Use of tracer injections and synoptic sampling to measure metal loading from acid mine drainage

U.S. Department of the Interior—U.S. Geological Survey

Stream-discharge measurements are needed to understand the effects of metal loading from mine drainage

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 depends on the toxicity of a particular metal, how much of the metal enters the stream, and whether or not the metal remains in the stream in a toxic form. This discussion deals with accounting for how much metal enters the stream and whether it stays in the stream. The amount of metal entering the stream is called the mass loading and is calculated as the product of metal concentration and stream discharge. The overall effect of high metal concentrations on streams and aquatic organisms is unclear without discharge measurements.

A traditional discharge measurement is obtained by dividing a stream into small sections and measuring the cross-sectional area and the average water velocity in each section. Summing the measurements of all the sections gives the discharge of the entire stream. This method works well where the channel bottom and banks are smooth. In mountain streams, however, the stream bottom typically is covered with cobbles, allowing much of the water to flow through the cobbles of the streambed where it cannot be measured by a flow meter (fig. 1). Thus, accurate discharge measurements are difficult to obtain in mountain streams, even under the best of conditions.

An approach for mountain streams

A recent study by the U.S. Geological Survey (USGS) as part of the Toxic Substances Hydrology Program illustrates a practical approach to obtaining and using discharge measurements in mountain streams. The study area was in Chalk Creek, a tributary of the Arkansas River in Colorado that receives mine drainage from the Golf Tunnel adit (figs. 2 and 3). Metal-rich mine drainage from the

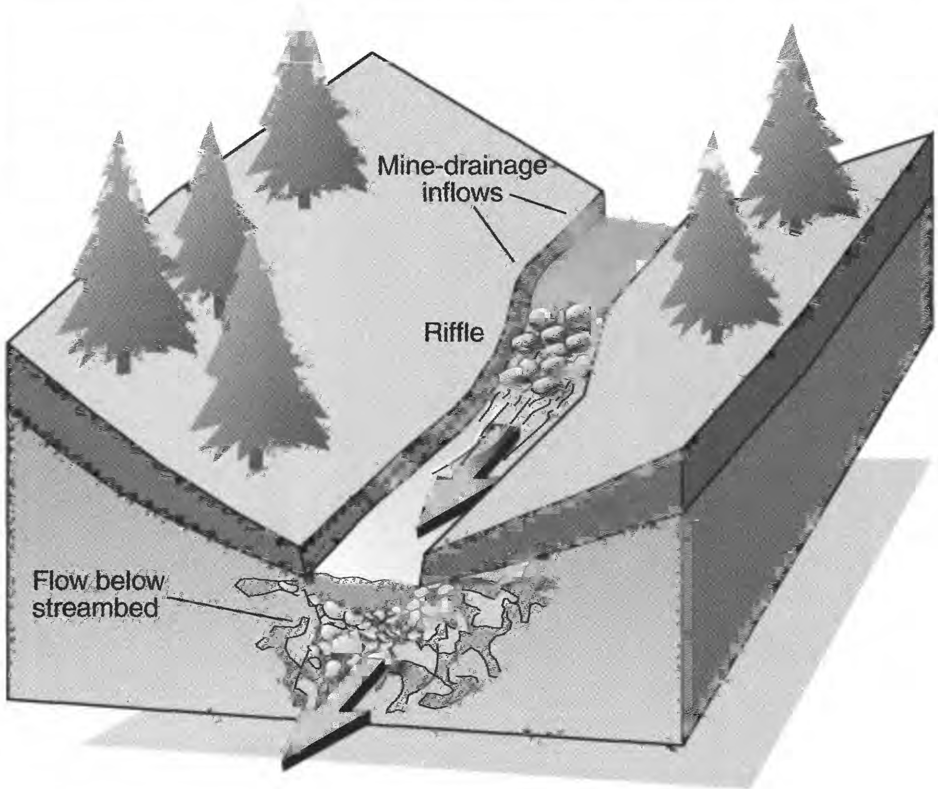

Figure 1. Block diagram illustrating the flow of mountain streams through cobbles below the streambed. Flow through the cobbles cannot be measured by a flow meter.

Figure 2. Looking downstream at old mine workings and the capped tailings pile in Chalk Creek, Colorado.

