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Quantification of Metal Loads by Tracer-Injection and Synoptic-Sampling Methods in Cataract Creek, Jefferson County, Montana, August 1997

Water-Resources Investigations Report 00-4237

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

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**By Thomas E. Cleasby, David A. Nimick, and
Briant A. Kimball**

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U.S. Department of the Interior

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U.S. Geological Survey

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CONVERSION FACTORS, ABBREVIATED WATER-QUALITY UNITS, AND ACRONYMS

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
foot per second (ft/s)	0.3048	meter per second (m/s)
gallon (gal)	3.785	liter (L)
inch (in.)	0.0254	meter (m)
mile (mi)	1.609	kilometer
pound (lb)	0.436	kilogram

Temperature can be converted from degrees Celsius ($^{\circ}\text{C}$) to degrees Fahrenheit ($^{\circ}\text{F}$) by the following equation:

$$^{\circ}\text{F} = 9/5 (^{\circ}\text{C}) + 32$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviated units used in this report:

g/L	grams per liter
L	liter
L/s	liters per second
$\mu\text{S/cm}$	microsiemens per centimeter at 25 degrees Celsius
$\mu\text{g/L}$	micrograms per liter
$\mu\text{g/s}$	micrograms per second
μm	micrometer
mg/L	milligrams per liter
mg/s	milligrams per second
mL/min	milliliters per minute

Acronyms used in this report:

ICP-AES	inductively coupled plasma-atomic emission spectrometry
RSD	relative standard deviation
USGS	U.S. Geological Survey

Quantification of Metal Loads by Tracer-Injection and Synoptic-Sampling Methods in Cataract Creek, Jefferson County, Montana, August 1997

By Thomas E. Cleasby¹, David A. Nimick¹, and Briant A. Kimball²

Abstract

A study was conducted in the Cataract Creek drainage of west-central Montana in August 1997 to quantify and identify the principal sources of metal loads to Cataract Creek. Loads were calculated for an approximately 8-mile reach of Cataract Creek from near midbasin to the mouth by using streamflow information determined at mainstem and inflow sites using tracer-injection methods together with concentrations of major ions and metals that were determined in synoptic water-quality samples.

Instantaneous loads were computed for dissolved major ions (calcium, magnesium, and sulfate), as well as for dissolved and total-recoverable metals (iron, manganese, and zinc). The largest load increases in Cataract Creek for sulfate, manganese, and zinc were attributable to Uncle Sam Gulch. This single tributary source accounted for about 33 percent of the dissolved sulfate load, 60 percent of the dissolved manganese load, and over 90 percent of the dissolved zinc load entering Cataract Creek. Upstream from Uncle Sam Gulch, surface and subsurface inflows from the Eva May, Cataract, Boulder Chief, Ida M., Lower Hattie Ferguson, and Upper Hattie Ferguson Mine areas contributed smaller amounts of zinc loads to Cataract Creek.

On the basis of loads quantified in Cataract Creek, Uncle Sam Gulch is the major contributor of metals in the basin. Only small load increases occurred from sources upstream from Uncle Sam Gulch. Improvement in water quality of Cataract Creek, therefore, could be maximized by remediation efforts to reduce metal loads from Uncle Sam Gulch.

INTRODUCTION

Acid drainage from inactive mines and prospects and natural weathering of mineralized rock has affected the quality of water, aquatic habitat, and stream biota in streams throughout the western United States. The generation of acid, mostly by oxidation of pyrite and other sulfide-rich ore exposed to the atmosphere by mining operations, can liberate metals found within the mineralized rock. Metals such as aluminum, cadmium, copper, iron, lead, manganese, and zinc can be released to streams in high concentrations by this chemical process. The primary effect of high metal concentrations is degraded water quality and aquatic habitat, which consequently affects aquatic and fishery resources. The mass of a metal transported downstream, referred to as the metal load carried by the stream, depends upon the metal concentration in the stream and the streamflow. Metal loads indicate the effect that inflows with high metal concentrations have on receiving streams.

Streams of the Boulder River watershed, located in west-central Montana near the town of Basin (fig. 1), drain a highly mineralized area which has been extensively mined since the late 1800s. Most mining activity ceased by the 1940s, although some mining has occurred as recently as the 1990s. Ore bodies within the mineralized rock contain sulfur-bearing minerals; consequently, acid drainage occurs in Basin, Cataract, and High Ore Creeks, as well as the Boulder River. Metesh and others (1995) identified 58 inactive mines and 5 mill sites in the Cataract Creek drainage and noted that this basin has the largest number of inactive mines, tailings piles, and mine dumps in the Beaverhead-Deerlodge National Forest (fig. 1).

In 1996, the U.S. Geological Survey (USGS), began to investigate ways to develop efficient and cost-effective methods for characterizing the effects of acid

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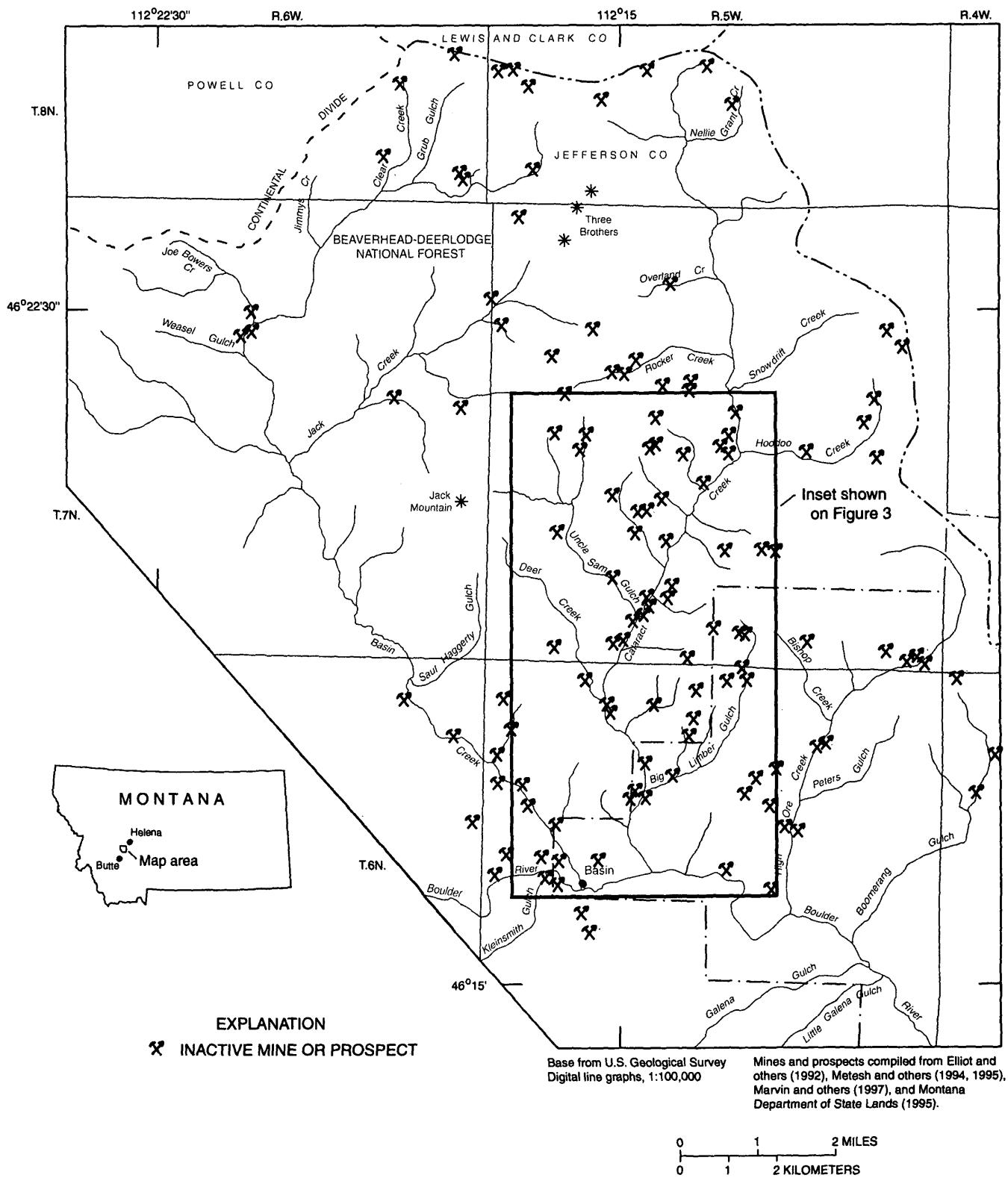


Figure 1. Location of study area.

mine drainage. The Boulder River watershed was selected to serve as a pilot study for this effort. Although inactive mines and prospects, tailings piles, and mine dumps have been identified in the tributary basins of Basin, Cataract, and High Ore Creeks, the principal sources and quantity of metals discharging to the streams were not well understood. Mine-related metal-loading sources may originate either from visible surface inflows, such as discharge from mine adits and drainage from waste rock and tailing piles, or from diffuse subsurface flows that drain similar mine settings but enter the stream as ground water. Upon entering the stream, water may flow either on the surface or within the coarse substrate of the streambed (fig. 2), especially in high-gradient mountain streams.

The streamflow component flowing through the streambed substrate (hereinafter referred to as hyporheic flow) cannot be measured by traditional current-meter methods. To account for this flow, tracer-injection methods can be used to quantify total stream-

flow by using changes in concentration of a tracer (chloride) injected at a constant rate and assuming conservation of mass (Kimball, 1997). By combining detailed information on total streamflow (obtained by the tracer-injection investigation) and metal mass-balance information (obtained by the synoptic water-quality sampling), principal sources and metal loads from both surface and subsurface inflows can be determined. These methods (hereinafter referred to as the metal-loading study) were used to determine principal sources and metal loads along a 40,905-ft reach of Cataract Creek (fig. 3).

Purpose and Scope

This report presents the results of a study to quantify and identify the principal sources of metal loads to Cataract Creek. Physical and chemical data were collected at 46 mainstem and 25 inflow sites during August 12-13, 1997. The study reach extended

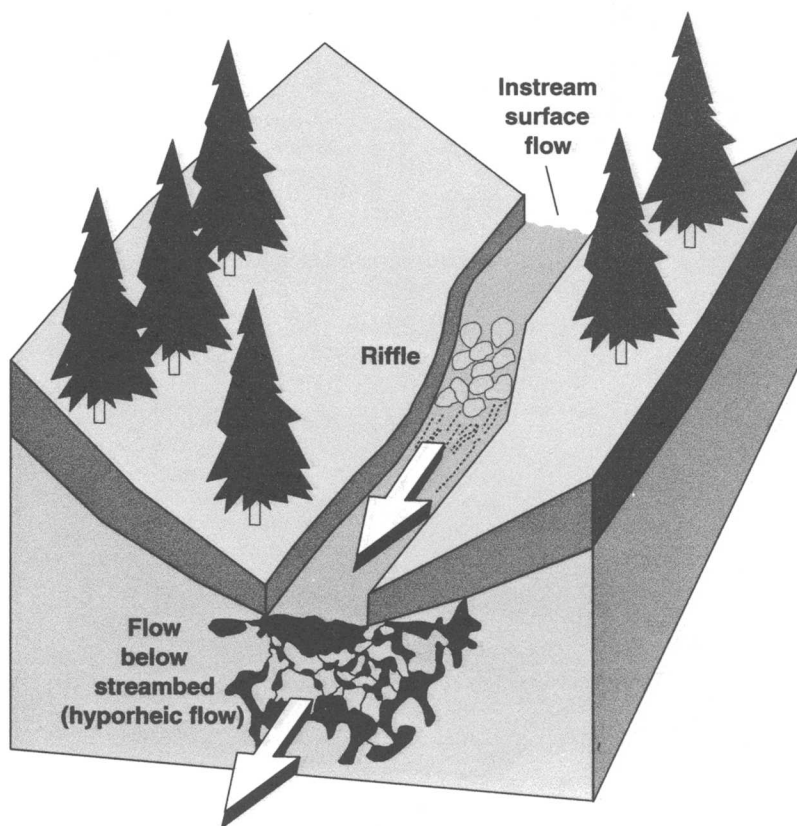


Figure 2. Conceptual diagram of surface and hyporheic flow components of total streamflow in a coarse-substrate mountain stream.

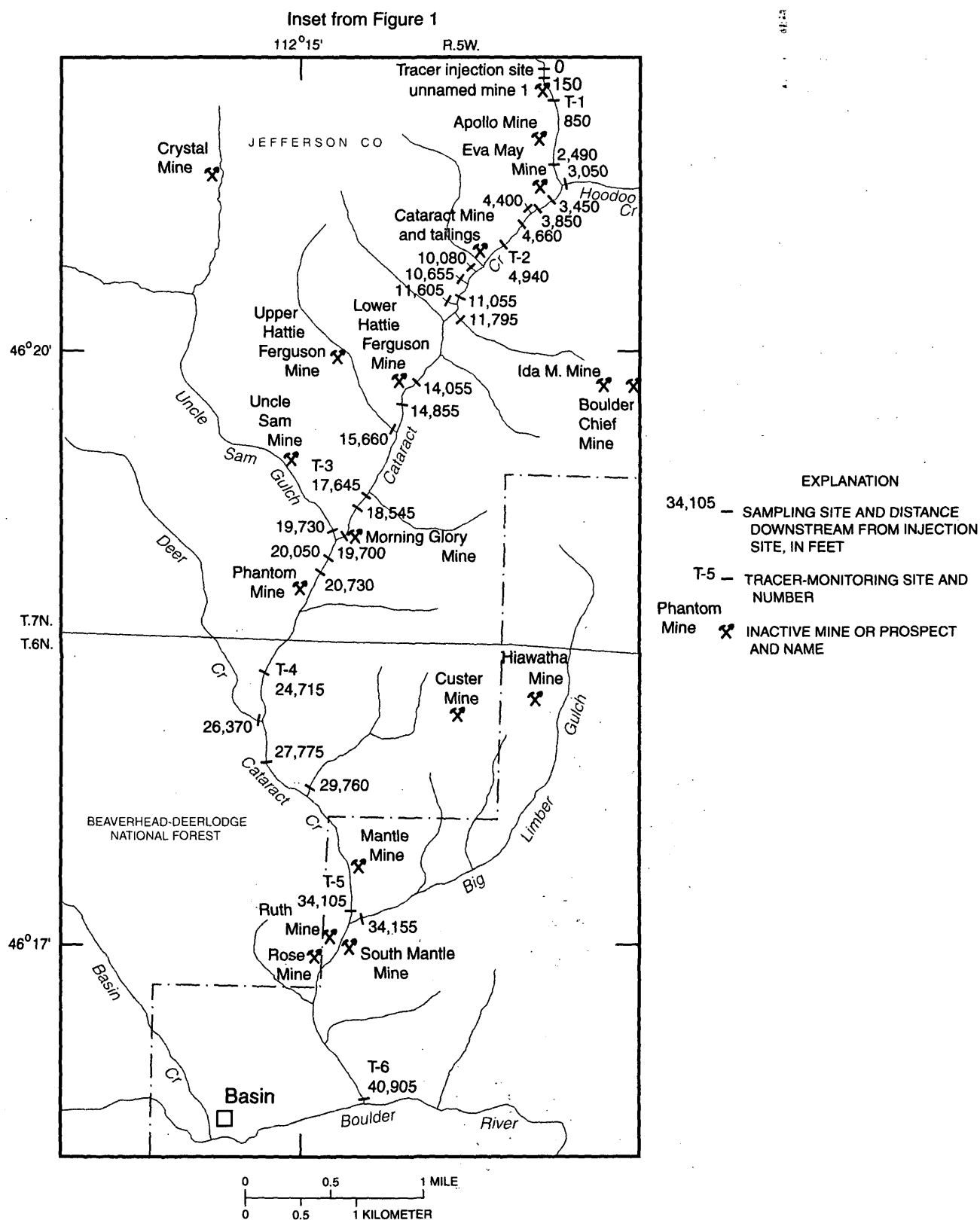


Figure 3. Detailed location of study reach, selected inactive mines or prospects, and selected sampling sites, Cataract Creek drainage, Montana.

from the tracer injection site on Cataract Creek, 3,050 ft upstream from Hoodoo Creek, to the confluence of Cataract Creek with the Boulder River, a distance of 40,905 ft, or about 8 mi (fig. 3). Metal loads were quantified using streamflow data, calculated by the tracer-injection methods, and water-quality data, determined from analyses of selected major ions and metals from the synoptic sampling. Downstream profiles provided spatial information on load changes needed to identify the principal sources of metal loads to Cataract Creek.

Description of the Study Area

The headwaters of Cataract Creek originate in the Beaverhead-Deerlodge National Forest at an altitude of about 8,200 ft. The stream is about 13 mi long and flows into the Boulder River about 1 mi east of Basin, Montana, at an altitude of 5,300 ft. At its headwaters, Cataract Creek meanders through relatively low gradient, high mountain meadows. The streambed in these upper reaches is composed of silt, sand, cobbles, and boulders. Just upstream from Uncle Sam Gulch (fig. 1), the topography steepens, and Cataract Creek flows through a narrow cascading reach that extends downstream to about Big Limber Gulch. The streambed within this cascading reach is composed mostly of large boulders and bedrock. Downstream from Big Limber Gulch, the valley broadens and the topography flattens. The streambed in these lower reaches is a mixture of boulders and cobbles.

