REMEDIAL OPTIONS EVALUATION FOR THE ABANDONED ATLIN RUFFNER MINE

Ryan Mills, M.Sc., P.Geo.[1]
Kun Jia, M.Sc., G.I.T.[2]
Mehrnoush Javadi, Ph.D.[3]
Joanna Runnells, M.Env.Sc., P.Geo., EP [4]
Lily Whitehead-Delong, M.Sc., P.Geo.[5]

[1] Senior Hydrogeologist,
AECOM Canada Ltd., Burnaby, BC, Canada

[2, 3] Hydrogeologist/Geochemist,
AECOM Canada Ltd., Burnaby, BC, Canada

[4] A/Sr. Contaminated Sites Expert, Crown Contaminated Sites Program
BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development

[5] Sr. Contaminated Sites Specialist, Crown Contaminated Sites Program
BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development

ABSTRACT

Groundwater and surface water are important natural resources that require protection during all phases of the mine life cycle. The ability of a remedial solution to achieve water quality criteria is a key consideration during the development and selection of remedial alternatives. Characterization of hydrology and hydrogeology is required to inform technical aspects of remedial planning. This case study presents the remedial options evaluation undertaken for the remote abandoned Atlin Ruffner Mill and Tailings Site in a complex geological setting.

Groundwater downgradient of the Former Tailings Pond was affected by acid rock drainage and metal leaching, with low pH and elevated concentrations of sulphate, fluoride, arsenic, cadmium and zinc. Six remedial options capable of removing and/or cutting off the exposure pathways of contaminant concern were developed and evaluated: off-site disposal, in-situ isolation, on-site landfill disposal, in-situ soil stabilization, in-situ amendment, and permeable reactive barrier.

A water balance and water quality model was developed to quantitatively predict water quality in the receiving environment for each remedial option. In-situ isolation was selected as the preferred remedial option for the Site, which included a piped surface water diversion, two interceptor trenches and a bituminous geomembrane liner over the Former Tailings Pond. The Phase 2 Remedial Works have been completed, resulting in desaturation of the tailings, and improved downgradient groundwater quality.

Keywords: Abandoned mine, remote, remedial option evaluation, water balance, water quality model

INTRODUCTION

Background

The Atlin Ruffner Mill and Tailings site is located approximately 28 kilometres northeast of Atlin, British Columbia (BC) on the northwest slope of Mount Vaughan (Figure 1). Mining operations at Atlin Ruffner commenced in 1900 and lead, zinc, silver, copper, cadmium, and gold were mined and milled intermittently until 1981. A total of 3,535 tonnes of ore were milled, with recovery of 138,493 kg lead, 13,540 kg zinc, 2,079 kg silver, 920 kg copper, 15 kg cadmium and 3.4 kg gold (MINFILE, 2010). The Site is now under the care of the Crown Contaminated Sites Program (CCSP) within the British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development.

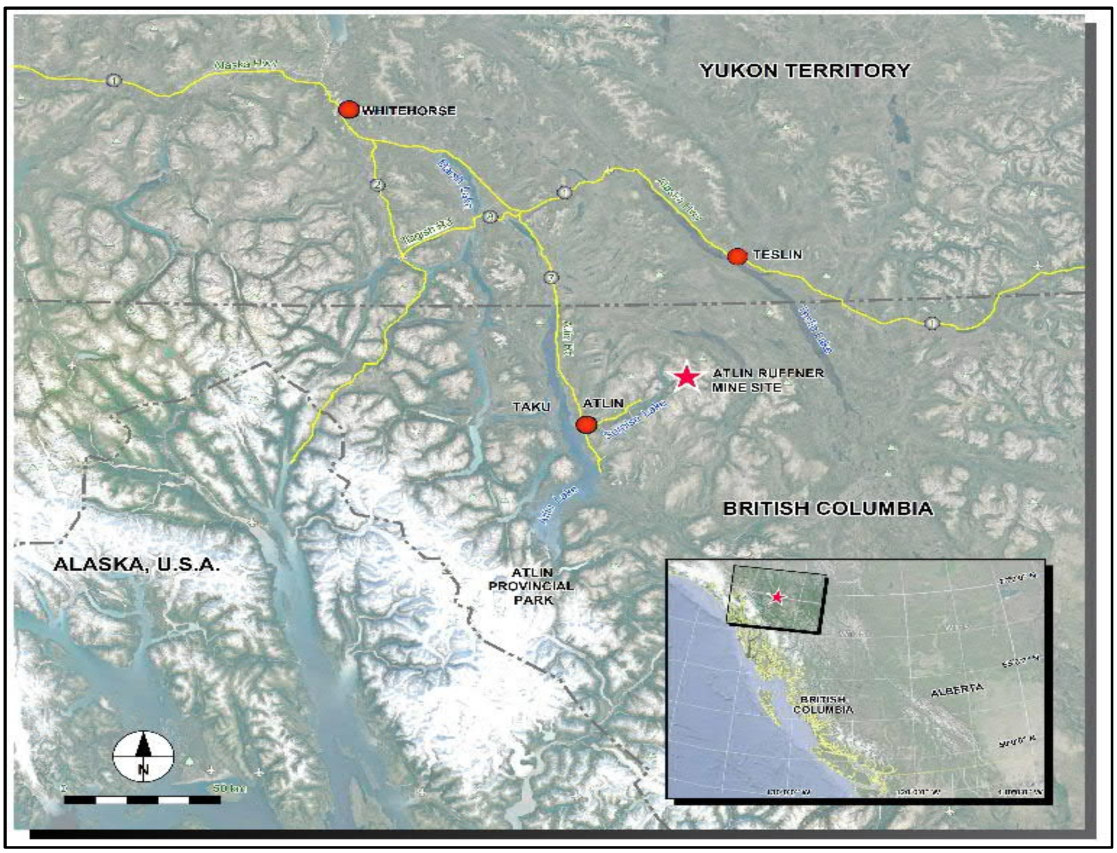

Figure 1. Site Location. The Mine site is located approximately 28 kilometers northeast of Town of Atlin, British Columbia (BC), Canada.

