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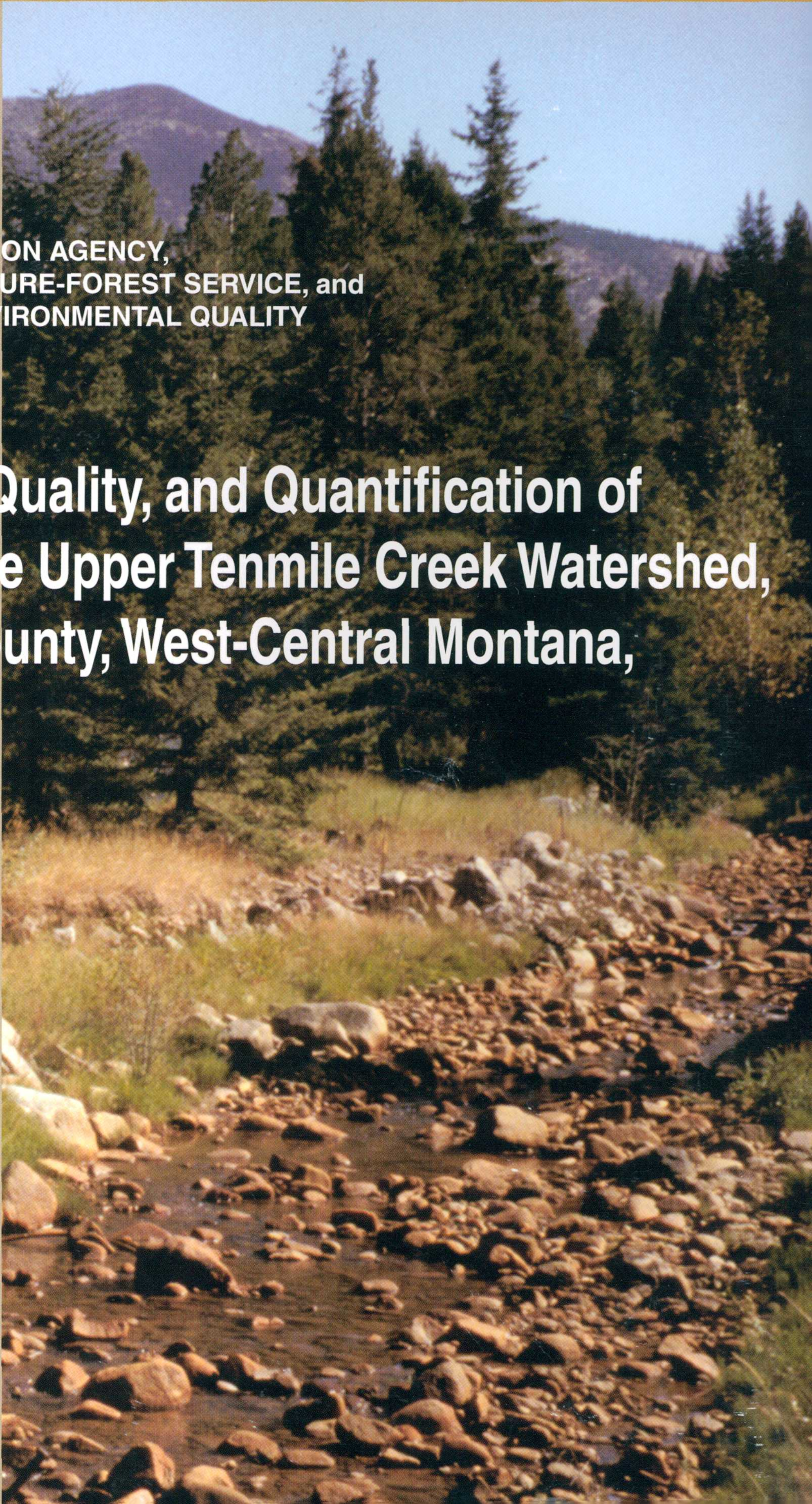

In cooperation with the
U.S. ENVIRONMENTAL PROTECTION AGENCY,
U.S. DEPARTMENT OF AGRICULTURE-FOREST SERVICE, and
MONTANA DEPARTMENT OF ENVIRONMENTAL QUALITY

Streamflow, Water Quality, and Quantification of Metal Loading in the Upper Tenmile Creek Watershed, Lewis and Clark County, West-Central Montana, September 1998

Water-Resources Investigations
Report 02-4072

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

COVER: Tenmile Creek near Rimini, Montana, looking upstream. Photograph by D.A. Nimick, U.S. Geological Survey.

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By Thomas E. Cleasby and David A. Nimick

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Helena, Montana
April 2002

U.S. Department of the Interior

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CONVERSION FACTORS, ABBREVIATED WATER-QUALITY UNITS, AND ACRONYMS

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.028317	cubic meter per second
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
gallon	3.785	liter
gallon per minute (gpm)	0.06309	liter per second (L/s)
mile (mi)	1.609	kilometer
pound (lb)	453.6	gram

Degree Celsius (°C) may be converted to degree Fahrenheit (°F) by using the following equation:

$$°F = 9/5(°C)+32$$

Degree Fahrenheit (°F) may be converted to degree Celsius (°C) by using the following equation:

$$°C = 5/9(°F-32)$$

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
µS/cm	microsiemens per centimeter at 25 degrees Celsius
µg/L	micrograms per liter
µg/s	micrograms per second
µm	micrometer
mg/L	milligrams per liter
mg/s	milligrams per second
mL/min	milliliters per minute

Water-year definition:

A water year is the 12-month period from October 1 through September 30. It is designated by the calendar year in which it ends.

Acronyms used in this report:

EPA	U.S. Environmental Protection Agency
MDEQ	Montana Department of Environmental Quality
NWQL	U.S. Geological Survey National Water Quality Laboratory, Denver, Colo.
RPD	relative percent difference
USDA-Forest Service	U.S. Department of Agriculture-Forest Service
USGS	U.S. Geological Survey

Streamflow, Water Quality, and Quantification of Metal Loading in the Upper Tenmile Creek Watershed, Lewis and Clark County, West-Central Montana, September 1998

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Abstract

The principle sources of metal loads entering upper Tenmile Creek during September 1998 were identified and quantified by combining and analyzing streamflow data determined from tracer-injection and current-meter methods with metal-concentration data determined from synoptic water-quality sampling. The upper study reach extended 1.8 miles downstream from a site above Banner Creek to the City Diversion on Tenmile Creek for Helena's municipal water supply. The lower study reach extended 8 miles downstream from the City Diversion to the Tenmile Water Treatment Plant.

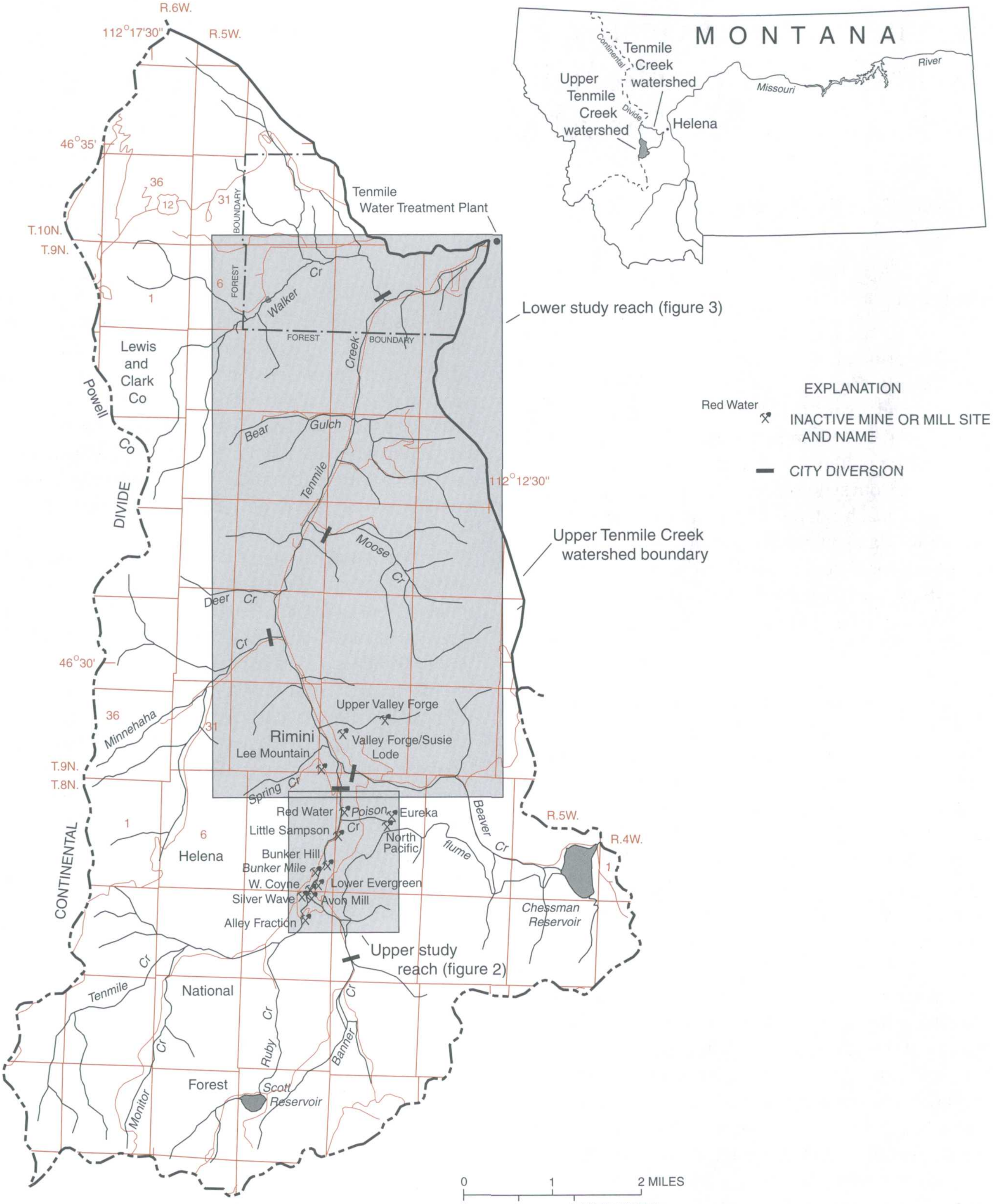
During the time of this investigation, streamflow in the upper study reach was augmented by water release from a storage reservoir and was many times greater than that in the lower study reach, where the majority of the streamflow was diverted to the Tenmile Water Treatment Plant. The low streamflow in the lower study reach offered little dilution capacity to metal loads entering Tenmile Creek, and source loads greatly influenced mainstem concentrations in this reach.

Metal concentrations in all mainstem samples collected in the upper study reach were less than Montana human-health standards. In the lower study reach, concentrations of total-recoverable arsenic in almost 90 percent of stream samples exceeded the Montana human-health standard. Cadmium and lead concentrations in Tenmile Creek exceeded human-health standards downstream from the Lee Mountain Mine area and the Valley Forge/Suzie Lode adit. Metal concentrations exceeded Montana aquatic-life criteria in parts of both the upper and lower study reaches. In the upper study reach, aquatic-life criteria were not exceeded in Tenmile Creek upstream from the Bunker Hill Mine area, except for total-recoverable lead. Downstream from the Bunker Hill Mine area, all zinc concentrations in all stream samples exceeded the acute aquatic-life criterion. In the lower study reach, cadmium, copper, lead, and zinc concentrations in Tenmile Creek exceeded the acute aquatic-life criteria near the Lee Mountain Mine area and the Valley Forge/Susie Lode adit. Downstream from the Valley Forge/Susie Lode adit, metal concentrations generally decreased.

Metal loads generally enter Tenmile Creek in six short stream sub-reaches that are adjacent to inactive mines. Four of the sub-reaches were in the upper study reach near the Bunker Hill, Little Sampson, and Red Water Mines, plus the tributary Poison Creek, which drains the areas near the North Pacific and Eureka Mines. In the lower study reach, significant metal loading occurred in sub-reaches near the Lee Mountain Mine and the Valley Forge/Susie Lode adit. Nearly equal amounts of cadmium were contributed to Tenmile Creek in each study reach. More arsenic was contributed in the lower study reach, while sources in the upper study reach contributed more copper, lead, and zinc to Tenmile Creek.

INTRODUCTION

The upper Tenmile Creek watershed (fig. 1) in west-central Montana is typical of many headwater areas in the western United States where acid drainage from mine lands has affected the quality of water and aquatic resources (Parrett and Hettinger, 2000). Inactive mines, mine-related structures, and mine wastes and tailings throughout the upper Tenmile Creek watershed are artifacts of more than a hundred years of mining (Metesh and others, 1986). Water samples collected in previous studies of the upper Tenmile Creek watershed indicated that concentrations of some metals exceeded human-health standards and fresh-



Base map modified from U.S. Geological Survey digital data, 1:24,000, 1961-89 (streams); U.S. Census Bureau tiger-line digital data, 1:100,000, 1992 (roads). Albers Equal Area Conic Projection Standard, parallels 46°00' and 48°00', central meridian 109°30'.

Figure 1. Location of study area.

water aquatic-life criteria (Metesh and others, 1998; Montana Department of State Lands, 1999; Parrett and Hettinger, 2000). Although many potential metal sources are visible in the upper Tenmile Creek watershed, metal inputs to the stream have not been sufficiently quantified.

Metal-loading studies have been useful for characterizing water quality in historical mining areas and identifying metal source areas and pathways (for example, Kimball, 1997; Kimball and others, 1999; Cleasby and others, 2000). In these studies, detailed downstream profiles of metal loads along a stream were constructed from streamflow data (obtained by tracer injection) and metal-concentration data (obtained by synoptic water-quality sampling) at many closely spaced sites. Downstream changes in metal loads in the stream were attributed to influent sources along the stream as well as to instream geochemical reactions occurring in the mainstem channel. Comparison of loads among many sites then was used to identify the relative magnitude of metal inputs to the stream from individual source areas. This type of information is essential for determining priority areas for cleanup actions. Similar methods were used in this study to determine the relative importance of the various source areas of metal loading to Tenmile Creek.

In addition to the effect of historical mining, streamflow in parts of the upper Tenmile Creek watershed is routinely depleted during low-flow periods by water diversions used to supply the municipal needs of the City of Helena. In response to efforts to improve water-quality and streamflow conditions, information was needed concerning specific source areas of metal loading in the watershed and the potential ability of the Tenmile Creek channel to convey water during low-flow conditions when natural channel losses may exceed available flow.

Purpose and Scope

The purpose of this report is to present the results of a metal-loading study conducted on two reaches of the upper Tenmile Creek watershed during September 1998. These results describe the streamflow and quality of water in Tenmile Creek, quantify metal loads entering Tenmile Creek, and identify the predominant source areas contributing these metals. Along with the metal-loading results, this report also presents supplemental synoptic streamflow measurements that were made to determine if flow is lost from the channel along the lower reach of Tenmile Creek. This study was conducted in cooperation with the U.S. Environmental Protection Agency (EPA), the U.S. Department of Agriculture-Forest Service (USDA-Forest Service), and the Montana Department of Environmental Quality (MDEQ).

Metal-loading data were collected during September 8-10, 1998, along the 1.8-mi reach of Tenmile Creek starting about 1,600 ft upstream from Banner Creek and ending at the City Diversion on Tenmile Creek (upper study reach, fig. 2). Metal-loading data were collected during September 3-6, 1998 along an 8-mi reach of Tenmile Creek starting just downstream from the City Diversion and ending at the Tenmile Water Treatment Plant (lower study reach, fig. 3). A total of 87 sites on Tenmile Creek, 31 surface-inflow sites, and one subsurface leachate site were sampled. Metals of particular concern were arsenic, cadmium, copper, lead, and zinc. In this report, the term "metal" includes arsenic even though this element is classified as a metalloid.

Acknowledgments

The authors acknowledge, with great appreciation, the many individuals who aided in this study. Special thanks go to the City of Helena's Water Department for their cooperation during this study and to the land owners who allowed access to the stream. Thanks also are due to the many people in the U.S. Geological Survey (USGS) who aided in both field and office work during this project. Also, thanks go to the following volunteers for their assistance in data collection: Ray TeSoro, Bo Stuart, Jack Kaiser, and Melanie Scott of the U.S. Department of Agriculture-Forest Service; Mike Bishop from the U.S. Environmental Protection Agency; Jesse Aber from the Montana Department of Natural Resources and Conservation; and Patricia Hettinger from the Lewis and Clark County Water Quality Protection District.

Description of the Study Area

This study was conducted in the upper Tenmile Creek watershed (fig. 1), which extends from the Con-

Inset from Figure 1 (upper study reach)

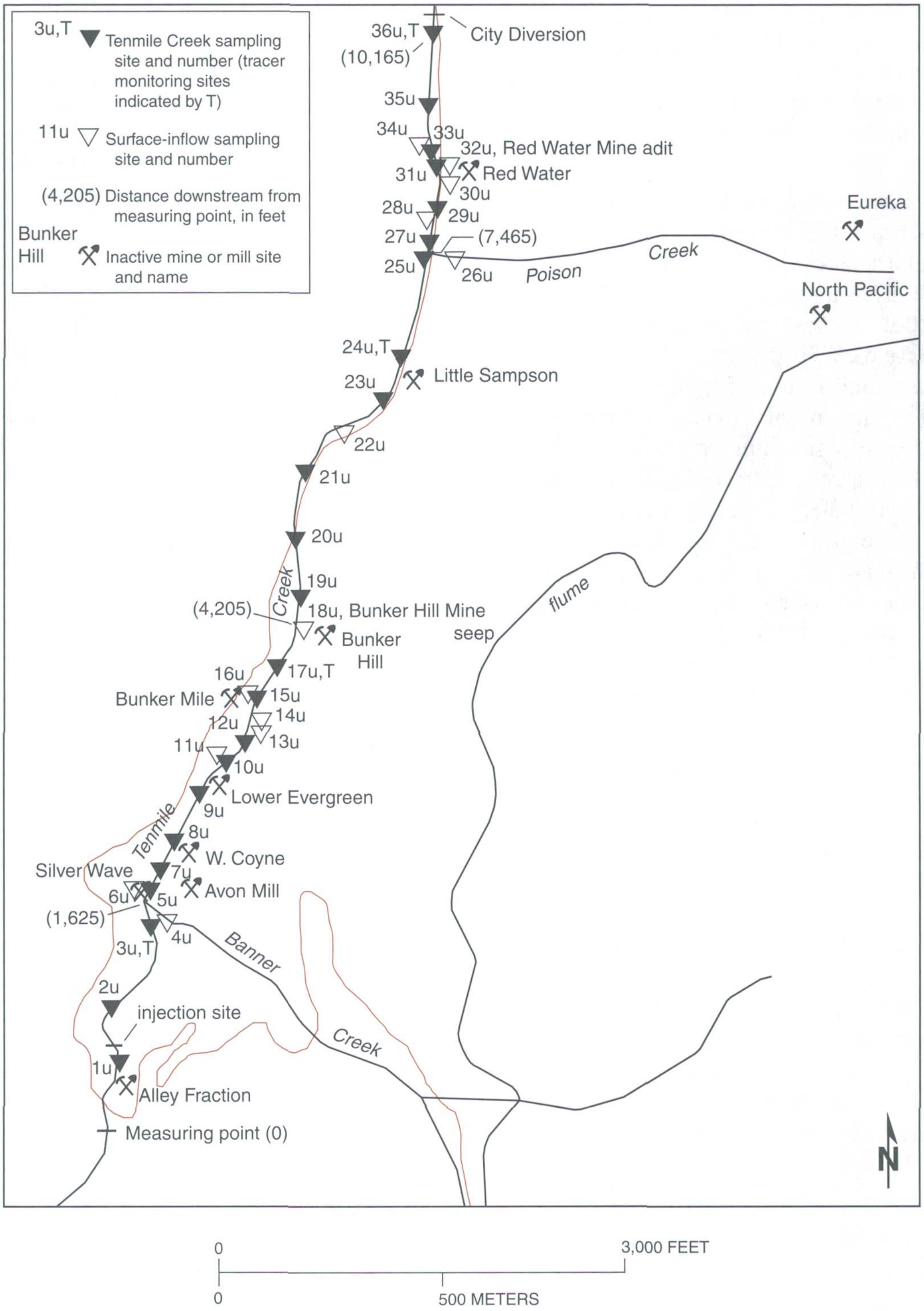


Figure 2. Location of sampling sites and selected mine sites in the upper study reach, Tenmile Creek, Montana.