The geology of the Cataract Creek drainage has been described in detail by Ruppel (1963) and Becraft and others (1963). The dominant geologic features in the study area are the Boulder Batholith and the overlying Elkhorn Mountain Volcanics. The ore veins that were explored and mined within the drainage were rich in sulfide minerals such as arsenopyrite, chalcopyrite, pyrite, galena, tetrahedrite, and sphalerite (Woodward, 1986).

Acknowledgments

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tion in allowing access to their lands. Appreciation is extended to Robert E. Broshears, DeAnn M. Dutton, Jon M. Evans, Robert L. Runkel, Katherine Walton-Day, and Tracy J. Yager of the USGS and volunteer Bryn Kimball for assistance in data collection and to Linda J. Gerner and Fredrick J. Rossi of the USGS for assistance with data collection and laboratory analyses.

METHODS OF DATA COLLECTION

A reconnaissance of the study reach was conducted 3 weeks before the start of the tracer injection. Sites to be sampled synoptically were selected and marked with flagging, and their distances downstream from the tracer-injection point were measured using a tape measure and recorded (table 1). Sampling sites on Cataract Creek were selected upstream and downstream from visible inflows, tailings piles, and other mining-related features that possibly could affect metal loads in the stream. All visible surface inflows were selected for sampling. To detect possible subsurface inflow, additional mainstem sites were selected in longer subreaches that had no visible surface inflow or mining disturbance. No sampling sites were located in the reach downstream from Big Limber Gulch to a short distance upstream from the mouth of Cataract Creek because of restricted access to the stream. Base-flow conditions absent of precipitation runoff were targeted to minimize complications of distinguishing sustained input of metals from short-term input associated with overland runoff.

Tracer Injection and Synoptic Sampling

Streamflow computed from current-meter measurements conducted at nine sites on August 11, 1997 were used to estimate the volume of tracer solution needed for the tracer injection. Before the start of the tracer injection, an ample volume of tracer solution was prepared in a 400-gallon plastic wading pool by mixing 720 pounds of sodium chloride (NaCl) with 1,300 L of stream water. This mixture ratio produced a concentration of chloride well above ambient stream concentrations, but below chloride saturation. This solution was injected continuously into Cataract Creek at a rate of 435 mL/min (0.00725 L/s) using a positive-

Table 1. Synoptic sampling site locations, Cataract Creek drainage, Montana

[Abbreviation: T, tracer-monitoring site]

Site number and distance downstream from tracer-injection site, in feet	General site description
Cataract Creek	
0	Tracer-injection site (3,050 feet upstream from Hoodoo Creek)
150	At small cascade
850	T-1
1,370	About 150 feet upstream from right-bank mine dump of unnamed mine 1
1,610	Just upstream from small mine dump at Apollo Mine
1,690	Downstream from mine dump at Apollo Mine
2,490	About 200 feet upstream from start of mine dump at Eva May Mine
3,450	Downstream from Hoodoo Creek
3,850	Along bend in stream, swift current, and constricted flow, upstream from Eva May Mine tailings
4,660	Adjacent to tailings pile at Eva May Mine
4,940	T-2, downstream from tailings at Eva May Mine
5,940	Downstream from large bend in stream, low gradient reach
6,800	Adjacent to road on right bank along large bend in stream
7,900	Downstream from old cabin
8,700	Downstream from mine dump, adjacent to Cataract Mine tailings
9,220	Downstream from mine dump, adjacent to Cataract Mine tailings
10,380	Downstream from end of the large flood plain, Cataract Mine tailings on both banks of Cataract Creek
11,055	Ponded water along right bank
12,115	Upstream from large clear-cut area
13,255	Upstream from Lower Hattie Ferguson Mine
14,055	Downstream from Lower Hattie Ferguson Mine. No visible inflow from mine along this reach
14,855	Upstream from left-bank inflow
15,655	Downstream from right-bank inflow draining the Upper Hattie Ferguson Mine area
16,845	Cataract Creek
17,645	T-3, downstream from logging-road ford
18,545	Cataract Creek
19,245	Upstream from Morning Glory Mine
19,700	Upstream from Uncle Sam Gulch, downstream from Morning Glory Mine
20,050	Downstream from Uncle Sam Gulch
20,730	Downstream from cabin
21,130	Cataract Creek
21,715	Along cascades downstream from small mine dumps
22,315	Cataract Creek
22,915	Downstream from small inflow
23,715	Cataract Creek
24,715	T-4
25,215	Upstream from start of canyon
26,335	Upstream from Deer Creek
26,590	Downstream from Deer Creek
26,970	100 feet downstream from large concrete bridge
27,775	Just downstream from second, wooden bridge
29,970	Downstream from old cabin on right bank
31,470	Along cascade section, road very close to stream

Table 1. Synoptic sampling site locations, Cataract Creek drainage, Montana (Continued)

Site number and distance downstream from tracer-injection site, in feet	General site description
<u>Cataract Creek—Continued</u>	
32,970	Wide section of canyon
34,105	T-5, upstream from Big Limber Gulch
34,355	Downstream from Big Limber Gulch
40,905	T-6, Cataract Creek at mouth
<u>Surface-inflow sites</u>	
160	Right-bank inflow
1,615	Right-bank inflow from mine dump
1,691	Right-bank inflow
3,050	Hoodoo Creek, left-bank inflow
4,400	Right-bank inflow from tailings at Eva May Mine
4,941	Right-bank inflow coming under road in a pipe
8,820	Right-bank inflow downstream from mine dump at Cataract Mine
9,225	Right-bank inflow with visible iron staining, Cataract Mine tailings
10,080	Right-bank inflow with iron staining in the vicinity of Cataract Mine tailings
10,655	Right-bank inflow
11,605	Right-bank inflow with iron staining
11,795	Left-bank inflow from Boulder Chief and Ida M. Mines, about 500 feet upstream from Lower Hattie Ferguson Mine
12,120	Left-bank inflow
14,860	Left-bank inflow
15,660	Right-bank inflow from Upper Hattie Ferguson Mine
15,845	Right-bank inflow
17,545	Left-bank inflow
19,730	Uncle Sam Gulch, right-bank inflow
21,315	Left-bank inflow, waste-rock piles on both sides of the stream
22,565	Left-bank inflow
22,715	Left-bank inflow
24,495	Right-bank inflow draining from oxbows
26,370	Deer Creek, right-bank inflow
29,760	Left-bank inflow
34,155	Big Limber Gulch, left-bank inflow

displacement metering pump system. The tracer injection was maintained for 34.6 hours from August 12, 1997 at 0831 to August 13, 1997 at 1910. Five samples of the tracer solution were collected periodically throughout the injection period to confirm a steady-state concentration. The chloride concentration of each tracer-solution sample was determined by measuring the density of the tracer solution with a laboratory-grade hydrometer and converting density to chloride concentration (Weast and Astle, 1981). The chloride concentration ranged from 130.0 g/L to 134.9 g/L; the average concentration (133.2 g/L) was used for calculating streamflow.

Water samples were collected at six sites, referred to as tracer-monitoring sites (fig. 3), to document the downstream movement of the tracer solution. Each tracer-monitoring site was sampled for ambient instream (background) chloride concentration before the arrival of the tracer. Many samples were collected during the tracer injection. These water samples were collected by manual and automatic samplers at a single point near midstream and subsequently were filtered through a 0.45- μ m capsule filter for laboratory analysis of dissolved chloride.

Stream velocities computed from the nine current-meter measurements were used to estimate the travel time needed for the injected chloride to achieve equilibrium throughout the study reach. After equilibrium was reached, synoptic water samples for chemical

analysis were collected in acid-washed bottles at each pre-selected sampling site on August 13, 1997 (fig. 3). To reduce the possible effect of load changes caused by diel variation in streamflow, samples were collected and processed as rapidly as possible. At sampling sites where stream mixing was believed to be complete, samples were collected at a single vertical near midstream. Equal-width, depth-integrated sampling methods were used at sites immediately downstream from surface inflows where mixing was expected to be incomplete. The samples then were transported to a central processing location near the middle of the study reach. Field values of specific conductance and pH were determined on an unfiltered aliquot of each sample. A second unfiltered aliquot was drawn for analysis of total-recoverable metals. Samples for major ions and dissolved metals were filtered through a 0.1- μ m plate filter. Chloride and sulfate concentrations were analyzed by the USGS laboratory in Salt Lake City, Utah, using ion chromatography. The minimum reporting levels for analyses done by ion chromatography are 0.01 mg/L for chloride and 0.01 mg/L for sulfate (Kimball and others, 1999). Cation and metal concentrations were analyzed by the USGS laboratory in Lakewood, Colo., using inductively coupled plasma-atomic emission spectrometry (ICP-AES). The minimum reporting levels for constituents analyzed by ICP-AES methods are presented in table 2 (Walton-Day and others 1999).

Table 2. Minimum reporting levels for constituent concentrations

[Abbreviations: ICP-AES, inductively coupled plasma-atomic emission spectrometry; IC, ion chromatography; μ g/L, micrograms per liter; mg/L, milligrams per liter]

Constituent	Minimum reporting level	Method
Major ions (in mg/L)		
Calcium	¹ 0.05	ICP-AES
Magnesium	¹ 0.02	ICP-AES
Sodium	¹ 0.06	ICP-AES
Potassium	¹ 0.02	ICP-AES
Chloride	² 0.01	IC
Sulfate	² 0.01	IC
Dissolved and total-recoverable metals (in μg/L)		
Aluminum	¹ 50	ICP-AES
Copper	¹ 50	ICP-AES
Iron	¹ 20	ICP-AES
Manganese	¹ 5	ICP-AES
Zinc	¹ 10	ICP-AES

¹Walton-Day and others, 1999.

²Kimball and others, 1999.

Quality Assurance

Data-collection and analytical procedures used in this study incorporated practices designed to control, verify, and assess the quality of sample data. Methods and associated quality control for collection and processing of water samples are described by Knapton (1985) and Horowitz and others (1994).

The precision of analytical results can be estimated by calculating the relative standard deviation (RSD) of each constituent analyzed in a group of samples. The RSD is calculated using the following equation:

$$RSD = \frac{S}{\bar{x}} \times 100 \quad (1)$$

where

- RSD = relative standard deviation
- S = standard deviation of concentrations in samples, and
- \bar{x} = mean of concentrations in samples.

Quality-assurance procedures used for the analysis of chloride and sulfate are described by Kimball and others (1999). Analytical precision was determined by repeated analysis of three reference samples (table 3). Two reference samples (SR16 and SR104) had concentrations within the range of concentrations of the envi-

ronmental samples (0.2 to 8.5 mg/L for chloride and 6.0 to 99.2 mg/L for sulfate). The relative standard deviations for replicate analyses of these two reference samples were 1.5 and 1.8 percent for chloride and 1.5 and 3.0 percent for sulfate. These values indicate that the analytical precision for analyses of environmental samples probably was less than 2.0 percent for chloride and less than 3.0 percent for sulfate.

The accuracy and precision of metal analyses performed by ICP-AES were determined by repeated analysis of USGS standard reference samples T-135 and T-143 (table 4). Accuracy was determined for each metal by comparing the most probable value for each reference sample (Long and Farrar, 1995; Farrar and Long, 1997) to the average analytical value. In most cases, the most probable value was within two standard deviations of the average analytical value. Analytical precision was assessed with the relative standard deviation of the replicate analyses of the reference samples. Relative standard deviations were less than 10 percent, except for copper, which had a relative standard deviation of about 12 percent in reference sample T-135. The precision for these reference samples probably is better than the precision obtained for environmental samples because variability introduced during sample collection and processing was not included.

Table 3. Quality-assurance data for dissolved chloride and sulfate analyses

[Analyses performed using ion chromatography. Abbreviation: mg/L, milligrams per liter. Symbol: --, not determined]

Reference sample	Most probable value, ¹ in mg/L	Utah District laboratory		
		Number of analyses	Average value (standard deviation), in mg/L	Relative standard deviation, in percent
Chloride concentration				
SR16 ²	5.00	129	5.00 (0.089)	1.8
SR104 ³	--	41	8.21 (0.12)	1.5
M102 ⁴	44.0	22	44.4 (1.41)	3.0
Sulfate concentration				
SR16 ²	50.0	129	46.3 (0.69)	1.5
SR104 ³	--	41	6.30 (0.19)	3.0
M102 ⁴	420.0	22	397.0 (12.3)	3.0

¹The most probable value was calculated by determining the median of many analyses reported by laboratories using various analytical methods (Kimball and others, 1999).

²SR16 is a standard reference sample from an independent laboratory.

³SR104 is a reference sample collected from Cataract Creek during the metal-loading study.

⁴M102 is a U.S. Geological Survey standard reference sample.

Table 4. Quality-assurance data for dissolved cation and metal analyses

[Analyses performed using inductively coupled plasma-atomic emission spectrometry. Abbreviations: µg/L, micrograms per liter; mg/L, milligrams per liter. Symbol: --, not determined; <, less than minimum reporting level]

Constituent (reporting units)	Most probable value ¹ (standard deviation)	Average value (standard deviation)	Relative standard deviation, in percent
Sample T-135 (6 analyses)			
Calcium (mg/L)	10.4 (0.6)	10.8 (0.41)	3.8
Magnesium (mg/L)	2.00 (0.09)	2.27 (0.07)	3.2
Potassium (mg/L)	.96 (0.09)	.95 (0.04)	3.8
Copper (µg/L)	62.0 (4.2)	59.0 (7.1)	12.1
Iron (µg/L)	228 (11)	234 (15.3)	6.5
Manganese (µg/L)	423 (20)	459 (28.5)	6.2
Zinc (µg/L)	48.2 (4.7)	48.8 (3.9)	8.1
Sample T-143 (2 analyses)			
Calcium (mg/L)	53.7 (0.48)	53.5 (0.48)	.9
Magnesium (mg/L)	10.4 (0.5)	10.6 (0.03)	.3
Potassium (mg/L)	2.50 (0.21)	2.72 (0.02)	.6
Aluminum (µg/L)	22.1 (8.3)	<50	--
Copper (µg/L)	22.3 (1.9)	<50	--
Iron (µg/L)	222 (14)	237 (1.6)	.7
Manganese (µg/L)	18.2 (1.9)	20.6 (1.9)	9.2
Zinc (µg/L)	20.0 (2.2)	17.6 (0.5)	2.6

¹The most probable value was calculated by determining the median of many analyses reported by laboratories using various analytical methods (Long and Farrar, 1995; Farrar and Long, 1997).

Two field blanks were collected and analyzed along with the environmental samples to identify the presence and magnitude of contamination that could potentially bias analytical results. These blanks were subjected to the same processing methods used in the collection of the environmental samples and were analyzed for the same constituents. Concentrations of all constituents were less than the minimum reporting level, except for one calcium value which was slightly greater than two times the minimum reporting level. Consequently, analytical results for the environmental samples are assumed to be free of significant or systematic bias from contamination associated with sample collection and processing.

TRACER-INJECTION RESULTS

A profile of constituent loads in a stream along many sampled points can reveal notable spatial differences and identify the location of significant sources. Because load is defined as the product of streamflow and metal concentration, accurate streamflow measurements are necessary for meaningful results. Tracer-injection methods, which use the principle of conservation of mass to calculate streamflow at synoptic sampling sites represent an alternative to traditional current-meter methods for determining streamflow in

mountain streams, particularly where traditional methods are hampered by irregular cross sections and turbulent flow (Kimball, 1997). Tracer-injection methods also account for the portion of flow that moves through the gravels and cobbles (hyporheic flow). This hyporheic flow cannot be measured by current-meter methods; therefore, loads would be underestimated using streamflow values obtained by current-meter measuring techniques if hyporheic flow was a substantial portion of the total streamflow. Another advantage of the tracer-injection method is that synoptic samples for determination of streamflow can be collected at numerous sites more quickly than streamflow can be measured with a current-meter. Thus, streamflow in a long study reach can be characterized in less time using the tracer-injection method, and the potential effect of temporal changes in streamflow that could complicate a synoptic profile of loads can be minimized.

Downstream Travel and Dilution

During continuous tracer injection, the downstream movement of the tracer solution is documented by sampling a few key sites called tracer-monitoring sites. Six tracer-monitoring sites, located from 850 to 40,905 feet downstream from the injection site (fig. 3, table 1), were sampled to track the movement of the

tracer solution during this study. The first monitoring site was located as close to the tracer-injection site as possible to minimize the potential for ground-water inflow to increase streamflow between the sites and interfere with the mass-balance calculations, but far enough downstream to ensure complete mixing of the tracer. The remaining monitoring sites were located at intervals designed to separate the stream into reaches having similar flow and velocity patterns. As a result, these sites were positioned just upstream from major hydrologic changes such as tributary inflows.

