

A Practical Application of Mass-Balance Methods for Predicting Mine Drainage Water Quality – Climate Influences and Best Practices

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Abstract

Water quality models have evolved to become a key component of the environmental and engineering studies that are typically performed for permitting, mine planning and mine design. As the results derived from these models are used to support fundamental decision-making processes, it is essential that the simulated results are representative of the system being modeled. Mass-balance approaches have been developed to estimate the drainage water quality from mine sites; however, model outputs using these methods can be sensitive to site-specific climatic conditions. Therefore, it is important to understand the climatic influences at each site to determine if the conceptual approach is suitable for the system being modeled.

This paper examines the differences of using loading rates and assigned water qualities, derived from humidity cell tests, to simulate mine site water quality and the influences various climatic scenarios can have on the model outputs. Advantages and disadvantages of each method are presented along with a discussion of best practice modeling techniques to ensure an appropriate method is selected to produce simulated water qualities that are representative of a modeled system.

Key Words: water quality modeling, mine water quality, climate, best practices

Introduction

Water quality modeling is an integral component of the mine design process. The results of water quality predictions are often used to develop mine water and material management strategies and mitigation strategies during the engineering design stage of a project. Water quality monitoring programs are then developed to confirm that the mine can operate in a manner that is environmentally protective throughout the life of mine (LOM). Therefore, water quality models must provide a reasonable representation of the system to impart confidence that the simulated results are conservative but also realistic.

Water quality predictions are generally based on the use of input source terms that are selected to simulate the drainage quality from site facilities that will be constructed during mining (e.g., waste rock piles and tailings storage facilities). Inputs can be derived from a number of sources, including laboratory testing, field scale testing, and site specific water quality monitoring of natural and operational waters. The results of the laboratory-based humidity cell test (HCT) procedure (ASTM D5744-07) are commonly used to derive input source terms that can be incorporated into geochemical models. These data tend to be the only available data source for mine-related runoff within the timeline of most mine permitting projects; data from field scale leach tests and site specific monitoring data tend to become available as projects advance. In order to advance mine permitting projects, assumptions are made using the available HCT data as source term inputs to water quality predictions.

The results of the HCT procedure can be used to define several types of source term inputs, including: a chemical loading rate per unit of mass in mg/kg/week, a chemical loading rate per reactive surface area of material in mg/m²/week or an assigned water quality in mg/L based on a period of observation in the HCT (INAP, 2009). There are no widely-accepted criteria for the application of the results of laboratory-based kinetic tests for the purpose of water quality modeling. The interpretation of the results of kinetic testing

for the purpose of input to water quality predictions is largely judgement based. Assigned water qualities assume that all water coming into contact with a tested material adopts the quality observed in the lab test, whereas loading rates assume a constant flux of mass into a simulated volume of water. Application of these different approaches to calculating source term water quality can yield different model results, even for source terms derived from the same HCT sample. The assigned water quality approach assumes that the results of an HCT are analogous to the weathering of mine materials in a field condition, which may not be realistic depending on difference in site climatic conditions, differences in sample preparation and scale (MEND, 2009). A mass based approach, on the other hand, can require the use of arbitrary scaling factors to arrive at realistic solutions. Regardless of approach, drainage chemistry depends on both primary mineral reactions, and precipitation and dissolution of secondary minerals (MEND, 2009), which are factors that may be strongly influenced by site-specific conditions. The model approach should be conservative and take into account all relevant factors that can influence site water quality.

This paper examines the differences that arise through the use of two different approaches: applying a chemical loading rate per unit mass, and an expected water quality derived from one HCT charge to the same mine site facility. These are referred to herein as mass-based and assigned water quality approaches, respectively. The advantages and disadvantages of both of these approaches are also discussed as part of the current study. A case study of a hypothetical mine in Canada is provided to demonstrate these approaches.