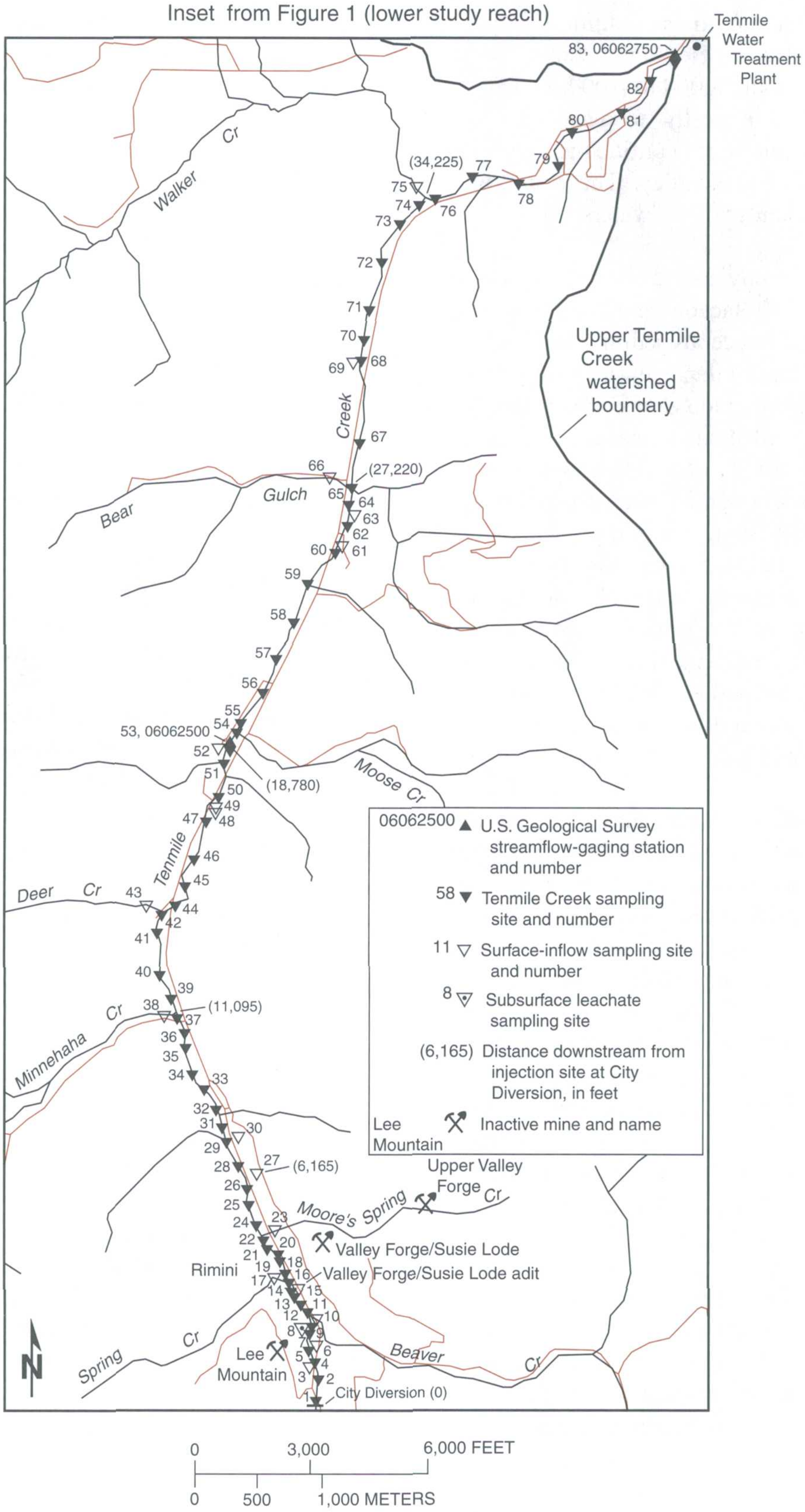


Figure 3. Location of sampling sites and selected mine sites in the lower study reach, Tenmile Creek, Montana.

tinental Divide downstream to the Tenmile Water Treatment Plant (Parrett and Hettinger, 2000). Altitudes range from about 8,000 to 4,000 ft. The terrain in the watershed is mostly steep and mountainous. Mountain ridges confine the very narrow upper Tenmile Creek valley. The small town of Rimini is near the center of the watershed.

Geology of the study area is characterized by large areas of exposed Cretaceous and Tertiary igneous rocks, small areas of Cretaceous sedimentary rocks, and a thin veneer of glacial deposits and alluvium in valleys. Bedrock units include Cretaceous metamorphosed sandstone and siltstone, Cretaceous andesitic volcanic rocks of the Elkhorn Mountains Volcanics, Cretaceous granitic rocks of the Boulder batholith, and Tertiary volcanic rocks composed of rhyolite and tuff. According to Knopf (1913), two periods of mineralization occurred in this area--one during the late Cretaceous and one during the late Tertiary period. The mineralization during the first period resulted predominately in silver-lead ore bodies, rich in galena and pyrite. The mineralization of the second period resulted in disseminated gold ore.

The City of Helena receives most of its municipal water supply from the upper Tenmile Creek watershed. The water-supply storage and delivery system includes Chessman and Scott Reservoirs (fig. 1) in the headwaters of the watershed and one main diversion on Tenmile Creek plus five water-diversion structures on tributaries to Tenmile Creek. The principle diversion is the City Diversion on Tenmile Creek upstream from Rimini. Tributary diversions are on Banner, Beaver, Minnehaha, Moose, and Walker Creeks. Water diverted from Banner Creek is routed to Chessman Reservoir. Water from the other diversions is routed directly to the Tenmile Water Treatment Plant through underground pipes.

Streamflow in upper Tenmile Creek is confined mostly to a narrow incised channel with a streambed of boulders and cobbles. The gradient of the stream is fairly steep in the upper study reach, where the streambed drops about 720 ft over a distance of about 1.8 mi.

The valley in the lower study reach is wider than that in the upper study reach, although the streambed is still composed mostly of boulders and cobbles. The gradient of the stream in the lower reach is more moderate than that of the upper reach, as the streambed drops about 920 ft over a distance of 8 mi. USGS streamflow-gaging stations on Tenmile Creek near Rimini (station 06062500) and on Tenmile Creek at Tenmile Water Treatment Plant, near Rimini (station 06062750) were operated during the study (fig. 3).

METHODS OF DATA COLLECTION

A reconnaissance of each study reach was conducted before the start of each tracer injection. Sampling sites were selected, and their distances along the channel downstream from an initial starting point were measured with a tape and recorded. These distances and a brief description of each sampling site are listed in tables 5 and 6 (at back of report). Sampling sites on Tenmile Creek were selected upstream and downstream from visible inflows, tailings or waste-rock piles, and other mining-related structures that potentially could contribute metal loads to the stream. To detect loads from subsurface flow, additional sampling sites were selected at locations that had no visible inflow or mining disturbances.

Streamflow

Tracer-injection methods for determining streamflow represent a good alternative to traditional current-meter methods, particularly where the traditional methods are hampered by very irregular channel cross sections or turbulent flow that greatly decrease the accuracy of streamflow measurements. Also, the tracer-injection method accounts for any hyporheic flow that is missed by traditional surface measurements. Another advantage of the tracer-injection method is that the information needed to calculate streamflow can be collected more quickly than a large number of current-meter measurements can be made, thus allowing flow in a study reach to be characterized in less time and minimizing the potential effect of diurnal streamflow changes that could skew the load calculations.

Tracer-injection methods (Kimball, 1997; Kimball and others, 1999; Cleasby and others, 2000; Nimick and Cleasby, 2001), using chloride as the tracer, were used to calculate streamflow in each study reach. The tracer injection rate, tracer-solution concentration, instream background concentration of the tracer, and the instream concentration of the tracer at equilibrium conditions are required to calculate streamflow.

During each of the tracer injections, water samples for chloride analysis were collected frequently at several stream sites, referred to as tracer-monitoring sites, to document the downstream movement and equilibrium concentration of the injected tracer. Each tracer-monitoring site was sampled before, during, and after the tracer injection. These samples were collected near midstream, either manually or with an automatic sampler, and were filtered through a 0.45-µm capsule filter.

The tracer injection in the upper study reach started at 0955 hours on September 8, 1998, and ended at 1505 hours on September 9, 1998. Before the start of the injection, an ample volume of tracer solution was prepared in a 450-gallon plastic tank by mixing 400 pounds of sodium chloride (NaCl) with 325 gallons of stream water. This mixture produced a chloride concentration much higher than ambient stream concentrations, but less than the concentration at which the solution would be saturated with respect to chloride. The solution was injected continuously at a rate of 480 mL/min into Tenmile Creek about 1,600 ft upstream from Banner Creek at a point between sites 1u and 2u (fig. 2) using a positive-displacement pump system. The pump system was controlled and monitored by an electronic-data logger during the 29-hour injection period. Seven samples of the tracer solution were collected during the injection period to document any variation in tracer-solution concentration. The chloride concentration in tracer-solution samples was determined by measuring the density of the solution with volumetric glassware and an analytical balance. The density was converted to concentration using data in Weast and Astle (1981). The chloride concentrations in the tracer-solution samples ranged randomly from 87.6 to 97.9 g/L, and the average concentration (93.6 g/L) was used for calculating streamflow.

Continuous tracer injection cannot be used to calculate streamflow if tracer mass is lost by sorption, volatization, chemical reaction, or streamflow seepage loss. The mass of the injected tracer thus is presumed to remain in solution as it travels downstream. After correcting for instream background chloride concentrations, any decrease in chloride concentration between consecutive sites is presumed to be caused by dilution from inflows entering between the two sites. The inflow necessary to achieve this dilution can be calculated to quantify the total streamflow at the downstream site, including surface flow above the streambed and flow through the channel substrate (hyporheic flow), both of which can freely interchange and typically are in equilibrium with the injected tracer.

Total streamflow at the first site downstream from a continuous tracer-injection site is calculated using equation 1:

$$Q_a = \frac{Q_{inj}(C_{inj} - C_o)}{(C_a - C_o)} \qquad (1)$$

where:

Q_a is the total streamflow at the first site downstream from the tracer 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 background concentration of the tracer upstream from the tracer injection site, in mg/L; and
C_a is the tracer concentration, in mg/L, at the first downstream site.

When the streamflow and instream tracer concentration are known for one site on the mainstem, equation 2 can be used to calculate streamflows at each successive downstream site along the mainstem:

$$Q_b = \frac{Q_a(C_a - C_i)}{(C_b - C_i)} \qquad (2)$$

where:

Q_b is the streamflow at the next downstream site (site b), in L/s,
Q_a is the streamflow at the previous upstream site (site a), in L/s,
C_a is the instream tracer concentration at the previous upstream site, in mg/L,
C_i is the tracer concentration in the water entering the stream between the two sites, in mg/L; and
C_b is the instream tracer concentration at site b, in mg/L.

The tracer injection in the lower study reach started at 0910 hours on September 3, 1998, and ended at about 1900 hours on September 6, 1998. The tracer solution for the lower injection was prepared by mixing about 250 pounds of NaCl with 200 gallons of stream water. The solution was injected continuously into Tenmile Creek just downstream from the City Diversion at 133 mL/min for the duration of the injection. Samples of the tracer solution were collected periodically during the injection period to document any variation in tracer-solution concentrations. The chloride concentrations in these samples progressively decreased during the study and ranged from 99 g/L at the start of the study to 85 g/L at the end. These decreasing concentrations and other problematic conditions affecting streamflow equilibrium complicated the calculation of streamflow in the lower study reach. Additional interpretation of the tracer data, discussed in the streamflow section, was necessary for determining streamflow in the lower study reach.

To determine if Tenmile Creek loses streamflow in the lower study reach, flow was measured at nine sites using concurrent spot-tracer injections and current-meter measurements. A spot-tracer injection is similar to a continuous-tracer injection in that both use the dilution of the injected tracer and equation 1 to determine streamflow. A spot injection is much shorter in duration than a continuous injection and is designed to determine streamflow at a single site rather than at numerous sites over a long reach. Because of the shorter injection time, the tracer does not fully saturate the subsurface (hyporheic) flow that moves through the interstices of the streambed gravels and cobbles. Thus, the streamflow measured using this technique primarily represents the surface flow in the channel and typically is similar to streamflow measured by a current meter.

Synoptic Water-Quality Sampling

Synoptic samples were collected in acid-washed 4-L polyethylene bottles at pre-selected sampling sites. Synoptic samples were collected on September 9, 1998, in the upper study reach, and on September 6, 1998, in the lower study reach. To reduce the possibility of load changes caused by diurnal variation in streamflow, samples were collected and processed as rapidly as possible during each sampling day. At sampling sites where stream mixing was assumed to be good, depth-integrated samples were collected at a single vertical near midstream. Equal-width and depth-integrated samples were collected at sites, such as those immediately downstream from an inflow, where mixing was expected to be incomplete. Once collected, the samples were transported to a central processing location near the middle of each study reach. Field values of pH were determined from an aliquot of each sample. A second unfiltered aliquot was drawn for analysis of total-recoverable metals. A third aliquot was filtered through a 0.1-µm plate filter for the analysis of dissolved metals. Aliquots for analysis of total-recoverable and dissolved metals were acidified with ultrapure nitric acid to a pH of less than 2. A fourth unfiltered aliquot was drawn for the analysis of chloride and sulfate. For selected sites in the lower study reach, an additional aliquot was filtered through a 0.001-µm tangential-flow plate filter. These ultrafiltrate samples were analyzed for dissolved metals. Samples were processed, filtered, and preserved in accordance with procedures described by Ward and Harr (1990), Horowitz and others (1994), and Wilde and others (1998).

Dissolved chloride and sulfate concentrations were determined by the USGS research laboratory in Salt Lake City, Utah, using ion chromatography. Dissolved and total-recoverable metal concentrations were determined by the USGS National Water Quality Laboratory (NWQL) in Denver, Colo. Dissolved and total-recoverable arsenic concentrations were determined using hydride-generation atomic-absorption spectroscopy. Inductively coupled plasma-mass spectrometry was used in the analyses of dissolved and total-recoverable aluminum and dissolved iron, manganese, and zinc. Graphite-furnace atomic-absorption spectroscopy was used in the analyses of dissolved and total-recoverable cadmium, copper, and lead. Total-recoverable iron and zinc were analyzed using flame atomic-absorption spectroscopy. These analytical methods are described by Fishman and Friedman (1989), Fishman (1993), Garbarino and Taylor (1996), Hoffman and others (1996), and Garbarino and Stuzeski (1998). Water-quality data collected during this study are reported in tables 5 and 6.

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 the collection and processing of water samples are described by Horowitz and others (1994), and Wilde and others (1998).

The quality of analytical results reported for water samples can be evaluated with data from quality-control samples that were processed in the field and analyzed in the laboratory using the same collection, processing, and analytical procedures that were performed on the environmental samples. These quality-control samples, which consisted of duplicates and blanks, provide information on the precision and bias of the overall field and laboratory process. During this study about 6 percent of the total samples collected and analyzed were quality-control samples. In addition to quality-control samples submitted from the field, internal quality-assurance practices at the NWQL were performed systematically to provide quality control of analytical procedures (Pritt and Raese, 1995). These internal practices included analyses of quality-control samples such as calibration-standard samples, standard-reference samples, duplicate samples, deionized-water blank samples, or spiked samples. The number of internal quality-control samples constituted at least 10 percent of the total number of samples analyzed.

Precision of analytical results are affected by many sources of variability within the field and laboratory environments including sample collection, processing, and analysis. To assess this variability, four duplicate samples were collected in the field to provide data on precision for samples that were exposed to all sources of variability. Each duplicate sample was collected by splitting a single 4-L composite sample into two separate samples. Each sample was then analyzed separately. Analytical results for field duplicate samples are presented in tables 5 and 6.

Precision of analytical results for a constituent can be described by the relative percent difference (RPD) of the concentrations in the duplicate analyses. The RPD is calculated for a constituent by dividing the absolute value of the difference between the two concentrations by their mean value and then multiplying by one hundred. RPD values for constituents in the four field duplicates were mostly less than 15 percent, except for dissolved iron and total-recoverable aluminum, and indicate good overall precision of the analytical results. The RPD for total-recoverable aluminum in two of the duplicate samples was about 18 to 60 percent, indicating that precision for total-recoverable aluminum was poor and that the samples were affected by field contamination, laboratory imprecision, or both. The RPD for dissolved iron in one duplicate sample was about 70 percent. This single large difference appears to be a random occurrence and indicates no systematic analytical problem for dissolved iron.

Four blank samples of ultrapure deionized water were analyzed for this study to identify the presence and magnitude of possible contamination that could originate from sample collection or processing, and potentially bias analytical results. The water for each blank was processed through the same sampling equipment using the same handling procedures that were used for the collection of the environmental samples. Blank samples were analyzed for the same properties and constituents as those of the environmental samples to identify the presence of any detectable constituent contamination. Constituent concentrations in the blanks were all less than the minimum reporting level. Results are presented at the end of tables 5 and 6.

STREAMFLOW

Streamflow in Tenmile Creek was dramatically different in the two study reaches during the period of data collection. Natural streamflow in the upper study reach was augmented by a steady release of water from Scott Reservoir. Almost all the flow in Tenmile Creek was diverted at the City Diversion at the downstream end of the upper study reach. Consequently, flow in Tenmile Creek in the lower study reach was much less than that in the upper study reach.

Upper Study Reach

Tracer-monitoring sites in the upper study reach were located at sites 3u, 17u, 24u, and 36u (fig. 2). Data from samples collected approximately hourly at these sites were used to graphically display the temporal variation of dissolved chloride concentrations in the upper study reach (fig. 4) as the tracer moved downstream. Ideally, these graphs have three distinct

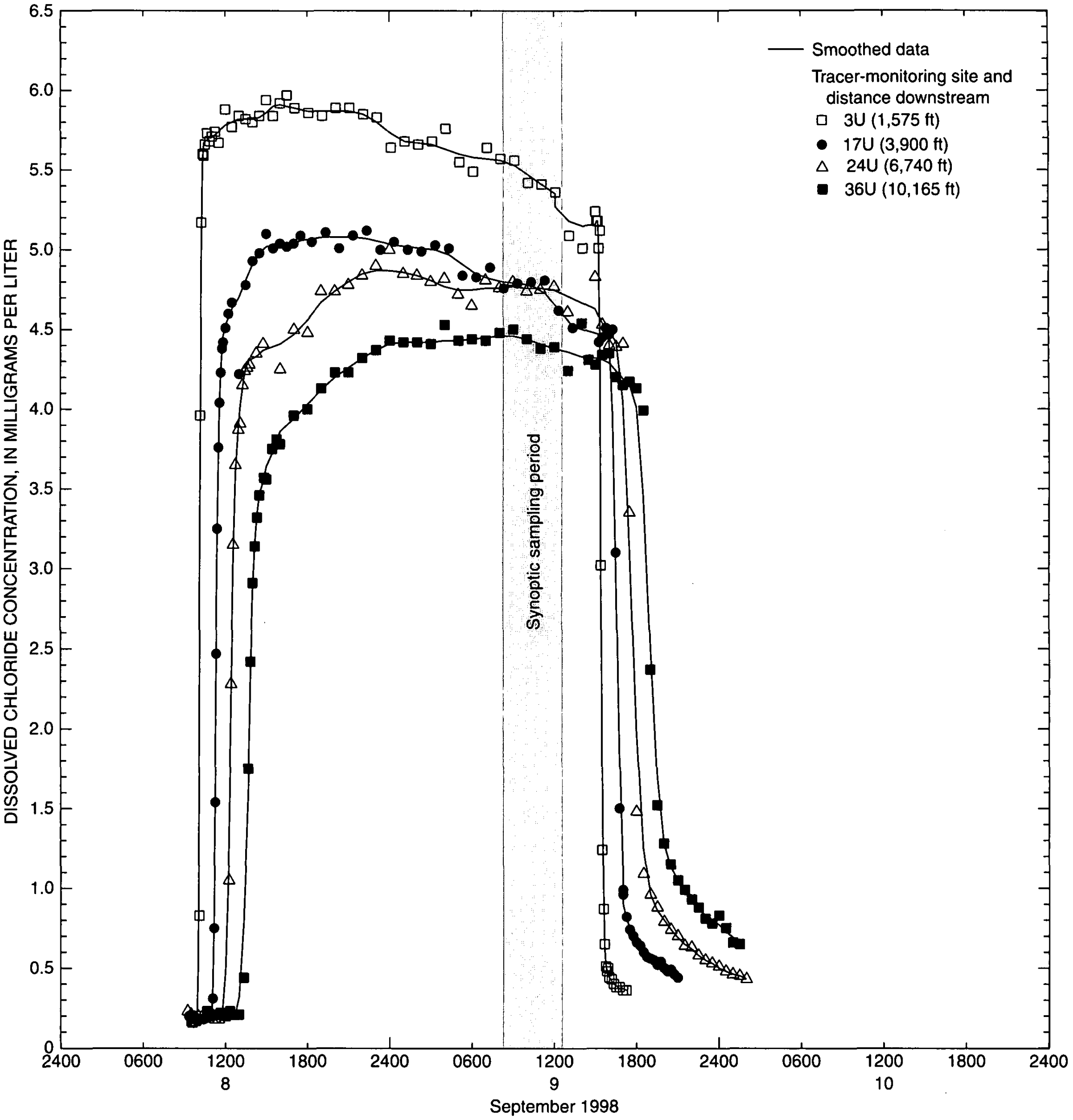


Figure 4. Temporal concentration profile of dissolved chloride at tracer-monitoring sites in the upper study reach, Tenmile Creek, Montana, September 8-10, 1998.

periods that show the arrival, plateau, and departure of the tracer. For each tracer-monitoring site, the plateau period is defined as the time when the tracer is at equilibrium within the stream system. When streamflow at the most downstream site has reached equilibrium with the injected tracer, a plateau of relatively stable chloride concentrations should exist at each site throughout the study reach until the tracer injection is terminated. Data from tracer-monitoring sites are used to verify that a plateau concentration was reached at each site. Ideally, synoptic samples for characterizing metal loads are collected during the plateau period.

