF. The diversion of STREAM 2 around the TMF is represented as imperfect as: 1) the diversion channels are defined by a conservatively assumed 60% mean effectiveness as an input term, and 2) there still be a small catchment area that is below the diversion channels.

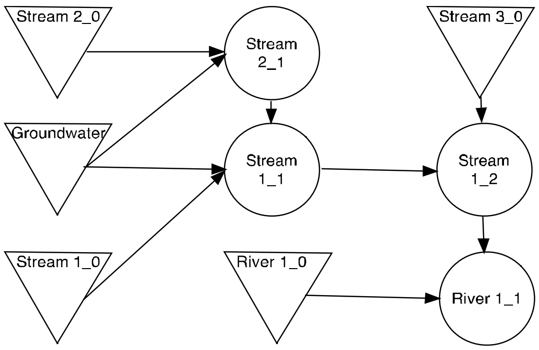


Figure 2. Existing Site Water Network
Material

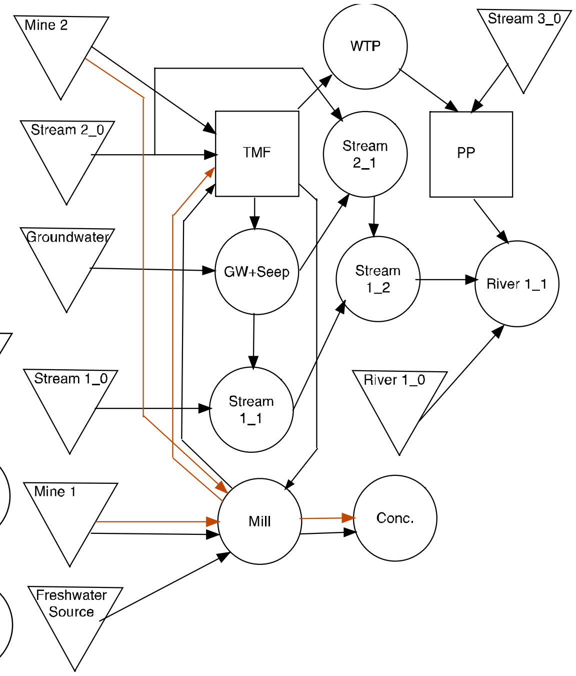


Figure 3. Operations Site Water and
Network. Material flows in brown

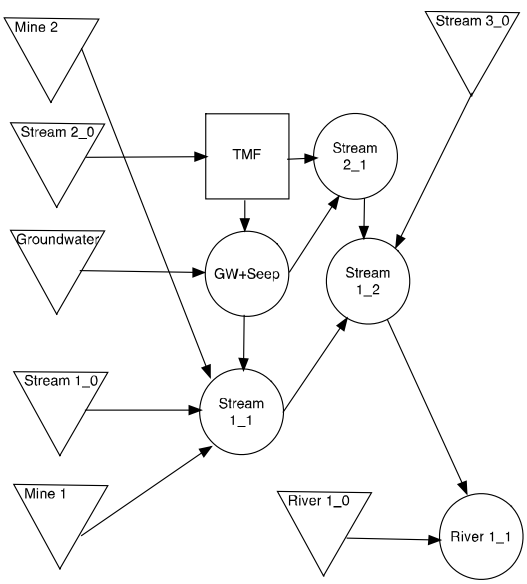


Figure 4. Closure Site Wide Water Network

The controls on the release of flows from the nodes of the network are individual to each of the components. For example, the flow from the TMF to seepage is represented as a fixed flow while the flow to the mill is variable, dependent on what the mill production rate is while also maintaining the specified water cover over the deposited tailings (to preclude near-neutral metal leaching). The rate of water treatment is controlled by the quantity of surplus water and the variable operating rate of the WTP.

The closure phase of the model network (Figure 4) sees the removal of the WTP, the PP and the MILL. In addition, all material flows are ended and the STREAM 2 diversion around the TMF is removed. The TMF releases water to STREAM 2-1 and STREAM 3 flows direct to STREAM 1-2.

