Flow and Load Accretion Study Improved Understanding of Hyporheic Exchange plus Contaminant Plume Sources and Transport

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Abstract

Groundwater quality downstream of a tailing impoundment area (TIA) was found to have elevated sulfate and selenium concentrations. An interpreted sulfate plume largely agreed with the interpreted shallow groundwater flow regime and a TIA source; however, its leading edge was confounded by higher background concentrations. Sporadic, anomalous selenium concentrations were noted at wells near the area presenting higher background sulfate. Unlike sulfate, the selenium source was not clear. A hypothesis for the selenium source and higher background sulfate was hydraulic communication between the nearby creek and shallow groundwater. A flow and load accretion study classified losing/gaining reaches to assess this hypothesis.

Keywords: Tailings seepage, background concentrations, natural sources, sulfate, selenium

Introduction

The mine is located in northwest British Columbia, Canada. The mine has been operating as an open pit mine for almost a decade, with tailings deposition commencing at the north end of the Tailings Impoundment Area (TIA) at the start of operations and at the south end of the TIA approximately 2 years later. The TIA straddles a topographic divide in a north-south trending valley.; hence, the site is conceptualized as two distinct regions: the North Valley and the South Valley. Each end of the TIA is contained by a tailings impoundment dam (e.g. South Dam) and downstream of each is a reclaim dam (e.g. South Reclaim Dam [SRD]).

The focus of this study is the South Valley. During pre-development conditions, the South Valley included Upper Lake that existed upstream of the South Dam. Upper Lake drained to Trail Creek, a meandering creek flowing south and discharging to Lower Lake approximately 2 km downstream of the South Dam. As part of mine development, Upper Lake was drained and the upper reaches of Trail Creek (i.e., upstream of the SRD) have not conveyed surface flows since construction of the South Dam. The other important hydrological feature in the South Valley is Camp Creek, a tributary to Trail Creek that continues to flow in mine operations. The headwaters of Camp Creek are approximately 4 km upstream of, and 450 m higher than, the South Valley and adjacent to the mine's open pit (Fig. 1).

Most groundwater flow in the South Valley is interpreted to occur in two hydrostratigraphic units (HSUs): a largely unconfined shallow aquifer, and a deep aquifer that is reasonably hydraulically isolated from the overlying shallow aquifer by an aquitard HSU. Groundwater quality downstream in the South Valley is monitored by over 30 monitoring wells. Routine monitoring of water levels and water chemistry supports the interpretation of groundwater flow in the shallow and deep aquifer HSUs. A Trigger Response Plan (TRP) was developed for the mine, in adherence with its permit conditions, that supports the monitoring and water management at the site. In the South Valley, seven constituents of potential concern (COPCs) are included in the TRP. Each COPC includes two trigger values that, if exceeded, may result in additional actions to be protective of the downstream

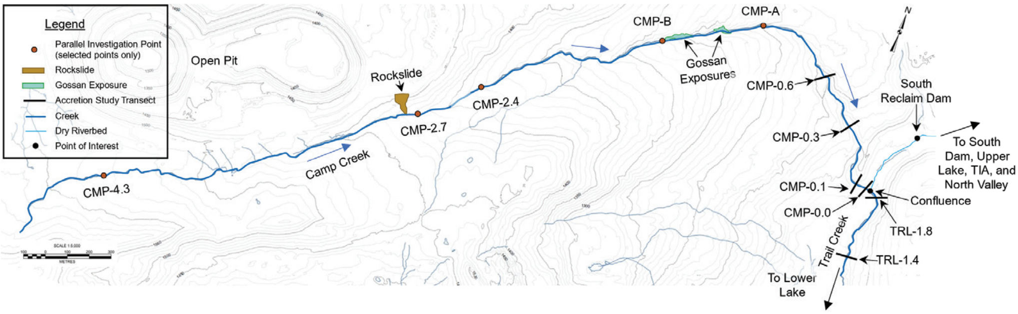

Figure 1 *Camp Creek Study Area, within the South Valley. Camp Creek extends north and west of the confluence, while Trail Creek continues south of the confluence*

environment. Sulfate and selenium are two (of seven) COPCs identified in the TRP for the South Valley.

