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Geochemical assessment of a closed tailings storage facility as part of a mine closure plan

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Abstract

Boliden Mineral AB appointed SLR Consulting Limited (SLR) to provide geochemical advice regarding a closed tailings storage facility (TSF) associated with a former Pb/Zn mine in Vassbo, Sweden. SLR conducted the sampling of tailings to undertake detailed geochemical characterisation to identify the mineralogy, risk of acid production and leachability of contaminants of concern. This included Bureau Communautaire de Référence (BCR) leaching and upflow kinetic leaching analysis to enable modelling of elemental source depletion rate. The mineralogy of the tailings was dominated by quartz, with minor components of albite, calcite and feldspar, and trace levels of cerussite, a Pb carbonate. Acid base accounting confirmed that tailings material is non-acid forming (NAF) and has some buffering capacity. The pH sequential leaching and BCR sequential extraction results were used to assess the dominant controls on the solubility of metals/metalloids within the tailings material.

They have shown that 89 to 98% of the Pb is in an easily liberated form in carbonates (cerussite), sorbed to metal hydroxides and/or organic compounds. Most of the Pb is in the carbonate form, which aligns with the mineralogical analysis. Cd and Zn both show similar solubilities, controlled by carbonate phases and phases sorbed to metal hydroxides. The upflow study results informed the derivation of kappa values to model the metal source term rate of decline. The study showed that leaching of Pb, Zn and Cd could fall below the related environmental quality standards (EQS), potentially within a 50–1,600-year period.

Given the predicted metal concentration in the tailings leachate, the incorporation of passive treatment is considered an option which requires further investigation as a potential mitigation scheme to treat the groundwater at the site.

Keywords: *geochemistry, mine closure, tailings, source term modelling, passive treatment*

1 Introduction

SLR Consulting Limited (SLR) was appointed by Boliden Mineral AB to undertake a geochemical characterisation study to improve the current understanding of the geochemical environment within the Vassbo mine area located 15 km northwest of Idre, Dalarna County, Sweden. The study focused on characterising tailings material within the tailings storage facility (TSF), with supplementary samples taken of glacial till adjacent to the TSF.

The objective of the study was to understand the solubility controls of the dominant heavy metals in the tailings within the TSF and how this might change over time. This in turn led to informing the design of future surface and groundwater treatment and quality controls which may be required for the drainage emanating from the TSF.

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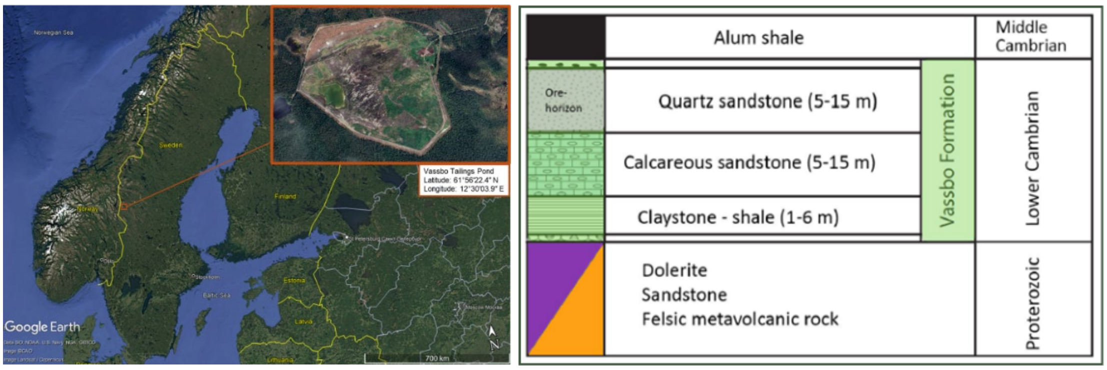
2 Site location and background

The Vassbo mine was operational between 1960 and 1982, extracting Pb ore through open pit and underground mining. The economic mineralisation in Vassbo was present within a 5–12 m-thick quartz-sandstone layer located relatively close to the surface. The ore was held in a carbonaceous silica geology, which led to the formation of carbonate-rich tailings material.