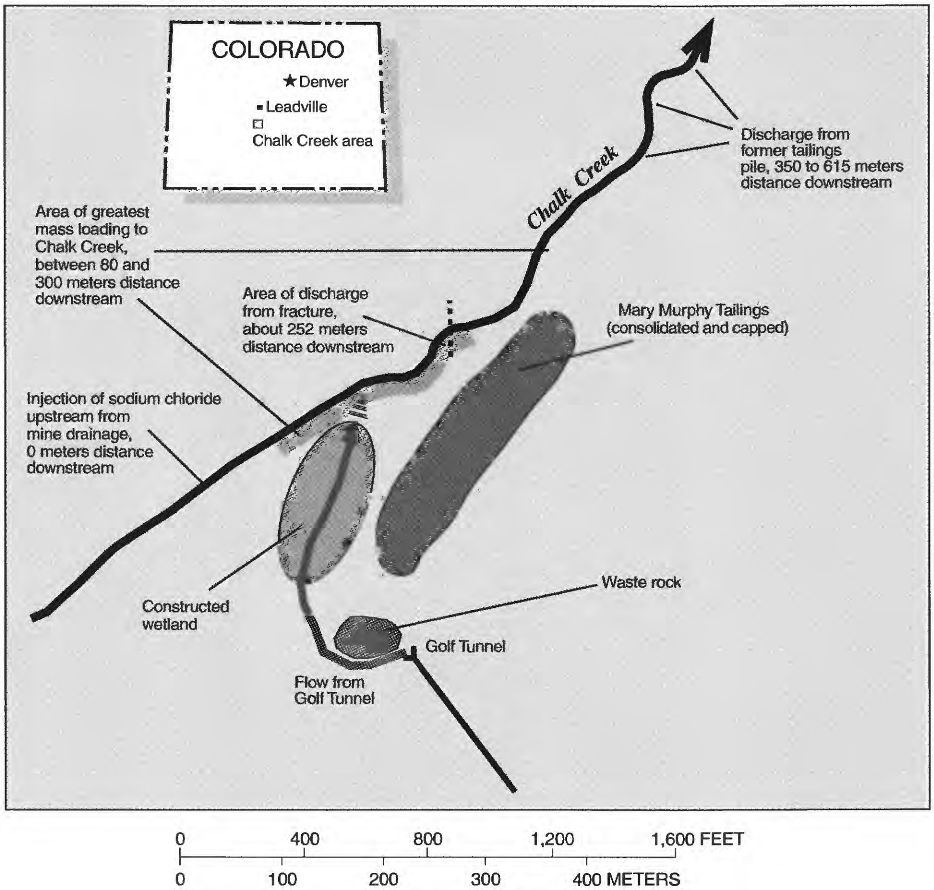

Figure 3. Chalk Creek study section.

Golf Tunnel is routed around waste rock and a capped tailings pile into a constructed wetland. From the wetland, the mine drainage enters Chalk Creek from small springs and seeps along the stream. Regulatory and land-management agencies have asked two basic questions about Chalk Creek. First, is there more than one source of mine drainage that affects the stream and, if so, does a remediation plan need to account for drainage from more than one source? Second, have past remediation efforts been successful? To address these questions, we employed a tracer-dilution method and synoptic sampling. Synoptic sampling is the collection of samples from many locations during a short period of time, typically a few hours. Thus, it is like 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 precisely by adding a dye or salt tracer to a stream, measuring the dilution of the tracer as it moves downstream, and calculating discharge from the amount of dilution. Because we know the concentration of the injected tracer and the rate at which it is added to the stream, we know the mass that is added to the stream. By measuring the concentration of the tracer upstream and downstream from the injection point, we can calculate the discharge in the stream downstream from the injection point. Mathematically, this is written

$$Q_s = (C_i * Q_i)/(C_B - C_A)$$

where

Q_s is the discharge of the stream,
C_i is the tracer concentration in the injection solution,
Q_i is the rate of the injection into the stream,
C_B is the tracer concentration downstream from the injection point, and
C_A is the tracer concentration upstream from the injection point.

