

Cases and Solutions

Quantification of mine-drainage inflows to Little Cottonwood Creek, Utah, using a tracer-injection and synoptic-sampling study

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Abstract. Historic mining in Little Cottonwood Canyon in Utah has left behind many mine drainage tunnels that discharge water to Little Cottonwood Creek. To quantify the major sources of mine drainage to the stream, synoptic sampling was conducted during a tracer injection under low flow conditions (September 1998). There were distinct increases in discharge downstream from mine drainage and major tributary inflows that represented the total surface and subsurface contributions. The chemistry of stream water determined from synoptic sampling was controlled by the weathering of carbonate rocks and mine drainage inflows. Buffering by carbonate rocks maintained a high pH throughout the study reach. Most of the metal loading was from four surface-water inflows and three subsurface inflows. The main subsurface inflow was from a mine pool in the Wasatch Tunnel. Natural attenuation of all the metals resulted in the formation of colloidal solids, sorption of some metals, and accumulation onto the streambed. The deposition on the streambed could contribute to chronic toxicity for aquatic organisms. Information from the study will help to make decisions about environmental restoration.

Keywords. Loading - Metals - Mine drainage - Tracer-injection - Utah

Introduction

Historic mining in Little Cottonwood Canyon in Utah has left behind many mine drainage tunnels that discharge water to Little Cottonwood Creek. Environmental restoration in a watershed is an expensive proposition. Decisions about restoration of the stream environment require detailed information about inflows of mine drainage to the stream. With limits on spending, however, data collection can be very

limited (Glaze 1998). An approach is needed that can provide detailed information in the least expensive way.

Watershed chemistry traditionally has been quantified by sampling the watershed outlet (Lawrence and Driscoll 1988; Campbell and others 1991). A water-quality sample at the outlet integrates sources and processes that occur in the watershed. To understand and quantify the impacts of many individual sources within the watershed requires a spatially detailed scale of integration rather than integration at the outlet. By taking samples at stream sites that bracket potential sources of metals and acid along the stream, the watershed is divided up into segments that quantify all the inflows in individual stream segments. The integration of stream segments accounts for the net effects of watershed sources on the stream.

A detailed understanding of sources and processes does not come from measuring concentration alone; it also requires measuring discharge to provide load profiles of metals in the stream. Yet, quantifying discharge in mountain streams presents unique challenges. Measuring discharge by dividing a stream cross section into rectangular areas and measuring a mean velocity for each area is complicated in mountain streams because of the roughness of cobbled bottoms and the pools and riffles. An even greater obstacle is that much of the water in mountain streams flows among the cobbles, in the hyporheic zone (Bencala and others 1990; Harvey and Bencala 1993). Thus, a measurement in the stream channel misses the hyporheic flow, resulting in an underestimate of metal loads. An injected tracer follows the water through cobbled bottoms and accounts for this subsurface flow. Results from the tracer injection also provide the hydrological framework for synoptic sampling and solute-transport modeling. Tracer-injection methods have been used to measure discharge for many years (Kilpatrick and Cobb 1985). The application of tracer-injection methods used here has been developed specifically to investigate loadings by mine drainage through work in mining districts of Colorado (Bencala and others 1990; Kimball 1997).

Since 1986, the US Geological Survey, as part of the Toxic Substances Hydrology Program, has developed methods to understand the impacts of mine drainage in a watershed (Kimball 1991). Bencala and McKnight (1987) described the detailed sampling required to understand stream profiles of metal loading in a watershed. Bencala and others (1990) refined tracer-injection methods for upland watersheds. Additionally, computer simulation models to understand the reactive transport of metals have allowed interpretation of physical and chemical processes that affect transport (Broshears and others 1993; Runkel and others 1996a, 1996b; Kimball and others 1994; Broshears and others 1995, 1996; Harvey and Fuller 1998). As the models have been developed, the methods have been applied to help land-management agencies make decisions about remediation (Kimball 1997).

Chemical reactions of metals from mine drainage are well documented (Barnes and Clarke 1964; Nordstrom and Alpers 1999). What is added by studying these reactions with tracer injection and synoptic sampling is the hydrologic context for quantifying the impact of the reactions. This paper illustrates the authors' approach through an application to the watershed of Little Cottonwood Creek, Utah, in September 1998. The objectives of the work in Little Cottonwood Creek were threefold: (1) to determine the most significant inflows of mine drainage to Little Cottonwood Creek, (2) to identify areas where subsurface inflows of metals occur, and (3) to identify the extent of natural attenuation of metals through chemical and biological processes.

Description of the study area

Little Cottonwood Creek begins at about 3,400 m in the Wasatch Mountains and descends more than 2,000 m in the study reach. The substantial drop in elevation results in a cascading stream with many pools and riffles. The study reach was 8,300 m long, beginning near the base of the Sunnyside Lift at Alta Ski Resort, and ending just upstream from the inflow of Red Pine Fork, downstream from Tanner Flat Campground (Fig. 1). For the synoptic sampling, stream sites were chosen to bracket 33 inflows and areas where subsurface inflow was likely. The inflows included seeps, springs, drainage from mine tunnels, and all major tributary streams.

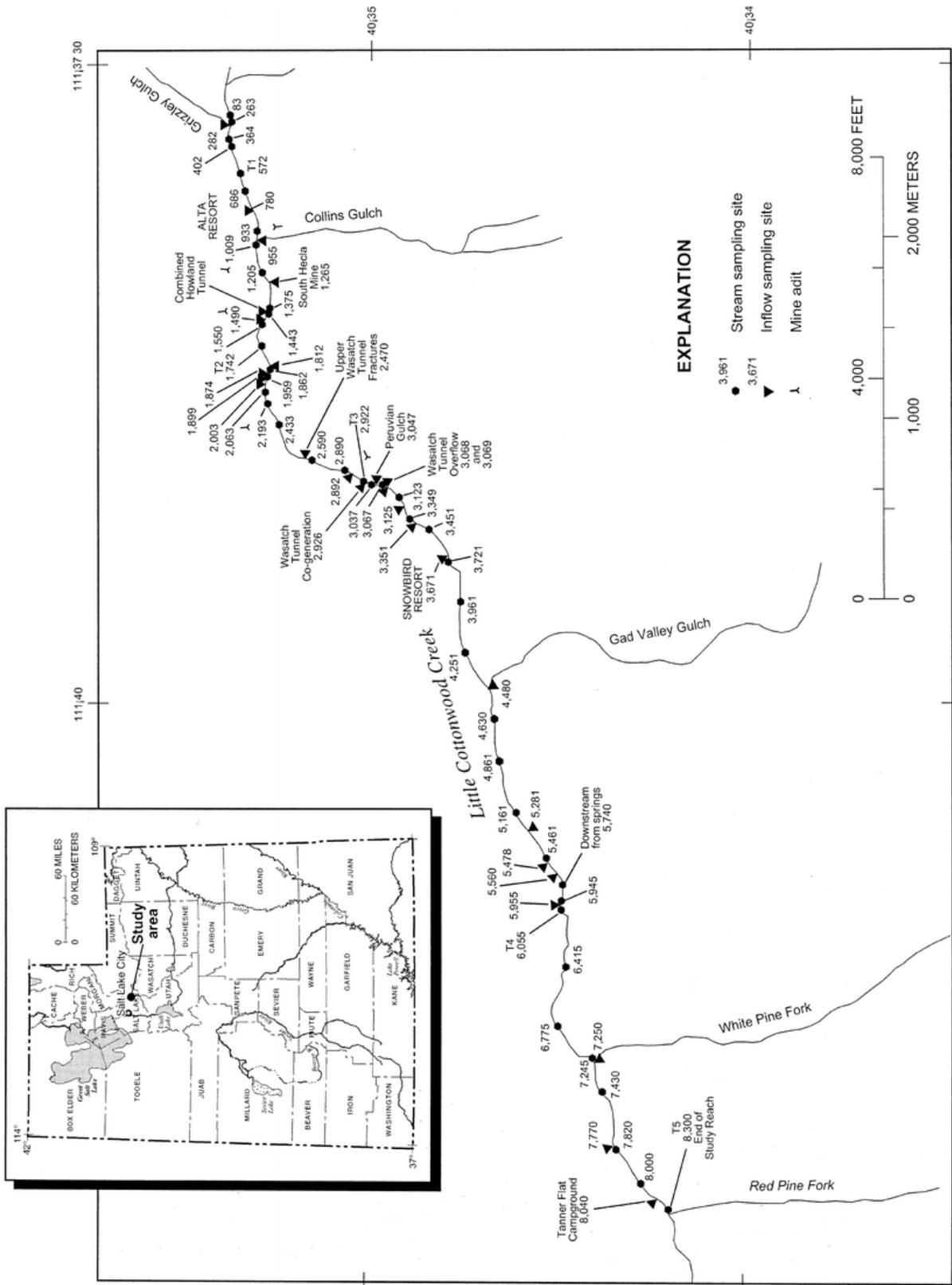


Fig. 1. Location of stream and inflow sampling sites, Little Cottonwood Creek, Utah, September 1998

