

**IMPACT OF MINE DRAINAGE AND DISTRIBUTION OF METAL LOADING
SOURCES IN THE JAMES CREEK WATERSHED
ASSESSED UNDER LOW-FLOW CONDITIONS**

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Abstract

Increasing environmental awareness over the past several decades has led to widespread concern about the adverse effects that heavy mining has had on the environment. These effects are felt particularly in the form of water contamination from acid mine drainage and metal dissolution from mining waste rock. The goal of the current study was to assess these effects on the James Creek watershed located in northwestern Boulder County, Colorado, where mining was prevalent from the 1850s – 1980s. Specifically, a conservative chloride tracer was injected in two adjacent reaches of James Creek in order to quantify stream discharge, and synoptic samples were taken to identify the sources that of metal and acid contamination in the creek and to quantify the loading of these metals. The results of this study suggest that there are several metal sources along the stretch of the Upper James Creek, including significant sources from the Fairday Mine area, an unidentified zinc source at about 2.7 km downstream of the injection, and a major metal source near the treatment plant. The Little James Creek, in addition to another metal source located 4.5 km downstream of the injection, are the two major metal contributors in Lower James Creek. Our results may be somewhat limited in identifying all potential contamination sources in James Creek because of the low flow conditions in the creek when our experimentation was carried out. Finally, our results suggest that the effects of metal loading in the creek are spatially restricted by precipitation of metals.

Introduction

The environmental health of historically mined areas is significantly threatened by the process of acid mine drainage and the resulting water contamination poses a problem for both aquatic life and human drinking water. Acid mine drainage occurs when rocks containing sulfide minerals from mines or tailings piles interact with air and water to produce sulfuric acid. The production of sulfuric acid not only creates acidic conditions in the surface or groundwater into which the sites drain, but it also causes the dissolution of heavy metals from waste rock, which can also contaminate the water [Drever, 1997].

The watershed of interest in this study is the James Creek watershed, encompassing about 48 km² in northwestern Boulder County, Colorado. The James Creek watershed contributes directly to the water supply for Jamestown, Colorado, a town of approximately 250 residents, and includes the James and Little James Creeks. James Creek is a tributary of Lefthand Creek, and is thus considered to be a part of the Lefthand Creek watershed. Therefore, water quality concerns are not only relevant to the 250 residents of Jamestown, but also to all 14,000 residents in the Lefthand Creek watershed [Duren et al., 2001].

The area around the James and Little James Creeks is typically referred to as the Golden Age Mining district, where mining for gold, silver, lead, fluorspar, and uranium took place from the 1850s – 1980s [Duren et al., 2001]. Metal contamination in the James Creek watershed was discovered when, in response to the Clean Water Act, Section 303(d), states were obligated to identify water bodies with poor water quality and to propose standard contamination levels above which the concentrations could pose a threat to either aquatic or human well being. The Little James Creek was on the 1998 list for Colorado as not being in attainment for pH and metal concentrations. Although James Creek was not included on this list because tests revealed it was in attainment, it is still worthwhile to study in order to fully understand the affects the Little James Creek has on James Creek after their confluence [Colorado Water Quality Control Division, 2002].

Two portions of James Creek are under consideration in this study. The first is the 5 km stretch starting at the road crossing upstream of John Jay Mine and ending at the Jamestown water treatment plant (JWTP); the second portion is the 5 km stretch starting at the JWTP and ending at the confluence of James Creek with Lefthand Creek. For the purpose of this study, these two stretches of creek will be referred to as the Upper James Creek and the Lower James

Creek, respectively. The land adjacent to Upper James Creek contains several mining areas, as well as a tailings pile near the JWTP. The two mining areas along the Upper James Creek are John Jay mine and Fairday Mine. The land adjacent to Lower James Creek is used mostly for residential purposes. There are no mines located in the immediate vicinity of the creek, but there is an old tailings pile that is now the site of Elysian Park, the town park. Another site of interest along this section of creek is Curie Springs, located downstream from Jamestown, where uranium rich water was bottled for medicinal purposes as late as the 1950s. We are interested in these areas, as well as any other inflowing water sources, to see if they contribute significantly to metal concentrations in the creek.

In order to fully understand the effects of metal contamination, it is necessary to measure metal loading. Metal loading rates (mass per time) are calculated as the product of metal concentrations (mass per volume) and stream discharge rates (volume per time). Typically, discharge has been measured using the cross-sectional area of the stream and a flow meter to measure water velocity [Kimball, 1997]. However, flow meter measurements underestimate stream discharge because they cannot account for water flow through streambed sediments and cobbles. Such an underestimation would also lead to error in the calculation of metal loading rates. Therefore, an alternative method has been devised to mitigate this error [Kimball, 1997; Kimball et al., 2001a; Kimball et al., 2001b].

Experiments involving injections of conservative tracers (e.g., sodium chloride) and synoptic sampling over the reach of the stream affected by mine drainage produce more accurate calculations of stream discharge and more precisely identify potential sources of contamination [Kimball, 1997; Kimball et al., 2001a; Kimball et al., 2001b]. These methods have been successfully employed in studies examining the effects of acid mine drainage on the water quality in Cement Creek (Colorado) and in Little Cottonwood Creek (Utah) [Kimball et al., 2001a; Kimball et al., 2001b]. We also anticipated that the use of a tracer injection and synoptic sampling in our study would help identify less obvious contamination sources, such as contaminated groundwater, which cannot be seen by observing surface runoff or seepage into the creek.