Information on the movement of the chloride tracer is gained by constructing temporal concentration

profiles of the change in chloride concentration with time for each tracer-monitoring site (fig. 4). Ideal temporal concentration profiles of an injected tracer have three distinct regions that show the arrival, plateau, and departure of the tracer. Arrival time is defined as the time in which the tracer reaches a concentration midway between the ambient (background) tracer concentration and the plateau concentration (Zellweger and others, 1988). Once the tracer concentration has reached equilibrium at a site, a generally stable plateau concentration exists until the tracer injection is terminated. The departure interval of the tracer starts when the tracer injection is terminated and chloride concen-

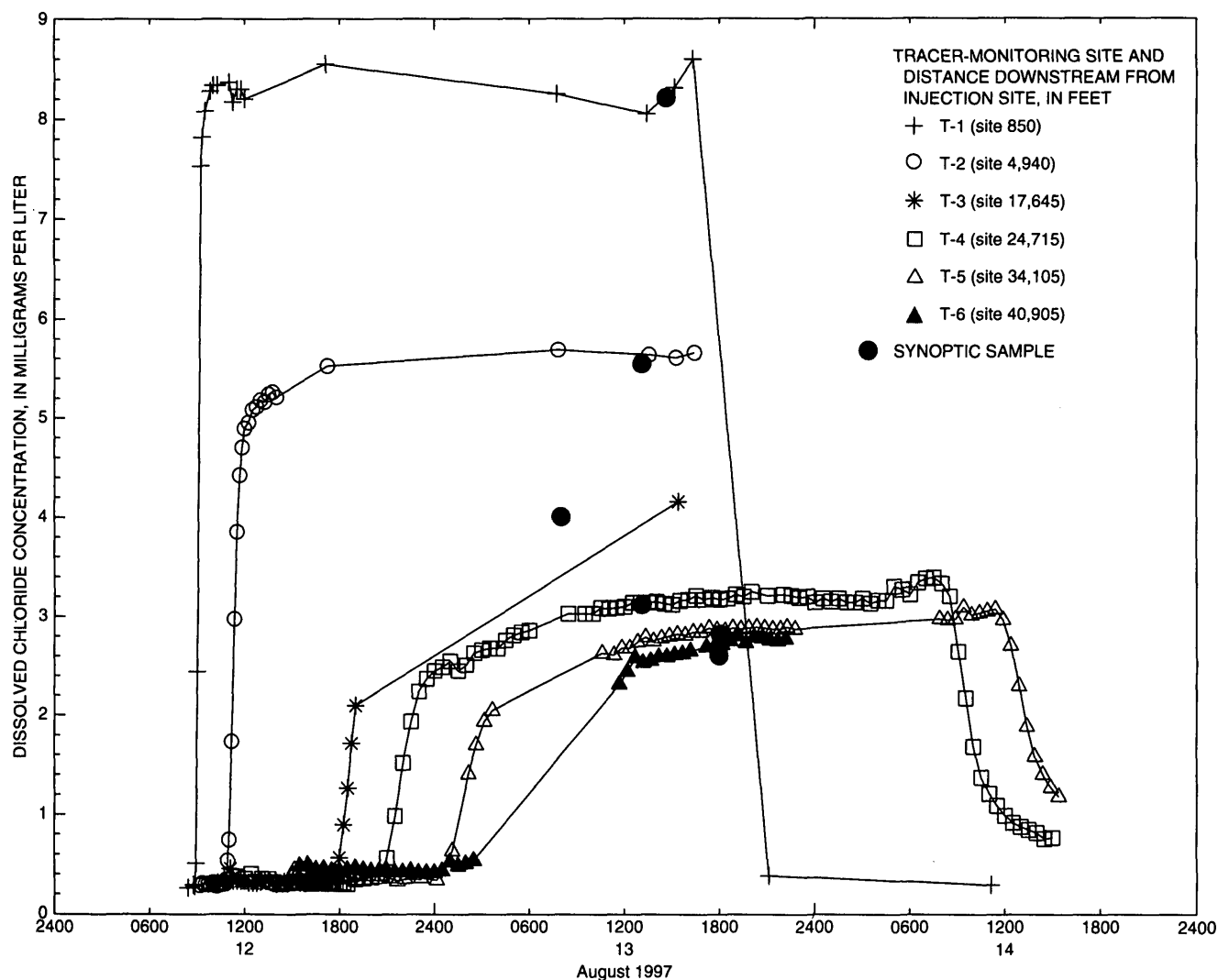


Figure 4. Temporal concentration profiles of dissolved chloride at tracer-monitoring sites, Cataract Creek, Montana, August 12-14, 1997.

trations decrease from plateau to ambient concentrations. The arrival of the tracer was used to calculate travel time between tracer-monitoring sites and cumulative travel time for the entire study reach (table 5). As the tracer moves downstream during the plateau period, it typically becomes diluted by inflows. Therefore, in a gaining stream, the magnitude of the plateau concentration decreases downstream as the instream flow increases. Data from the tracer-monitoring sites are used to verify that a relatively stable plateau concentration was reached at each site. Minor changes in chloride concentration during the plateau phase can be caused by natural streamflow variations, analytical error, or both.

Plateau concentrations were determined for each tracer-monitoring site from graphs showing the rate of change in tracer concentration. For example, data for site T-4 are illustrated in figure 5. The arrival of the tracer is seen as a sharp positive increase in the rate of change of the tracer concentration, and the departure is defined by an equally sharp negative rate change in tracer concentration. The plateau phase at a monitoring site was defined as the period of time between the arrival and departure of the tracer. The plateau concentration for each tracer-monitoring site then was defined as the average concentration of all samples collected within this time period. This method was used for each monitoring site except for site T-3, where only one sample was collected during the plateau phase; the chloride concentration analyzed in this single sample was used for the plateau concentration because chloride concentrations at tracer-monitoring sites upstream

and downstream from site T-3 were at plateau when this sample was collected. It was assumed that T-3 was also at plateau. Samples for the departure of the tracer were not collected at T-2, T-3, and T-6 (fig. 4).

Calculation of Streamflow

Streamflow can be calculated at any site downstream from the tracer-injection site using the instream tracer concentration and the concentration and injection rate of the tracer solution. The instream tracer concentration was determined at each synoptic sampling site from a smoothed profile of tracer (chloride) concentrations determined in synoptic samples collected during the plateau phase. The chloride concentrations reported by the laboratory were smoothed (fig. 6) using an algorithm described by Velleman and Hoaglin (1981). Adjustment was made for the changes in chloride concentration near major surface inflows. For these locations, reported concentrations were substituted for smoothed values upstream and downstream from these major inflows (table 6). The combination of smoothed and reported values were used in calculating streamflow.

The mass of the injected tracer is presumed to remain in solution as it travels downstream. After correcting for ambient (background) instream chloride concentration, any decrease in chloride concentration is assumed to be the result of dilution from inflows. The magnitude of streamflow necessary to achieve this dilution can be calculated to quantify the total streamflow, including both surface flow above the streambed

Table 5. Travel time of the tracer solution between tracer-monitoring sites, Cataract Creek, Montana, August 12-14, 1997

[Abbreviations: mg/L milligrams per liter]

Tracer-monitoring site (fig. 3)	Distance downstream from tracer-injection site (feet)	Dissolved chloride concentrations (mg/L)			Travel time for subreach (minutes)	Cumulative travel time (minutes)	Average velocity for subreach (feet per second)
		Ambient	Plateau ¹	C ₅₀ ²			
T-1	850	0.26	8.31	4.03	35	35	0.40
T-2	4,940	.29	5.62	2.66	130	165	.52
T-3	17,645	.31	4.15	1.92	458	623	.46
T-4	24,715	.37	3.17	1.40	182	805	.65
T-5	34,105	.39	2.86	1.24	229	1,034	.68
T-6	40,905	.48	2.76	1.14	230	1,264	.49

¹Plateau concentration is defined as the equilibrium tracer concentration that exists at a site after the arrival of the tracer.

²C₅₀ is the concentration midway between the plateau and ambient concentrations.

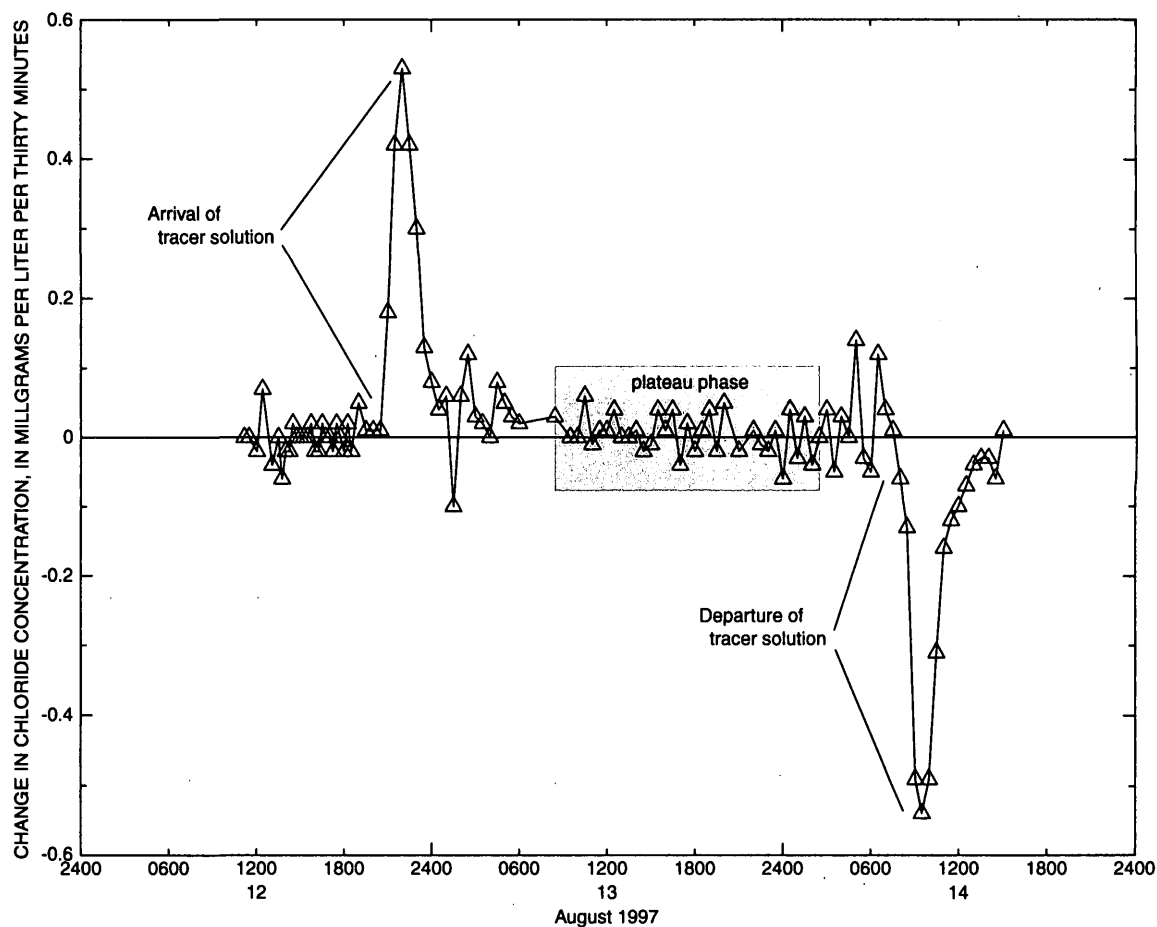


Figure 5. Rate of change in dissolved chloride concentration at tracer-monitoring site T-4, Cataract Creek, Montana, August 12-14, 1997.

and hyporheic flow through the channel substrate. This measure of total streamflow at sampling sites can then be used to quantify inflow between mainstem sites and to compute constituent loads. For this study, the injection rate was 435 mL/min (0.00725 L/s), and the concentration of the tracer solution was 219.5 g/L NaCl, or 133.2 g/L Cl (133,200 mg/L). Streamflow at the first mainstem site downstream from the tracer-injection site is calculated using equation 2:

$$Q_a = \frac{Q_{inj}(C_{inj} - C_o)}{(C_a - C_o)} \quad (2)$$

where

Q_a is the streamflow at the first mainstem site downstream from the injection, in L/s;

Q_{inj} is the injection rate of the tracer solution, in L/s;

C_{inj} is the concentration of the tracer solution, in mg/L;

C_o is the ambient chloride concentration near the injection site, 0.25 mg/L; and

C_a is the chloride concentration at the first downstream site, in mg/L.

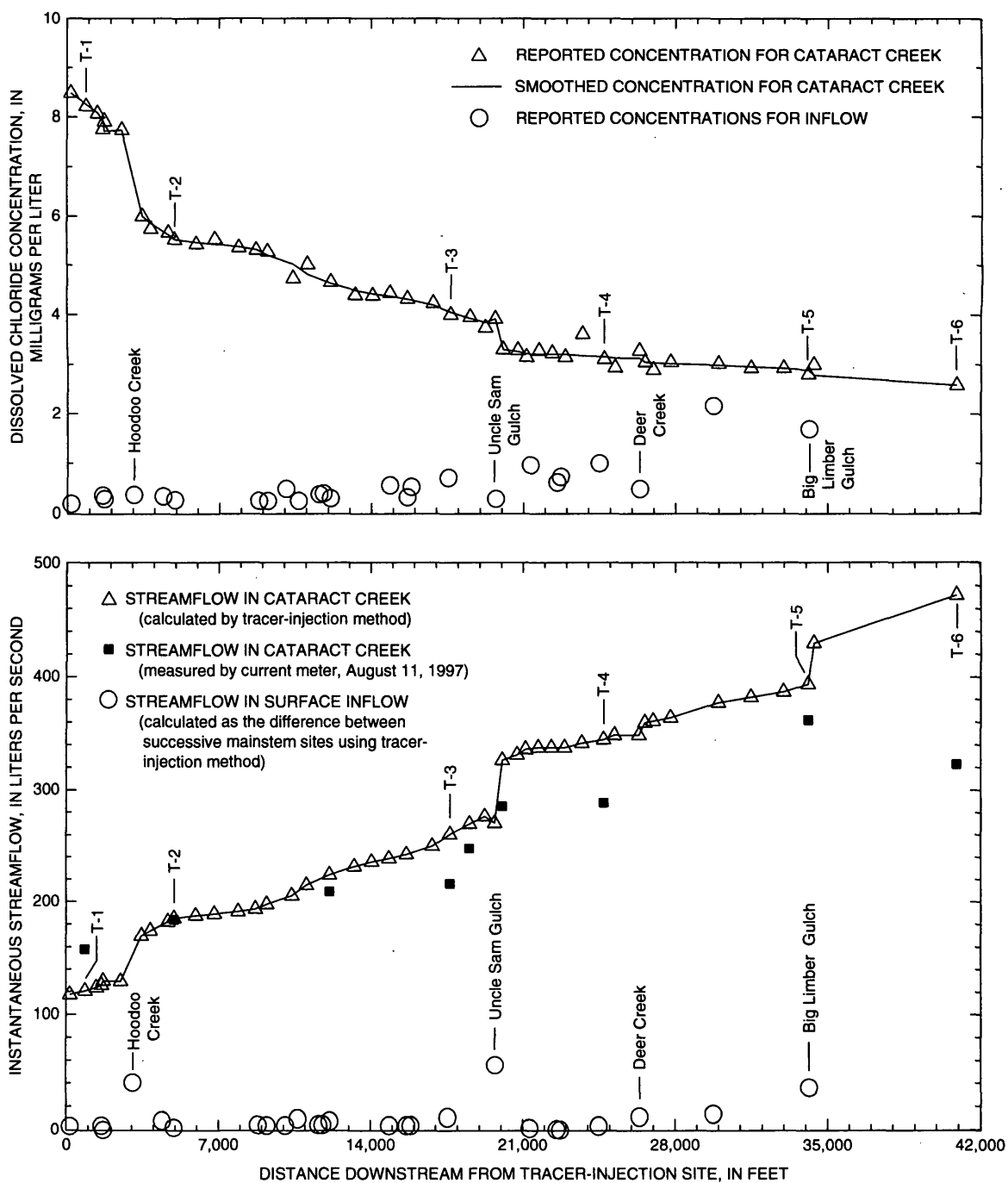


Figure 6. Dissolved chloride concentration (top) and streamflow (bottom) at synoptic sampling sites in the Cataract Creek drainage, Montana, August 13, 1997. T-1 to T-6 are tracer-monitoring sites.

