Development of a Water Quality Model for Gold Tailings in Northern Quebec

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Abstract
The use of field investigations in the development of a water quality model is presented for gold mine tailings in northern Quebec. The model was developed with three objectives: to assess the water quality that would result from the preferred closure option; to identify any issues that may require additional management; and to test the efficiency of potential mitigation activities for closure.Several conditions representing the preferred closure option were built into the model, and assumptions were made to complement the extensive database that was either available or was developed for the model. These conditions included the best estimates for conditions representing the preferred closure option. The modeling exerciseincluded a sensitivity analysis to identify the key controls on the arsenic concentrations in the Basin discharge and to understand the ranges of possible responses to various potential mitigation strategies.
In order to evaluate the uncertainties involved with the model, initial field sampling and laboratory evaluations were completed to provide initial input values guided by the model framework. A well-designed monitoring program during operation to test model assumptions and verify predictions was considered to be the most appropriate method of addressing additional uncertainties.

Key Words: Arsenic, Peat, Closure, Mitigation, Sensitivity

Introduction and Site Description
Mines AurizonLtée (Aurizon) owns and operates the Casa Berardi Mine near LaSarre, Québec. Casa Berardi is a 2,000 tonne per day underground gold operation with a cyanide-leach circuit in the concentrator. The current mine plan includes closure of the operation in 2019. The water quality after the mine ceases operation is a key component of the closure plan. A water quality model was developed for the site to predict water quality after closure and assess the effectiveness and suitability of the proposed closure plan.. The model was developed with three objectives: to assess the water quality after closure that would result from the preferred closure option; to identify any issues that may require additional management; and to test the efficiency of potential mitigation activities for closure.

The Casa Berardi tailings management area encompasses roughly 300 hectares. Tailings from the mill are currently stored in an above-ground impoundment containing three cells (Figure 1). Additionally, a Polishing Pond is located south of Cell 3. Cells 1 and 2 currently contain two historic types of tailings, designated as Old tailings (produced prior to Aurizon operation of the mill) and New tailings (produced since Aurizon has been operating the mill), while Cell 3 contains Old tailings only. The outlet for the tailings impoundment is located at the north end of the facility, and the process water basin located north and west of the three existing Cells drains through this outlet.

As part of the ongoing production plan, construction of tailings Cell 4 is proposed inside the process water basin. The new Cell 4 would be located to the west and south of Cell 3 and the Polishing Pond. Additionally, a third type of tailings, designated as Future tailings, is planned to be stored in the impoundment. These Future tailings are proposed to be stored in all four tailings Cells and in the Polishing Pond. Figure 1 illustrates the site plan for the tailings impoundment before the construction of Cell 4.

Methods

Model Objectives and Conceptual Design

The model was developed based on principles of water and mass balance as well as geochemical controls. Conceptually, the tailings impoundment was divided into compartments corresponding to the existing Cells 1, 2, 3, Polishing Pond, the proposed Cell 4, an "Overland" cell to capture southbound seepage from Cells 1, 2, and 3, and the remaining area of the Basin that contains peat sediments that will be partially flooded after closure. The modeled compartments were assumed to contain combinations of layers reflective of the actual or proposed field conditions: water, Old, New, and Future tailings, exposed peat, and flooded peat. Table 1 summarizes the physical characteristics of these materials, and Table 2 outlines the conceptual makeup of each area in the tailings impoundment. The conditions described in Tables 1 and 2 represent a Basecase scenario for the tailings that include the best estimates for conditions representing Aurizon's preferred closure option for the tailings management facility.