It is estimated that approximately 5 Mtons of ore was processed, with 10% sold as concentrate and approximately 4.4 Mtons deposited as tailings in the TSF covering an area of approximately 75 hectares. The perimeter embankments of the TSF were raised in stages using the upstream construction method. This reached a final height of 11 m above the ground surface by the cessation of operations in 1982. Since the operations ceased, the surface of the TSF has been partially rehabilitated through the placement of sewage sludge and seeding to encourage vegetation growth. The embankment across the site was formed from local moraine material, used to prevent wind-blown dust generation.

The superficial geology comprises glacial till and paleochannels with peat in some areas. The glacial till varies between 5 and 10 m in thickness. The surficial deposits overlie shales which are typically 13 m thick. The Vassbo formation follows, dominated by sandstones composed of > 90% quartz (quartz arenite).

The geological sequence and site location are shown in Figure 1.



(a) (b)

Figure 1 (a) Site location; (b) Geological sequence

3 Methodology

The method employed to understand the geochemical impact of the tailings on the environment included:

- development of a sampling program and associated field work conducted to obtain representative samples
- a sequence of static and kinetic laboratory testing procedures
- development of a site-specific geochemical and leaching model.

3.1 Fieldwork and laboratory testing

Samples of tailings were taken from trial pits located across the TSF where it was safe to excavate, with the sampling influenced by a number of onsite observations including colour changes of the lithology and olfactory indicators. The sampling comprised the use of trial pit excavation and included a minimum of 3 depths in each trial pit. Given the age of the TSF (> 50 years), which was vital to understand any segregation of metal ions within the tailings and their relationship to the degree of weathering/seepage. The number of samples satisfied the technical guidance (MEND 1994). Glacial till samples were taken to improve understanding of the geochemistry of the underlying material and assess the influence of dust dispersion or accidental release during mine operations. The location of the sampling is shown in Figure 2.

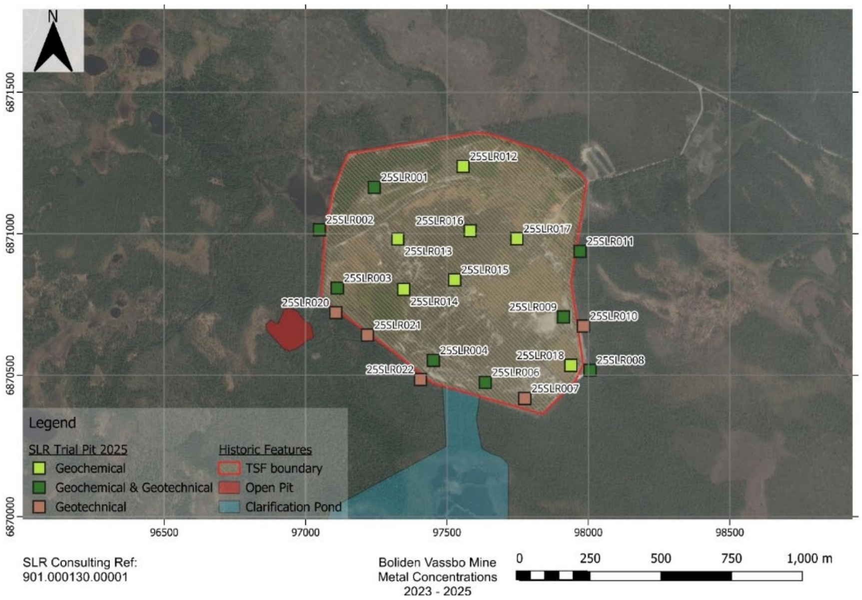


Figure 2 Sampling program trial pit locations

The laboratory appointed to perform the testing was the accredited CEGeochem Laboratories based in Ashover, Derbyshire, United Kingdom.

The testing consisted of:

- static testing on glacial till and tailings samples. This comprised acid base accounting, mineral and lithogeochemical analysis (X-ray diffraction [XRD]) and energy dispersive X-ray fluorescence (ED-XRF), pH-dependent leaching and sequential extraction (Bureau Communautaire de Référence [BCR])
- kinetic testing on tailings samples. This involved the use of upflow percolation column studies (in accordance with BS EN174405 [British Standards Institution 2022]; the European and British standard specifying the procedure for the determination of acid-soluble salts in aggregates). This enabled the calculation of kappa values for use in source depletion modelling. Kappa values are used in geochemical studies to populate a declining source term model for the long-term prediction of metal leaching from deposits such as tailings. Their use is further described below.