The objective of this study is to (1) identify the sources that might be responsible for metal and acid contamination in the creek and (2) quantify the amount of metals being introduced into the each reach of James Creek. This knowledge is important not only for the

consideration of the effects of metal contamination on aquatic life and human drinking water, but it is also important to determine if the James Creek watershed should be included on the U.S. Environmental Protection Agency's National Priority List for remediation under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA; i.e., the "Superfund" list).

Methods and Materials

Field Experimentation

The methods used to evaluate metal contamination in the each reach of James Creek were adapted from previous tracer injection and synoptic sampling experiments performed by Kimball et. al.. To measure stream discharge, a conservative tracer (chloride) was injected above the JWTP and monitored just upstream of the confluence of James Creek with Lefthand Creek. To measure metal loading, the stream was sampled at intervals of about 200 m while the injected tracer concentration was on its plateau.

In the first part of the experiment, a 3 M solution of NaCl (concentration determined experimentally) was injected into Lower James Creek for 3 hours and 15 minutes (from 10:45 am until 2:00 pm). The injection solution was prepared in 2-44 gallon trashcans using 80 lbs. NaCl in approximately 40 gallons of water for each barrel. After stirring the solutions for about 30 minutes, excess NaCl was removed from the barrels. During the injection experiment, six samples were taken of the injection solution (three from each barrel), in order to accurately determine its concentration. The second barrel of injection solution was determined to be at a slightly higher concentration than the first. Therefore, chloride concentrations of samples taken when the solution from the second barrel was in the stream were corrected to the concentration of the first barrel (3 M).

The 3 M NaCl solution was injected into Lower James Creek at a rate of $1.26 \text{ L}\cdot\text{min}^{-1}$; monitoring of the pump throughout the injection ensured the pump rate remained constant. Over the course of the injection, six water samples were taken upstream of the injection site in order to determine the background concentration of chloride in James Creek.

There were two sites on the Lower James Creek where water samples were collected in order to monitor the chloride tracer concentration as a function of time. The upstream monitoring site was located about 107 m downstream from the injection, just upstream from the

confluence of the Little James and James Creeks. The downstream monitoring site was located 5212 m downstream from the injection site, just upstream from the confluence of James Creek with Lefthand Creek. At the upstream site, samples were taken every minute during the leading and trailing edges of the tracer concentration, and were taken approximately every thirty minutes while the tracer concentration was on its plateau. At the downstream monitoring site, samples were taken approximately every five minutes for the duration of the experiment.

In the second part of the experiment, water samples were taken at synoptic sample sites located 200 m apart over the stretch of the creek. In order to better bracket the area around Elysian Park, synoptic samples in this area were taken at intervals of 100 m. Figure 1 shows a map of where synoptic samples were taken along the stretch of Lower James Creek. An ion specific electrode (ISE) with chloride probe was used to monitor the relative change in chloride concentrations at the upstream and downstream monitoring sites in order to determine when the plateau had been reached. Once the plateau was reached at the downstream sample site, synoptic sampling began along Lower James Creek. In addition to synoptic samples, four potential inflowing water sources were sampled for metal analysis. Two of the sampled inflows appeared to be gulches flowing into Lower James Creek, most likely the Buffalo and Castle Gulches. The third inflow was sampled from ponds located in the vicinity of Curie Springs. The final inflow was a ground water source located across the road from the creek that could potentially affect the Lower James Creek by flowing under the road toward the creek.

