SELENIUM CONCENTRATION AND LOADING IN THE VICINITY OF BULLMOOSE MINE DURING POST-CLOSURE PHASE

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ABSTRACT

Selenium release from mine waste materials triggers significant environmental and social problems. This article reports results of a case study of concentrations and loads of selenium in the vicinity of the closed Bullmoose coal mine located in northeastern British Columbia. To illustrate what has been happening in the post-closure phase, we analyzed historical data on total selenium concentrations at the discharge point (SP-2) and in the receiving stream over an eight-year period after the mine was closed. It was found that selenium concentrations in the receiving Bullmoose Creek exceeded the current water quality guideline of 2 μg/L. The highest selenium loads were discharged at SP-2 in June (65%). A linear regression analysis showed a slight downward trend in June selenium loads discharged. Correspondingly, the stream received the highest proportion of selenium in June, and June stream selenium loads also showed a slight downward trend. Dilution was thought to be the major factor in dictating stream selenium concentration in the high-flow period. Even though the stream received minimal loads of selenium in September, consistent monitoring on stream selenium concentrations in this low-flow period was important due to low dilution and possible selenium desorption via hyporheic exchange.

KEY WORDS

Mine waste materials, mine water pollution, coal mine closure practices.

INTRODUCTION

One of the most significant environmental issues facing the global mining industry is water pollution by toxic substances released from large waste materials generated during mining and mineral processing (Bridge 2004, Liu et al. 2011). Geochemical weathering of these massive waste streams can generate a great diversity of toxic constituents to receiving waters and soil, resulting in significant impacts on water quality and aquatic ecosystems (Alpers et al. 2005, Da Pelo et al. 2009, Razo et al. 2004). Among these constituents, selenium has become a primary concern due to its bioaccumulation up the food chain (Hamilton 2004, Lemly 2004, 2002, Muscatello et al. 2008). Selenium release from mine waste is a complex process and is affected by a variety of mineralogical, geochemical and hydrological factors. The mineralogical and geochemical factors are associated with selenium's modes of occurrence and mineral associations. Selenium can be present in host rock as elemental selenium, associated with sulfides, adsorbed selenate and/or selenite, associated with organics, or associated with silicate matrix (Hendry et al. 2015, Lussier et al. 2003, Ryan and Dittrick 2000, Stillings and Amacher 2010). The different modes of occurrence and mineral associations lead to differences and complexities in release mechanisms and ecotoxicity. For example, selenium associated with sulfides is susceptible to leaching through exposure of the minerals to air and water, while selenium present in silicate matrix is not readily leachable (Lussier et al. 2003). During initial weathering, selenite may be the dominant species and is much more toxic for organisms than the methylated forms of selenium (Jonnalagadda and Rao 1993, Ziemkiewicz et al. 2011). The hydrodynamic factor involves water and air movement through waste materials that provides oxygen and moisture for chemical and microbial reactions to occur and mobilize reaction products out of waste materials (Fala et al. 2005, Molson et al. 2005).

The complexity of selenium release is compounded by the fact that selenium usually occurs in host rock with multiple other toxic elements, such as arsenic, cadmium, and mercury and they can be released together (Al-Abed et al. 2006, Al-Abed et al. 2007, Zajusz-Zubek and Konieczyński 2003). Their coexistence in receiving waters can pose complex environmental and ecological risks (Jonnalagadda and Rao 1993, Magos and Webb 1976, Palmisano et al. 1995, Skerfving 1978). For example, the methylated selenium derivatives have strong synergistic toxicity with arsenic (Jonnalagadda and Rao 1993), while selenium as selenite has a relative protective effect on acute and subacute toxicity of methylmercury (Skerfving 1978). A variety of strategies have been implemented to cope with pollution from mine waste materials: source control that prevents constituents from forming and migrating at the source; water treatment that removes constituents from mine drainage; and natural attenuation that acts without human intervention (Chang et al. 2000, Fukushi et al. 2003, Hageman et al. 2013, Johnson and Hallberg 2005, Ling et al. 2015). The implementation of these strategies requires characterizing and determining the sources of selenium and how these sources are related to changes in mine closure and water management practices. This type of information will help estimate the type and degree of management required and the time frame over which management strategies need to be in place upon closure of mines. This information is particularly important considering that active water treatment facilities may outlive the mining companies that operate them. This article reports results of a case study of selenium concentrations and loads in the vicinity of the closed Bullmoose coal mine located in the northeastern British Columbia. The findings may provide some insights into the degree of care and the length of time required in the post-closure phase.

