Mine Closure 2026 – AB Fourie, G Boggs, J Heyes & M Tibbett (eds)
© 2026 Australian Centre for Geomechanics, Perth, ISSN 2208-8296
doi:10.36487/ACG_repo/2615_87

Integrating targeted geochemical experiments and process-based modelling to support defensible mine closure water quality predictions at Iron Crown mine

Laura Volden [a,*], Dirk Kirste [a], Kelly Sexsmith [a]

[a] *SRK Consulting, Canada*

Abstract

Mine closure planning for mine-impacted water bodies requires predictive tools capable of defensibly forecasting long-term water quality under evolving hydrologic and geochemical conditions. At the Iron Crown mine (British Columbia, Canada), Canyon Lake provides a case study demonstrating an iterative, closure-focused approach to developing a process-based water quality model to support closure design and risk management. An initial PHREEQC-based model developed in 2019 identified key uncertainties in source loading, sediment reactivity and seasonal stratification that limited confidence in long-term closure predictions. A subsequent gap assessment informed a targeted characterisation program in 2023, including expanded lake profiling, detailed sediment geochemistry and laboratory batch experiments designed to constrain sediment–water interactions.

Batch experiments on representative shallow and deep sediments, reacted with synthetic low- and circumneutral-pH waters, were coupled with kinetic reaction path modelling to quantify mineral dissolution and precipitation, sulphide oxidation, and adsorption processes. History-matched simulations were used to derive defensible, process-based source terms, replacing empirical assumptions and reducing uncertainty in model inputs critical for closure planning.

The updated, seasonally resolved PHREEQC model incorporates a refined water balance, improved source loading estimates for tailings run-off, seepage, groundwater and natural inflows, and geochemical controls constrained by experimental results. Model validation demonstrates that the revised configuration reproduces observed stratification and worst-case deep-water conditions. Results confirm that tailings beach run-off is the dominant closure-relevant loading pathway, with secondary contributions from oxidised shallow sediments, while deep sediments remain effectively non-reactive.

Application of the calibrated model to evaluate tailings cover performance indicates that a reduction in tailings run-off of approximately 75% is required to achieve near-neutral pH and concentrations below screening criteria for most constituents of interest, with residual cobalt loading attributed to shallow sediments.

The close agreement between measured and predicted concentrations in Canyon Lake supports the use of the model as an appropriate tool for evaluating the effectiveness and limitations of potential remediation measures.

Keywords: *mine closure, geochemical modelling, PHREEQC, ML/ARD*

1 Introduction

Canyon Lake, located at the historic Nimpkish iron mine (Iron Crown) on Vancouver Island, British Columbia, Canada, is a small (~3.8 ha) water body impacted by legacy tailings deposition and subsequent metal leaching

* Corresponding author. Email address: lvolden@srk.com

and acid rock drainage (ML/ARD) in seepage and run-off in contact with the tailings and sediment–water geochemical interactions (Figure 1).

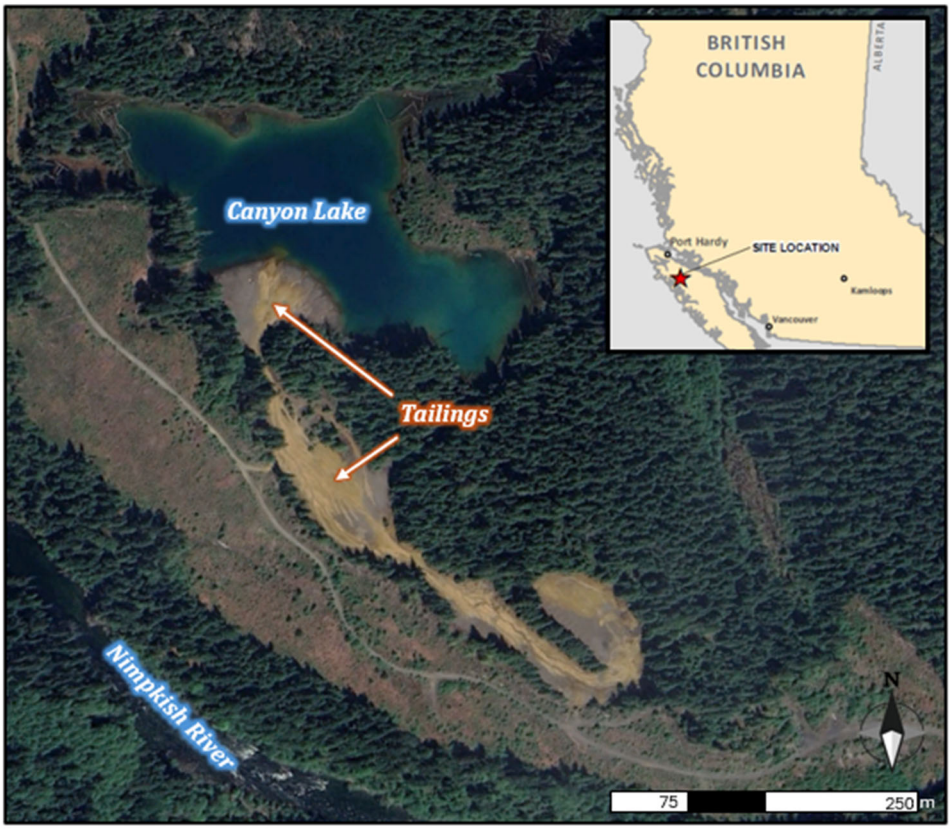

Figure 1 Iron Crown mine and Canyon Lake location

Tailings deposited during historical operations migrated into the lake, forming a tailings beach and sediment deposits across the lake bed that continue to influence water quality. The water quality in Canyon Lake varies seasonally, with persistently acidic conditions at depth, surface dilution to near-neutral pH during winter and spring, and episodic mixing that results in uniform, mildly acidic conditions; dissolved metal concentrations are inversely related to pH and increase during more acidic periods. As closure planning advances, predicting long-term water quality evolution under changing hydrologic and geochemical conditions requires a defensible, process-based modelling framework.

An initial PHREEQC-based water quality model developed by SRK Consulting Canada Inc. (SRK) in 2019 (SRK Consulting 2019), together with supporting analyses, identified key uncertainties in source loading, sediment reactivity and internal lake processes that limited confidence in closure predictions. A subsequent geochemical gap assessment (SRK 2022) defined targeted data collection to reduce these uncertainties, leading to expanded field characterisation and laboratory investigations completed in 2023. These efforts included detailed sediment geochemistry, lake profiling and batch experiments coupled with reaction path modelling to better constrain sediment–water interactions and dominant geochemical controls.