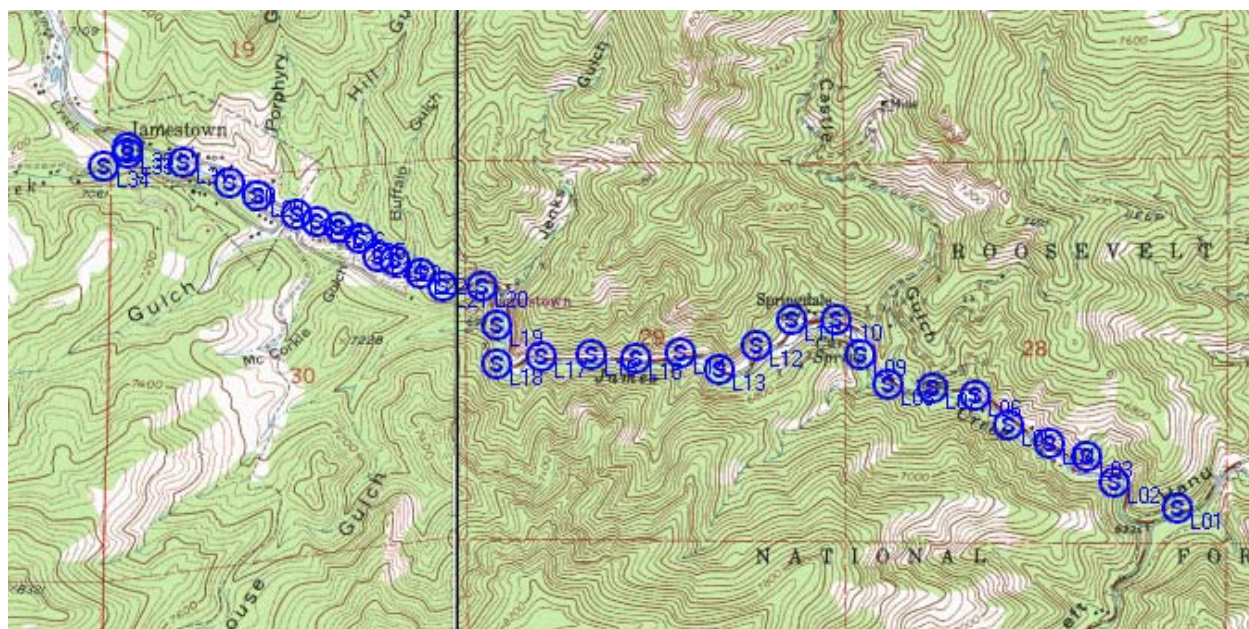
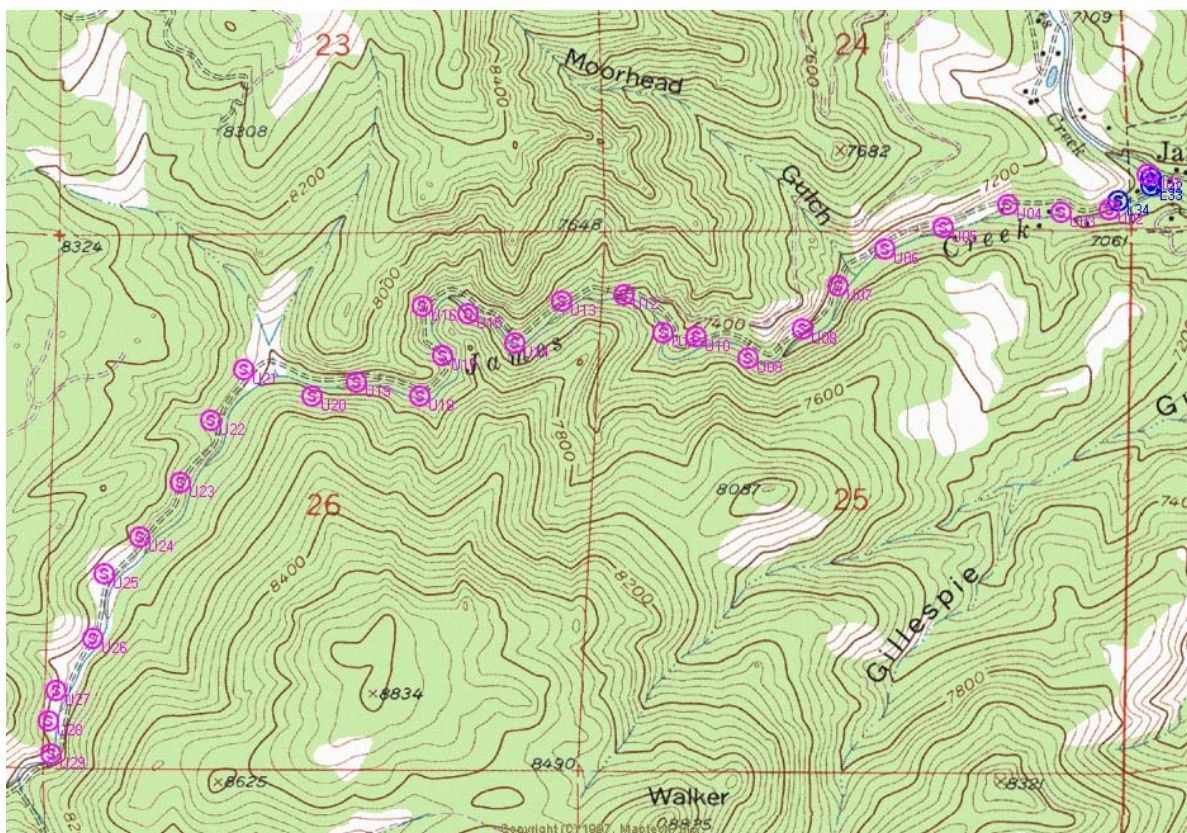


Figure 1 – Map of Synoptic Sample Sites along the Lower James Creek

A similar procedure was used for the Upper James Creek, as well. A 6.2 M NaCl solution was injected into the upper stretch at a rate of $0.82 \text{ L} \cdot \text{min}^{-1}$ for 4 hours and 20 minutes. The chloride tracer concentration was monitored as a function of time at two stations downstream of the injection. The upstream site was located at approximately 90 m downstream of the injection, and the downstream sampling site was located at 4940 m downstream of the injection, at the JWTP. Sampling rates are similar to those of the Lower James Creek portion.