DATA SOURCES

Site description

The case study site was the Bullmoose mine, an open-pit coal mine located in the eastern foothills of the Rocky Mountains (coordinates: 55°6'41"N, 121°29'56"W), northeastern British Columbia, Canada. Coal in the Gates Formation was exploited by the mine from 1983 to 2003, with an annual production capacity of approximately 2.3 million tonnes of metallurgical coal (Lamberson and Bustin 1988, Lane 2001, 2004). The mine was operated under the British Columbia Ministry of Environment Permit No. 6757 (last revised in April 2006) (Berger 2014). Mine closure occurred in April 2003 and the mine is permanently closed. The mine is located south of the confluence of South and West Bullmoose Creeks, which join to form Bullmoose Creek. Bullmoose Creek flows easterly to its junction with the Wolverine River which in turn flows into the Murray River. The Murray River sub-basin is one of seven priority sub-basins in the

Peace River Planning Unit for which water quality assessments are being conducted (Butcher 1987a). The constituent of main concern from the mine in this study is selenium.

Water quality monitoring stations

The applicable effluent discharge permit (Permit PE-6757) requires the Bullmoose mine to undertake water quality monitoring in the vicinity of the mine (Butcher 1987b). The location of the main water quality monitoring stations is as follows and shown in Figure 1.

- Upstream of the mine site: E206228 on South Bullmoose Creek; E206225 on West Bullmose Creek upstream of sedimentation pond SP-3
- Contributing sources: sedimentation ponds SP-1, SP-2, and SP-3
- Downstream of the mine site: E206227 on West Bullmoose Creek downstream of all three sedimentation ponds; 0410094 on Bullmoose Creek 1.2 km downstream from the mine; E206232 on Bullmoose Creek 20 km downstream from the mine

The three sedimentation ponds collect maintenance shop effluent, pit water, and surface runoff from the plant site, waste dumps, and mine area. The Permit authorizes the discharge of decant from these ponds to Bullmoose Creek during the free-flowing period and exfiltration to West Bullmoose Creek for the rest of the year (Butcher 1987a). Two groundwater monitoring wells has been dry for a few years and there has been no discharge from the tailings impoundment.

Water quality monitoring data

Total selenium has been monitored at the aforementioned monitoring stations as per the requirements specified in the Permit. Consistent monitoring is required in June and September. Total selenium concentration was determined using the ICP-MS (inductively coupled plasma mass spectrometry) cell collision instrument. All mine surface water runoff and drainage from SP-1 has been diverted to SP-2 since 2005. Even though SP-1 and SP-3 do not directly discharge any drainage to the receiving waters, water quality within the two ponds is still being monitored. The analyses on selenium loads and concentrations at the discharge point, i.e., SP-2, and in the receiving streams were conducted for an eight-year period from 2006 to 2013. Data used in this study were obtained from the British Columbia Ministry of Environment (http://www.env.gov.bc.ca/emswr/).