The results of these investigations were used to refine the conceptual model and develop an updated numerical water quality model for Canyon Lake. Integration was achieved by using history-matched reaction path models of the batch experiments to generate a seasonally resolved shallow-water sediment (oxidized nearshore lakebed sediment) interaction source term for the lake model, while the deep-water sediment (unoxidized sediment from deeper parts of the lake) results were used to justify excluding deep-water sediments as a reactive source. This replaced the earlier empirical sediment assumptions with process-based inputs.

These process-based inputs replaced the earlier empirical sediment assumptions, resulting in improved source term definitions and representation of geochemical controls. The revised model was calibrated to

current conditions and subsequently used to evaluate the effect of reducing tailings-derived loading, representing varying cover efficiencies, on long-term water quality.

This paper presents the updated conceptual and numerical modelling approach, including integration of experimental results into model parameterisation, and demonstrates how iterative refinement improves confidence in predictions of both baseline conditions and remedial performance for closure planning.

2 Investigation design and approach

The investigation followed an iterative, model-driven approach in which data collection and experimental work were designed to directly address uncertainties identified in earlier modelling efforts.

To systematically address these uncertainties, a formal geochemical gap assessment was completed (SRK Consulting 2022), incorporating a comprehensive review of available surface water, groundwater, sediment and porewater data. The assessment identified critical data gaps, including limited characterisation of tailings run-off variability, insufficient understanding of the role of lake sediments in buffering or contributing solute loads, and inadequate temporal resolution of lake stratification and seasonal water quality dynamics.

A targeted field and laboratory program was designed and implemented, leading to the 2023 field investigations and a series of laboratory-based experiments. Field investigations included targeted geochemical sampling and in situ data collection. Samples from this program were characterised and used in a series of hypothesis-driven batch experiments and associated model simulations aimed at evaluating sediment–water interactions under representative geochemical conditions.

Reaction path models of the experiments were generated to establish rates and controls on solution chemistry. This integrated experimental–modelling framework was used to directly constrain key inputs to the Canyon Lake water quality model, reducing reliance on empirical assumptions and improving representation of sediment–water interactions, including the role of lake sediments as sources or sinks of solutes within the system.

3 Field and laboratory characterisation – methods and results

Field investigations included expanded lake water quality monitoring, seasonal depth profiling, and collection of representative shallow-water and deep-water sediment samples. Lake water samples were collected across multiple seasons to improve understanding of temporal variability, while depth profiles of pH, conductivity and reduction-oxidation (redox) conditions were used to characterise seasonal stratification and mixing behaviour. Sediment sampling targeted both oxidised nearshore materials and shallow sediments from the deeper, anoxic portion of the lake to capture variability in geochemical conditions and reactivity. Herein, ‘shallow-water’ and ‘deep-water’ sediments refer to surficial lake bed sediments from the shallow nearshore zone (oxidised, orange) and from the deeper parts of the lake (unoxidised, grey-black), respectively. Both are tailings-affected sediments in contact with lake water; neither refers to buried or natural underlying sediments.

Lake water samples were collected as near-surface grab samples from 2 ongoing monitoring stations (one near the north-western shore and one at the tailings beach) on 5 to 6 occasions through 2023. Depth profiles of pH, temperature, specific conductance, dissolved oxygen and oxidation-reduction potential (ORP) were measured bimonthly at 5 locations using a YSI multimeter lowered from a small boat (continuous profiles with depth rather than at fixed intervals). Shallow-water sediments were collected from the lake shore with a cleaned shovel, and deep-water sediments were collected near the lake centre using a gravity-deployed Petite Ponar dredge; samples were purged with nitrogen and frozen for shipment. Porewater for one shallow and one deep sediment was extracted by squeezing with a 10-tonne hydraulic press (SRK Consulting 2024).

Laboratory characterisation of sediments included acid-base accounting, elemental analysis and mineralogical assessment to evaluate acid generation potential, buffering capacity and the distribution of metals within solid phases.

Aqueous chemistry results indicate that Canyon Lake is a calcium-sulphate-type system (i.e. a water in which calcium is the dominant cation and sulphate the dominant anion) with pronounced seasonal variability. Surface water pH was near neutral during periods of high precipitation and became acidic during drier conditions, with corresponding increases in dissolved constituent concentrations (Figure 2). Depth profile data demonstrate seasonal stratification, where near-surface dilution during winter and spring overlies more acidic conditions at depth, followed by full mixing during summer and fall (Figure 3). Several metals (including copper, cobalt, zinc, iron and aluminium) had elevated concentrations that were strongly correlated to pH.

