INTEGRATING DECISION ANALYSIS, ENGINEERING AND WATER QUALITY MODELLING FOR REMEDIAL OPTION EVALUATION OF THE 2200 LEVEL AND MOUNT SHEER TOWNSITE AT BRITANNIA MINE

Kun Jia, M.Sc., P.Geo.[1]
Ryan Mills, M.Sc., P.Geo.[2]
Stephen Sumsion, P.Eng.[3]
Tyler O'Grady, P.Ag.[4]

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

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

[3] Senior Environmental Engineer,
AECOM Canada Ltd., Burnaby, BC, Canada

[4] Senior Contaminated Sites Specialist,
Crown Contaminated Sites Program, BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development, Surrey, BC, Canada

ABSTRACT

This case study presented a modified MAA approach that considers copper load reduction and cost to evaluate and select a preferred remedial option for the management of mine waste. A remedial option evaluation was undertaken to identify, design, cost and evaluate risk-based remedial options that could be employed to reduce copper loadings to Britannia Creek by >50% and address unacceptable aquatic risks at the 2200 Level of Britannia Mine. Previous investigations found the primary sources of copper were waste rock, highly leachable copper plant residuals and contaminated soils.

Remedial approaches were screened for five Areas of Environmental Concern (AECs) using a modified Multiple Accounts Analysis approach with input from experienced professionals at technical workshops. Five remedial options were designed for the 2200 Level and two remedial options were developed for Mount Sheer using best management practices for control of metal leaching and acid rock drainage. Remedial options utilized passive approaches to maintain separation between clean water and waste materials at the remote unpowered site. Remedial options and detailed cost estimates were developed in consideration of the Overall Closure Plan Framework for the Britannia Mine Site.

A water balance and water quality model was developed based on the Conceptual Site Model to quantitatively estimate copper load reduction to Britannia Creek for each remedial option. Input data for the model was obtained from public sources and historical studies documenting the extents of the AECs, geochemistry of waste materials, hydrology and hydrogeology. The model was used to predict water quality in Britannia Creek and estimate copper load reduction for each remedial option. Two options did not achieve the remedial goal of 50% copper load reduction and were abandoned. The other three options met the remedial goal with an estimated reduction of 65-69%. The preferred remedial option was selected after consideration of capital costs, long-term costs and estimated load reduction that is supported by a rapid, defensible and traceable evaluation process.

Keywords: Abandoned mine, conceptual site model, remedial option evaluation, water quality model

INTRODUCTION

Background

The Britannia Mine is located approximately 45 km north of Vancouver near the community of Britannia Beach, BC (Figure 1). The mine operated from about 1904 until 1974 and was an important source of copper ore for almost 70 years. Although historical milling operations took place adjacent to the Sea to Sky Highway on what is now the Britannia Mine Museum property, mining activities extended several kilometers inland. Mining operations included drilling, blasting, open pit and underground mining, waste rock deposition, operation of copper launders, milling, ore concentration and shipment. Over 50 million tons of ore was removed in the form of pyrite, chalcopyrite, sphalerite, galena, gold and silver.