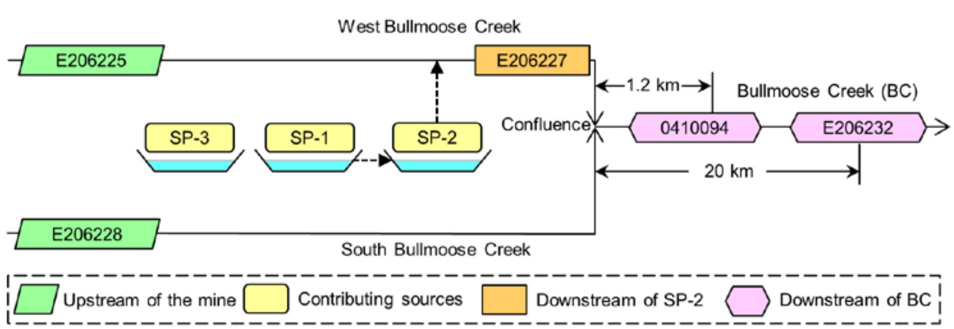

Figure 1 Main water quality monitoring stations in the vicinity of Bullmoose mine

RESULTS AND DISCUSSION

Selenium concentration at upstream and downstream monitoring stations

Comparison of selenium levels upstream and downstream of the mine indicated that the mine contributed elevated levels of selenium to the receiving waters. Figure 2 shows selenium concentrations monitored at the two upstream and three downstream monitoring stations over the study period. The data monitored at the two upstream stations, E206225 and E206228, represented selenium natural background concentrations, which were consistently below the current applicable water quality guideline of 2 µg/L for total selenium (British Columbia Ministry of Environment Water Protection & Sustainability Branch 2015). Selenium concentrations monitored at the three downstream stations: E206227, 0410094 and E206232, all exceeded the guideline concentration, indicating that the mine operation contributed to the elevated levels of selenium in the receiving streams.

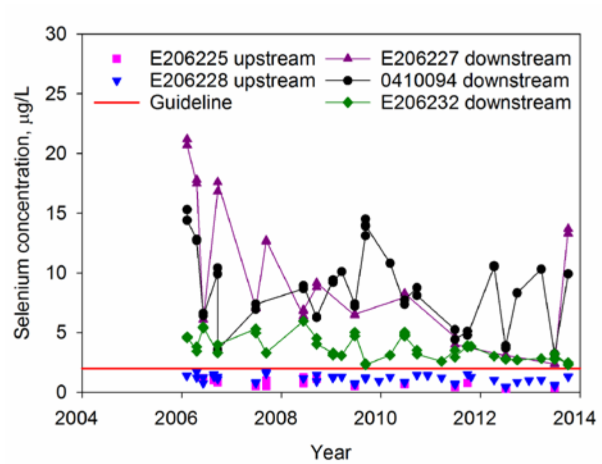

Figure 2 Selenium concentrations at the two upstream stations: E206228 and E206225, and three downstream stations: E206227, 0410094, and E206232, with increasing distance from the mine

Selenium loads discharged at SP-2

The mine has been discharging selenium to the receiving waters via SP-2 in the post-closure phase. Figure 3 plots selenium levels in the three sedimentation ponds over the study period. There has been no direct discharge to the receiving waters from SP-1 and SP-3, and selenium concentrations in these two ponds remained relatively constant over the study period. Selenium levels in SP-2 did not show any noticeable trend. Under the Permit requirements, consistent monitoring in SP-2 was required for June that represents the high-low period and September that represents the low-flow period, even though occasional monitoring was carried out for other months. The seasonality in weather patterns is characterized by a spring freshet (early May to June), declining summer flows, fall low flows typically occurring in September or October, and extreme low flows during the winter (Butcher 1987b).

Considering seasonal weather patterns, attempts were made to separate concentration data into individual months. Figure 4 (A) shows selenium concentrations for individual months together with average monthly drainage flow rates at SP-2. The drainage flow pattern, monitored in 2013, reflected the weather pattern, with June having the highest flow and September being the low flow period. The average monthly selenium loads discharged at SP-2 were determined by multiplying average monthly selenium concentrations, i.e., the average of all available concentration data for a particular month over the study period, by corresponding average monthly drainage flow rates. The distribution of average monthly loads were then calculated, which was shown in Figure 4 (B). There was a significant correlation between monthly selenium loads distribution and drainage flow rate. June, with the highest drainage flow rate, was the month that SP-2 discharged the highest percentage of selenium (65%). Even though selenium concentration in September was high (Figure 4 (A)), the percentage of selenium loads discharged in September was minimal due to the very low drainage flow rate. These results demonstrated the importance of accurate and consistent monitoring of drainage flow rate in selenium loads calculation.