Although there are dozens of inactive mines in the Alta area, most of the mine drainage discharges to Little Cottonwood Creek from mine drainage tunnels (Calkins and Butler 1943). A single inflow near the Gold Miner's Daughter parking lot (1,403 m, Fig. 1) combines discharge from the Howland, Toledo, and Flagstaff tunnels. The Wasatch Tunnel combines the drainage from many mines and discharges to the stream in at least three places when the mine pool behind a bulkhead is about 91 m deep (Douglas Evans, Salt Lake County Water Conservancy District, personal communication 1999). The most upstream discharge, when the mine pool is deeper than 91 m, is through fractures and a small tunnel in a rock face near the stream at 2,470 m. A second inflow at 2,926 m discharges Wasatch Tunnel water that is used to cool the electrical generation turbine at Snowbird Ski Resort. Finally, the remaining discharge from the Wasatch Tunnel enters the stream in two pipes at 3,068 and 3,069 m. At the time of the study, this water was being treated for removal of metals before being discharged to the stream. The presence of multiple sources of mine drainage makes Little Cottonwood Creek a suitable location to demonstrate the use of mass-loading analysis to answer questions about the effects of mine drainage.

Methods

Sampling and analysis

Stream samples were collected using a DH-81 sampler for equal-width integration (Ward and Harr 1990). Samples were composited into a clean 1.8-l bottle that was shielded from direct sunlight in dark plastic bags, and then transported to a central area for filtration. Samples were filtered through a 0.45- μm filter for analysis of anions by ion chromatography and metals by inductively coupled argon plasma-atomic emission spectrometry (ICP-AES). More reliable dissolved metal concentrations were obtained with filtration through a 10,000-dalton filter (ultrafiltration), also by ICP-AES. An unfiltered, acidified sample was analyzed by ICP-AES for total-recoverable metal concentrations. Colloidal metal concentrations were calculated by subtracting the ultrafiltrate concentration from the total-recoverable concentration. This procedure is sufficiently sensitive to detect colloidal iron (Fe), and in some instances, colloidal copper (Cu). However, many colloidal metal concentrations were too low to be detected by this indirect measurement (Kimball and others 1994).

Quantification of inflow discharge

Quantification of metal loads requires accurate discharge measurements. Discharge is calculated from a tracer injection by the conservation of mass; the mass injected by the pump equals the mass in the stream after accounting for the background concentration. A sodium chloride tracer of 154,570 mg/l Cl was injected at a constant rate into Little Cottonwood Creek, starting at 10:45 on 17 September and ending at about 17:45 on 18 September. The mass of a tracer or a metal (in mg/s) is the product of the discharge (in l/s) and concentration (in mg/l). Rearranging the equation for the conservation of mass, the discharge in the stream downstream from the injection site is:

$$Q_s = \left(\frac{Q_i C_i}{C_s - C_s^P} \right) \quad (1)$$

where Q_s is the discharge in the stream, in l/s; Q_i is the discharge of the injection pump, in l/s; C_i tracer concentration in the injectate solution, in mg/l; C_s tracer concentration in the stream downstream from the injection, in mg/l; and C_s^P background concentration of the tracer in the stream

(in mg/l).

Large amounts of sodium chloride salt are used on the road in Little Cottonwood Canyon to keep it open for recreation in the winter months. "presynoptic" samples were obtained from the stream 2 days before the tracer injection started to quantify the background Cl concentrations for the discharge calculation. There were no storms in the intervening time. There was not a presynoptic sample for every stream site, so values were interpolated between the sites where samples were available. Because of the high background concentrations of Cl, there was a slight change in Eq. (1) from the equation in Broshears and others (1993).

Quantification of mass loading

A concentration of a metal in a stream generally will be somewhere within the range of all the inflow concentrations (Bencala and McKnight 1987). The particular inflows that have the greatest impact on stream concentrations are not necessarily those that have the highest metal concentrations. This is illustrated by rearranging the mass-balance equation to show the dependence of the downstream concentration:

$$C_B = \frac{(C_A Q_A + C_I^E (Q_B - Q_A))}{Q_B} \quad (2)$$

where C_B tracer concentration at a downstream site, in mg/l; Q_A is the discharge at an upstream site (Q_s for the first calculation), in l/s; C_A tracer concentration at an upstream site, in mg/l; C_I^E effective concentration of the inflow, in mg/l; and Q_B discharge at a downstream site, in l/s.

The total discharge of the inflow is represented by the difference between stream discharge upstream and downstream from the inflow. The effective inflow concentration is the discharge-weighted average concentration of the total volume of inflow, and is defined by mass balance:

$$C_I^E = \frac{(Q_B C_B - Q_A C_A)}{(Q_B - Q_A)} \quad (3)$$

where all the terms have been defined above.

From Eq. (2), two inflows may have the same concentration, but the one with the greater discharge will cause a greater increase in concentration downstream. An inflow may have a metal concentration only slightly greater than the stream, but its discharge may make an impact on the stream substantial. Thus, inflows must be evaluated in terms of their discharge as well as their concentration to calculate load as the product of the two.

Results

Results of the chemical analyses are presented graphically in this report. The precision of analysis for the Cl tracer and for each of the solutes was used to determine significant changes downstream. A decrease in Cl concentration had to exceed the analytical precision to be considered a real increase in flow. Likewise, an increase or decrease in metal or SO_4 concentration also had to be greater than the

precision to be considered an environmental change downstream. Discharge and load profiles only indicate changes that meet these criteria.

Discharge from tracer-injection

The downstream variation of presynoptic and synoptic Cl concentrations is illustrated in Fig. 2. A third line indicates the difference between synoptic and presynoptic Cl. This represents the Cl added by the tracer injection. The resulting discharge calculation gives a continuous, detailed accounting of the increase in discharge (Fig. 3). The increase in discharge between two stream sites represents the total inflow from surface and subsurface inflow to the stream in that stream segment.

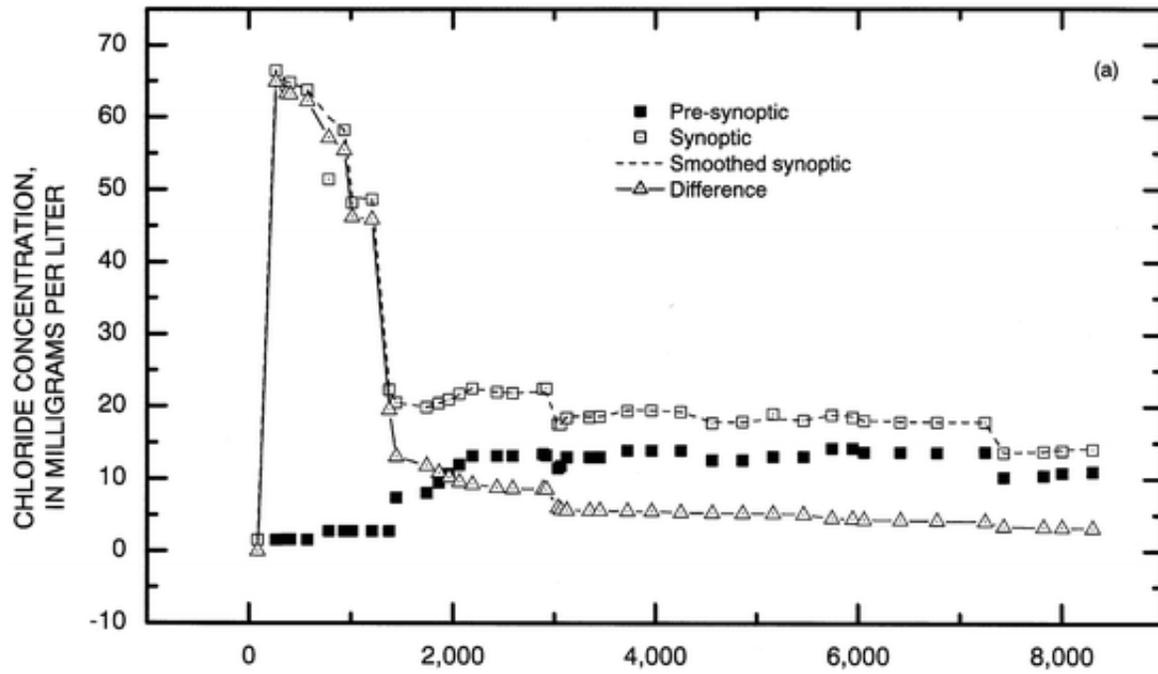


Fig. 2. Downstream profile of chloride concentration from presynoptic and synoptic sampling, Little Cottonwood Creek, Utah, 18 September 1998

