Use of Tracer-Injection and Synoptic-Sampling Studies to Quantify Effects of Metal Loading from Mine Drainage

By Briant A. Kimball, Robert L. Runkel, Kenneth E. Bencala, and Katherine Walton-Day

ABSTRACT

Thousands of abandoned and inactive mines are located in environmentally sensitive mountain watersheds. Cost-effective remediation of the effects of metals from mining in these watersheds requires knowledge of the most significant sources of metals. The significance of a given source not only depends on the concentration of a toxic metal, but also on the total mass of metal added to streams. To determine loads, we combined tracer-injection methods, to provide reliable discharge measurements on a watershed scale, with synoptic sampling, to provide spatially detailed concentration data. The resulting load profiles indicate which sources have the greatest impact on streams, where the streambed will receive metal precipitates, and where ground-water inflows are the greatest. This information is an important part of planning for remediation.

INTRODUCTION

Thousands of abandoned and inactive mines are located in environmentally sensitive mountain watersheds. Cost-effective remediation of the effects of metals from mining in these watersheds requires science-based knowledge of metal sources, transport, and effects. Regulatory and land management agencies need the answers to some basic questions to plan cost-effective remediation. First, which sources of mine drainage in a watershed have the greatest effect on the stream? Second, what natural processes or instream chemical reactions move metals from the water column to the streambed where the metals can affect aquatic organisms? Finally, does a remediation plan for an individual site need to account for the complexity of surface- and ground-water sources of metals?

The purpose of this discussion is to present an approach that represents a practical application of the research methods and models that have been developed as part of the Upper Arkansas Surface-Water Toxics Project as part of the Toxic Substances Hydrology Program. A recent study in Cement Creek, Colorado, a tributary of the Animas River, illustrates the approach used to provide pre-remediation information as part of the Abandoned Mine Lands Initiative. Because Cement Creek receives mine drainage from many sources in the watershed it is a good watershed to demonstrate the complexity of mine-drainage inflows and the availability of solutions (fig. 1).

AN APPROACH FOR MOUNTAIN STREAMS

Because of the work of many local, State, and Federal agencies, much is known about the location and chemical character of mine drainage in the Western United States. Information about individual mines can indicate potentially toxic sources of metals to streams but does not necessarily provide the complete picture for making decisions about remediation on a watershed scale. The complete picture of the effects of metals on a stream is not just the metal concentration, which directly relates to acute toxicity, but also the metal load, which relates to chronic toxicity. Calculating load