Methods

A deterministic mass balance model was developed to simulate the water quality of a hypothetical Tailings Storage Facility (TSF) using the GoldSim™ Contaminant Transport Module (GoldSim, 2010). The facility was assumed to have a one kilometre squared tailings beach filled to the design storage capacity of five million tonnes of tailings. Downstream of the tailings beach, runoff and seepage waters drain to a collection pond with a maximum capacity of 115,000 m³. The collection pond was assumed to be at capacity at the beginning of the model simulations.

Processes that could impact the water quality in the TSF collection pond, which were incorporated into the GoldSim mass-balance model include:

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|---------------------------|---|
| 1) Precipitation: | Dilution of standing water from meteoric water falling directly on the pond. |
| 2) Evaporation: | Concentration of pond water. |
| 3) Tailings Beach Runoff: | Concentration of site water runoff over mine waste materials. For the current evaluation, it was assumed that seepage and runoff would have the same water quality, and all precipitation was released as runoff. |

The composition of direct precipitation was assumed to be pure water containing no total dissolved solids (TDS) and only contributed dilution to the TSF collection pond.

Geochemical source terms, representative of tailings runoff, were calculated as the average of the last five weeks of humidity cell testing. An example of these calculations is provided in Table 1. Two approaches were used to evaluate the effect of runoff from the tailings beach:

- 1) A chemical loading rate per unit mass; and
- 2) An expected source term water quality.

In concept, the model is expected to predict the same trends for every modeled parameter since only one source contributes chemical load to the TSF collection pond (i.e. tailings beach runoff). For the purpose of the discussion in this paper, only sulphate concentrations are presented to highlight the differences of mass-based and assigned water quality predictions.

The mass-based and assigned water quality approaches were applied to simulate the TSF collection pond water quality for a synthetic climate developed to represent an Arctic Canadian environment characterized by distinct seasonal periods. Runoff over the tailings beach was assumed to be distributed from May to October with freshet occurring in June to coincide with the spring snowmelt. Evaporation occurred from June to September. The distribution of these two parameters is presented in Table 2.

Table 1. Geochemical Source Terms

Parameter	Units	Tailings Hcell-1 ^a					
		Wk 56	Wk 57	Wk 58	Wk 59	Wk 60	Model Source Term ^c
Volume in	mL	500	500	500	500	500	-
Volume out	mL	472	434	468	455	480	-
[Sulphate (SO ₄)]	mg/L	234	310	272	286	262	273
[Sulphate (SO ₄)]	mg/kg/week ^b	11.0	13.5	12.7	13.0	12.6	12.6

Notes:

- a) Humidity cell results are hypothetical.
- b) Loading rates were reduced by a factor of 10 to account for preferential flow pathways in the TSF.
- c) Average of the last five weeks of testing.

Table 2. Monthly Precipitation and Evaporation Distributions

Month	Distribution	
	Precipitation	Evaporation
January	0	0
February	0	0
March	0	0
April	0	0
May	0.05	0
June	0.42	0.15
July	0.23	0.37
August	0.15	0.32
September	0.1	0.16
October	0.05	0
November	0	0
December	0	0

Mass-based approach loadings occurring during the winter months were stored and released during freshet in June. To evaluate the sensitivity of the mass-based and assigned water quality approaches to defined climate boundary conditions, TSF collection pond water quality was projected for the following three scenarios:

- **Base Case** – Net Surplus Scenario: Annual precipitation greater than annual evaporation.
- **Sensitivity Case 1** – Reduced Precipitation Scenario: Annual evaporation was greater than annual precipitation.
- **Sensitivity Case 2** – Increased TSF Footprint: Base Case Scenario with a five-fold increase in the TSF area.

The model attributes for each of these scenarios is presented in Table 3.