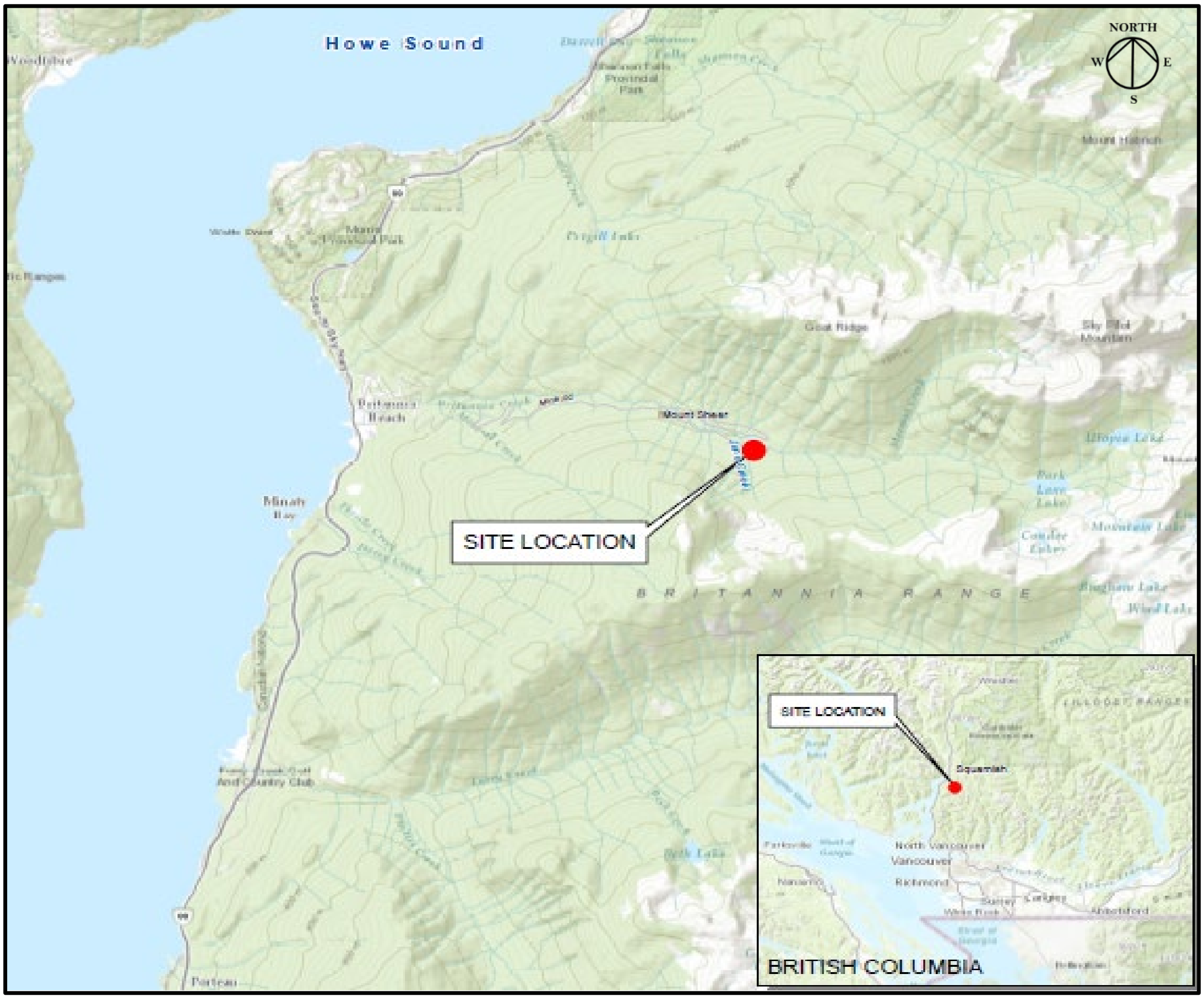


Figure 1. Location of 2200 Level Waste Rock Pile at Britannia Mine.

Mining resulted in acid rock drainage, metal leaching and contamination of groundwater and surface water that has adversely affected the receiving environment in local creeks and Howe Sound for over 100 years. Britannia Creek is the receiving environment for metal loadings from various contaminant sources including the 2200 Level waste rock pile, highly leachable residues, and slag-like residues from the former copper launders at the 2200 Level and Mount Sheer Townsite. Previous investigations developed a preliminary conceptual model (Golder 2015), delineated contamination (Golder 2018) and evaluated risks to human health and the ecology (Golder 2019) of the area and found unacceptable risks to aquatic and terrestrial ecology. AECOM was contracted by the Crown Contaminated Sites Program of the British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development who are responsible for the identification, investigation and remediation of high-risk contaminated sites on provincial land to protect human health and the environment to complete this remedial option evaluation (AECOM 2020).

Remedial Objectives

The Britannia Mine Remediation Project has established an Overall Closure Plan Framework to guide remedial efforts. The primary remedial objectives for the Britannia Creek watershed are:

- To cost-effectively reduce the dissolved copper loadings from the 2200 level area to Reach 2 of Britannia Creek by 50% to facilitate a reduction of risk to aquatic life in Britannia Creek.
- To cost-effectively reduce the risk to terrestrial ecology associated with three hot spots areas including: 1) the Copper Plant Highly Leachable Residue Area; 2) the Copper Plant Slag-Like Residue Area, and the Mount Sheer Copper Launder Soil Halo Area.

Secondary remedial objectives are:

- To address the human health and socio-economic considerations during remediation of the Site.

Remedial Areas

The areas of environmental concern (AECs) at the 2200 Level (Figure 2) that contribute to degraded water quality, unacceptable aquatic ecological risk in Reach 2 of Britannia Creek and other potential ecological risks include:

- **Copper Plant Slag-like Residue (**footprint of 3,151 m^2): These residues are highly leachable causing groundwater contamination that is contributing to unacceptable aquatic ecological risks to Britannia Creek and unacceptable terrestrial ecological risk.
- **Copper Plant Highly Leachable Residue (**footprint of 449 m^2): The residues are exposed at ground surface, are the most leachable at the 2200 Level and cause unacceptable terrestrial ecological risk.
- **2200 Level Waste Rock Pile (**footprint of 22,832 m^2): The waste rock consists of Type I Waste Rock (unvegetated) and Type II (vegetated) waste rock, is potentially acid generating and is contributing to contamination that is contributing to the unacceptable aquatic ecological risks in Britannia Creek.
- **2200 Level Waste Rock Pile Soil Halo (**footprint of 2,890 m^2): The contaminated soil halo is not producing unacceptable terrestrial risks. Soil contamination is limited to surficial soils and the area is heavily forested and is not likely a significant contributor to contaminant loads to Britannia Creek.
- **Jane Creek**: Jane Creek contributes significant flows and relatively minor (3 to 16%) contaminant loads to Britannia Creek. Some of the flows in Jane Creek may infiltrate into the 2200 Level Waste Rock Pile and produce increased volumes of contaminated groundwater flows that contributes to the unacceptable aquatic ecological risks to Reach 2 of Britannia Creek.
- **Mount Sheer Copper Launder Soil Halo** (footprint of 5,765m^2): The area surrounding the copper launder contains contaminated soils that result in unacceptable terrestrial ecological risk. The risk to aquatic ecology is acceptable because of minimal copper loading contributions to Britannia Creek.