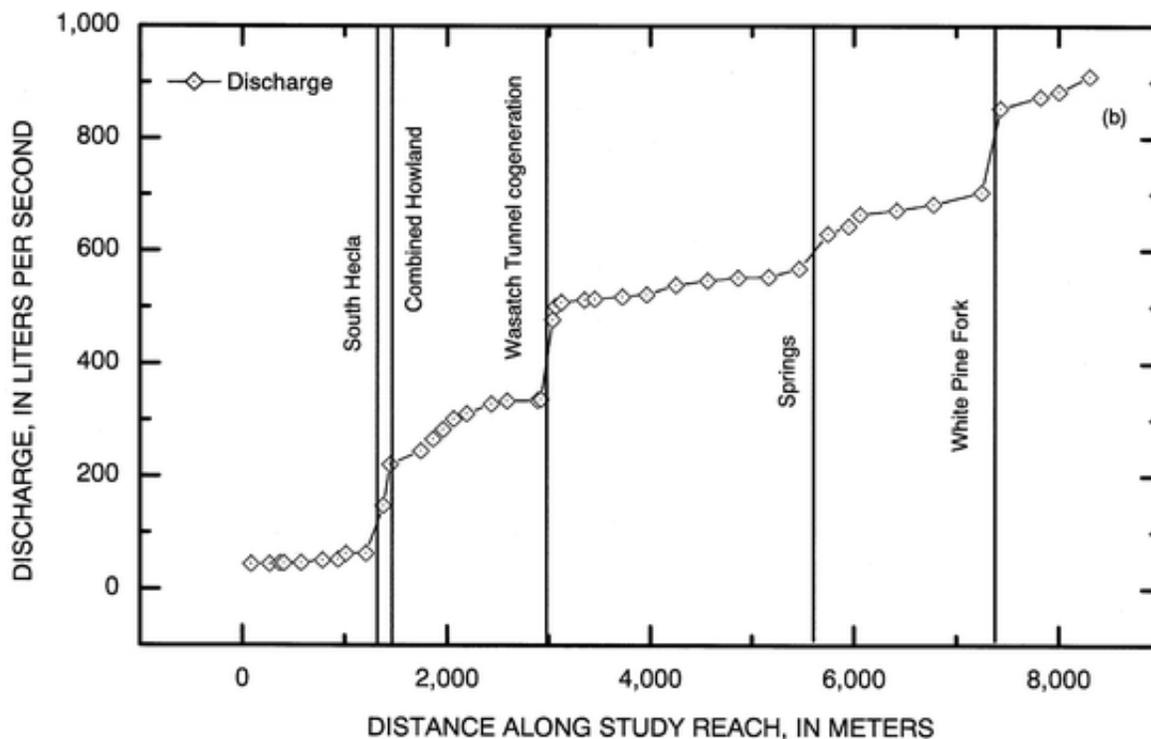


Fig. 3. Downstream profile of discharge calculated from tracer dilution, Little Cottonwood Creek, Utah, 18 September 1998

Discharge increased by 867 l/s along the study reach. The five largest tributary inflows were White Pine Fork (7,250 m), the Wasatch Tunnel cogeneration inflow (2,926 m), the South Hecla Mine (used part of the year for making snow at Alta, 1,265 m), the combined Howland Tunnel (1,403 m), and a series of springs where the canyon is constricted by bedrock near 5,560 m. These inflows accounted for 59% of the increase along the study reach. The median increase in discharge for all the stream segments was 9.3 l/s, and the smallest inflow detected was less than 1 l/s. This indicates the ability of the tracer-dilution method to define small increases in discharge to quantify metal loads.

Chemistry from synoptic sampling

Synoptic sampling provides a spatially detailed picture of changes in stream chemistry, which allows for the interpretation of impacts caused by the different sources of metals. The background chemistry of water in Little Cottonwood Creek upstream from mine inflows was a calcium-magnesium bicarbonate type, which is typical of water draining carbonate rock. The weathering reactions resulted in a pH greater than 8.0 for the entire study reach (Fig. 4). The carbonate rocks in the watershed are sufficient to buffer effects of sulfide oxidation reactions, and the pH of inflows was relatively high for mine drainage. The percentage of Ca and SO₄ increased with the inflows from mine drainage.

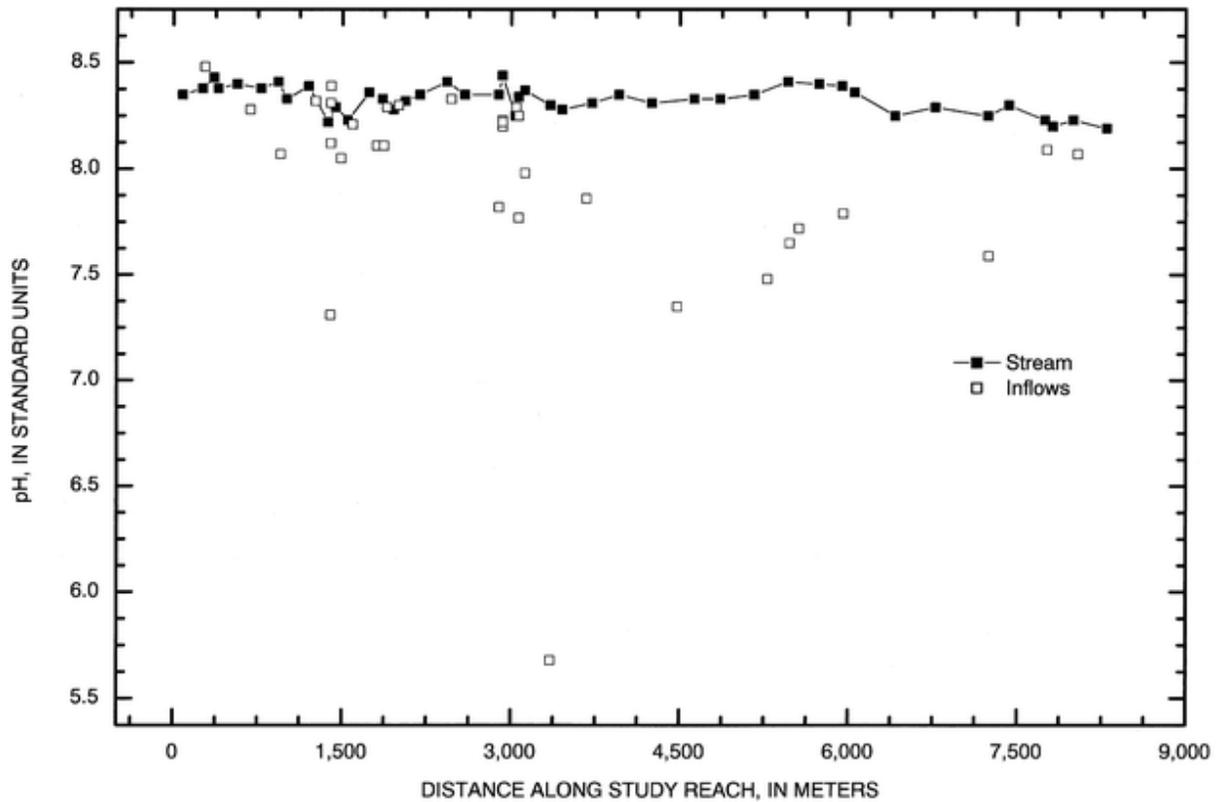


Fig. 4. Downstream profile of pH, Little Cottonwood Creek, Utah, 18 September 1998

Metal concentrations changed substantially along the study reach. Concentrations of Cu, Mn, and Zn increased downstream from the combined Howland Tunnel inflow (in the stream at 1,443 m), the Wasatch Tunnel cogeneration inflow (3,037 m), and the Tanner Flat Campground (8,300 m). Concentrations of Zn exceeded in-stream water-quality standards downstream from the Wasatch Tunnel cogeneration inflow (Fig. 5a). Although Cu concentrations were relatively high, they never exceeded the acute or chronic water-quality standards (Fig. 5b; Colorado Department of Public Health 2000).