Figure 1. Casa Berardi Tailings Facility with Flow Directions Indicated

Table 1. Model Characteristics

Material	Code in Model	Solids Arsenic Content (mg/kg)	Leachable Arsenic Content (mg/kg)	Bulk Density (kg/L)	Porosity [-]	Water Arsenic Content (mg/L)	Kd (L/kg)
Future Tailings	F	5500	440	1.7	0.38	0.4	1100
New Tailings	N	5600	448	1.7	0.38	14	32
Old Tailings	O	5400	432	1.7	0.38	8	54
Peat	P	350	350	0.2	0.7	0.5	700
Water in Surface Flow / Runoff	W1	-	-	-	-	0	-
Water in Basin Pond	W2	-	-	-	-	0.01	-
Sludge	S	2000	2000	1.2	0.7	1	2000

Notes:
Data Source: EcoMetrix, 2010; URSTM, 2008
Leachable arsenic content was analyzed using MA. 100-Lix.com 1.0. See URSTM, 2008.

Table 2.Basecase Conditions for the Casa Berardi Tailings Basin Model

Model Cell	Cell Area	T1 Depth	T2 Depth	T3 Depth	Surface Flow / Runoff	T1	T2	T3	Net Precip on Cell	Fraction of Net Precip as Infiltration	Dam Seepage
	(m^2)	(m)	(m)	(m)		Material	Material	Material	(mm/a)	(-)	(m^3/m/a)
Cell 2	2.76E+05	8.5	3.5	4.5	W1	F	N	O	407	0.5	23.64
Cell 1	1.72E+05	6	0.3	7.5	W1	F	N	O	407	0.5	23.64
Cell 3	1.37E+05	1.5	6	NA	W1	F	O	NA	407	0.5	23.64
Polishing Pond	5.73E+04	4	0.5	NA	W1	F	S	NA	407	0.5	23.64
(land [1]	2.89E+05	NA	NA	NA	W1	NA	NA	NA	407	0.5	NA
Cell 4	8.24E+05	4	0.2	NA	W1	F	NA	NA	407	0.5	23.64
Expos Peat [2]	8.70E+05	1	NA	NA	NA	P	NA	NA	407	0.5	NA
Bas 'ond [2]	3.73E+05	1.5	NA	NA	W2	P	NA	NA	407	1	NA

Notes:
T1, T2, T3: Tailings compartments in a given Cell, from topmost to bottommost
Precip: Precipitation
NA: Not Applicable

Several conditions representing the preferred closure option were built into in the model, and several assumptions were made to complement the model's data base. The key assumptions and estimates used to modelthe Basecase scenario included the following:

- According to Mines Aurizon, future tailings at the surface will not be net acid generating because they will be low in sulphur and will have adequate neutralization potential to consume the small amounts of acid released when the sulphides oxidize at the surface.
- Old and New tailings will not generate acid because they will be covered by the Future tailings and will have sufficient moisture to limit transfer of oxygen and thus prevent oxidation. The acid-base accounting for the Old and New tailings has been described in detail in URSTM (2008).
- Arsenic content in existing tailings solids and porewaterat the site was assumed to be as described in URSTM (2008) and EcoMetrix (2010).
- The thickness of each tailings compartment was either measured from cross-sections of the existing and proposed strata in the tailings management facility, or was estimated based on professional judgment and experience.
- The seepage rates through the existing low permeability dams were provided in AMEC (2010) and were based on modeled estimates.
- Pore water quality in the Future tailings will be controlled by in-mill treatment that reduces arsenic concentrations in mill process water (Aube, pers. comm, 2010).
- Net precipitation estimates were provided by AMEC (2010).
- The fraction of net precipitation that infiltrates into the tailings was assumed to be and is considered to be very conservative.

The model was developed to be general enough to assess any constituent of potential concern. However, based on available data and the applicable regulatory standards at Aurizon's point of compliance, arsenic was determined to be the most influential constituent, and thus, the water quality assessment presented here was limited to arsenic.