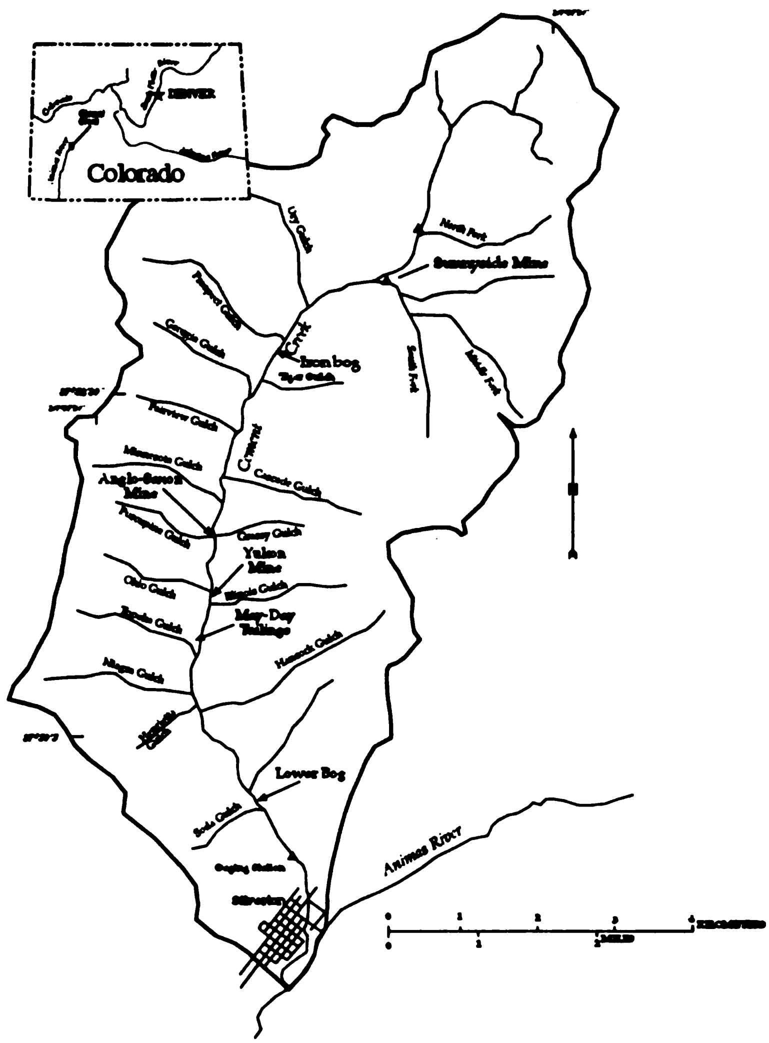

Figure 1. (a) Schematic watershed views showing (a) data collection at the watershed outlet verses (b) the detail of information needed for remediation decisions.

requires both chemical concentrations and discharge. Discharge measurements in mountain streams, however, are difficult, even under the best of conditions, because much of the flow in mountain streams is among the streambed cobbles. The Cement Creek study illustrates the combination of a tracer-dilution study for discharge determinations, with synoptic sampling for detailed chemical composition of stream and inflow sites. Synoptic samples are provide a "snapshot" of the changes along a stream at a given point in time.

Adding a tracer: Discharge by dilution

Discharge in mountain streams can be measured with good precision by adding a conservative dye or salt tracer to a stream and calculating discharge from the amount of dilution as the tracer moves downstream (Bencala and others, 1990; Kimball, 1997). Because we know the concentration of the injected tracer and the rate at which it is added to the stream, we know the mass added to the stream (Zellweger and others, 1988). By using the conservation of mass, we can calculate the discharge by measuring the concentration of the tracer upstream and downstream from the injection point. A 12-kilometer reach of Cement Creek was separated into two separate injection reaches because there was active remediation at the Sunnyside Mine. A sodium chloride tracer was added upstream from the mine and a lithium chloride tracer was added

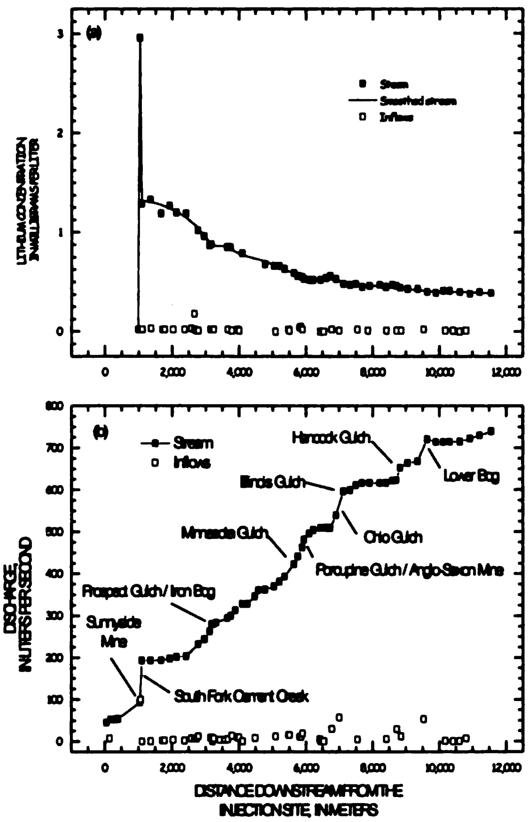

Figure 2. (a) Variation of lithium concentration with distance downstream from the injection site. The relatively low concentration of lithium in inflow samples indicates that lithium was an effective tracer.

downstream from the mine. After the tracers had reached a steady state along the stream reaches, synoptic samples were collected at sites downstream from the injection points to document the incrementaldecrease of tracer concentration due to water entering the stream (fig. 2a). The profile of lithium concentration allows the calculation of discharge at the synoptic sites (fig. 2b). With the tracer measurement, a change in discharge between two stream sites represents the total amount of water entering the stream from surface- and groundwater sources in that stream segment.

Synoptic sampling

Synoptic sampling includes both stream and inflow sites. Before the injection study, every visible inflow is identified for sampling. Stream sites for sampling are chosen upstream and downstream from each inflow, giving three points to make a mass-balance calculation for each inflow (points A, B, and I, fig. 3). Additional stream sites are chosen along the study reach to quantify ground-water inflows where there are no visible inflows (point C, fig. 3). Chemical analyses of synoptic samples provide a detailed profile of metal concentrations along the study reach.