In a gaining stream, the tracer becomes diluted by inflows as it moves downstream. Thus, the magnitude of the plateau concentration decreases downstream in a gaining stream. Changes in chloride concentrations at a site during the plateau period can be caused by changes in streamflow over time at the site (either diurnal variations or from rainfall runoff), changes in injection rate or concentration of the tracer solution, or analytical imprecision. The plateau concentration at the most upstream tracer-monitoring site (3u) was reached quickly and remained relatively unchanged for about 14 hours, then steadily decreased until the end of the injection period. For the upper study reach, the injection rate was nearly constant at 480 mL/min (0.0080 L/s). The concentration of the tracer solution randomly varied throughout the study period, ranging from 87.7 to 97.7 g/L. The average concentration (93.6 ± 3.95 g/L) was used for the calculation of streamflow. The decrease in the instream tracer concentration thus indicates that flow was increasing. The increase in flow probably was the result of a light rain that persisted throughout the day (September 9, when synoptic samples were collected). Data collected at tracer-monitoring sites 17u and 24u followed this same pattern of declining tracer concentrations during their respective plateau periods.

Equations 1 and 2 were used to calculate streamflow at the 23 mainstem sites in the upper study reach (figs. 2 and 5; table 1). If no surface inflow was sampled between consecutive mainstem sites to determine C_i, the median chloride concentration for all inflows sampled in the upper study reach was used as the value for C_i (0.47 mg/L Cl, table 1). The magnitude of each inflow was determined by the difference in streamflow between the Tenmile Creek sites immediately downstream and upstream from the inflow. Hydrologic sources for flow increases could include visible inflows that were sampled and unsampled diffuse ground-water discharge.

To minimize the effect of sampling and analytical variability, chloride concentrations for Tenmile Creek sites reported by the laboratory were smoothed using an algorithm that calculates smoothed values based on a series of running medians (Velleman and Hoaglin, 1981). These smoothed values were used to calculate streamflow in the upper study reach.

Streamflow increased from 145 L/s near the injection site (1u; 485 ft) to 185 L/s at the most downstream site (36u; 10,165 ft) in the upper study reach. Sampled surface inflows accounted for 36 L/s (90 percent) of the increase, leaving 4 L/s (10 percent) of the total increase attributable to unsampled seeps and subsurface inflow. Banner Creek (site 4u) contributed the most flow (23.2 L/s) to Tenmile Creek, accounting for about 60 percent of the total increase in streamflow. At two sites (23u and 36u), current-meter measurements were made on the same day that synoptic samples were collected (fig. 5). At both sites, these measurements were about 20 percent less than the streamflow calculated from the dilution of the tracer. Because of hyporheic flow, the tracer-calculated streamflow was expected to be greater than the streamflow measured with a current meter. These differences are in the same range as those reported in other similar studies (Kimball, 1997; Kimball and others, 1999; Cleasby and others, 2000).

Lower Study Reach

For several weeks prior to the start of the study, streamflow at the diversion on Tenmile Creek and the four diverted tributaries in the lower study reach (fig. 2) was diverted for municipal water supply. As a result, the channel downstream from the City Diversion was not receiving any surface flow and during this time period a portion of the stream channel just downstream from the City Diversion became dry. Two days before the lower tracer injection began, about 6 L/s of streamflow was released to Tenmile Creek at the City Diversion, and about 3 L/s of streamflow was released to Tenmile Creek from the diversion at Minnehaha Creek. During the continuous tracer injection, all streamflow in Beaver, Moose, and Walker Creeks was diverted from reaching Tenmile Creek. The extended period of dewatering and unusually warm, dry weather prior to the tracer injection depleted Tenmile Creek and its streambanks of moisture. When streamflow was released to the channel shortly before and during the injection, some of the water likely seeped into the dry parts of the streambed and banks and remained there as stored water. As streamflow was lost to bank storage, some of the injected tracer solution also was lost. As a result, less chloride remained in the stream, and chloride concentrations measured in synoptic samples at downstream sites were lower than they would have been if water had not infiltrated into the streambed and banks.

Because of the assumed loss of chloride tracer to bank storage, chloride concentrations decreased sharply from the City Diversion downstream about 5,000 ft and then more gradually through the next 14,000 ft to site 53 near Moose Creek (fig. 6). Down-

Table 1. Synoptic chloride concentrations and tracer-calculated streamflow in the upper study reach, Tenmile Creek, Montana, September 9, 1998

[Site description in Table 5. The "u" included with each site number indicates that the site is in the "upper" study reach. Data in **bold print** are for surface-inflow sites. Abbreviations: L/s, liter per second; mg/L, milligrams per liter. Symbol:--, no data]

Site number	Distance downstream from arbitrary measuring point (feet)	Chloride, dissolved (mg/L)	Chloride, smoothed[1] (mg/L)	Tracer-calculated streamflow, instantaneous (L/s)
1u	485	0.20	--	[2]145
2u	985	5.35	5.35	145
3u	1,575	5.34	5.34	146
4u	**1,625**	**.31**	--	**23.2**
5u	1,810	4.65	4.65	169
6u	**1,850**	**.44**	--	**.10**
7u	1,985	4.67	4.71	166
8u	2,265	4.71	4.67	168
9u	2,710	4.68	4.67	168
10u	2,970	4.67	4.67	168
11u	**3,060**	**.37**	--	**.34**
12u	3,240	4.61	4.66	168
13u	**3,325**	**.40**	--	**.22**
14u	**3,400**	**.27**	--	**.22**
15u	3,590	4.70	4.65	169
16u	**3,610**	**.80**	--	**.11**
17u	3,900	4.62	4.65	169
18u	**4,205**	**.51**	--	**.10**
19u	4,445	4.64	4.65	169
20u	4,955	4.66	4.64	169
21u	5,610	4.63	4.62	170
22u	**6,140**	**.45**	--	**1.69**
23u	6,440	4.51	4.58	172
24u	6,740	4.53	4.54	173
25u	7,450	4.54	4.51	175
26u	**7,465**	**.62**	--	**1.63**
27u	7,470	4.49	4.48	176
28u	**7,880**	**.74**	--	**1.88**
29u	8,020	4.39	4.44	178
30u	**8,720**	**.84**	--	**2.00**
31u	8,895	4.39	4.40	180
32u	**8,900**	**.90**	--	**2.42**
33u	9,035	4.50	4.35	183
34u	**9,045**	**.47**	--	**2.02**
35u	9,455	4.29	4.31	185
36u	10,165	4.28	4.29	185

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

[2] A tracer-calculated streamflow could not be determined for this site because it was located upstream from the tracer-injection site. Therefore, an estimated streamflow value equal to the streamflow at site 2u was assigned.

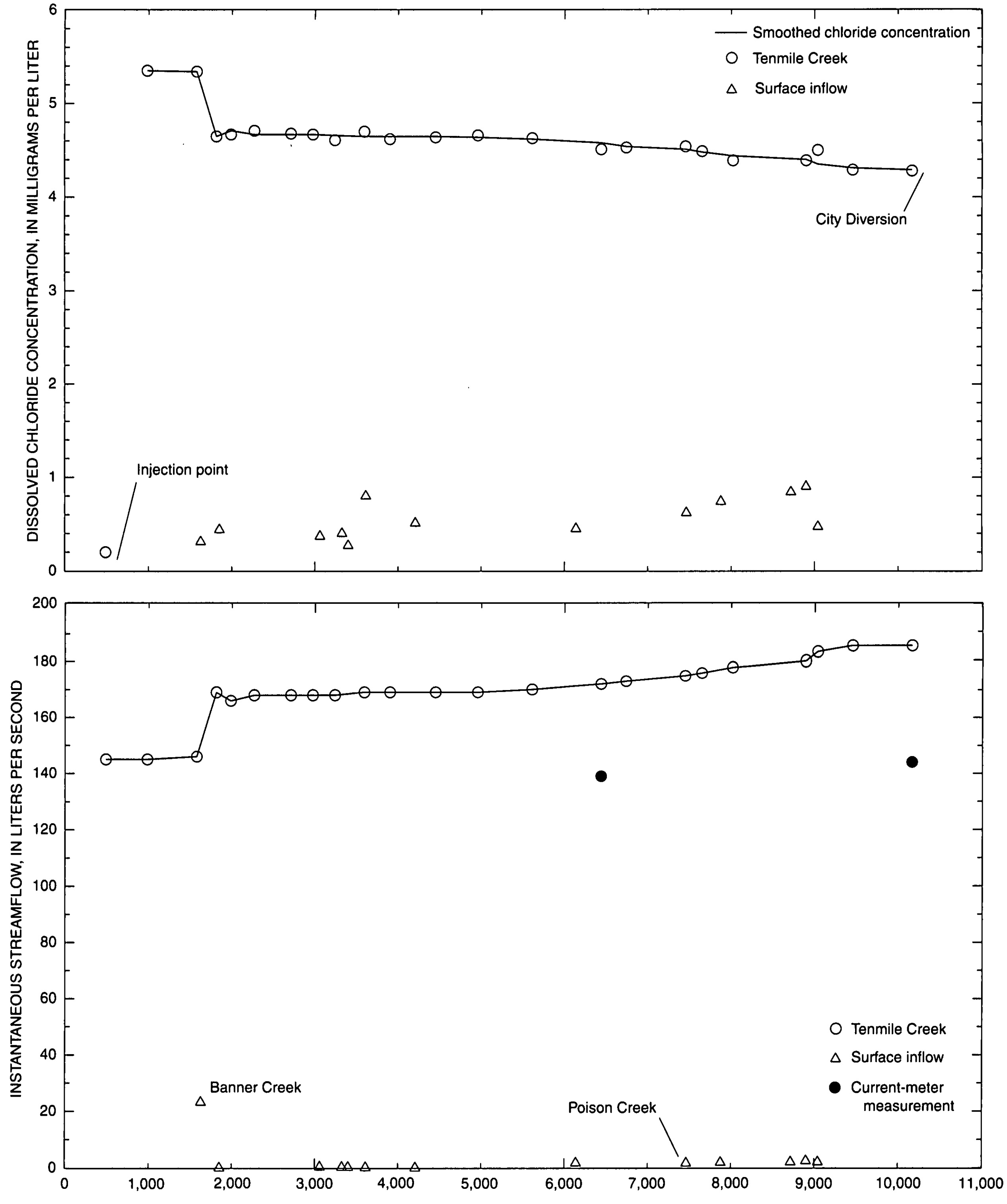


Figure 5. Dissolved chloride concentration (top) and instantaneous streamflow (bottom) at sampling sites in the upper study reach, Tenmile Creek, Montana, September 9, 1998.

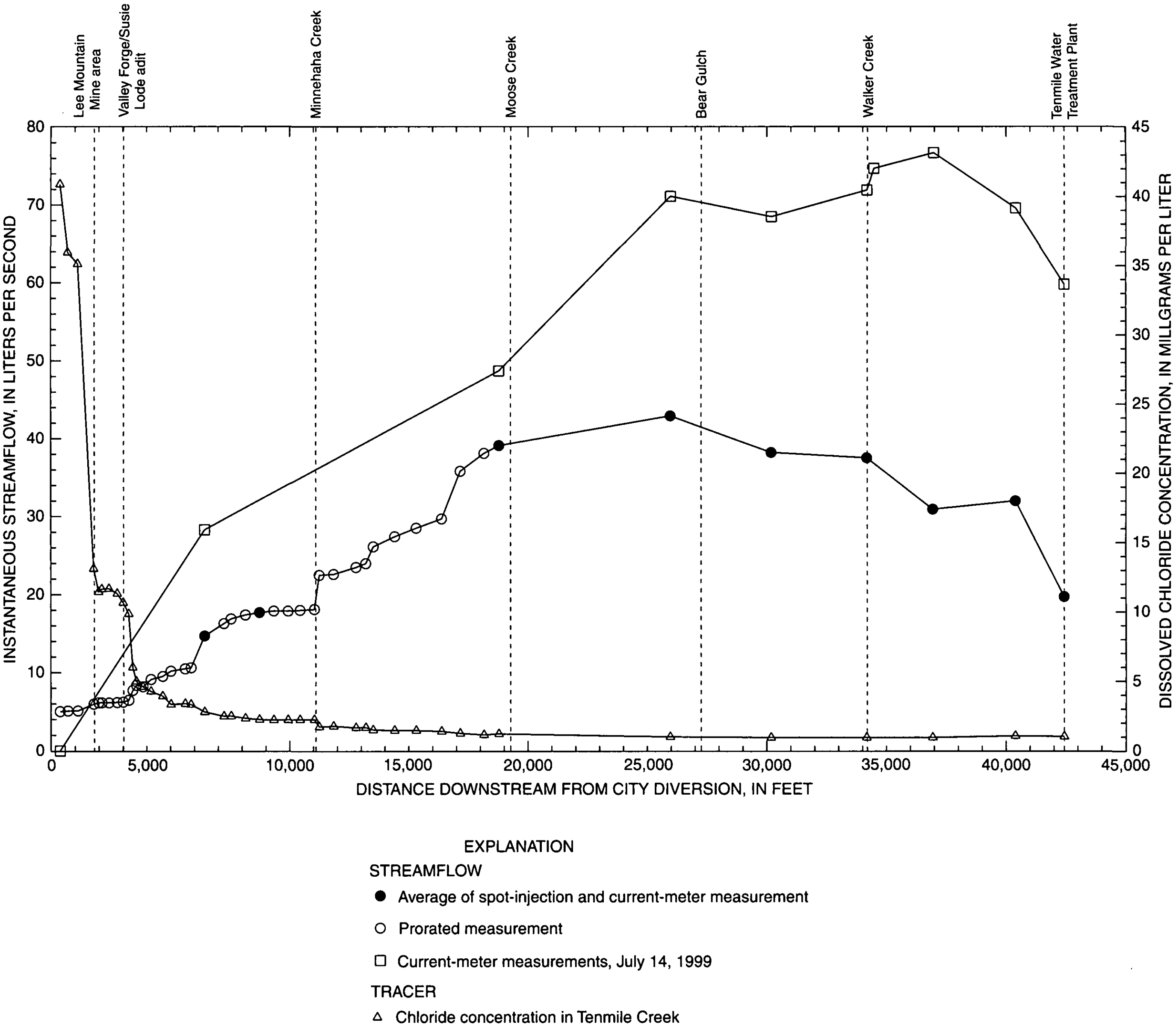


Figure 6. Dissolved chloride concentrations and instantaneous streamflow at selected sampling sites in the lower study reach, Tenmile Creek, Montana, September 6, 1998. Data from July 14, 1999, are from Parrett and Hettinger (2000).

stream from site 53, chloride concentrations were nearly constant and probably near background concentrations. From site 1 to site 53, where chloride concentrations appeared to be higher than background concentrations, streamflow was initially calculated using equations 1 and 2.

The flow and chloride loss introduced an unknown degree of error into the chloride mass-balance calculations, and streamflows calculated using equations 1 and 2 were larger than would be considered reasonable. As an example, streamflow in Tenmile Creek at site 53 (near the USGS streamflow-gaging station near Rimini, fig. 3) was calculated to be more than 500 L/s using equations 1 and 2 (table 2) due to the assumption that decreased concentrations indicate dilution by inflows. Streamflow determined from the spot injection at this site was 47 L/s, and the streamflow determined from a current-meter measurement was 31 L/s. On September 6, 1998, the daily mean streamflow recorded at the streamflow-gaging station was 28 L/s. Clearly, the streamflow value for site 53 calculated from the continuous tracer-injection data was too high by about an order of magnitude.

To adjust the magnitude of the tracer-calculated streamflows for the reach to site 53, a prorated streamflow was calculated for each site on Tenmile Creek where flow had not been measured by spot-injection/current-meter methods. The proration method is defined by equation 3. This method adjusted the tracer-calculated streamflow for an unmeasured site so that the prorated flow value fell between the measured flow values for the nearest upstream and downstream measured sites. In equation 3, sites a and b are adjacent mainstem sites, with site b downstream from site a. At measured sites (sites 1, 28, 33, 53, 62, 70, 74, 78, 81, and 83), the prorated streamflow was not calculated by equation 3 but rather was set equal to the measured flow.

$$q_{bpro} = \left(\left(\frac{q_b - q_a}{Q_{ds} - Q_{us}} \right) \cdot \left(Q_{dmeas} - Q_{umeas} \right) \right) + q_{apro} \quad (3)$$

where:

q_{bpro} is the prorated streamflow at site b, in L/s,

q_b is the tracer-calculated streamflow at site b, in L/s,

q_a is the tracer-calculated streamflow at the upstream adjacent site a, in L/s,

Q_{ds} is the tracer-calculated streamflow at the nearest downstream measured site, in L/s,

Q_{us} is the tracer-calculated streamflow at the nearest upstream measured site, in L/s,

Q_{dmeas} is the measured streamflow at the nearest downstream site, in L/s,

Q_{umeas} is the measured streamflow at the nearest upstream site, in L/s, and

q_{apro} is the prorated streamflow at site a, in L/s.

Listed below is an example calculation, using equation 3, of the prorated streamflow at site 4. All variables are in L/s. Streamflow values listed in table 2 were rounded after all calculations were completed.

$$q_{bpro} = \left(\left(\frac{5.86 - 5.02}{122 - 5.02} \right) \cdot \left(14.7 - 5.02 \right) \right) + 5.02 = 5.09 \text{ L/s}$$

Downstream from site 53, data for the continuous tracer injection were not used to determine streamflow because the injected chloride apparently did not reach this part of the study reach and because streamflow was lost through parts of this reach. Streamflow, and therefore load, data were available only for the six sites in this reach where spot-injection and current-meter methods were used. Streamflow at each of these six sites was assumed to be the average of the streamflow values determined by the two methods.