3.2 Analysis

Data collected from the geochemical testing was evaluated using PHREEQC geochemical modelling software to deduce salient geochemical and mineralogical controls by comparing results with modelled geochemical changes.

The results of the upflow percolation tests were used to define the rate of declining elemental source terms (e.g. as recommended by the UK Environment Agency in its Landsim Modelling Guidance) through calculating the kappa and kappa prime values presented in equations (1) and (2).

$$\kappa = \frac{\ln(C_{L/S}/C_0)}{L/S} \tag{1}$$

where:

ln = Natural Logarithm

κ = kappa value

L/S = liquid to solid ratio

$C_{L/S}$ = concentration at L/S

C_0 = initial concentration.

$$C_{(t)} = C_{(L/S=1)} \times (L/S^{-\kappa'}) \tag{2}$$

where:

κ' = kappa prime

L/S = liquid to solid ratio

$C_{(L/S=1)}$ = concentration at L/S = 1

$C_{(t)}$ = concentration at a defined time (t).

4 Results

4.1 Acid base accounting

The acid base accounting indicated that the tailings are non-acid generating, as shown in Figure 3.

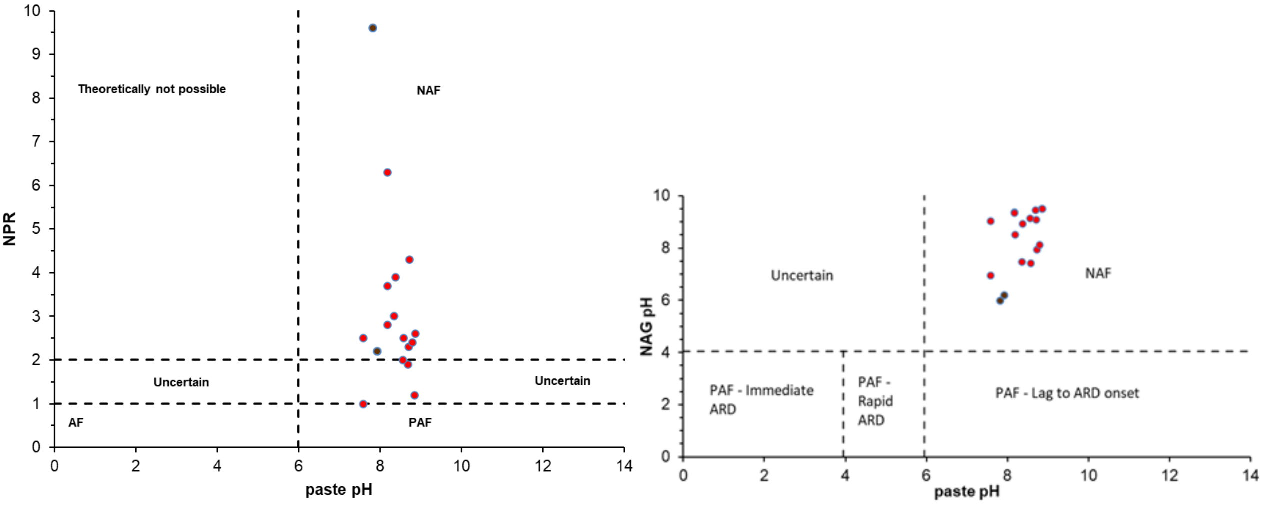


Figure 3 Neutralisation potential ratio (NPR) and net acid generation (NAG) testing results compared to paste pH (red circles – tailings, brown – glacial till) after Weber et al. (2006) and Morin & Hutt (2007)

4.2 Mineralogy

The mineralogy, as analysed by XRD of tailings material, was dominated by quartz (95.7% average) with minor albite, calcite, feldspar and cerussite.