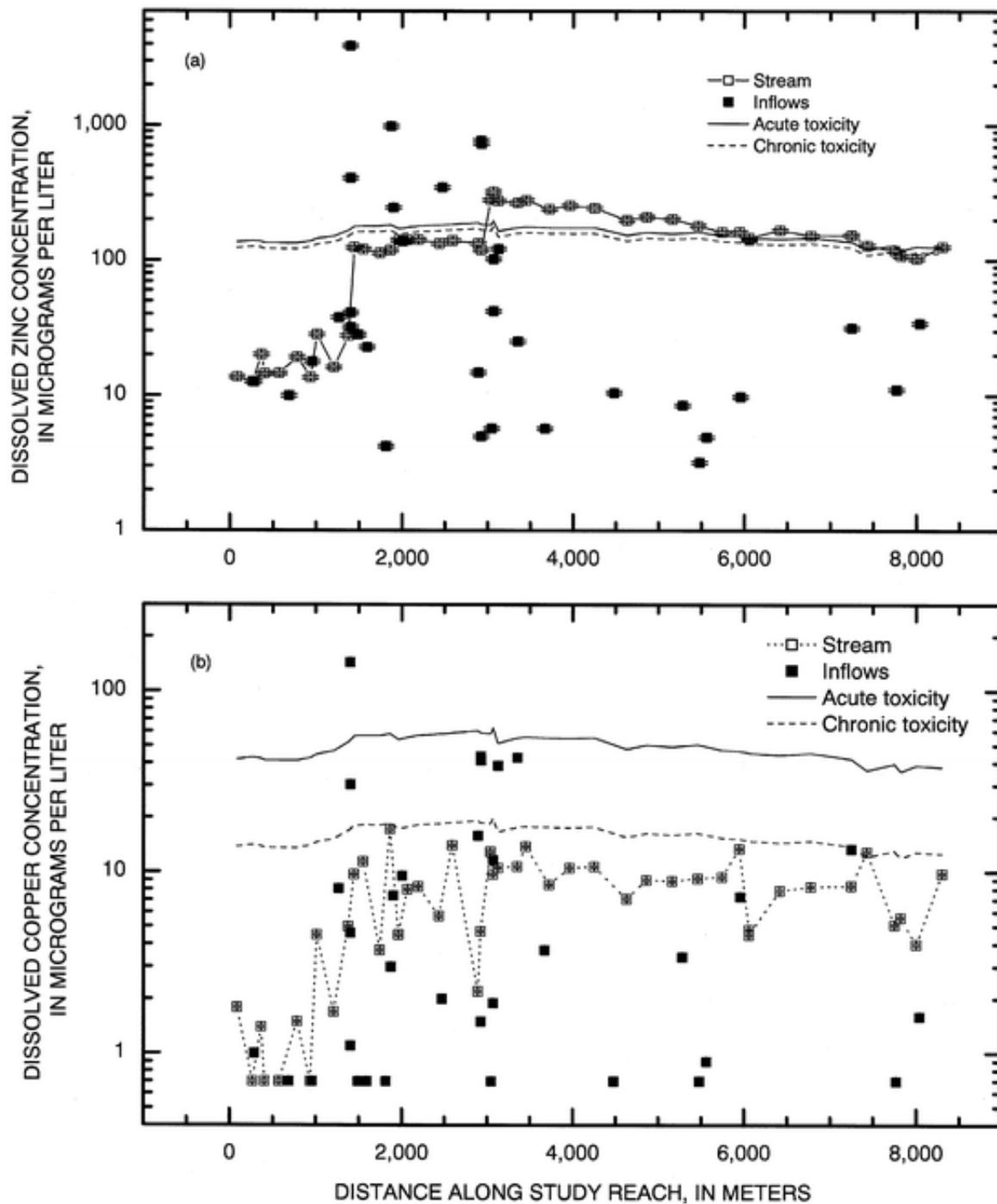


Fig. 5. Concentration of **a** zinc and **b** copper from stream and inflow samples, Little Cottonwood Creek, Utah, 18 September 1998. In-stream water-quality standards acute and chronic toxicity for aquatic organisms are based on the value of hardness

Colloidal concentrations of metals also were determined. Dissolved and colloidal Fe concentrations show that most of the Fe in the stream water was in colloidal form (Fig. 6). The patterns indicate that the concentration of colloidal Fe consistently decreased downstream from the principal sources and that the concentration of dissolved Fe remained nearly constant throughout the study reach. The processes affecting Fe concentrations, however, must be confirmed with mass-loading profiles.

Reactive Fe colloids have been described in other streams affected by mine drainage (Kimball and others 1992, 1995; Church and others 1997; Schemel and others 2000). The colloids provide a large amount of reactive surface area that may sorb metals such as Cu, Cd, Pb, and Zn. Although most of the Cu in stream-water was dissolved, the concentration of colloidal Cu also was measurable. The low concentrations of dissolved Cd and Pb in the stream may result from sorption to the Fe colloidal material. The decrease in colloidal Fe concentration downstream from the sources may indicate a transfer of the colloidal material from the water column to the streambed (Church and others 1997). On the streambed, benthic invertebrates often use part of the biofilm coating streambed cobbles (Kiffney and Clements 1993; Clements 1994). Metals sorbed to the colloidal Fe can be incorporated into the food-chain pathway through benthic grazers to fish, affecting the chronic toxicity in the stream (Woodward and others 1995).

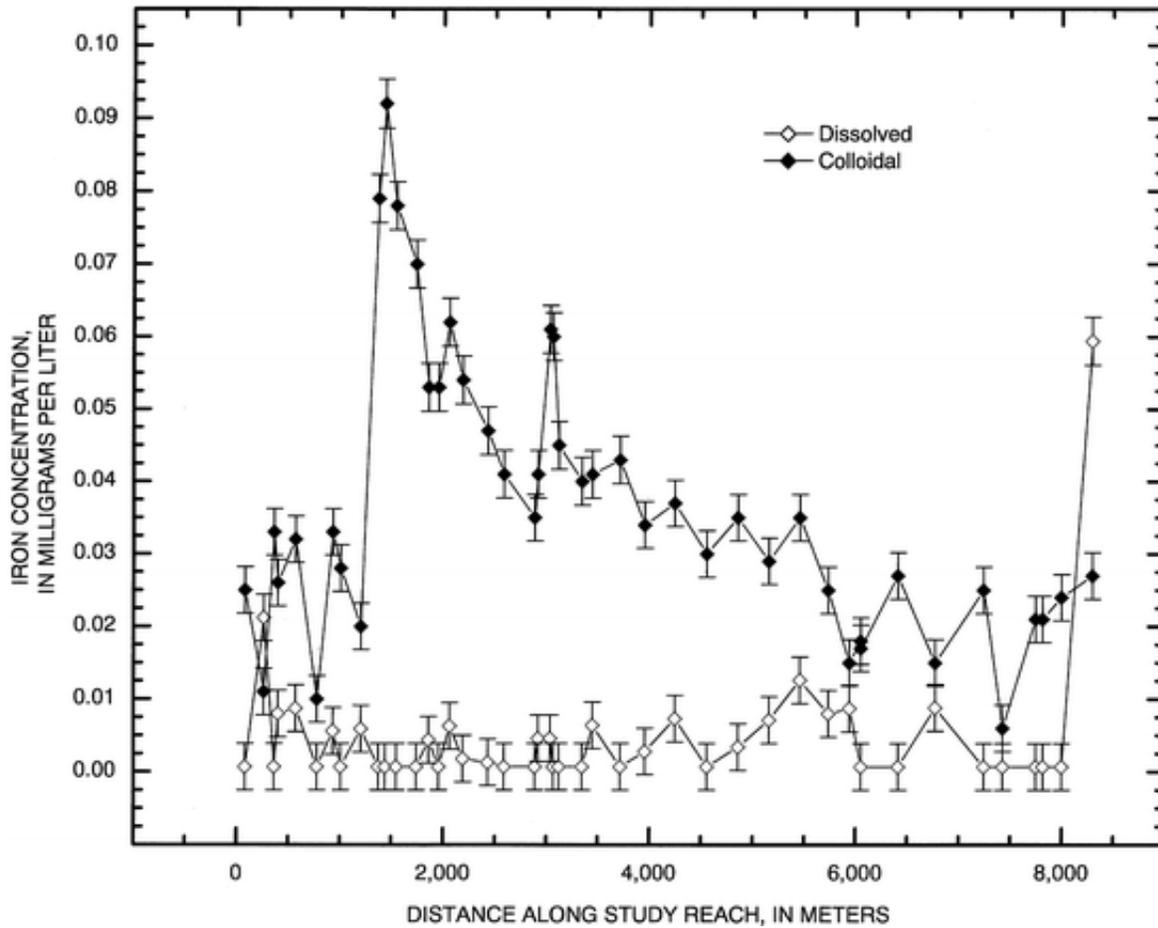


Fig. 6. Downstream profile of dissolved and colloidal iron concentrations, Little Cottonwood Creek, Utah, 18 September 1998