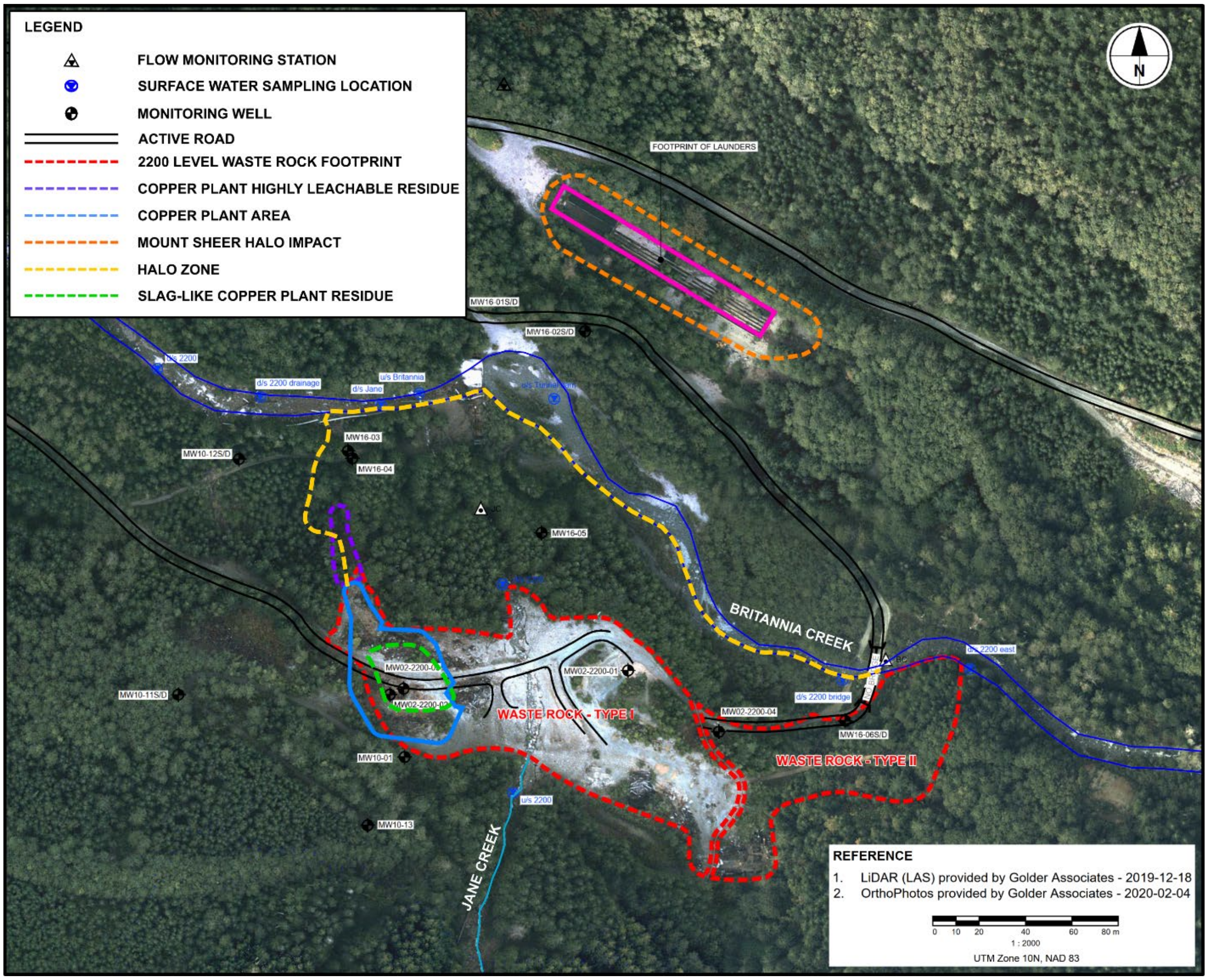


Figure 2. Areas of Environmental Concern (AECs) – 2200 Level and Mount Sheer.