Synoptic samples were also taken at approximately every 200 m along the entire stretch. . Figure 2 shows a map of where synoptic samples were taken along the stretch of Lower James Creek. Colorimeters were used to monitor the relative change in chloride concentrations at the upstream and downstream monitoring sites in order to determine when the plateau had been reached. Once the plateau was reached at the downstream sample site, synoptic sampling began along Upper James Creek. In addition to synoptic samples, two potential inflowing water sources were sampled for metal analysis. These inflows were located at the Fairday Mine tributary and at a stagnant pond at John Jay Mine.



Laboratory Analysis

For analysis of chloride concentrations of samples taken in the field, an ISE with chloride probe was used to make concentration measurements. Chloride concentrations were measured for the samples taken at each chloride monitoring site, for all synoptic samples, for the samples taken of the injection solutions and for the samples taken upstream of the injections. In addition to chloride measurements, pH was also measured on the synoptic samples.

Metal analysis, which included measurement of both total and dissolved metal concentrations, was performed on the 34 synoptic samples and the 4 samples taken of potential inflowing water sources for Lower James Creek, and on the 29 synoptic samples and the 2 samples taken of potential inflowing water sources for Lower James Creek. The total metal samples were prepared by acidifying the samples with 2-3 drops of trace metal grade nitric acid (HNO₃, VWR). The dissolved metal samples were prepared by first filtering through a 0.2 µm cellulose acetate membrane and then acidifying with 2-3 drops of trace metal grade HNO₃. Both total and dissolved metal samples were analyzed for concentrations of Al, Cu, Fe, Pb, Mn, U, and Zn using Inductively Coupled Plasma – Mass Spectrometry (ICP-MS).

Calculations

The chloride concentration results for the synoptic samples were used to calculate stream discharge at each sample site. Stream discharge was calculated according to the following equation:

$$Q_{AB} = \frac{C_i Q_i}{C_B - C_A} \quad (1)$$

where Q_{AB} is the stream discharge (L/s) between sampling points A and B, Q_i is the injection rate (L/s), C_i is the injection chloride concentration (mol/L), C_A is the upstream chloride concentration (moles/L), and C_B is the chloride concentration at downstream site B (moles/L).

Metal loading was calculated according to the method described earlier:

$$M_B = C_B Q_{AB} \quad (2)$$

where M_B is the metal loading of a particular metal at synoptic sample site B, C_B is the metal concentration of a particular metal at synoptic samples site B and Q_{AB} is the stream discharge between the upstream sample site and sample site B.

Results

Results from Chloride Analysis

The purpose of monitoring chloride concentrations at the upstream and downstream sites was (1) to calculate the travel time of the tracer (2) to ensure that the synoptic samples were taken while the concentration of the tracer had reached a plateau throughout the creek. The results of the chloride sampling for James Creek (Figure 3) show that the tracer arrived very quickly at the upstream sampling site, but took between two and a half hours and three and a half hours to reach the downstream monitoring site. This rate at which the tracer moved in the stream was determined by observing the time difference between the arrivals of the tracer at the two monitored sites, and was calculated to be 0.60 m/s for Lower James Creek and 0.40 m/s for Upper James Creek.

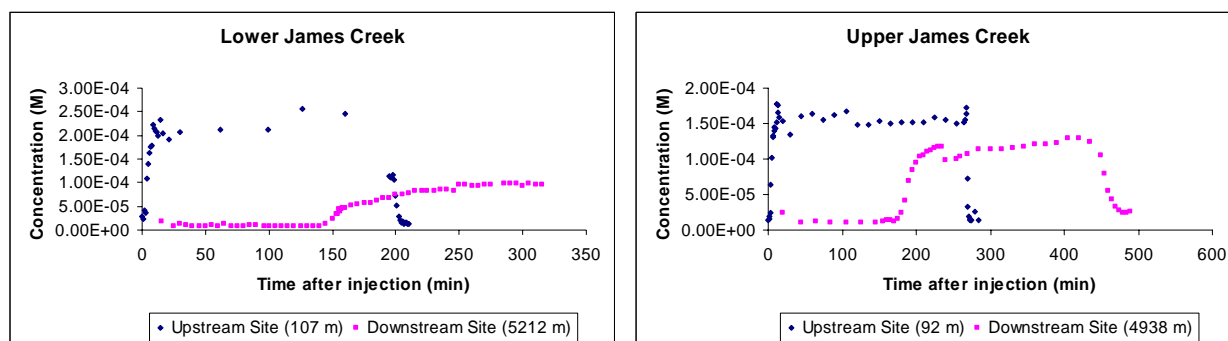


Figure 3 – Chloride concentration as a function of time

Abnormal weather conditions in the months leading up to our experiment, including a mild winter and a summer drought, caused the stream flow in James Creek to be much lower than normal. Due to the underestimation of travel time, the trailing edge of the tracer was not observed by samples taken at the downstream sampling site. However, it is clear from Figure 3 that a distinct concentration plateau was reached at the downstream monitoring site, and it was during this time that synoptic samples were taken.