Quantification from mass-loading profiles

Zinc

The loading profile of dissolved Zn in Little Cottonwood Creek illustrates three instructive ways to look at the information from calculating loads. The sampled in-stream load provides the most basic look at where metal loads increase and decrease along the study reach (Fig. 7a). Comparing the change in sampled in-stream load among stream segments ranks the largest metal sources in the watershed. The net change in load between two stream sites is calculated by:

$$\Delta M_S = C_B Q_B - C_A Q_A \quad (4)$$

where ΔM_S = the net change in load, in mg/s.

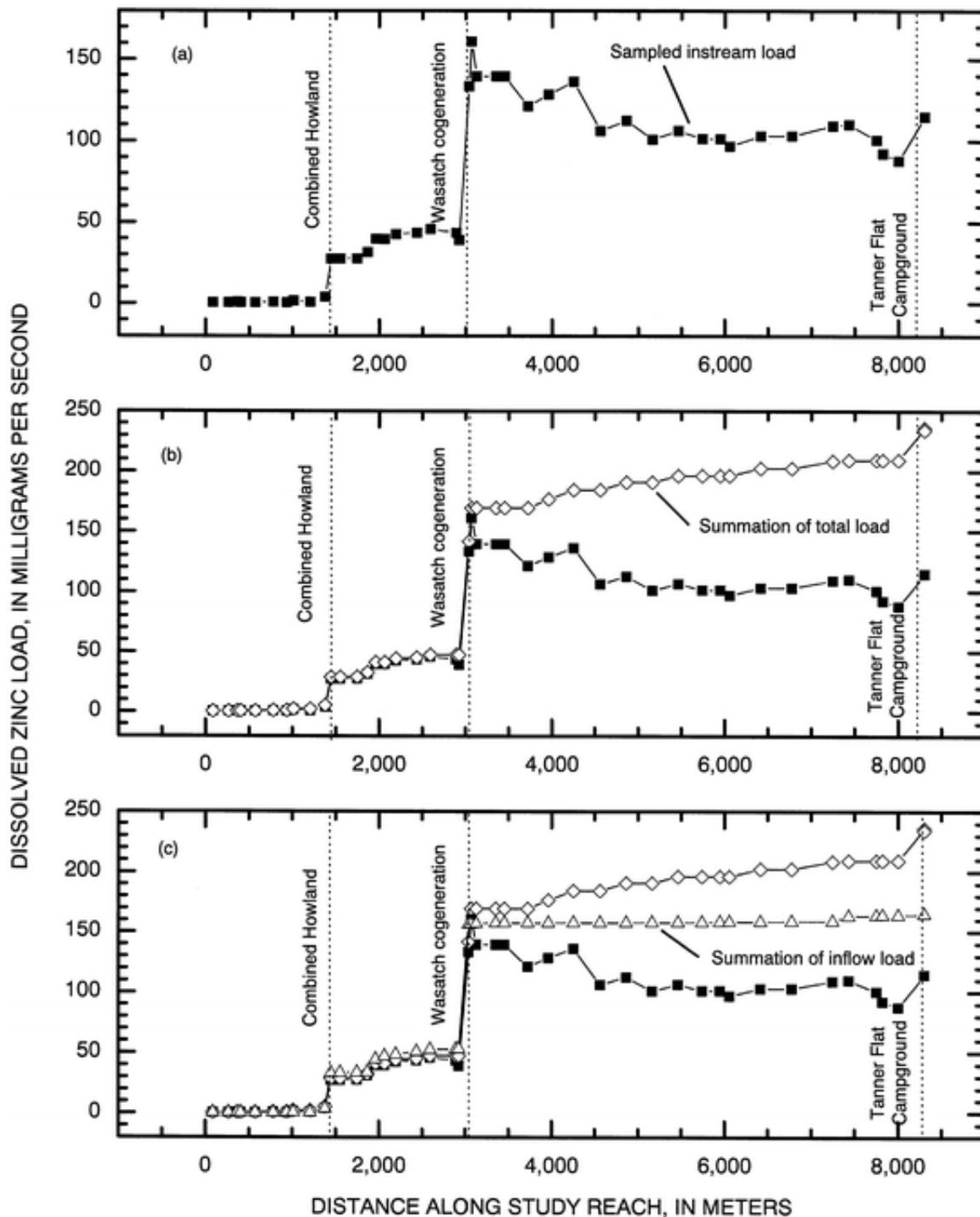


Fig. 7. Mass-loading profile of dissolved zinc showing **a** the sampled in-stream load, **b** the cumulative in-stream load, and **c** the cumulative inflow load, Little Cottonwood Creek, Utah, 18 September 1998. See text for explanation of the calculated values

The change in load can be positive or negative between two stream sites. A positive change indicates a metal source, whereas a negative change indicates a loss of metal mass through chemical reaction. Just because a net change is negative for a particular segment does not mean that metal loading did not occur. The negative loading could mean that chemical and biological processes removed more than the

metal source added. Careful investigation at the stream site is needed to distinguish between possibilities.

Ranking magnitudes of ΔM_S for Zn loading illustrates where the largest loads occur (Fig. 7a, Table 1). The two greatest loads are from the Wasatch Tunnel cogeneration inflow and discharge from the segment containing Peruvian Gulch. The third largest, Tanners Flat Campground, is a site containing mill tailings. The combined Howland Tunnel inflow drains several mines near Alta (Fig. 1). Quantification from the loading analysis indicates that the Wasatch Tunnel would be the largest source for remediation. In fact, the three stream segments ending at 3,037, 3,067, and 2,590 m are associated with the Wasatch Tunnel discharge; the combined loading is 124 mg/s.

Table 1. Summary of cumulative in-stream load, cumulative inflow load, and metal-loading sources, Little Cottonwood Creek, September 1998. *m* Meters: distance of stream site along study reach; all source values are in percent of cumulative in-stream load

Source	Zinc	Manganese	Sulfate	Copper
Cumulative in-stream load (mg/s)	236	21	35,700	36
Cumulative inflow load (mg/s)	164	19	33,600	12
	Source			
South Hecla Mine (1,375 m)	1.3	3.3	14	1.8
Combined Howland Tunnel (1,443 m)	10	24	5.8	3.9
Downstream from Hellgate Falls (1,862 m)	1.6	<0.1	2.3	10
Upper Wasatch Tunnel (2,590 m)	1.0	15	5.6	7.6
Wasatch Tunnel cogeneration (3,037 m)	40	31	19	13
Peruvian Gulch (3,067 m)	12	8.8	3.0	<0.1
White Pine Fork (7,430 m)	.3	<0.1	15	15
Tanners Flat Campground (8,300 m)	11	2.4	5.7	15

Another way to look at the load profile is to compare the sampled in-stream load with a cumulative summation of all the positive values of ΔM_S to give an estimate of total load to the stream. At the end of the study reach, this cumulative in-stream load provides a minimum estimate of loading along the entire study reach (Fig. 7b). For example, the cumulative in-stream load at the end of the reach indicates that at least 236 mg/s of Zn are added to the stream. This gives a perspective on the individual inflows. The Wasatch Tunnel cogeneration inflow accounted for 40% of the total, the Peruvian Gulch segment accounted for 12%, and Tanner Flat accounted for 11%, and the combined Howland inflow accounted for 10%.

