Seepage and water quality observations from three lysimeters constructed at a coal mine in northeastern, British Columbia, Canada

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Abstract

At a coal mine in northeastern British Columbia, Canada, three mine rock lysimeters were constructed to evaluate the relative performance of soil covers in reducing net infiltration, seepage volumes, and chemical loads potentially requiring treatment. Data collection is ongoing at the study site with interim results indicative that mine rock with an engineered cover produces less seepage than mine rock with a standard reclamation cover and a control pile without cover. Relevant hydro-climatic and loading data are presented for the mine rock lysimeters, and a water quality dataset spanning more than ten years is discussed.

Keywords: Waste rock, runoff, lysimeters, reclamation, cover systems, water quality

Introduction

Infiltration through waste rock piles mobilizes sulfide oxidation products as well as blasting residues (Wellen *et al.* 2015; Mahmood *et al.* 2017). Accordingly, parameters of concern at coal mines often include sulfate, nitrate and selenium, with mitigative measures such as passive and active treatment, waste submergence, seepage interception, and the application of cover systems, employed to achieve compliance with effluent standards and broader ecosystem health goals.

Work by others illustrates the utility of lysimeters in ground-truthing laboratory studies, while bridging understanding regarding flow and chemical processes occurring in mine waste at a large scale (e.g., Hansen *et al.* 2000; Smith *et al.* 2013, Muniruzzaman et al. 2021). Studies in the open scientific literature also report on the research objectives, experimental design, and/or general progress of lysimeter experiments involving cover system trials (e.g., Okan and Barbour 2003; Urrutia *et al.* 2011; Kahale *et al.* 2022).

At a coal mine in northeastern British Columbia (BC), three mine rock lysimeters were constructed to explore whether earlier application of soil covers reduces contaminant loading without substantive additional cost. The research objectives of this study include: i) measuring flow and water quality from covered and uncovered mine rock piles; and ii) comparing the relative performance of differing cover systems, in terms of volume and water quality of drainage output. Cover placement at the study site is hypothesized to reduce net infiltration into mine rock, thus reducing seepage volumes and chemical loads potentially requiring treatment.

Methods and Data Sources

A flat area of 100 m by 100 m on the 1,490 m elevation bench of the coal mine was selected for the mine rock lysimeters. Each lysimeter consists of an ~4 m tall mine rock pile built on a 17 m by 17 m base, complete with liner systems, a network of collection pipes, and containment berms. The lysimeters were constructed with non-PAG mine rock (i.e., siltstone, shale, sandstone and conglomerate) from the Middle and Lower Gates Formation (Stott, 1968), subunits which constitute ~85% of all mine rock at the study site. Median sulfur content (% S) and neutralization potential ratios (NPR, kg CaCO3/t) for mine rock is as follows: Middle Gates (0.09% S, NPR = 32); and Lower Gates (0.1% S, NPR = 62). Parameters of interest established through compliance monitoring include Se associated with pyrite oxidation and NO_3 associated with explosive use.

Seepage volume emanating from each lysimeter is first piped to a holding tank, then directed through a tipping bucket measuring device (1 tip = 1 L) where volumetric data is recorded by dataloggers. Lysimeter seepage water quality when sampled is analyzed for general parameters (e.g., pH and specific conductance), nutrients, major ions, and total and dissolved metals. To allow direct comparison between experimental piles, lysimeters were constructed from the same material (i.e., representative and <1 year old mine rock (0.5 m D90); bulk density ~1.7 t/m^3), using the same excavating equipment. Additional details for the lysimeters are provided in Tab. 1, noting pile masses and volumes are the same at L2 and L3 lysimeters, whereas owing to steeper side slopes and different morphometry, L2 and L3 tonnages are ~30% less than L1.

Precipitation data used in the study (e.g., to compute ratios of rainfall to seepage) are sourced from the mine site climate station (2016 through 2024). The mine site also maintains local hydrometric gauges and water quality sampling stations, with high quality and multi-decadal climate and streamflow data (e.g., daily yield data for Flatbed Creek; WSC 07FB009 (1982-2024)) also recorded by government monitoring agencies at several nearby stations.