Table 3. Model Scenario Attributes

Model Scenario	Precipitation (mm/yr)	Evaporation (mm/yr)	TSF Footprint (km ²)	TSF Collection Pond Area (km ²)
Base Case	840	550	1.0	0.1
Sensitivity Case 1	400	550	1.0	0.1
Sensitivity Case 2	840	550	5.0	0.1

Approximately 10,000 m³ of precipitation and 840,000 m³ of tailings beach runoff is expected to report to the TSF collection pond annually, and approximately 6,000 m³ of evaporation is removed annually for the base case. As a result of the small residence time of the pond (less than two months), steady state conditions are realized within the first two years of model simulations. Water quality results were projected for a period of 36 months.

Results

Approach 1 – Mass Based

In the mass-based approach, the humidity cell test was used to assign a loading rate. This approach assumes that mass released from the TSF is constant for each model scenario. Simulated TSF collection pond water quality results for the mass-based approach are presented in Figure 1, and summarized in Table 4.

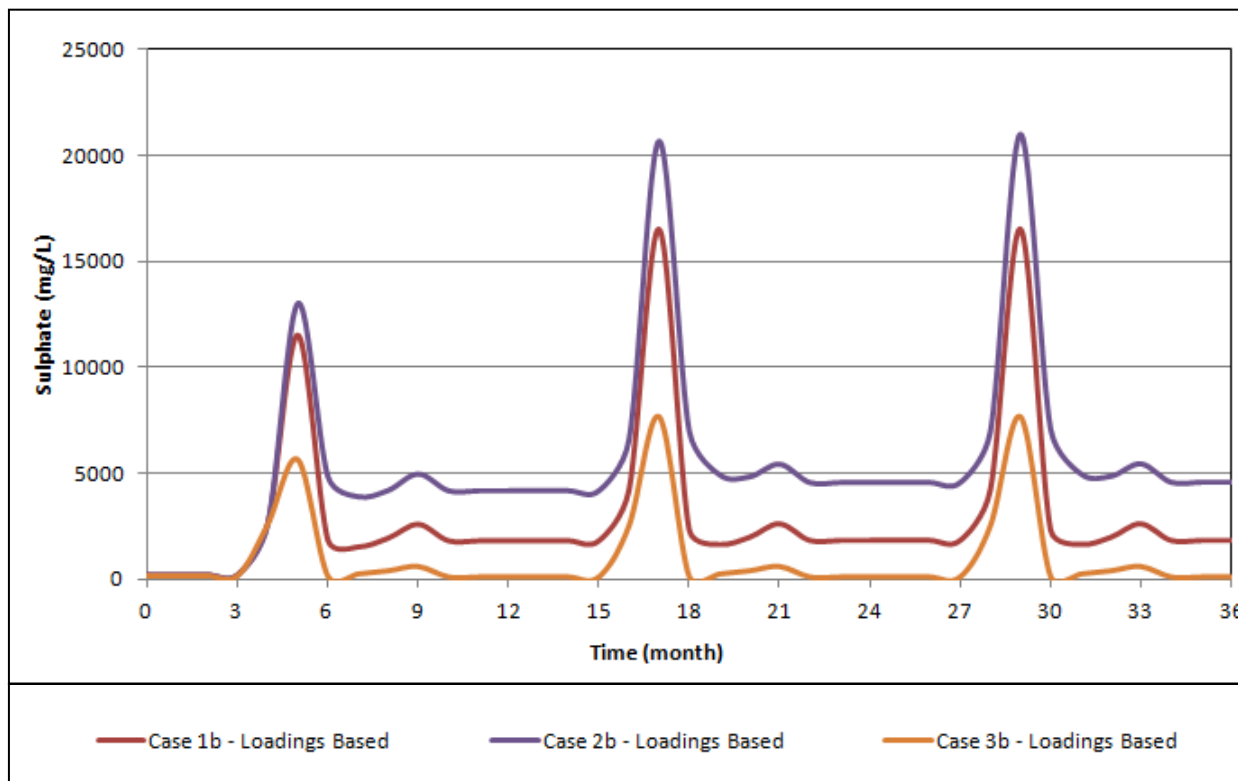


Figure 1. Simulated TSF Collection Pond Water Quality – Mass-based Approach

In the mass based approach, the TSF collection pond water quality is sensitive to the volume of runoff reporting to the pond, and considerable differences occur in the simulated sulphate concentrations for each model scenario. For example, the simulated range of sulphate concentrations (200 to 21,000 mg/L) for Sensitivity Case 1 are, on average, two times greater than the simulated range of concentrations (200 to 16,500 mg/L) yielded by the base case conditions. The annual runoff for these two scenarios is 400,000 and 840,000 m³/year, respectively. When the TSF surface area is increased by a factor of five (Case 3), the annual runoff increases to 4.2 Mm³/year and the simulated range of sulphate concentrations decreases to 138 to 7,661 mg/L.

Approach 2 – Assigned Water Quality

In the assigned water quality approach, the average sulphate concentration derived from humidity cell testing was assigned to all water originating from tailings runoff. The same sulphate concentration is applied to tailings runoff in each model scenario. In this approach the humidity cell results are scaled to the field condition based on the expected volumes draining from the tailings beach (i.e. the runoff volume

is multiplied by the assigned concentration to calculate the mass load reporting to the collection pond). The projected water quality results for the TSF collection pond are presented in Figure 2 and the range of simulated concentrations is provided in Table 4.

Table 4. Simulated Steady-state Sulphate concentrations (mg/L) in Collection Pond

Statistic	Base Case		Sensitivity Case 1		Sensitivity Case 2	
	Approach 1	Approach 2	Approach 1	Approach 2	Approach 1	Approach 2
Minimum	200	200	200	200	200	138
Maximum	273	16,501	276	20,978	273	7,661
Median	272	1,820	272	4,550	272	200
Average	261	2,931	261	5,402	262	975
Standard Deviation	26	3,741	27	4,343	25	1,946