Climate

The town of Atlin is located within the sub-alpine climatic zone at approximately 674 meters above sea level (masl) with average daily temperatures of 0.5°C. The coldest month is January (-12.8°C) and the warmest month is July (13.4°C). Average annual precipitation is 364.7mm, with 155mm falling as snow.

The mine site is located at an elevation of 1,170masl in a zone of sporadic permafrost. Average monthly precipitation and temperature data for Atlin (Station 1200560) are shown in Figure 2.

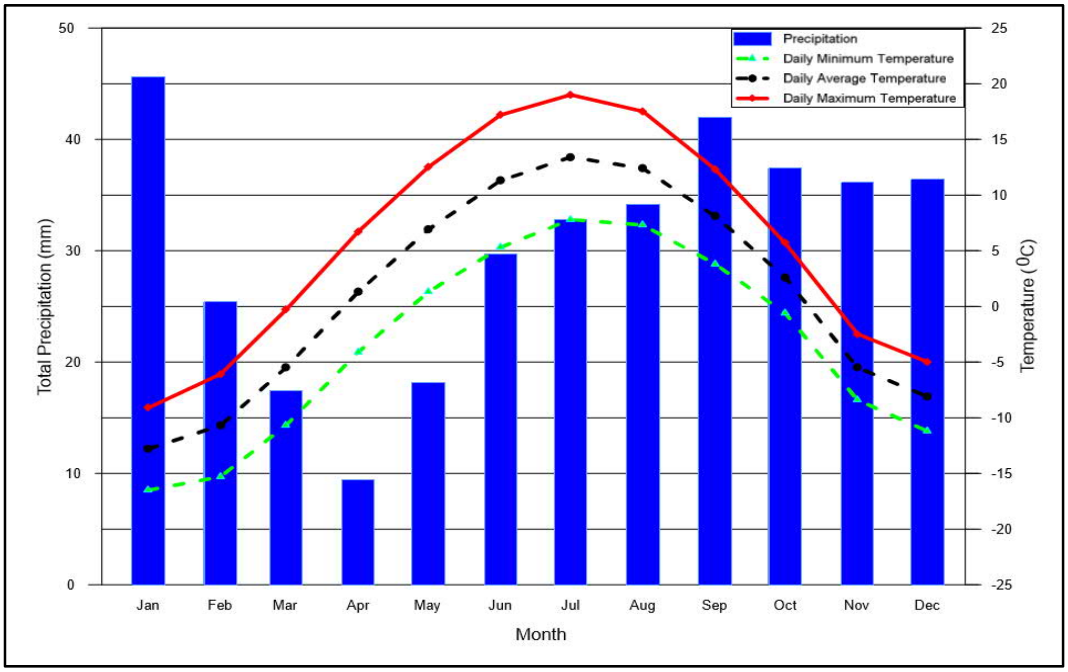

Figure 2. Precipitation and temperature in Atlin, British Columbia (1981-2010).

Prior to completion of the Phase One Remedial Works, the Site consisted of underground mine workings, a mill facility, several waste rock piles, a camp, laydown areas, access roads, a tailings pond and two sedimentation ponds (Figure 3). Groundwater has passively discharged from the underground mine since the mine was abandoned, presenting a risk to the physical and chemical stability of the Site.

Phase One Remedial Works undertaken in 2012 involved demolition of buildings and capping of contaminated areas with a one metre thick clean sand and gravel cover to address risks associated with ingestion of soil-borne contaminants by humans and wildlife. Groundwater monitoring indicated that concentrations of several analytes (e.g., SO4, F, Zn, and Cd) in groundwater downgradient of the Former Tailings and Sedimentation Ponds were increasing and did not meet the compliance conditions specified in the Hazardous Waste Regulation Approval. Geochemical investigations were undertaken to evaluate acid rock drainage and metal leaching (ARD/ML), and concluded that tailings contained low to moderately high sulphide-sulphur concentrations (i.e., <0.01 to 3.7wt.%) and had the potential to generate acid and leach a range of metals. Groundwater monitoring indicated the presence of a localized ARD/ML plume in the perched glaciofluvial aquifer downgradient of the Former Tailings and Sedimentation Ponds (Figure 3).