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LOAD PROFILES: A "SNAPSHOT" IN TIME

Zinc concentrations of stream and inflow samples illustrate the spatial detail along the 12-

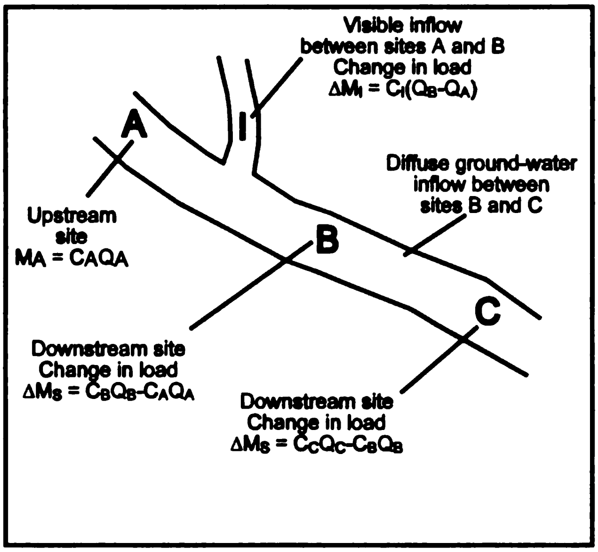

Figure 3. Schematic diagram showing mass-balance calculations around an inflow to a stream.

kilometer stream reach (fig. 4a). The instream concentration of zinc did not vary greatly, despite the large range of zinc concentration among the inflows. The profile of sampled instream load was calculated from the concentrations and the discharge values (fig. 4b). The profiles of concentration and load help answer the basic questions about the sources of metals and the effectiveness of remediation. First, although there are many sources of mine drainage, the principal sources are indicated by the sharp increases in the sampled instream load (fig. 4b).

Identifying important sources of metals

To rank the relative importance of the load from a particular stream segment or a group of stream segments requires another view of the load information. The net change in load between any two stream sampling sites can be positive, indicating an increase of load, or negative, indicating a loss through physical or chemical processes (fig. 3). The net change is:

Zinc concentrations of stream and inflow samples illustrate the spatial detail along the 12-kilometers stream reach (fig. 4a). The profile of sampled instream load was calculated from the concentrations and the discharge values (fig. 4b). The profiles of concentration and load help answer the basic questions about the sources of metals and the effectiveness of remediation. First, although there are many sources of mine drainage, the principal sources are indicated by the sharp increases in the sampled instream load (fig. 4b).

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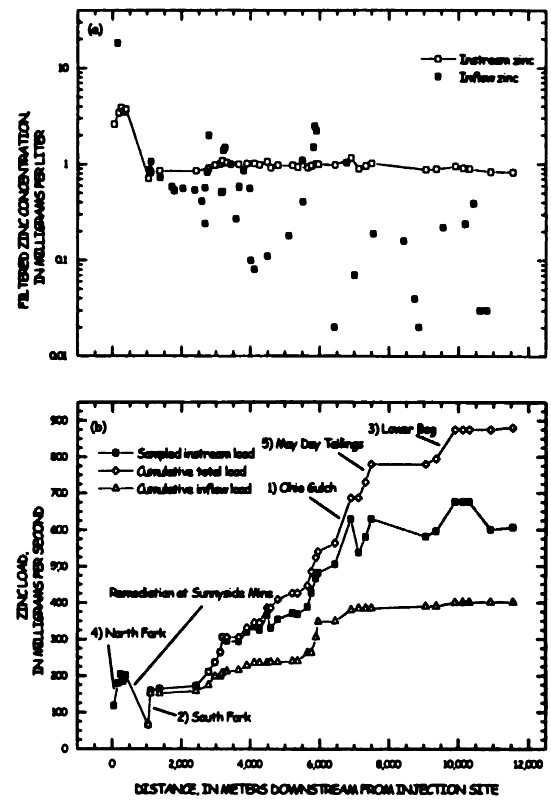

Figure 4. Variation of (a) zinc concentration and (b) zinc load with distance in samples from Cement Creek, Colorado. The five largest inflows are indicated by name and a number for its rank. The sampled instream load represents the calculated load at each stream site. The cumulative total load represents a summation of the entire load entering the stream. The cumulative inflow load represents the part of the total load that can be attributed to sampled inflows.

loss through physical or chemical processes (fig. 3). The net change is:

$$\Delta M_s = C_B Q_B - C_A Q_A \qquad (1)$$

where

ΔM_s is the net change in load for a stream segment, in milligrams per second,
C_B is the solute concentration at the downstream site, in milligrams per liter,
Q_B is the stream discharge at the downstream site, in liters per second,
C_A is the solute concentration at the upstream site, in milligrams per liter,
Q_A is the stream discharge at the upstream site, in liters per second.