Results

Climate conditions at the study site are characterized as continental, with cold snowy winters, warm summers, and a frost-free period of 120 days (GoBC 2021). Mean annual temperature at the study site is 1.0 °C, mean annual precipitation is 1,050 mm (60% of total is snowfall), and annual evaporation is on the order of 400 mm. Local watercourses exhibit a freshet dominated runoff regime, punctuated by periodic- high flow events, coinciding with large convective summer rainfall events. Mean annual runoff estimated for a local- high elevation monitoring station (i.e., 40 km^2, mean catchment elevation = 1,532 m asl) is 478 mm.

Representative seepage and water quality data for the lysimeters are shown in Fig. 1 and Fig. 2, respectively. Water quality data span the period 2013 to 2024, with sampling effort limited to the late-May through early-October period, when the underdrains of lysimeters are ice-free. Seepage records for lysimeters were also seasonal, with record periods as follows per lysimeter: L1 (Control; 2017 and 2019-2024); L2 (Standard reclamation cover; 2016, 2017 and 2019-2024); and, at L3 (Engineered cover; 2019, 2020 and 2024).

Fig. 1 shows seepage data in time series (upper panel; m^3/day) and cumulative volume (middle panel; m^3) formats, six-years after construction of the lysimeters. The lysimeters have been exposed to a wide range of hydro-climatic conditions. Standardized annual streamflow anomalies for a nearby hydrometric gauge (Flatbed Creek, 07FB009) confirm recent drier than average years to include 2014, 2021, 2022, 2023 and 2024, with wetter conditions evident in 2015, 2016, 2017, 2018 and 2020.

Table 1. Design basis for lysimeters constructed at study site.

Station ID	Mine Rock Size	Cover Description	Slope Angles
L1 (Control)	0.5 m D90	Uncovered	Angle of repose (37° slopes)
L2 (Standard reclamation cover)		0.3 m topsoil, reclamation vegetation	2:1 grade (27° slope angles)
L3 (Engineered cover)		0.3 m compacted till below 0.3 m topsoil, reclamation vegetation	2:1 grade (27° slope angles)

The three lysimeters exhibit unique flow signatures. For example, L3 (Engineered cover) exhibits a dampened seepage response to large rainfall event (i.e., less preferential flow) and less baseflow (or matrix flow). In comparison, the L1 and L2 lysimeters clearly report more seepage overall and are more responsive to rainfall events than L3. For a congruent ~3-month period depicted in Fig.1, cumulative precipitation reporting to each lysimeter, expressed as a volume over their footprints was 120 m^3, whereas cumulative seepage volumes at L1 (44 m^3) and L2 (51 m^3) were generally similar, and three-times greater than cumulative seepage measured at L3 (14 m^3).

Averaged over the ice-free period shown in Fig. 1, seepage at L3 was approximately 12% of measured precipitation, whereas L1 seepage (37%) and L2 seepage (43%) were roughly a factor of three higher. With the available data it was possible to develop a more fulsome comparison of cumulative seepage for the L1 (111 m^3) and L2 (109 m^3) lysimeters based on more than 600 days of overlapping data. This extended analysis provides added confidence that seepage production at L1 and L2 to date has been generally similar – rather than materially different.

Fig. 2 shows time series plots for pH, total alkalinity, chloride, calcium, nitrate, sulfate, and selenium from the three lysimeters. Time series for several parameters (e.g., TSS (not shown), total alkalinity (Fig. 2, panel 2), chloride (Fig. 2, panel 3) and calcium (Fig. 2, panel 4)) show considerable variability for five years, prior to showing more stable conditions post-2019. Post-2019 seepage from the lysimeters is slightly basic (pH 8.0 to 8.5; Fig. 2, panel 1)) and similar between sites, while total alkalinities vary seasonally and show similarity. Similarly, post-2019 calcium and sodium (not shown) signatures are also very similar and relatively stable interannually, suggesting that quasi-equilibrium conditions have been attained at the piles.