Input Terms

Input terms for background water quality, hydrology, and meteorology, waste rock and tailings loadings, mill and concentrator design, metallurgy bench scale testing, mine water quality, mine water flows, and water treatment were developed by other consultants.

Groundwater flows in the vicinity of the TMF (flowing to STREAM 2-1 and STREAM 1-1) were developed from external modelling. Solubility limits for the TMF Pond, exposed beach tailings, and TMF Pore Water were developed using external geochemical solubility modelling using the latest version of the PHREEQC code (USGS, 2011) and the mean unlimited concentrations in the reservoir as determined by a prior simulation using the same code for a operationally-defined time period as input source terms to the solubility modelling. The resulting concentration limits are applied to the relevant model node as in equation 4.

$$[[X]]_{node} = \min\langle [\mathbf{X}]_{\mathbf{mass\,balance}} | [\mathbf{X}]_{\mathbf{limit}} \rangle \quad (4)$$

Geochemical characterization work indicated that tailings, as generated from metallurgical test work, are at a low risk for net acid generation as they have sufficient neutralization potential to counter the acid potential of contained sulfide minerals (NPR > 2) but that neutral metal leaching may be an issue due to elevated content of the Se and Cd in the tailings. The ultrafine grind of the metallurgical process produces a high abundance of solid particulates smaller than 0.45 µm which report to the ‘dissolved’ phase of the supernatant thus leading to a potential over-prediction. The characterization work also includes kinetic testing. The results of were used to define the load rate source term of the TMF tailings beach.

The model was built so that the input terms are readily visible and can be easily changed via Dashboard elements in the model. This was done in recognition of for user input of changes in many of the input terms and the need for greater transparency of the model assumptions.

Water Quality Objectives

The Water Quality Objectives used in the model are a combination of Canadian Council of Ministers of the Environment (CCME) freshwater aquatic life guideline values (CCME, 2011) and a number of site-specific criteria developed with reference to measured water quality at the site. The PP water quality discharge criteria have been developed in an iterative process to establish levels at which a release of the PP water at a rate consistent with a minimum dilution of the PP flow by the receiving flow of 30 to 1. The development of these criteria is discussed further in a following section.

The TMF Pond monitoring WQOs are based on the CCME livestock guidelines (CCME, 2011). This reflects a desire to protect wildlife that may use the TMF Pond as a water source following closure but reflects that the TMF Pond is unlikely to support an aquatic population.

Model Simulation Parameters and Sub-models

The model was run on a monthly timestep and can be run for any simulation length although the standard period was designed to be 30 years. A brief explanation of some of the sub-models in the model is warranted and provided below.

Climate and Hydrology Sub- model

The climate and hydrology sub-model is run on a fixed input term basis with precipitation and lake evaporation being governed by the month of the year. From these input terms, runoff flow (ie m^3/hr) is calculated by multiplying the catchment area (m^2) by the annual precipitation (mm/month) by a runoff coefficient (unitless) and a runoff distribution (Equation 5).

$$Q_{runoff} = P_{annual} * \mathbf{k_{runoff}} * A_{catchment} * k_{catchment} \quad (5)$$

Direct precipitation flow to reservoirs (e.g. TMF Pond) is the precipitation multiplied by the reservoir water surface area. The lack of a shallow infiltration component dictates a high runoff coefficient for most of the model catchments. Only the area around the TMF has a specific groundwater term that has been determined by external groundwater modeling. The groundwater term is not linked to climate. The input terms for groundwater flow to the mine void have also been determined by independent groundwater modelling and are not coupled to climate but are scheduled to month and year under assumed average climatic conditions and mine development stages.

Water Treatment Sub- model

The WTP is represented in the model by applying a fixed maximum concentration limit for most of the water quality parameters on the flow passing through the WTP node. This limit does not change in response to changes in influent water chemistry. The operating function can be illustrated as equation 6.

$$[X]_{effluent} = min([X]_{limit} | [X]_{influent}) \quad (6)$$

The maximum concentrations are based on an input setting of the operating pH of the WTP. These are derived from bench scale treatability testing on a synthetic solution of anticipated WTP influent water quality.