Mathematical Basis

The mathematical basis of the model is the principle of mass conservation, assuming a steady-state flow through the entire modeled system. Each compartment was assumed to behave as a Continuous Stirred-Tank Reactor (CSTR). The mass balance equation governing the model was as follows:

$$N_{aq,i,t} = N_{aq,i,t-1} + \left(\sum_j F_{j \to i,t-1} - \sum_j F_{i \to j,t-1} \right) \Delta t + R_{aq,i,t-1}$$

Where:

$N_{aq,i,t}$ = Number of moles present in aqueous phase in compartment i at timestep t (mol)
$F_{j \rightarrow i,t}$ = Molar flow from compartment j to compartment i at timestep t (mol/s)
Δt = Magnitude of timestep (s)
$R_{aq,i,t}$ = Number of moles arriving in aqueous phase in compartment i at timestep t through a reaction mechanism (mol)

Under this assumption, the pore water or surface water in each compartment was assumed to be well-mixed, and therefore uniform in concentration throughout each compartment at each timestep. Thus, the arsenic concentration in surface flow or seepage leaving each compartment at each timestep was assumed to be equal to its concentration in pore water or surface water in that compartment. Similarly, the arsenic concentrations in solids were assumed to be uniform throughout each compartment.

The reaction term in the above mass balance used K_d values, which were specific to each compartment, in that initial concentrations in aqueous and solid phases in each compartment were used to estimate the K_d for that compartment. While it is known that pH affects arsenic speciation and sorption, the K_ds used in the model were held constant, since pH was assumed not to change appreciably over the modeled period. Note that Kds are typically only applicable to the system conditions, for which they were developed, including pH considerations. As far as the mechanics of the application of K_ds in the model are concerned, K_ds were applied to each compartment in each time step to determine how many moles of arsenic changed phase in that time step.

Model Hydrology

Hydrologic connections between areas in the tailings impoundment were modeled by creating a water balance for the impoundment area. Each Cell in the model was assumed to be made up of one or more vertically stacked compartments representing the various layers of tailings. Flow between the modeled compartmentsand flow out of the system werecontrolled by natural infiltration, runoff, and by the seepage out of each compartment through its bounding impermeable dams. These processes are illustrated in Figure 2. Figure 3 presents a schematic of the overall flow system created for the model.

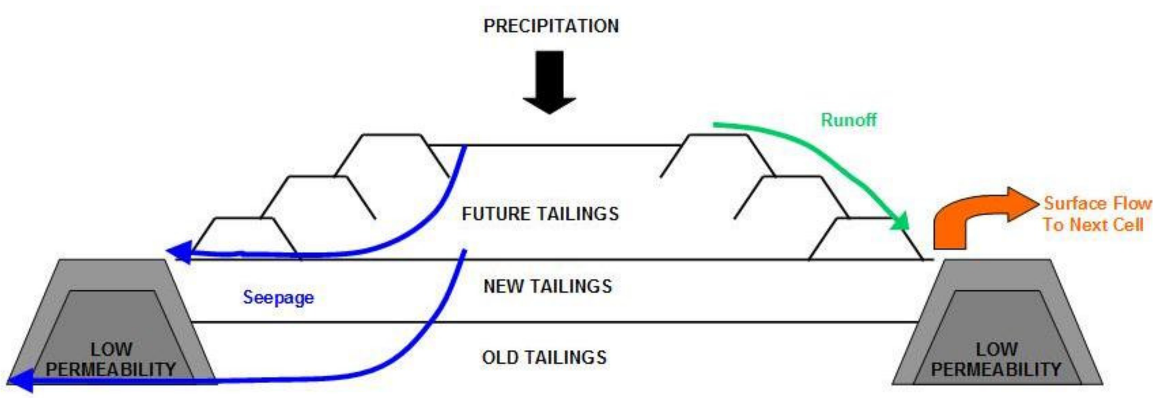

Figure 2.Hydrological Conceptual Model for Tailings Cells

Surface water in the model was assumed to follow a consistent route through the tailings impoundment system, which passed through the various compartments in sequence from Cell 2 to Cell 1, Cell 3, the Polishing Pond, Cell 4, the Basin Pond, and to discharge from the Basin Pond occurring through the outlet to the north. Surface flow into Cell 2, the first area in the chain, was assumed to be zero after closure.