Table 6. Dissolved chloride concentration and streamflow at synoptic sampling sites in the Cataract Creek drainage, Montana, August 13, 1997

[Abbreviations: L/s, liters per second; mg/L, milligrams per liter. Symbol: --, no data]

Distance downstream from injection site (feet)	Dissolved chloride concentration (mg/L)		Tracer- calculated streamflow (L/s)	Current-meter measured streamflow ² (L/s)
	Reported (unrounded)	Smoothed ¹		
Cataract Creek				
150	8.48	8.48	117	--
850	8.21	8.26	121	158
1,370	8.07	8.08	124	--
1,610	7.76	7.94	126	--
1,690	7.91	7.72	130	--
2,490	7.74	7.74	129	--
3,450	5.99	5.99	170	--
3,850	5.73	5.85	174	--
4,660	5.65	5.61	182	--
4,940	5.51	5.52	185	184
5,940	5.42	5.46	187	--
6,800	5.52	5.42	189	--
7,900	5.35	5.37	191	--
8,700	5.30	5.31	193	--
9,220	5.27	5.20	198	--
10,380	4.73	5.02	205	--
11,055	5.01	4.81	215	--
12,115	4.66	4.63	224	209
13,255	4.39	4.49	231	--
14,055	4.38	4.42	236	--
14,855	4.43	4.37	239	--
15,655	4.32	4.31	242	--
16,845	4.23	4.19	250	--
17,645	4.00	4.05	261	216
18,545	3.96	3.93	270	248
19,245	3.74	3.85	276	--
19,700	3.92	3.92	271	--
20,050	3.30	3.30	326	286
20,730	3.29	3.26	331	--
21,130	3.15	3.22	336	--
21,715	3.28	3.21	338	--
22,315	3.23	3.21	338	--
22,915	3.15	3.21	338	--
23,715	3.61	3.18	342	--
24,715	3.11	3.16	345	289
25,215	2.94	3.13	349	--
26,335	3.28	3.13	349	--
26,590	3.05	3.05	360	--
26,970	2.89	3.04	361	--
27,775	3.05	3.02	364	--
29,970	3.02	2.99	377	--
31,470	2.93	2.96	382	--
32,970	2.93	2.93	387	--
34,105	2.81	2.89	394	362
34,355	3.00	2.79	430	--
40,905	2.59	2.59	472	323

Table 6. Dissolved chloride concentration and streamflow at synoptic sampling sites in the Cataract Creek drainage, Montana, August 13, 1997 (Continued)

Distance downstream from injection site (feet)	Dissolved chloride concentration (mg/L)		Tracer- calculated streamflow (L/s)	Current-meter measured streamflow ² (L/s)
	Reported (unrounded)	Smoothed ¹		
		<u>Surface Inflow</u>		
160	.19	--	3.20	--
1,615	.36	--	3.76	--
1,691	.29	--	.01	--
3,050	.37	--	40.3	--
4,400	.34	--	7.93	--
4,941	.27	--	2.14	--
8,820	.25	--	4.30	--
9,225	.25	--	3.82	--
10,080	.49	--	3.82	--
10,655	.25	--	9.45	--
11,605	.38	--	4.64	--
11,795	.40	--	4.56	--
12,120	.30	--	7.48	--
14,860	.56	--	3.82	--
15,660	.32	--	3.86	--
15,845	.53	--	3.86	--
17,545	.71	--	10.5	--
19,730	.29	--	55.8	--
21,315	.96	--	1.49	--
22,565	.62	--	.01	--
22,715	.73	--	.01	--
24,495	1.00	--	3.16	--
26,370	.49	--	10.9	--
29,760	2.17	--	13.3	--
34,155	1.70	--	36.1	--

¹Reported chloride concentrations were smoothed using methods described by Velleman and Hoaglin (1981). Smoothed values were used in computing tracer-calculated streamflow.

²Current-meter measurements were conducted on August 11, 1997, two days before the synoptic samples were collected.

The calculated streamflow and ambient instream concentration for the first mainstem site then are used to calculate streamflow at the next downstream sampling site. Similarly, the streamflow and instream concentration for each mainstem site are used in calculating streamflow for the next downstream site. Equation 3 is used for these calculations:

$$Q_b = \frac{Q_a(C_a - C_i)}{(C_b - C_i)} \quad (3)$$

where

- Q_b is the streamflow at the downstream mainstem site (site b), in L/s;
- Q_a is the streamflow at the upstream mainstem site (site a), in L/s;
- C_a is the chloride concentration at the upstream site, in mg/L;
- C_i is the chloride concentration in the water that enters the stream between the two mainstem sites, in mg/L; and
- C_b is the chloride concentration at the downstream site, in mg/L.

If no surface inflow was sampled between the mainstem stream sites, then the average chloride concentration (0.56 mg/L) for all inflows sampled, including ambient concentration (0.25 mg/L) upstream from the injection site, in the study reach was used for the value of C_i (table 6). The magnitude of each inflow was determined by the difference in streamflow between the mainstem sites immediately downstream and upstream from the inflow. Streamflow values for inflow sites, listed in table 6, were calculated using unrounded mainstem values. The increase in streamflow for each subreach was the difference between flows at the upstream and downstream ends of the reach. Hydrologic sources accounting for flow increases could include the visible inflows that were sampled as well as unsampled diffuse seeps and ground-water discharge.

Using the instream chloride concentration from synoptic samples and the equations listed above, instantaneous streamflow was calculated at the 46 mainstem sites and 25 inflow sites sampled during this study (fig. 6). Streamflow in Cataract Creek increased from 117 L/s at the first site 150 ft downstream from the tracer injection to 472 L/s at the most downstream site 40,905 ft from the tracer injection, for a total increase of 355 L/s. Sampled surface inflows accounted for

238 L/s (67 percent) of the 355 L/s increase in the mainstem, leaving 117 L/s (33 percent) of the total increase attributable to unsampled seeps and subsurface inflow. Three major tributaries (Hoodoo Creek, Uncle Sam Gulch, and Big Limber Gulch) were responsible for about 55 percent of all surface inflows sampled during this study, with Uncle Sam Gulch being the largest contributor, accounting for about 23 percent of the surface inflow to Cataract Creek.

Several current-meter measurements of streamflow in Cataract Creek were made on August 11, 1997. Although these measurements were made two days before the synoptic samples were collected, they are compared to the streamflow values calculated from chloride concentrations in synoptic samples collected August 13, 1997. The comparison is assumed to be a reasonable basis for assessing differences in the two methods for determining streamflow because this study was done during base flow from August 11 through August 13, and streamflow appeared to be stable based on available stage references. Because hyporheic flow is included in the streamflow value obtained from the tracer-injection method, the tracer-calculated streamflow was expected to be greater than the current-meter streamflow, which does not measure hyporheic flow. Greater flow was detected by the tracer-injection method at all sites except for the most upstream site (site 850). Possibly, the tracer solution at this upstream site, which was near the injection point, may not have been fully mixed when the synoptic sample was collected, thereby leading to an underestimation of the tracer-calculated streamflow. At the other sites, the tracer-calculated streamflow ranged from <1 to 46 percent greater than the current-meter streamflow. These differences are in the same range as reported in other similar studies (Kimball, 1997; Kimball and others 1999).

Streamflow can only be determined by tracer-injection methods in a gaining stream reach where dilution effects on concentration can be translated to a quantifiable increase in flow. In a losing stream reach, the tracer concentration would remain constant even though instream flow decreases. The constant concentration would infer no change in flow, thereby resulting in an overestimation of flow in and downstream from the losing reach. A loss of flow of about 11 percent was indicated by the current-meter measurements made at the two sites 34,105 and 40,905 ft below the tracer-injection site near the downstream end of the study reach. In the area between these two sites, the topogra-

phy is predominated by a broad unconfined flood plain, which contrasts to the narrow, confined stream channel upstream from site 34,105. With this topographic change, a loss of streamflow to ground water can be expected and may explain why results from the two methods diverge more near the bottom of the study reach. Without additional information, it is uncertain whether the streamflow actually was increasing owing to subsurface inflow, if flow was being lost to ground water, or if more of the surface component of total streamflow was simply moving through the streambed as hyporheic flow through this section of Cataract Creek.

SYNOPTIC-SAMPLING RESULTS

Accurate concentration data are equally as important as representative streamflow values for compiling a meaningful profile of constituent loads for a stream. The synoptic samples collected at each of the 46 mainstem sites and 25 inflow sites were analyzed for pH, major-ion concentrations, and dissolved and total-recoverable metal concentrations (table 8, at back of report).

Physical Properties and Major-Ion Concentrations

Because the injected tracer solution increases the dissolved-solids concentration of stream water, the measured specific-conductance values for stream samples are greater than would be observed during ambient conditions. Specific-conductance values for inflows were variable and ranged from 57 (site 10,655) to 500 $\mu\text{S}/\text{cm}$ (site 29,760).

Values of pH in Cataract Creek were slightly basic and remained fairly constant (fig. 7) throughout the study reach, ranging from 7.38 (site 11,055) to 8.23 (site 27,775). The pH values for the inflows were more variable. Except for two values, inflow pH values were either near neutral or basic. Two small inflows, a right-bank inflow entering Cataract Creek downstream from the Cataract Mine tailings area (site 10,080) and a small right-bank inflow entering Cataract Creek just upstream from the Lower Hattie Ferguson Mine area (site 11,605), were slightly acidic, with pH values of 6.91 and 6.61, respectively.

Calcium, magnesium, and sulfate concentrations generally increased downstream (fig. 8). Calcium and magnesium are derived from the natural weathering of the rocks found throughout the watershed. In contrast, sulfate and metals, such as zinc, are liberated by oxida-

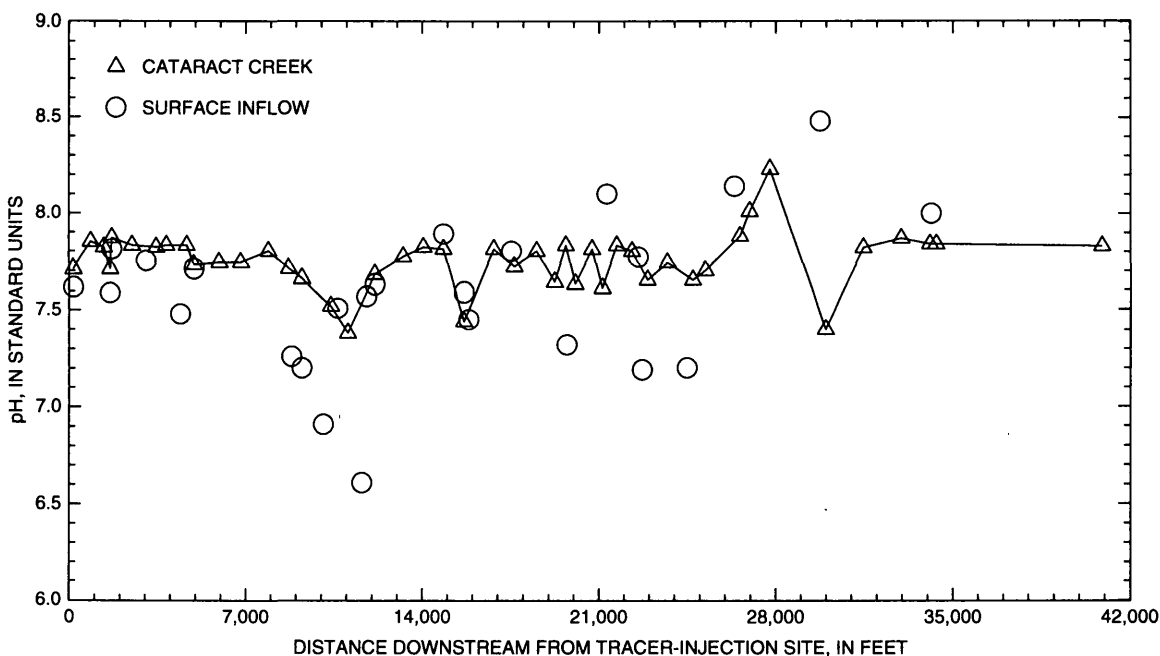


Figure 7. Downstream variation in pH in surface water from the Cataract Creek drainage, Montana, August 13, 1997.

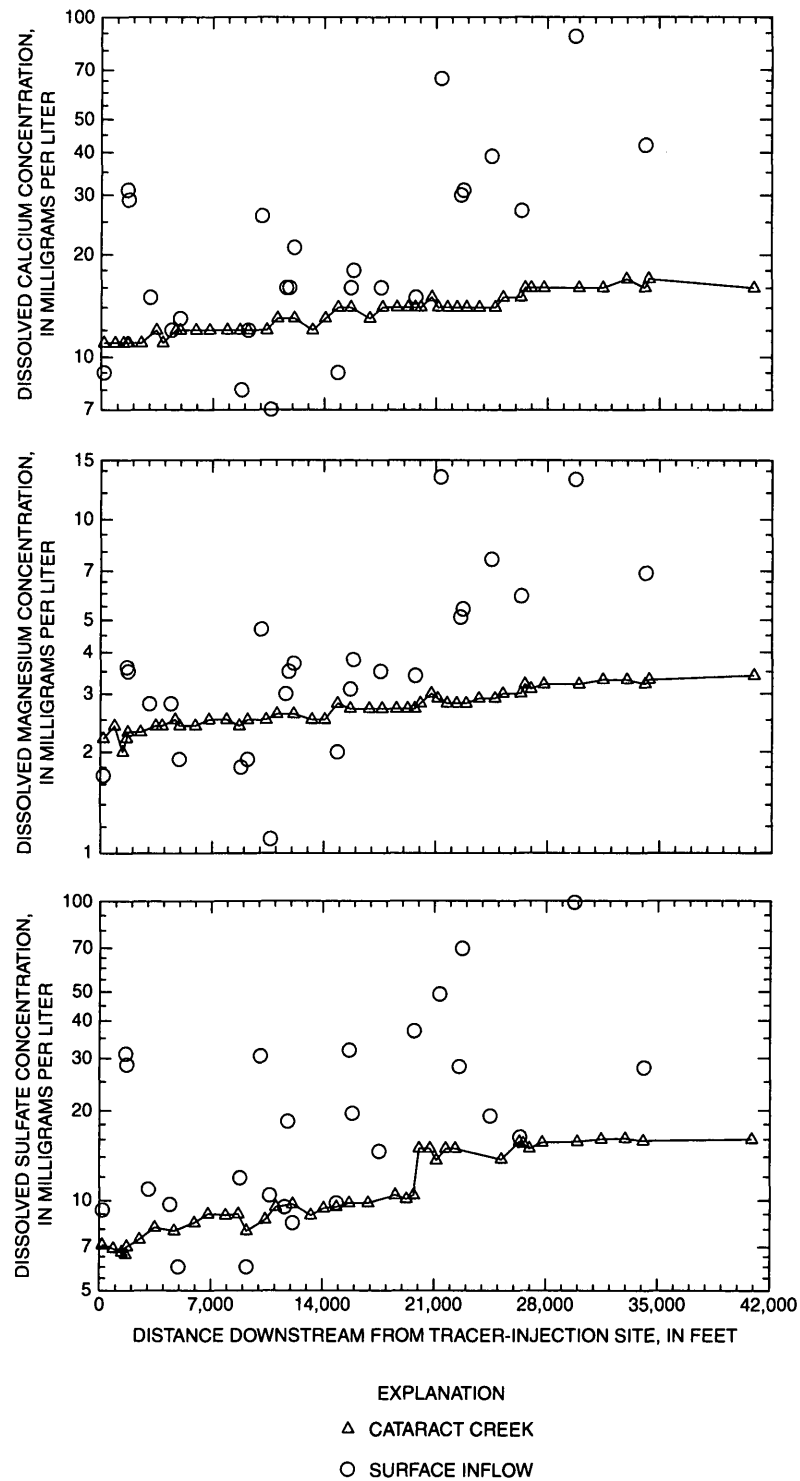


Figure 8. Concentrations of dissolved calcium, magnesium, and sulfate in synoptic samples collected in the Cataract Creek drainage, Montana, August 13, 1997.

tion of sulfide minerals found in the mineralized ore veins in the watershed. This geochemical reaction is accelerated after the sulfide-rich rocks are exposed during mining activities. The sulfate-concentration profile exhibits a downstream increase somewhat similar to the profiles for calcium and magnesium, but inflow from Uncle Sam Gulch causes a distinct concentration increase at site 20,050, just downstream from Uncle Sam Gulch.

Dissolved Metal Concentrations

Concentrations of only a few metals of interest in the synoptic samples (table 2) were significantly greater than minimum reporting levels. These metals--iron, manganese, and zinc--are discussed below. Concentration profiles for these metals are shown in figure 9.

Dissolved iron concentrations in Cataract Creek steadily decreased from the highest value of 299 $\mu\text{g/L}$ near the upper end of the study reach to the lowest value of 48 $\mu\text{g/L}$ at the mouth of Cataract Creek. Dissolved iron concentrations in Cataract Creek decreased sharply near the Eva May Mine area (between sites 2,490 and 3,450) and near Uncle Sam Gulch (between sites 19,700 and 20,050).

Concentrations of dissolved manganese upstream from Uncle Sam Gulch were low and ranged from less than the minimum reporting level of 5 $\mu\text{g/L}$ to 26 $\mu\text{g/L}$ just downstream from the Lower Hattie Ferguson Mine area (site 14,055). No visible surface inflow was observed near the Lower Hattie Ferguson Mine area and, therefore, the increase in concentration might have been caused by metal-rich subsurface inflow originating from the mine complex. The highest dissolved manganese concentration (97 $\mu\text{g/L}$) in Cataract Creek occurred at sites 20,050 and 20,730, just downstream from Uncle Sam Gulch. Downstream from this site, dissolved manganese concentrations remained elevated, but steadily decreased to the end of the study reach.

Dissolved zinc concentrations were nearly equal to or greater than the aquatic-life criterion for chronic toxicity in most samples collected from Cataract Creek downstream from the Eva May Mine area (3,850) (fig. 9). Assuming a hardness value equal to the maximum value in the mainstem samples (50 mg/L as CaCO_3), the aquatic-life criterion for chronic toxicity for zinc is

59 $\mu\text{g/L}$ and the criterion for acute toxicity is 65 $\mu\text{g/L}$ (U.S. Environmental Protection Agency, 1986).