REMEDIAL OPTION EVALUATION APPROACH

Screening of Remedial Approaches

AECOM adopted a simplified Multiple Accounts Analysis (MAA) approach for remedial option selection to ensure the remedial option selection process was transparent, defensible, and adequately documented while eliminating bias and subjectivity. The MAA approach is commonly used to identify and assess alternatives for mine waste disposal following the Canadian Guidelines for the Assessment of Alternatives for Mine Waste Disposal (Environment Canada 2016) but is not routinely applied to remediation projects. The following seven-step process was followed:

- **Step 1: Identify Potential Remedial Approaches.** The goal is to identify remedial approaches capable of meeting remedial objectives.
- **Step 2: Conduct Pre-Screening Assessment.** The goal is to remove approaches that have fatal flaws.
- **Step 3: Remedial Option Development.** This step involves assembling remedial approaches and describing the remedial alternatives.

- **Step 4: Development of Multiple-Accounts Ledger.** This is the beginning of a multiple accounts analysis and included setting up evaluation criteria (sub-accounts) and measurement criteria (indicators).
- **Step 5: Value-Based Decision Process.** During this step each sub-account and indicator was weighted in importance, and assigned a value (scoring, weighting, and quantitative analysis).
- **Step 6: Sensitivity Analysis and Documentation of Risks/Uncertainties:** A sensitivity analysis was conducted, recognizing not all stakeholders will not place the same importance on each impact.
- **Step 7: Document Results:** To improve readability of this report, the assessments for tailings and mine rock were structured into six sections that reflect the above steps.

For each AEC that posed unacceptable aquatic or terrestrial risks, the following potential remedial approaches that may achieve the remedial objectives were identified and evaluated:

- **Risk Management:** Considered administrative controls and/or monitoring.
- **Waste Excavation and Disposal:** Considered on-Site disposal at Jane Basin, a new on-Site permitted landfill, or an existing off-site permitted landfill.
- **In-Situ Waste Management:** Considered low permeability capping, isolation capping for terrestrial habitat, subsurface barrier walls and geochemical controls.
- **Water Management (Long-Term):** Considered diversion of clean runoff, preventing infiltration from Jane Creek, groundwater collection/treatment or installation of a permeable reactive barrier.

A multiple accounts ledger of accounts and sub-accounts was developed to score remedial approaches based on their ability to meet the primary and secondary remedial objectives are as outlined below:

Primary Objective Screening Indicators:

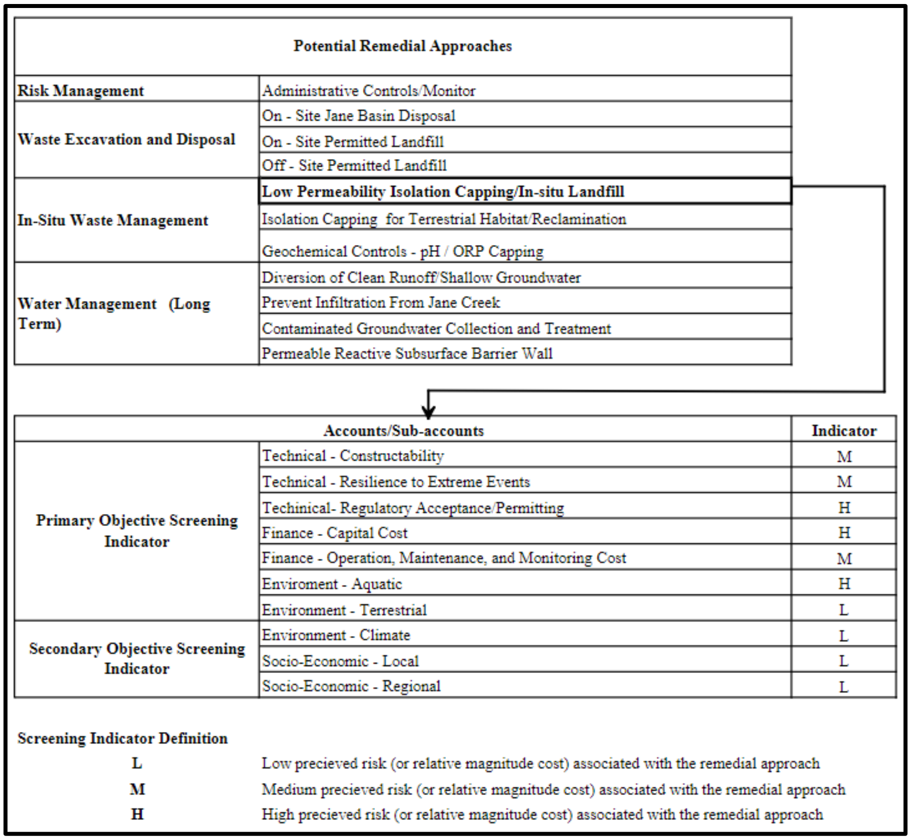
1. Technical - Constructability
2. Technical - Resilience to Extreme Events
3. Technical- Regulatory Acceptance/Permitting
4. Finance - Capital Cost
5. Finance - Operation, Maintenance, and Monitoring Cost
6. Environment - Aquatic
7. Environment - Terrestrial