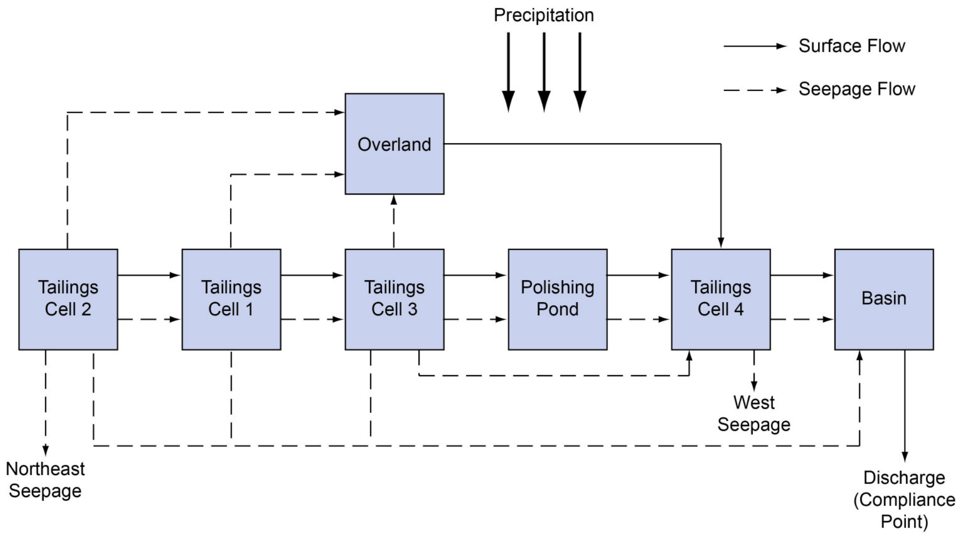

Figure 3.Flow Balance Conceptual Model

Seepage between compartments was considered to be two-dimensional. Both “parallel” seepage, which traced an identical route to the surface flow, and “perpendicular” seepage, which traced flow in any other direction, whether between compartments or exiting the system, were built into the model. If seepage occurred in either a parallel or perpendicular fashion from multiple compartments in the same Cell, seepage rates were assigned to each compartment inside that Cell based on the ratio of compartment depth to total depth of the Cell, ensuring each (horizontal) linear metre of impermeable dam was restricted to the same total seepage.

Considering this pro-rating of seepage according to compartment depths, compartment geometry was regarded as a significant factor in completing the flow balance for the system, and the measurements needed for the model were largely estimated from figures provided by Aurizon for the proposed closure plan, and are summarized in Table 2.

Once compartment geometry had been established, the water balance could be completely specified using the following input parameters:

- Total precipitation (mm/year);
- Fraction of precipitation infiltrating directly to the first subsurface layer (unitless);
- Total seepage rate through impermeable dams (m3/m/year);
- Exchange (flow) rate between the Basin Pond and its underlying peat (mm/year);
- Aqueous flow from the Future Tailings layer to Peat layer in Cell 4 (mm/year)

Values chosen for the first three of these parameters are presented in Table 2. The exchange rate between the pond water and the underlying peat was estimatedat 2,400 mm/year from flux calculations in the detailed sediment modeling reported elsewhere (EcoMetrix 2010). The exchange of water from the tailings to the underlying peat layer in Cell 4 was estimated, from experience, to have a value of approximately 10 mm/year.

Model Parameters
Average measured arsenic concentrations in solids and pore water were used as initial conditions in those media during model runs. Other initial conditions are presented in Table 1 and include the leachable arsenic contents of solids, bulk densities, porosities, and arsenic partition coefficients (K_d). The model was run for a total of 1,000 months with a timestep of one month.

Model Uncertainties and Sensitivity Analysis
In order to evaluate the uncertainties involved with the mass balance model, input parameters were categorized according to the inherent uncertainty in each value. In general, measured data, such as pore water and solids chemical analysis results and leachability test results, were considered to have few associated uncertainties, while parameters based on estimates were considered to have higher degrees of uncertainty.