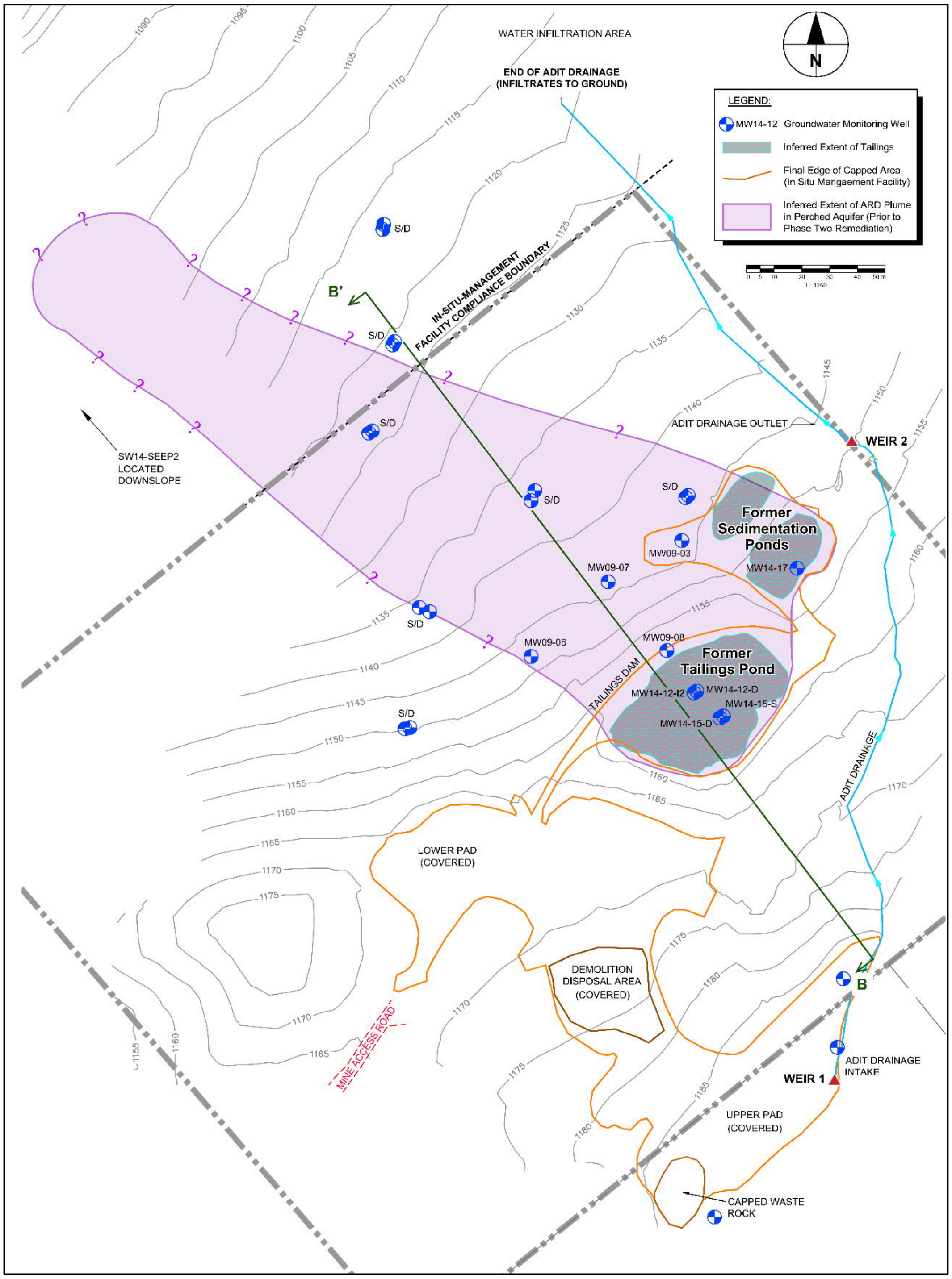

Figure 3. Groundwater and surface water monitoring locations. S/D refers to shallow/deep monitoring wells drilled on Site.

REMEDIAL OPTION DEVELOPMENT

The objective of this study was to develop and evaluate remedial options to address the non-compliant ground water quality at the In-situ Management Facility Compliance Boundary. The Remedial Objectives included the following:

- Provide a robust, long-term, risk-based remedial solution that is cost effective and feasible.
- Minimize costs associated with long-term care and maintenance.
- Comply with the standards and guidelines defined in the British Columbia Environmental Management Act, Hazardous Waste Regulations and BC Ministry of Environment and Climate Change (MOECC) Protocols for contaminated site assessment and remediation.

Based on the Remedial Objectives, seven remedial options were developed at the conceptual level to address the non-compliance issues associated with ARD/ML and ground water quality:

- Option 1: Off-site Disposal
- Option 2: In-situ Isolation
- Option 3: Encapsulation in On-Site Geomembrane Lined Landfill
- Option 4: Solidify or Stabilize Tailings
- Option 5: Neutralize Tailings
- Option 6: Passive Treatment of Groundwater Plume
- Option 7: Maintain Saturated Cover on Former Tailings and Sedimentation Ponds

The options were developed in consideration of the improved hydrogeological and geochemical conceptual models based on the results of detailed investigations undertaken after the Phase One Remedial Works.

PRELIMINARY SCREENING

Remedial options were evaluated from a feasibility, effectiveness, and cost prospective at the conceptual design stage to streamline the selection of a preferred remedial option and implementation of the selected remedial solution. Table 1 provides the advantages and disadvantages of each remedial option in consideration of the Remedial Objectives. Although the certainty of the outcome for Option 1 was high, it was too costly and would have required transport of large quantities of material to a hazardous waste landfill and the option was not considered further. For Options 4 and 5, the addition of amendments would result in an unacceptable increase in the volume of materials stored in the Former Tailings and Sedimentation Ponds and increased geotechnical risks. Furthermore, Option 4 was likely to be logistically challenging due to the small working area and had the highest cost. Option 6 was not likely to achieve the desired outcome without long-term studies to assess the feasibility of treating ARD/ML impacted groundwater using a permeable reactive barrier or diverting surface water to dilute concentrations in groundwater. Option 6 was not considered further because MOECC does not consider dilution to be a responsible method for treating contaminated groundwater, and treatability studies were likely to take several years. Options 2, 3 and 7 were selected as viable options to be further evaluated that required further evaluation to confirm feasibility.

Table 1. Preliminary Screening of the Remedial Options

Option		Description	Advantages	Disadvantages
1	Off-site Disposal	Excavate tailings and transport to permitted facility	• Highly certain performance. • Reduced maintenance requirements. • Reduced future liability.	• Excavation risk (increased waste volume). • High cost. • Risk of spill during transportation.
2	In-situ Isolation	Isolate tailings and sediments from surface water and groundwater flow without excavation.	• Avoids excavation risk. • Low cost. • Moderately certain performance. • Rapid implementation.	• Long-term maintenance requirements. • ARD/ML will continue to evolve. • Requires effective water management to reduce loading to environment. • Liner requires periodic replacement.
		Option: Neutralize tailings by adding lime before isolating.	• Highly certain performance and reduced potential to generate ARD/ML. • Reduced maintenance. • Reduced future liability.	• Increased geotechnical risk. • Increased cost for minimal benefit.
3	Encapsulation in On-Site Geomembrane Lined Landfill	Encapsulate tailings on site in a geomembrane lined landfill.	• Relatively low cost. • Moderately certain performance. • Rapid implementation. • Consolidates tailings for ease of management.	• Long-term maintenance requirements. • Excavation risk (increased waste volume). • ARD/ML will continue to evolve. • Requires effective water management to reduce loading to environment. • Liner requires periodic replacement.
		Option: Neutralize tailings by adding lime before encapsulating.	• Highly certain performance and reduced potential to generate ARD/ML. • Reduced maintenance. • Reduced future liability.	• Increased geotechnical risk. • Increased cost for minimal benefit.
4	Solidify or Stabilize Tailings	4a (In-Situ): Mix tailings with cement and lime in-situ to reduce contaminant mobility and bioavailability.	• Avoids excavation risk. • Highly certain performance and reduced potential to generate ARD/ML. • Reduced maintenance. • Reduced future liability.	• Increased geotechnical risk. • Relatively high cost. • Requires large quantities of cement. • Slower implementation due to need for testing to confirm feasibility.
		4b (Ex-Situ): Excavate tailings and mix with reagents at surface to reduce contaminant mobility and bioavailability. Place solidified tailings in Former Tailings and Sedimentation Ponds.	• Highly certain performance and reduced potential to generate ARD/ML. • Reduced maintenance. • Reduced future liability.	• Excavation risk (increased waste volume). • Increased geotechnical risk. • Highest cost. • Requires large quantities of cement. • Slower implementation due to need for testing to confirm feasibility.
5	Neutralize Tailings	Neutralize tailings by adding enough lime to offset acid generating potential.	• Highly certain performance and reduced potential to generate ARD/ML. • Reduced maintenance. • Reduced future liability.	• Increased geotechnical risk. • Requires large quantities of cement. • Not considered a remedial option by itself.