Streamflow in Tenmile Creek increased by about 38 L/s in the approximately 26,000-ft reach from site 1 just downstream from the City Diversion to site 62, which is about 2,000 ft upstream from Bear Gulch (fig. 6). Streamflow decreased in Tenmile Creek from 42.9 to 32.0 L/s in the approximately 14,000-ft reach between site 62 and site 81, which is about 2,000 ft upstream from the Tenmile Water Treatment Plant (figs. 3 and 6; table 2). In the 2,000-ft reach between site 81 and site 83 (Tenmile Creek at Tenmile Water Treatment Plant), streamflow decreased sharply from 32.0 L/s to 19.7 L/s. The daily mean flow at the time of the tracer study was 17.8 L/s at streamflow-gaging station 06062750 near site 83. To verify streamflow gains and losses documented during this study, a second set of synoptic current-meter streamflow measurements on Tenmile Creek was conducted in 1999 (Parrett and Hettinger, 2000). The second set of mea-

Table 2. Synoptic chloride concentrations and tracer-calculated streamflow in the lower study reach, Tenmile Creek, Montana, September 6, 1998

[Site description in table 6. Prorated streamflow was estimated by adjusting the tracer-calculated streamflow between sites where spot injection and current meter measurements were conducted. Data in **bold** print are surface inflow sites. Streamflow values less than 1.00 L/s are rounded to two significant digits after calculation. Streamflow values greater than 1.00 L/s are rounded to three significant digits after calculation. Abbreviations: L/s, liters per second; mg/L, milligrams per liters. Symbol: --, no data]

Site number	Distance downstream from tracer-injection point (feet)	Chloride, dissolved (mg/L)	Tracer-calculated streamflow, instantaneous (L/s)	Prorated streamflow (L/s)	Average of spot-injection and current-meter measured streamflow (L/s)
1	0	--	[1]5.02	--	5.02
2	365	40.87	5.02	5.03	--
3	**665**	**6.40**	**.84**	**.07**	**--**
4	695	35.95	5.86	5.09	--
5	1,115	35.11	6.03	5.11	--
6	**1,245**	**71.55**	**.01**	**.01**	**--**
7	1,780	13.12	16.4	5.96	--
8	**1,800**	**1.04**	**--**	**--**	--
9	1,985	11.45	18.5	6.14	--
10	**2,000**	**1.03**	**.09**	**.01**	**--**
11	2,120	11.65	18.6	6.14	--
12	2,420	11.68	18.6	6.15	--
13	2,765	11.33	19.3	6.20	--
14	3,015	10.67	19.9	6.25	--
15	**3,040**	**.98**	**2.10**	**.21**	**--**
16	3,250	9.86	22.4	6.46	--
17	**3,305**	**.33**	**15.3**	**1.26**	**--**
18	3,415	6.00	37.7	7.72	--
19	3,575	4.99	45.8	8.39	--
20	3,850	4.60	43.6	8.21	--
21	4,180	4.27	54.6	9.12	--
22	4,675	3.93	59.5	9.52	--
23	**4,890**	**.60**	**8.04**	**.66**	**--**
24	5,020	3.33	67.5	10.2	--
25	5,620	3.38	71.5	10.5	--
26	5,865	3.32	72.4	10.6	--
27	**6,165**	**2.01**	**49.2**	**4.07**	**--**
28	6,435	2.79	122	14.7	14.7
29	7,245	2.48	165	16.3	--
30	**7,375**	**2.91**	**15.7**	**.60**	**--**
31	7,545	2.49	181	16.9	--
32	8,145	2.33	193	17.4	--
33	8,735	2.24	202	17.7	17.7
34	9,335	2.21	205	17.9	--
35	9,935	2.22	205	17.9	--
36	10,440	2.24	206	18.0	--
37	11,040	2.24	207	18.1	--
38	**11,095**	**.32**	**62.0**	**4.40**	**--**
39	11,245	1.72	269	22.5	--
40	11,845	1.77	271	22.6	--
41	12,790	1.66	284	23.5	--
42	13,200	1.67	291	24.0	--

Table 2. Synoptic chloride concentrations and tracer-calculated streamflow in the lower study reach, Tenmile Creek, Montana, September 6, 1998 (Continued)

Site number	Distance downstream from tracer-injection point (feet)	Chloride, dissolved (mg/L)	Tracer-calculated streamflow, instantaneous (L/s)	Prorated streamflow (L/s)	Average of spot-injection and current-meter measured streamflow (L/s)
43	**13,285**	**.49**	**19.1**	**2.10**	**--**
44	13,510	1.50	321	26.1	--
45	14,410	1.47	339	27.4	--
46	15,315	1.46	355	28.5	--
47	16,380	1.40	372	29.7	--
48	**16,935**	**.56**	**43.4**	**3.05**	**--**
49	**16,985**	**.76**	**43.4**	**3.05**	**--**
50	17,160	1.26	459	35.8	--
51	18,155	1.15	492	38.1	--
52	**18,685**	**.43**	**13.9**	**1.00**	**--**
53	18,780	1.22	506	39.0	39.0
62	25,965	1.00	--	--	42.9
70	30,185	.95	--	--	38.2
74	34,175	.95	--	--	37.5
78	36,935	.95	--	--	30.9
81	40,390	1.07	--	--	32.0
83	42,435	1.03	--	--	19.7

[1] A tracer-calculated streamflow could not be determined for this site because it was not far enough downstream from the tracer-injection site to achieve complete mixing of the tracer solution. Therefore, an estimated streamflow value equal to the streamflow at site 2 was assigned.

surements confirmed that Tenmile Creek gained streamflow from the City Diversion to about Walker Creek and lost streamflow downstream from Walker Creek to the Tenmile Water Treatment Plant.

WATER QUALITY

The synoptic samples collected at the 87 main-stem sites on Tenmile Creek and the 32 surface-inflow sites in the upper and lower study reaches were analyzed for pH, chloride, sulfate, and dissolved and total-recoverable metals concentrations (tables 5 and 6). Water-quality standards for some of these constituents that may adversely affect human health or aquatic life have been established by the State of Montana (Montana Department of Environmental Quality, 1999; table 3).

Two levels of water-quality criteria, chronic and acute, have been established for metals for the protection of freshwater aquatic life (table 3). Criteria generally are established to protect the most sensitive organisms within an aquatic community. Chronic criteria are established for protection against long-term exposure to moderately elevated constituent concentrations. If concentrations exceeding chronic criteria persist for long periods, detrimental effects on growth and reproduction may be seen in aquatic organisms. Acute criteria are established for protection against short-term exposure to highly elevated constituent concentrations that can be lethal to aquatic organisms. Several metals at low concentrations can affect aquatic organisms. Because tolerances to metal exposure can vary among species or between individuals within the same species, aquatic-life criteria are only general guidelines for potential toxicity. The Montana criteria for metals toxicity are based on total-recoverable concentrations,

Table 3. Montana water-quality standards

[Abbreviation: µg/L, micrograms per liter. Symbol: --, no standard has been established]

Constituent	Human-health standard[1] (µg/L)	Aquatic-life criterion[1]	
		Chronic (µg/L)	Acute (µg/L)
Aluminum	--	87	750
Arsenic[2]	18	150	350
Cadmium	5	[3].83/[4]1.4	[3].95/[4]2.1
Copper	1,300	[3]2.8/[4]5.2	[3]3.8/[4]7.3
Iron	--	1,000	--
Lead	15	[3].54/[4]1.3	[3]14/[4]34
Zinc	2,100	[3]37/[4]67	[3]37/[4]67

[1] Montana Department of Environmental Quality (1999). Except for aluminum, water-quality standards are based on total-recoverable concentrations.

[2] A new human-health standard for arsenic (10 µg/L) has been established by the U.S. Environmental Protection Agency (2001). The new standard is not enforceable until January 2006.

[3] Criterion for upper study reach based on water hardness of 25 mg/L as calcium carbonate.

[4] Criterion for lower study reach and tributaries based on water hardness of 50 mg/L as calcium carbonate.

except for aluminum, which is based on the dissolved concentration. However, because the criteria are subject to ongoing research, both dissolved and total-recoverable metal concentrations are discussed in this report. Aquatic-life criteria for cadmium, copper, lead, and zinc vary with hardness (Montana Department of Environmental Quality, 1999), with metal toxicity decreasing as water hardness increases. For comparison to ambient metal concentrations, aquatic-life criteria were calculated using a hardness of 25 mg/L $CaCO_3$ for the upper study reach and 50 mg/L $CaCO_3$ for the lower study reach. Criteria for the four diverted tributaries in the lower study reach were calculated using a hardness of 25 m/L $CaCO_3$. These values are based on average hardness concentrations in samples collected in the Tenmile Creek watershed in 1997 (Parrett and Hettinger, 2000).

Upper Study Reach

During the tracer injection, streamflow in the upper study reach was augmented by water releases from a storage reservoir and was greater than natural flow conditions. This greater volume of flow helped dilute the concentrations of metals in Tenmile Creek. The pH in samples collected in the upper study reach ranged from about 4.0 to 7.9 (fig. 7; table 5). Water at all but four sampling sites had pH that was near neutral, with values ranging from a pH of 6.82 to 7.87. The four exceptions had pH values ranging from 3.98 to 5.00 and were samples from three right-bank inflows and Poison Creek (site 26u; 7,465 ft). Two of these inflows (sites 13u and 14u between 3,325 ft and 3,400 ft) were downstream from the Lower Evergreen Mine (fig. 2) and the other inflow was at the base of the Bunker Hill Mine (site 18u; 4,205 ft).

In the upper study reach, metal concentrations in Tenmile Creek (mainstem) samples were notably less than Montana human-health standards (tables 3 and 5). These concentrations indicate that metals in Tenmile Creek upstream from the City Diversion pose little risk to human health during low-flow conditions, as similarly concluded by Parrett and Hettinger (2000). Downstream concentration profiles for sulfate and metals in the upper study reach and, where applicable, water-quality standards are shown in figure 8.

Although mainstem arsenic concentrations increased slightly through the upper study reach, none exceeded 6 µg/L (fig. 8; table 5). The highest arsenic concentrations (12 to 92 µg/L, total recoverable) were measured in two adits and several seeps, with the maximum value occurring at the Red Water Mine adit (site 32u; 8,900 ft).

Concentrations of cadmium, manganese, and zinc in Tenmile Creek followed the same downstream pattern. Upstream from the inflow at the Bunker Hill Mine (site 18u; 4,205 ft), dissolved concentrations were less than or only slightly higher than the minimum reporting level (0.1 µg/L Cd, 4 µg/L

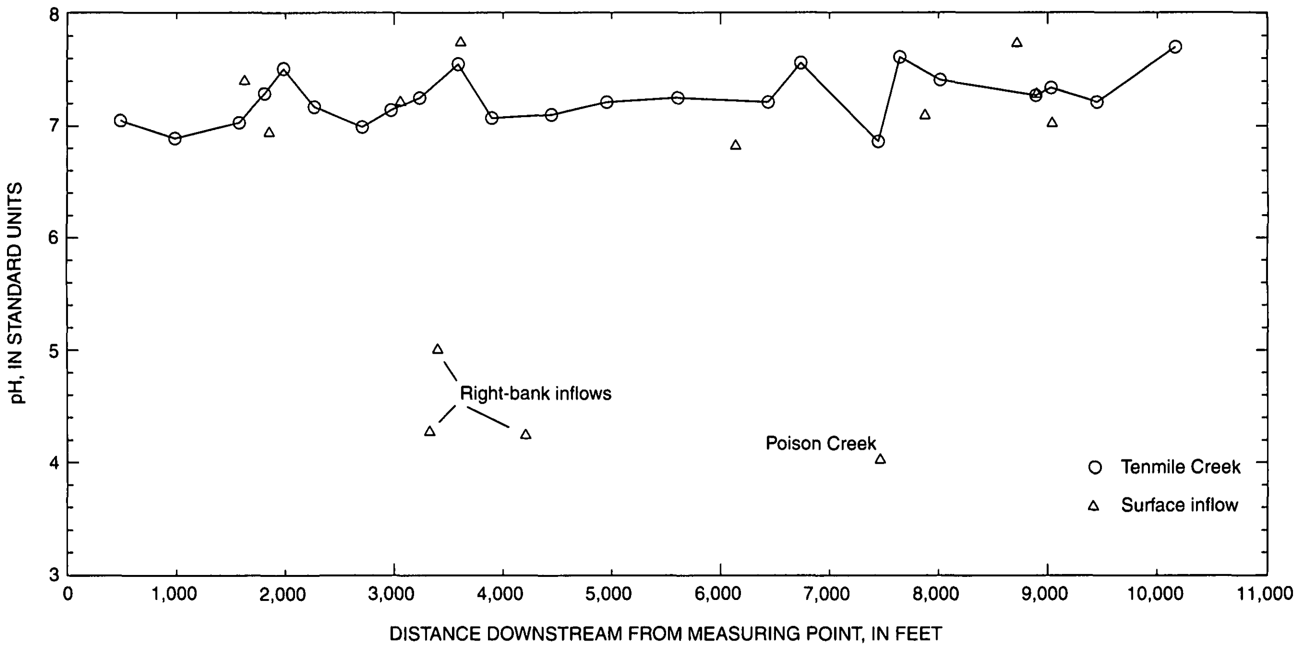


Figure 7. Variation of pH in samples collected in the upper study reach, Tenmile Creek, Montana, September 9, 1998.

Mn, and 20 µg/L Zn). Downstream from site 18u, mainstem concentrations increased and remained high to the end of the upper study reach. Concentrations of cadmium, manganese, and zinc in Tenmile Creek increased notably at three other sites--downstream from the Little Sampson Mine (site 24u; 6,740 ft), Poison Creek (site 27u; 7,470 ft), and the Red Water Mine adit (site 33u; 9,035 ft). The highest dissolved concentrations of these metals in inflows were at the seep near the Bunker Hill Mine (site 18u; 227 µg/L Cd and 38,600 µg/L Zn) and the Red Water Mine adit (site 32u; 4,650 µg/L Mn). Total-recoverable zinc concentrations were similar to dissolved concentrations in both the mainstem and inflows, indicating that zinc was primarily dissolved.

Mainstem concentrations of copper were less than 8 µg/L (fig. 8; table 5) and remained relatively unchanged throughout the upper study reach except for one obvious increase downstream from Poison Creek (site 27u; 7,470 ft). The copper concentrations in Poison Creek (site 26u; 352 µg/L dissolved and 358 µg/L total-recoverable) were the highest in the upper study reach. Other inflows with high copper concentrations were the three acidic seeps at sites 13u, 14u, and 18u between 3,240 ft and 4,445 ft. Copper concentrations in the other inflows were similar to the mainstem concentrations.

At the near-neutral pH of the water in the upper study reach, lead was present primarily in particulate form. Most dissolved lead concentrations in Tenmile Creek were less than the minimum reporting level of 1 µg/L. The highest dissolved lead value in Tenmile Creek was 1.5 µg/L at site 27u (7,470 ft) just downstream from Poison Creek. Total-recoverable lead concentrations in Tenmile Creek increased downstream from the three acidic inflows (sites 13u, 14u, and 18u between 3,240 ft and 4,445 ft) and Poison Creek (site 26u; 7,465 ft). These elevated concentrations persisted to the end of the upper study reach, with the maximum concentration of total-recoverable lead reaching 4.7 µg/L at site 27u downstream from Poison Creek.

Metal concentrations for samples collected in the upper study reach are compared to State of Montana aquatic-life criteria (fig. 8; table 3). Aquatic-life criteria were not exceeded in water from Tenmile Creek (mainstem) upstream from the Bunker Hill Mine (site

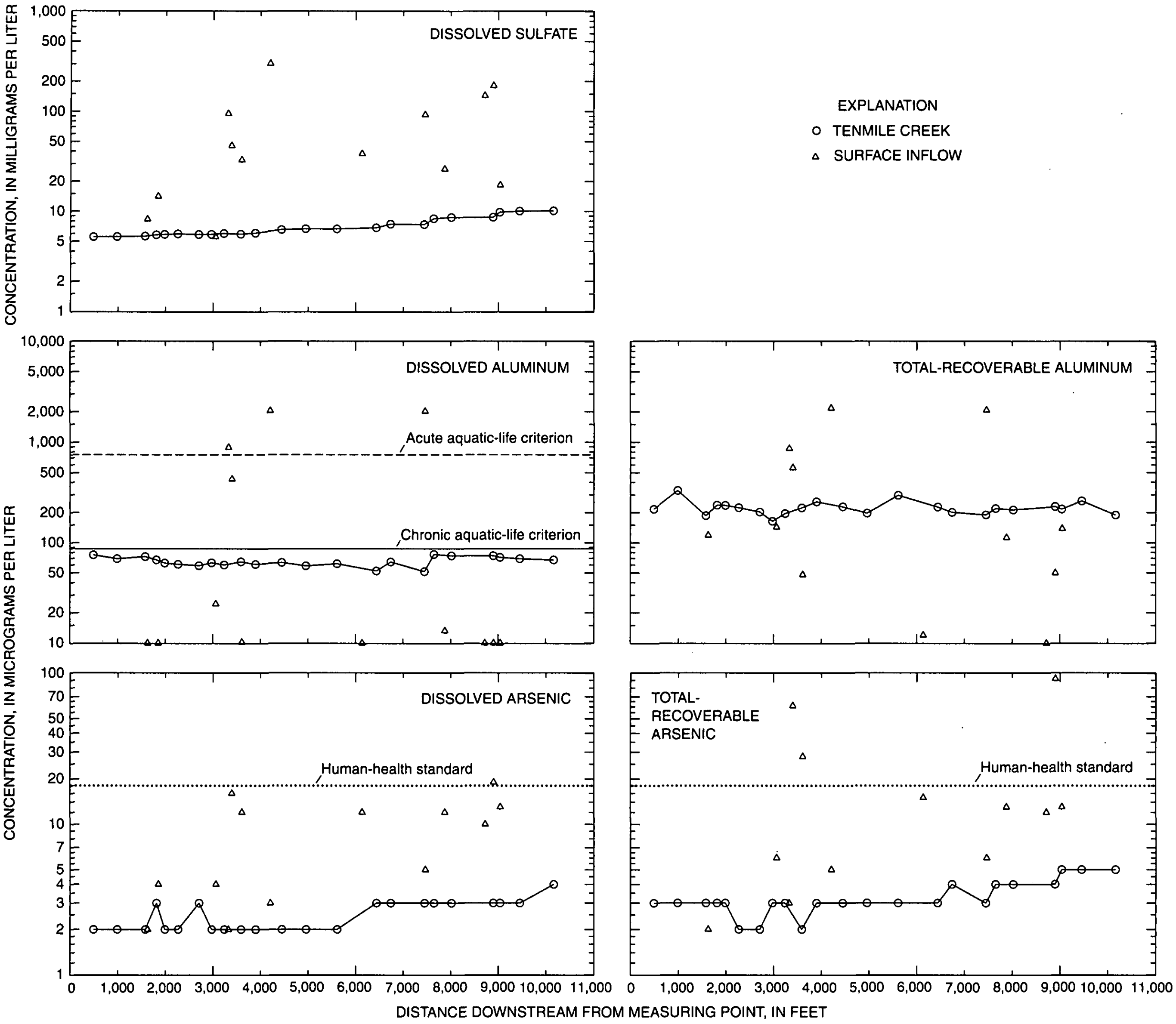


Figure 8. Constituent concentrations in the upper study reach, Tenmile Creek, Montana, September 9, 1998. Human-health standards and aquatic-life criteria are from Montana Department of Environmental Quality (1999). Values equal to or less than the minimum reporting level are plotted at the minimum reporting level.