The tracer also helps define hydrologic properties such as the velocity of the streamflow, travel time in the stream, the mixing of solutes, the quantity of inflow from tributaries and ground water, and the transient storage in streambed cobbles. To define these properties in Chalk Creek, a sodium chloride tracer was added at a constant rate for 24 hours at a point upstream from the mine drainage and chloride concentration was monitored at several sites downstream from the injection point. There are three main segments on a plot of time versus discharge for two sites (fig. 4). First, there is the arrival of the tracer at the two sites (fig. 4, segment A). The difference between these times of arrival indicates the "time of travel" between

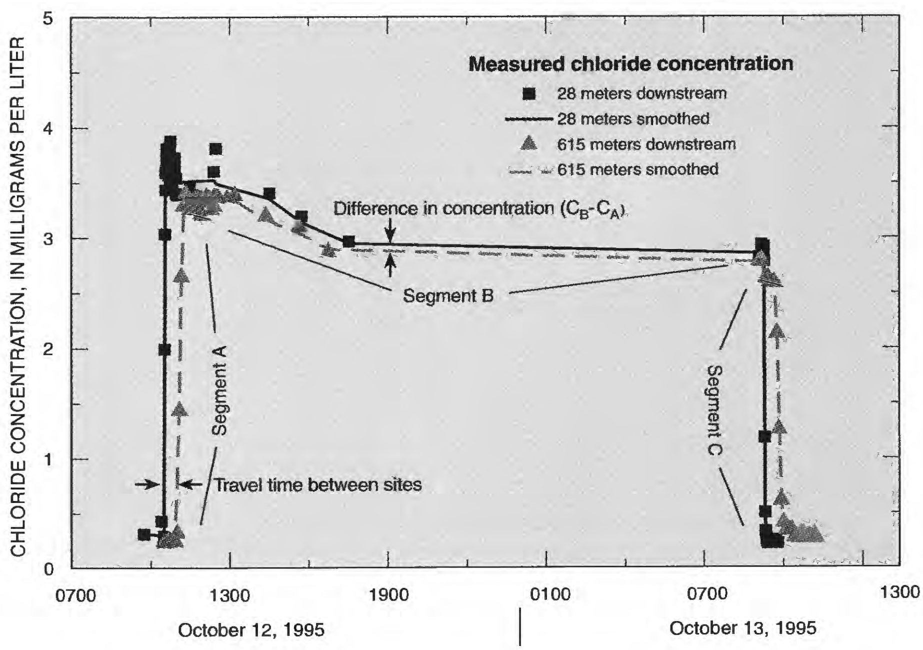

Figure 4. Chloride concentration versus time for two sites in Chalk Creek, Colorado. The difference in discharge is represented by the lower concentration at the downstream site. The travel time between the sites is represented by the difference in time between the arrival and the departure of the tracer at both sites.

sites. Second, there is a "plateau" segment (fig. 4, segment B). The difference between concentrations at the two sites during the plateau is an indication of the difference in discharge at the two sites. The tracer is diluted by the additional water that enters the stream. Finally, there is the decrease of the tracer concentration at two sites after we stopped adding the tracer (fig. 4, segment C). This segment gives the same information as the arrival of the tracer.

Tracer-dilution and flow-meter discharge measurements at various distances from the tracer-injection point are compared in figure 5. Discharge calculated from the tracer dilution is greater because it includes water flowing through the cobbles. The "smoother" pattern in the tracer-dilution discharge helps in determining where ground-water inflow is occurring and in the calculation of more accurate mass loading of metals.

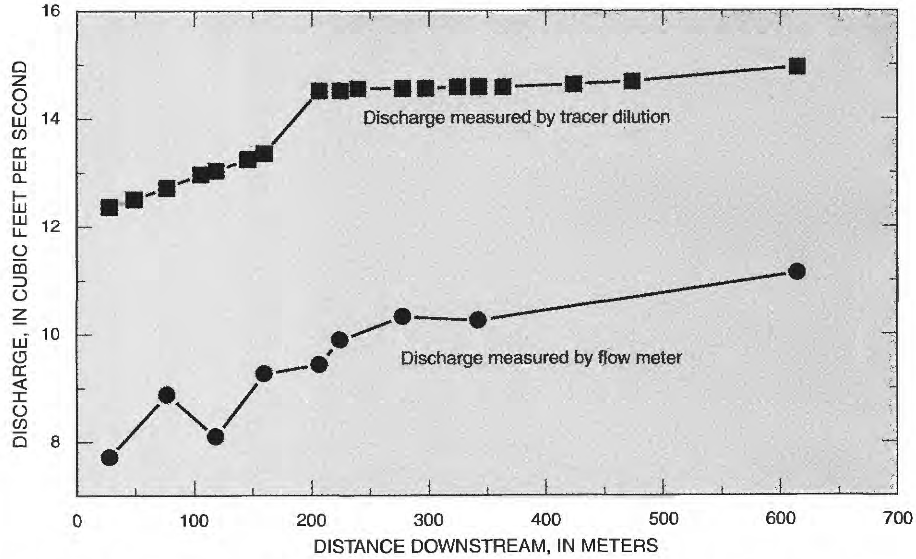

Figure 5. Comparison of discharge calculated by flow-meter and tracer-dilution methods.