Option		Description	Advantages	Disadvantages
6	Passive Treatment of Groundwater Plume	Passive treatment of the ARD/ML plume using a permeable reactive barrier or dilution.	• Avoids excavation risk. • Does not require electrical power.	• Slower implementation due to need for testing to confirm feasibility. • Uncertain performance, especially if ARD/ML impacts increase over time. • Requires regular monitoring, maintenance and replacement of reactive media.
7	Maintain Saturated Cover on Former Tailings and Sedimentation Ponds	Establish and maintain a saturated cover over Former Tailings and Sedimentation Ponds to limit progression of ARD/ML.	• Avoids excavation risk. • Relatively low cost. • Reduced potential to generate ARD/ML if tailings remain saturated.	• Requires storage of water in Former Tailings and Sedimentation Ponds. • Increased geotechnical risk. • Further investigation required to confirm ability to maintain positive water balance. • Water balance sensitive to effects of natural variability or climate change.

HYDROGEOLOGICAL CONCEPTUAL MODEL

Based on hydrogeological investigations conducted between 2009 and 2014 (AECOM, 2015), the following five hydrostratigraphic units were identified: 1) Tailings; 2) Shallow Perched Aquifer; 3) Intermediate Aquitard; 4) Deep Unconsolidated Aquifer; and 5) Bedrock. As shown on the simplified cross section B-B' (Figure 4), the hydrogeological conceptual model identified seepage losses from the Adit Drainage and direct precipitation as the primary contributors of water to the Former Tailings Pond and the shallow perched aquifer, which contributed to the production of an ARD/ML groundwater plume. Downslope of the Site, deep groundwater was also shown to combine with groundwater in the perched aquifer prior to discharging to surface at springs near the Compliance Boundary.

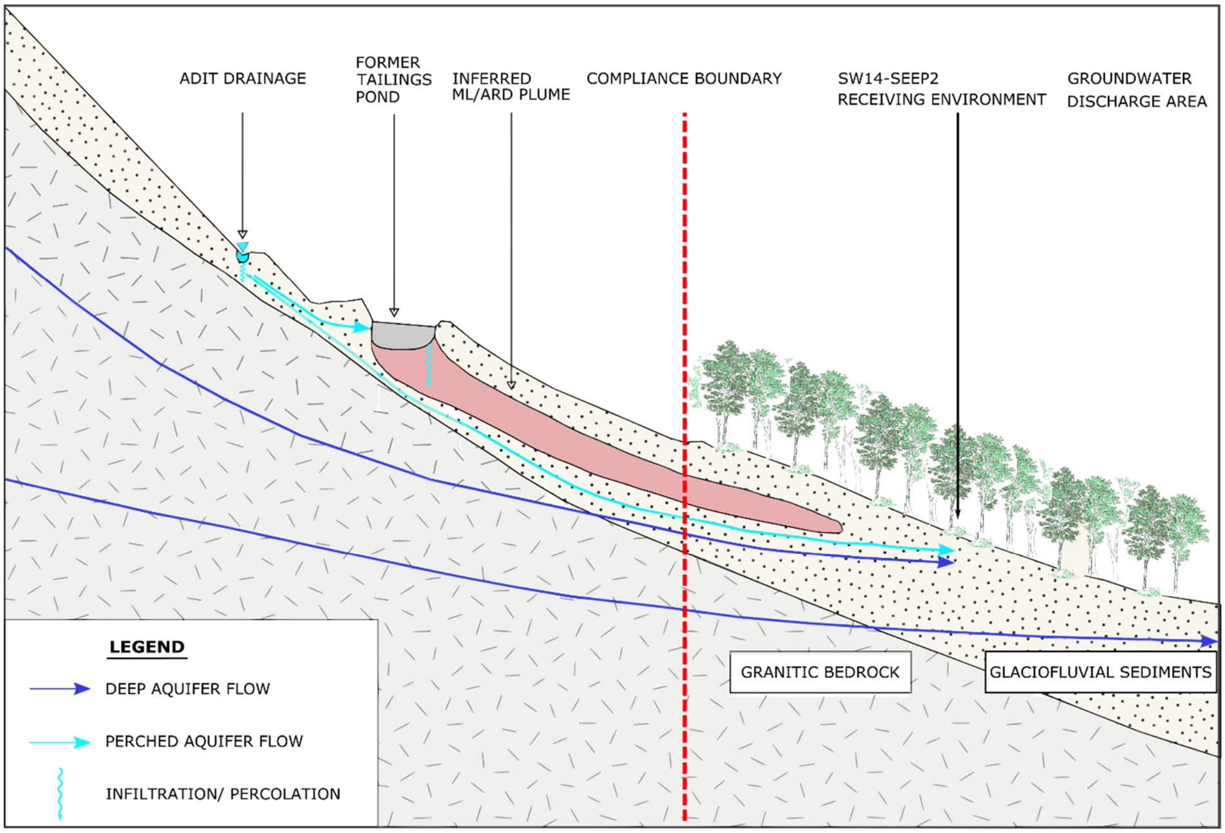

Figure 4. Hydrogeological Conceptual Model – Cross Section B-B'