The glacial till (fines) mainly consists of quartz (74.4% average) and anorthite (14.4% average). The remaining mineral phases included muscovite, chlorite, kaolinite, illite, albite, feldspar and cerussite. The assemblage is indicative of well-weathered minerals.

The interpretation of the XRD spectra presented Pb in 2 forms. The dominant form was as a Pb carbonate (cerussite) with trace concentrations identified in feldspars.

4.3 pH-dependent leaching and modelling solubility controls

An example of the leaching envelopes for Pb and Zn is shown in Figure 4. Here they are compared to PHREEQC geochemical modelling results for their respective carbonate minerals.

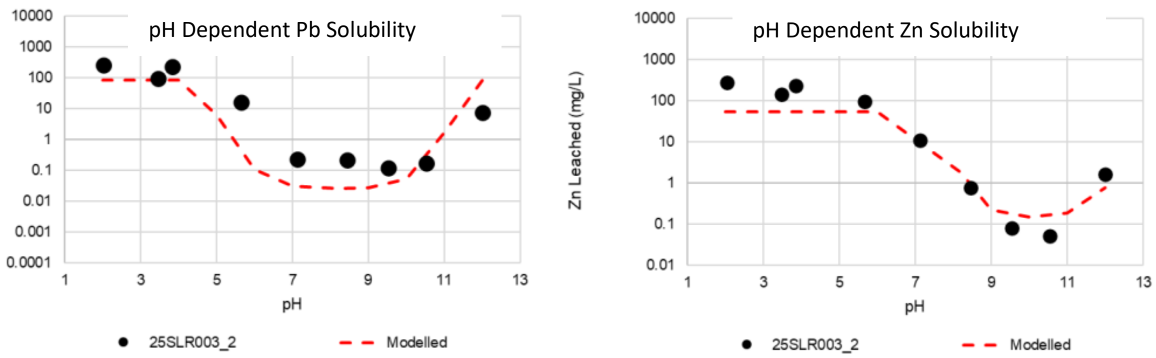


Figure 4 Comparison of the PHREEQC geochemical model (dotted line) with observed datasets for Pb and Zn pH-dependent leaching studies (circles)

The geochemical modelling results indicated that Pb, Zn and Cd solubility in the system is primarily governed by their carbonate phases, i.e. cerussite ($PbCO_3$), smithsonite ($ZnCO_3$) and otavite ($CdCO_3$). The inclusion of trace $ZnCO_3$ and $CdCO_3$in the PHREEQC simulations significantly improved the model fit to observed datasets for Zn and Cd, confirming carbonate phases are most likely controlling Zn^{2+} and Cd^{2+} activity. Similarly, Pb solubility envelopes were well described by the solubility model for $PbCO_3$.

4.4 Bureau Communautaire de Référence sequential extraction

The extraction was successfully completed for a number of heavy metals, with Figure 5 depicting the results for Pb. This confirmed that Pb, Zn and Cd are primarily present as a carbonate phase such as $PbCO_3$. The result also suggests a minor proportion of the metals may be associated with amorphous Fe/Mn oxides or present as complexes with organic matter or within sulphide minerals. Whilst the latter is interpreted from the BCR leaching experiments, in reality the presence of sulphide is unlikely, as indicated by the XRD spectra interpretation. The results of the sequential testing aligned with the interpretation from the pH sequential extraction and the mineralogy phases identified.

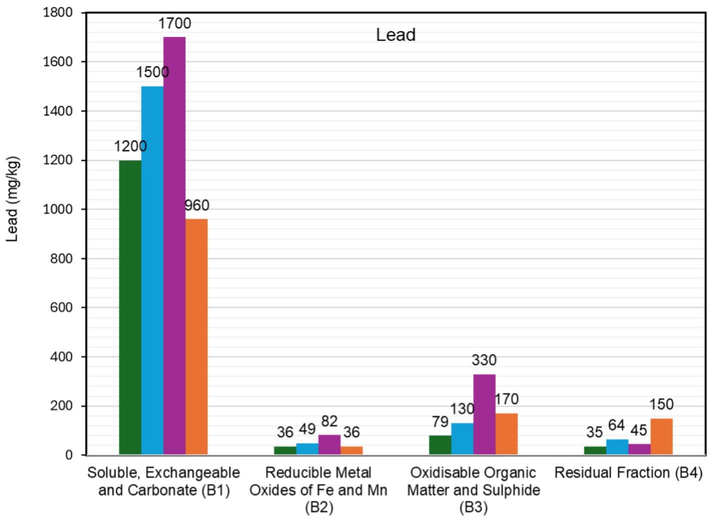


Figure 5 Distribution of Pb from Bureau Communautaire de Référence sequential extraction. The colours represent the different sample depths: green = shallowest, orange = deepest