The rate of treatment is based on setting a treatment rate on an annual basis so as to process the annual surplus TMF water volume in a minimal amount of time but maintaining continuous operations. The nominal treatment rate of the plant is 300 m^3/hr but is allowed to operate within +/- 30%. During the pre-development and transition phases, the treatment plant is modeled to run at maximum treatment rate but this can be altered to accommodate a lower start-up treatment rate.

Tailings Management Facility Sub- model

The TMF in the model is a multipart node that consists of: the TMF Impoundment (the geometry of physical space and the deposited solids that fill it), the TMF Pond (the physical space of the TMF Impoundment not occupied by solids and the water within this space), the TMF Porewater (the water occupying the void space of the deposited solids), the TMF Dam and the TMF Pond. Each of these components is defined somewhat differently. The fundamental input terms are the stage storage curves that define the geometry of the impoundment. The water and material inflows are stored with the geometry of the solids being modeled, defined as the surface of a perfect inverted cone. This representation greatly simplifies the calculation in the absence of a complete geometric model of tailings deposition. The solids geometry defines the volume of water required to maintain the prescribed water cover. The geometry of TMF Pond is defined by the geometry of the TMF Solids as well as the original ground as represented by the stage storage curves when the TMF Solids are completely submerged. The solids are represented as being deposited in a fully consolidated fashion with no further loss of void space being modelled.

The TMF Beach in the model represents the area and volume of tailings that are above the TMF Pond. Under the Water Management Strategy, there is no exposure of the tailings during operations but following closure there will be some exposed beach tailings. The model is also built to simulate the effect of exposed beach tailings if the water cover is not maintained. The exposed beach tailings will contribute load, as calculated by multiplying the waste characterization kinetic cell load rates (as mass/area/time) by the area of beach exposure and a scaling factor with a solubility control imposed on the beach runoff and seepage flows (as supplied from direct precipitation). This approach eliminates the need to discretely model the volume of unsaturated tailings which would require unavailable data.

Examples of the Model-Mine Plan Iterative Process

There are two major aspects of the mine plan that have been directly affected by the results that the model produced. These are the management of the TMF surplus water volume and the relocation of the Polishing Pond.

The original Water Management Strategy entailed a release of surplus TMF water to a Polishing Pond located in the STREAM 2 catchment below the TMF via a Water Treatment Plant. The surplus volume of the TMF Pond would be stored *in-situ* with the WTP operating only when the discharge could be accommodated by the receiving environment without exceeding WQOs (ie the Polishing Pond would effectively have no storage capacity).

The first versions of the model with this Water Management Strategy in place showed that the capacity required for the TMF Pond under these conditions would not be feasible so that it was necessary to change the strategy. The first modification expanded the role of the Polishing Pond to also encompass the surplus water storage requirement previous taken up by the TMF Impoundment. The model results with this modification showed that the capacity requirement of Polishing Pond to store the WTP discharge for seasonally controlled release could not be accommodated within the original location of the Polishing Pond (below the TMF in the STREAM 2 watercourse). There was insufficient dilution available at the discharge location (STREAM 1-1) to allow reasonably achievable Polishing Pond water quality due to the limited flow available in STREAM 1. This led to the relocation of the Polishing Pond.

The new Polishing Pond location was chosen on the basis of a map study with specific location data available at that time. The new location required a new set of stage storage curves to define the geometry of the Polishing Pond. These could be determined by geometric analysis of the elevations of the location using 3D mapping software. The physical suitability and characteristics of the location had not been determined via site-investigations so that a number of assumptions had to be made about the site and incorporated into the model. This included an assumption of zero seepage and the assignment of the same runoff coefficient for STREAM 3 as for the rest of the model.