If there were no losses or no negative values of ΔM_S in the study reach, then the cumulative in-stream load would equal the sampled in-stream load. Such a match indicates conservative transport through the study reach. On the other hand, if there is a difference between the cumulative in-stream load and the sampled in-stream load, the difference indicates the extent of natural attenuation of metals. Comparison between the cumulative in-stream load and the sampled in-stream load does not add new information, but it provides a visual frame of reference to see the effects of natural attenuation. For example, the extent of Zn attenuation downstream from the Wasatch Tunnel

cogeneration inflow (3,037 m) is apparent when compared with the cumulative in-stream load (Fig. 7b). The loss of Zn is from chemical reaction that removes Zn from the water column. Because there is no corresponding increase in Zn in the colloidal load, this loss is to the streambed and not to colloids in the water column.

Samples of inflows allow yet another way to look at the metal loading. Using the inflow concentrations, we define the inflow load as the product of a sampled inflow concentration and the increase in stream discharge for each segment:

$$\Delta M_I = C_I (Q_B - Q_A) \quad (5)$$

where ΔM_I = the net change in load based on inflow concentrations, in mg/s (Fig. 7c).

If there is a difference between the cumulative in-stream load and the cumulative inflow load, the difference indicates the extent of "unsampled inflow." Perhaps the best example in Little Cottonwood Creek was the stream segment including Peruvian Gulch (ending at 3,067 m). The inflow load of Peruvian Gulch, ΔM_I , based on the increase in discharge and the sampled Zn concentration of Peruvian Gulch, indicates essentially no contribution to the load of Little Cottonwood Creek. However, the segment accounted for the second largest increase in Zn load among all the stream segments, based on ΔM_S . This condition indicates unsampled inflow may be entering Little Cottonwood Creek in that stream segment. The unsampled inflow must have a higher Zn concentration than Peruvian Gulch water, and could be leakage from the Wasatch Tunnel.

If a sampled inflow underestimates or overestimates the Zn loading, the effective inflow concentration [Eq. (3)] can be calculated. This effective inflow concentration may resemble concentrations of mine drainage from adits in the watershed. For example, a calculated (effective) inflow concentration for the Peruvian Gulch segment is 0.7 mg/l, which is comparable to water from the Wasatch Tunnel mine pool (Douglas Evans, Salt Lake County Service Area personal communication 1998). Differences between values of C^E_I and C_I are indicated by a divergence between the cumulative in-stream and cumulative inflow loads on a graph (Fig. 7c). The segment at Tanners Flat Campground illustrates the divergence between the curves. The sampled inflow concentration for a stream segment may be lower than the effective inflow concentration because it is not representative of all the water entering the stream, particularly subsurface water.

These three views of loading help to understand the sources of metal loading, the natural attenuation of metals, and the extent of unsampled inflow. With this background, the loading profiles of other metals and sulfate can provide detailed information about metal loading to Little Cottonwood Creek.

Manganese

The mass-loading profile of dissolved Mn (Fig. 8a) resembled that of Zn in many respects (Fig. 7c). Except for Tanners Flat Campground, Mn had the same principal sources as Zn (Table 1). The four largest sources of Mn load accounted for 87% of the cumulative in-stream load. The load profile indicates that extensive natural attenuation of Mn occurred downstream from the Wasatch Tunnel cogeneration inflow. Colloidal concentrations of Mn generally were below detection, so the loss of Mn was directly to the streambed, not to colloids.

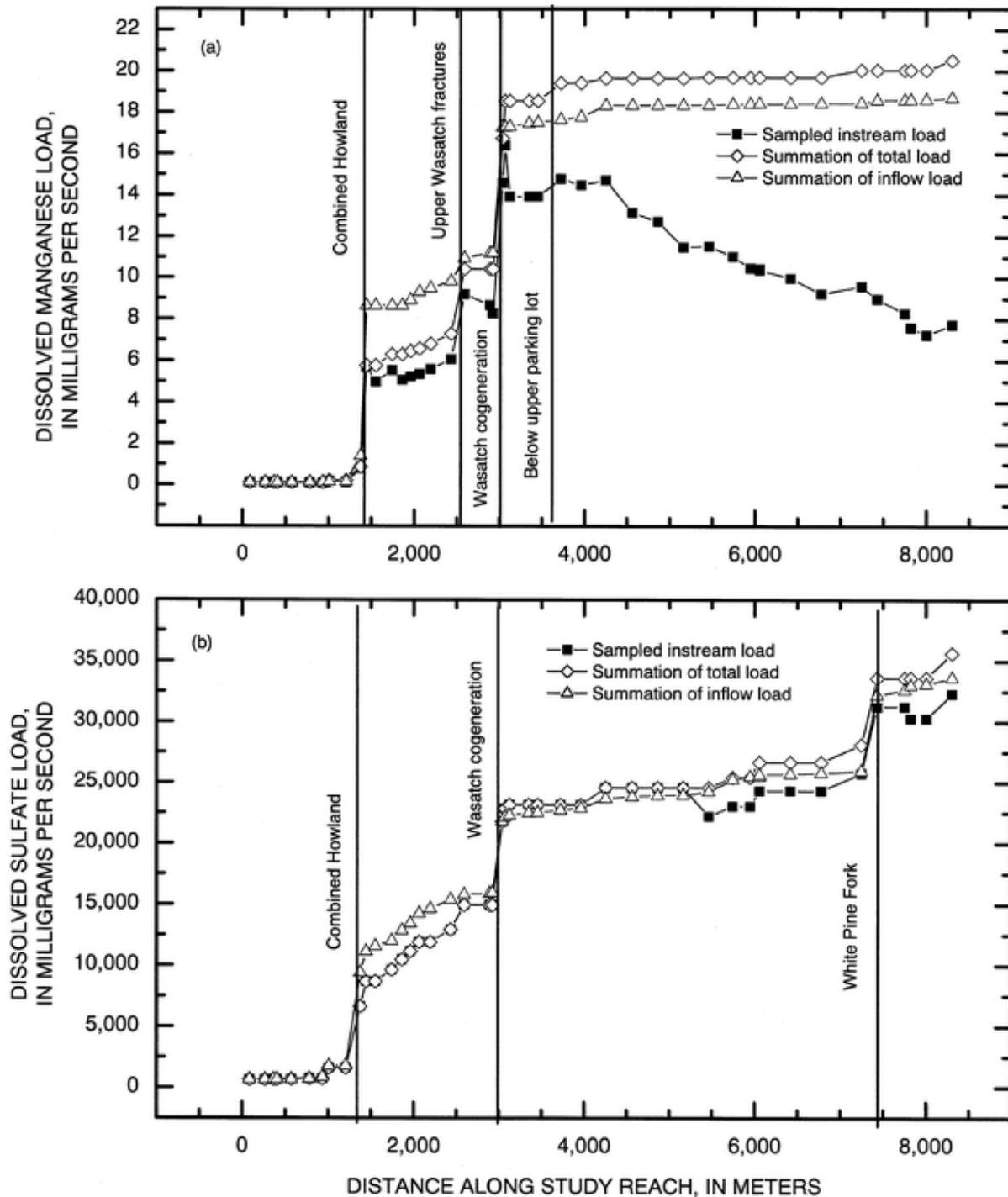


Fig. 8. Mass-loading profiles of **a** manganese and **b** sulfate, Little Cottonwood Creek, Utah, 18 September 1998

In the stream segment that includes the inflow from the combined Howland Tunnel, the inflow load for Mn exceeds the total load (Fig. 8a). This circumstance is not common. The sampled inflow had 0.1 mg/l Mn and was collected at a point after the discharges of the Howland Tunnel, the Flagstaff Tunnel, and a third non-tunnel flow came together. A calculated, effective inflow concentration was 0.067 mg/l Mn, which is less than the sampled concentration. However, the circumstance could also

mean that the Mn load decreased because of reactions, which would be likely at the high pH of the stream (8.29).

Downstream from the Wasatch Tunnel cogeneration inflow, the increases in cumulative in-stream and cumulative inflow loads were quite comparable, and so the sampled inflow was representative of all the water entering the stream. However, the inflows from the upper Wasatch Tunnel fractures and Peruvian Gulch mostly represented unsampled inflow, because sampled inflow concentrations of Mn for both were not high enough to account for the increases in load that were measured by stream samples. Unsampled Mn inflow at these two locations indicates that there could be substantial amounts of water entering the stream that likely came from the Wasatch Tunnel mine pool.