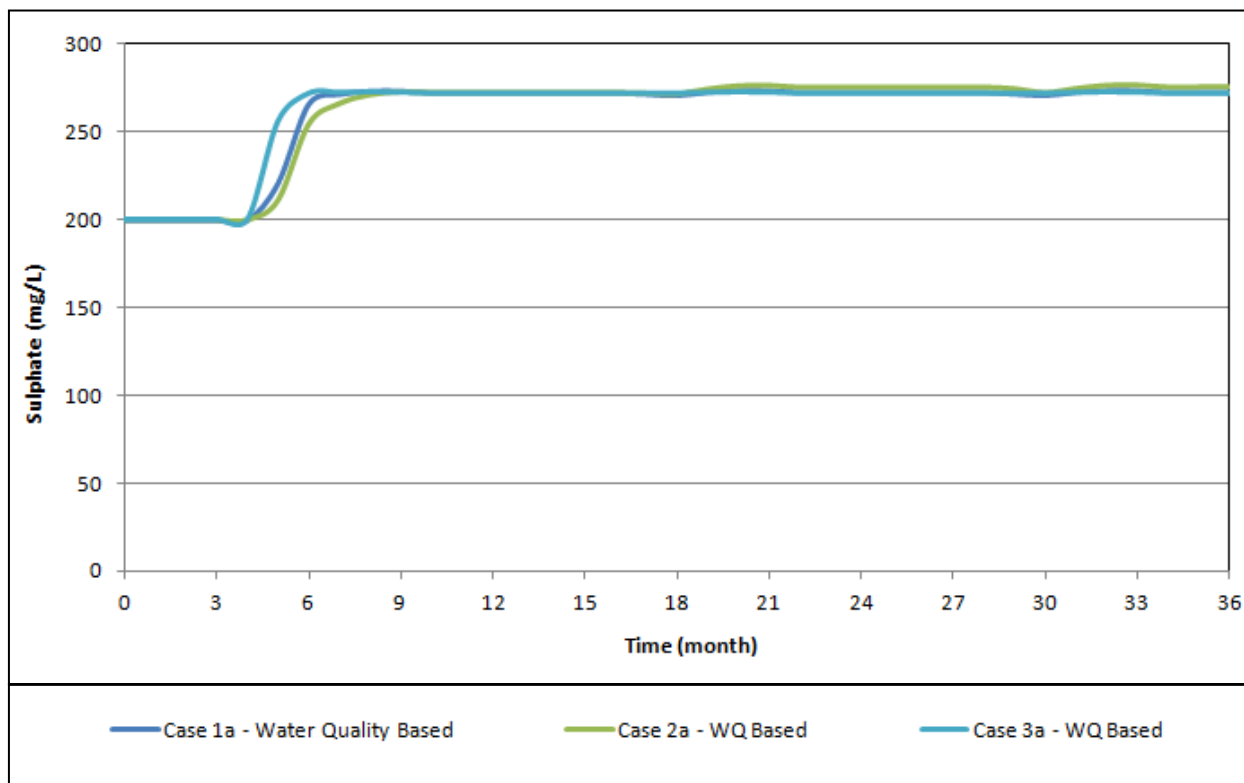


Figure 2. Simulated TSF Collection Pond Water Quality – Assigned Water Quality Approach

Sulphate concentrations increased from 200 mg/L to approximately 275 mg/L, which is similar to the source term concentration of 273 mg/L used to represent the tailings runoff and seepage water quality. As shown in Figure 2, there are only minor differences between the simulated TSF collection pond concentrations for the set of assumptions defined for each modeled scenario. These differences can be attributed to changes in the proportion of direct precipitation and evaporation relative to the TSF runoff for each model scenario. Although numerical differences occur in the modeled concentrations (Table 4), the differences in the simulated TSF collection pond water quality are negligible when the results of each sensitivity case are compared. The water quality returns to a steady state concentration regardless of precipitation / evaporation, and TSF footprint. Compared to Approach 1, the assigned water quality approach is less sensitive to climate and footprint.

Discussion

Two water quality modeling methods were used to simulate the water quality of a hypothetical TSF collection pond. Approach 1 used loading rates calculated from a humidity cell test, whereas Approach 2 used an assigned water quality to represent the drainage chemistry from the TSF. Simulated results for these two approaches are provided in Figure 3. The source terms used to simulate the water qualities presented in Figure 3 were derived from the same humidity cell. As demonstrated by Figure 3, the two different approaches yield considerably different results.