4.5 Kinetic testing and modelling

The 4 samples assessed in upflow percolation columns were composite and comprised fractions taken from different depth intervals across the TSF. The results showed that over time the pH varied between 6.27 and

7.87 (confirming the non-acid producing classification), with total alkalinity decreasing from between 100 and 58 mg/L to 37 and 19 mg/L, where it stabilised.

The declining source term modelling generally achieved R^2 values of > 0.9 for most datasets, indicating a strong agreement between the experimental data and the model predictions. The fitted k' parameters varied between 0.349 and 1.034 kg/L, reflecting differences in leaching behaviour among the modelled trace metals and the influence of differences in sample source term composition. Zn generally exhibited the highest k' values, suggesting a faster decline of mass flux rates in comparison to the Pb and Cd leaching models.

The $C_{(L/S = 1)}$ parameter revealed that the Zn leachate concentrations at L/S=1 were generally higher than those for Pb, whilst Cd concentrations were consistently the smallest, supporting the lower mobility of this element in this system. Coefficient of variation values were generally low, supporting the reliability of the fitted models. Based on the k' model, the calculated $C_{(L/S = 1)}$ values for Pb, Zn and Cd showed good agreement with experimental datasets from upflow percolation studies. Examples of the kappa prime fits for Pb, Zn and Cd are presented in Figure 6.