Under normal conditions, the tracer concentration should decrease between upstream and downstream sample sites due to inflowing water sources. This behavior is exhibited in Figure 4 for the Upper James Creek. However, the chloride concentrations measured for our synoptic samples did not reflect this dilution for the Lower James Creek because most of the potential inflow sources had dried up as a result of the drought. The measured concentrations were

relatively stable however a jump in chloride concentration was observed for sites after 1800 m downstream from the injection sites. Data obtained from chloride analysis of the synoptic sample site was used to calculate stream discharge at each sample site, according to Equation 1. Because there were no significant inflowing water sources along the stretch of the Lower James Creek, an increase in stream discharge was not observed as a function of distance downstream.

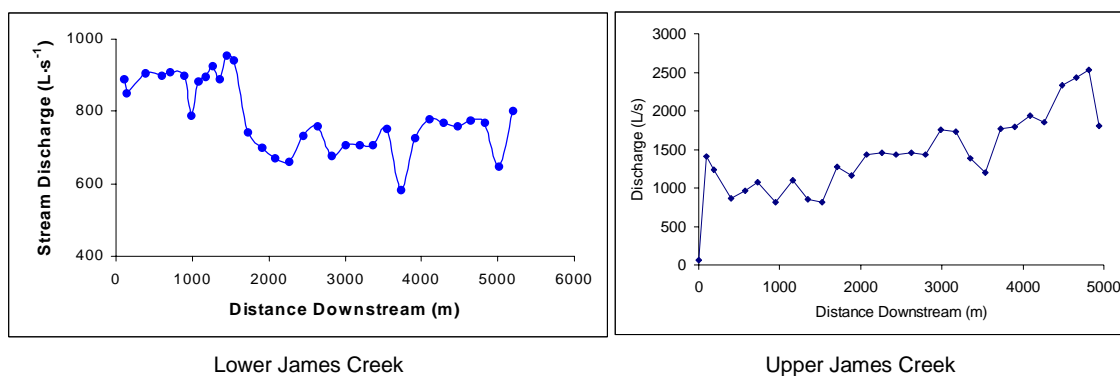


Figure 4 – Results of chloride concentration measurements taken of the synoptic samples

Results from Metal Analysis

The results of metal analysis reported directly from the ICP-MS were in terms of metal concentrations for both total and dissolved metal types. For the purpose of further metal analysis, the concentration of colloidal metal was taken to be the difference between the total and dissolved metal concentrations. Concentrations for each of the three metal types are shown in Figure 5 as a function of distance downstream from the injection, for all of the metals analyzed except for zinc in Lower James Creek. There was some question about the validity of the measurements made for zinc, and they are therefore omitted from the results for the lower portion of the creek. Also shown on the graphs are the ICP-MS detection limits for each metal. For those samples with metal concentrations below the detection limit of the instrument, the concentrations were taken to be the concentration of that metal at its detection limit.