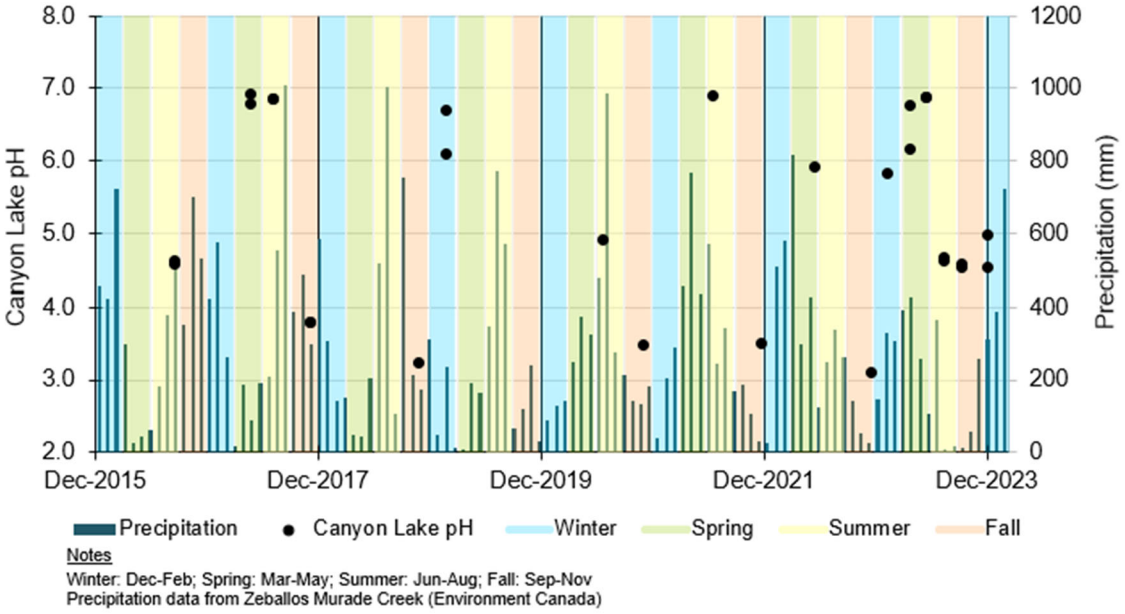

Figure 2 Seasonal variability in Canyon Lake pH and precipitation

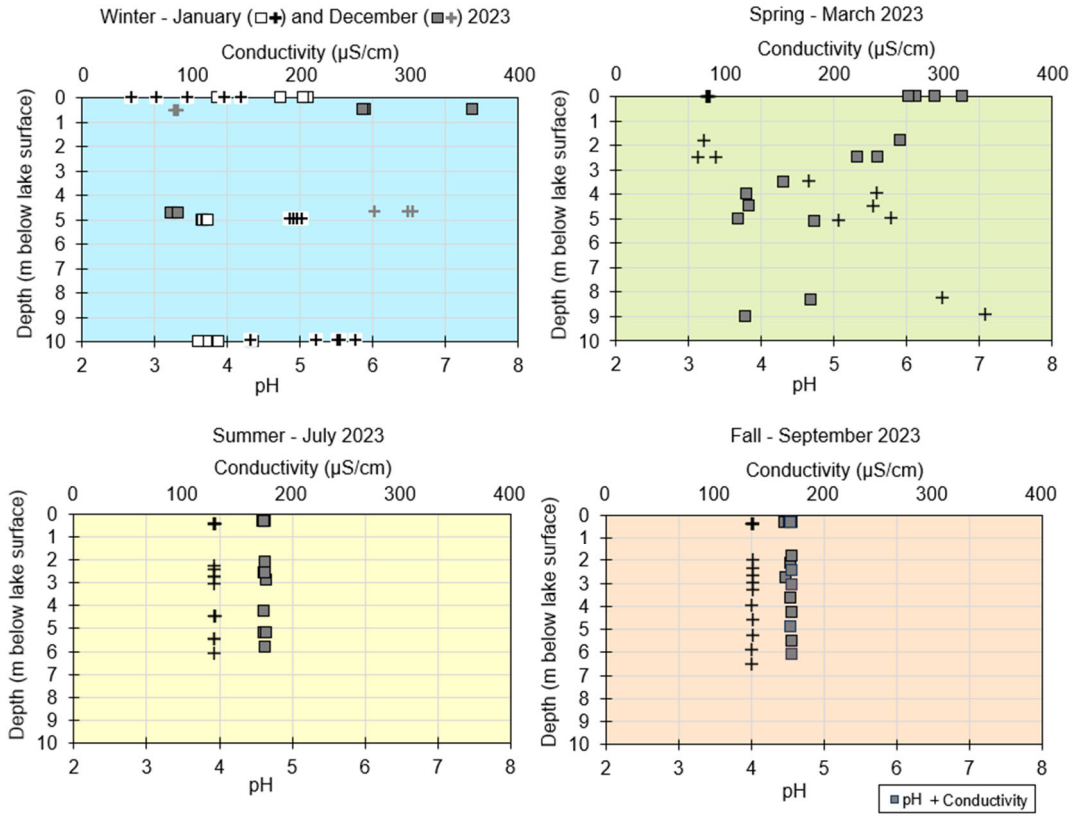

Figure 3 Seasonal depth profiles in conductivity and pH in Canyon Lake

Shallow-water sediments were generally more oxidised and locally acidic, with some samples classified as potentially acid generating, whereas deep-water sediments remained neutral and non-acid generating under current conditions. Mineralogical and bulk chemistry data indicated that shallow-water sediments are dominated by silicate minerals with limited available carbonate, while deep-water sediments contain higher proportions of iron oxyhydroxides and calcite, providing greater buffering capacity. Sulphide minerals (primarily pyrite) were identified in both shallow- and deep-water sediments; however, their influence on acid generation is largely expressed in the shallow, oxidised zone, whereas in deeper sediments, sulphide oxidation is limited and neutralisation capacity dominates.

Porewater data from sediments indicated relatively dilute compositions and were considered of limited reliability; their primary use was to initialise the cation exchange and adsorption site composition in the batch experiment reaction path models.

4 Batch experiments and reaction path modelling: methods and results

Four bench-scale batch experiments were conducted and then simulated with kinetically controlled PHREEQC reaction path models. Each experiment reacted approximately 200 g of moist, homogenised sediment with 500 mL of synthetic lake water in a 1 L flask (2.5:1 solution-to-solid ratio) over 10 days, following a modified shake flask extraction procedure (Price 2009). Representative shallow- and deep-water sediments were each reacted with synthetic low-pH and circumneutral lake waters, with a deionised-water blank for each sediment. The pH, electrical conductivity and ORP were measured at least daily, and solution samples were collected on a front-loaded schedule (most frequently in the first 2 days) and analysed for anions and dissolved metals. Experiments were left open to the atmosphere, consistent with oxidising ORP values measured at depth in the lake. History matching of the reaction path models was used to quantify contributions from mineral reactions, adsorption and cation exchange (SRK Consulting 2024).

Results indicate that sediment-driven reactions dominate solution chemistry and are largely independent of initial water composition. Shallow-water sediments produced acidic conditions (terminal pH ~4.7–5.3) and are interpreted to be net acid generating, whereas deep sediments buffered to near-neutral pH (~6.8–7.0) due to higher carbonate content. In both cases, rapid early increases in calcium and sulphate were attributed to gypsum dissolution, followed by continued contributions from pyrite oxidation (sulphate generation) and calcite dissolution (pH buffering). Goethite precipitation was identified as a key secondary phase controlling iron and adsorption capacity.

Trace metal behaviour was primarily controlled by cation exchange and adsorption/desorption processes. Cation exchange dominated in shallow-water sediments with lower iron oxyhydroxide content, while adsorption was more significant in deep-water sediments due to higher iron oxyhydroxide abundance. Metal mobilisation was driven by mineral dissolution and exchange reactions rather than initial solution chemistry, although transient attenuation of some elements (e.g. copper, aluminium) occurred under low-pH conditions due to preferential adsorption.

Sensitivity analysis demonstrated that model outcomes are most influenced by calcite and pyrite reactivity, gypsum abundance, cation exchange capacity and adsorption site density. Among these, cation exchange exerted the strongest control on divalent metal concentrations, while adsorption was most important for aluminium, copper and silicon.

Overall, the integrated experimental–modelling approach demonstrates that shallow-water sediments are a source of acidity and metals, and were incorporated into the lake model as a process-based interaction source term derived from the reaction path models. Deep-water sediments, by contrast, were shown to be carbonate-buffered and effectively non-reactive under current conditions, and were therefore represented as a non-reactive boundary, i.e. excluded as a loading source. This finding – not an empirical assumption – defines how each sediment type enters the numerical model (Section 6.2).