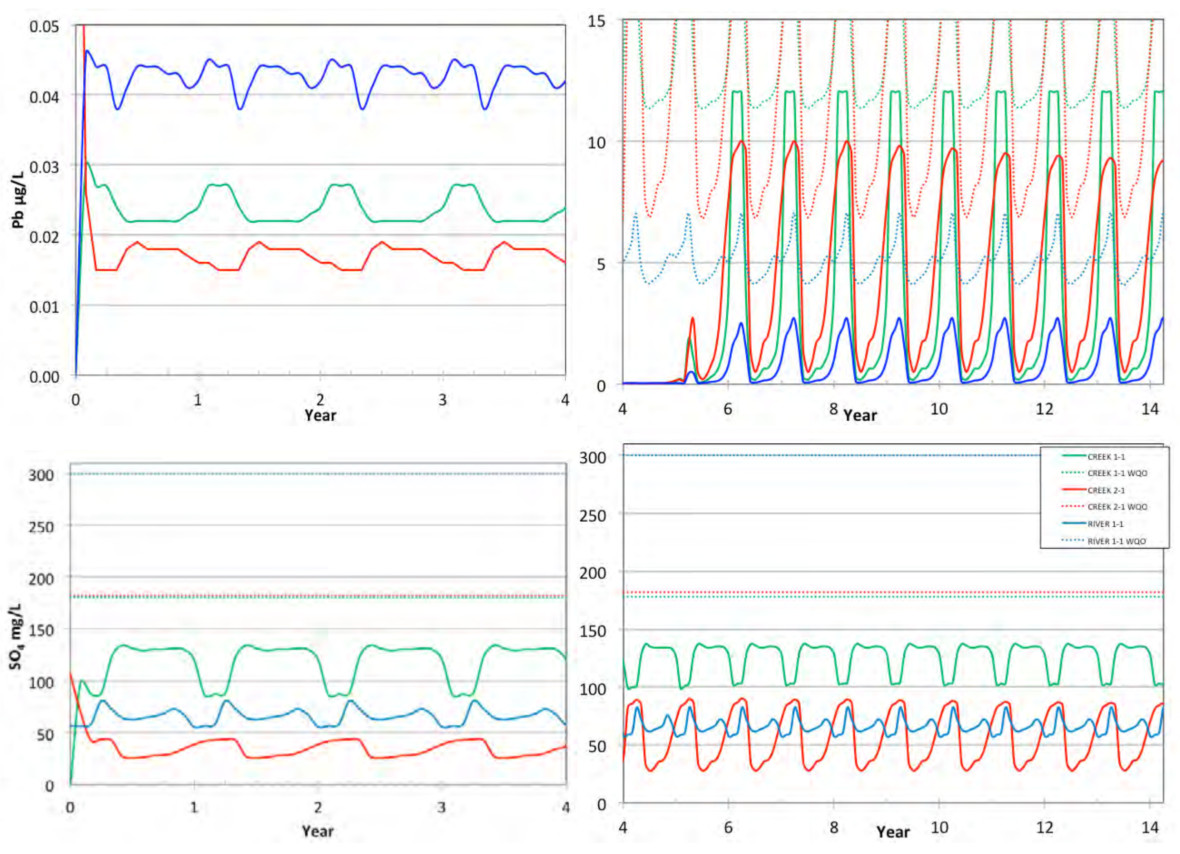
Another example of the iterative process is the application of the Polishing Pond water quality discharge criteria. These criteria set what the maximum allowable concentration of a parameter is in the Polishing Pond for release to the receiving environment. This was defined in the first iteration of the model to mean a release at the specified concentrations that would not cause Water Quality Objective exceedances in the receiving environment. As the changes in water quality concentration in the receiving environment is more a function of the “load” (ie concentration x flow) contributed by the Polishing Pond, the criteria was further defined by fixing the discharge rate for the Polishing Pond at a fixed fraction of the receiving flow. This dilution factor changed from 15 at the original Polishing Pond location to 30 at the new location of the Polishing Pond with discharge to RIVER 1 rather than STREAM 1. The increased dilution factor reflects the greater receiving water flow capacity in RIVER 1 located approximately 13 km downstream and also receiving flow from a significantly larger catchment (as defined by an input term catchment value and the climate submodel).