Synoptic sampling: A "snapshot" in time to compare metal loading of sources

Site-to-site differences in the tracer concentration during the plateau segment are a result of dilution. These differences are used to calculate stream discharge. Synoptic samples are collected during this period, giving a "snapshot" of the stream profile that includes both discharge and metal concentrations and providing a detailed profile of zinc concentrations in both the stream and the inflows along the stream reach (fig. 6a). To interpret these concentrations, the concentrations and the discharge were multiplied to develop a mass-loading profile (fig. 6b). These profiles help answer the basic questions about the effectiveness of remediation and the sources of metals.

About 6 percent of the total zinc load enters the stream reach from upstream sources. There is a large range in zinc concentration among the inflows, from about 0.1 to 82 milligrams per liter (mg/L). The increase in zinc concentration of the stream from about 0.04 to 0.4 mg/L corresponds to the highest inflow concentrations. Inflows between 80 and 300 meters (m) downstream have about the same zinc concentration as water from the Golf Tunnel, about 10 mg/L. These high concentrations indicate that zinc is not removed as the water flows from the Golf Tunnel through the constructed wetland area to the stream. Altogether, the seeps and springs with Golf Tunnel water represent about 72 percent of the total zinc load at 615 meters, the end of the study reach.

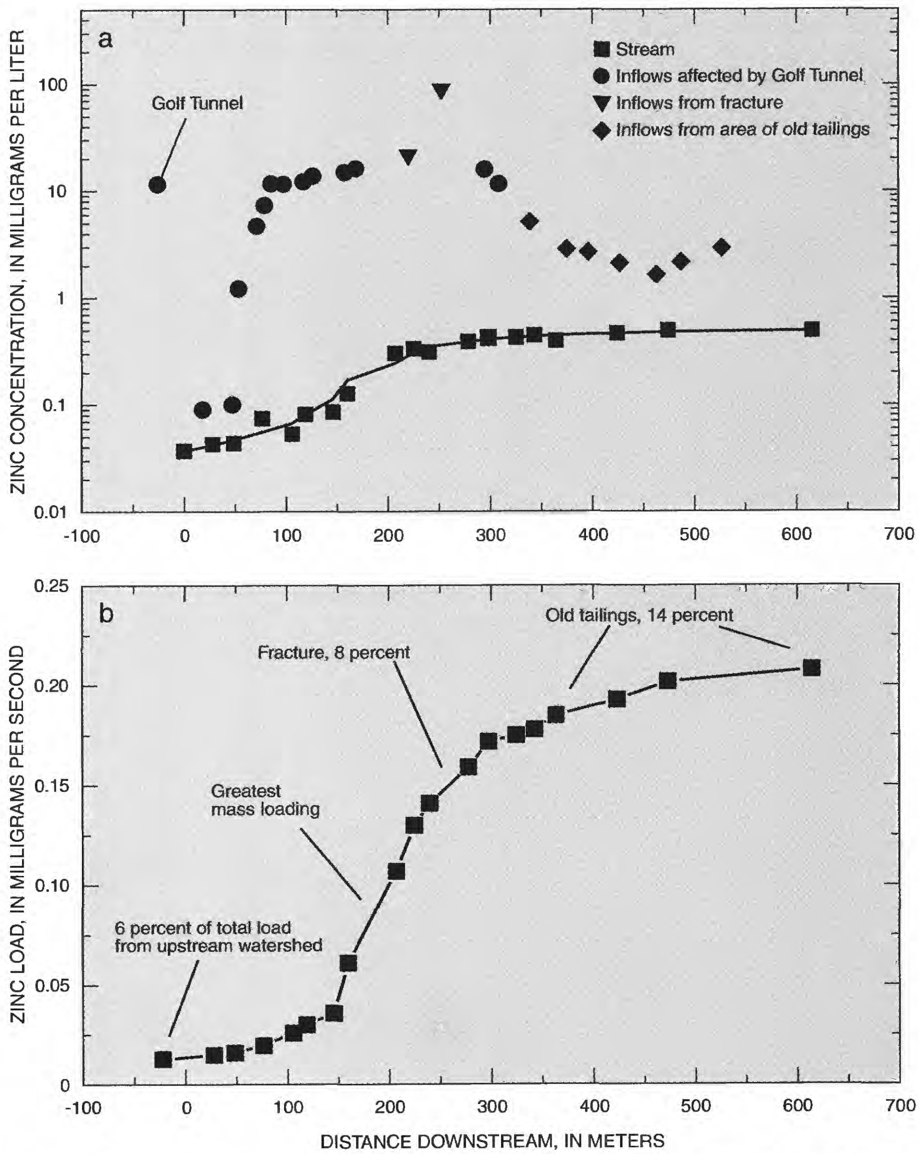

Figure 6. (a) Zinc concentration and (b) zinc mass loading with distance for Chalk Creek, Colorado. The zinc concentration in the Golf Tunnel discharge is shown for reference to the inflow concentrations along the stream.

A few of the inflows near 250 m downstream have higher zinc concentrations than those from the Golf Tunnel (fig. 6a). These inflows are located where a fracture, which has been identified in several ground-water wells, crosses the stream (fig. 3). The higher zinc concentrations represent a second source of metal-rich water. Water from the fracture contributes only about 8 percent of the total zinc load (fig. 6b); thus, the high concentrations do not always indicate the most substantial sources to the stream. Downstream from 350 m, inflow concentrations of zinc generally are about 2 mg/L. These inflows are in the section of the stream where tailings piles have been removed. These concentrations represent loading of zinc, most likely from a ground-water plume that originated from the old tailings. If this source is from a plume, the contribution is expected to diminish over time, but currently the area of the old tailings contributes about 14 percent of the zinc load to the stream.

Conclusions