Although these criteria apply to the total-recoverable concentrations in this report, they are also compared to the dissolved zinc concentrations, because the dissolved fraction of zinc is more readily assimilated by organisms. From the injection site to the Eva May Mine area (site 3,850), dissolved zinc concentrations were less than the minimum reporting level of 10 $\mu\text{g/L}$. Dissolved zinc concentrations in samples collected adjacent to the Eva May Mine tailings (site 4,660) to just upstream from Uncle Sam Gulch (site 19,700) ranged from 30 to 60 $\mu\text{g/L}$; the concentration in one sample (60 $\mu\text{g/L}$) from the Lower Hattie Ferguson Mine area (site 14,855) exceeded the aquatic-life criterion for chronic toxicity (fig. 9). Downstream from Uncle Sam Gulch to the mouth of Cataract Creek, dissolved zinc concentrations ranged from 256 to 470 $\mu\text{g/L}$; the highest concentration occurred just downstream from Uncle Sam Gulch (site 20,050). Dissolved zinc concentrations remained elevated, but steadily decreased downstream to the end of the study reach. The aquatic-life criterion for acute toxicity (65 $\mu\text{g/L}$ for zinc) was exceeded in every sample collected from Cataract Creek downstream from Uncle Sam Gulch.

Cadmium and copper are other metals commonly associated with acid mine drainage. Because the minimum reporting levels for the ICP-AES analytical method used for this study were high relative to the instream concentrations of dissolved cadmium and copper at many sites, concentration profiles for these metals are not presented. However, cadmium and copper concentrations can be estimated because the correlations between dissolved zinc concentrations and dissolved cadmium and copper concentrations (fig. 10) are good on the basis of data for water-quality samples collected from the Cataract Creek drainage during low-flow conditions in 1996-98 and analyzed by other methods having lower minimum reporting levels (Nimick and Cleasby, 2000). Where dissolved zinc concentrations range from <10 to 60 $\mu\text{g/L}$ upstream from Uncle Sam Gulch, estimated concentrations would be about <0.01 to 0.18 $\mu\text{g/L}$ for dissolved cadmium and <8.0 to 10 $\mu\text{g/L}$ for dissolved copper. Downstream from Uncle Sam Gulch, estimated concentrations would range from about 2.7 to 5.4 $\mu\text{g/L}$ for dissolved cadmium and 20 to 31 $\mu\text{g/L}$ for copper.

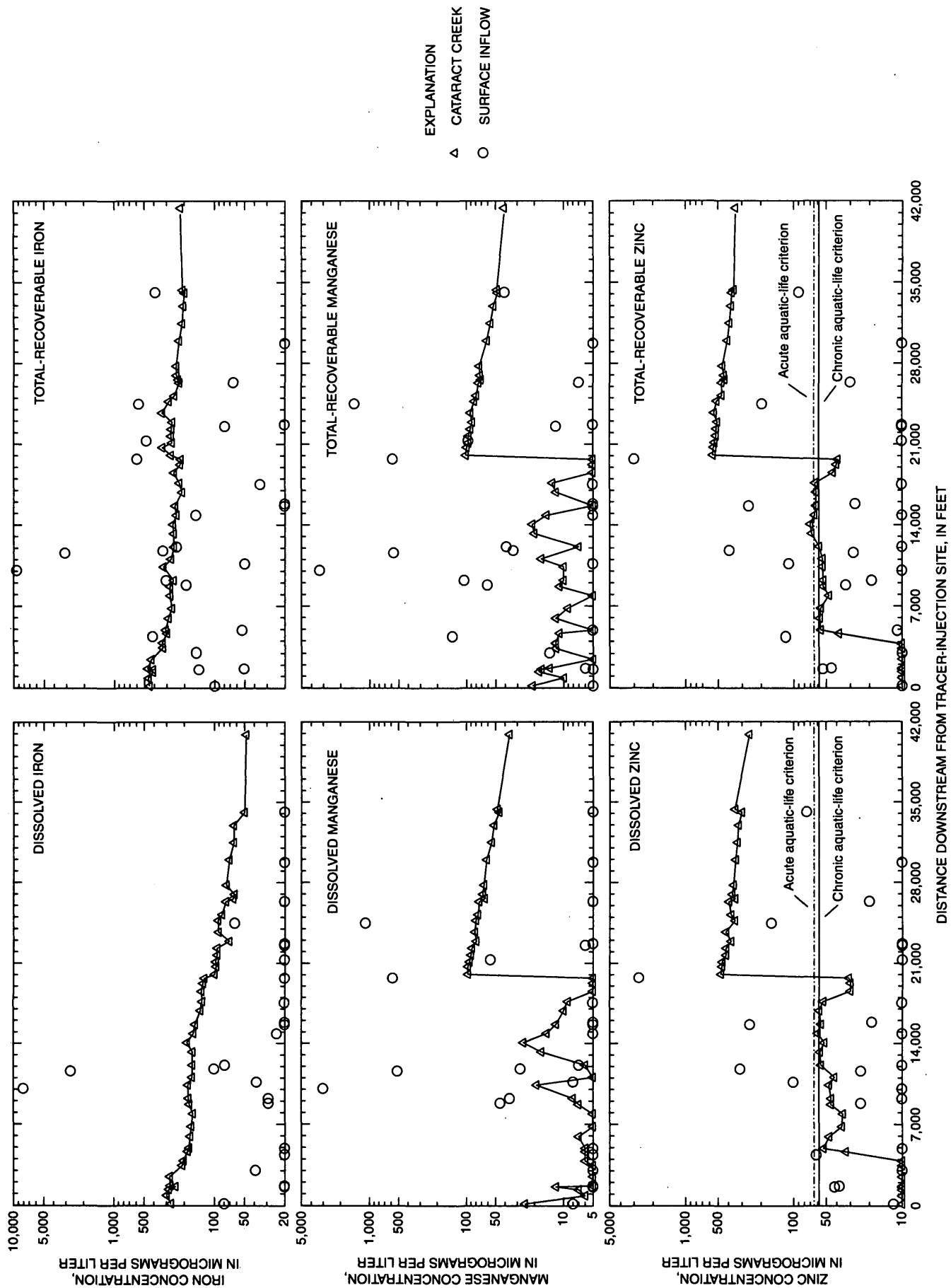


Figure 9. Concentrations of iron, manganese, and zinc in synoptic samples collected in the Cataract Creek drainage, Montana, August 13, 1997. Values equal to or less than the minimum reporting level for each metal are plotted on the x-axis. Acute and chronic aquatic-life criteria for zinc based on an assumed hardness of 50 mg/L as CaCO_3 .

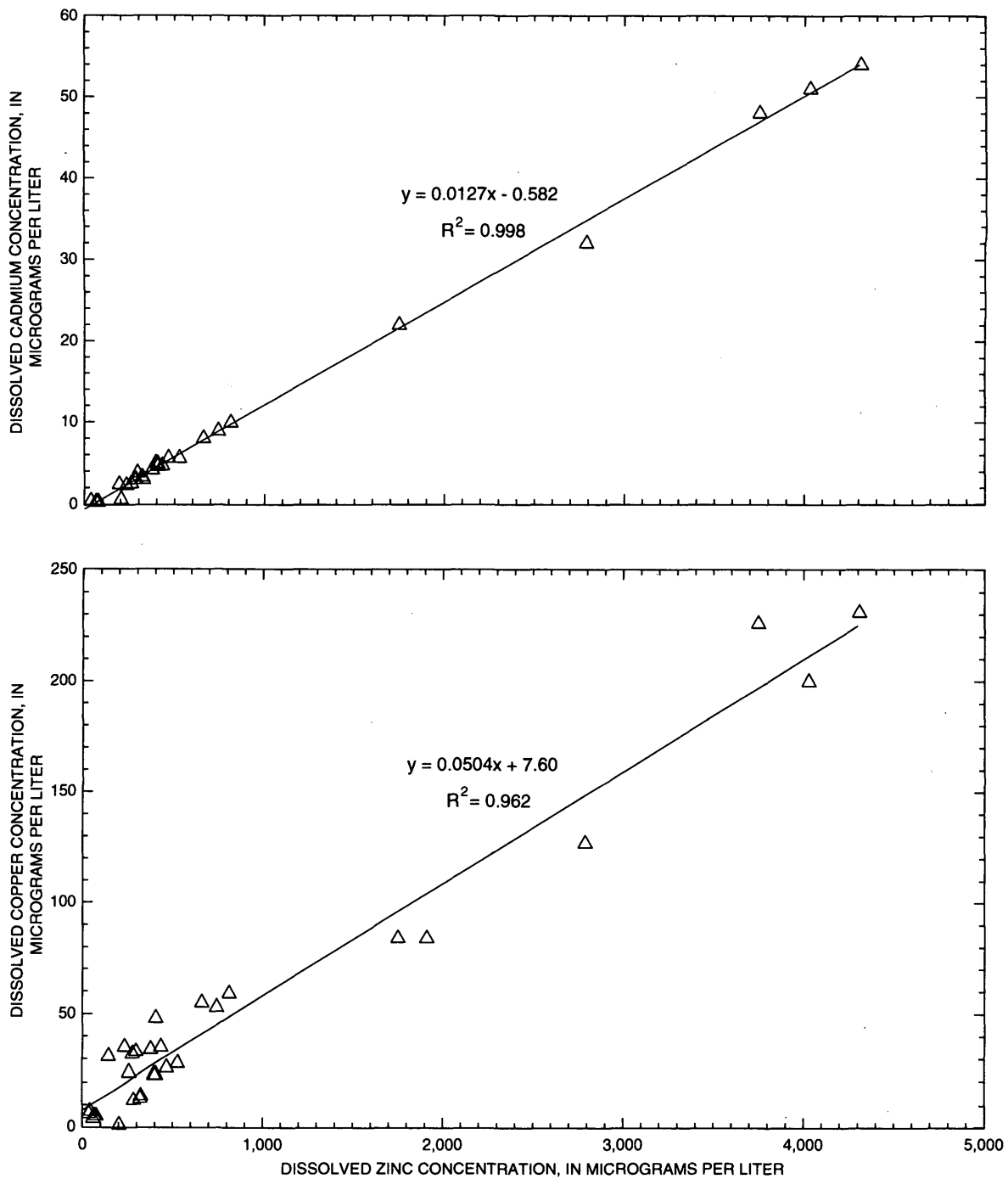


Figure 10. Relation of dissolved zinc to dissolved cadmium concentration (top) and dissolved copper concentration (bottom) in water samples collected during low flow in the Cataract Creek drainage, Montana, 1996-98 (Nimick and Cleasby, 2000).

Total-Recoverable Metal Concentrations

Total-recoverable iron concentrations in Cataract Creek (fig. 9, table 8) generally decreased downstream to just above Uncle Sam Gulch (site 19,700), then increased just below the confluence (site 20,050). This increase was not observed in the dissolved fraction and probably indicates that the dissolved iron contributed to Cataract Creek from Uncle Sam Gulch quickly forms colloids, which aggregate to form solids. Because dissolved iron concentrations in Cataract Creek decreased substantially immediately below Uncle Sam Gulch (site 19,730) even as total-recoverable iron was increasing, it may be possible that the aggregation of colloids serves to geochemically accelerate the partitioning of iron out of solution to a colloidal phase. Dissolved iron concentrations in Cataract Creek upstream from Uncle Sam Gulch consistently comprised about 60 percent of the total-recoverable concentrations. This proportion of the dissolved fraction decreased to less than 40 percent in samples downstream from Uncle Sam Gulch.

The concentration profiles for total-recoverable manganese and zinc in Cataract Creek (fig. 9) closely follow the profiles for the dissolved concentrations of these metals. Generally, total-recoverable manganese concentrations were relatively low upstream from Uncle Sam Gulch, increased sharply immediately below the confluence, then remained elevated downstream from Uncle Sam Gulch although concentrations gradually declined to the mouth of Cataract Creek. Concentrations of total-recoverable zinc were low upstream from the Eva May Mine area (site 3,850), moderate between the Eva May Mine area (site 4,400) and Uncle Sam Gulch (site 19,730), and high downstream from Uncle Sam Gulch (site 20,050). The highest total-recoverable values of 101 $\mu\text{g/L}$ for manganese and 555 $\mu\text{g/L}$ for zinc occurred at the site just downstream from Uncle Sam Gulch (site 20,050). Concentrations of total-recoverable zinc slightly exceeded the criterion for chronic toxicity of 59 $\mu\text{g/L}$ in some samples collected between the Eva May Mine area (site 4,400) and the site just upstream from Uncle Sam Gulch (site 19,700). From Uncle Sam Gulch to the mouth of Cataract Creek, total-recoverable zinc concentrations exceeded the criterion for acute toxicity of 65 $\mu\text{g/L}$ in all samples. Downstream from Uncle Sam Gulch, dissolved manganese and zinc concentrations generally comprised 70 to more than 95 percent of the total-recoverable concentrations (table 8).

Similar to their dissolved counterparts, total-recoverable cadmium and copper concentrations were not high enough to be reliably determined by the analytical methods used for this study. Concentrations of total-recoverable cadmium were less than the minimum reporting level (5.0 $\mu\text{g/L}$). Total-recoverable copper concentrations were less than minimum reporting level (50 $\mu\text{g/L}$) except for mainstem samples collected downstream from Uncle Sam Gulch between sites 20,730 and 24,715. Detectable total-recoverable copper concentrations ranged from 50 to 56 $\mu\text{g/L}$ in the short reach below Uncle Sam Gulch, barely exceeding the 50 $\mu\text{g/L}$ minimum reporting level. Uncle Sam Gulch was the only inflow having copper concentrations (dissolved = 67 $\mu\text{g/L}$, total-recoverable = 382 $\mu\text{g/L}$) greater than the minimum reporting level.

QUANTIFICATION OF LOADS

The load carried by a stream is the mass of a constituent transported downstream. For conservative constituents, loads are additive as inflows contribute their load in a cumulative manner to the load in the receiving stream. For comparative purposes, the transport rates of loads are commonly expressed in terms of mass per unit time (for example, milligrams/second for instantaneous load; kilograms/year for annual load). Instantaneous loads at the time of sampling were calculated as the product of constituent concentration and streamflow. Instantaneous loads were calculated for the 46 mainstem and 25 inflow sites for the dissolved major ions calcium, magnesium, and sulfate, as well as for the dissolved and total-recoverable metals iron, manganese, and zinc (table 7). Although instantaneous loads represent one point in time, downstream profiles of multiple sites provide a comparative picture of sources and instream processes over the travel time through the study reach as long as hydrologic conditions are stable.

Downstream load profiles graphically illustrate the spatial distribution of loads at many individual locations. These profiles can be examined to identify where substantial increases in instream load occur, which can indicate important sources contributing constituent load. Profiles for two different loads, the instream load and the cumulative surface-inflow load were compared in this study. The profile of instream load represents what was actually measured at each

Table 7. Instantaneous loads of major ions and metals in the Cataract Creek drainage, Montana, August 13, 1997

[Abbreviations: mg/s, milligrams per second. Symbols: <, less than; --, no data]

Site number and distance downstream from injection site (feet)	Calcium, dissolved load (mg/s)	Magnesium, dissolved load (mg/s)	Sulfate, dissolved load (mg/s)	Iron, total- recover- able load (mg/s)	Iron, dissolved load (mg/s)	Manganese, total- recoverable load (mg/s)	Manganese, dissolved load (mg/s)	Zinc, total-recov- erable load (mg/s)	Zinc, dissolved load (mg/s)
Cataract Creek									
150	1,290	261	826	52.3	31.6	2.44	2.96	<1.17	<1.17
850	1,370	285	836	55.5	36.2	1.24	.684	<1.21	<1.21
1,370	1,320	245	833	51.3	35.2	2.29	.893	<1.24	<1.24
1,610	1,390	278	829	52.2	30.8	2.14	1.51	<1.26	<1.26
1,690	1,440	299	916	60.7	35.8	1.87	<.650	<1.30	<1.30
2,490	1,420	297	954	55.3	35.9	<.645	<.645	<1.29	<1.29
3,450	2,020	416	1,370	55.8	35.5	2.09	<.850	<1.70	<1.70
3,850	1,990	412	--	57.4	35.3	2.09	1.08	<1.74	<1.74
4,660	2,100	450	1,440	54.0	33.6	1.91	1.06	6.84	5.92
4,940	2,130	452	--	56.9	33.2	<.925	1.11	10.3	9.84
5,940	2,280	453	1,560	53.7	32.6	2.24	1.27	10.7	8.77
6,800	2,320	474	1,710	50.1	32.2	1.69	<.945	10.5	6.87
7,900	2,340	479	1,710	52.9	31.2	<.955	<.955	8.92	6.67
8,700	2,300	465	1,750	53.6	34.2	2.03	1.32	10.3	8.65
9,220	2,410	504	1,560	50.7	35.8	1.93	1.56	10.5	8.89
10,380	2,520	517	1,760	66.1	37.5	2.10	3.82	11.0	9.59
11,055	2,790	554	2,040	58.3	35.8	3.59	<1.08	11.5	9.14
12,115	2,930	586	2,180	56.9	37.1	1.48	1.35	13.0	12.5
13,255	2,880	582	2,060	58.9	38.3	4.55	3.92	15.7	13.1
14,055	3,040	594	2,210	61.3	44.3	4.96	6.02	16.6	12.2
14,855	3,340	665	2,270	57.1	38.7	3.70	3.50	15.4	14.4
15,655	3,000	648	2,380	60.0	37.8	1.23	2.88	14.9	13.5
16,845	3,290	681	2,440	52.7	34.4	2.90	2.43	15.6	14.6
17,645	3,680	706	--	58.3	34.4	3.28	2.30	16.4	13.8
18,545	3,750	724	2,810	68.3	36.3	<1.35	<1.35	11.5	8.11
19,245	3,850	738	2,770	60.5	35.9	<1.38	<1.38	11.0	8.20
19,700	3,810	745	2,820	58.6	34.2	<1.36	<1.36	10.6	8.51
20,050	4,610	920	4,840	88.4	32.7	32.8	31.7	181	153
20,730	4,920	980	4,930	110	31.7	32.8	32.0	181	152
21,130	4,830	965	4,560	89.0	32.7	32.0	31.4	180	153
21,715	4,840	962	5,040	91.5	31.6	32.2	30.4	176	143
22,315	4,790	950	5,020	90.8	31.9	30.9	29.7	175	142
22,915	4,670	939	--	89.0	24.2	29.5	26.8	171	128
23,715	4,820	1,010	--	114	31.1	31.1	28.2	186	145
24,715	4,950	1,010	--	98.4	31.6	28.5	27.7	177	120
25,215	5,340	1,050	4,770	87.6	29.4	27.5	26.4	160	132
26,335	5,320	1,060	5,490	78.4	26.8	26.0	25.8	161	138
26,590	5,660	1,140	5,580	83.6	23.2	25.7	23.3	157	125
26,970	5,620	1,110	5,390	87.0	22.9	26.4	24.7	160	133
27,775	5,820	1,180	5,680	88.1	27.6	26.9	24.2	166	130
29,970	5,970	1,200	5,920	85.4	26.7	23.2	23.4	155	129
31,470	6,190	1,270	6,120	80.9	24.4	21.9	21.0	150	126
32,970	6,390	1,290	6,230	80.3	24.9	20.3	20.2	147	125
34,105	6,280	1,270	6,240	79.2	19.5	19.1	18.0	147	118
34,355	7,100	1,440	--	90.4	--	21.0	20.8	154	150
40,905	7,700	1,590	7,570	104	22.5	19.3	17.2	162	121