Secondary Objective Screening Indicators:

1. Environment - Climate
2. Socio-Economic - Local
3. Socio-Economic - Regional

A value-based decision process was then implemented, and screening indicator values were assigned in a systematic manner as shown for the example for the “Low Permeability Location Capping/In-situ Landfill” of the Copper Plant Highly Leachable Residues in Figure 3. Screening indicators were defined and subsequently ranked as Low (L), Medium (M) and High (H) based on the perceived risk or relative magnitude cost specific to each remedial approach, screening indicator and AEC. Scoring was completed by the technical team based on the remedial objectives and their collective experience in contaminated site and mine remediation in a facilitated workshop format. By following this procedure, it is obvious to others why a score for a given indicator has been assigned. Because the qualitative value scale has been developed collaboratively, there is built in confidence amongst the project team that scoring is reasonable.

This process was repeated until all remedial approaches had been evaluated for every AEC.



Potential Remedial Approaches	
Risk Management	Administrative Controls/Monitor
Waste Excavation and Disposal	On - Site Jane Basin Disposal
	On - Site Permitted Landfill
	Off - Site Permitted Landfill
In-Situ Waste Management	**Low Permeability Isolation Capping/In-situ Landfill**
	Isolation Capping for Terrestrial Habitat/Reclamination
	Geochemical Controls - pH / ORP Capping
Water Management (Long Term)	Diversion of Clean Runoff/Shallow Groundwater
	Prevent Infiltration From Jane Creek
	Contaminated Groundwater Collection and Treatment
	Permeable Reactive Subsurface Barrier Wall

Accounts/Sub-accounts		Indicator
Primary Objective Screening Indicator	Technical - Constructability	M
	Technical - Resilience to Extreme Events	M
	Techinical- Regulatory Acceptance/Permitting	H
	Finance - Capital Cost	H
	Finance - Operation, Maintenance, and Monitoring Cost	M
	Enviroment - Aquatic	H
	Environment - Terrestrial	L
Secondary Objective Screening Indicator	Environment - Climate	L
	Socio-Economic - Local	L
	Socio-Economic - Regional	L

Screening Indicator Definition

L	Low precieved risk (or relative magnitude cost) associated with the remedial approach
M	Medium precieved risk (or relative magnitude cost) associated with the remedial approach
H	High precieved risk (or relative magnitude cost) associated with the remedial approach

Figure 3. Preliminary Screening of Remedial Approaches for Low Permeability Isolation Capping / In-situ Landfill to Manage Copper Plant Highly Leachable Residues

This scoring was repeated for all AECs and remedial approaches until all of the primary and secondary screening indicators have been qualitatively scored. Following screening of each remedial approach based on their risk profile and/or relative costs, a secondary screening process evaluated each remedial action in its entirety. Each of the remedial actions was ranked based on their anticipated ability to achieve the primary remedial objectives as follows:

- **Class 1**: Likely to cost-effectively achieve primary Aquatic and Terrestrial objectives.
- **Class 2**: May assist in cost-effectively achieve Aquatic and Terrestrial objectives.
- **Class 3**: Unlikely to cost-effectively achieve primary Aquatic and Terrestrial objectives.

Each of the remedial actions was also ranked based on their anticipated ability to achieve the secondary remedial objectives as follows:

- **Class 4**: Likely to cost-effectively improve human health or socio-economic factors.
- **Class 5**: Unlikely to cost-effectively improve human health or socio-economic factors.

Remedial Options Short List and Selection Process

Remedial approaches for each AEC were assembled to produce a short list of five remedial options that were advanced to conceptual design, costing, and detailed evaluation. Short-listed remedial options for the 2200 Level are summarized in Table 1.

Following completion of conceptual design, remedial costs were estimated for each option to inform option selection in consideration of project management, engineering design, site preparation, remediation, restoration, and long-term monitoring and maintenance (LTMM) costs over the first 30 years. The lifespan and replacement costs of engineered components was also considered. This allowed for a full life-cycle cost to be assigned to each option, thereby avoiding unintentional selection of options that have lower capital costs at the expense of relatively high operational costs.