Flushing of blasting residues occurred much sooner at L1 (Control) versus the two covered lysimeters (Fig. 2, panel 5; nitrate). Nitrate concentrations at L1 remained elevated to a threshold of ~5 mg/L through autumn 2015, while concentrations remained elevated to the same threshold at L2 and L3 through autumn 2017.

Time series plots for magnesium (not shown), sulfate (Fig. 2, panel 6) and selenium (Fig. 2, panel 7) show several commonalities. Of note, Mg, SO_4 and Se concentrations at L2 and L3 are very similar for the post-2019 period. These two lysimeters are covered, have similar morphometry and same tonnages of mine rock on their pads. Given the similar sulfate and selenium concentrations at L2 and L3 while acknowledging seepage production at L3 (Engineered cover) is lower than at L2 (Standard reclamation cover), field data support a conclusion that sulfate and selenium loading at L3 lysimeter is less than loading at L2 (Fig. 1, lower panel).

Mg, SO_4 and Se plots show consistently higher concentrations at L1 (Control) compared to L2 and L3, for the post-2019 period. Greater mass and different morphometry at L1 versus L2 and L3 lysimeters may explain the higher seepage concentrations at L1. By applying a scaling factor to L1 concentration data that accounts for the mass differences at the lysimeters, Mg, SO_4 and Se data show far better alignment across the three sites. Additionally, it is also plausible that ingress of the oxidation front in L1 is promoting sulfide weathering, which is more pronounced in the uncovered pile (L1), due to unimpeded convective oxygen flow.

Regarding recent upward trending in Mg, SO_4 and Se, at all three lysimeters, the collection of additional data may confirm continued upward trending, or alternatively, it is plausible that quasi-steady state conditions have been reached and a return to more typical hydro-climatic conditions will be commensurate with better (lower concentration) seepage water quality. Generally dry conditions have prevailed locally since 2021, with extreme drought conditions occurring in 2024.

Discussion

This paper presents interim water balance and chemical findings from this multi-year research initiative. Data collected thus far indicates the engineered cover pile (L3) produces less seepage than the standard reclamation covered lysimeter (L2) and control pile (L1). While hypothesized that seepage production at L2 would be lower than L1 on account of cover placement, several years of field data confirm seepage production at L1 and L2 to be more similar than different.

Chemistry data from the lysimeters for several parameters (e.g., TSS, total alkalinity, chloride and calcium) showed considerable variability over the first five years of measurement, then reached quasi-equilibrium conditions from 2019 onward. Flushing of blasting residues occurred much sooner at uncovered L1 (Control) compared to the two covered lysimeters. Mg, SO_4 and Se concentrations at L2 and L3 are very similar for the post-2019 period, while concentrations for these same parameters were higher at L1. Owing to lower seepage production at L3 versus L1 and L2 and given that seepage chemistry is either the same (L2) or elevated (L1) compared to L3, load reductions appear achievable by placing engineered cover systems over mine rock (e.g., 30 cm compacted till, 30 topsoil, vegetated).

Future study phases should continue the monitoring of lysimeter seepage and water quality, while considering integration of additional sensors in piles (e.g., soil moisture and oxygen probes), as well as autosamplers and continuously recording sensors (e.g., specific conductance and water temperature), to advance overall study objectives. A portion of seepage reporting from the lysimeters is associated with infrequent, but episodic, seepage events attributable to large storms (e.g., convective rainfall event >30 mm/day). However, the water quality database for the lysimeters is currently biased toward low-moderate seepage conditions, and future sampling efforts should aim to fill this knowledge gap.

At the conclusion of mining and should cover systems be broadly applied to waste rock facilities, design specifications for cover systems merit careful contemplation of datasets developed at the experimental scale while reconciling learnings with conceptual understanding garnered for entire facilities and at larger spatial scales. In addition, future reclamation activities need to be cognizant of the climate conditions forecasted for mine closure and beyond. Forward looking climate change projections (e.g., downscaled 8-GCM ensemble, SSP3-7.0) indexed to a baseline of 1991-2020 predict warmer conditions at the study site (+3°C), coincident with increases in precipitation (+35%) and evaporation (+25%) by 2100.