Sulfate

The loading profile of SO_4 is instructive because it indicates transport behavior that was different from the behavior of Zn and Mn. Like the profile of Zn load, the profile of SO_4 indicates that the Wasatch Tunnel cogeneration inflow was a principal source (Fig. 8b, Table 1). However, White Pine Fork and the South Hecla Mine also contributed substantial SO_4 loads. At each of these inflows, the sampled in-stream load, the cumulative in-stream load, and the cumulative inflow load are nearly equal for SO_4 . This indicates that there was very little chemical reaction removing SO_4 from the water column. The only process that might remove SO_4 at these high pH values would be incorporation of SO_4 into Fe colloidal material as it forms, which can occur in waters affected by mine drainage, but at such high pH this is not likely (Bigham and others 1990).

The similarities between total and inflow loads for SO_4 also indicate less unsampled inflow of SO_4 than for the metals. This could be a result of the smaller difference between the SO_4 concentrations between the stream and the inflows. Thus, the sampled inflows are more representative of the effective inflow concentrations. Also, SO_4 moves through the subsurface without being affected by precipitation or sorption reactions, so there should be less variability than for the inflow concentrations of metals, because the metals are reactive.

Iron

The principal sources of Fe to Little Cottonwood Creek were the South Hecla Mine inflow, the combined Howland Tunnel inflow, and the Wasatch Tunnel cogeneration inflow (Fig. 9b). Because Fe is so reactive in many streams (Kimball and others 1994) it is very difficult to quantify loads for Fe, and it was not included in Table 1. As Fe entered the stream, which had a pH greater than 8.0, any dissolved Fe was transformed to colloidal Fe before it was sampled downstream. Thus, the sampled in-stream load of dissolved Fe did not show any increase except at the inflows downstream near White Pine Fork and Tanners Flat Campground (Fig. 9a). Colloidal Fe generally was lost from the water column to the streambed during transport. Colloidal Fe is not toxic to aquatic organisms, but it can sorb metals that are toxic (Chen and Meyer 1998). The Fe colloids become part of the biofilm covering the streambed cobbles and thus are ingested by benthic grazers. This gives the opportunity for metals to enter the food-chain and contribute to the chronic toxicity of the stream (Clements 1994).

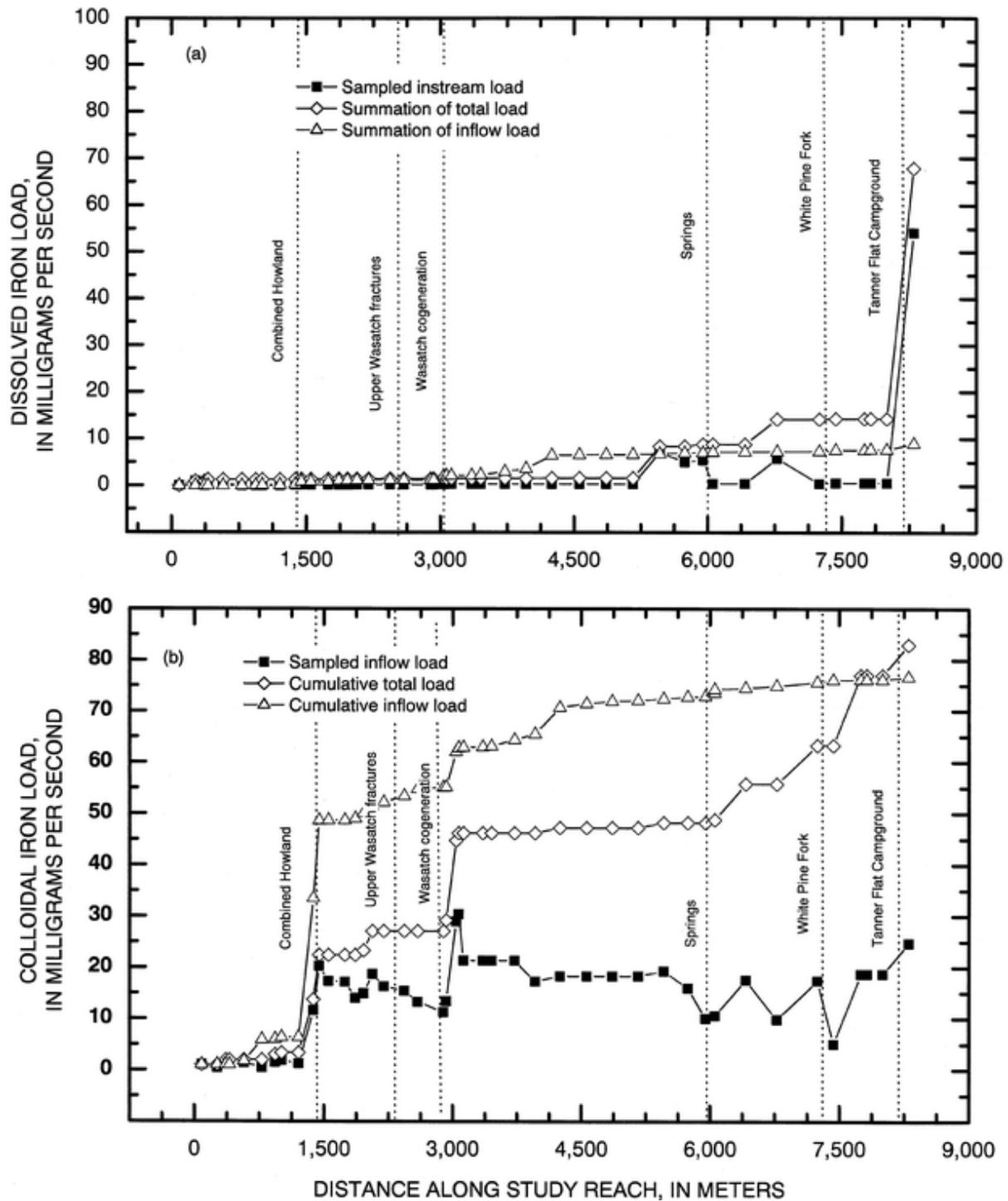


Fig. 9. Mass-loading profiles of **a** dissolved and **b** colloidal iron, Little Cottonwood Creek, Utah, 18 September 1998

Copper

Both dissolved and colloidal concentrations of Cu were measured in Little Cottonwood Creek, but the colloidal Cu concentrations did not have a consistent pattern like the colloidal Fe concentrations. At several locations, the decrease in dissolved Cu corresponded to an increase in colloidal Cu. This occurred downstream from inflows at 3,067, 4,630, and 6,055 m. Generally, the dissolved concentrations of Cu were higher than the colloidal concentrations, and so only dissolved Cu was considered for a loading profile (Fig. 10). There are four principal sources of Cu along the study reach, namely, the inflows from the Hellgate area, the Wasatch Tunnel cogeneration inflow, White Pine Fork, and Tanners Flat Campground (Table 1). The high pH of the stream and the presence of Fe colloidal material would favor either sorption of dissolved Cu onto the Fe colloids (Webster and others 1998), or coprecipitation with Fe (Hem and Skougstad 1960). The Fe colloids are continually deposited on the streambed (Fig. 9b), and this may be the mechanism for the loss of Cu load.