WATER BALANCE AND WATER QUALITY MODEL

A simple deterministic spreadsheet model incorporating was developed to evaluate the water balance and predict concentrations of analytes at the point of discharge to the receiving environment (SW14-SEEP2). The model was then used to assess the feasibility of the remedial options that were advanced beyond preliminary screening (Options 2, 3 and 7). Key components of the water balance were precipitation, evapotranspiration, seepage inputs from the Adit Drainage to the perched aquifer, and discharge of groundwater from the deep aquifer to the receiving environment. The model was informed by measured seepage losses from the Adit Drainage, estimates of direct precipitation on the Former Tailings Pond, theoretical calculations of infiltration through geomembrane liner defects. Geochemical source terms were assigned to the various flows based on measured data and geochemical characterization results. Sulphate was used as a conservative element to calibrate the model. The conceptual model of the water balance and water quality model is provided in Figure 5.

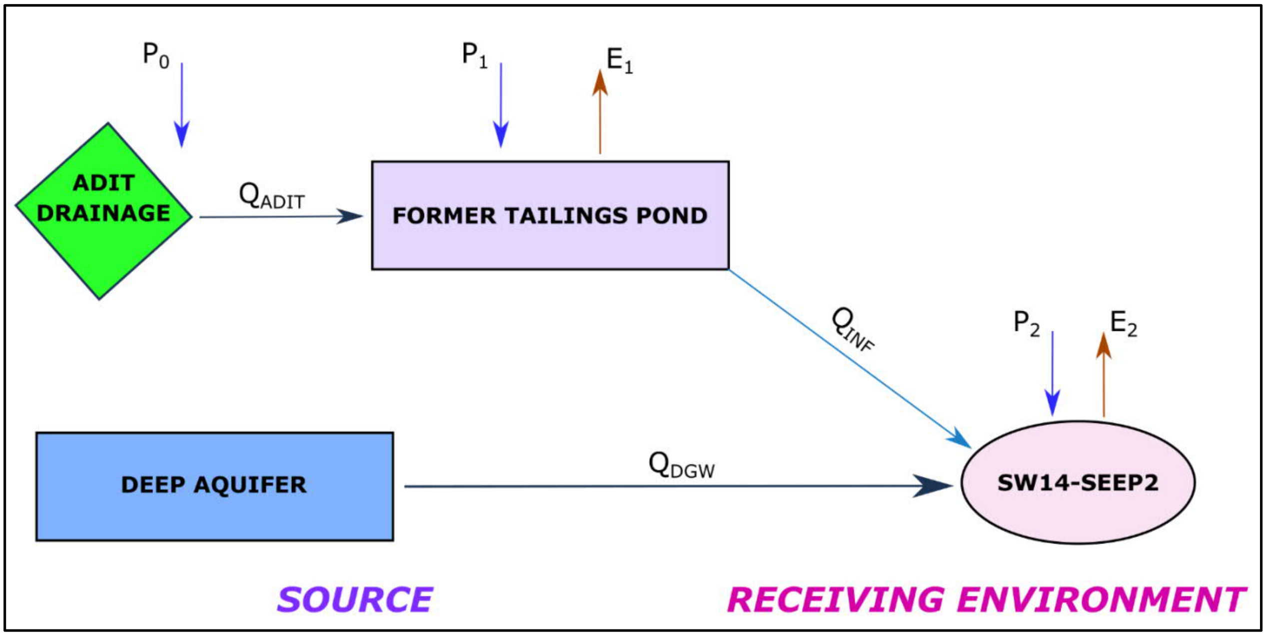

Figure 5. Conceptual Water Balance Model

Groundwater flow was assumed to be uniform through a cross-section with a unit width of one meter. Steady-state flow conditions were assumed such that there was no change in water storage within the tailings pond or mdelled hydrostratigraphic units over time. Hydraulic conductivity values were assigned to each hydrostratigraphic unit based on measured results. Meteoric inputs including rainfall and snowfall were based on Canadian Climate Normals (1980-2010) for Atlin (Station 1200560), and seasonal fluctuations were not considered in this model. Evapotranspiration at the Site was estimated to comprise 40% of total precipitation on an annual basis. Groundwater has historically been observed to discharge to surface near the toe of the slopes above the Former Tailings Pond, where ponding of surface was observed on top of the capped tailings. Surface runoff was considered to be negligible due to the very coarse soil texture and the lack of established surface drainage pathways or erosion more that 30 years after the mine was abandoned. Further, strong vertically downward hydraulic gradients have been observed in shallow multilevel wells installed within and around the Former Tailings Pond.

The perched aquifer becomes thinner in the downslope direction. Groundwater from the perched aquifer and deep aquifer combine below surface prior to discharging to the receiving environment in the form of seeps. SW14-SEEP2 is located approximately 375m downslope of the Former Tailings Pond, and represents the receiving environment. At steady-state, the water balance for Cross Section B-B' is expressed as:

$$Q_{SW14-SEEP2} = (P_0+P_1-E_1) + (P_2-E_2) + Q_{ADIT} + Q_{DGW} \qquad \text{(Equation 1)}$$

where $Q_{SW14\text{-}SEEP2}$ is the flux at SW14 - SEEP2, P_0 is the total precipitation falling on the catchment contributing to the Former Tailings Pond, P_1 is the total precipitation falling on the Former Tailings Pond, P_2 is the total precipitation falling on the SW14-SEEP2 catchment downstream of the Former Tailings Pond, E_1 is the evaporation from the Former Tailings Pond, E_2 is the evapotranspiration from the SW14-SEEP2 catchment downstream of the Former Tailings Pond, Q_{DGW} is the groundwater discharge from the deep aquifer to SW14-SEEP2 and Q_{ADIT} is the seepage loss from the Adit Drainage to the underlying perched aquifer.