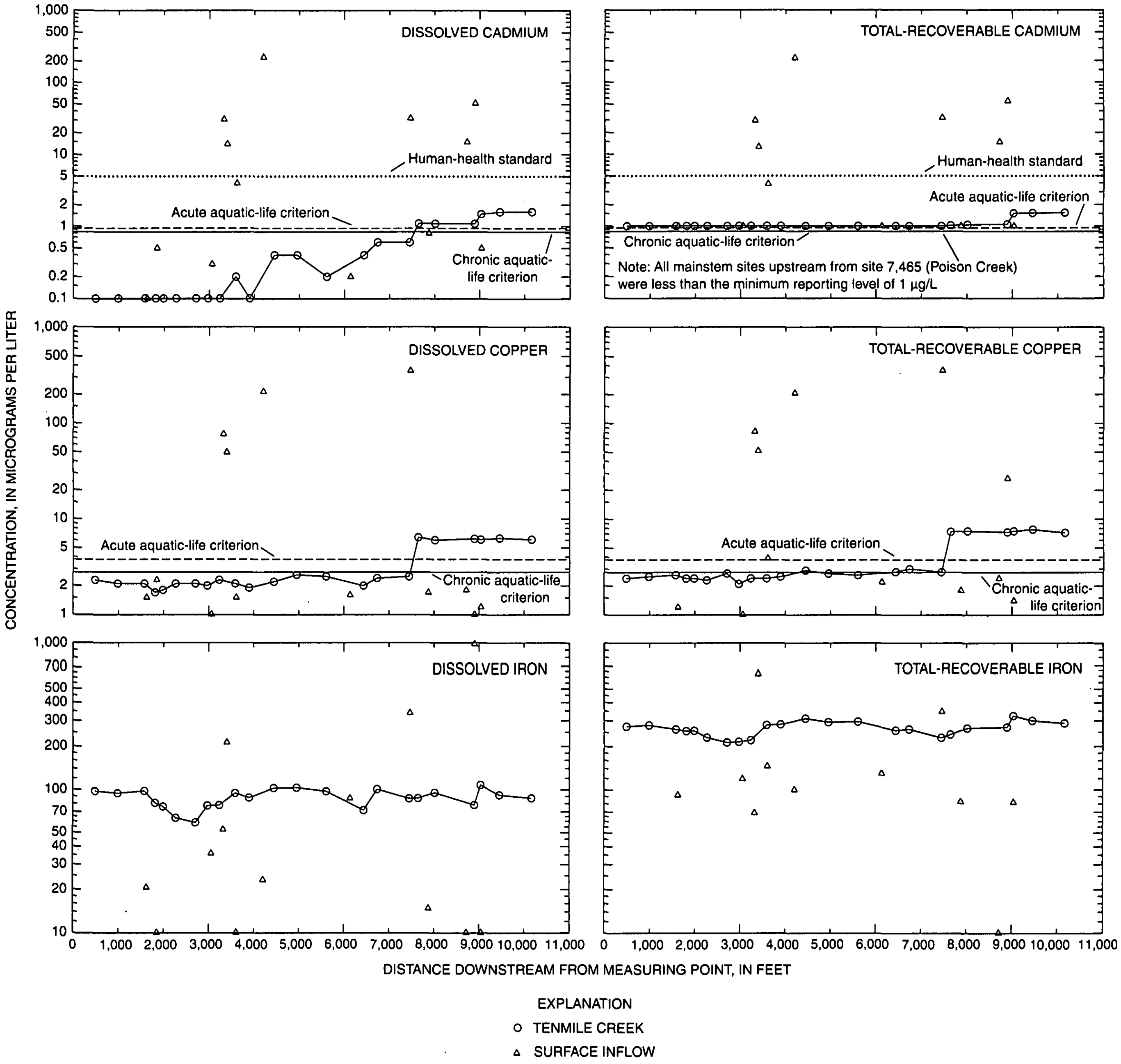


Figure 8. Constituent concentrations in the upper study reach, Tenmile Creek, Montana, September 9, 1998. (Continued)

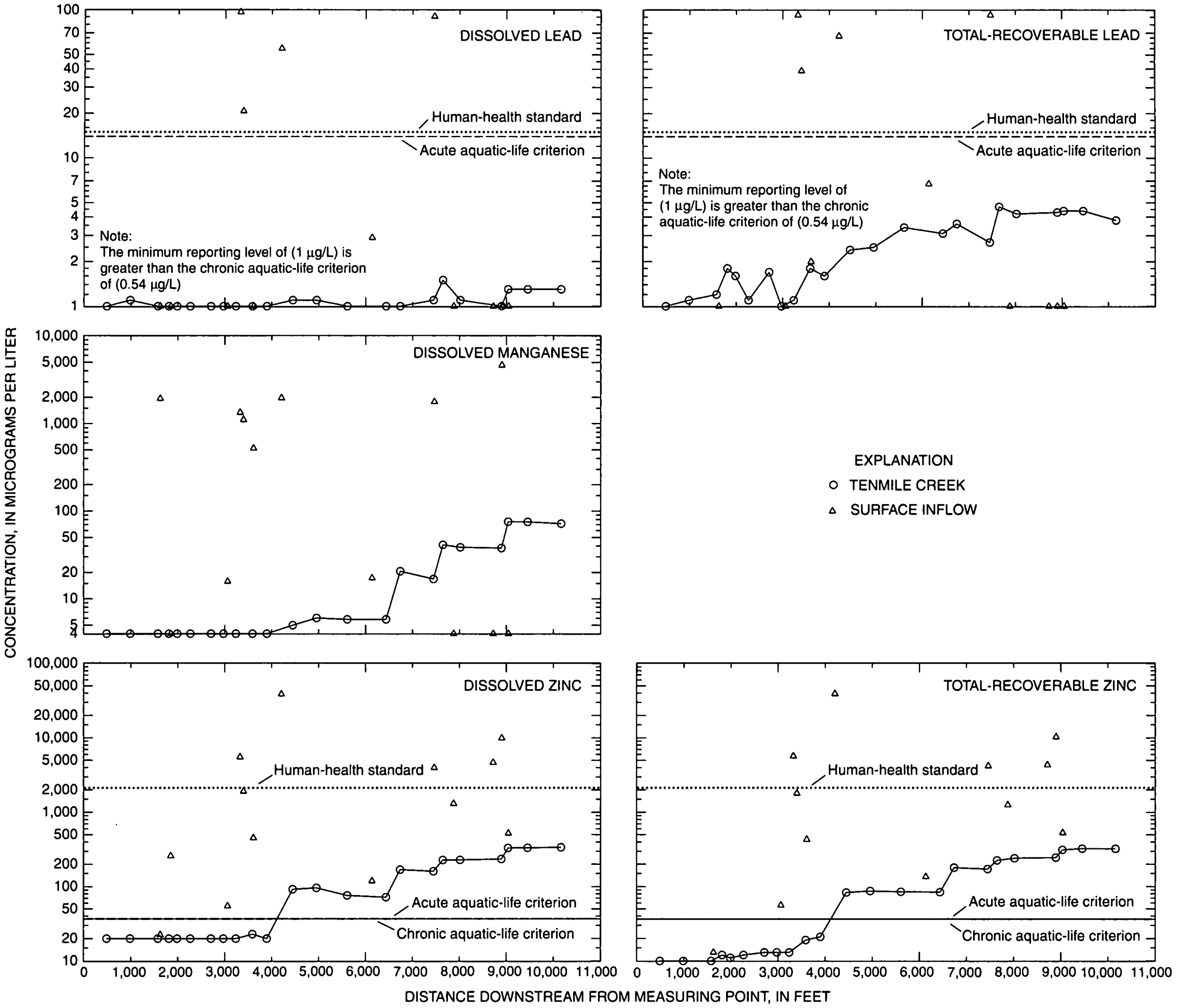


Figure 8. Constituent concentrations in the upper study reach, Tenmile Creek, Montana, September 9, 1998. (Continued)

18u; 4,205 ft) except for total-recoverable lead. Copper concentrations exceeded the chronic criterion in several mainstem sites in the reach downstream from the Bunker Hill Mine to Poison Creek. Downstream from the Bunker Hill Mine area, all mainstem zinc concentrations exceeded the acute criterion. Downstream from Poison Creek (site 26u; 7,465 ft), all mainstem cadmium and copper concentrations also exceeded the acute criterion. Mainstem total-recoverable lead values exceeded the chronic aquatic-life criterion throughout the upper study reach.

Lower Study Reach

Streamflow in the lower study reach was much less than that in the upper study reach as the result of withdrawals for water supply, and channel losses offered little or no dilution capacity to metals loads entering Tenmile Creek. The pH in samples collected in the lower study reach ranged from 2.79 to 8.83 (fig. 9; table 6). Mainstem pH values in Tenmile Creek were all greater than 6, except for a short reach downstream from Beaver Creek (site 11; 2,120 ft) to about 500 ft downstream from Spring Creek (site 20; 3,850 ft). Two acidic inflows, one from a seep near the Lee Mountain Mine (pH of 2.79 at site 8; 1,800 ft) and the other from the Valley Forge/Susie Lode adit (pH of 3.82 at site 15; 3,040 ft), were the predominant sources contributing to the lower pH in this stream reach. All other surface inflows in the lower study reach had pH values greater than 6.

Concentration profiles for sulfate and metals in the lower study reach and applicable water-quality standards are shown in figure 10. Mainstem concentrations of all constituents, except for arsenic and iron, increased sharply in the area of the Lee Mountain Mine (from site 5 to 11; 1,115 to 2,120 ft). No surface inflow was noted between sites 5 and 10; therefore, the increases in instream metal concentrations presumably resulted from diffuse shallow ground water that was seeping into Tenmile Creek from the mine area. A pit was dug in the Lee Mountain Mine tailings exposed in the streambank (site 8; 1,800 ft), and the water seeping from the tailings was sampled. Concentrations of

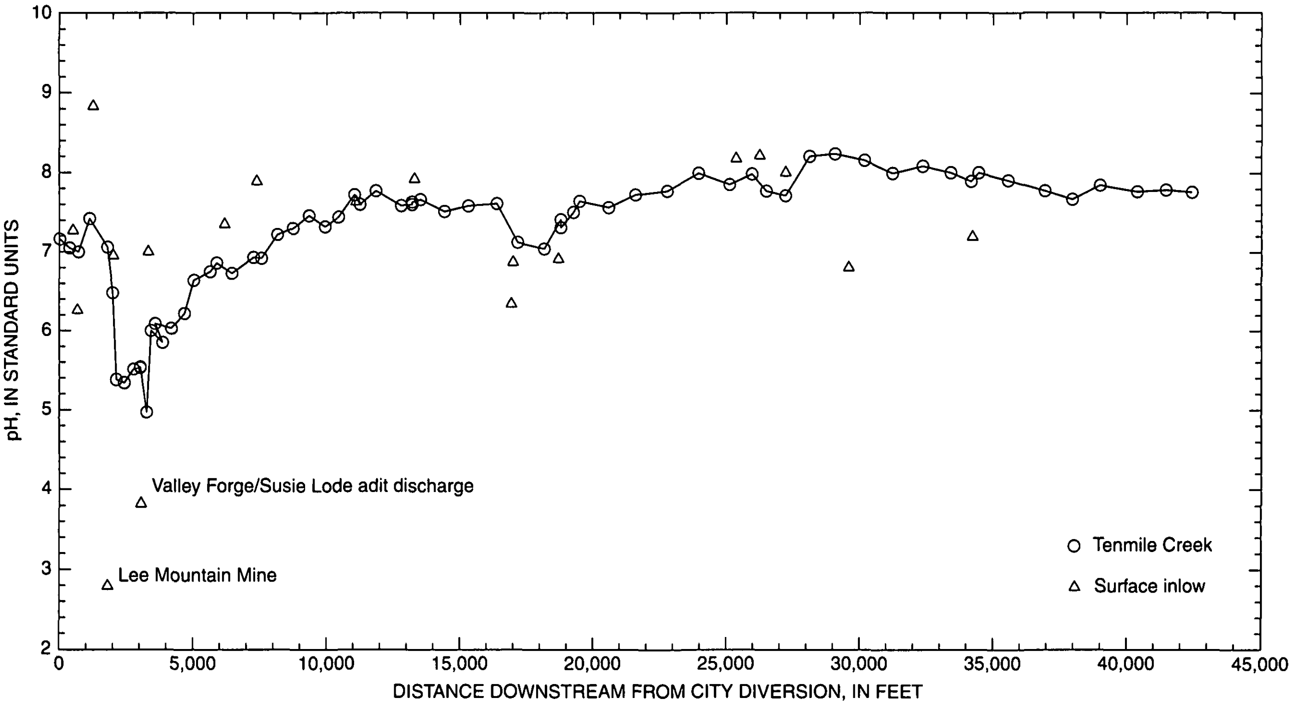


Figure 9. Variation of pH in the lower study reach, Tenmile Creek, Montana, September 6, 1998.

almost all constituents in this sample were the highest measured during this study (tables 5 and 6). Although the dissolved arsenic concentration in the Lee Mountain leachate (site 8; 1,900 µg/L) was 190 times greater than the mainstem concentrations just upstream (site 7; 10 µg/L), dissolved arsenic concentrations in Tenmile Creek immediately downstream from this area decreased abruptly (site 9; 2 µg/L), probably because the dissolved arsenic adsorbed to or co-precipitated with the visibly evident iron oxyhydroxides that rapidly formed in the stream. Near the downstream edge of the Lee Mountain Mine (site 11), cadmium concentrations in Tenmile Creek were more than 17 times greater than concentrations upstream from the area (site 5), manganese concentrations were about 28 times greater, and zinc concentrations were almost 11 times greater. Mainstem arsenic concentrations increased sharply just downstream from the Valley Forge/Susie Lode adit (site 16; 3,250 ft). Sulfate, aluminum, cadmium, copper, manganese, and zinc concentrations in Tenmile Creek increased slightly just downstream from site 16 (3,250 ft). Both dissolved and total-recoverable zinc concentrations in the mainstem reached their maximum concentrations of about 5,000 µg/L at site 16 (3,250 ft). Generally, downstream from site 16, concentrations of all constituents, except arsenic, either abruptly or gradually decreased through the rest of the lower study reach. Most constituent concentrations decreased to levels equal to or less than concentrations at site 1. Arsenic concentrations decreased for a short distance downstream from site 16, but then began increasing (dissolved) or leveling off (total-recoverable) near site 28 (6,435 ft).

Mainstem concentrations of arsenic, cadmium, lead, and zinc exceeded the State of Montana human-health standards at numerous sites in the lower study reach (fig. 10; tables 4 and 6). Most of the maximum concentrations in Tenmile Creek occurred just downstream from the Valley Forge/Susie Lode adit (site 16; 3,250 ft). The human-health standard for arsenic (18 µg/L) was exceeded in over half of the samples for dissolved arsenic and almost 90 percent of the samples for total-recoverable arsenic. The only mainstem reach where total-recoverable arsenic did not exceed the human-health standard was from the City Diversion (site 1) to just upstream from Beaver Creek (site 9). The human-health standard for cadmium (5 µg/L) was exceeded in most samples from Tenmile Creek collected between Beaver Creek and Deer Creek (site 9 to site 41; 1,985 to 12,790 ft). The human-health standard for lead (15 µg/L) was exceeded in all total-recoverable samples from Tenmile Creek collected between site 7 (1,780 ft) and site 21 (4,180 ft) and at site 25 (5,620 ft). The human-health standard for zinc (2,100 µg/L) was exceeded in total-recoverable and dissolved samples collected between site 11 (2,120 ft) and site 28 (6,435 ft).

Metal concentrations in samples collected in the lower study reach are compared to State of Montana aquatic-life criteria (fig. 10; table 3 and 4). Based on the concentrations measured during this study, aluminum, arsenic, cadmium, copper, iron, lead, and zinc have the potential to adversely affect the aquatic community in the lower study reach during low-flow conditions. In the lower study reach, aluminum exceeded the chronic aquatic-life criterion of 87 µg/L in samples from Tenmile Creek from site 11 to site 16 (2,120 ft to 3,250 ft). One Tenmile Creek sampled site, site 16, (3,250 ft) exceeded the arsenic chronic aquatic-life criterion of 150 µg/L. Almost all of the samples from Tenmile Creek upstream from Moose Creek, about 20,000 ft (site 55) had dissolved and total-recoverable cadmium concentrations that exceeded the chronic aquatic-life criterion of 1.4 µg/L. Dissolved and total-recoverable cadmium concentrations in samples from Tenmile Creek also exceeded the acute criterion (2.1 µg/L) from site 7 (1,780 ft) to site 51 (18,155 ft). Dissolved copper concentrations in samples collected from Tenmile Creek exceeded the chronic aquatic-life criterion (5.2 µg/L) from site 9 to site 26 (1,985 to 5,865 ft) and sites 2 and 4, and total-recoverable copper concentrations exceeded the chronic criterion from site 1 to site 36 (0 to 10,440 ft). The acute aquatic-life criterion for copper (7.3 µg/L) was exceeded for dissolved copper from site 9 to site 24 (1,985 to 5,020 ft) and for total-recoverable copper from sites 9 to 31 (1,985 to 7,545 ft). Dissolved iron concentrations exceeded the chronic aquatic-life criterion (1,000 µg/L) in samples from five consecutive sites on Tenmile Creek from sites 16 to 21 downstream from the Valley Forge/Suzie Lode adit. Total-recoverable iron concentrations exceeded the chronic criterion in a slightly longer reach from sites 9 to 26 (1,985 to 5,865 ft). Many samples collected in the lower study reach had dissolved lead concentrations that were less than the minimum reporting level of 1 µg/L, which is less than the chronic criterion of 1.3 µg/L. Dissolved lead concentrations were higher than the minimum reporting level only at sites 1 and 2 and from site 7 to site 19 (1,780 to 3,575 ft); most stream samples between these sites exceeded the

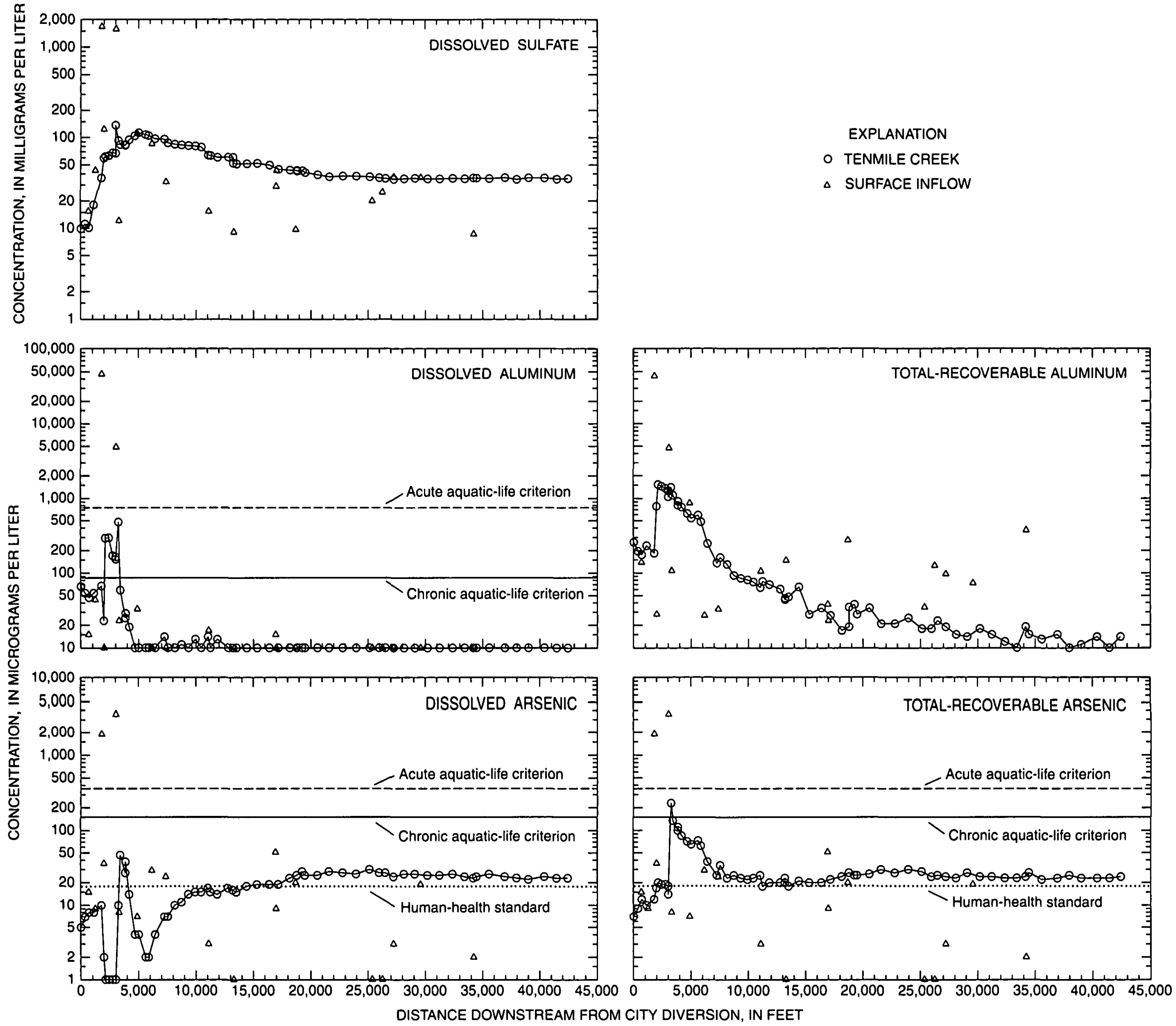


Figure 10. Constituent concentrations in the lower study reach, Tenmile Creek, Montana, September 6, 1998. Human-health standards and aquatic-life criteria are from Montana Department of Environmental Quality (1999). Values equal to or less than the minimum reporting level are plotted at the minimum reporting level.