Table 7. Instantaneous loads of major ions and metals in the Cataract Creek drainage, Montana, August 13, 1997
(Continued)

Site number and distance downstream from injection site (feet)	Calcium, dissolved load (mg/s)	Magnesium, dissolved load (mg/s)	Sulfate, dissolved load (mg/s)	Iron, total- recover- able load (mg/s)	Iron, dissolved load (mg/s)	Manganese, total- recoverable load (mg/s)	Manganese, dissolved load (mg/s)	Zinc, total-recov- erable load (mg/s)	Zinc, dissolved load (mg/s)
<u>Surface-inflow sites</u>									
160	27.7	5.30	29.8	.320	.256	<.016	.024	<.032	.037
1,615	117	13.7	117	.542	<.075	.018	<.018	.202	.158
1,691	<.290	<.035	<.285	<.001	<.001	<.001	<.001	<.001	<.001
3,050	585	113	437	6.16	1.56	.560	<.201	<.403	<.403
4,400	94.7	22.2	77.1	3.29	<.159	1.11	<.040	.934	.495
4,941	28.3	3.97	12.7	.113	<.043	<.011	<.011	.023	<.020
8,820	32.8	7.65	51.0	.825	.130	.262	.193	.140	.104
9,225	45.8	7.26	22.9	1.17	.111	.405	.138	.073	<.038
10,080	97.7	18.0	116	36.2	30.8	12.5	11.6	<.040	<.040
10,655	62.4	10.5	98.4	.469	.355	.052	.071	1.05	.958
11,605	74.4	13.7	44.3	14.4	12.6	2.62	2.40	.130	.112
11,795	71.4	16.1	84.7	1.50	.462	.148	.130	1.79	1.43
12,120	155	27.5	63.1	1.79	.594	.291	.050	<.075	<.075
14,860	32.7	7.67	38.5	.590	.093	<.019	<.019	<.038	<.038
15,660	61.1	11.8	121	<.077	<.077	<.019	<.019	1.00	.988
15,845	68.8	14.7	75.8	<.077	<.077	<.019	<.019	.102	.072
17,545	167	36.7	153	.368	<.210	.053	<.052	<.105	<.105
19,730	860	191	2,070	33.1	<1.12	32.2	32.4	167	152
21,315	99.1	20.0	73.2	.714	<.030	.143	.084	<.015	<.015
22,565	.30	.051	.281	<.001	<.001	<.001	<.001	<.001	<.001
22,715	.310	.054	.697	<.001	<.001	<.001	<.001	<.001	<.001
24,495	122	23.9	60.7	1.80	.200	4.54	3.50	.620	.508
26,370	291	64.8	178	.710	<.218	.080	<.054	.329	.216
29,760	1,180	176	1,320	<.266	<.266	<.067	<.067	<.133	<.133
34,155	1,500	248	1,000	14.3	<.722	1.49	<.180	3.25	2.73

mainstem sampling site. These loads are the net result of contributions from the sampled surface inflows and any unsampled inflow (primarily ground water), as well as any loss of load caused by streamflow loss, the formation and streambed deposition of colloids, or other geochemical reactions. The instream loading profile is the most important because it defines the net effect of all metal inputs and losses in the stream. The cumulative surface-inflow load is the cumulative downstream sum of all the visible inflow loads that were quantified. The profile of cumulative surface-inflow loads probably represents a minimum value for inflow loading to the stream because subsurface inflows are not included. In reaches where the cumulative surface-inflow load exceeds the instream load, it is likely that some physical or geochemical process is removing the constituent from the water column of the mainstem. A value equal to the minimum reporting level was used to calculate loads at sites where concentrations were less than this value.

Major Ions

The instream-load profiles for calcium and magnesium (fig. 11) were similar. Instream loads increased in a downstream direction through the study reach, ranging from 1,290 to 7,700 mg/s for calcium and 261 to 1,590 mg/s for magnesium. The instream load for both constituents increased about 5-fold through the study reach, with large increases resulting from tributaries such as Uncle Sam Gulch and Big Limber Gulch in the mid and lower part of the study reach. Visible surface inflows accounted for nearly 90 percent of the increase in instream calcium load and about 80 percent of the instream magnesium load throughout the study reach.

The instream-load profile for sulfate (fig. 12) is similar to the load profiles for calcium and magnesium. The cumulative surface-inflow load accounted for nearly all of the changes in the instream sulfate load. The instream sulfate load increased about 8-fold through the study reach. The largest sulfate load was from Uncle Sam Gulch (site 19,730, table 7), which contributed about 33 percent of the cumulative surface-inflow load entering Cataract Creek.

Metals

The load profile for dissolved iron is shown in figure 13. Two inflows, site 10,080 and 11,605--both

right bank inflows in the area of the Cataract Mine tailings--contributed the vast majority of the dissolved iron loading observed throughout the study reach. The combined dissolved iron load of these two inflows was greater than the instream load at the mouth of Cataract Creek. The instream dissolved iron load consistently diverged from the cumulative surface-inflow load downstream from these two tributaries, indicating that dissolved iron was being removed from the water column. This pattern of iron removal has been documented in similar studies of mining areas (Kimball and others, 1994). In the neutral pH range found in Cataract Creek, the dissolved ferrous iron in mine drainage is oxidized to ferric iron, which precipitates as colloidal-sized particles of iron oxyhydroxide. These particles aggregate into larger particles, which in turn settle from the water column, or are trapped by algae on streambed cobbles, leaving an iron coating over the streambed. Other dissolved metals are removed from the water column as they coprecipitate with or adsorb to the iron oxyhydroxides.

The total-recoverable iron was different from that of dissolved iron (fig. 13). Instead of a generally decreasing downstream load, as seen in the dissolved profile, the instream load of total-recoverable iron was fairly constant from the beginning of the study reach to Uncle Sam Gulch. Downstream from Uncle Sam Gulch at site 20,050, the instream total-recoverable iron load increased substantially. This increase in instream load was largely maintained, but fluctuated from Uncle Sam Gulch to the end of the study reach. Unlike the dissolved load, no clear or sustained decreasing trend was detected in the instream total-recoverable iron load. Similar to the dissolved load, inflows at sites 10,080 and 11,605 contributed a large percentage of the cumulative surface-inflow load for total-recoverable iron. Uncle Sam Gulch (site 19,730) and, to a lesser extent, the inflow at site 34,155, also were major contributors to the cumulative surface-inflow loads of total-recoverable iron. These four inflows contributed about 83 percent of the cumulative surface-inflow load. The increase in the total-recoverable iron load downstream from Uncle Sam Gulch, where no increase was seen in the dissolved iron load, supports the hypothesis that dissolved iron is transformed to colloidal iron in the water column.

Instream loads calculated for dissolved manganese (fig. 14) upstream from Uncle Sam Gulch (site 19,700) were low and somewhat variable, ranging from

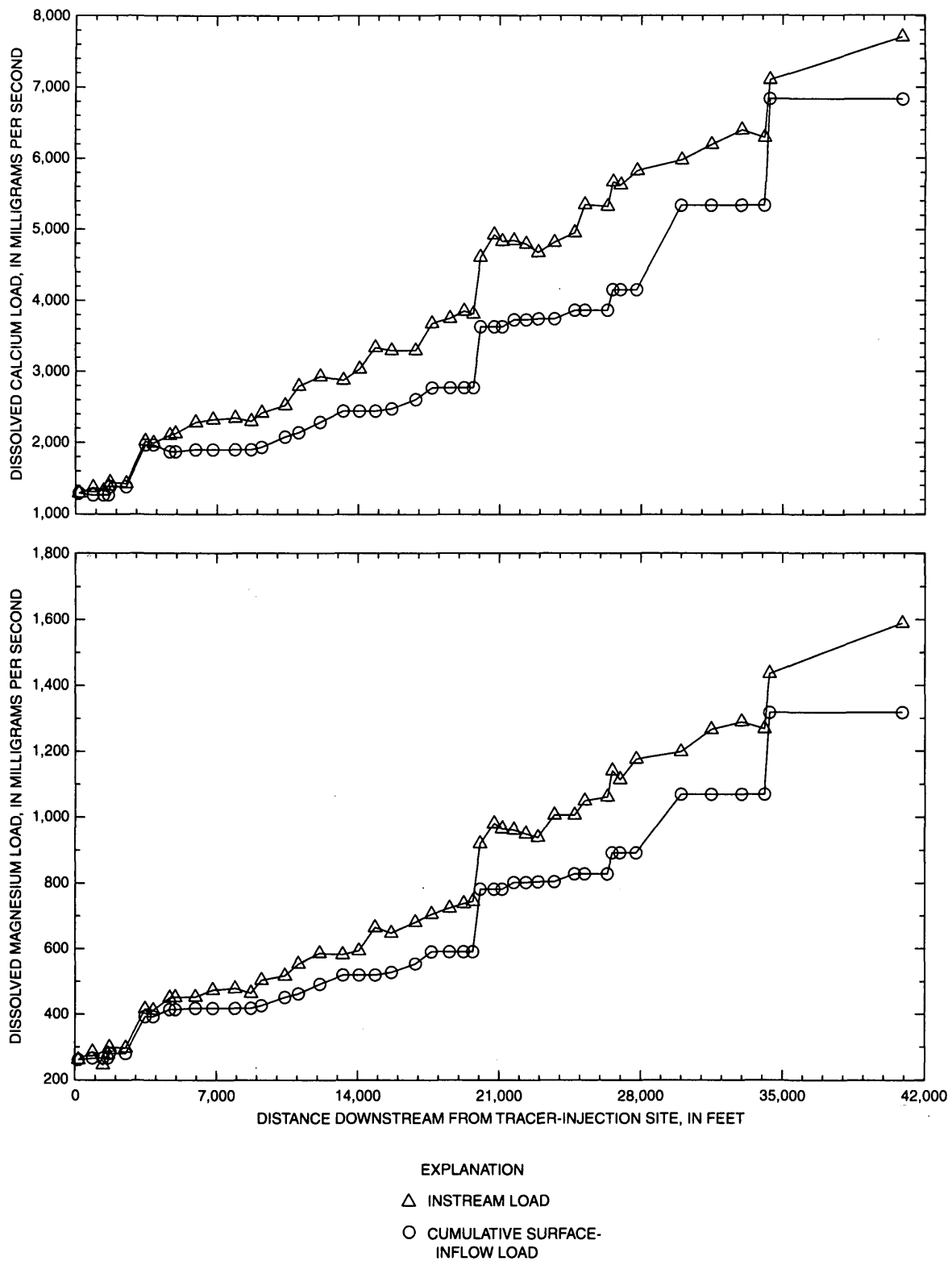


Figure 11. Instantaneous instream load and cumulative surface-inflow load of dissolved calcium (top) and magnesium (bottom) in Cataract Creek, Montana, August 13, 1997.

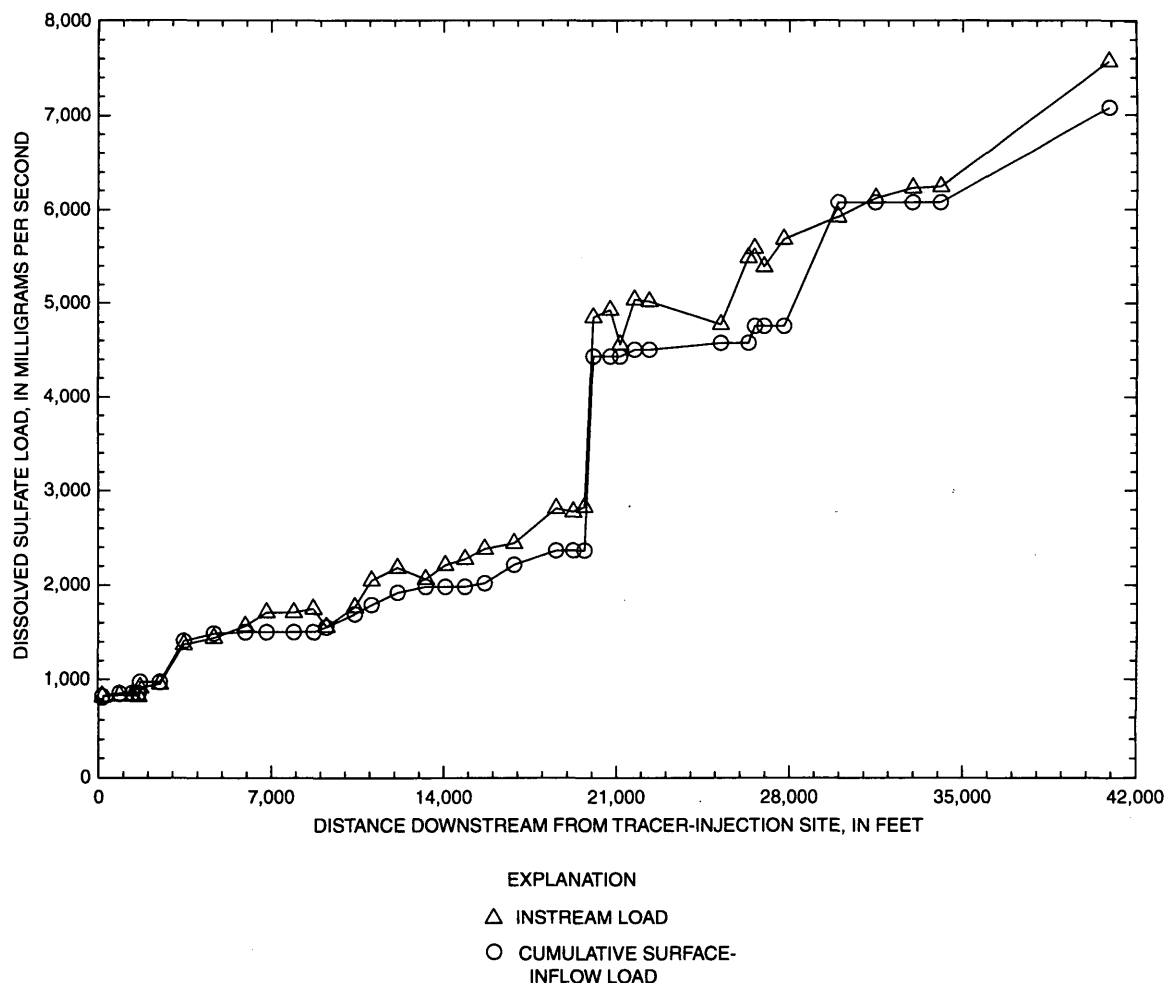


Figure 12. Instantaneous instream load and cumulative surface-inflow load of dissolved sulfate in Cataract Creek, Montana, August 13, 1997.

<0.645 to 6.02 mg/s for all sites. Visible inflows contributed little dissolved manganese in this upper reach, except for the inflow at site 10,080, a right-bank inflow in the vicinity of the Cataract Mine tailings area. This relatively large inflow load (11.6 mg/s, table 7), however, only minimally increased the instream load of dissolved manganese. The subsequent decrease of this load might indicate a geochemical removal of manganese from the water column, such as coprecipitation or adsorption to the iron colloids. The instream load substantially increased at Uncle Sam Gulch (site 19,730) to about 32 mg/s. From Uncle Sam Gulch downstream to the mouth, the instream load steadily decreased from about 32 to 17.2 mg/s, indicating that dissolved manganese was being removed gradually from the water column by a physical or chemical process.