The discharge water quality criteria themselves are based on previously-issued discharge permits in the same jurisdiction as this project. Specific simulation of the case of the Polishing Pond being at the discharge criteria concentrations was built into the model to demonstrate that downstream water qualities would not exceed WQOs when under this scenario. The model results show explicitly that the discharge of Polishing Pond water under the specified conditions (seasonal release at a 30x dilution) and at the discharge criteria would not cause downstream WQO exceedances.

The model has also been modified as changes to the mine plan that were made independent of the model results.

Selected Model Results
A few model results are presented to illustrate the type of results that the model produces. They represent only a small portion of the results that can be produced by the model as the model tracks 48 water quality parameters in each pathway and reservoir at the monthly model timestep.

The primary goal of the water quality model was to obtain water quality results and comparison to WQOs. A few of these parameters (Zn, Pb, and SO_4) for the predevelopment and the operational periods are shown as Figure 5. Lead is the most critical parameter as it comes closest to exceeding WQOs.



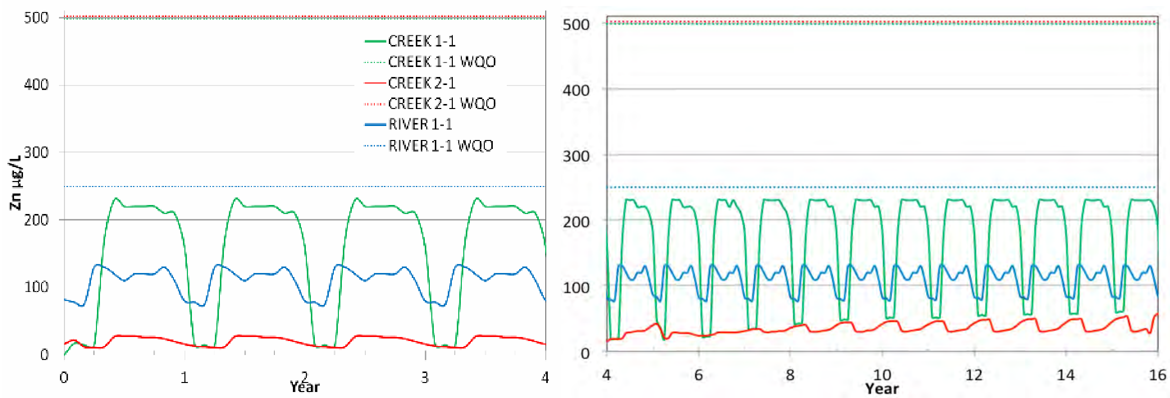
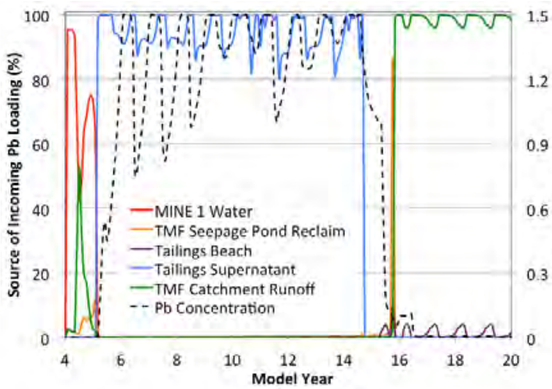


Figure 5.Zn, Pb, and SO_4 Concentrations at Model Compliance Points in Predevelopment (years 0 to 3l {left column}, Development (year 4) and Operational Period (years 4-14) {Right Column}. Note Y-Scale Change between left and right Graphs for Pb.

The model can also report the origin of load sources to a reservoir as shown in Figure 6. Incidentally, this shows the dominant origin of lead in the TMF Pond to be the tailings supernatant and also show the effect of the removal of the TMF diversions.

A second group of results are the water balance results. An example of this is shown in Figure 7, representing the closure TMF spillway flow. This is a necessary part of the TMF engineering design process that the original the model is intended to support.