In addition to sulfate, elevated dissolved selenium concentrations exceeding TRP-defined trigger values were recorded at some deep aquifer monitoring wells, with one well located downstream of the SRD and near Camp Creek. Boundaries associated with a potential selenium plume have not been interpreted to date and the source(s) of the selenium loading to the deep aquifer is uncertain. Similar and elevated sulfate and selenium concentrations were also observed at the Camp Creek surface water station during the same period as the selenium trigger exceedances, which prompted speculation that Camp Creek may be a source of loading to this station and the deep aquifer.

Flow and load accretion studies help to identify losing and gaining (i.e. hyporheic) reaches in a watercourse. Losing reaches can act as recharge to the groundwater flow system and may represent an external loading source to groundwater chemistry and may locally influence redox conditions leading to changes in water quality. Gaining reaches may reflect areas of groundwater discharge to the watercourse. Therefore, a flow and load accretion study was performed to:

- Document losing and gaining reaches along Camp Creek and Trail Creek and assess seasonal variations in discharge and load.
- Assess the potential for hydraulic communication between surface watercourses and the South Valley shallow aquifer as well as the deep aquifer, downgradient of the SRD.
- Update the conceptualization of interactions of Camp and Trail Creeks to the South Valley.

These study results would also support an updated understanding of sources and constituent transport in the South Valley. As well, given the observation that Camp Creek has historically presented elevated concentrations of sulfate and selenium, a parallel reconnaissance study was carried out near the Camp Creek headwater region (i.e. near the open pit) to identify potential source area(s) of these COPC loadings to the creek.

Methods

The flow and load accretion study was carried out at the mine over two approximate two-week field programs (October 2021 and July 2022) during seasonal, low flow conditions. Low flow conditions were targeted for the study to provide optimal conditions to estimate baseflow contributions not influenced by preceding or concurrent rainfall or snowmelt (i.e. not influenced by runoff generated discharge). A salt dilution gauging method, using sodium chloride, was employed to measure discharge at six transects to calculate the flow components. Water quality samples were collected at the same time as discharge measurements to calculate loads.

Six transects were defined along the lower 600 m of Camp Creek (i.e. CMP-0.6, CMP-0.3, CMP-0.1, CMP-0.0) to 500 m downstream of its confluence with Trail Creek (i.e. TRL-

1.8, TRL-1.4; Fig. 1). The upper and lower boundaries of the study area were based on the hydrostratigraphy of the South Valley and encompassed the local area associated with monitoring wells where dissolved selenium TRP exceedances were observed. The location of the six transects (i.e. a transect at the upper and lower boundary of the study area, plus four intermediary transects) were field fit as part of the October 2021 program and were largely based on the evaluation of channel morphology and flow conditions as described in the *Manual of British Columbia Hydrometric Standards* (Resources Information Standards Committee [RISC] 2018) for salt dilution gauging.

Surface water discharge measurements were recorded from October 11 to October 22, 2021, and from July 11 to July 27, 2022, following the procedures described in RISC (2018). Discharge measurements were taken from downstream to upstream (to prevent contamination) and from all six transects over a 12-hour period, which equated to a single accretion study transect monitoring event. Five accretion study transect monitoring events occurred during the October 2021 program and six transect monitoring events occurred during the July 2022 program. Water quality sampling was completed immediately upstream of each transect following discharge measurement. Field parameters and samples were collected as per the procedures in the *British Columbia Field Sampling Manual* (Clark 2013). A total of 30 surface water samples were collected at the six transects as part of the October 2021 field program, and 36 samples collected as part of the July 2022 field program.

As noted above, a parallel investigation program was conducted in the Camp Creek headwater region to identify a possible loading source(s) or area(s) of sulfate and selenium to Camp Creek. Specifically, surface water samples were collected in October 2021 at a routine monitoring station (i.e. CMP-4.3) near the Camp Creek headwaters and six other stations downstream and along an approximate 2 km reach (i.e. from CMP-4.3 to CMP-2.4; Fig. 1). Stream conductivity measurements using a water quality meter were also taken along this reach in October 2021, which was used to indicate areas of increased loading (i.e. higher conductivity measurements could relate to higher sulfate concentrations) and support the identification of ideal locations for water quality sampling.