Table 1. Summary of 2200 Level Remedial Options and Remediation Phases

	Areas of Environmental Concern (AECs)				
Remedial Option	**Copper Plant Highly Leachable Waste**	**Copper Plant Slag-Like Residuals**	**Type 1 Waste Rock**		
			Direct Precipitation	**Jane Creek**	**Surface and Groundwater Run-On**
Remedial Phases	**Phase 1**		**Phase 2**		
Option 1	Excavate	Low Permeability Cap	No Action	Divert Through Solid Pipe	None
Option 2		Excavate			
Option 3			Low Permeability Cap	Incorporated into Low Permeability Cap	Surficial Diversion Ditch
Option 4		Low Permeability Cap			
Option 5		Excavate	No Action	Divert Through Solid Pipe	Interception Trench

The overall goal was to select a remedial option that will provide the most environmental benefit per unit of cost expenditure. The remedial goal for the 2200 level is primarily related to water quality (copper concentrations in Britannia Creek), so a water balance and water quality model was developed to simulate contaminant load reductions that would result from each option using a catchment hydrology approach and the conceptual hydrogeological model. Remedial options for Mount Sheer are unlikely to have an effect on copper loading to Britannia Creek, and are not specifically discussed in this paper.

WATER BALANCE AND WATER QUALITY MODEL

A water balance and water quality model was developed to quantitatively estimate copper load reduction for each short-listed remedial option. The model considered both natural and mine-impacted contact water flows and chemistry to establish a water balance and load for the watershed hosting the 2200 Level.

Water Balance Model

The water balance model was based on a preliminary conceptual model that was expanded to consider the entire surface water catchment for Jane Creek and the 2200 Level to estimate copper load reduction in response to each remedial option. The model considers both natural and mine-impacted contact water flows and therefore establishes the water balance for the 2200 Level. A schematic of the conceptual water balance model is shown on Figure 4.

Surface water catchments were delineated for the 2200 Level based on the watercourse layers and topographic mapping available from online geospatial data sources. The Upper Jane Creek catchment is very large (1,716,095 m^2) and is not shown on the figure due to scale limitations. Surface water monitoring station u/s 2200 is the discharge point for the Upper Jane Creek catchment and was assumed to represent the net flow of surface water and groundwater to the Lower Jane Creek catchment. Groundwater within the catchments discharges to Britannia Creek.