In order to further investigate how these uncertainties might affect the results of the model, a sensitivity analysis was designed and executed. The following variables were selected to develop the sensitivity analysis, based on sensitivity of results to the variables, as well as the feasibility of achieving changes to the variables in the field:

- The seepage rate through the impermeable dams;
- The area of the pond over the flooded peat within the Basin;
- The initial arsenic concentration in the pore water in the peat; and,
- The fraction of net precipitation that infiltrates the tailings relative to the fraction that runs off the tailings.

Results and Discussion
The mass balance model predicted arsenic concentrations in the Basin Pond as a function of time over the modeled period. Under the CSTR assumption these concentrations are assumed to be equal to the concentrations of arsenic in the Basin Pond discharge, which is the compliance point for discharge from the tailings impoundment. For the Basecase Scenario, the predicted concentrations at the discharge point exceeded the current regulatory benchmark, Directive 019 (Gouvernement du Québec, 2012), value for allowed discharge of 0.2 mg/L (Figure 4). The maximum concentration attained in the Basin Pond was 0.64 mg/L in month 332, but the curve reached 0.62 mg/L within 12 months of time zero, retaining a slightly convex shape from then until the end of the model run.

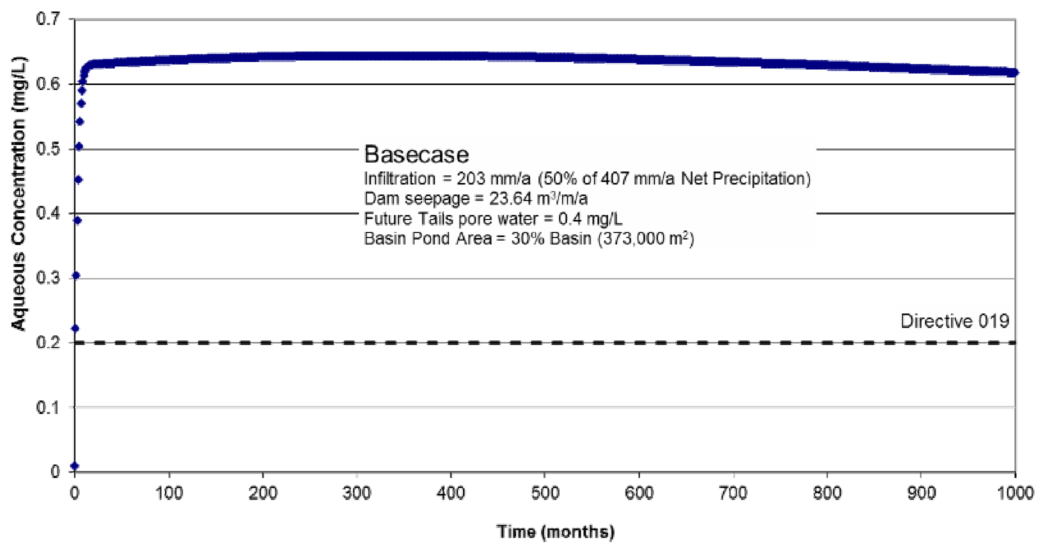

Figure 4. Mass Balance Model Results for Arsenic in the Basecase Scenario

A selection of graphical results for the sensitivity analysis is shown in Figures5 through 8 for the scenarios outlined in Table 3. These results present a number of scenarios encompassing varying seepage rates from the low permeability dams and varying Basin Pond areas.