In July 2022, water quality samples were also collected upstream and downstream of large gossanous exposures along a 500 m long southeast facing embankment of Camp Creek, downstream of the 2 km reach sampled in October 2021. In total, 12 water quality samples were collected in the upper reaches of Camp Creek as part of the extended study program.

All water quality samples collected were submitted for a standard groundwater quality monitoring analytical suite (e.g. physical parameters, nutrients, total and dissolved metals). Of the many constituents measured, only sulfate and selenium are discussed in this paper.

Results and Discussion

Data from both field programs showed flows in Camp Creek decreased in the downstream direction (i.e. CMP-0.6 to CMP-0.0), while flows in Trail Creek (i.e. TRL-1.8 to TRL-1.4) increased in the downstream direction. The transition between decreasing and increasing flows was noted to occur in the vicinity of the confluence between the two creeks (i.e. CMP-0.0 to TRL 1.8). In October 2021, the flow increase was observed to occur downstream of the confluence of the two creeks (i.e. CMP-0.0 to TRL-1.8), while in July 2022, the flow increase occurred more gradually and farther downstream (i.e. TRL 1.8 to TRL 1.4).

Where the discharge rate in the creek decreased between transects in the downstream direction, a losing reach was interpreted. Where the discharge rate increased between transects at a rate greater than the contributing watershed runoff could account for, a gaining reach was interpreted. Thus, data from both field programs showed the lower reaches of Camp Creek were losing reaches, and the upper reaches of Trail Creek were gaining reaches (Fig. 2). As well, both the location of the losing to gaining transition and magnitude of flows to Trail Creek may be associated with seasonality in the water table due to fluctuations in the elevation of Lower Lake or variability in shallow groundwater

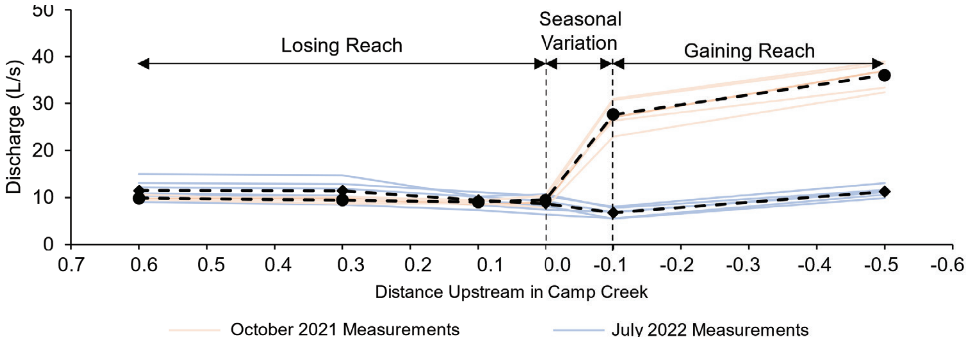

Figure 2 *Camp Creek Discharge in October 2021 and July 2022*

flows discharging to Trail Creek; however, piezometric data from nearby monitoring wells or Upper Lake were not available to further investigate these possibilities.

Sulfate concentrations were observed to be steady along the Camp Creek transects and then decrease downstream of the confluence with Trail Creek (Fig. 3; Fig. 4A). Similarly, selenium concentrations were observed to generally increase slightly or be relatively stable from upstream to downstream for both programs (Fig. 3, Fig. 5A). However, calculation of both sulfate and selenium loads (i.e. concentration × discharge) showed increases along Trail Creek, particularly in October 2021, which aligned with interpreted gaining reaches (see Fig. 4B, Fig. 5B).

These results indicate Trail Creek gaining conditions may be associated with; 1) flow and loads lost from upstream losing reaches along Camp Creek, or 2) contaminated groundwater from upgradient areas of the South Valley. For the first possibility, neither the summation of the sulfate load, nor the selenium load lost from upstream reaches account for the entire sulfate and selenium loads gained between TRL-1.8 and TRL-1.4.