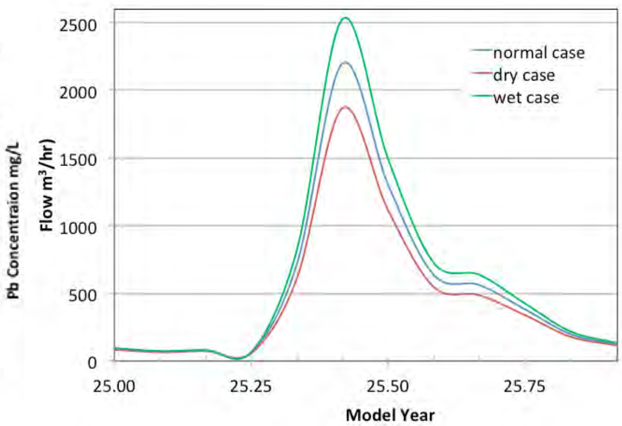


Figure 6. Origin of Lead Loading to TMF Pond under

Figure 7. TMF Spillway Flow in Year 25 normal, wet, and dry climate cases.

Finally the model also produces the results needed for the staging of the TMF dam in the form of the required elevations for the dam crest, the spillway, and a suggested staging taking into account the environment design flood, the need for tailings storage capacity and the need for temporary storage between the spillway and the dam crest (to prevent over-topping). This is seen in Figure 8.

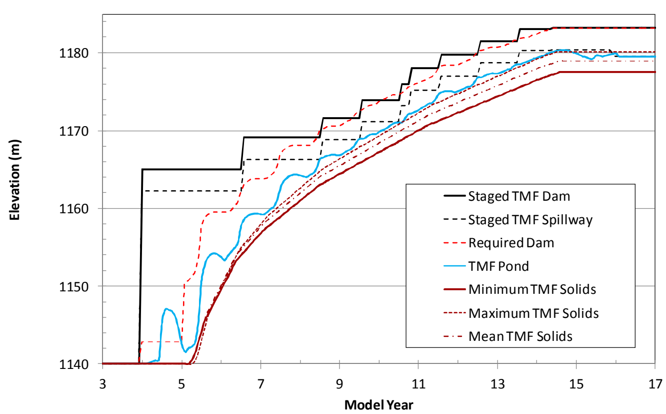


Figure 8. TMF Dam and Contained Solids Elevations

The impact of each of these limitations on the model results is specific to each water quality parameter, although on an overall basis the assumptions used to account for the limitations produce conservative errors in over-predicting the mean concentrations of the water quality parameters.

Outcomes

The results of these additional studies may result in both additional data that could be used as refinement of the input sources terms as well as changes in the overall mine layout that would require changes to the underlying pathway structure of the model. This is likely to include a more detailed water balance concerning the Polishing Pond to include seepage and the possible diversion of upstream catchment area.

Going forward, the model is intended to be run with uncertainty simulations to assess the sensitivity of model results to individual input terms. This will help identify where effort needs to be directed in characterization and design of the project for the greatest reward in project optimization.

The Model Player File and the User Interface

A key consideration in constructing this model was to produce a model that was useable for an end user with a minimal amount of modeling experience and an interface that is intuitive rather than relying on extensive user documentation. This allows the end user to easily make changes in input terms.

Acknowledgements

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References

CCME (2011), *Canadian Environmental Quality Guidelines Summary Table*, Viewed November 5, 2011, http://st-ts.ccme.ca/

GoldSim (2010), *GoldSim User Guide*, Viewed 5 November 2011, http://c0046032.cdn.cloudfiles.rackspacecloud.com/GoldSim%20Vol%201.pdf

USGS (2011), *PHREEQC (Version 2)--A Computer Program for Speciation, Batch-Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations*. Viewed 5 November 2011, http://wwwbrr.cr.usgs.gov/projects/GWC_coupled/phreeqc/

Acronyms

PP: Polishing Pond
TMF: Tailings Management Facility
WTP: Water Treatment Plant
WQO: Water Quality Objective