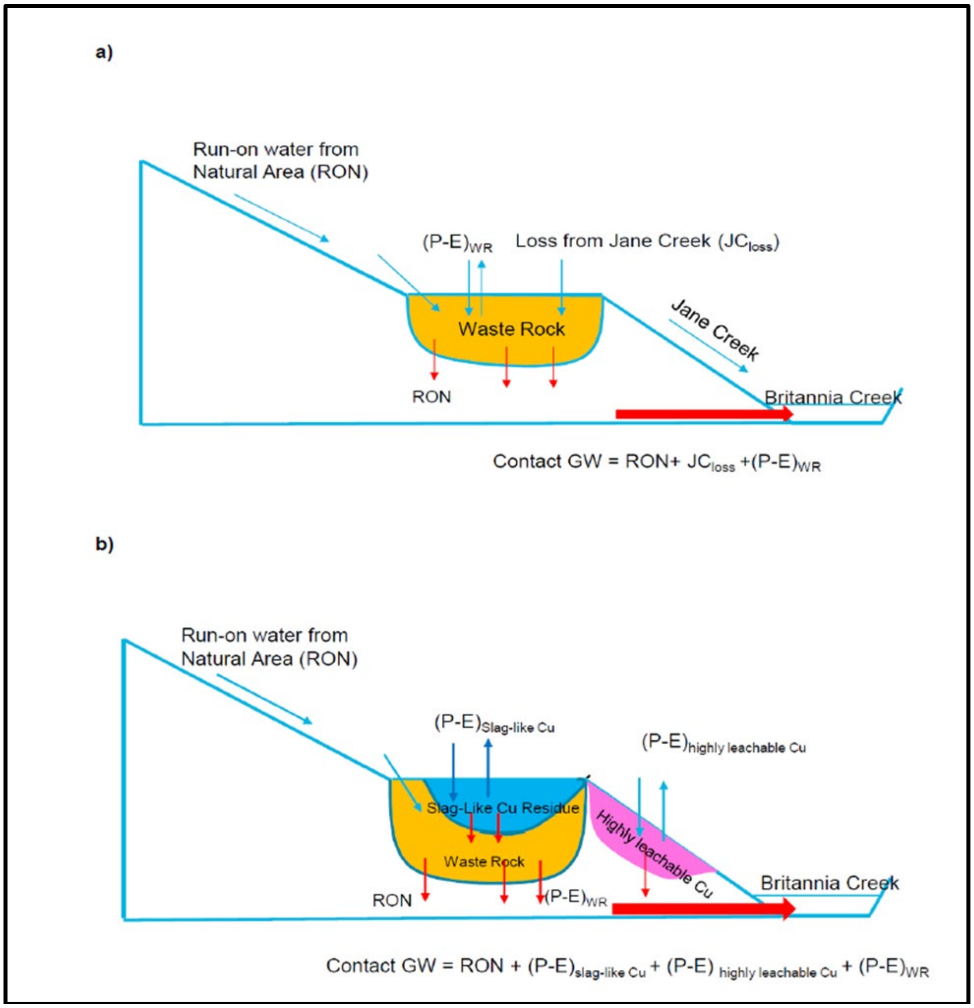


Figure 4. 2200 Level Water Balance Conceptual Model. a) Waste Rock Area; b) Highly Leachable Waste and Copper Plant Area. Where Contact GW is the contaminated groundwater flux which water percolates through contaminant source areas and eventually discharges to Britannia Creek. RON is the direct precipitation of the up-slope undisturbed nature areas which run-on to the site in the form of overland or shallow groundwater flows. P is total direct precipitation falling onto the contaminant source areas. E is evapotranspiration from the contaminant source areas. JC_{Loss} is the seepage loss from Jane Creek to the underlying 2200 Level waste rock pile.

Surface water catchments were further subdivided based on geochemical sources to allow for tracking of flows and contaminant loadings. Surface water run-on water from the upslope undisturbed areas was assumed to be free of copper and other contaminants prior to discharging to the 2200 Level waste rock pile, where it tends to infiltrate through the mine waste and becomes contact water. Direct precipitation and snowmelt also infiltrate through the mine waste and becomes contact water. It was assumed that precipitation falling on the 2200 Level Waste Rock Pile Soil Halo downgradient of the waste rock pile was not significantly influenced by metals-contaminated soil and therefore does not contribute to contaminant loading to Britannia Creek. A portion of the flow in Jane Creek was inferred to infiltrate through the coarse waste rock and recharge the shallow aquifer below the 2200 Level Waste Rock Pile and contribute to contaminant loading to Britannia Creek. Water balance equations were developed for each catchment and sub-catchment contributing to contaminant loading in Britannia Creek in consideration of all components of the hydrologic cycle (i.e. rainfall, snowfall, evapotranspiration, runoff, infiltration, seepage, etc.) to estimate water flows and the resultant contaminant loading for existing conditions and in response to each of the five remedial options under consideration. Parameters were assigned using direct measurements, historical reports, and public meteorological and geospatial datasets.

The water quality model is a mass balance model and was developed to estimate the copper loading to Britannia Creek under existing conditions and for each remedial option. Geochemical source terms for waste rock, copper plant highly leachable residue and copper plant slag-like residue were developed based on the results of shake flask extraction (SFE) testing, and in consideration of available seepage and groundwater quality data to support a preliminary assessment of loading and identification of any data gaps. Contaminant loading was simulated by assigning contaminant source terms to corresponding flows.

Water Balance Model Results

The water balance results for existing conditions and five remedial options is summarized in Table 2.

Table 2. Summary of Water Balance Results - Existing Conditions and Remedial Options

Source Area	Component	Existing Condition		Option 1		Option 2		Option 3		Option 4		Option 5	
		L/s	%	L/s	%	L/s	%	L/s	%	L/s	%	L/s	%
Waste Rock - Type I	Contact Groundwater	7.94	100.0%	4.35	54.8%	4.35	54.8%	1.74	21.9%	1.74	21.9%	2.35	29.6%
Waste Rock - Type II	Contact Groundwater	2.00	100.0%	2.00	100.0%	2.00	100.0%	0.95	47.4%	0.95	47.4%	0.80	39.9%
Copper Plant Residue	Contact Groundwater	0.24	100.0%	0.02	10.0%	Source is removed		Source is removed		0.02	10.0%	Source is removed	
Waste Rock Below Copper Plant Residue	Contact Groundwater	1.24	100.0%	1.02	82.4%	1.24	100.0%	0.32	26.1%	0.32	26.1%	0.44	35.6%
Highly Leachable Copper Residue	Contact Groundwater	0.03	100.0%	Source is removed		Source is removed		Source is removed		Source is removed		Source is removed	
Total Contact Groundwater	m^3/yr	361,215		233,283		239,422		95,015		95,782		113,212	
	L/s	11.5		7.4		7.6		3.01		3.04		3.6	
Total Contact Groundwater Reduction (%)				35%		34%		74%		73%		69%	

The volume of contact water (primarily groundwater) for each source area was calculated to illustrate the relative importance of each flow component for each remedial option. For existing conditions, the water balance model calculated a total of 361,215 m^3/yr (11.5 L/s) of contact groundwater discharge to

Britannia Creek. Approximately 70% of the total contact groundwater is derived from the Type 1 Waste Rock. This significant groundwater flow is primarily due to the large volume of run-on from upslope areas, and exfiltration (seepage) from Jane Creek, which together comprised 61% of the total water inputs. Options 1 and 2 reduced the volume of contact groundwater by approximately 34-35%. Options 3, 4 and 5 reduced the volume of contact groundwater by over 69-74% due to diversion of surface water run-on from upslope areas and control/diversion of Jane Creek.