For the second possibility, a calculation was undertaken to estimate the possible groundwater discharge concentrations contributing to the observed flow and load increases downstream of Camp Creek (i.e. the difference in mass loading rates between TRL-1.4 and CMP-0.0 was divided by the difference in volumetric flow rates between these two transects). The estimated sulfate concentration was approximately 135 mg/L, which was comparable to concentrations associated with the leading edge of the interpreted sulfate plume at that time. The same calculation was undertaken between TRL-1.8 and TRL-1.4, which provided an estimated baseflow sulfate concentration of 60 mg/L which is not considered to be representative of the sulfate plume (i.e. downstream of the leading edge and near background concentrations). Overall, these results support the interpretation of the

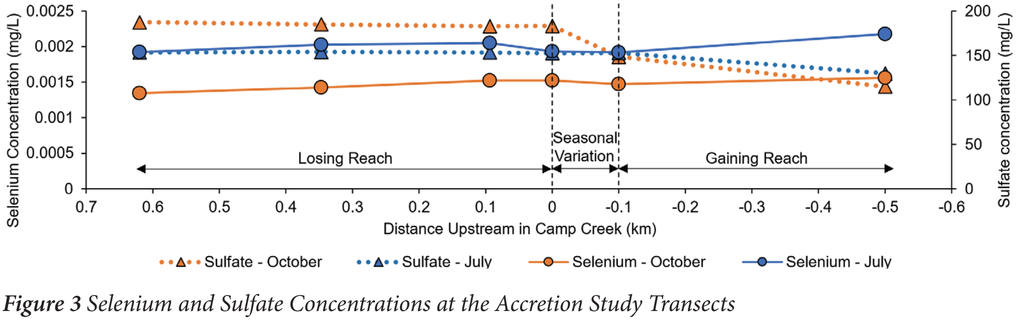

Figure 3 *Selenium and Sulfate Concentrations at the Accretion Study Transects*

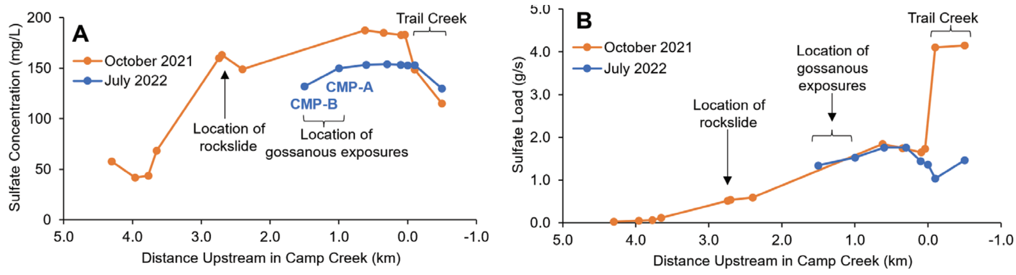

Figure 4 *Sulfate Concentration (A), and Sulfate Load (B) in Camp Creek and Trail Creek*

leading edge of the sulfate plume was between CMP-0.0 and TRL 1.4 at the time of the study.

Differences are noted in the October 2021 data between the sulfate and selenium loads from CMP 0.0 to TRL 1.4. The variation between the two loads cannot be conclusively explained from the study data. Elucidation of the different rate of increase for the selenium load relative to the sulfate load while reaching a similar magnitude increase will require additional data to resolve.

The losing reach noted along Camp Creek supports the possibility of Camp Creek as a loading source to the shallow and possibly deep aquifer. As described earlier, the upstream source of loading to Camp Creek was investigated in parallel with the flow and load accretion study. Results and findings from this investigation near the Camp Creek headwaters were as follows:

- Results from conductivity measurements (i.e. assumed to be a proxy for sulfate) taken along a 2 km reach of the Camp Creek headwaters showed decreasing values from CMP-4.3 to a location 300 m downstream, which then increased gradually for the next 1.2 km (i.e. CMP-2.8). At CMP-2.7, a rockslide of material used to construct the pit access road was observed near the creek embankment. Conductivity increased markedly, by nearly 50%, downstream of the rockslide. A similar trend was noted for sulfate and selenium concentrations, with approximately 2 to 3 times higher values from upstream to downstream of the rockslide (see Fig. 4A, Fig. 5A).
- Discharge measurements were recorded along the Camp Creek headwaters using the same method as the flow and load accretion study, which were used to support the calculation of loading estimates. The results for sulfate loads are shown in Fig. 4B, which indicate loading rates increased from 0.1 g/s to 0.5 g/s upstream versus downstream of the rockslide, respectively; however, the largest sulfate loading rates (of 1.8 g/s) were noted farther downstream and include an approximate 500 m (long) gossanous exposure along Camp Creek. A similar trend was noted for selenium (Fig. 5B), whereby loading rates downstream of the rockslide were 0.002 mg/s (relative