Table 3. Selected Sensitivity Scenarios for the Casa Berardi Tailings Basin Model

Figure Number	Seepage ($m^3/m/a$)	Infiltration (mm/a)	Basin Pond Area (%)	Arsenic in Peat Pore Water (mg/L)
5	23.64	203	10	0.5, 0.2, 0.1
6	23.64	203	65	0.5, 0.2, 0.1
7	5	203	10	0.5, 0.2, 0.1
8	5	203	65	0.5, 0.2, 0.1

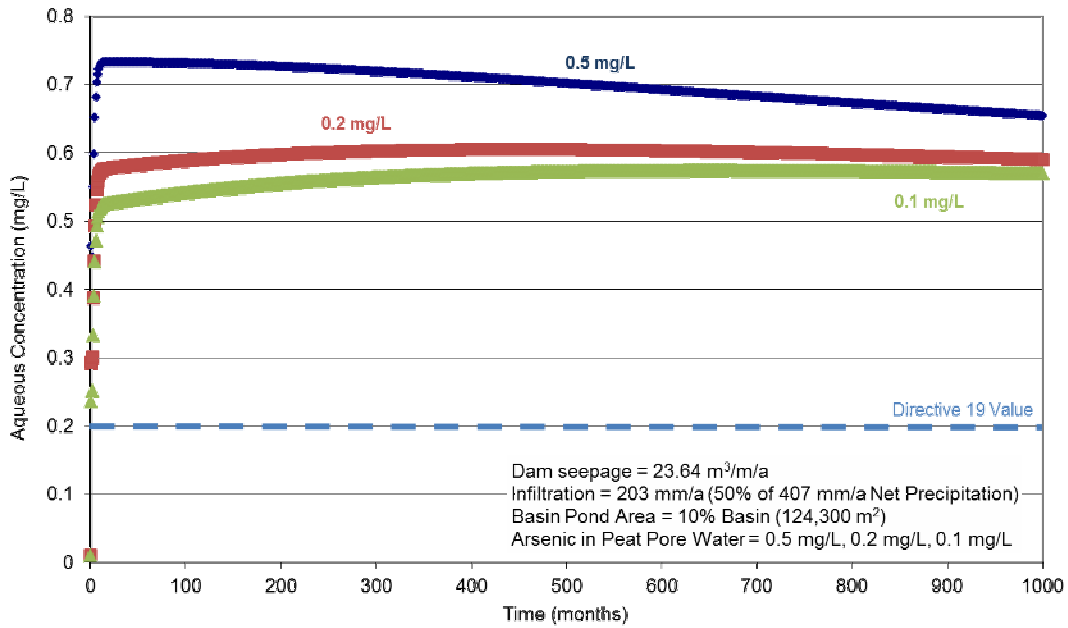

Figure 5.Mass Balance Model Results for Arsenic Assuming Full Seepage through Low Permeability Dams and 10% of the Current Basin Area Flooded

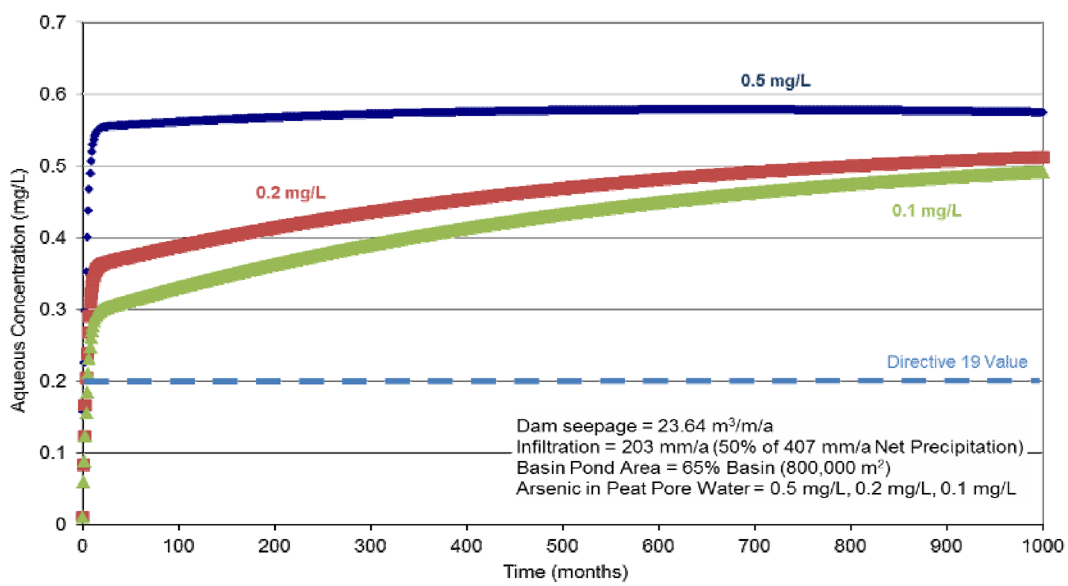

Figure 6.Mass Balance Model Results for Arsenic Assuming Full Seepage through Low Permeability Dams and 65% of the Current Basin Area Flooded