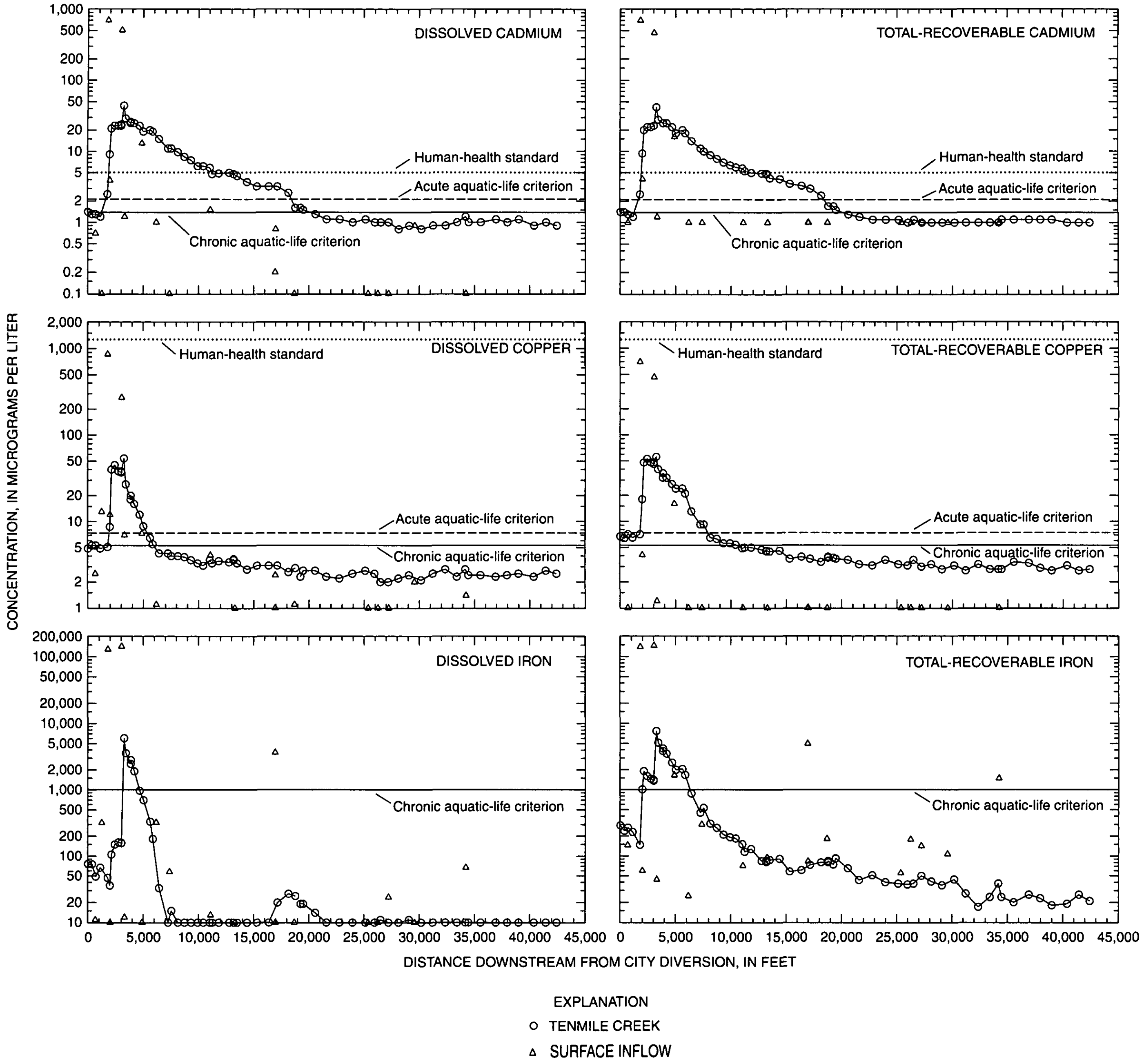


Figure 10. Constituent concentrations in the lower study reach, Tenmile Creek, Montana, September 6, 1998. (Continued)

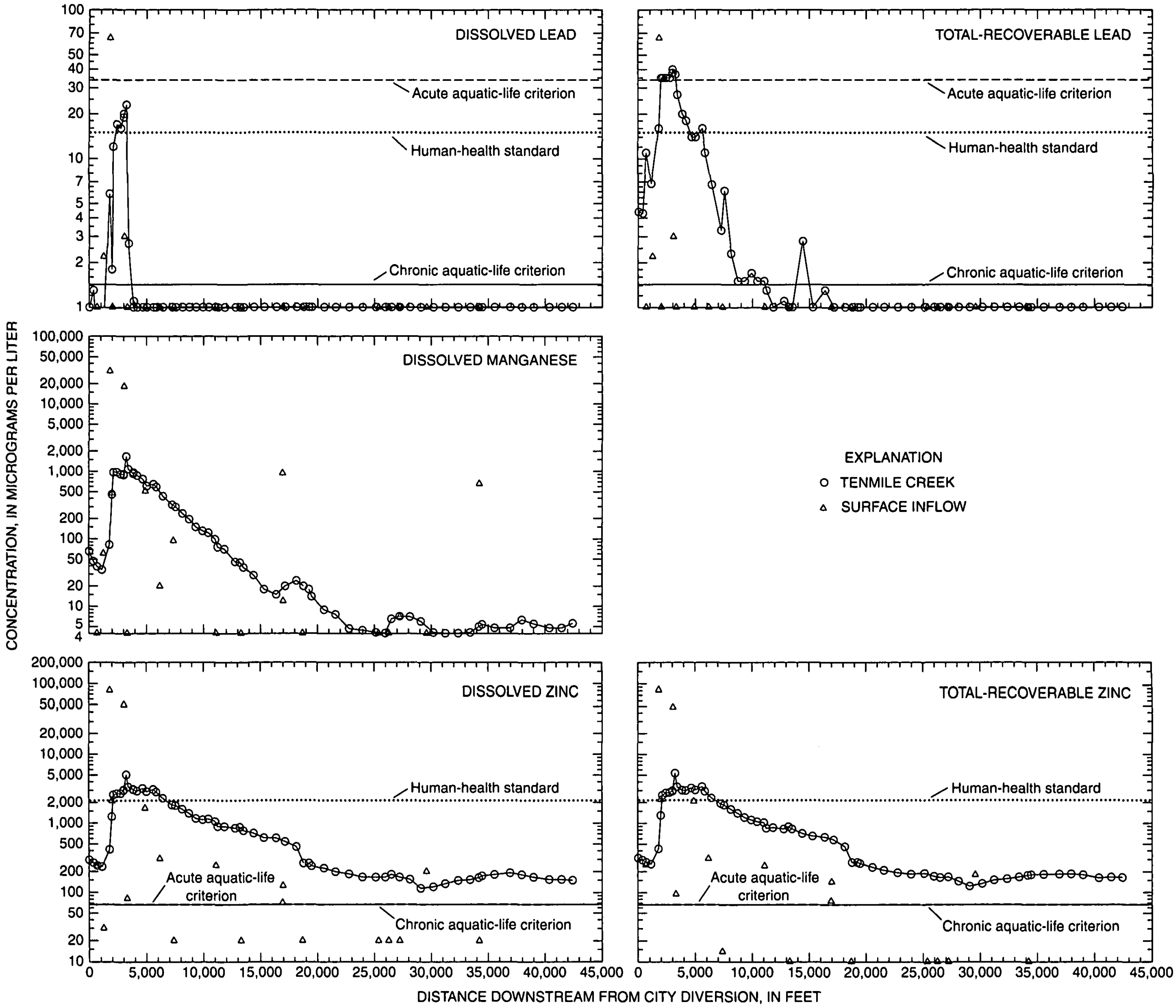


Figure 10. Constituent concentrations in the lower study reach, Tenmile Creek, Montana, September 6, 1998. (Continued)

Table 4. Summary of exceedances of State of Montana human-health and aquatic-life standards[1] for water from the lower study reach, Tenmile Creek, Montana, September 1998

[Exceedances are listed for mainstem sites but not inflows to Tenmile Creek. Aquatic-life criteria for the lower study reach are based on a hardness of 50 mg/L as calcium carbonate. Aquatic-life criteria are applicable to total-recoverable concentrations, but exceedances of dissolved concentrations are also listed for comparison. Abbreviation: µg/L, micrograms per liter. Symbol: --, not applicable]

	Human health		Aquatic life			
Constituent	Standard (µg/L)	Sites or stream reach with exceedance	Chronic criterion (µg/L)	Sites or stream reach with exceedance	Acute criterion (µg/L)	Sites or stream reach with exceedance
Aluminum, dissolved	--	--	87	site 11 to 16	150	--
Arsenic, dissolved[1]	18	site 16 to 20, site 45 to 83[2]	150	--	350	--
Arsenic, total[1]	18	site 11 to 83[2]	150	site 16	350	--
Cadmium, dissolved	5	site 41, site 9 to 47	1.4	site 1, site 7 to 55	2.1	site 7 to site 51
Cadmium, total recoverable	5	site 9 to 40	1.4	site 1 and 22, site 7 to 55	2.1	site 7 to site 51
Copper, dissolved	1,300	--	5.2	site 2 and 4, site 9 to 26	7.3	site 9 to site 24
Copper, total recoverable	1,300	--	5.2	site 1 to 36	7.3	site 9 to site 31
Iron, dissolved	--	--	1,000	site 16 to 21	--	--
Iron, total recoverable	--	--	1,000	site 9 to 26	--	--
Lead, dissolved	15	site 12 to 16	1.3	site 2, site 7 to 18	24	--
Lead, total recoverable	15	site 25, site 7 to 21	1.3	site 45 and 47, site 1 to 39	34	site 9 to 16
Zinc, dissolved	2,100	site 11 to 28	67	All sites	67	All sites
Zinc, total recoverable	2,100	site 11 to 28	67	All sites	67	All sites

[1] Montana Department of Environmental Quality (1999).

[2] A new human-health standard for arsenic (10 µg/L) has been established by the U.S. Environmental Protection Agency (2001). The new standard is not enforceable until January 2006. This new standard will increase the number of sites with exceedances.

chronic aquatic-life criterion for lead, with a maximum dissolved lead concentration of 23 µg/L occurring below the Valley Forge/Suzie Lode adit discharge. Total-recoverable lead concentrations exceeded the chronic criterion over a more extended reach from site 1 to just downstream from Minnehaha Creek (site 38; 11,095 ft) and sites 45 and 47. Total-recoverable lead exceeded the acute criterion (34 µg/L) from sites 9 to16 (1,985 to 3,250 ft). Dissolved and total-recoverable zinc concentrations in all samples from Tenmile Creek in the lower study reach exceeded both the chronic and acute aquatic-life criteria of 67 µg/L.

To characterize metal concentrations in the four tributary streams that are diverted for public water supply, samples were collected from Beaver Creek, Minnehaha Creek, Moose Creek, and Walker Creek upstream from the diversions. These samples were collected on September 4, 1998, two days before the synoptic samples were collected in the lower study reach (table 9, back of report). Based on data collected by Parrett and Hettinger (2000), a hardness of 25 mg/L $CaCO_3$ was used to calculate aquatic-life criterion for the four tributaries. In Minnehaha Creek, concentrations of dissolved (1.5 µg/L) and total-recoverable (1 µg/L) cadmium exceeded the chronic aquatic-life criterion of 0.83 µg/L. Concentrations of dissolved (70 µg/L) and total-recoverable (140 µg/L) copper in Beaver Creek substantially exceeded the acute aquatic-life criterion of 3.8 µg/L. Beaver Creek drains Chessman Reservoir, which is treated with copper sulfate to reduce biological growth. This treatment likely causes the elevated copper concentration in Beaver Creek. Concentrations of dissolved (237 µg/L) and total-recoverable (240 µg/L) zinc also substantially exceeded the acute aquatic-life criterion of 37 µg/L in Minnehaha Creek.

QUANTIFICATION OF METAL LOADING

Load is the mass of a constituent transported downstream during a given period of time. For comparative purposes, loads are commonly expressed in terms of mass transported per unit time (for example, micrograms/second for instantaneous loads or kilograms/year for annual loads). Load is calculated as the product of constituent concentration and streamflow. For constituents whose mass is not lost by sorption, volatization, or chemical reaction, loads are additive as inflows contribute their load in a cumulative manner to a stream system. The effect of loads contributed by inflows on instream concentrations in the mainstem is dependent on the volume of water in the receiving stream and the resulting dilution available upon mixing.

Instantaneous loads for each sample collected during this study were calculated for sulfate and dissolved and total-recoverable metals. Calculated instantaneous loads are presented in table 7 (at back of report) for the upper study reach and in table 8 (at back of report) for the lower study reach. Where a constituent concentration was less than the minimum reporting level, the minimum reporting level was used to calculate load. Downstream profiles of constituent loads are presented in figures 11-19.

Downstream load profiles illustrate the spatial distribution of loads at many individual locations. The load profiles can be examined to identify where instream loads in the mainstem increase. These increases can indicate important sources that contribute constituent load to Tenmile Creek. Stream segments where constituent loads are added to or removed from the water column can be identified by comparing two different types of load profiles: the mainstem load and the cumulative surface-inflow load. The profile of mainstem load represents what was actually measured at each mainstem sampling site. This load is the net result of contributions from the sampled surface inflows and any unsampled inflow (primarily ground water and unsampled seeps), as well as any loss of load caused by either the formation and streambed deposition of colloids or other geochemical reactions. The mainstem load profile is the more important of the two load profiles 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 surface inflows that were sampled and quantified. The profile of the cumulative surface-inflow load represents a minimum value for inflow loading to the stream, because subsurface inflows are not included. When the mainstem load is greater than the cumulative surface inflow, additional loading from ground water and unsampled seeps is indicated. When the cumulative surface-inflow load is greater than the mainstem load, a loss in load by geochemical precipitation and streambed deposition, or a streamflow loss through the banks or streambed, is indicated.

Upper Study Reach

Load profiles for sulfate and metals in the upper study reach are shown in figures 11-15. The downstream profile of sulfate load in Tenmile Creek (fig. 11) generally followed the cumulative surface-inflow load between site 1u (485 ft) and site 17u (3,900 ft, just upstream from the Bunker Hill Mine). Downstream from the seeps near the Bunker Hill Mine (site 19u to site 32u; 4,445 to 8,900 ft), the mainstem load was slightly greater than the cumulative surface-inflow load, indicating that sulfate was added from other sources, either by ground-water discharge or unsampled seeps. Because no surface inflow was noted near the Little Sampson Mine (between sites 23u and 24u), any loading coming from the mine area would have entered Tenmile Creek as subsurface flow and would not have been accounted for in the cumulative surface-inflow load. This pattern reversed farther downstream where the cumulative surface-inflow load downstream from the Red Water Mine adit (site 32u) was greater than the mainstem load. The calculated sulfate load (290 mg/s) for the right-bank seeps at site 30u (fig. 11; table 7) was relatively large, especially in comparison to the small increase in mainstem load (30 mg/s) in this area. The entire instream flow increase between sites 29u and 31u was assigned to the right-bank seeps (site 30u) because inflows from the left bank were not observed. However, unaccounted subsurface inflow to Tenmile Creek from the left bank likely occurred, as observed several hundred feet downstream at site 34u. Surface flow from the seeps at site 30u was visually estimated at 0.06 L/s, which is much smaller than the 2.00 L/s that was calculated for this flow by tracer (table 1), which would include any additional ground-water inflow. If flow from site 30u was overestimated, then the calculated sulfate load for the right-bank seeps (site 30u) also would be overestimated, and the overestimated flow likely would affect the calculated inflow loads for all of the metals at site 30u.

Dissolved arsenic loads (fig. 12) increased from 290 to 742 μg/s in the upper study reach. This 2.5-fold increase was relatively small in comparison to the increases in load of some of the other metals. The seemingly large increases in the mainstem load at sites 5u, 9u, 23u and 36u (fig. 12; table 7) probably are the result of unrounded laboratory concentrations that were rounded to one significant figure, which can greatly influence the load calculations and resulting

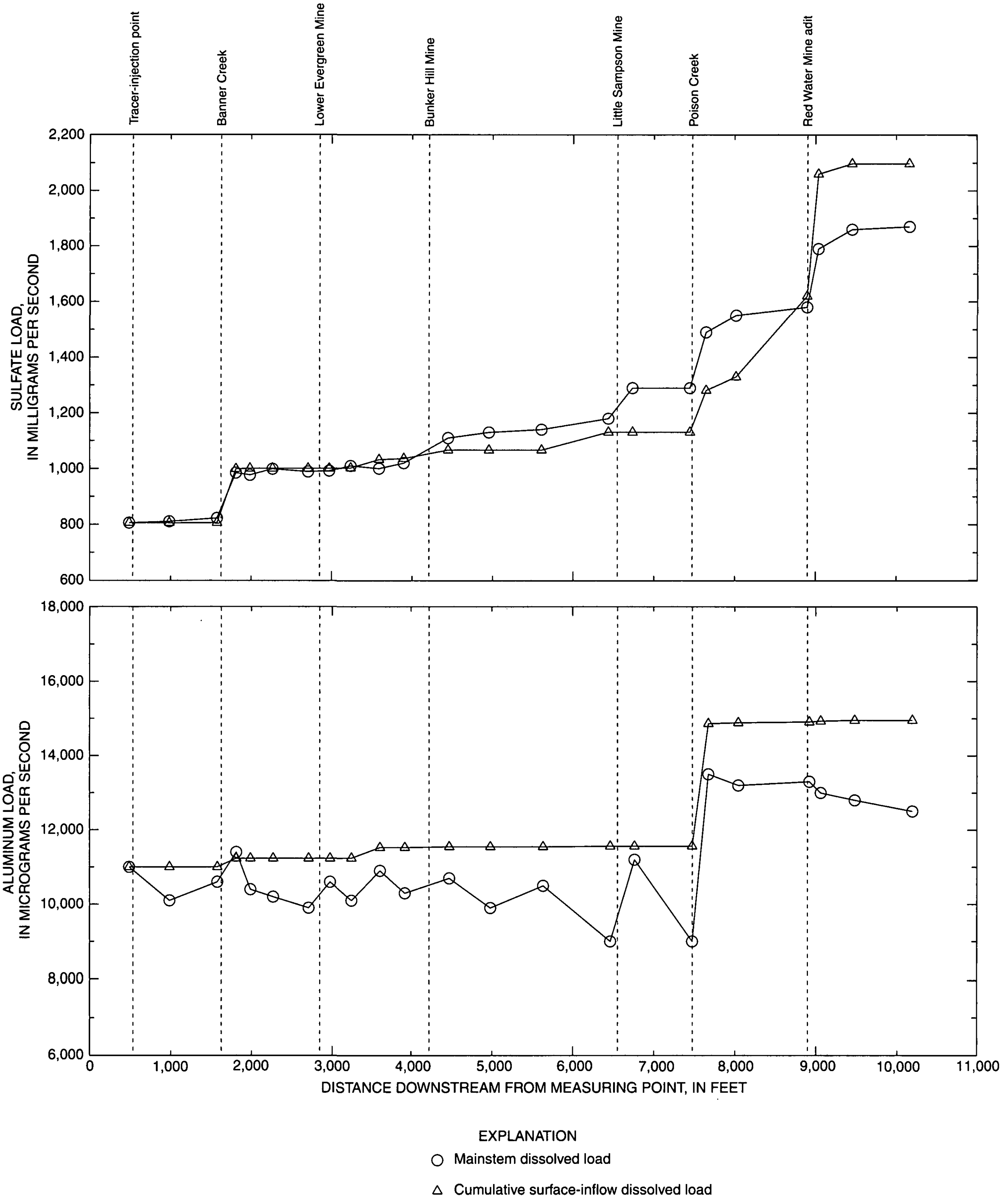


Figure 11. Instantaneous loads of dissolved sulfate (top) and aluminum (bottom) in the upper study reach, Tenmile Creek, Montana, September 9, 1998.