5 Canyon Lake conceptual model

Canyon Lake water quality is influenced by multiple source inputs and geochemical processes. The initial water quality modelling, supplemented by targeted field characterisation and coupled experimental–modelling work, informed the development of an updated conceptual model that forms the basis of the revised numerical water quality model. A visual representation of the conceptual model is provided in Figure 4 and described below.

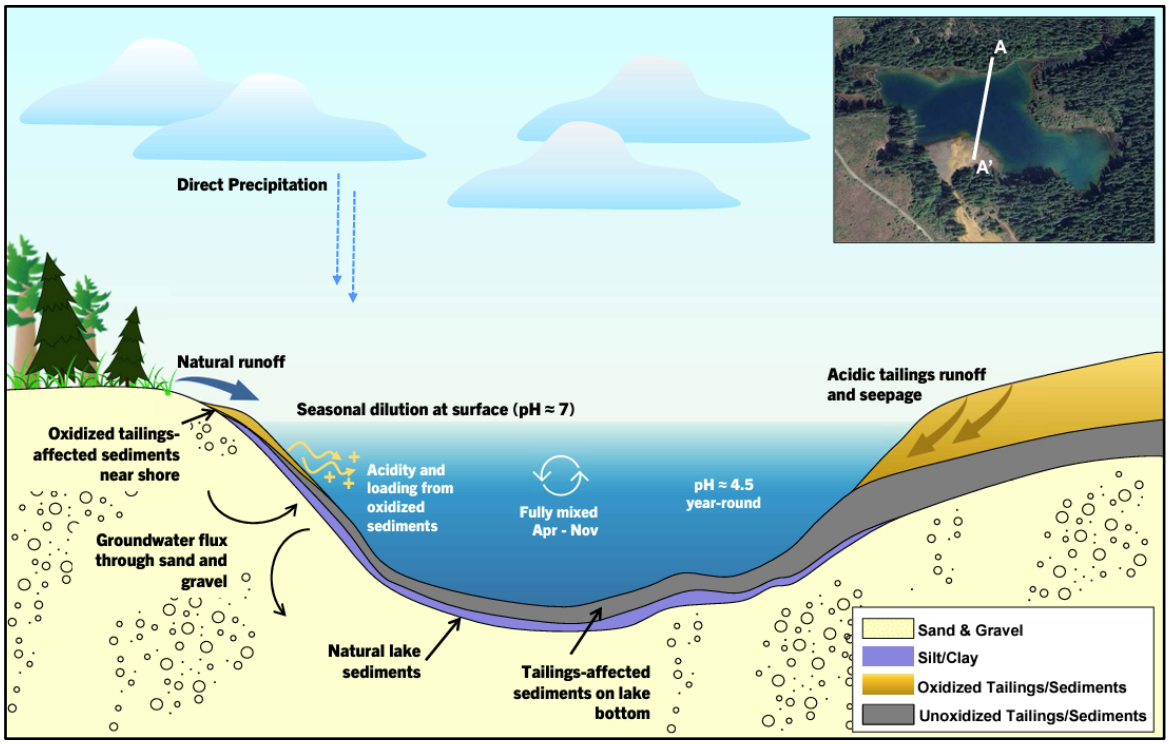

Figure 4 Canyon Lake geochemical conceptual model

Canyon Lake is a naturally occurring lake that received inputs of tailings while the Iron Crown mine was operational between 1959 and 1963. The basin is shallow near the edges, with a maximum depth of approximately 23 m in the southeast lobe. A tailings beach enters the lake at the south side and natural lake sediments are overlain by a layer of tailings throughout that ranges in thickness from 0.07–1.1 m (AtkinsRéalis 2024). Sediments near the shore in the shallow water are oxidised and appear orange in colour, where the sediments in the deeper portions of the lake are unoxidised and appear grey-black. The tailings-affected sediments that are in contact with the lake water are the focus of this study, rather than the natural, underlying sediments.

Inputs to Canyon Lake include direct precipitation, natural run-off, groundwater flux through the sand and gravel aquifer, and contact water run-off from the tailings beach. Contributions from the tailings beach run-off are acidic with high concentrations of dissolved constituents, whereas precipitation, natural run-off and groundwater flux are neutral pH, low concentration contributions. In addition, as demonstrated by experimental work, water in Canyon Lake interacts with the shallow-water sediments to generate acidity and elemental loading near the shores of the lake.

The pH of Canyon Lake is acidic at depth year-round, with measurements ranging from 3.5–4.6. Direct precipitation provides seasonal dilution at surface, resulting in neutral pH measurements in the winter and spring months at the surface of Canyon Lake. Following periods of heavy precipitation, mixing in the lake occurs and pH measurements are consistently near a value of 4.5 throughout the entire depth profile. Concentrations of dissolved elements have an inverse relationship with pH, where values are higher in seasons with lower pH; notably aluminium, iron, cadmium, cobalt, copper and zinc, which are all considered constituents of interest (COIs) in Canyon Lake.

Canyon Lake water quality may be influenced by several geochemical processes including:

- mineral dissolution and precipitation
- sulphide oxidation
- adsorption/desorption and exchange of trace elements on/off mineral surfaces
- concentration of lake waters through evaporation.

The experimental data and coupled reaction path modelling, in combination with the monitoring data as the pH of Canyon Lake varies, suggest that all of these processes are taking place at Canyon Lake. For example, aluminium and iron are more mobile under acidic conditions where the corresponding mineral phases are not stable and therefore dissolve. Trace metals such as cadmium, cobalt, copper and zinc are also more mobile under acidic conditions due to the instability of the iron minerals that provide adsorption surfaces and lower preference on adsorption sites for cations as the pH decreases. Higher oxygen content in shallow lake waters lead to sulphide oxidation in the sediments; a source for acidity driving dissolution of carbonate minerals and leading to an increase in calcium that resulted in cation exchange and mobilisation of trace metals from exchange sites in the sediment.

Run-off from the tailings beach is the main contributor to acidity and loading in Canyon Lake. Interaction with shallow-water sediments that have been affected by mine operations and weathered over the years also contributes acidity and loading but on a smaller scale. The deep-water sediments do not appear to interact with the lake water. This was supported by the high concentration of carbonate present in the deep-water sediments and the outcome of the batch experiments. If the deep-water sediments were interacting, the buffering capacity (i.e. carbonate) should have been consumed through contact with the acidic lake water over time.

6 Canyon Lake water quality model

6.1 Model approach

The Canyon Lake water quality model was developed using the publicly available speciation and mass transfer code PHREEQCI 3.6.2, developed by the United States Geologic Survey (Parkhurst & Appelo 1999). PHREEQC was selected because it has the ability to simulate geochemical processes (e.g. speciation, redox transformations, solubility controls) that will influence water quality in Canyon Lake. PHREEQC is widely accepted by local, national and international regulatory authorities as an appropriate modelling tool for predicting water quality in mining environments.