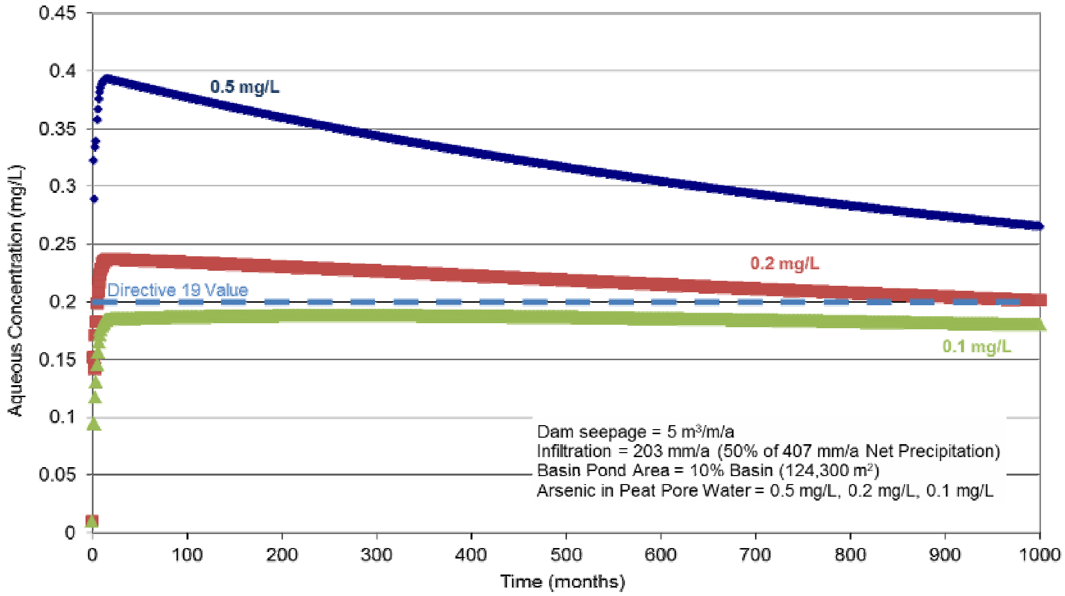

Figure 7.Mass Balance Model Results for Arsenic Assuming Low Seepage through Low Permeability Dams and 10% of the Current Basin Area Flooded