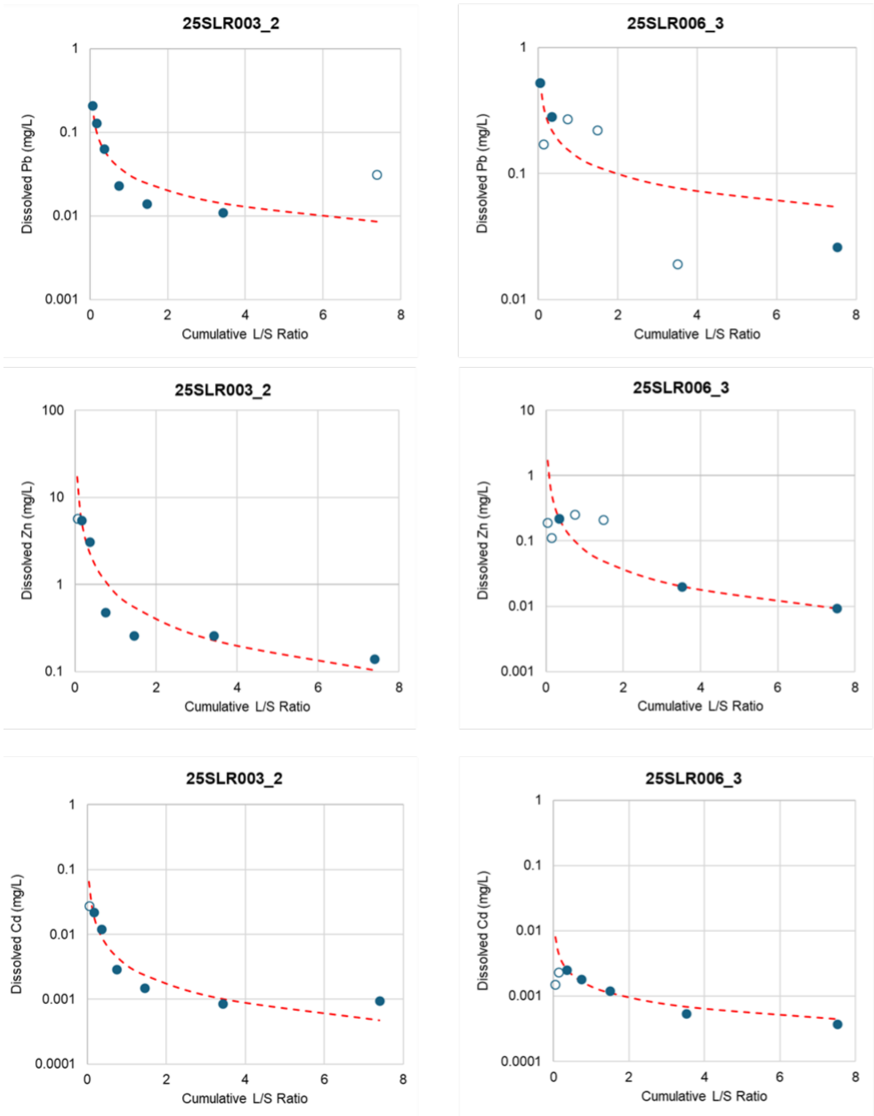


Figure 6 Kappa prime model fits for Pb (top), (middle) and Cd (bottom)

Pb mass flux profiles exhibited a declining source term leaching behaviour, suggesting that the elution of early pore volumes from drainage of the TSF will exhibit elevated dissolved phase concentrations. As shown in Figure 6, dissolved Zn concentrations also exhibit a declining mass flux profile with all high source term samples producing peak Zn concentrations within the first 2 fractions.

Advection flux modelling results were used to predict drainage concentration profiles over time as presented using a conceptual model shown in Figure 7. Model outputs are based on continual porewater flushing from infiltration, which assumes that the tailings remain hydraulically active and uncapped during this time. A secondary confirmatory phase of site investigation is due in 2027, which will enable further optimisation of the tailings chemistry interpretation and impact.

The model assumes that precipitation in the form of snow and rainfall infiltrates the tailings. The total precipitation was adjusted by the potential evaporation. This was obtained from the Swedish Meteorological Office. The porosity of the tailings and the depth of the phreatic surface were obtained from historic site investigation information, with the phases of the metals of interest obtained from the XRD spectra and BCR extraction interpretation. The underlying material is likely to comprise moraine material, which can be relatively permeable (peat and sand) and therefore may not be limiting in terms of the underdrainage of the TSF. Ongoing site investigation (during 2026–2027) will be useful to confirm this aspect of the project.