Uncle Sam Gulch accounted for about 60 percent of the cumulative surface-inflow load of dissolved manganese throughout the study reach. The inflow at site 10,080 and Uncle Sam Gulch were the only two significant inputs of dissolved manganese to Cataract Creek. The load profile for total-recoverable manganese closely reflected the dissolved load profile and is not presented.

Similar to manganese, the major features of the dissolved zinc load profile (fig. 14) are the relatively small loads upstream from Uncle Sam Gulch (site 19,730), the large load contributed by Uncle Sam Gulch, and a small decrease in instream load between Uncle Sam Gulch and the mouth of Cataract Creek. The instream zinc load increased 17-fold immediately

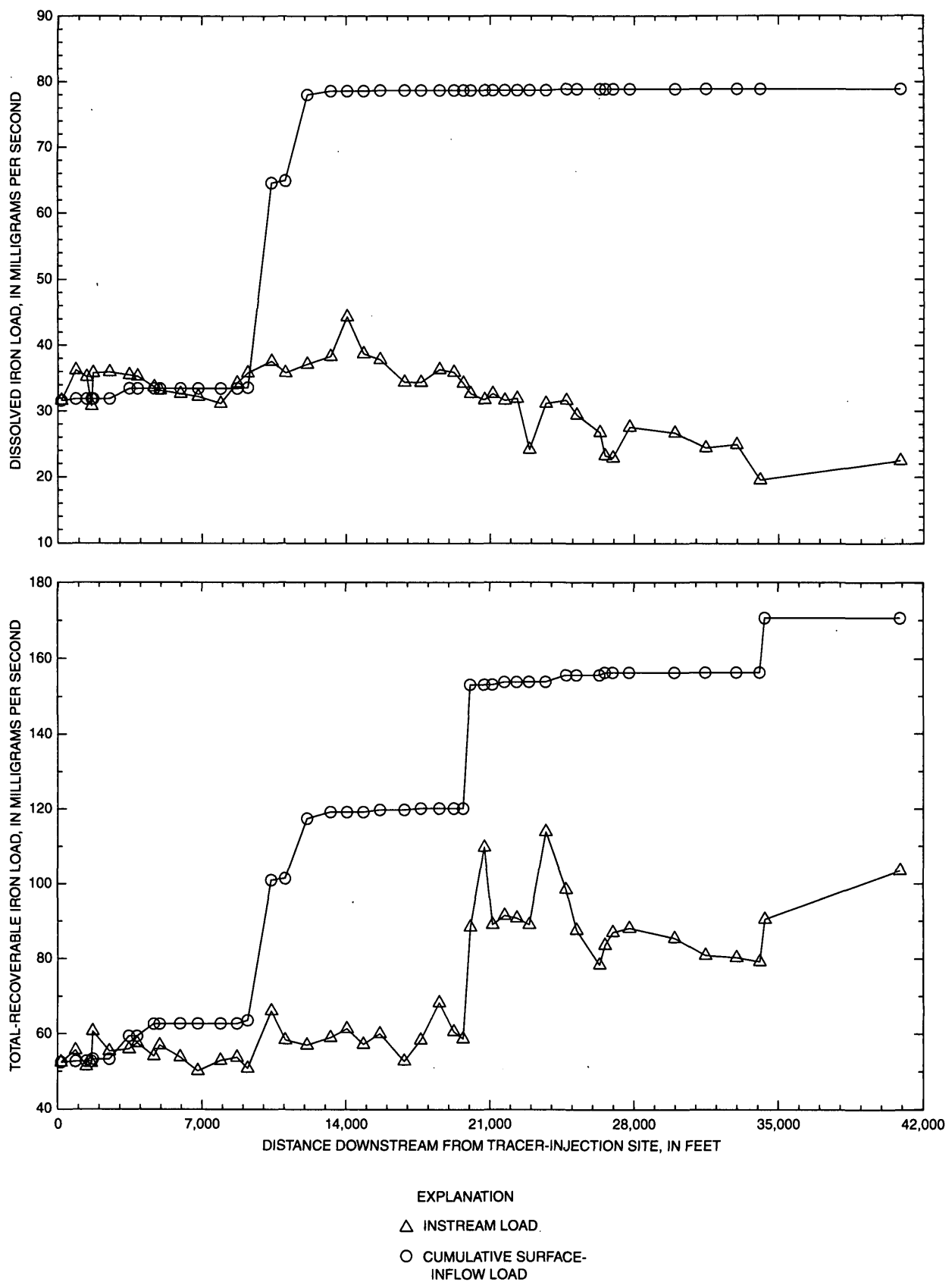


Figure 13. Instantaneous instream load and cumulative surface-inflow load of dissolved iron (top) and total-recoverable iron (bottom) in Cataract Creek, Montana, August 13, 1997.

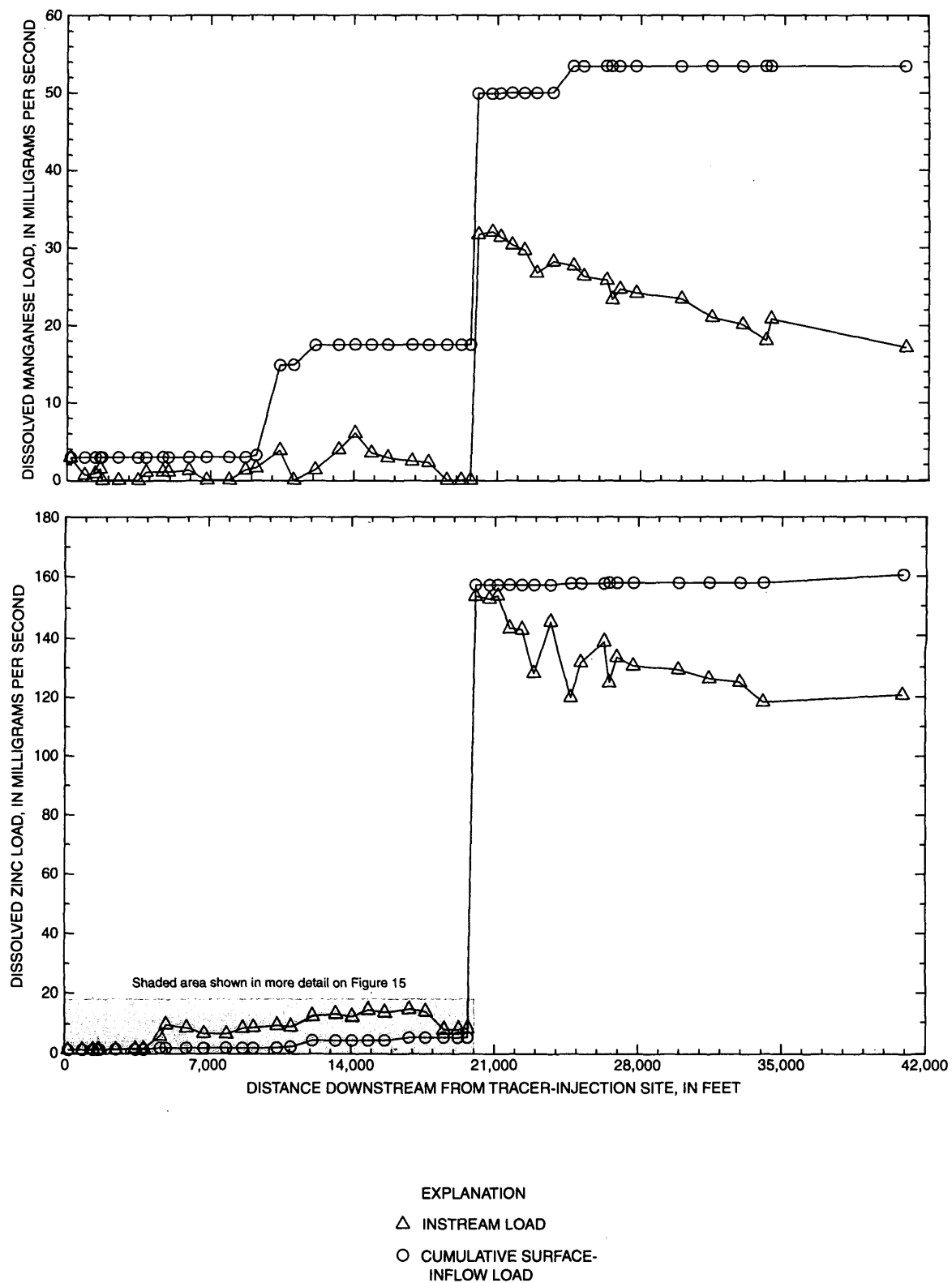


Figure 14. Instantaneous instream load and cumulative surface-inflow load of dissolved manganese (top) and zinc (bottom) in Cataract Creek, Montana, August 13, 1997.

downstream from Uncle Sam Gulch. Like dissolved manganese loads, dissolved zinc loads decreased consistently from 153 mg/s downstream from Uncle Sam Gulch to 121 mg/s at site 40,905. Uncle Sam Gulch accounted for over 90 percent of the cumulative surface-inflow load of dissolved zinc. No other substantial increases in instream dissolved zinc load were observed. The inflow at site 10,080 that contributed a substantial amount of iron and manganese did not provide a corresponding input of zinc.

Figure 15 shows an enlarged display of the dissolved zinc load profile for the portion of Cataract Creek upstream from Uncle Sam Gulch (shaded on

figure 14). Because the load from Uncle Sam Gulch (site 19,730) is large in comparison to the other sources, the graph of dissolved zinc load for the entire study reach (fig. 14) lacks resolution for the smaller sources upstream from Uncle Sam Gulch. The upper subreach from the tracer-injection site to Uncle Sam Gulch contributed about 7 percent of the dissolved zinc load at the mouth of Cataract Creek. Dissolved zinc concentrations were less than the minimum reporting level of 10 µg/L from site 150 to 3,850; thus, loads were considered to be minimal (<2 mg/s) at these upstream sites. The inflow from the Eva May Mine area between sites 3,850 and 4,940 was the largest source of dissolved zinc load in this upper subreach

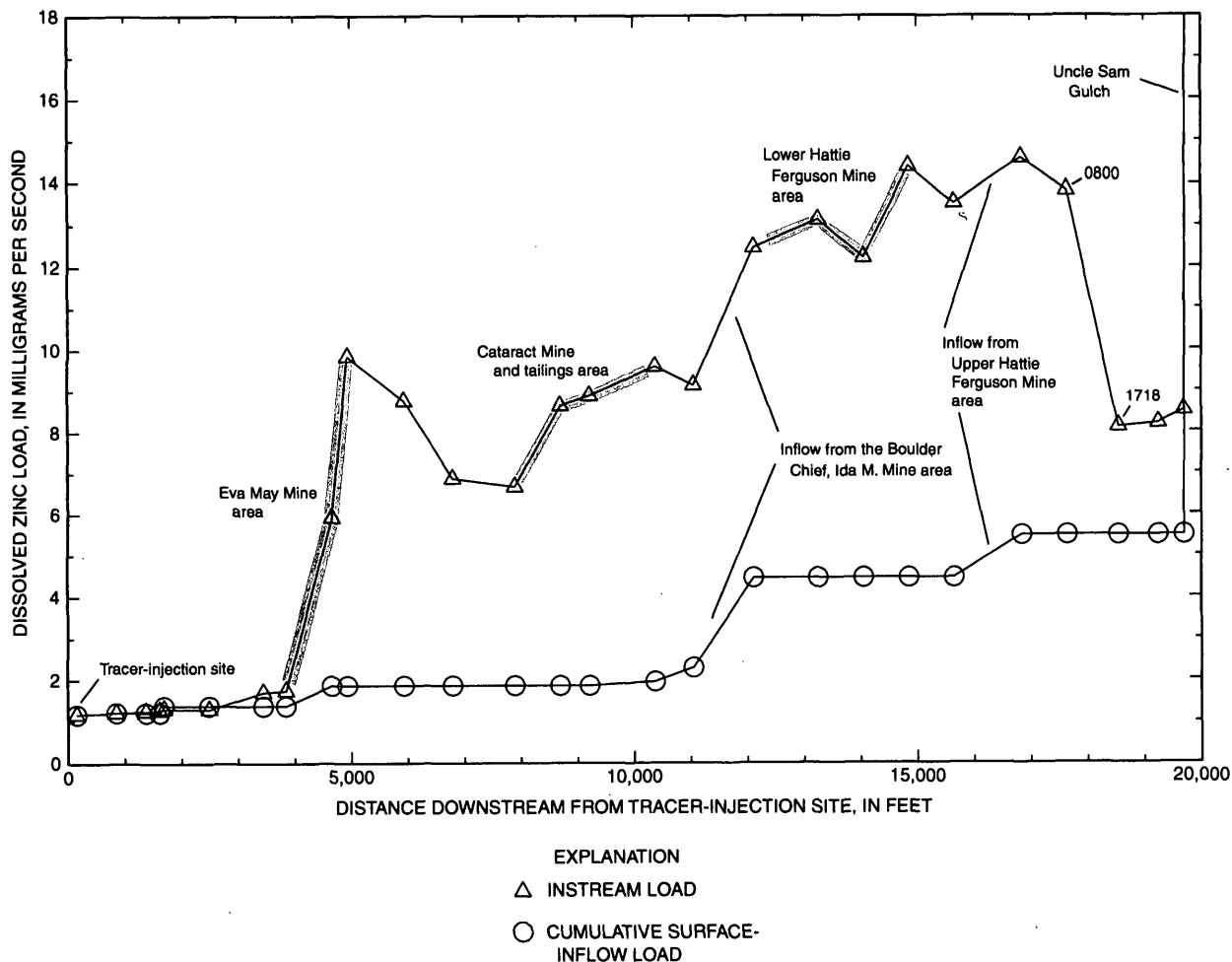


Figure 15. Instantaneous instream load and cumulative surface-inflow load of dissolved zinc in Cataract Creek, Montana, from the tracer-injection site to Uncle Sam Gulch, August 13, 1997. The load decrease between sites 17,645 and 18,545 (sampled at 0800 and 1718, respectively) likely was caused by diel variation in dissolved zinc concentrations.

(increase of about 9 mg/s). Between the Eva May Mine area and just upstream from Uncle Sam Gulch (site 19,700), instream loads increased slightly from about 10 mg/s (site 4,940) to the maximum instream load of about 14.6 mg/s just downstream from the inflow that drains the Upper Hattie Ferguson Mine area (site 16,845). Other sources that increased the dissolved zinc load were seen around the Cataract Mine area, the inflow from the Boulder Chief and Ida M. Mine areas, the Lower Hattie Ferguson Mine area, and the inflow from the Upper Hattie Ferguson Mine area. The increases in instream load attributable to the Boulder Chief, Ida M., and the Upper Hattie Ferguson Mine areas were caused primarily by the surface inflows that drain these areas. In contrast, the increases in dissolved zinc load at the Eva May, Cataract, and Lower Hattie Ferguson Mine areas apparently were caused primarily by subsurface inflow.

The instream load of dissolved zinc decreased from 13.8 to 8.1 mg/s in the short reach between sites 17,645 and 18,545 (fig. 15). Although load decreases can infer a geochemical process removing metal from the water column, this particular decrease may be the result of the synoptic-sampling strategy and 24-hr (diel) variations in dissolved zinc concentration. The synoptic-sampling plan divided the study reach into three segments to allow a longer time period for the chloride tracer to reach a plateau phase in the downstream segments. Therefore, the three segments were sampled sequentially in a downstream order, but each segment was sampled in the upstream direction to minimize effects of streambed disturbance on the collection of samples. Sampling began on August 13 at site 17,645 at 0800, the most downstream site in the first segment. Site 18,545, the first mainstem site downstream of site 17,645, but the most upstream site and last to be sampled in the second segment, was sampled at 1718, or over 9 hours later than site 17,645. On the basis of intensive hourly automated sampling conducted for 2 days at site 40,905 in October 1998 during base-flow conditions, dissolved zinc concentrations apparently have a diel variation of about 25 percent, with the highest concentrations occurring at about 0900 and the lowest concentrations at about 1700 (unpublished data). If dissolved zinc concentrations exhibit similar diel variation in the reach of Cataract Creek between sites 17,645 and 18,545, then the 41-percent decrease in load (fig. 15) may partly be explained by a daily cycle in concentration rather than a geochemical or streamflow loss. This cyclical variation in dissolved

zinc concentrations may also affect other minor gains and losses in instream load to varying degrees, depending on time differences between samples. Therefore, minor fluctuations in downstream loads may be ambiguous, but major increases are still reasonably interpreted as significant sources. The load profile for total-recoverable zinc closely reflected the dissolved load profile and is not presented.

METAL SOURCES

Metal concentrations in the Boulder River between Basin and Boulder increase, presumably because of the effects of inactive mines. The largest load of metals to this reach comes from Cataract Creek (Nimick and others, 1999). On the basis of this study, the largest contributor of metals to Cataract Creek is Uncle Sam Gulch. Therefore, Uncle Sam Gulch potentially could be prioritized for cleanup. Remediation efforts to reduce metal loading from Uncle Sam Gulch could produce improvements in the water quality of lower Cataract Creek below Uncle Sam Gulch and in the Boulder River downstream from Cataract Creek.