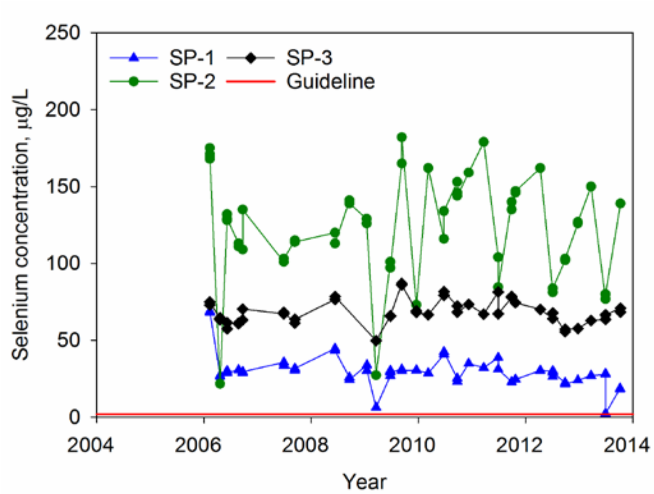

Figure 3 Selenium concentrations at the three sedimentation ponds: SP-1, SP-2, and SP-3

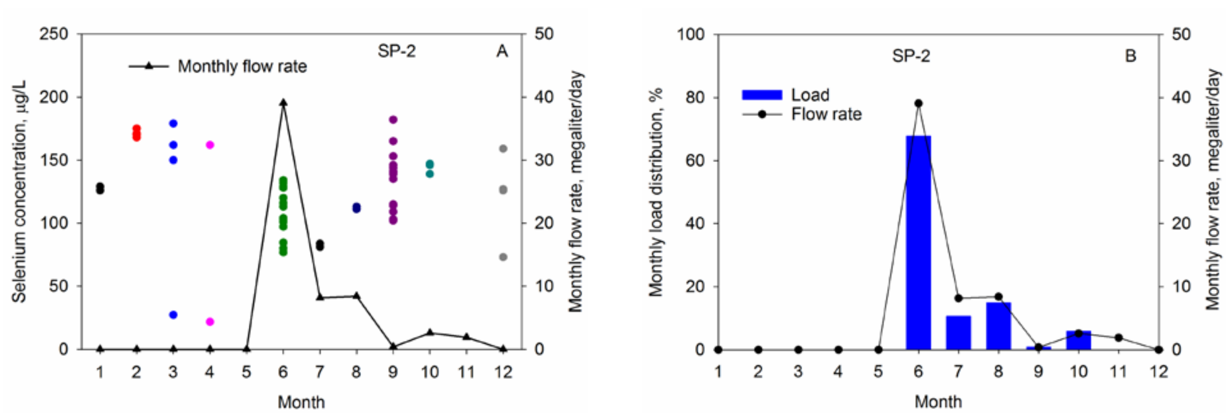

Figure 4 (A) Selenium concentrations for individual months and average monthly drainage flow rates at SP-2; (B) Selenium monthly loads distribution at SP-2

Selenium loads discharged in June seemed to show a slight downward trend (Figure 5). The exact cause of this decrease was unknown. It could result from certain closure practices that reduce selenium release from the source, i.e. waste rock. It could also be a result of water management practices, such as the development of vegetated wetlands on the mine (Davies 1995), which are capable of significantly removing selenium from water (Lin et al. 2002, Zhang and Moore 1996). A minimal amount of selenium was discharged in September and no trend in selenium loads was identified with this month.