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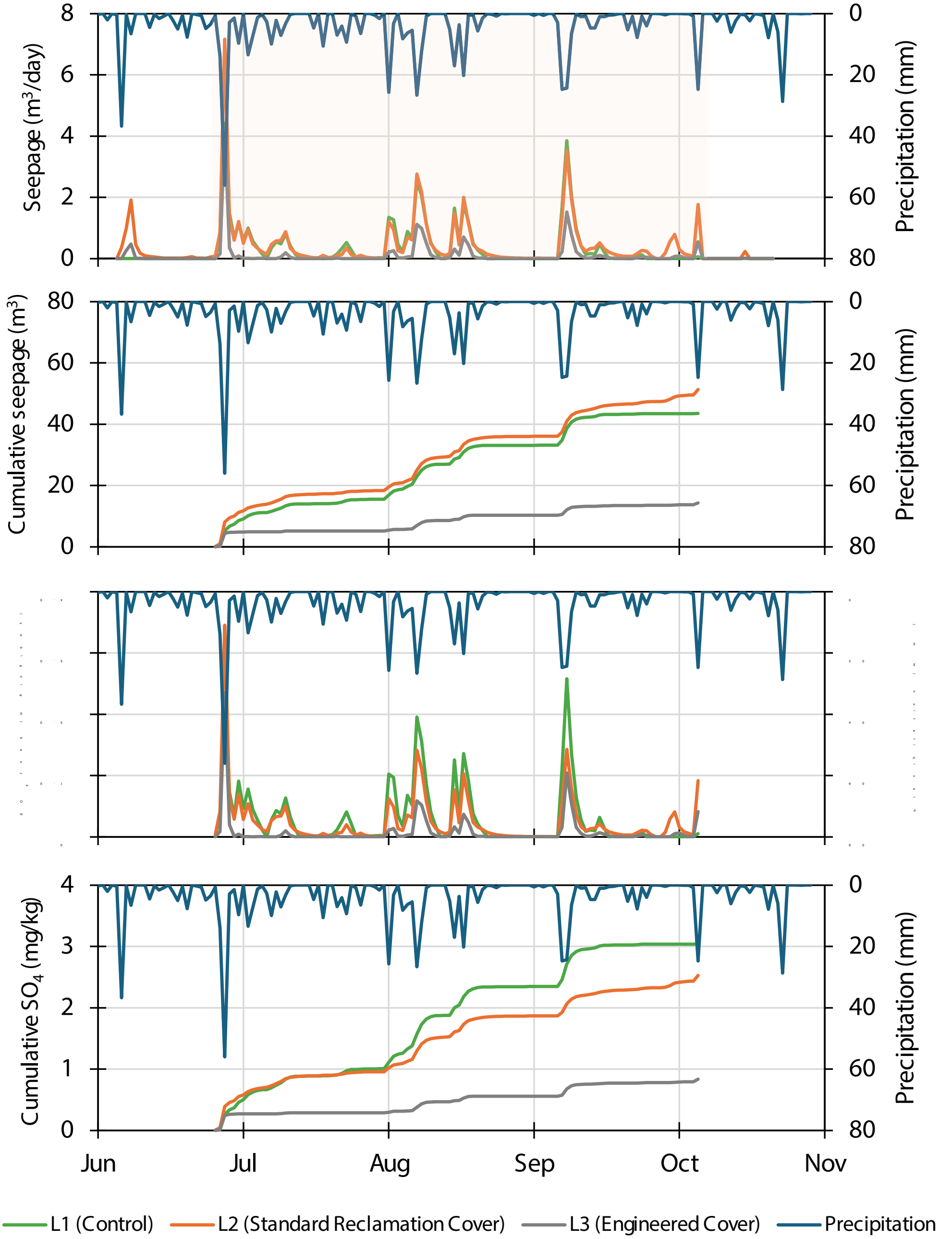

Figure 1: *Time series illustrating patterns of seepage and precipitation (upper panel), cumulative seepage and precipitation (second panel), daily sulfate loading (third panel) and cumulative sulfate loading (lower panel), 6-years following commissioning of the three lysimeters.* SO_4 *data shown in the third and lower panels are standardized by mass per mine rock lysimeter.*