The model was set up as a continuous simulation to represent seasonal changes in water quality in Canyon Lake from 2019 to 2035 using 4 seasonal timesteps: fall (September–November), winter (December–February), spring (March–May) and summer (June–August). The water balance was provided by CH2M Hill Canada Ltd. (2018) with these timesteps, which were carried forward into the geochemical model. At each timestep, each flow that could influence the water quality in Canyon Lake was assigned an input chemical source term based on monitoring data or, in the case of the shallow lake sediments, from the batch experiments. Flows were mixed in Canyon Lake based on their relative proportions according to the following formula:

$$C_{lake} = \frac{V_{lake,t_i} \times C_{lake,t_i} + \sum_{i=1}^{n} Q_i \times C_i}{V_{lake,t_{i+1}} - E_{lake,t_i}} \quad (1)$$

where:

C_{lake} = the predicted concentration in Canyon Lake

V_{lake,t_i} and $V_{lake,t_{i+1}}$ = the lake volumes at the current and subsequent timesteps, respectively

E_{lake,t_i} = evaporation at time = i

C_i = the concentration of each inflow

Q_i = the corresponding inflow volume.

Following each mix, the lake water was evaporated to account for evapoconcentration and the lake volume was then brought back to full capacity. The solution was then equilibrated with mineral phases to allow dissolution and precipitation, equilibrated with an adsorption surface and saved to be brought forward to the next timestep. Reaction temperatures were set for each timestep based on seasonal monitoring data.

6.2 Model inputs

6.2.1 Source chemistry and model constituents

The Canyon Lake water quality model simulates general parameters (pH, alkalinity, redox), major ions, nutrients and dissolved trace elements. Source term chemistry was developed from monitoring data for all inflows, including the existing inventory of lake water, direct precipitation, natural run-off, groundwater inflow, tailings beach run-off and tailings seepage. Sediment interaction inputs were derived from batch experiments and reaction path modelling. Source term inputs for COIs are presented in Table 1.

Direct precipitation was represented using assumed rainwater composition (pH 4.9, Eh 550 mV, temperature 8.5°C) with negligible dissolved ions and metals.

Natural run-off was represented using average concentrations from available stream monitoring data. Water chemistry was generally consistent across locations and time; however, data availability is limited and primarily historical.

Groundwater inflow was represented by a calcium-bicarbonate-type composition based on available monitoring data from an upgradient aquifer. Groundwater chemistry is relatively consistent seasonally, and average concentrations from multiple sampling events were used as model inputs.

Tailings beach run-off was characterised using intermittent sampling data collected under varying hydrologic conditions. Water chemistry is strongly influenced by tailings contact, with consistently low pH and elevated sulphate and trace element concentrations. Variability in concentrations reflects dependence on rainfall events; average values were used for model inputs.

Tailings seepage was represented using monitoring data from multiple wells within the tailings deposit. Although some variability in pH and dissolved constituents was observed, seepage chemistry was generally consistent and was represented using average concentrations derived from a multiyear dataset.

Shallow sediment interaction was represented using kinetically controlled reaction path modelling applied at seasonal (3-month) timesteps. A proportion of oxidised lake bed sediments (5–10 cm thickness over ~52% of the lake bed) was reacted with overlying lake water at a 1:65 solid-to-solution ratio. Initial water chemistry for each timestep was derived from the preceding mixing step, and sediment properties (mineralogy, exchangeable cations and adsorption site occupancy) were based on representative shallow sediments from the batch experiments and updated between timesteps. Seasonal temperature was applied, and oxygen conditions were set to equilibrium with the atmosphere (pO_2 = 0.01 bar). Resulting water chemistry was incorporated into the lake mixing model as a sediment interaction source term.

6.2.2 Water balance

The water balance provided in CH2M Hill Canada Ltd. (2018) formed the basis of the Canyon Lake water quality predictions (Table 2). Relative proportions for each of the inflows, as well the volume of Canyon Lake, were based on the CH2M Hill (2018) water balance and then adjusted during model validation as described in Section 6.3.

Table 1 Source terms for constituents of interest in mg/L

Parameter	Lake inputs				Lake inventory				Shallow-water sediment interaction			
	Tailings run-off	Natural run-off	Tailings seepage	Groundwater inflow	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
pH	2.6	7.1	6.8	6.1	5.6	6.1	5.5	3.8	5.4	5.2	4.8	5.1
Aluminium	44	0.0092	0.022	0.0048	0.38	0.42	0.27	1	0.019	0.032	0.13	0.1
Cadmium	0.0039	0.000037	0.0005	0.000013	0.000081	0.000096	0.00011	0.00015	0.0000049	0.000012	0.000029	0.000027
Calcium	200	30	426	7.6	13	18	21	21	22	26	37	26
Cobalt	2.5	0.0004	0.22	0.00013	0.052	0.054	0.053	0.087	0.28	0.31	0.41	0.24
Copper	12	0.0013	0.022	0.00038	0.19	0.15	0.14	0.32	0.24	0.29	0.54	0.34
Iron	310	0.029	4	0.0068	0.34	0.33	0.074	0.84	0.018	0.013	0.01	0.02
Sulphate	1,577	8.5	1,349	1.4	38	49	55	77	76	92	124	97
Zinc	0.55	0.005	0.16	0.0041	0.012	0.014	0.016	0.022	0.098	0.12	0.17	0.096

Table 2 Canyon Lake water balance (CH2M Hill Canada Ltd. 2018) in m^3

Season	Direct precipitation	Run-off		Groundwater input		Losses		Lake storage	Δ Lake storage
		Tailings	Other	Tailings	Other	Lake evaporation	Lake seepage		
Fall (Sept–Nov)	22,464	14,852	49,828	542	27,678	3,464	113,886	171,993	−1,985
Winter (Dec–Feb)	24,504	16,474	60,191	1,079	30,765	0	105,011	199,995	28,002
Spring (Mar–May)	9,829	5,878	11,409	1,143	32,241	6,357	58,440	195,699	−4,296
Summer (Jun–Aug)	4,229	2,047	2,104	459	29,327	10,633	49,255	173,978	−21,721

6.2.3 Mineral phases, thermodynamic data and adsorption

Mineral phases that were allowed to dissolve or precipitate were entered in the model as equilibrium phases. The model started with goethite to provide initial adsorption sites, the initial amount of which was based on mineralogy. Additional phases, including aluminium-sulphate/hydroxide minerals, iron, lead and calcium sulphate minerals, and manganese, calcium and magnesium carbonate minerals were included in the model based on saturation indices and post-experiment mineralogy (Table 3). No initial amount of these phases was included, but each was allowed to precipitate from solution.