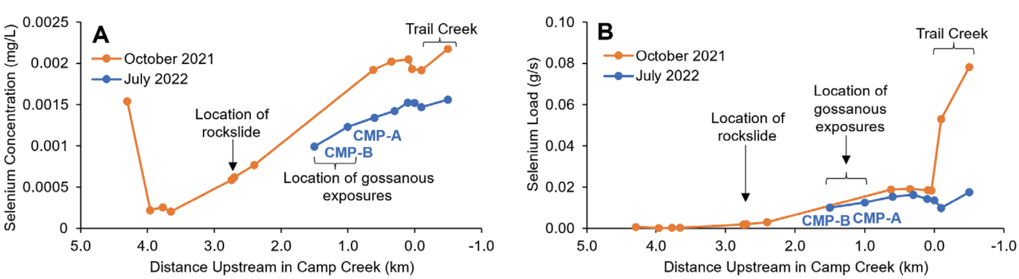

Figure 5 *Selenium Concentration (A), and Selenium Load (B) in Camp Creek and Trail Creek*

to 0.0004 mg/s upstream) and increased by approximately one order of magnitude downstream of the gossan exposures to 0.02 mg/s.

- Day and Marquez (2023) state that natural gossan found in similar deposits in northwest BC contain high pyrite and average selenium contents. Selenium may be present in gossan material as sulfide minerals, retained by adsorption to iron oxyhydroxides, or coprecipitated with jarosite and gypsum. Therefore, in addition to loading from the rockslide, weathering of gossan may be a source of sulfate and selenium loading to Camp Creek that is transported downstream toward the South Valley and Trail Creek.

Conclusions

Results from the flow and load accretion study support the following interpretations of the South Valley hyporheic interactions:

- Camp Creek is interpreted to be a losing creek along its lower reaches, while upper reaches of Trail Creek are generally gaining, with seasonal variation.
- There is potential for hydraulic communication between surface watercourses and the South Valley shallow aquifer and potentially the deep aquifer, therein supporting the likelihood for higher background sulfate values in areas of the South Valley near Camp Creek (i.e. downstream of the SRD).
- The leading edge of an interpreted sulfate plume in the South Valley shallow aquifer was better constrained by results from the flow and load accretion study. That is, the leading edge is interpreted to be downgradient of the SRD and contributes to baseflow and loadings reporting to Trail Creek.

The upper reaches of Camp Creek were identified as contributing substantial loadings to the creek, which included a rockslide near CMP-2.7 and a 1.4 km reach (downstream of the rockslide) that includes a 500 m (long) gossanous exposure. Given these observations, this study suggests the naturally mineralized nature of surface or near surface exposures along Camp Creek embankments likely influence the creek's chemistry, which is conveyed farther downstream and toward the South Valley.

The following is a list of recommendations for future work to build upon the conclusions from the flow and load accretion study:

- Source Identification: Map the rock exposures along the upper reaches of Camp Creek and collect samples of gossan material, as well as rockslide material, for static testing and mineralogy; the latter testing would help assess the degree of influence of these potential source(s) of SO_4 to Camp Creek
- Flow Mapping: Carry out a tracer study along the losing reaches of Camp Creek to assess the flow distribution from Camp Creek to the shallow and deep groundwater systems in the South Valley.

The flow and load accretion study demonstrates the interconnected state of this watershed, which is not uncommon in other watersheds. Hyporheic exchange should not be discounted when investigating contaminant sources and transport, and the confounding effects of multiple contaminant sources should not be viewed as insurmountable. Investigative methods such as flow and load accretion studies are effective tools for the dissociation of sources, as noted by this study in better constraining a plume's leading edge, despite being masked by elevated background conditions.

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