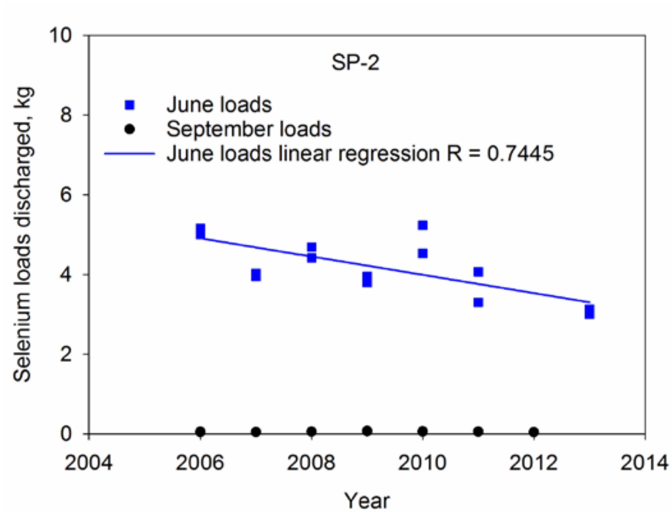

Figure 5 Selenium loads at SP-2 in June and September over the study period

Selenium loads and concentrations at the receiving stream

Figure 6 (A) shows selenium concentrations in the receiving Bullmoose Creek at E206232 for individual months together with average monthly stream flow rates. As required by the Permit, June and September have the most frequent monitoring events. Similar to SP-2 (Figure 4 (A)), the stream flow pattern reflected the seasonal variation of weather, with June having the highest stream flow and September being the stream low-flow period. Figure 6 (B) shows that there was a strong correlation between selenium loads received by the stream and stream flow rates. The highest percentage of selenium loads, i.e., 70%, was received in June, the high-flow period. This was in agreement with the loads distribution of SP-2, which showed that the highest percentage of selenium loads was discharged to the receiving stream in June (Figure 4 (B)). Compared with SP-2 (Figure 5), a similar slight downward trend was also observed with the stream selenium loads received in June (Figure 7). There was a minimal amount of selenium received by the stream in September (Figure 7), corresponding to the minimal amount of selenium discharged at SP-2 in September (Figure 5).

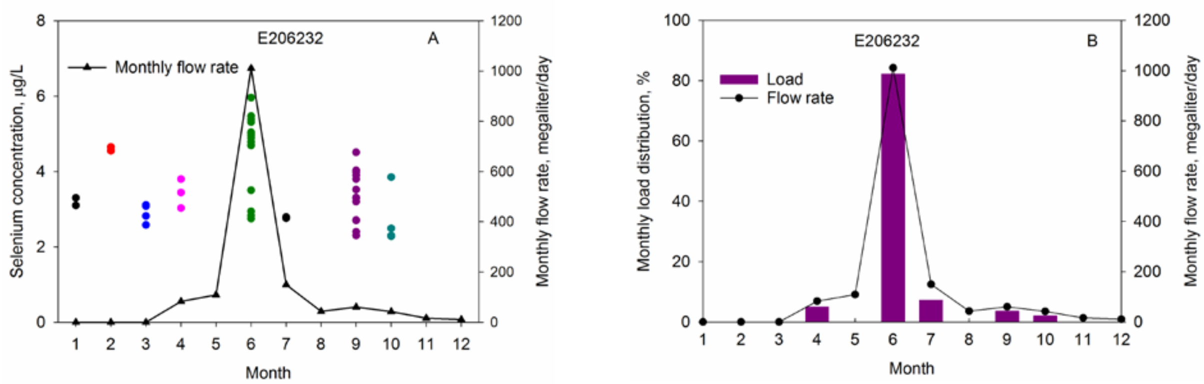

Figure 6 (A) Selenium concentrations for individual months and average monthly stream flow rates at E206232; (B) the distribution of selenium loads received at E206232