Measuring stream discharge using tracer-dilution methods allows the calculation of mass loading for Chalk Creek and provides answers for the two basic questions. First, there appears to be more than one source of mine drainage, and each source contributes water with different zinc concentrations. Water from two sources, the Golf Tunnel and a fracture that crosses the stream, contributes zinc, but most of the load comes from the Golf Tunnel. Second, there are still effects of metals on the stream in the area where old tailings were removed; those effects likely will decrease with time.

The data obtained from many samples collected along just 600 m of stream provides the information necessary to calculate a loading curve and guide future cleanup efforts. The detailed mass-loading curve indicates the sections of the stream where metals enter the stream. The example of Chalk Creek shows that the highest inflow concentrations do not always indicate the most significant sources of metal loading. This would not be apparent, however, without using tracer-dilution discharge measurements to help focus on those sections of the stream with the greatest loading. On the basis of this and other work, the regulatory agencies are now directing remediation efforts toward both sources of mine drainage.

—Briant A. Kimball

Sources of Additional Information

The following publications contain additional information on tracer-dilution methods and other applications related to mine-drainage problems.

Bencala, K.E., McKnight, D.M., and Zellweger, G.W., 1990, Characterization of transport in an acidic and metal-rich mountain stream based on a lithium tracer injection and simulations of transient storage: Water Resources Research, v. 26, no. 5, p. 989-1000.

Broshears, R.E., Bencala, K.E., Kimball, B.A., and McKnight, D.M., 1993, Tracer-dilution experiments and solute-transport simulations for a mountain stream, Saint Kevin Gulch, Colorado: U.S. Geological Survey Water-Resources Investigations Report 92-4081, U.S. Geological Survey, Denver, Colorado, 18 p.

Stream Solute Workshop, 1990, Concepts and methods for assessing solute dynamics in stream ecosystems: Journal of North American Benthological Society, v. 9, p. 95-119.

Kimball, B.A., Broshears, R.E., Bencala, K.E., and McKnight, D.M., 1994, Coupling of hydrologic transport and chemical reactions in a stream affected by acid mine drainage: Environmental Science & Technology, v. 28, p. 2065-2073.

Information on technical reports and data related to mine-drainage studies can be obtained from:

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Information on the Toxic Substances Hydrology Program can be obtained by accessing the home page on the World Wide Web at:

http://toxics.usgs.gov/toxics/

Information on mine-drainage issues can be obtained by accessing the home page on the World Wide Web at:

http://water.wr.usgs.gov/mine