Evaporation was only applied to the portion of the Former Tailings Pond (50% of surface area) that was observed to be submerged in water. Evaporation from the remaining area of the Former Tailings Pond and the upslope catchment was assumed to be negligible because the pond is not vegetated, surficial materials were observed to be dry, and infiltration was observed to be rapid during previous investigations. Q_{ADIT} was calculated to be 0.01 L/s based on the difference between continuous discharge measurements at two V-notch weirs installed upstream (Weir 1) and downstream (Weir 2) of the Former Tailings and Sedimentation Ponds, and the volume of infiltration to the Former Tailings Pond catchment (Figure 2). Groundwater infiltration to the perched aquifer (Q_{INF}) was calculated to be 0.47 L/s to 2.76 L/s based on measured groundwater elevations and measured hydraulic conductivity values for the tailings. Q_{DGW} was calculated to range from 0.004 L/s to 1.30 L/s based on mean annual groundwater elevations and measured hydraulic conductivity values for the deep aquifer.

The water quality model is a mass balance model developed to predict water quality in the receiving environment (SW14-SEEP2) by assigning geochemical source terms to each flow component identified in the water balance model. Sulphate (SO_4^{2-}) was selected to calibrate the mass balance model because it generally behaves conservatively under the conditions typically observed in nature and is not typically affected by chemical reactions along groundwater flow pathways. As shown in Figure 5, ARD/ML impacted groundwater migrates downward from the Former Tailings Pond to the underlying perched aquifer, and mixes with groundwater discharging from the deep aquifer before it discharges to the receiving environment at SW14-SEEP2. Concentrations of chemical constituents at SW14-SEEP2 were calculated using Equation 2 assuming mass was conserved:

$$C_{SW14-SEEP2} = \frac{\sum_{i=1}^{N} Q_i C_i}{\sum_{i=1}^{N} Q_i} \qquad \text{(Equation 2)}$$

where $C_{SW14\text{-}SW14\ -\ SEEP2}$ is the contaminant concentration at the point of discharge to the receiving environment, Q_i is flow rate for each distributed component and C_i is contaminant concentration for each component for all loading sources reported for the modelled point of discharge (SW14-SEEP2). Sulphate concentrations in the tailings area ($C_{MW09\text{-}08}$), deep groundwater (C_{DGW}) and receiving environment ($C_{SW14\text{-}SEEP2}$) were assigned based on measured mean annual concentrations.

Model Calibration

The water balance model was calibrated to match observed 2016 and 2017 flows at SW14-SEEP2. Measured water levels were adopted as input parameters. Hydraulic conductivity values measured for the tailings and perched aquifer were relatively consistent, and geometric mean values were adopted as input parameters without further adjustment during calibration. However, measured hydraulic conductivity values for the deep aquifer were more variable, and ranged from 1.45×10^{-6} m/s to 4.68×10^{-4} m/s, with a geometric mean of 4.17×10^{-5} m/s. During calibration, the hydraulic conductivity of the deep aquifer was systematically adjusted to match the discharge measured at SW14-SEEP2 (0.1 L/s to 0.3 L/s). The best calibration results were achieved when a hydraulic conductivity value of 6.0 $\times 10^{-5}$ m/s was assigned to the deep aquifer to match a measured discharge of 0.2 L/s. This produced a mixing ratio of 1:13 for the ARD-affected groundwater (Q_{INF}) and groundwater flowing in the deep aquifer (Q_{DGW}).

Model Validation

The model was subsequently validated using measured water quality data from monitoring wells along the groundwater flow pathway and within the ARD/ML plume. Measured sulphate concentrations were used to calculate the time derivative of concentrations in groundwater for each monitoring well along the groundwater flow pathway. The time derivative of sulphate was calculated based on observed concentration changes between two sampling events conducted in July and September 2016, divided by the travel time between two adjacent wells. The time derivative of sulphate along the plume ranged from 6.3 to 7.2 mg/L/day. However, concentrations observed at SW14-SEEP2 are much lower than would be predicted in the absence of mixing with deep groundwater, and the rate of increase in sulphate concentrations was only 0.5 mg/L/day. By assuming the plume has reached steady state, the mixing ratio at SW14-SEEP2 was calculated to be 1:12 to 1:14, which was consistent with the value derived from the independent water balance calculation (1:13). This supports the interpretation that groundwater from the perched aquifer and the deep aquifer undergo simple mixing prior to discharge at SW14-SEEP2, and validates use of the mean mixing ratio (1:13) to predict mass loading at SW14-SEEP2.

REMEDIAL OPTION EVALUATION

Each of the remedial options that advanced through the preliminary screening process were evaluated using the calibrated and validated water balance and water quality model by adjusting flow parameters and geochemical source terms to reflect implementation of each remedial option as follows:

Option 7 - Maintain saturated cover on former tailings and sedimentation ponds

Model results indicated a water deficit for the Former Tailings Pond when evaluated on an annual basis ($Q_{INF} > Q_{ADIT}$). The potential vertical infiltration fluxes through the Former Tailings Pond were calculated assuming saturated conditions using measured vertical groundwater gradients and hydraulic conductivity values. The results of the water balance indicated a deficit of water in the Former Tailings Pond on an annual basis, suggesting it would not be feasible to maintain saturated conditions within the Former Tailings Pond for most of the year without significant inputs of surface water. The option of diverting additional water to the Former Tailings Pond was not pursued due to the uncertainty associated with maintaining a positive water balance and the costs of continuous monitoring and maintenance of an earthen dam and spillway. If saturation was not maintained, oxidation of sulfides in the tailings would be expected to continue to degrade water quality in the perched aquifer. This is consistent with field observations of ponded water on top of the tailings following snowmelt and periods of intense precipitation. Furthermore, seasonal inputs of water would be likely to flush ARD/ML byproducts downward to perched aquifer for the foreseeable future. Option 7 was not considered further due to the high level of uncertainty and likely high cost.

Option 2 - In-situ isolation

To evaluate Option 2, sulphate concentrations at the receiving environment (SW14-SEEP2 location) were calculated using the water balance and water quality model to determine which components of the groundwater and surface water flows reporting to the Former Tailings Pond required collection and diversion to achieve acceptable water quality in the receiving environment. Calculations considered both the lateral groundwater discharge into the Former Tailings Pond and surface water infiltration through possible geomembrane liner defects.