The thermodynamic database used for the aqueous species, gases and minerals was the Lawrence Livermore National Laboratory (LLNL) database issued with PHREEQC, modified from the LLNL database for EQ3/6 (Wolery 1992).

Adsorption modelling focused on goethite as the adsorption site source based on observations in the mineralogical analysis. The adsorption dataset was based on data of the Dzombak & Morel (1990) 2-layer surface complexation model, which was developed for adsorption to ferrihydrite. Ferrihydrite was included in the model initially, but better agreement was achieved between monitoring data and model results when goethite was used as the adsorption surface. As goethite was identified by X-ray diffraction in the sediments, it was appropriate to use goethite for solubility of the adsorption surface. Adsorption site density was set based on ferrihydrite to 0.2 mol weak sites and 0.005 mol strong sites and a surface area of 53,300 m^2/g.

Table 3 Equilibrium phases used in the Canyon Lake model

Mineral phase	Chemical formula	Mineral phase	Chemical formula
Alunite	$KAl_3(OH)_6(SO_4)_2$	Anglesite	$PbSO_4$
Gibbsite	$Al(OH)_3$	Rhodochrosite	$MnCO_3$
Goethite	FeOOH	Gypsum	$CaSO_4{:}2H_2O$
Melanterite	$FeSO_4{:}7H_2O$	Calcite	$CaCO_3$
Pyrite	FeS_2	Magnesite	$MgCO_3$
Magnetite	Fe_3O_4		

6.3 Model validation and sensitivity analysis

Model predictions were compared to seasonal averages of monitoring data (2019–2023), with 5, 13, 18 and 11 data points available for winter, spring, summer and fall, respectively. Validation focused on pH and major ion concentrations during periods when the lake was assumed to be fully mixed. The model represents a fully mixed system and does not capture short-term surface dilution during high precipitation, particularly in winter and spring.

Initial model results overpredicted dissolved concentrations relative to monitoring data. Evaluation of acidity sources indicated that neither shallow sediment interaction (pH ~4.4–5.4), nor proton generation from goethite and gibbsite precipitation, could account for observed low pH values. Tailings beach run-off was therefore identified as the primary control on acidity, and run-off proportions were adjusted during calibration to match observed pH.

Following calibration to pH, discrepancies between modelled and observed concentrations were interpreted to reflect differences in sampling representativeness rather than model performance. Most historical monitoring data were collected at the surface and were influenced by dilution during precipitation events, whereas the model simulates a fully mixed system more representative of bulk conditions.

To evaluate model performance on a comparable basis, a depth-based correction was developed using conductivity measurements collected during 2023 profiling. Conductivity values at depth were consistently approximately 3 times higher than those measured at the surface during periods of high precipitation,

indicating that surface samples were substantially diluted relative to the bulk lake or deeper water column. This relationship was used to derive an adjustment factor to approximate the concentrations that would have been observed at depth under the same conditions as the historical monitoring dataset.

For comparison purposes, modelled concentrations (excluding pH) were divided by a factor of 3 to align with the dilution-affected surface monitoring data. When this adjustment is applied, modelled results show good agreement with monitoring data for most parameters, with the exceptions of calcium, which is underpredicted, and zinc, which is overpredicted. Select elements are presented in Figure 5 for reference. These discrepancies suggest that additional calcite and/or gypsum dissolution may be occurring beyond what is currently represented (e.g. shallow sediment interaction) and that zinc may have a stronger affinity for adsorption than is simulated.

Importantly, the adjustment factor is not intended to calibrate the model but rather to reconcile differences in sampling conditions and enable an appropriate comparison between modelled results and monitoring data. The unadjusted model results more closely represent water quality at depth during periods of elevated conductivity and low pH, which correspond to the worst-case conditions both temporally and within the water column. These conditions are most relevant for closure planning and evaluation of remedial options.

Sensitivity analysis evaluated uncertainty in key inputs, including the proportion of natural versus tailings run-off, reactive sediment thickness and adsorption capacity. Model results were highly sensitive to run-off partitioning, with increased tailings contribution resulting in lower pH. Best-fit run-off proportions ranged from 21–49% tailings-derived, depending on the season (Table 4).

Reactive sediment thickness (5 versus. 10 cm) had minimal impact on model outputs, with only minor increases in sulphate at greater thickness; a value of 5 cm was adopted. Adsorption capacity, represented by goethite abundance, influenced pH and variability in aluminium and iron, but had limited effect on other parameters, indicating that adsorption is a secondary control on overall water chemistry.