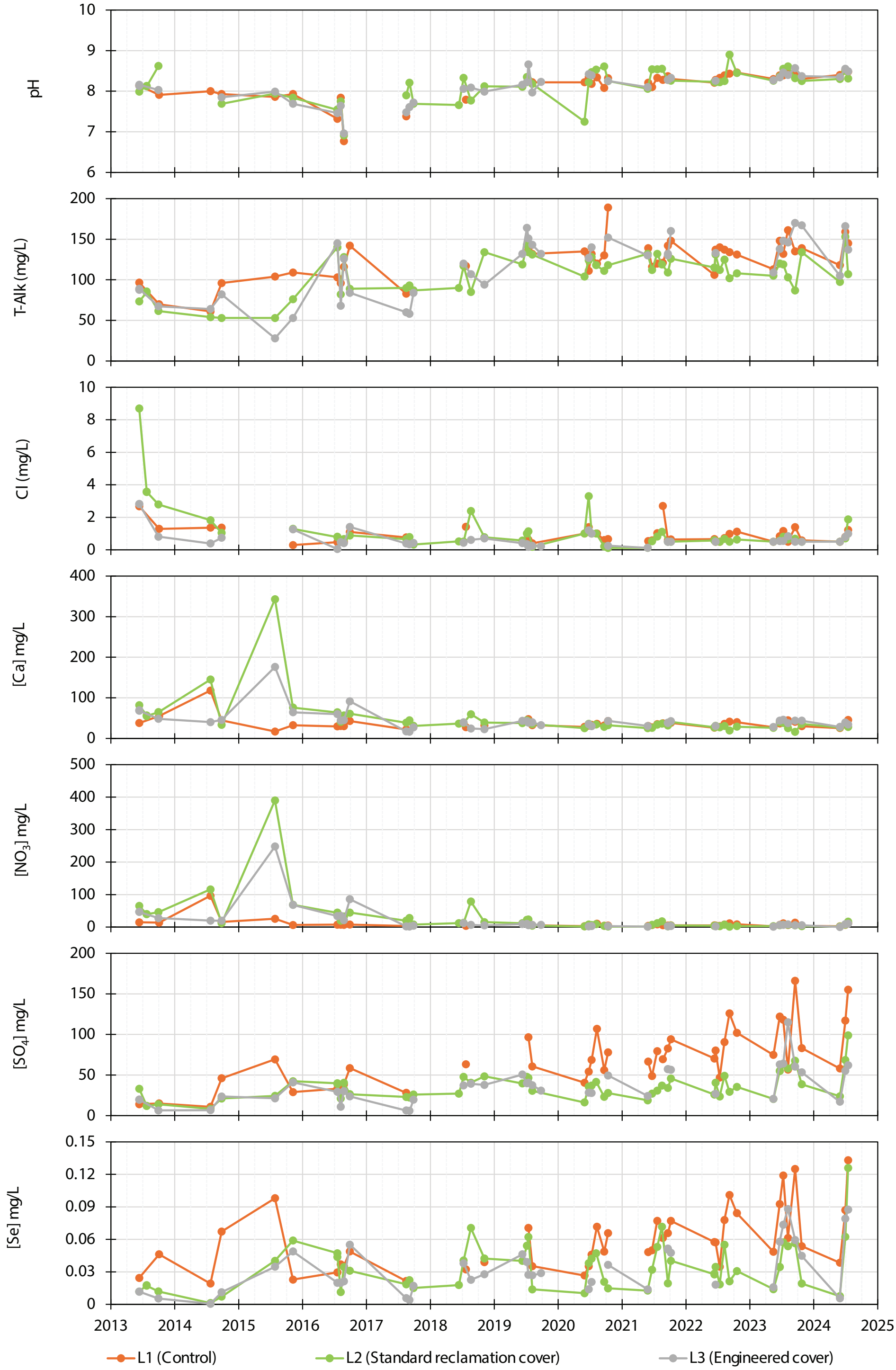

Figure 2: *Time series plots showing pH, total alkalinity, chloride, calcium, nitrate, sulfate and selenium measured for the period 2013-2024 at three mine rock lysimeters.*