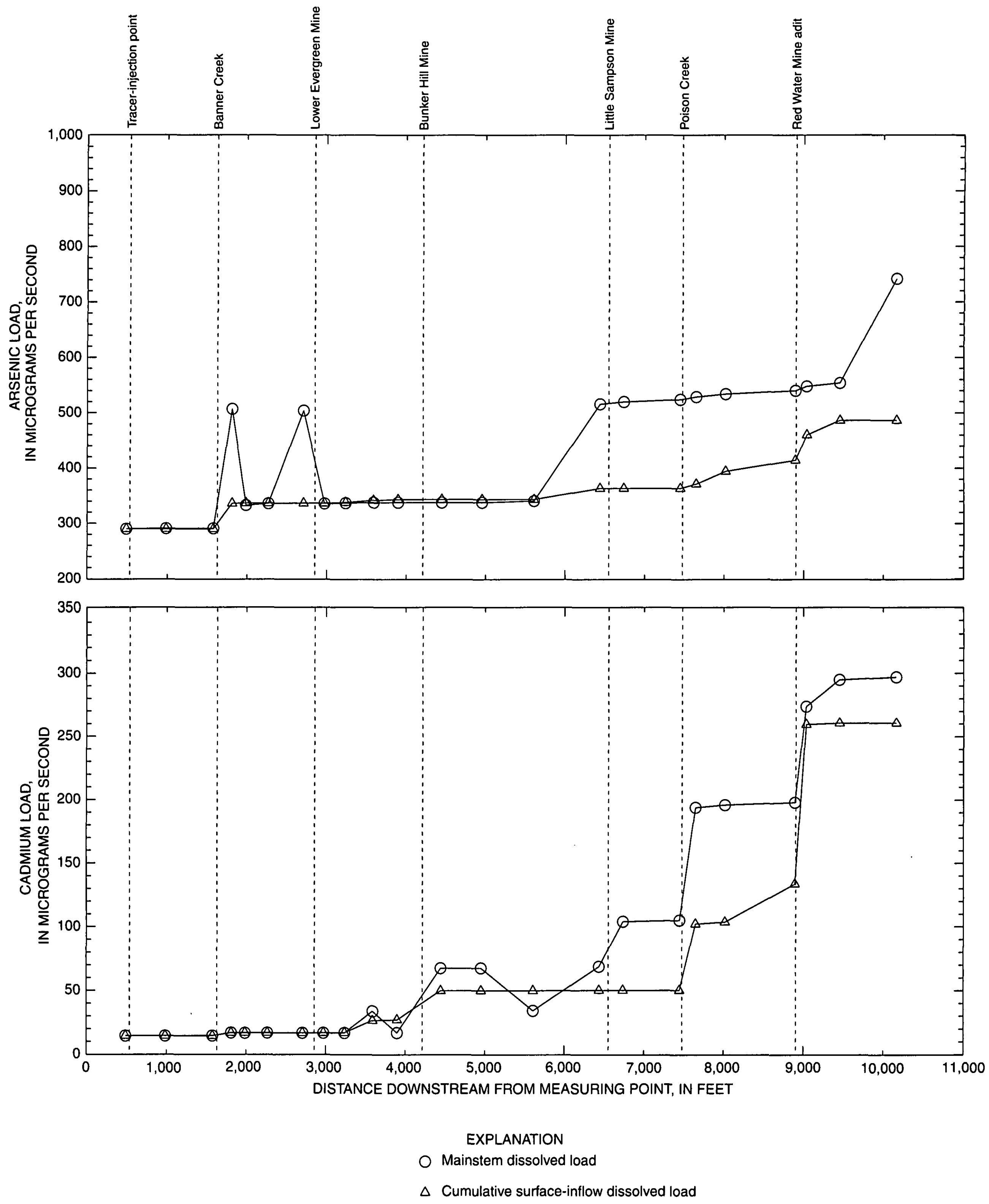


Figure 12. Instantaneous loads of dissolved arsenic (top) and cadmium (bottom) in the upper study reach, Tenmile Creek, Montana, September 9, 1998.

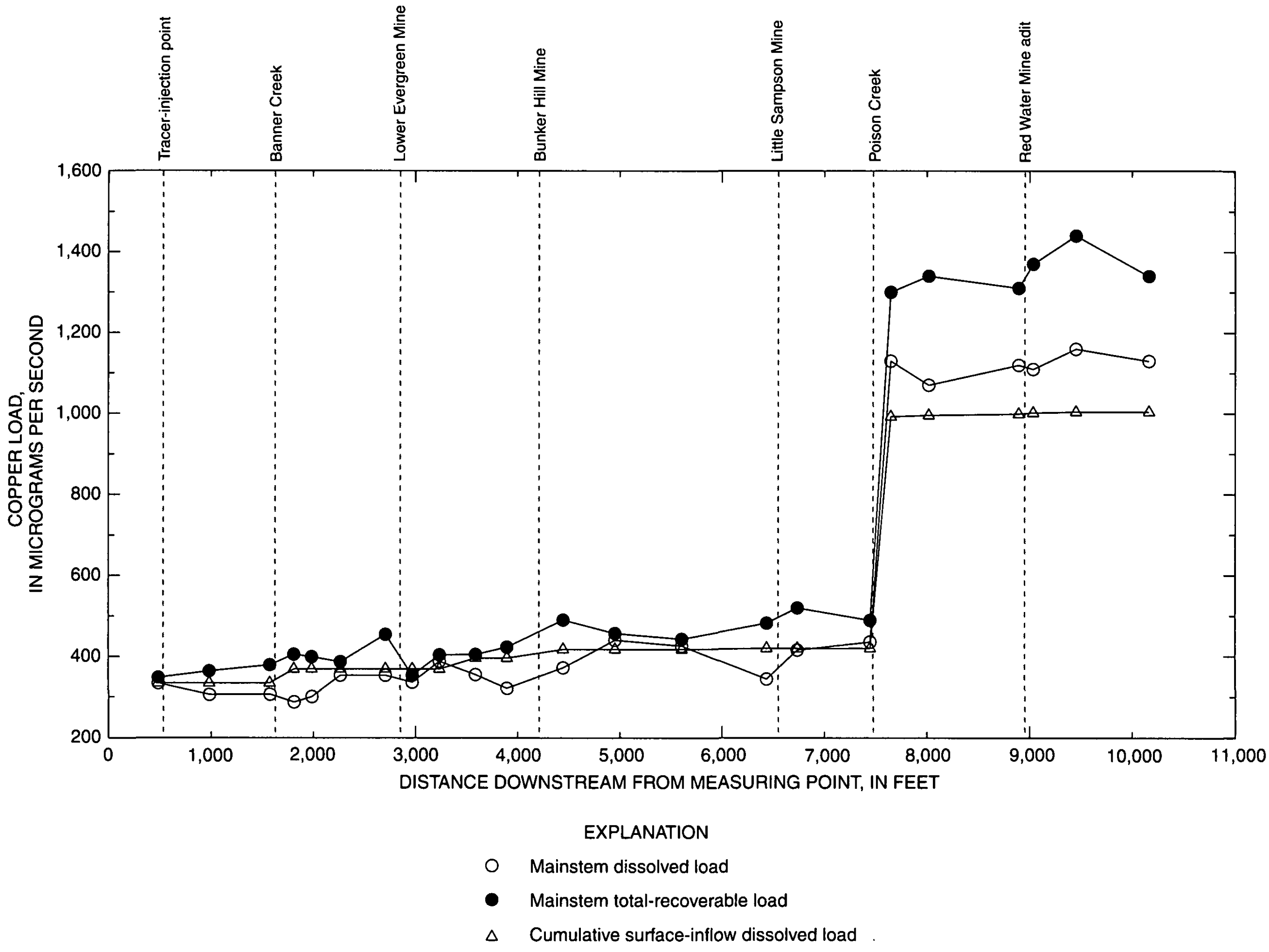


Figure 13. Instantaneous loads of dissolved and total-recoverable copper in the upper study reach, Tenmile Creek, Montana, September 9, 1998.

between-site differences. Rounding effects can be proportionally significant for low concentrations; dissolved arsenic concentrations in the upper study reach were consistently low and ranged from 2 to 4 µg/L (table 5). The most important feature of the arsenic load profile in the upper reach is that the cumulative surface-inflow load for dissolved arsenic near the downstream end of the reach is less than the mainstem load, indicating that additional arsenic loading from ground water or unsampled seeps augments arsenic loads from surface inflows.

The mainstem dissolved-cadmium load increased considerably (over 20-fold) through the upper study reach from <14.5 to 297 µg/s (fig. 12; table 7). From sites 1u to 17u (485 to 3,900 ft), all concentrations of dissolved cadmium, except for site 15u (3,590 ft), were less than the minimum reporting level of 0.1 µg/L (table 5), indicating that loading was not substantial through this reach. Downstream from site 17u, the mainstem dissolved-cadmium load increased notably in four stream reaches. Sources or source areas contributing cadmium were the seep at the Bunker Hill Mine (site 18u; 4,205 ft), the stream reach between sites 23u and 24u (6,440 to 6,740 ft) near the Little Sampson Mine, the inflow from Poison Creek (site 26u; 7,465 ft), and water from the Red Water Mine adit (site 32u; 8,900 ft). These four sources or source areas accounted for about 80 percent of the mainstem load at the downstream end of the upper study reach.

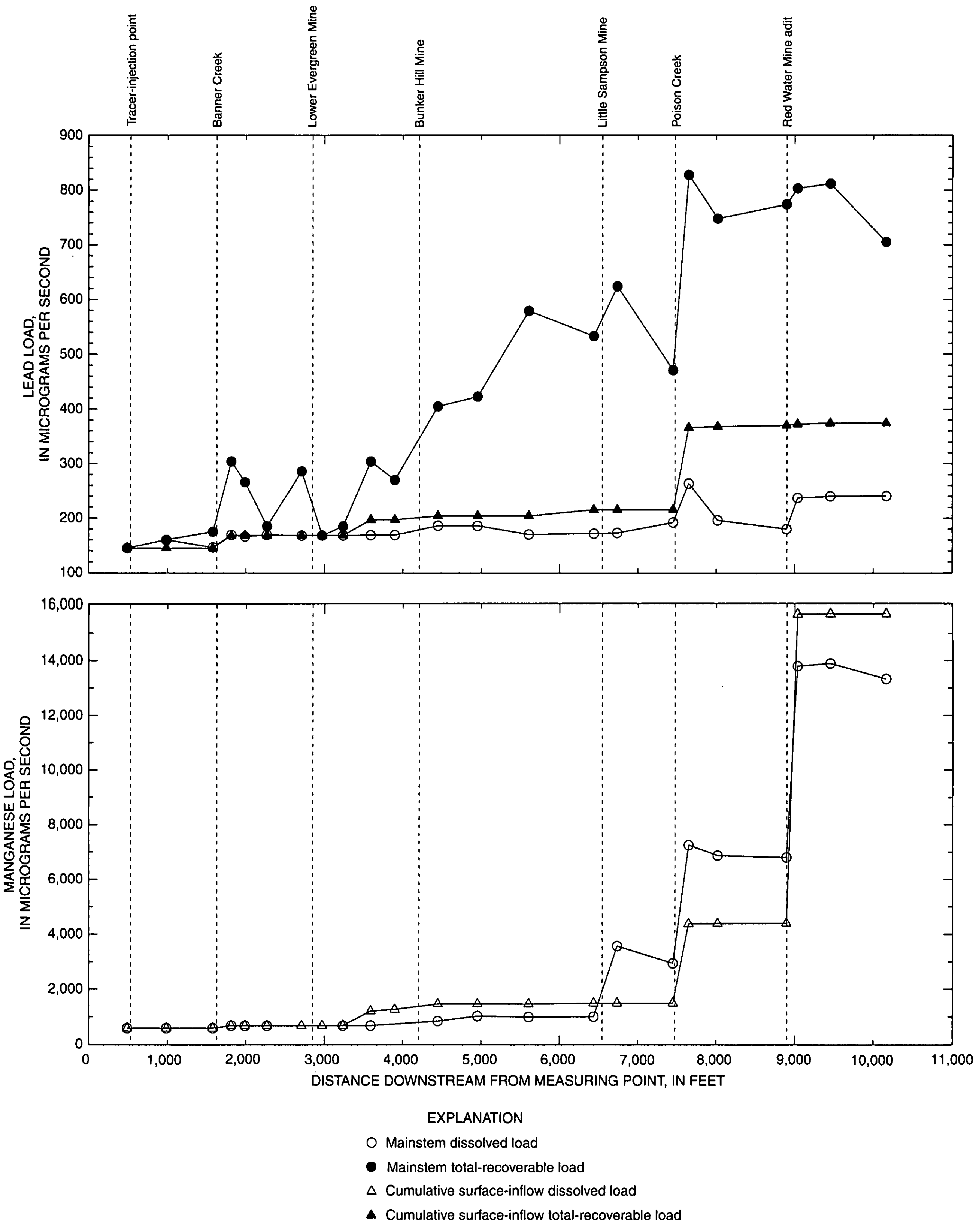


Figure 14. Instantaneous loads of dissolved and total-recoverable lead (top) and dissolved manganese (bottom) in the upper study reach, Tenmile Creek, Montana, September 9, 1998.

The mainstem dissolved-copper load increased (about 3.4 fold) from 334 to 1,130 µg/s. This increase was more similar to the increase in arsenic load (about 2.5-fold) than the increase in cadmium load (over 20-fold). However, unlike either arsenic or cadmium, almost all of the copper loading in the upper study reach came between mainstem sites 25u and 27u (fig. 13). The increase in dissolved copper load between these sites accounted for 87 percent of the increase in the dissolved copper load to the entire upper study reach and 82 percent of the increase in total-recoverable copper load. Most of the copper load increase in the mainstem came directly from the surface inflow of Poison Creek (site 26u; 7,465 ft). However, the higher mainstem loads relative to the surface-inflow loads indicates either additional copper loading from groundwater sources in the vicinity of Poison Creek, or instream mobilization of copper from the streambed associated with the decreased pH (fig. 7).

Almost all mainstem dissolved-lead concentrations upstream from the Bunker Hill Mine inflow (site 18u; 4,205 ft) were less than the minimum reporting level; thus dissolved lead loads were assumed to be relatively small in this stream reach. Downstream from site 18u, instream dissolved lead loads ranged from about 170 to 241 µg/s (fig. 14). The instream total-recoverable lead load increased (4.9-fold) from 145 to 705 µg/s through the upper study reach. A large increase in the mainstem total-recoverable lead load from 423 µg/s to 579 µg/s occurred between sites 204 and 214, (4,955 and 5,610 ft). The reason for this increase is unclear. Loads for the inflows upstream from this area were relatively small and subsurface loading in this area for other metals did not occur. An increase in total-recoverable lead load, representing about 27 percent of the load increase through the upper study reach, was contributed by Poison Creek (151 µg/s).

The mainstem dissolved-manganese load (fig. 14; table 7) increased considerably (more than 20-fold) from <580 to 13,330 µg/s through the upper study reach. Loads upstream from the Little Sampson Mine area (near site 23u; 6,440 ft) were small. Downstream from site 23u, the sum of the loads from three sources--the Little Sampson Mine area between sites 23u and 24u, Poison Creek (site 26u), and the Red Water Mine adit (site 32u)--was greater than the mainstem load at the end of the upper study reach. Mainstem loads downstream from each of these main sources decreased slightly, indicating that some of the dissolved manganese was being removed from the water, likely by precipitation and subsequent deposition on the streambed. This pattern of manganese removal has been observed in other streams (Kimball and others, 1999). Inflow from the Red Water Mine adit (site 32u) produced the largest increase in mainstem dissolved-manganese load. This source alone accounted for more than 50 percent of the dissolved manganese load in Tenmile Creek at the downstream end of the upper study reach.

The mainstem dissolved-zinc loads (fig. 15; table 7) increased considerably (more than 20-fold) from <2,900 to 62,700 µg/s through the upper study reach, proportionally similar to cadmium and manganese. The mainstem dissolved-zinc load closely reflected the total-recoverable load, indicating that the majority of the zinc was in the dissolved fraction. Dissolved zinc loads were relatively small upstream from the Bunker Hill Mine (18u; 4,205 ft). Downstream from this upper stream segment, four sources--the Bunker Hill Mine area (site 18u), the Little Sampson Mine area (between sites 23u and 24u), Poison Creek (site 26u), and the Red Water Mine adit (site 32u)--accounted for almost 82 percent of the dissolved zinc load at the downstream end of the upper study reach. Similar to manganese, the area around the Red Water Mine adit was the largest single source of zinc and contributed about 38 percent of the load at the downstream end of the upper study reach.

Lower Study Reach

Load profiles for sulfate and metals in the lower study reach are shown in figures 16-20. Calculated loads from the results of the synoptic sampling are presented in table 8.

The mainstem sulfate load (fig. 16; table 8) increased steadily from site 4 to 29 (695 to 7,245 ft). Sulfate loads increased near the Lee Mountain Mine (sites 5 to 11) and downstream from the Valley Forge/Susie Lode adit (site 15; 3,040 ft), but most of the load entered the stream between sites 18 and 29 (Tenmile Creek downstream from Spring Creek, 3,415 to 7,245 ft). The sample from site 27, a surface inflow from a swampy area, had a relatively large sulfate load (348 µg/s). The mainstem load profile was greater than the

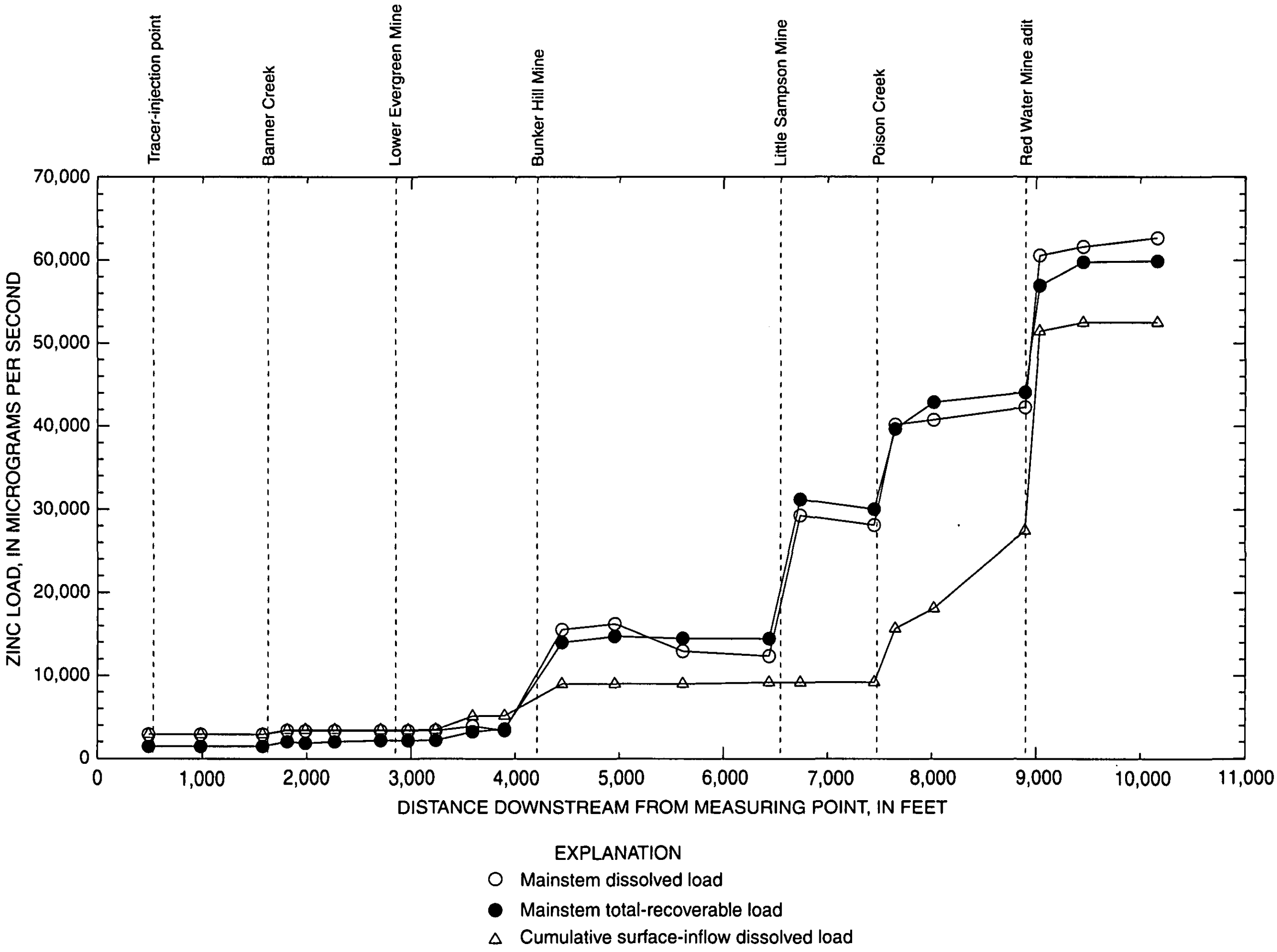


Figure 15. Instantaneous loads of dissolved and total-recoverable zinc in the upper study reach, Tenmile Creek, Montana, September 9, 1998.

cumulative surface-inflow load profile (fig. 16), indicating that sulfate was added by either ground-water discharge or unsampled seeps in this area. Mainstem sulfate loads from site 29 to 53 (18,780 ft) increased slightly, with the most significant surface loading coming from a swampy area drained by two right-bank inflows at sites 48 (16,935 ft) and 49 (16,985 ft). Downstream from site 53 to the end of the lower study reach, sulfate loads gradually decreased owing to loss of streamflow (fig. 6).