In the mass-based approach (Approach 1), an equal amount of sulphate was released from the TSF on a monthly basis. All of the mass was assumed to be instantaneously dissolved in the TSF runoff draining to the collection pond. The water quality was therefore controlled by the volume of water flushing the tailings beach. In Sensitivity Case 1, the annual precipitation (400 mm) was approximately two times less than the Base Case precipitation depth of 840 mm/year, resulting in a similar reduction in runoff from the TSF. The reduction in flow resulted in a simulated TSF collection pond water quality that was generally two times greater than the sulphate concentrations produced during the Base Case scenario (Figure 3). In Sensitivity Case 2, the increased footprint resulted in a five-fold increase in the TSF runoff volume, yielding much lower concentrations in the collection pond relative to the Base Case (Figure 3).

For the three climatic scenarios evaluated, Approach 2 produced similar results with differences only occurring due to dilution from direct precipitation and evaporative effects occurring in the TSF collection pond. The defined model inputs produced flow rates that are much larger than the maximum capacity of the TSF collection pond (115,000 m³) for each model scenario. These flow rates resulted in a short residence time ranging from approximately 1.5 weeks (Sensitivity Case 2) to 3.5 months (Sensitivity Case 1). As a result, the pond water was replaced several times per year for each scenario. The majority of this water was displaced by TSF runoff, since the direct precipitation and evaporation accounted for less than one percent of the total inflow to the facility. The assigned TSF runoff water quality was equal for each of the modeled scenarios, and similar simulated sulphate concentrations were realized in the TSF collection pond for each case.