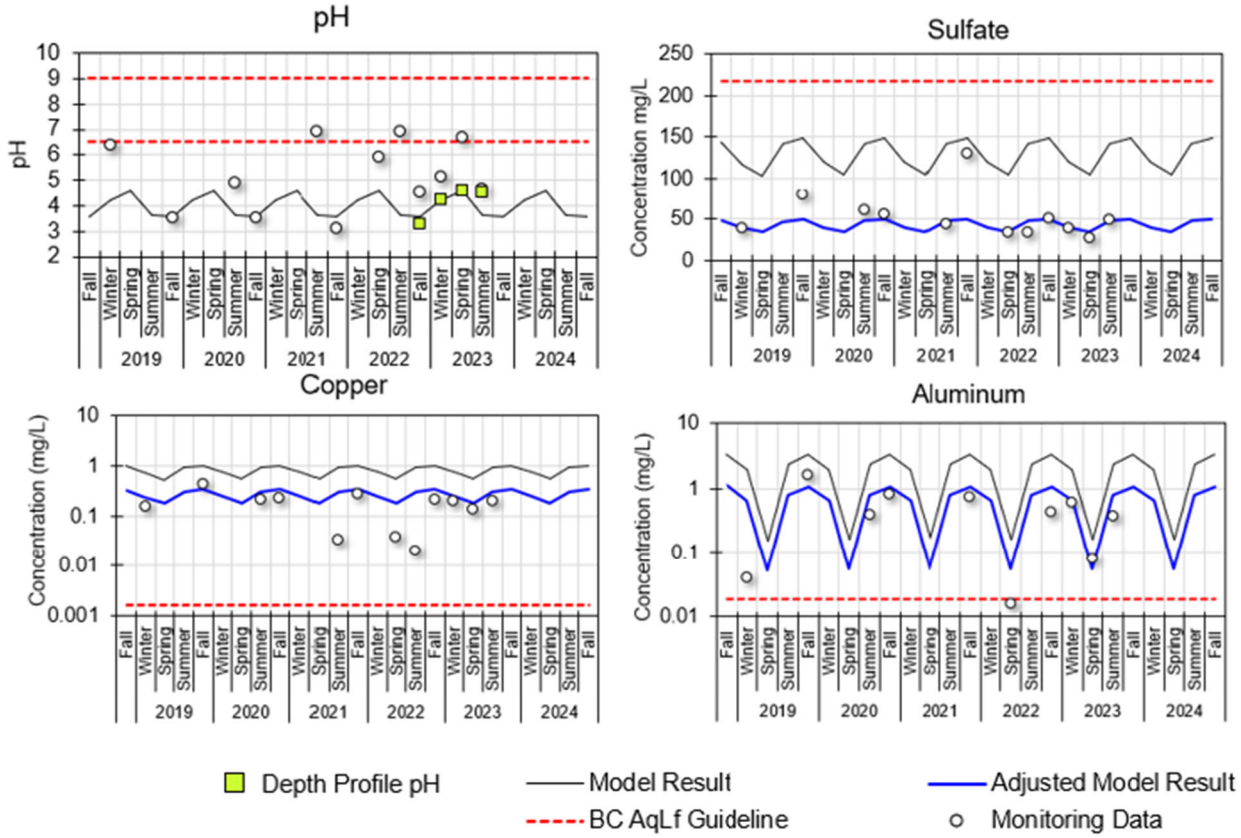

Figure 5 Model validation results for pH, sulphate, copper and aluminium compared to the BC aquatic life guideline

Table 4 Relative proportion of tailings beach and natural run-off used in model inputs

Season	Relative run-off proportion	
	Tailings beach	Natural
Fall (Sept–Nov)	23%	67%
Winter (Dec–Feb)	21%	79%
Spring (Mar–May)	24%	76%
Summer (Jun–Aug)	49%	51%

6.4 Model results

Projected concentrations of COIs are presented in Table 5. COIs include parameters that exceed or approach applicable screening criteria (pH, aluminium, iron, cadmium, cobalt, copper, zinc), where screening criteria were based on the most stringent of the British Columbia water quality guidelines for the protection of aquatic life, wildlife and recreational use (British Columbia Ministry of Environment and Climate Change Strategy 2018); for copper, the British Columbia Contaminated Sites Regulation value was adopted as the most stringent applicable criterion. Criteria are used for screening purposes only and do not represent a regulatory compliance evaluation, as well as indicators of key geochemical processes (calcium and sulphate). Model outputs represent unadjusted concentrations and are considered conservative, reflecting worst-case conditions at depth during stratified periods.

Table 5 Canyon Lake seasonal model results for constituents of interest (mg/L)

Parameter	Screening criteria	Fall	Winter	Spring	Summer
pH	6.5–9.0	**3.6**	**4.2**	**4.6**	**3.6**
Aluminium	0.019	**1.09**	**0.65**	**0.055**	**0.81**
Cadmium	0.00011	0.00011	0.00008	0.00006	0.000097
Calcium	-	13	11	10	12
Cobalt	0.004	**0.10**	**0.09**	**0.09**	**0.11**
Copper	0.0017	**0.35**	**0.26**	**0.19**	**0.32**
Iron	0.35	0.00013	0.000017	0.0000067	0.0001
Sulphate	218	50	40	35	47
Zinc	0.029	0.029	0.027	**0.029**	**0.034**

Notes: Values presented are average for each season. **Red** text indicates value exceeds screening criteria.

Under current conditions, the model predicts seasonal variability in Canyon Lake water quality, with pH ranging from 3.6 to 4.6 and lower values during summer and fall. Peak concentrations of sulphate and trace elements coincide with these periods, reflecting increased metal mobility under acidic conditions. Modelled concentrations of aluminium, cadmium, cobalt, copper and zinc exceed screening criteria year-round.

Following calibration to current conditions, the model was used to evaluate the effect of reducing tailings-derived loading, representing increasing cover efficiency. A 50% reduction in tailings run-off increases pH to 5.3–7.1, with screening criteria achieved during winter and spring (Figure 6). Concentrations of most COIs decrease substantially; however, cadmium, copper, and zinc continue to exceed criteria during summer and fall, and cobalt remains elevated year-round.