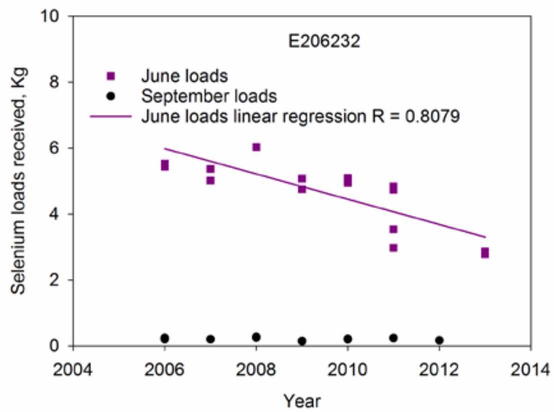

Figure 7 Selenium loads received at E206232 in June and September over the study period

To test whether stream selenium levels can be predicted simply by combining selenium loads discharged at SP-2 and stream dilution, a mass balance calculation was carried out based on the assumption that dilution is the only factor that determines stream selenium levels. This calculation was done for June that represents the high-flow period and September that represents the low-flow period. The predicted concentrations were then compared with the actual monitoring data (Figure 8). Even though for June the predicted concentrations did not exactly fit with the actual monitoring data, the results were satisfactory in indicating that dilution was the major factor in controlling stream selenium levels in the high-flow period. However, for September the actual monitoring data were significantly higher than the predicted ones. This poor fitting implied that in this low-flow period, dilution was not the controlling factor that determined stream selenium levels. Instead, hyporheic exchange could have occurred in this low-flow period that increased selenium levels via processes such as desorption (Oram et al. 2010). Therefore, careful monitoring of selenium levels in this low-flow period is particularly important in assessing the ecological risk of selenium pollution.

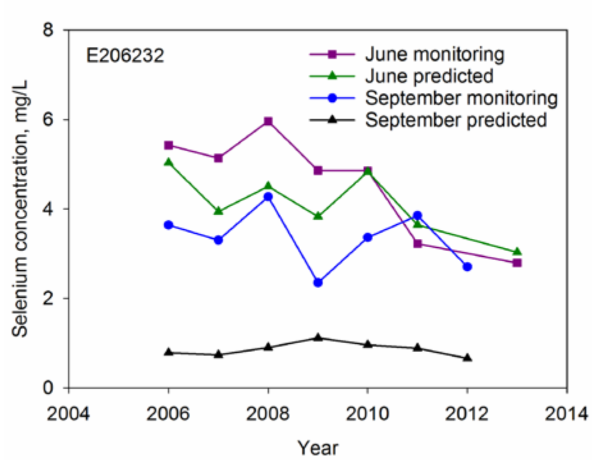

Figure 8 Comparison of predicted stream selenium concentrations with the actual monitoring data for June and September

CONCLUSION

Selenium loads and concentrations at the point of discharge and in the receiving stream in the post-closure phase of the Bullmoose mine were analyzed. Selenium levels in the receiving Bullmoose Creek downstream of the mine exceeded the current applicable water quality guideline of 2 µg/L over the study period. The highest proportion of selenium loads was discharged at the sedimentation pond SP-2 in June due to the very high drainage flow rate in this month. Selenium loads discharged at SP-2 in June showed a slight decreasing trend, but the reason for the decrease was unclear. Selenium loads discharged at SP-2 in September was minimal due to the very low drainage flow rate in this month. Correspondingly, the Bullmoose Creek received the highest proportion of selenium in June high-flow period and a minimal amount in September low-flow period. Selenium loads received by the stream in June also showed a slight downward trend. Dilution was thought to be the major factor in determining selenium levels in the receiving stream in the high-flow period. Even though selenium loads received in September was minimal, special care should be taken to monitor stream selenium levels in this low-flow period due to low dilution and possible selenium desorption via hyporheic exchange. Further research should be carried out to confirm the decreasing trends observed in selenium loads discharged in June and correlate these trends with release rates at sources of selenium and with changes in mine closure and water management practices. Building these correlations will provide insights into closure practices that minimize contaminant release from sources and water management practices that ameliorate selenium levels in water.

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