When the simulated TSF collection pond results were compared for the two model approaches, the mass-based approach generally produced much higher concentrations for all three modeled scenarios under the defined model boundary conditions. For example maximum simulated sulphate concentrations of 16.5 g/L (Base Case), 21 g/L (Sensitivity Case 1) and 7.6 g/L (Sensitivity Case 2) were much higher than the respective maximum concentrations of 273 mg/L, 276 mg/L and 273 mg/L yielded in the assigned water quality approach.

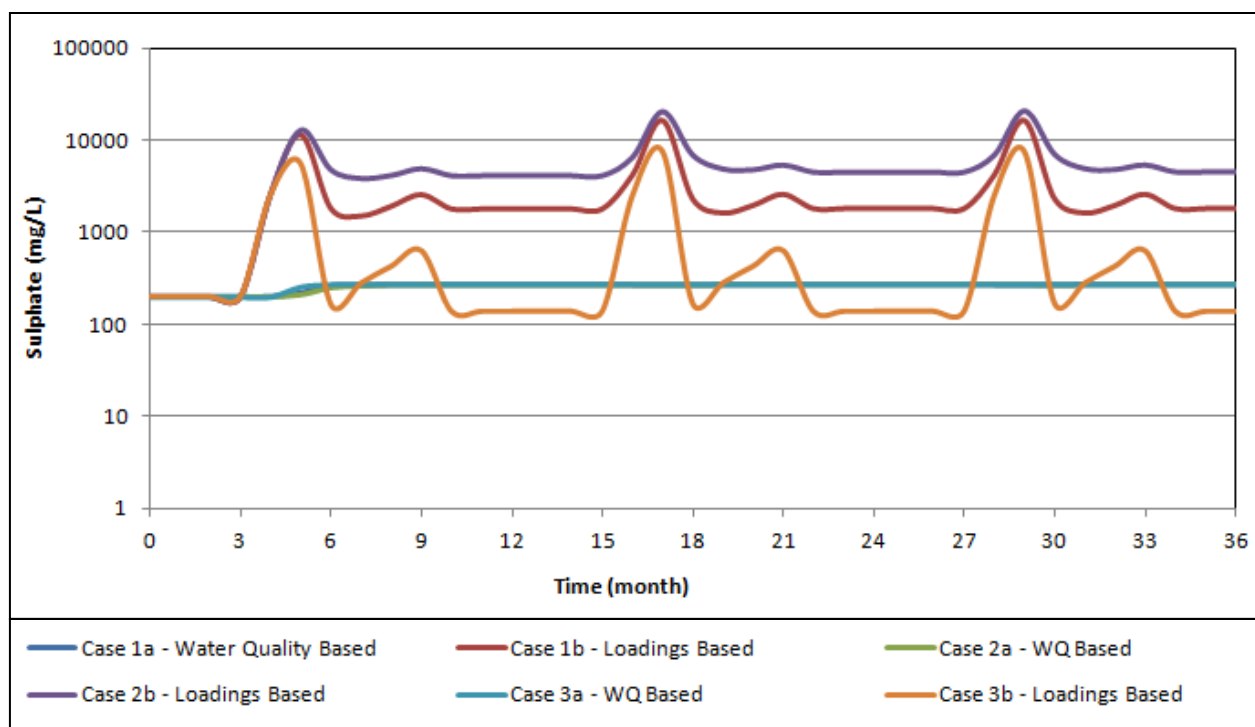


Figure 3. Simulated TSF Collection Pond Water Qualities

In reality, simulated sulphate concentrations on the order of 7.6 to 21 g/L are not expected to occur in a TSF collection pond. It is more likely that these concentrations would be controlled by gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) saturation, which commonly occurs at mine sites. It is probable that these elevated output concentrations would be reduced using judgement-based scaling factors. It is difficult to quantify the solid-solution ratio under hypothetical site conditions. Thus, scaling factors would be arbitrary until more reliable information, such as analogue data from similar sites, became available. Alternatively, concentrations could be reduced by the use of geochemical speciation models. In these instances, the simulated concentrations would likely be compared to concentrations observed in geochemical tests, such as HCT results, to determine a “reasonable” order of magnitude.