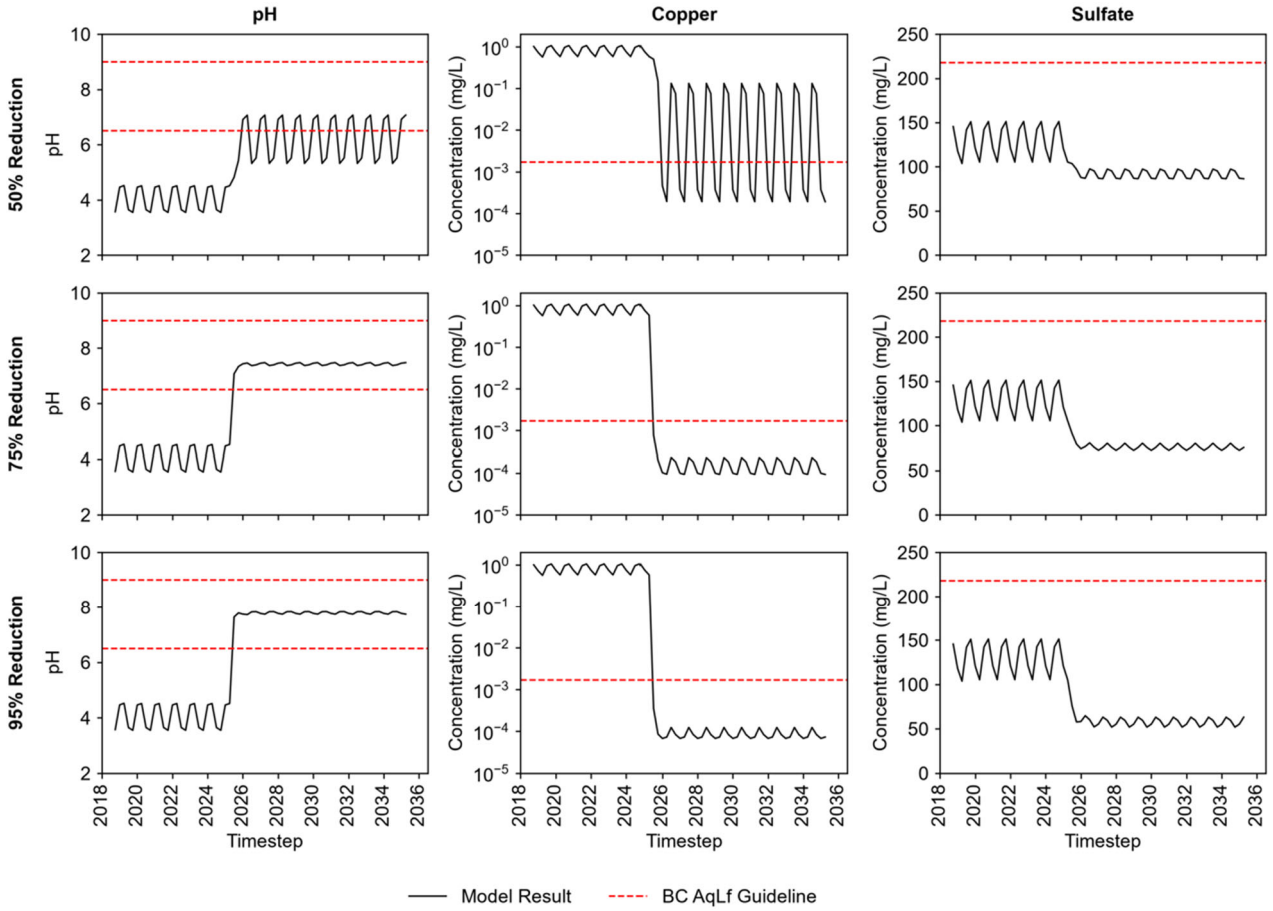

Figure 6 Model results for pH, copper and sulphate in Canyon Lake following 50, 75 and 95% reduction in tailings run-off compared to the BC aquatic life guideline

At 75% reduction, seasonal variability in pH is minimal (7.4–7.5), and all COIs, with the exception of cobalt, are below screening criteria year-round, typically by at least an order of magnitude. Increasing the reduction to 95% results in only minor additional improvements, with pH ranging from 7.7 to 7.8 and similarly low concentrations for most parameters (Figure 6). Persistent exceedance of cobalt is attributed to ongoing release from oxidised shallow sediments, indicating a secondary loading source independent of tailings run-off.

Across all scenarios, water quality responds rapidly to reductions in tailings loading, with stabilisation occurring within approximately one year. However, the model assumes constant sediment interaction and does not account for long-term depletion of reactive phases or progressive improvement in sediment-derived water quality. As a result, predicted concentrations are considered conservative with respect to long-term conditions.

Overall, the results indicate that reducing tailings-derived loading is effective in improving water quality, with a threshold of approximately 75% reduction required to achieve compliance for most parameters. Residual metal loading from shallow sediments, particularly for cobalt, may require additional consideration in closure planning.

7 Conclusion

Model results confirm that tailings beach run-off is the dominant source of acidity and metals in Canyon Lake, with model outputs highly sensitive to the proportion of run-off in contact with tailings. Under current conditions the lake is predicted to remain acidic year-round (pH 3.6–4.6), with lower pH and peak concentrations of sulphate and trace elements occurring during summer and fall. Aluminium and iron concentrations are controlled by precipitation of gibbsite and goethite, respectively, while adsorption does

not represent a significant attenuation mechanism for trace metals. With the exception of iron, which is limited by the representation of solubility and reduction-oxidation (redox) conditions, the model is considered appropriate for predictive use.

Application of the calibrated model to evaluate tailings cover scenarios indicates that reducing tailings-derived loading is effective in improving water quality. A 50% reduction in run-off is insufficient to achieve compliance with screening criteria, whereas a 75% reduction results in near-neutral pH and concentrations below criteria for all constituents of interest except cobalt. Further reduction to 95% provides minimal additional benefit, with persistent cobalt exceedances attributed to continued release from oxidised shallow-water sediments. These results indicate that while tailings cover is the primary control on water quality improvement, secondary loading from shallow sediments may influence long-term outcomes.

Water quality responds rapidly to reductions in tailings loading, with stabilisation occurring within approximately one year; however, the model does not account for progressive depletion of reactive sediment phases. As a result, predicted concentrations are considered conservative, and further long-term improvements in sediment-derived loading are expected.

Overall, the updated modelling framework provides a robust tool for evaluating closure options and demonstrates the importance of coupling experimental data with process-based modelling to constrain key uncertainties. The results highlight the need to prioritise management of tailings-derived loading while recognising the role of secondary sediment sources, supporting defensible decision-making to achieve water quality objectives and protect downgradient receptors.

Acknowledgement

The authors would like to acknowledge Harvey Bains, Matthew Andersen and Jonathan Croston of AtkinsRéalis for their oversight of remedial activities at the Iron Crown site and their contributions to this work. We also gratefully acknowledge the ’Namgis First Nation for their support and engagement throughout the project.

References

AtkinsRéalis 2024, *Preliminary and Detailed Site Investigation - Iron Crown Mine Tailings Site*, draft report prepared for the BC Ministry of Water, Land and Resource Stewardship, Crown Contaminated Sites Program, AtkinsRéalis Ref: 693196.

British Columbia Ministry of Environment and Climate Change Strategy 2018, *British Columbia Approved Water Quality Guidelines: Aquatic Life, Wildlife and Agriculture*, Water Protection Branch, Victoria.

CH2M Hill Canada Ltd. 2018, *Iron Crown Mine Tailings Site: Conceptual Model*, prepared for the Ministry of Forests, Lands, Natural Resource Operations and Rural Development.

Dzombak, DA & Morel, FMM 1990, *Surface Complexation Modeling: Hydrous Ferric Oxide*, Wiley-Interscience, New York.

Parkhurst, DL & Appelo, CAJ 1999, *User’s Guide to PHREEQC (Version 2): A Computer Program for Speciation, Batch-Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations*, Water Resources Investigations Report 99-4259, U.S. Geological Survey, Reston.

Price, WA 2009, *Prediction Manual for Drainage Chemistry from Sulphidic Geologic Materials,* MEND Report 1.20.1. Mine Environment Neutral Drainage (MEND) Program, Natural Resources Canada, Ottawa.

SRK Consulting 2019, *Iron Crown Mine – Canyon Lake Water Quality Predictions*, memo prepared for SNC Lavalin, 21 pages, 2 appendices.

SRK Consulting 2022, *Geochemical Gap Assessment and Recommendations for the Canyon Lake Water Quality Model – Iron Crown Mine*, memo prepared for SNC Lavalin, 6 pages, 2 appendices.

SRK Consulting 2024, *Canyon Lake Geochemical Characterization and Water Quality Model Update – Iron Crown Mine*, report prepared for AtkinsRéalis and the Ministry of Environment and Climate Change Strategy, 70 pages, 9 appendices.

Wolery, TJ 1992, *EQ3/6: Software Package for Geochemical Modeling of Aqueous Systems: Package Overview and Installation Guide, computer software (Version 8.0)*, Lawrence Livermore National Laboratory Report UCRL-MA-10662 PT 1, Livermore.