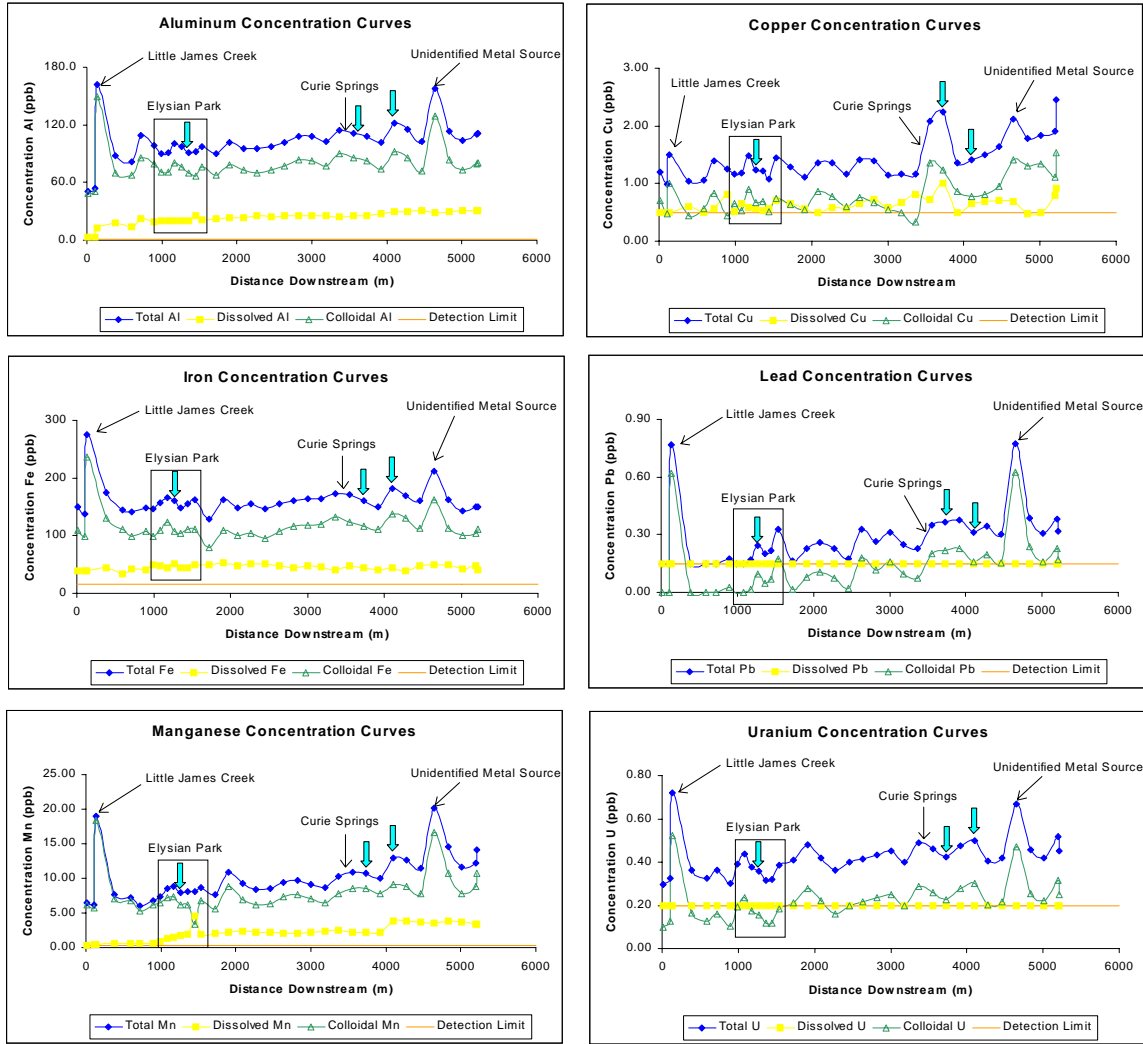


Figure 5a: Metal Concentration Curves from synoptic samples in Lower James Creek: Samples taken around the park area enclosed in the rectangle, black arrows point to significant geographical areas (Little James Creek, Curie Springs, and an unidentified metal source), and the green arrows point to sites just downstream from the three remaining inflows were sampled.

It is important to note that because the dissolved metal concentrations are relatively constant at all the synoptic sample sites, the shape of the colloidal metal concentration curve greatly resembles the total metal concentration curve. The geographical significance of trends observed on the metal concentrations curves will be discussed in further detail in the section addressing metal loading. The results for metal concentration and metal loading were very similar in nature, and it is more useful to consider the impacts of the metals on the stream from the standpoint of metal loading.



Figure 5b: Metal Concentration Curves from synoptic samples in Upper James Creek: Green arrows point to sampled inflows (John Jay Mine, and Fairday Mine).

Discussion

Metal Loading

Metal loading graphs (Figure 6) were generated for aluminum, copper, iron, lead, manganese, zinc, and uranium according to Equation 2, using the measured metal concentrations and stream discharge rates at each synoptic sample site. The accumulation curves are included on the graphs in Figure 5 first, to identify points along James Creek where significant increases in metal loading were observed, and second, to help illustrate the total amount of metal that accumulates over the stretch of the creek. It is important to note that not all of the accumulated metals remain in the water for the entire stretch of the creek, because some metals are being removed through attenuation.

The graphs in Figure 6a emphasize that there are two distinct spikes in metal loading along Lower James Creek shared by all six metals. The first spike occurred just downstream from the confluence of Little James Creek with James Creek, and the second spike was observed about 4.5 km downstream from the injection site. The source of this spike is at this point unidentified, but appears to be a significant metal contributor.

Samples taken from Lower James Creek in the region that bracketed Elysian Park did not contain as much metal loading as was expected prior to experimentation. Increases in the metal loading of aluminum, iron, manganese, and uranium in this area were relatively small. However, more significant increases in metal loading of copper and lead are seen at sites adjacent to the park. The left over tailings pile could be the cause of these observed metal loadings in the Lower James Creek.

The only other significant spike in metal loading was observed for copper in the vicinity of Curie Springs. It was surprising that a corresponding increase in uranium loading was not also observed, given the past use of the land. With respect to the remaining sampled inflow sites, they do not appear to have contributed significantly to metal loading. With the exception of copper, the other metals do not see any significant increases in metal loading between 500-4000 m and any observed variations in metal loading within this stretch of stream were relatively small. It is interesting to note that sites where an increase in metal loading was observed were generally followed decreased metal loading at sites immediately downstream.