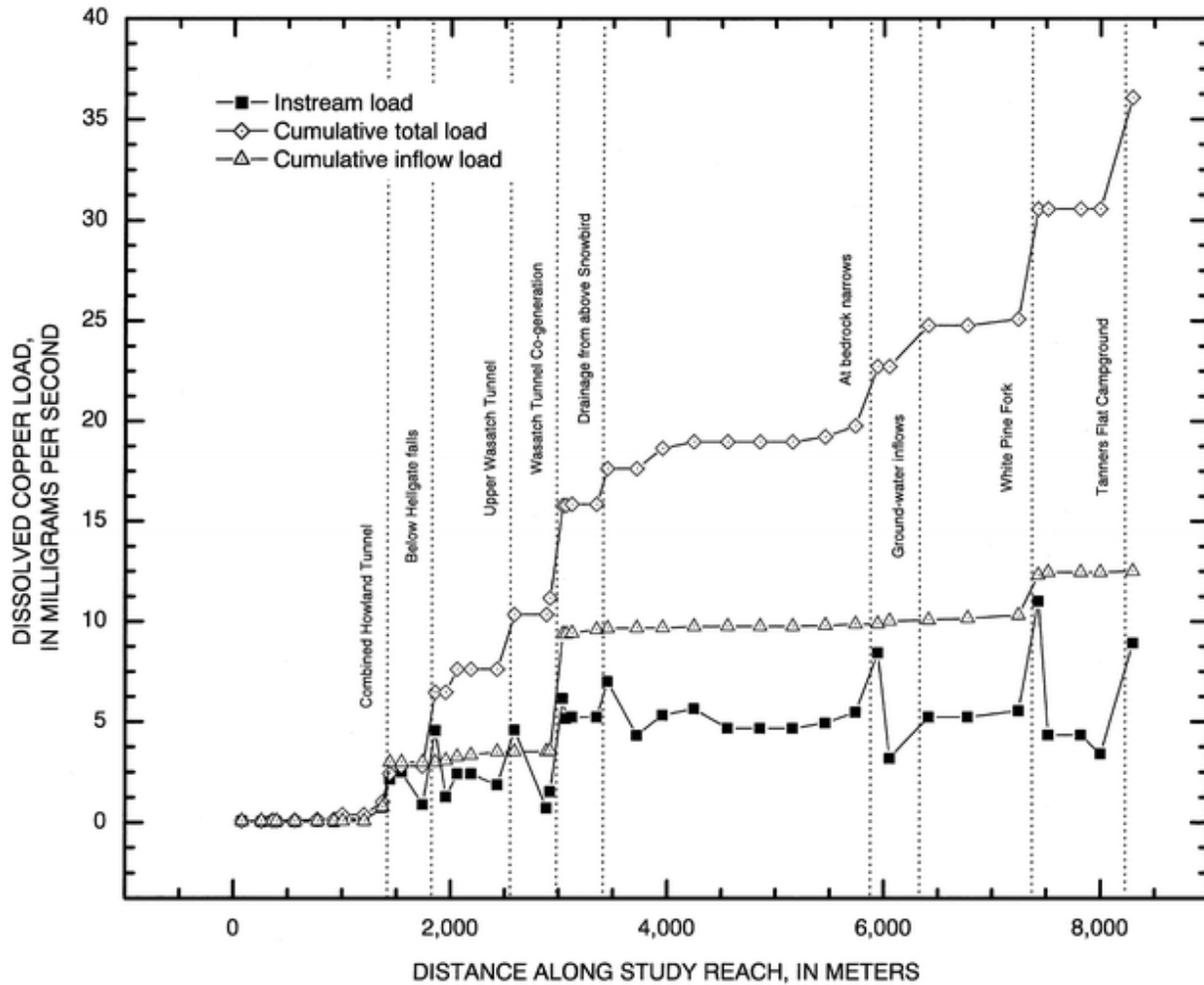


Fig. 10. Mass-loading profiles of dissolved copper, Little Cottonwood Creek, Utah, 18 September 1998

With results for Zn, Mn, SO₄, and Cu, Table 1 provides a summary of the major areas of metal loading in Little Cottonwood Creek. The release of Wasatch Tunnel water from the cogeneration inflow at 2,926 m accounts for the largest loading for most of the metals. This water comes directly from the mine pool in the Wasatch Tunnel and is not treated. The substantial loading of Zn and Mn in the next stream segment, which ends at 3,067 m and includes Peruvian Gulch, is likely a result of leakage from the mine pool, because there is no direct discharge from the Wasatch Tunnel in that stream segment. The pattern of Cu loading differs from Zn and Mn. This likely is a result of Cu being associated with specific ore bodies such as the unmined deposit at White Pine Fork.

Classification of inflows

During the initial reconnaissance of Little Cottonwood Creek, all the visible inflows were identified and 33 locations were chosen for synoptic sampling. The purpose of sampling the inflows was not to sample each and every inflow, but to sample a representative range of inflow concentrations.

It is useful to classify inflows to highlight similarities, and to provide useful information for considering remediation options. Classification also provides a means of linking the results of the synoptic sampling to geological and biological studies. Because water-rock reactions with the different mineral assemblages lead to particular chemical signatures in water entering the stream. Variation in chemistry of inflows often can be explained by differences among mineralogy of ore bodies and alteration suites.

Patterns in the chemistry and pH of inflows were evaluated by using principal components analysis (PCA): a multivariate analysis technique (Mathsoft 1999). Principal components represent a new, transformed set of reference axes that are linear combinations of the original variables. Chemical concentrations (in millimoles per liter) and pH were used in the calculations. The transformation orients the data points so that the first of the new axes, principal component 1 (PC1), is oriented along the direction of the greatest variance in the data. The second principal component (PC2) is orthogonal to PC1, and is oriented to show the next greatest amount of variance in the data. This is easy to picture in two dimensions. One can imagine drawing a line that would go through the two most distant points in a bivariate plot of data; that would be the direction of PC1. It would be at some angle to the original x and y axes, but any point along the line could be described by a linear equation. PC2 would be drawn perpendicular to PC1 and it would have its own linear equation. Each of the original data points could be described by new coordinates using PC1 and PC2. With PCA, there is a description of the data according to the greatest distinction among samples. In multidimensional space, each subsequent principal component is orthogonal to the first two and represents a decreasing amount of the total variance. Typically, the first two or three principle components show enough of the variance in the data set to enable the recognition of patterns or groups among samples; this is the advantage of using the method for multivariate data.

Inflow samples are plotted by their PCA scores; the scores are the coordinates of the original data points on the new principal component axes (Fig. 11). Arrows, or vectors, drawn on the plot indicate the correlations of original variables with the principal component axes. Groups of vectors indicate the four principle chemical reactions that generate the chemical composition of these inflow samples:

1. The dissolution of carbonate rocks produces Ca, Mg, and alkalinity and causes an increase in pH. Thus the vectors for pH, Ca, Mg, and alkalinity all cluster together.
2. The oxidation of pyrite produces Al, Fe, and Si as the acid produced dissolves aluminosilicate minerals.
3. Base-metal sulfides oxidize to produce Cu, Mn, Zn, and SO_4 . This oxidation produces less acid than pyrite oxidation, and the vectors for these metals are not directly opposite the pH vector like the vectors for Al, Fe, and Si. These metals represent the ore bodies. Although the vector for Pb is not quite covariant, it is important in the same samples.
4. Na and Cl concentrations are from road salt that affects some inflow samples.

Samples in group III occur farther down the canyon. Their chemistry has been affected by some pyrite oxidation and aluminosilicate weathering of granodiorite, but they reflect less influence from carbonate dissolution. Concentrations of base metals in group III samples were much lower; the influence of ore deposits was mostly upstream. White Pine Fork (7,250 m) and the inflow at 3,351 m are sources of metal load. White Pine Fork had relatively high concentrations of Cu and molybdenum that could reflect weathering of an unmined ore deposit within the drainage (BA Kimball, US Geological Survey unpublished data). The inflow from Tanner Flat Campground (8,040 m) does not reflect the loading that occurred in that stream segment because the metal loading at the campground was from subsurface inflow.

Conclusions

Tracer injection and synoptic sampling provided a means to quantify inflows to Little Cottonwood Creek. Discharge determined from tracer-injection methods showed that Little Cottonwood Creek is a gaining stream; the increase in downstream discharge was from both mine drainage and non-mining inflows, and represents the total surface and subsurface contribution from each inflow. The chemistry of stream water determined from synoptic sampling was controlled by the weathering of carbonate rocks and mine drainage inflows. Weathering reactions resulted in a high pH in the stream and in most inflows. Principal sources of metal loading by surface-water inflows included the Wasatch Tunnel cogeneration discharge, the combined Howland Tunnel inflow, the South Hecla Mine, and White Pine Fork. Substantial subsurface inflows of metal load occurred near Peruvian Gulch, Tanners Flat, and where the canyon narrows downstream from Snowbird Resort. The subsurface inflow near Peruvian Gulch may be discharge from the Wasatch Tunnel mine pool. These subsurface inflows represent unsampled inflow to the stream. Natural attenuation of all the metals resulted in the formation of colloidal solids, sorption of some metals, and accumulation onto the streambed. The deposition on the streambed could contribute to chronic toxicity for aquatic organisms. The chemical character of most inflows falls into three groups that differ because of the changing geological setting and influence of mines along the study reach.

This study identifies the principal inflows that contributed metal load to Little Cottonwood Creek, the areas where natural attenuation contributed metals to the streambed, and areas where substantial subsurface loading occurred. This information can help in making decisions about environmental remediation and indicate areas of the stream that might require more study.

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