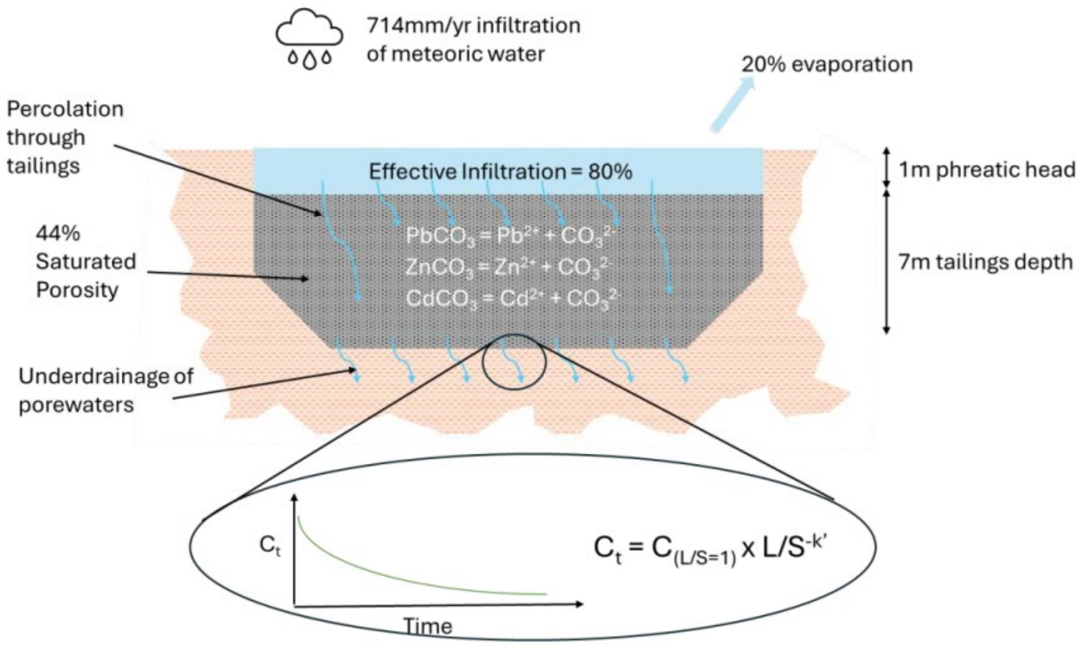


Figure 7 Modelling used to assess the depletion rate of metals within tailings

The bioavailable environmental quality standard (EQS) for Pb, Zn and Cd was calculated using the Swedish Environmental Protection Agency (Naturvårdsverket) (Oorts et al. 2021) and plotted on the declining source model for each of the metals of concern (Figure 8).

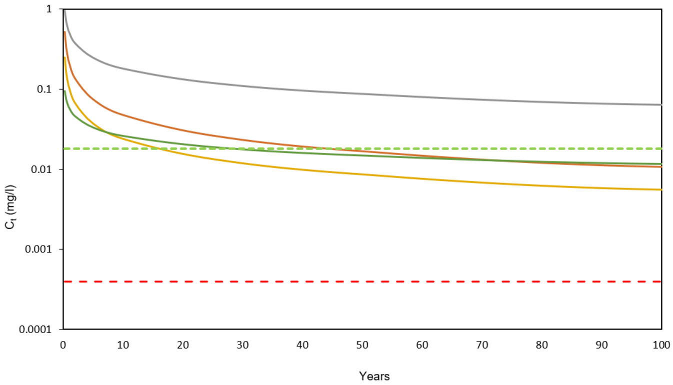
The advection model for the study demonstrated that it was possible to estimate the times for the leached metals in the 4 samples analysed to reach the EQS, and these are shown in Table 1.

Table 1 Calculated years to meeting bioavailable environmental quality standards (EQS) using a declining source term model

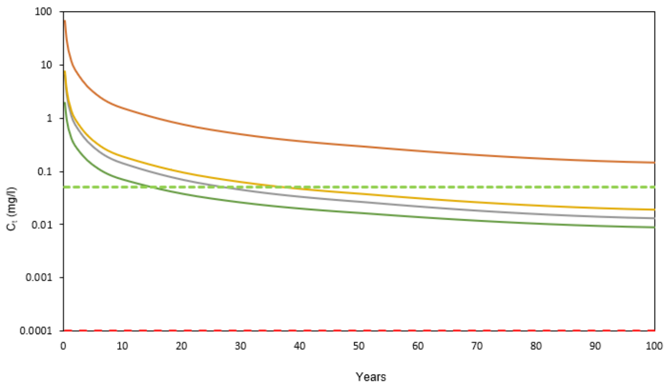
Element	$EQS_{Bioavailable}$	Time to reach EQS (years)			
		Sample 1	Sample 2	Sample 3	Sample 4
Pb	0.018	45	1,643	16	29
Zn	0.051	275	27	37	14
Cd	0.0012	56	25	0*	10

* majority of samples measured below Cd limit of detection

The results presented comparisons between the different horizons in the tailings, with the upper horizon likely to be more leached and deeper horizons likely to be less leached. Pb has been modelled to decrease in the drainage of the upper and middle layers of the tailings to below the calculated EQS between years 16 to 45. One sample exceeded 1,600 years, which was related to the deep (less weathered) samples. Zn is modelled to decrease in the drainage to below the calculated EQS between years 14 to 37. Cadmium is modelled to decrease in the drainage to below the calculated EQS between years 10 to 56. A review of the declining source term suggested that the metals will continue to leach from the TSF and therefore intervention in the form of leachate treatment would be required.