Metal loads from sources in Cataract Creek upstream from Uncle Sam Gulch are minimal in comparison to the loads in Uncle Sam Gulch. However, reductions in loads from the Eva May, Cataract, Boulder Chief, Ida M., Lower Hattie Ferguson, and Upper Hattie Ferguson Mine areas collectively could improve water quality upstream from Uncle Sam Gulch. If improvements in water quality were to occur, it is likely that there would be a beneficial effect on the aquatic community in the upper 20,000 ft of the Cataract Creek study reach above Uncle Sam Gulch. Because of the greater degradation of water quality below Uncle Sam Gulch, water-quality improvements would need to be substantial in order to benefit the aquatic community.

SUMMARY AND CONCLUSIONS

Streams of the Boulder River watershed drain a mineralized area that has been extensively mined since the late 1800s. Although inactive mines have been identified, the metal load from acid mine drainage to Cataract Creek had not been previously quantified. This report quantifies, and identifies the principal sources of metal loads to Cataract Creek. This study was conducted in the Cataract Creek drainage during baseflow conditions in August 1997 along an approximately 8-mi (40,905-ft) reach of Cataract Creek from

near midstream to the mouth. Loads were determined using tracer-injection and synoptic-sampling methods. Using downstream changes in tracer (chloride) concentration, streamflow was determined at 46 mainstem sites and 25 surface-inflow sites during this study. Streamflow increased by 355 L/s through the study reach. Sampled surface inflows accounted for 238 L/s of this increase, whereas 117 L/s, or 33 percent of the total increase, was attributable to unsampled seeps and subsurface inflow.

Instantaneous instream and visible surface-inflow loads for dissolved calcium, magnesium, and sulfate, as well as dissolved and total-recoverable iron, manganese, and zinc were computed from the streamflow data calculated from tracer injection methods together with concentration data from synoptic samples. The instream dissolved sulfate load increased about 8-fold through the study reach. Visible surface inflows accounted for most of the 8-fold increase throughout the study reach. The largest increase in instream sulfate load was from Uncle Sam Gulch, which accounted for about 33 percent of the cumulative surface-inflow load entering Cataract Creek. Instream loads of dissolved manganese in the upper part of the study reach were low; a large input was contributed to Cataract Creek by the inflow at site 10,080 in the area of the Cataract Mine tailings. The largest increase in instream load of dissolved manganese was from Uncle Sam Gulch (site 19,730), which accounted for about 60 percent of the cumulative surface-inflow load. The inflow at site 10,080 and Uncle Sam Gulch were the only two significant inputs of dissolved manganese. In the reach downstream from Uncle Sam Gulch, instream dissolved manganese load decreased from about 32 to 17.2 mg/s, presumably as a result of a physical or chemical process that removed manganese from the water column.

The main source of dissolved zinc in Cataract Creek is Uncle Sam Gulch (site 19,730), which increased the instream load about 17-fold. Uncle Sam Gulch accounted for over 90 percent of the cumulative surface-inflow of dissolved zinc entering Cataract Creek. Similar to the dissolved manganese load, the instream load of dissolved zinc decreased from the maximum value of 153 mg/s just downstream from Uncle Sam Gulch to 121 mg/s at the lower end of the study reach (site 40,905). Several small sources of zinc were identified in the nearly 20,000-ft reach of Cataract Creek upstream from Uncle Sam Gulch. The dissolved zinc load in this upper reach increased from <2 mg/s to

about 14 mg/s just downstream from the inflow that drains the Upper Hattie Ferguson Mine area. The inflow load (9 mg/s) from the Eva May Mine area was the single largest source of dissolved zinc in this upper reach. Other sources of dissolved zinc load included the inflow from the Cataract, Boulder Chief, Ida M., Lower Hattie Ferguson, and Upper Hattie Ferguson Mine areas.

The load profile for dissolved iron was much different than the profiles for other constituents. The instream load consistently diverged from the cumulative surface-inflow load, indicating that iron was being removed from the water. In the near-neutral pH range of Cataract Creek, the reactive nature of iron promotes the formation of colloidal-sized particles. These particles aggregate into larger particles, which in turn can settle from the water column or can be trapped by algae on streambed cobbles, leaving an iron coating over the streambed. Other dissolved metals are removed from the water column as they coprecipitate with or adsorb to the iron oxyhydroxides. This process likely is responsible for the decreases in the dissolved manganese and zinc loads downstream from Uncle Sam Gulch (site 19,730). The cumulative surface-inflow load for dissolved iron was dominated by the two inflows at sites 10,080 and 11,605, which accounted for about 90 percent of the increase in the cumulative surface-inflow load. These large inputs, however, only minimally affected the instream load, providing further evidence that dissolved iron was being removed from solution throughout much of the study reach.

On the basis of the loads quantified in Cataract Creek, Uncle Sam Gulch is the major contributor of metals. Only small load increases occurred from sources upstream from Uncle Sam Gulch near the Eva May, Cataract, Boulder Chief, Ida M., Lower Hattie Ferguson, and Upper Hattie Ferguson Mine areas. Improvement in the water quality of Cataract Creek, therefore, could be maximized by remediation efforts that reduce metal loads from Uncle Sam Gulch.

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DATA

Table 8. Water-quality data for synoptic samples collected in the Cataract Creek drainage, Montana, August 13, 1997

[Abbreviations: µg/L, micrograms per liter; mg/L, milligrams per liter. Symbols: <, less than; --, no data]

Site number and distance downstream from tracer- injection site (feet)	Time	pH, field (stand- ard units)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Sulfate, dissolved (mg/L as SO ₄)	Aluminum, total recoverable (µg/L as Al)
Cataract Creek								
150	1450	7.71	11	2.2	7.4	0.73	7.1	<50
850	1438	7.85	11	2.4	7.5	.72	6.9	<50
1,370	1428	7.82	11	2.0	7.0	.69	6.7	<50
1,610	1405	7.71	11	2.2	7.0	.71	6.6	<50
1,690	1415	7.87	11	2.3	7.2	.71	7.0	<50
2,490	1345	7.83	11	2.3	7.2	.72	7.4	<50
3,450	1330	7.82	12	2.4	6.2	.73	8.1	56
3,850	1319	7.83	11	2.4	6.0	.70	--	55
4,660	1305	7.83	12	2.5	5.9	.70	7.9	<50
4,940	1300	7.73	12	2.4	5.8	.70	--	<50
5,940	1248	7.74	12	2.4	5.6	.72	8.4	53
6,800	1236	7.74	12	2.5	5.8	.73	9.0	<50
7,900	1225	7.80	12	2.5	5.7	.74	8.9	<50
8,700	1220	7.71	12	2.4	5.4	.70	9.0	<50
9,220	1140	7.66	12	2.5	5.7	.71	7.9	<50
10,380	1115	7.52	12	2.5	5.4	.71	8.6	<50
11,055	1100	7.38	13	2.6	5.5	.76	9.5	<50
12,115	1025	7.68	13	2.6	5.4	.76	9.7	<50
13,255	1005	7.77	12	2.5	5.2	.72	8.9	<50
14,055	0952	7.82	13	2.5	5.1	.70	9.4	<50
14,855	0945	7.81	14	2.8	5.4	.79	9.5	<50
15,655	0827	7.44	14	2.7	5.3	.73	9.8	<50
16,845	0810	7.81	13	2.7	5.2	.73	9.8	<50
17,645	0800	7.72	14	2.7	5.1	.78	--	<50
18,545	1718	7.80	14	2.7	4.9	.81	10.4	<50
19,245	1710	7.64	14	2.7	5.1	.80	10.1	<50
19,700	1700	7.83	14	2.7	5.0	.82	10.4	<50
20,050	1705	7.63	14	2.8	4.7	.82	14.9	81
20,730	1630	7.81	15	3.0	4.8	.83	14.9	83
21,130	1620	7.61	14	2.9	4.6	.81	13.6	84
21,715	1600	7.83	14	2.8	4.6	.79	14.9	85
22,315	1552	7.80	14	2.8	4.6	.80	14.9	85
22,915	1530	7.65	14	2.8	4.4	.72	--	81
23,715	1508	7.74	14	2.9	4.7	.77	--	137
24,715	1406	7.65	14	2.9	4.5	.78	--	91
25,215	1705	7.70	15	3.0	4.7	.82	13.7	78
26,335	1925	--	15	3.0	4.7	.82	15.7	67
26,590	1915	7.88	16	3.2	4.7	.83	15.5	70
26,970	1910	8.01	16	3.1	4.5	.85	14.9	88
27,775	1900	8.23	16	3.2	4.7	.85	15.6	76
29,970	1835	7.40	16	3.2	4.5	.86	15.7	69
31,470	1824	7.82	16	3.3	4.6	.86	16.0	71

Table 8. Water-quality data for synoptic samples collected in the Cataract Creek drainage, Montana, August 13, 1997 (Continued)

Site number and distance downstream from tracer-injection site (feet)	Aluminum, dissolved (µg/L as Al)	Copper, total recoverable (µg/L as Cu)	Copper, dissolved (µg/L as Cu)	Iron, total recoverable (µg/L as Fe)	Iron, dissolved (µg/L as Fe)	Manganese, total recoverable (µg/L as Mn)	Manganese, dissolved (µg/L as Mn)	Zinc, total recoverable (µg/L as Zn)	Zinc, dissolved (µg/L as Zn)
Cataract Creek									
150	<50	<50	<50	447	270	21	25	<10	<10
850	<50	<50	<50	459	299	10	6	<10	<10
1,370	<50	<50	<50	414	284	18	7	<10	<10
1,610	<50	<50	<50	414	244	17	12	<10	<10
1,690	<50	<50	<50	467	275	14	<5	<10	<10
2,490	<50	<50	<50	428	278	<5	<5	<10	<10
3,450	<50	<50	<50	328	209	12	<5	<10	<10
3,850	<50	<50	<50	330	203	12	6	<10	<10
4,660	<50	<50	<50	297	185	11	6	38	33
4,940	<50	<50	<50	307	179	<5	6	56	53
5,940	<50	<50	<50	287	175	12	7	57	47
6,800	<50	<50	<50	265	170	9	<5	56	36
7,900	<50	<50	<50	277	163	<5	<5	47	35
8,700	<50	<50	<50	278	177	11	7	53	45
9,220	<50	<50	<50	256	181	10	8	53	45
10,380	<50	<50	<50	323	183	10	19	54	47
11,055	<50	<50	<50	271	167	17	<5	54	42
12,115	<50	<50	<50	254	166	7	6	58	56
13,255	<50	<50	<50	255	166	20	17	68	57
14,055	<50	<50	<50	260	188	21	26	70	52
14,855	<50	<50	<50	239	162	15	15	64	60
15,655	<50	<50	<50	248	156	5	12	62	56
16,845	<50	<50	<50	211	138	12	10	62	58
17,645	<50	<50	<50	223	132	13	9	63	53
18,545	<50	<50	<50	253	135	<5	<5	43	30
19,245	<50	<50	<50	219	130	<5	<5	40	30
19,700	<50	<50	<50	216	126	<5	<5	39	31
20,050	<50	<50	<50	271	100	101	97	555	470
20,730	<50	52	<50	331	96	99	97	548	460
21,130	<50	52	<50	265	97	95	93	536	457
21,715	<50	55	<50	271	94	95	90	521	422
22,315	<50	52	<50	269	94	91	88	518	421
22,915	<50	50	<50	263	71	87	79	506	379
23,715	<50	56	54	333	91	91	82	543	423
24,715	<50	55	<50	285	92	83	80	513	348
25,215	<50	<50	<50	251	84	79	76	459	378
26,335	<50	<50	<50	225	77	75	74	462	397
26,590	<50	<50	<50	232	65	71	65	436	347
26,970	<50	<50	<50	241	63	73	68	442	370
27,775	<50	50	<50	242	76	74	66	457	359
29,970	<50	<50	<50	227	71	62	62	410	343
31,470	<50	<50	<50	212	64	57	55	393	331

Table 8. Water-quality data for synoptic samples collected in the Cataract Creek drainage, Montana, August 13, 1997 (Continued)

Site number and distance downstream from tracer-injection site (feet)	Time	pH, field (stand-ard units)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Sulfate, dissolved (mg/L as SO ₄)	Aluminum, total recoverable (µg/L as Al)
Cataract Creek—Continued								
32,970	1815	7.87	17	3.3	4.6	.91	16.1	66
34,105	1803	7.84	16	3.2	4.6	.84	15.8	66
34,355	1800	7.84	17	3.3	4.5	.92	--	73
40,905	1758	7.83	16	3.4	4.4	.87	16.0	72
Surface-inflow sites								
160	1447	7.62	9	1.7	2.7	.47	9.3	64
1,615	1400	7.59	31	3.6	4.0	.66	31.0	<50
1,691	1420	7.81	29	3.5	4.4	.66	28.5	<50
3,050	1338	7.75	15	2.8	3.7	.66	10.9	106
4,400	1310	7.48	12	2.8	3.6	.76	9.7	209
4,941	1300	7.71	13	1.9	3.2	.61	6.0	93
8,820	1155	7.26	8	1.8	2.3	.50	11.9	299
9,225	1143	7.20	12	1.9	3.1	.70	6.0	171
10,080	1125	6.91	26	4.7	3.8	1.11	30.5	<50
10,655	1104	7.51	7	1.1	2.5	.44	10.4	<50
11,605	1050	6.61	16	3.0	4.0	.97	9.5	<50
11,795	1038	7.57	16	3.5	4.4	.95	18.4	184
12,120	1020	7.63	21	3.7	3.9	.99	8.4	97
14,860	0940	7.89	9	2.0	3.8	.60	9.8	413
15,660	0822	7.59	16	3.1	3.8	.83	31.9	<50
15,845	0820	7.45	18	3.8	3.2	1.01	19.6	<50
17,545	1734	7.80	16	3.5	4.9	.96	14.6	43
19,730	1705	7.32	15	3.4	3.0	.78	37.0	445
21,315	1613	8.10	66	13.4	7.1	1.51	49.1	<50
22,565	1545	7.77	30	5.1	4.7	1.04	28.1	<50
22,715	1540	7.19	31	5.4	4.7	1.18	69.7	<50
24,495	1448	7.20	39	7.6	6.4	1.69	19.2	<50
26,370	1921	8.14	27	5.9	4.3	1.25	16.3	<50
29,760	1842	8.48	88	13.2	13.1	1.94	99.2	<50
34,155	1757	8.00	42	6.9	9.6	2.03	27.8	372

Table 8. Water-quality data for synoptic samples collected in the Cataract Creek drainage, Montana, August 13, 1997 (Continued)

Site number and distance downstream from tracer-injection site (feet)	Aluminum, dissolved (µg/L as Al)	Copper, total recoverable (µg/L as Cu)	Copper, dissolved (µg/L as Cu)	Iron, total recoverable (µg/L as Fe)	Iron, dissolved (µg/L as Fe)	Manganese, total recoverable (µg/L as Mn)	Manganese, dissolved (µg/L as Mn)	Zinc, total recoverable (µg/L as Zn)	Zinc, dissolved (µg/L as Zn)
Cataract Creek—Continued									
32,970	<50	<50	<50	207	64	53	52	380	323
34,105	<50	<50	<50	201	50	48	46	373	301
34,355	50.2	<50	<50	210	--	49	48	358	349
40,905	<50	<50	<50	219	48	41	36	344	256
Surface-inflow sites									
160	52.7	<50	<50	100	80	<5	8	<10	12
1,615	<50	<50	<50	144	<20	5	<5	54	42
1,690	<50	<50	<50	51	<20	6	<5	45	38
3,050	<50	<50	<50	153	39	14	<5	<10	<10
4,400	<50	<50	<50	415	<20	140	<5	118	62
4,940	<50	<50	<50	53	<20	<5	<5	11	<10
8,820	<50	<50	<50	192	29	61	45	33	24
9,225	<50	<50	<50	305	29	106	36	19	<10
10,080	<50	<50	<50	9,470	8,080	3,280	3,020	<10	<10
10,655	<50	<50	<50	50	38	5	8	111	101
11,605	<50	<50	<50	3,110	2,720	566	518	28	24
11,795	<50	<50	<50	328	101	33	28	394	314
12,120	<50	<50	<50	240	79	39	7	<10	<10
14,860	<50	<50	<50	154	24	<5	<5	<10	<10
15,660	<50	<50	<50	<20	<20	<5	<5	261	256
15,845	<50	<50	<50	<20	<20	<5	<5	27	19
17,545	<50	<50	<50	35	<20	5	<5	<10	<10
19,730	<50	382	67	593	<20	578	581	2,990	2,720
21,315	<50	<50	<50	479	<20	96	57	<10	<10
22,565	<50	<50	<50	79	<20	12	6	<10	<10
22,715	<50	<50	<50	<20	<20	<5	<5	<10	<10
24,495	<50	<50	<50	571	63	1,440	1,110	196	161
26,370	<50	<50	<50	65	<20	7	<5	30	20
29,760	<50	<50	<50	<20	<20	<5	<5	<10	<10
34,155	<50	<50	<50	395	<20	41	<5	90	76