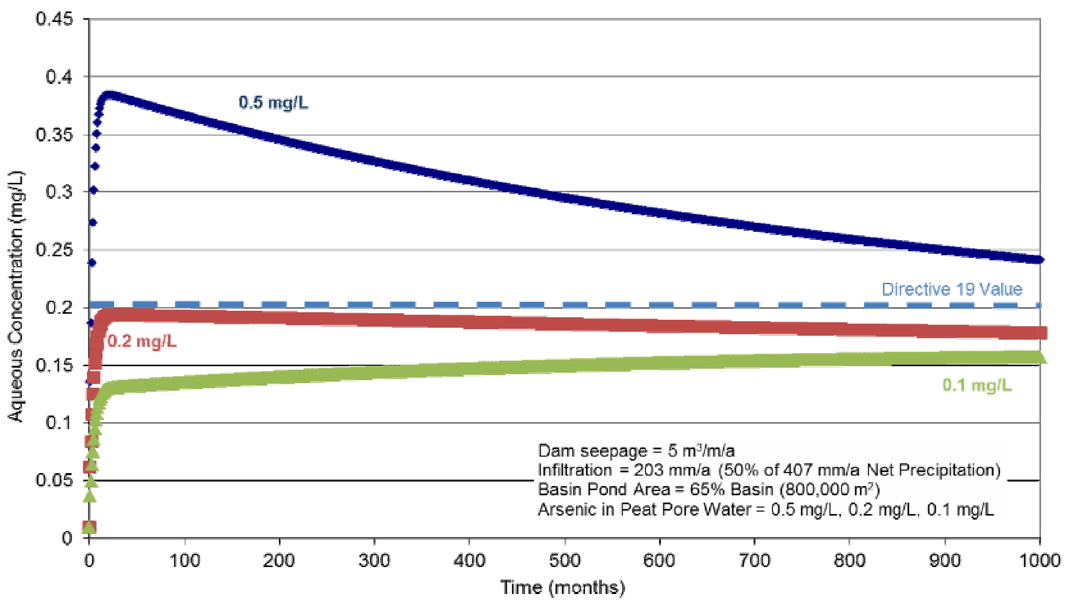

Figure 8.Mass Balance Model Results for Arsenic Assuming Low Seepage through Low Permeability Dams and 65% of the Current Basin Area Flooded

The pond area, seepage rates, and arsenic concentrations in pore water of the peat all appeared to play a significant role in determining the shapes of the Basin Pond arsenic concentration versus time curves. Lower seepage rates, for example, tended to shorten response times (that is, time to achieve a peak arsenic concentration), as shown in Figures 7 and 8 compared to Figures 5 and 6, respectively. Lower arsenic peat porewater concentrations tended to lengthen response times, as demonstrated in all four sensitivity Figures. At full seepage rates, larger pond areas tended to lengthen response times as shown in Figure 6, compared to smaller pond areas as shown in Figure 5.

None of the scenarios run at the Basecase seepage rate through the impermeable dams produced Basin Pond concentrations lower than 0.2 mg/L for arsenic, as demonstrated in Figures 5 and 6. Several of the scenarios run with a reduced seepage rate, however, did achieve this objective, but only in combination with reduced initial arsenic concentrations in peat pore water (see the curves for 0.1 mg/L in Figures 7 and 8). The Basin Pond area did not appear to make a substantial difference in the final arsenic concentrations when the initial concentrations of arsenic in the peat pore water were high, but a larger area was beneficial when values in the peat pore water were lower.

The sensitivity analysis also showed that lower net infiltration can result in lower arsenic concentrations in the Basin Pond discharge. However, lower infiltration is not required if decreased seepage through impermeable dams and decreased arsenic concentrations in peat pore water are achieved first.

Conclusions and Considerations

The Basecase Scenario established in the mass balance model for the Casa Berardi tailings impoundment predicted arsenic concentrations at the Basin Pond outlet that were greater than the Directive 019 value for arsenic. The sensitivity analysis showed that if required, the model has identified strategies that can be employed to reduce loadings to the system to aid in meeting the Directive 019 value. Additionally, the study of the Basin sediments (EcoMetrix, 2010) showed that the concentrations of arsenic in the peat can be managed during operation to achieve lower concentrations at closure. The pond can be maintained at the maximum flooded area after closure to minimize concentrations in the Basin discharge. The current closure plan for the Casa Berardi mine is therefore considered appropriate for controlling arsenic concentrations at the Basin Pond outlet.

It was recommended to Mines Aurizonthat a monitoring program be developed and executed over the operating period leading to closure in 2019 to ensure continued calibration of the water quality mass balance model, as well as to determine the need, if any, for implementation of mitigation measures. In particular, it was recommended that water balance parameters, such as seepage rates through the low permeability dams, as well as arsenic concentrations in peat pore water, be quantified in the proposed program. It was also recommended that the water quality model be revised in the future to allow calibration during operations to verify predictions with the newly acquired field monitoring data, and to allow for investigation of geochemical uncertainties in the model.

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