(a)



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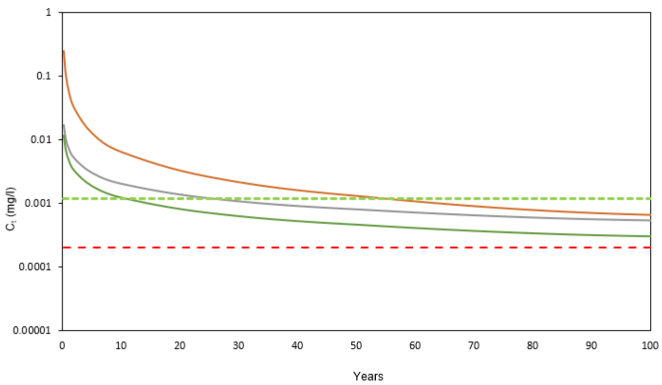

(c)

Figure 8 Declining source term for Pb (top), Zn (middle) and Cd (bottom) compared to respective environmental quality standards values (grey = deepest sample, brown and yellow = middle, green = shallow)

5 Conclusions and recommendations

From the results of the acid base accounting and mineralogical analysis of samples of glacial till, the following conclusions are made:

- The glacial till is non-acid forming (NAF) overall, with uncertainty coming from a low neutralisation potential.
- Glacial till is quartz-dominated to between 72.9 and 75.8%. anorthite (13.8–14.9%) is present, with the bulk of the remaining composition being clay minerals including chlorite and kaolinite.
- $PbCO_3$, a Pb carbonate, is also present in trace amounts. This is likely from documented spilled tailings that were also observed during the sampling program.

From the static and kinetic geochemical testing of the tailings material, the following conclusions are made:

- Tailings material tested is NAF.
- Mineralogical investigation of the tailings material indicates that they are predominately composed of quartz, with minor components of albite, calcite, feldspar and $PbCO_3$.
- Pb solubility is dominantly controlled by carbonates (cerussite, $PbCO_3$). As shown in Bureau Communautaire de Référence sequential extraction, 73 to 89% of Pb extracted was in the B1 (acid-soluble) fraction, which is associated with carbonates. This is supported by mineralogical testing identifying $PbCO_3$ across the tailings material.
- Cd and Zn are likely distributed between carbonates and metal hydroxides due to the relatively even split between the acid-soluble (B1) and oxidisable (B3) fractions.
- The geochemical speciation model supported the evidence that Pb, and to some extent Zn and Cd solubility, are controlled by carbonate phases. Where modelled, dissolution curves of each metals' respective carbonate phase showed agreement with the sequential pH extraction results.
- Pb, Cd and Zn solubility appear to be adequately described by the dissolution of $PbCO_3$, otavite and smithsonite. These trace elements exhibit a characteristic solubility curve, with increased solubility at low pH due to carbonate dissolution and at high pH due to the prevalence of metal-hydroxy(oxide) aqueous complexes.
- Advective flux leaching models suggest that metal/metalloid concentrations will decline below bioavailable and hardness-derived environmental quality standards (EQS) after a number of years, based on the experimentally derived kappa and kappa prime values.

For the modelled period, where discharge could exceed the EQS, passive groundwater treatment systems could provide a suitable solution to ensure that discharge from the site is kept below site-specific EQS. SLR Consulting Limited is currently progressing these recommendations with additional site investigation and laboratory experiments to assess the potential for passive treatment of metals emanating from the tailings dam drainage, and this will be reported in 2027.

Acknowledgement

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References

British Standards Institution 2022, *BS EN174405; 2022 Tests for the Chemical Properties of Aggregates – Part 5 : Determination of Acid Soluble Chloride Salts*, London.

MEND 1994, *Review of Waste Rock Sampling Techniques,* SENSE Consultants Limited, Golder Associates, Laval University.

Morin, K & Hutt, N 2007, *Morison Project - Prediction of Metal Leaching and Acid Rock Drainage, Phase 1.*, Minesite Drainage Assessment Group.

Oorts, K, Smolders, E, Lanno, R & Chowdhury, MJ 2021, 'Bioavailability and ecotoxicity of lead in soil: implications for setting ecological soil quality standards', *Environmental Toxicology and Chemistry*, vol. 40, no. 7, pp. 1950–1963.

Weber, PA, Hughes, JB, Conneer, LB, Lindsay, P and Smart, R 2006, *Short-Term Acid Rock Drainage Characteristics Determined by Paste pH and Kinetic NAG Testing: Cypress Project, New Zealand*.