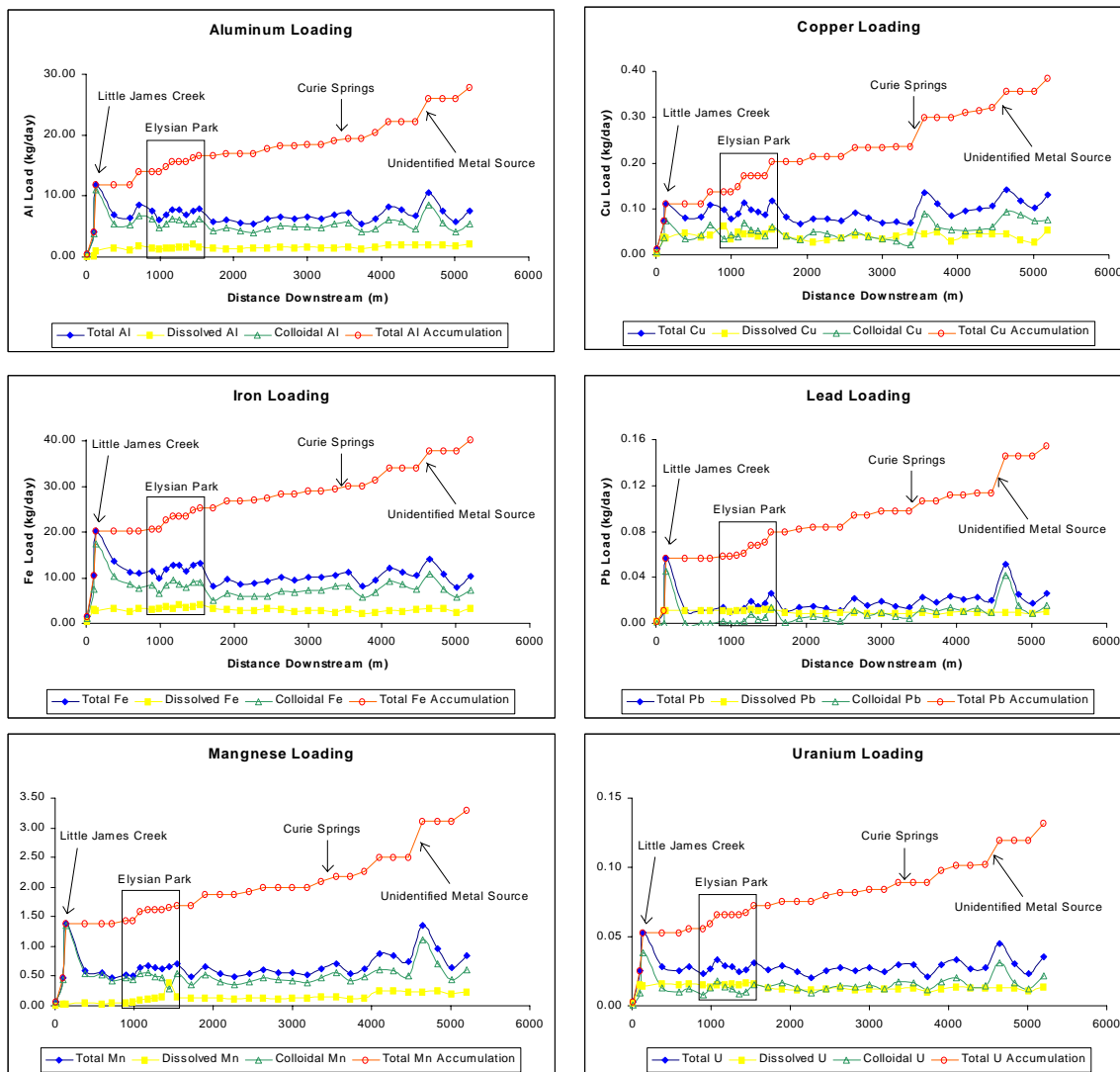


Figure 6a – Metal Loading and Accumulation Graphs (Lower James Creek) – Metal loading curves for total, dissolved, and colloidal metals are given in blue, yellow, and green, respectively. Metal accumulation graphs, generated by adding all the consecutive increases in metal loading, are shown in red.

The graphs of Figure 6b emphasize the metal loading of Upper James Creek. All seven metals observed shared a significant spike near sampling site 3. This site is located near the JWTP, and could potentially be produced by the tailings pile north of the JWTP on a nearby hill. Surprisingly, there is no evidence of metal loading from the John Jay Mine site, as there is no spike in the graphs at this location. However, uranium, copper, and lead all exhibit an increase in load near the confluence of Upper James Creek and the Fairday Mine tributary. Interestingly, the concentrations of copper and lead are very low in the influent samples collected. These metals are most likely introduced by a groundwater source separate from the influent tributary.

The only other significant metal loading source is between sites 13 and 14, at 2.7 km downstream of the injection. This location sees a significant loading of zinc, with no obvious source.