The direct use of HCT results as input to a water quality introduces uncertainty into the overall predictions. As stated in MEND (2009), “drainage chemistry depends on both the primary mineral reactions and the precipitation and dissolution of the resulting secondary minerals”. Indeed, these are processes that can be controlled by site-specific factors such as climate and the solid-to-solution contact ratio that is imparted by the scale of the test versus site conditions and channelization of flow through a facility. It is difficult to simulate these processes in a laboratory setting. However, given that the available reactive surface area of a mine waste facility is dominated by the fines component (Morin and Hutt, 1997) in the same way as an HCT (comprised of material less than 6.3 mm in diameter), it is reasonable to assume that the drainage quality from an HCT is a valid starting point for simulating mine waste drainage quality.

It is important to note that only conservative model results are presented here for the purpose of highlighting differences between assigned water quality and mass-based model approaches. The model approach should be applied on a case-by-case basis based on available data, best professional judgment and site-specific requirements. Whenever practicable, the model inputs and results should be verified

using large scale field tests, and site-specific monitoring as the project advances. Additionally, the model approach and results may need to be re-evaluated as additional data become available and site conditions change.

Conclusions

A model was developed for a hypothetical Tailings Storage Facility to evaluate the differences of two approaches to simulate the water quality in a pond collecting drainage from the facility. The assigned water quality approach assumed that the drainage water quality from the TSF was independent of the volume of runoff and remained equal regardless of climate variations. Conversely, the mass-based approach assumed a constant flux of mass was released into variable runoff volumes. For the defined model boundary conditions, these approaches produced significantly different results (Figure 3) when geochemical source terms (i.e. runoff water quality and mass loading rates) were calculated from the same humidity cell test results.

Mass-based approaches are useful tools for simulating water quality ranges that can occur as a result of climate variations such as increased and/or decreased runoff that is common to mine sites exhibiting seasonality. At mine sites where large quantities of mine waste materials (e.g. waste rock, tailings, etc.) are produced, the reactive mass can be overestimated, resulting in an overestimate of the mine site water quality. For example, the model provided in this paper yielded a maximum sulphate concentration of 21 g/L using a mass-based approach. Model artifacts such as unrealistically high concentrations are often corrected through the development of solubility limits calculated by equilibrating simulated solutions with credible mineral phases or applying additional scaling factors, such as channelization factors. Although this model artifact is highlighted in this paper as part of a hypothetical facility, this is a common occurrence when modeling mine site water qualities using mass based approaches.

An alternative approach is to apply the humidity cell water quality directly to represent the drainage water quality from a mine site material. The use of empirical data in mass balance models limits the application of scaling factors, which can often be considered questionable, or the need to develop solubility limits. However, at mine sites where the effects of evaporation or direct precipitation are not predominant, it is difficult to simulate the natural variability that may occur using this approach without varying the input source terms since material drainage water qualities are considered constant.

Water quality models are intended to provide an indication of the expected drainage chemistry and do not directly translate to concentrations that may result under actual conditions. Regardless of the approach selected to evaluate mine site water quality, the model should be sufficiently robust to provide ranges of concentrations that can be expected during the life of mine and post-closure (Maest et al., 2005), such that contingency and alternate management strategies can be adapted and implemented based on the results of operational water quality monitoring data. Water quality models should be considered as “living” tools that are frequently updated throughout the life of mine with operational water quality monitoring results. In this manner, the results can be validated or corrected to confirm that site-specific water management strategies are environmentally protective.

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