Water Quality and Mass Loading Model Results

Table 3 presents the contaminant loading results for existing conditions and five remedial options. As shown on Table 3, Options 1 and 2 are not anticipated to achieve the remedial goal of a 50% reduction in copper loading without additional remedial components. Options 3, 4 and 5 were simulated to achieve the remedial goal of 50% reduction in copper loading to Britannia Creek.

Table 3. Summary of Mass Loading Results for Each Remedial Option

Source Area	Source Concentration	Mass Loadings									
		Option 1		Option 2		Option 3		Option 4		Option 5	
	mg/L	g/d	%	g/d	%	g/d	%	g/d	%	g/d	%
Waste Rock - Type I	1.27	478	50.0%	478	49.3%	191	41.0%	191	40.1%	258	48.7%
Waste Rock - Type II	1.27	219	22.9%	219	22.6%	104	22.2%	104	21.8%	87	16.5%
Copper Plant Residue	4.76	10	1.0%	-	-	-	-	10	2.1%	-	-
Waste Rock Below Copper Plant Residue	1.27	112	11.8%	136	14.1%	35.6	7.6%	35.6	7.5%	48.7	9.2%
Highly Leachable Copper Residue	12.6	-	-	-	-	-	-	-	-	-	-
Jane Creek	0.062	136	14.2%	136	14.0%	136	29.1%	136	28.5%	136	25.6%
Total Copper Loadings (g/day)		955	100.0%	969	100.0%	466	100.0%	476	100.0%	530	100.0%
Copper Load Reduction (g/day)		541		527		1,029		1,019		966	
Copper Load Reduction (%)		36%		35%		69%		68%		65%	

REMEDIAL OPTION SELECTION

Costs were normalized to Option 1 to produce relative costs for each option as shown in Table 4.

Table 4. Cost Benefit Ranking for Each Remedial Option Relative to Option 1

Category	Option 1	Option 2	Option 3	Option 4	Option 5
Copper Load Reduction (%)	36	35	69	68	65
Total Capital Costs Relative to Option 1	1.0	1.4	3.4	2.6	2.3
Rank on Load Reduction / Capital Costs	1	4	5	3	2
Total Long-Term Monitoring and Maintenance (30-Year) Relative to Option 1	1.0	0.83	1.47	1.48	0.87
Rank on Load Reduction / 30-Year LTMM Costs	3	1	4	5	2
Total Capital Cost + 30 Year LTMM Cost Relative to Option 1	1.0	1.0	2.1	1.8	1.3
Copper Load Reduction / Total Relative Cost	36.0	34.2	33.2	37.1	49.0
Rank on Load Reduction / Capital + 30-Year LTMM Costs	3	4	5	2	1

The preferred remedial option for the 2200 Level was selected using the following formula:

$$\textbf{Evaluation Metric} = \frac{\textbf{Estimated Reduction in Dissolved Copper Loading}}{\textbf{Estimated Total Costs}}$$

Based on the water balance and water quality model, Options 1 and 2 were simulated not to achieve the targeted 50% reduction in copper loadings to Britannia Creek and therefore were not recommended for further consideration despite having the lowest capital costs and relatively low 30-year LTMM costs. Options 3, 4 and 5 predicted copper loading reductions of 65-69% that meet the goal of a 50% reduction in copper loadings to Britannia Creek to be protective of aquatic life. Options 3 and 4 (both involving an expensive low permeability cover) had significantly higher capital and LTMM costs than Option 5, resulting in lower copper load reduction per unit cost. Therefore, Option 5 was selected as the preferred remedial option in consideration of capital costs, LTMM costs and estimated load reduction. It included excavation of Copper Plant High Leachable Waste and Copper Plant Slag-Like Residuals combined with diversion of run-on from upslope areas and diversion of Jane Creek through a solid pipe. Phase 1 Remedial Works were focused on excavation and disposal of highly contaminated materials. Phase 2 Remedial Works were focused on surface water and groundwater management and minimizing the diversion of clean water around the waste. The entire process was completed in four months.

CONCLUSIONS

This case study presented a modified Multiple Accounts Analysis approach that considers copper load reduction and cost to evaluate and select a preferred remedial option for the management of mine waste. This decision analysis process allows for rapid identification and evaluation of known remedial approaches and their probability of success based on the type and source of contamination, site conditions, and disposal options. Options were designed to conceptual level to support costing and evaluation of the environmental benefit of each remedial option. A water balance and water quality model were used to estimate copper load reduction for each remedial option and confirm engineering feasibility of various water management approaches. Project risks and uncertainties were documented in a risk register. Option 5 was selected as the option that best satisfies the remedial objectives subject to the residual data gaps. This approach avoids commitment of excess financial resources and can be used to evaluate the value of additional investigation against residual project risks. Results demonstrate the value of an integrated approach to rapidly identify, design, and evaluate remedial options following a logical framework that is transparent, traceable and defensible.

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