The lateral groundwater discharge calculation considered a highly conservative scenario which assumed the diversion pipeline would only capture 80% of the seepage from the Adit Drainage, and the efficiency of the Interceptor Trench was assumed to be 90%. The remaining 10% of the lateral groundwater discharge was assumed to report to the Former Tailings Pond ($Q_{LATERAL}$) as follows:

$$Q_{LATERAL} = (Q_{ADIT} + P_0) \times 20\% \times 10\% = (\frac{0.01L}{s} + \frac{0.0136L}{s}) \times 20\% \times 10\% = 4.7\times10^{-4} \text{ L/s} \quad \text{(Equation 3)}$$

The vertical surface water leakage to the Former Tailings Pond through theoretical defects in the geomembrane liner was calculated using Bernoulli's equation for free flow through an orifice:

$$Q_{VERTICAL} = \pi \cdot C_B \cdot (r_0)^2 \cdot (2gh_w)^{0.5} \quad \text{(Equation 4)}$$

where $Q_{VERTICAL}$ is leakage rate through a theoretical hole in the geomembrane (m^3/s), C_B is coefficient related to the shape of the hole (C_B = 0.6 for sharp edges), r_B is the radius of the hole (m), g is acceleration due to gravity (m/s^2), and h_w is the leachate head on the liner (m). The geomembrane liner was assumed to be located between two infinitely pervious media (i.e. sand and gravel found on Site). Concentrations observed at monitoring well MW09-08 were assigned as the tailings source term for predictive modelling. A detailed summary of input parameters and predicted concentrations at SW14-SEEP2 are provided in Table 3.

Option 3 (Encapsulation)

To evaluate Option 3, sulphate concentration at the receiving environment (SW14-SEEP2) was calculated using water balance and water quality model. Because the tailings are relocated to an engineered geomembrane lined facility located in an upland area, lateral groundwater discharge to the facility was not anticipated.

Vertical surface water leakage through theoretical defects in the composite liner were calculated using the Giroud et al. (1989) equation, which considers a geomembrane liner placed on underlying low permeability soil. The Giroud et al. (1989) equation calculates the flow through a circular defect under the assumption that the head of liquid on the top of liner is less than the thickness of the low-permeability soil component of the liner as follows:

$$Q_{VERTICAL} = 0.976 \times Cqo \times d^{0.2} \times hw^{0.9} \times Ks^{0.74} \quad \text{(Equation 5)}$$

where $Q_{VERTICAL}$ is the discharge through a geomembrane hole (m^3/s), C_{q0} is the contact quality factor (dimensionless), d is the diameter of the circular defect (m), h_w is the head above the geomembrane liner (m), and K_s is the saturated hydraulic conductivity of the low permeability soil component of the liner (m/s). Concentrations observed at monitoring well MW09-08 were assigned as the tailings source term for predictive modelling. A detailed summary of input parameters and predicted concentrations at SW14-SEEP2 are provided in Table 4.

<u>Summary of water balance and water quality modelling results</u>

Remedial Option 7 was found to be infeasible. Remedial Options 2 and 3 are primarily focused on limiting the surface and groundwater inputs to the Former Tailings Pond and exfiltration from the Former Tailings Pond to the underlying perched aquifer. Based on the results presented in Tables 3 and 4, the predicted concentrations at SW14-SEEP2 are very similar for Option 2 and Option 3, and all concentrations met BCWQG. This indicates that both two options are equally able to achieve good water quality at SW14-SEEP2. Measured concentrations at SW14-SEEP2 are anticipated to be better than predicted herein due to attenuation mechanisms (e.g. sorption, precipitation, etc.) that are known to occur in natural groundwater flow systems.

Table 3. Estimated Infiltration Through Geomembrane Liner Defects – Option 2

Input Parameter	**Value**	**Description**
r_B (m)	0.001	Assumed 2 mm diameter circular defect
Number of Holes/m^2	0.0003	Assumed number of defects per unit area of BGM liner
Area (m^2)	2,000	Area of BGM liner: 50m (width)×40m (length)
n	0.6	Assumed number of holes in BGM liner
h_w (m/s)	0.001	Assumed hydraulic head above BGM liner
$Q_{LATERAL}$ (L/s)	4.7×10^{-4}	Groundwater seepage and precipitation reporting to tailings pond per meter width
$Q_{VERTICAL}$ (L/s)	2.6×10^{-4}	Infiltration through liner defects per meter width
Predicted Concentrations at SW14-SEEP2 (mg/L)		
SO_4	28.9	< BCWQG MAC
F	0.371	< BCWQG MAC
Al	0.0083	< BCWQG MAC
Cd	0.00028	< BCWQG MAC
Cu	0.00092	< BCWQG MAC
Mn	0.047	< BCWQG MAC
Ni	0.0045	< BCWQG
Zn	0.0392	< BCWQG MAC

Notes: BCWQG MAC = British Columbia Approved and Working Water Quality Guidelines. Guidelines for parameters that are hardness dependent were calculated using the local background hardness concentration of 100 mg/L.

Table 4. Estimated Infiltration Through Geomembrane Liner Defects – Option 3

Parameter	**Value**	**Description**
r_B (m)	0.001	Assumed 2 mm circular defect
Number of Holes/m^2	0.0003	Assumed number of defects per unit area of BGM liner
Area (m^2)	2,100	Estimated area of BGM liner for containment cell: 60m (length)×35m (width)
n	0.63	Assumed number of holes in BGM liner
Contact factor C_{q0}	0.21	Good contact factor
h_w (m/s)	0.01	Assumed hydraulic head above composite liner
Ks (m/s)	1.0×10^{-7}	Hydraulic conductivity of low permeability soil component
$Q_{VERTICAL}$ (L/s)	6.5×10^{-8}	Infiltration through liner defects per meter width
Predicted Concentrations at SW14-SEEP2 (mg/L)		

Parameter	Value	Description
SO_4	28.2	< BCWQG MAC
F	0.359	< BCWQG MAC
Al	0.0083	< BCWQG MAC
Cd	0.000076	< BCWQG MAC
Cu	0.000083	< BCWQG MAC
Mn	0.0083	< BCWQG MAC
Ni	0.0041	< BCWQG
Zn	0.0042	< BCWQG MAC

Notes: BCWQG MAC = British Columbia Approved or Working Water Quality Guidelines. Guidelines for parameters that are hardness dependent were calculated using the local background hardness concentration of 100 mg/L.