Calculation of the minimum total load entering the stream along a study reach is the cumulative sum of all the positive values of for individual stream segments. The percentage of the cumulative total load that is contributed by any one segment is found by dividing the value of for that segment by the cumulative sum (fig. 4b). For example, the contribution from Ohio Gulch between 6,447 meters and 6,907 meters is about 14 percent of the cumulative total load. This calculation points out the five largest loads to Cement Creek (fig. 4b).

The sampled instream load also indicates the effectiveness of remediation at the Sunnyside Mine (fig. 4b). Almost all the zinc load that was present upstream from the mine was removed. The remediation decreased the zinc load that Cement Creek contributes to the Animas River, but substantial loads downstream from the Sunnyside Mine add a large zinc load.

The profile of sampled instream load indicates that there were many small sources of zinc load all along the study reach. All these relatively small sources add up to a substantial percentage of the cumulative total load. This "dispersed" loading complicates plans for remediation because even if the major sources can be controlled, the many small sources may still contribute too much zinc to allow adequate stream recovery. So a remediation plan for this stream would be immense. The load profile indicates that there may be some cost-effective targets for remediation that may decrease the input of zinc to the Animas River. This may be a more reasonable objective than trying to lower zinc concentrations to aquatic standards in Cement Creek itself.

Identifying effects on the stream

The difference between the sampled instream load and the cumulative total load indicates how much zinc was removed from the stream through chemical and physical processes (fig. 4b). If there were no instream losses of load, then the sampled instream load and the cumulative total load would be exactly the same. The two accounts of load only differ if there are stream segments with negative values of . Where the net change in load decreased, zinc was removed from the stream and added to the streambed. In those stream segments, metals should be more available to benthic invertebrates and the likelihood that metals enter the food chain is great. For example, between 6,907 meters and 7,131 meters downstream, a large amount of zinc was removed and there was visual evidence of the precipitate on the streambed. Stream segments where metals are added to the streambed will be the most affected parts of the stream.

Identifying ground-water inflow

A second way to view the net change in zinc load is possible if there is a sampled inflow in a stream segment. The change in mass can be expressed as:

$$\Delta M_I = C_I (Q_B - Q_A) \qquad (2)$$

where

ΔM_I is the net change in load for a stream segment, assuming that the inflow concentration represents the average concentration of water entering the stream in that stream segment,
C_I is the solute concentration in the inflow sample, in milligrams per liter, and

Q_B and Q_B are as defined previously. The cumulative sum of values is the cumulative inflow load and represents that part of the cumulative total load that can be attributed to sampled inflows (fig. 4b).

If C_I is an accurate representation of the concentration for all the water entering the stream in that segment, then ΔM_I will equal ΔM_S. If ΔM_S. is greater than ΔM_I, the difference between them may be due to the diffuse seepage of ground-water inflow. This could result from an average concentration of water entering the stream that is greater than the concentration sampled in the inflow. Although this is not proof of ground-water inflow, it indicates a likely source of ground water with a higher concentration entering the stream in that segment. Thus, differences between the cumulative total load and the cumulative inflow load could indicate zones of ground-water inflow. For the Cement Creek data in the stream reach around Ohio Gulch, from 6,447 meters to 6,907 meters downstream, meters shows a substantial difference between the two calculations. Although there was loading from the visible inflow of Ohio Gulch, the total load was greater, so there must have been zinc load from ground-water input.

This information is important for evaluating specific sites for remediation. A remediation plan must account for visible and dispersed sources of metal load, and this likely is the easiest way to identify the presence of dispersed ground-water inflow. It assumes that the average concentration of water entering the stream is the same as the sampled inflow concentration. If the sampled inflows completely accounted for the entire load entering the stream, then the cumulative total and the cumulative inflow loads would be the same.

The load profile answers important questions about sources of mine drainage, where the streambed is affected, and inputs of ground water. The load profile summarizes the effects of particular sources on the stream. These are important answers needed for effective remediation planning.

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