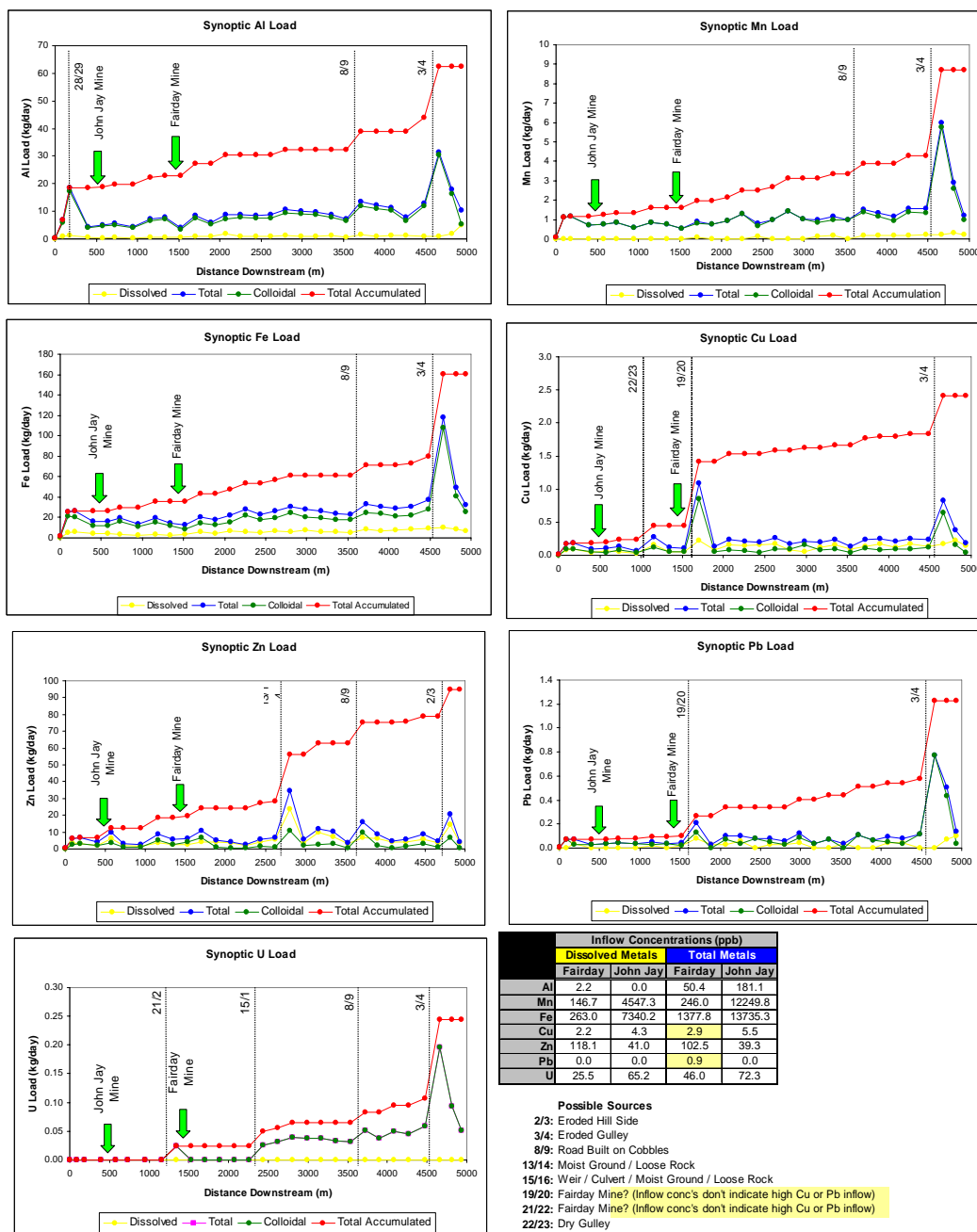


Figure 6b – Metal Loading and Accumulation Graphs (Upper James Creek) – Metal loading curves for total, dissolved, and colloidal metals are given in blue, yellow, and green, respectively. Metal accumulation graphs, generated by adding all the consecutive increases in metal loading, are shown in red.

Evidence of Precipitation

The observed decreases in metal loading that usually accompanied any observed increases in loading suggested that precipitation of metals into the stream sediments might be happening. In order to determine if this process could possibly have taken place, an area of stream about 4.5 km downstream from the injection of the Lower James Creek (where the unidentified spike in metals was observed) was examined for evidence of precipitation. Figure 7 shows pictures of the streambed taken in this vicinity. Picture (b), taken just downstream from the observed spike in metals, appears to have distinctly lighter sediment than sites examined either upstream or downstream from this location (pictures (a) and (c), respectively). This could be visible evidence of aluminum precipitation into the creek. Although other metals could not be observed visibly for precipitation, it is reasonable to conclude that the reason the metal loading decreases downstream from this site is the result of precipitation. This assumption could also hold for other areas of the Lower James Creek where increased metal loading is immediately followed by decreased metal loading.



Figure 7 – Evidence of Precipitation: Pictures show a progressive downstream view of stream around the unidentified metal source about 4.5 km downstream from the injection site; (a) was taken upstream from the source, (b) was taken downstream from the source, where precipitation was expected to be taking place, and (c) was taken downstream of where the decrease in metal loading was observed.

Conclusions

The Fairday Mine area, the unidentified zinc source at 2.7 km downstream of the upper injection, and the tailings pile near the JWTP appear to be the primary sources of metals in Upper James Creek. The Little James Creek and the unidentified inflow located about 4.5 km downstream from the lower injection site appear to be greatest sources of metal loading into Lower James Creek. The effects of metals entering the creek at these and other inflows are

spatially controlled as a result of metal precipitation. It is surprising that Elysian Park and John Jay Mine were not as significant as metal contributors as was expected prior to experimentation. This does not mean that the reclaimed tailings area and the mine do not pose a threat as metal sources to James Creek. Our results may be limited in identifying all contributing metal sources due to the extremely dry conditions under which the experiment was carried out.

At this point, it is too early to recommend appropriate remediation efforts for the James Creek watershed, but future research will contribute even more knowledge about the sources and consequence of metal loading in the James Creek watershed. Current research in the watershed includes conducting similar tracer on the Little James Creek when flow conditions will permit, and sedimentation analysis to study the attenuation phenomenon. The results from this would provide more complete picture about the effects of mining on water quality in the James Creek Watershed.

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