FINAL SCREENING

A final screening Remedial Option screening considered the overall implementation schedule and costs to differentiate between Options 2 and 3, and aid in selection of the preferred remedial option.

The selected remedial option had to meet CCSP's desired implementation schedule, with on-site construction activities scheduled to begin as soon as possible. Estimated construction schedules for each option were developed based on the productivity of the construction crews during Phase One Remedial Works assuming one crew, with work tasks occurring in series. As shown on Figure 6, Option 2 produced the shortest on-Site construction schedule and indicated construction could be completed in less than eight (8) weeks. Option 3 produced a longer construction schedule, requiring approximately 12 weeks on-Site. The optional neutralization of the tailings with lime was estimated to extend construction by one week for both options.

Remedial costs were estimated for Options 2 and 3 based on unit costs available for previous construction activities conducted at the Site and based on cost estimating databases in consideration of the remoteness of the Site. Option 2 was found to be the most cost-effective option. Costs were normalized to the lowest cost option (Option 2) to produce relative costs as shown in Figure 6. Costs associated with the optional neutralization of the tailings with lime were also estimated.
Options 2 and 3 were ranked based on the ability to meet CCSP's Remedial Objectives for the Site, which considered technical feasibility, implementation schedule and costs. Option 2 was found to be the technically feasible, cost-effective, and constructible within the short construction season, and was chosen as the preferred remedial option for the Site. The incorporation of lime to neutralize the tailings increased the cost associated with Options 2 and 3 without a significant incremental benefit. The optional lime neutralization was not selected due to the unacceptable geotechnical risks associated with placement of additional material within the Former Tailings Pond and near the crest of a steep slope. Furthermore, there was limited incremental benefit to downgradient water quality because of the very low residual water flux through the tailings.

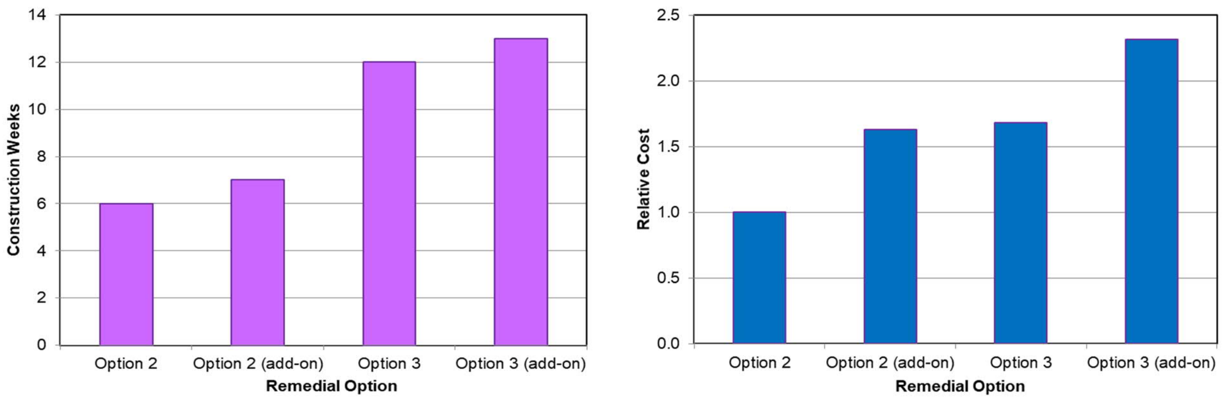

Figure 6. Estimated schedule and costs for construction of Remedial Options 2 and 3.

CONCLUSIONS

This case study presented a simple approach that allows for cost-effective development and evaluation of remedial options for remote abandoned mine sites. A robust hydrogeological conceptual model is required to support development of an integrated water balance. The hydrogeological conceptual model was developed based on direct characterization of solid phase geochemistry, aquifer properties, groundwater levels, surface water flows and water quality. To realize the full value of the model, it is important that the model be updated after each drilling, sampling and characterization program.

A simple spreadsheet-based water balance and water quality model was used to confirm the feasibility of select remedial options and aid in the evaluation and selection of the preferred remedial option. The model calibration and validation results indicated that the model was suitable for predicting water quality at SW14-SEEP2. The model was used to predict water quality for remedial options to confirm their feasibility and evaluate their ability to meet water quality guidelines in the receiving environment. Concentrations of contaminants of concern at SW14-SEEP2 were predicted to be below British Columbia Approved and Working Water Quality Guidelines for both Options 2 and 3, indicating both options were equally able to achieve compliant water quality in the receiving environment.

Options 2 and 3 were further evaluated based on implementation schedule and cost, and indicated that effective management of surface water and groundwater could achieve the CCSP's remedial goals without excavating and relocating the tailings to an ex-situ geomembrane-lined facility. Estimated costs for Option 2 were approximately 70% lower, and the construction schedule was six weeks shorter than Option 3. Residual risks and long-term monitoring requirements for both options were similar.

The results highlight the value of a simple balanced approach to identify and evaluate remedial options using a robust conceptual model informed by Site characterization and monitoring data. The Phase 2 Remedial Works were completed in 2018, resulting in desaturation of the tailings, and improved downgradient groundwater quality.

REFERENCES

AECOM. 2015. Atlin Ruffner Mill and Tailings Site – 2014 Additional Field Investigation to Address Non-Compliance Report, 28 April 2015.

Giroud, J.P., and Bonaparte, R. 1989a. Leakage through liners constructed with geomembranes—Part I: Geomembrane liners. Geotextiles and Geomembranes, 8(1): 27–67.

Giroud, J.P., and Bonaparte, R. 1989b. Leakage through liners constructed with geomembranes—Part II: Composite liners. Geotextiles and Geomembranes, 8(2): 71–111.

Rowe, R.K. 1998. Field study of wrinkles in a geomembrane at a composite liner test site. Geotechnique, 49: 1196–1211.