The only appreciable arsenic loading in the lower study reach (fig. 17) came from the Valley Forge/Susie Lode adit (site 15; 3,040 ft). The mainstem dissolved-arsenic load increased (more than 100-fold) from less than 6 to 710 μg/s, and the mainstem total-recoverable arsenic load increased (more than 10-fold) from 112 μg/s to almost 1,500 μg/s from this single source. Downstream from this source, both the dissolved and total-recoverable loads very quickly decreased, presumably in response to the rapid drop in pH (fig. 9). The dissolved load reached a minimum value in the reach just below Moore's Spring Creek (site 23; 4,890 ft). Downstream from site 25, the mainstem dissolved-arsenic load increased until it was almost equal to the total-recoverable load. This increase in dissolved arsenic load down to site 37 above Minnehaha Creek (11,040 ft) coincident with the increasing pH through this reach (fig. 9) probably indicates a shift in arsenic partitioning causing desorption of arsenic from aluminum and iron colloids.

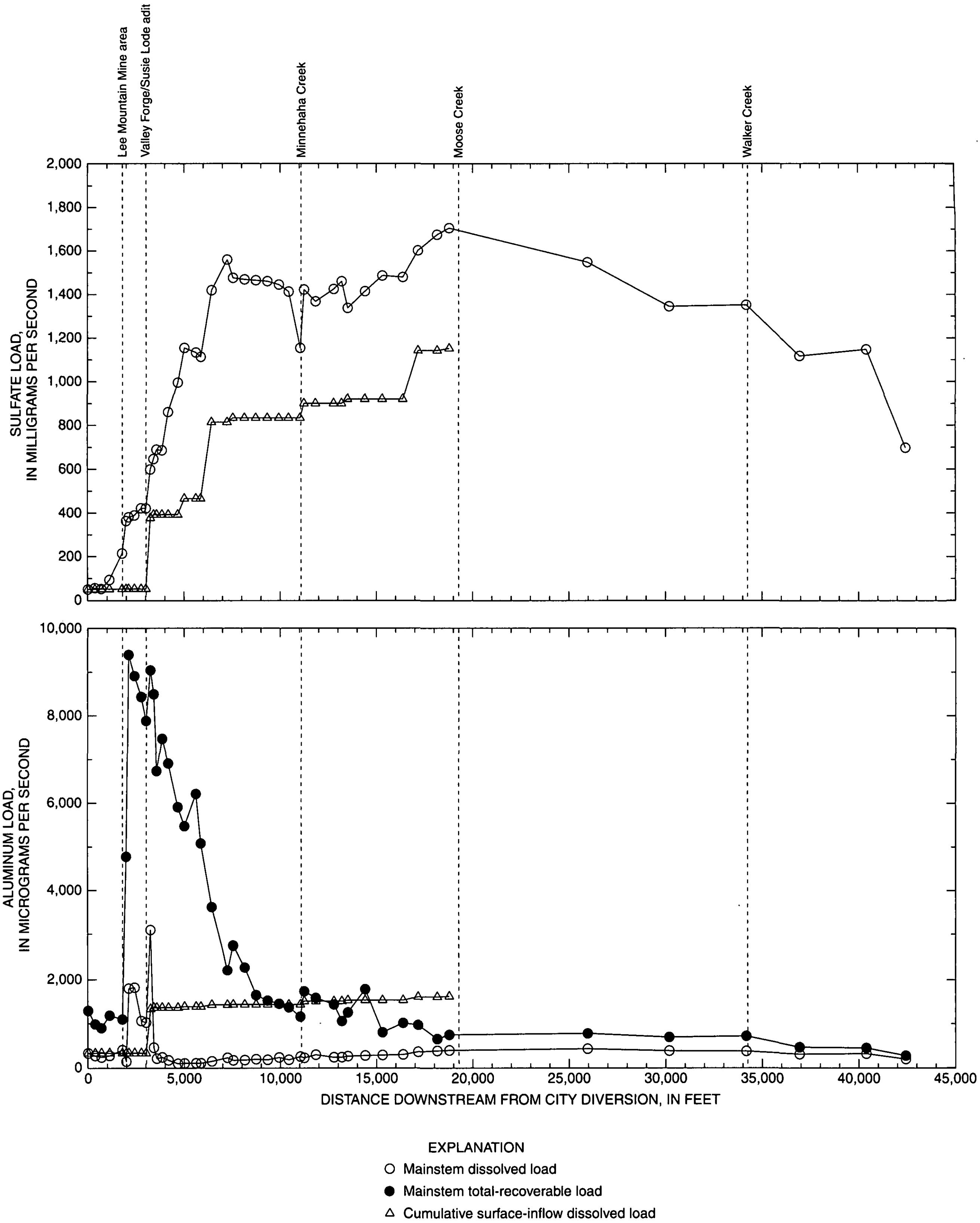


Figure 16. Instantaneous loads of dissolved sulfate (top) and dissolved and total-recoverable aluminum (bottom) in the lower study reach, Tenmile Creek, Montana, September 6, 1998.

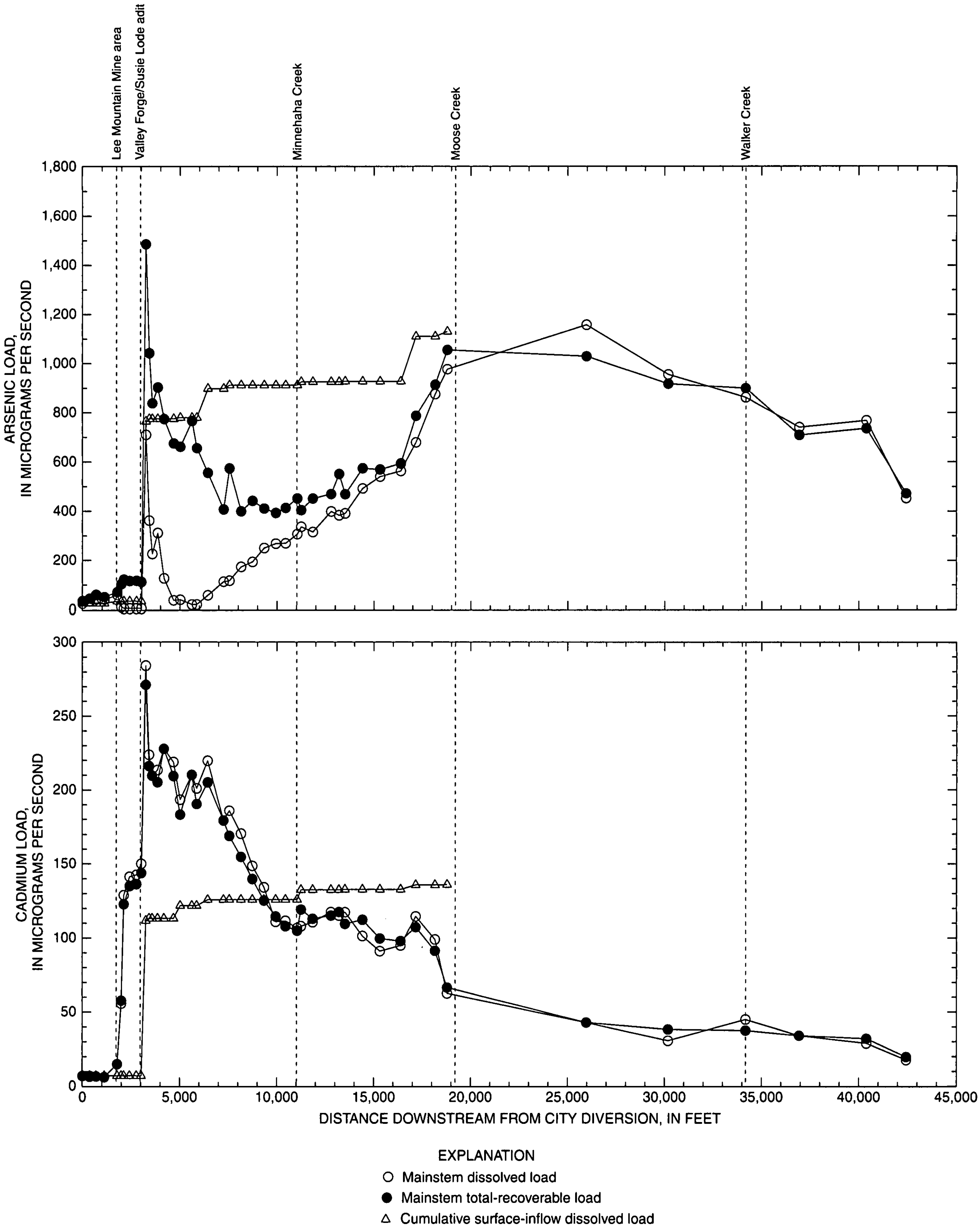


Figure 17. Instantaneous loads of dissolved and total-recoverable arsenic (top) and cadmium (bottom) in the lower study reach, Tenmile Creek, Montana, September 6, 1998.

Similar to arsenic, the maximum mainstem cadmium load (about 285 µg/s) in the lower study reach (fig. 17; table 8) was measured just downstream from the Valley Forge/Susie Lode adit (site 15; 3,040 ft). The area near the Lee Mountain Mine (sites 5 to 11) and the Valley Forge/Susie Lode adit contributed almost equally to this sharp increase in cadmium load. Downstream from these two sources, the cadmium load steadily decreased, indicating a sustained loss of cadmium load from the water column, possibly through sorption to colloids. Throughout the study reach, the mainstem dissolved-cadmium load was similar to the total-recoverable load, indicating that most of the cadmium load in the lower study reach was in the dissolved phase.

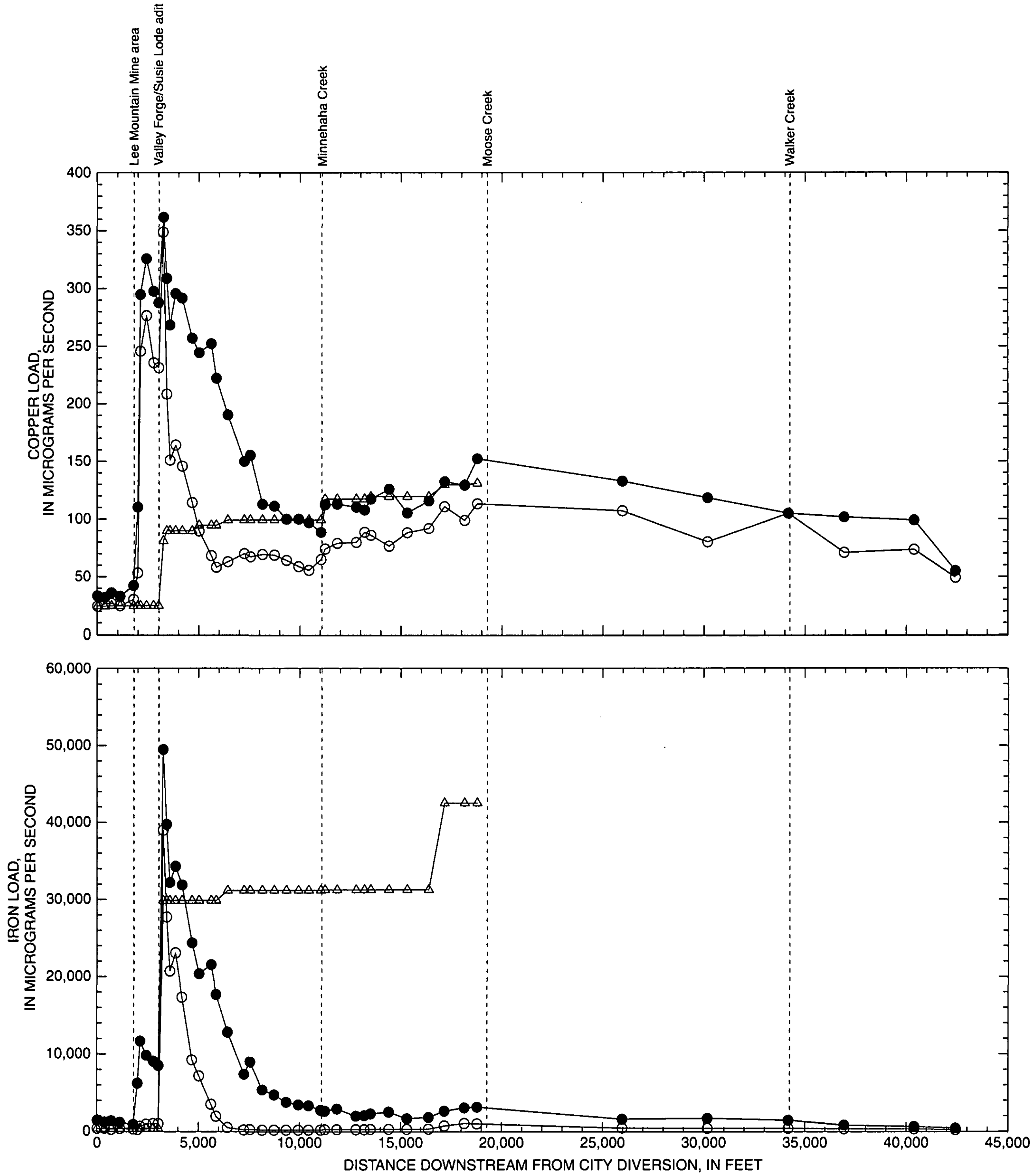
Similar to arsenic and cadmium, the maximum mainstem dissolved- and total-recoverable copper loads (about 350 µg/s) were measured just downstream from the Valley Forge/Susie Lode adit (site 15; table 8) (fig. 18). However, unlike cadmium, most of the copper load at site 16 came from the Lee Mountain Mine area (sites 5 to 11). Most of the remaining load came from the Valley Forge/Susie Lode adit. Downstream from the Valley Forge/Susie Lode adit, the mainstem copper load gradually decreased, possibly as the result of copper being sorbed to colloids and subsequently deposited on the streambed.

Because dissolved lead concentrations were below the minimum reporting level in the lower study reach, a downstream profile of dissolved lead load could not be determined. The largest increase in the total-recoverable lead load (fig. 19; table 8) was measured in the mainstem below the Lee Mountain Mine area (sites 5 to 11), representing a 6-fold increase over the load upstream from site 5. The inflow from the Valley Forge/Susie Lode adit added very little lead and did not substantially increase the lead load in Tenmile Creek. Below the Valley Forge/Susie Lode adit, lead loads generally decreased, with a few exceptions.

The maximum mainstem dissolved-manganese load (10,800 µg/s) was measured downstream from the Valley Forge/Susie Lode adit (fig. 19; table 8). About one-half of this value can be attributed to the area near the Lee Mountain Mine (sites 5 to 11) and one-half to the Valley Forge/Susie Lode adit (site 15). The dissolved manganese load decreased gradually to the end of the lower study reach.

A near-maximum mainstem total-recoverable zinc load (about 35,000 µg/s) was measured just downstream from the Valley Forge/Susie Lode adit (fig. 20; table 8). Similar to manganese, about one-half of this load entered Tenmile Creek near the Lee Mountain Mine (sites 5 to 11) and about one-half came from the Valley Forge/Susie Lode adit (site 15). The mainstem total-recoverable zinc load decreased between site 16 and site 20 (3,850 ft) and then increased downstream to a maximum at site 25 (5,620 ft). The valley bottom between sites 21 to 25 was wet and swampy, and the increased zinc load in this reach may have come from seepage from this area. The mainstem sulfate load also increased in this reach, but the loads of other metals either did not increase, or increased very slightly. Mainstem zinc loads decreased below site 25 to about 11,000 ft, and then maintained a fairly constant load to about 17,500 ft.

The mainstem zinc load rapidly decreased from about 17,500 to 10,600 µg/s between sites 51 and 53 (18,155 to 18,780 ft). This particular decrease may be artificially large as the result of diel (24-hour) variation in dissolved zinc concentrations and the timing of synoptic-sample collection. Concentrations of zinc have been shown to exhibit a diel cycle, with concentrations peaking in the morning and decreasing through the day to a minimum value in late afternoon (Cleasby and others, 2000; Nimick and Cleasby, 2001). If zinc concentrations exhibited a similar diel variation in Tenmile Creek, then at least part of the 40-percent decrease in load between these nearby sites sampled 8 hours apart (at different phases in the concentration cycle) is most likely attributable to diel variation rather than a geochemical reaction. This diel variation presumably also caused the similar decrease in the cadmium loads in this reach (fig. 17). Diel cycles have been observed to a lesser degree for other metals and the effect of timing of synoptic-sample collection for other metals is probably minor.



EXPLANATION

○ Mainstem dissolved load

● Mainstem total-recoverable load

△ Cumulative surface-inflow dissolved load

Figure 18. Instantaneous loads of dissolved and total-recoverable copper (top) and iron (bottom) in the lower study reach, Tenmile Creek, Montana, September 6, 1998.

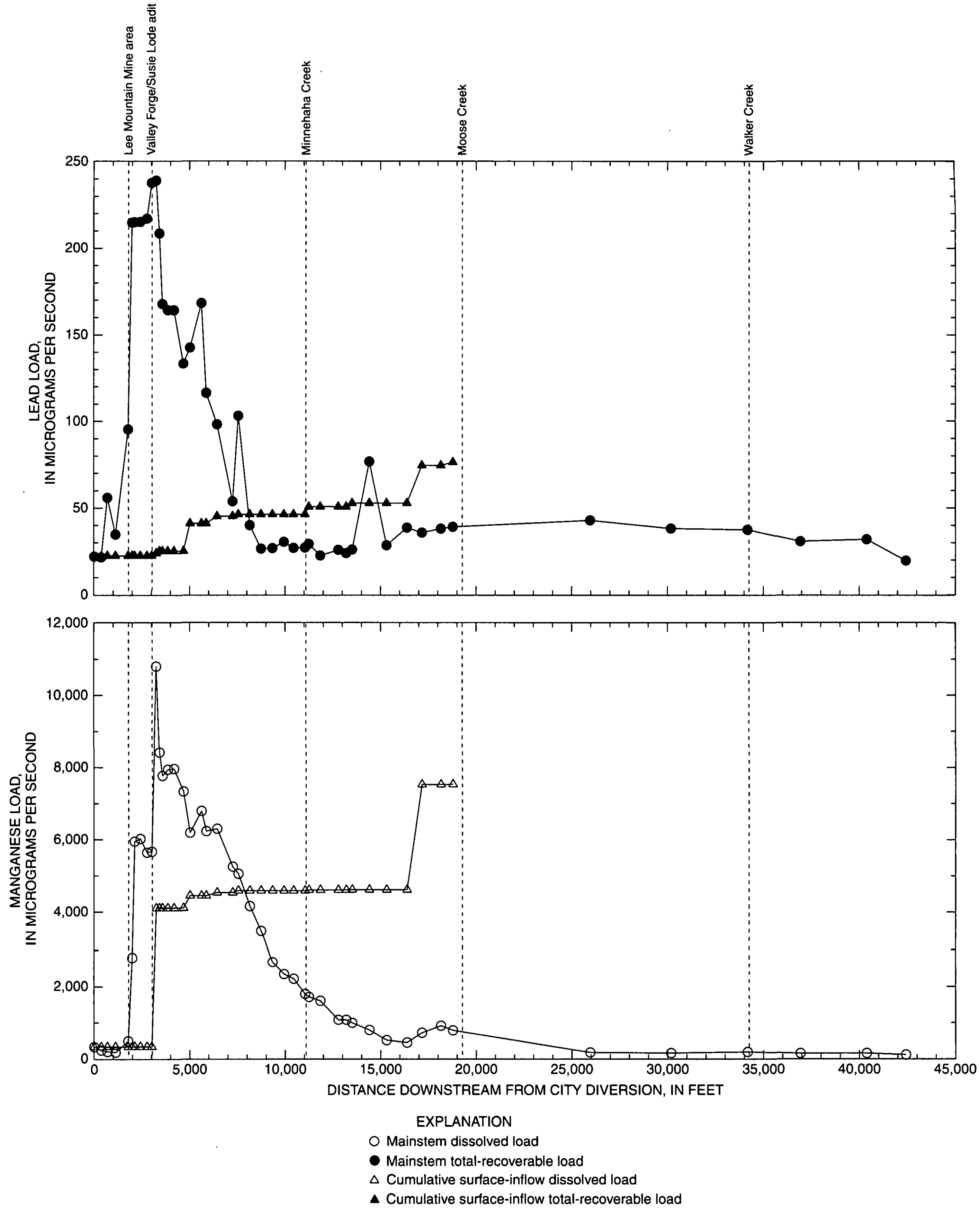


Figure 19. Instantaneous loads of total-recoverable lead (top) and dissolved manganese (bottom) in the lower study reach, Tenmile Creek, Montana, September 6, 1998.

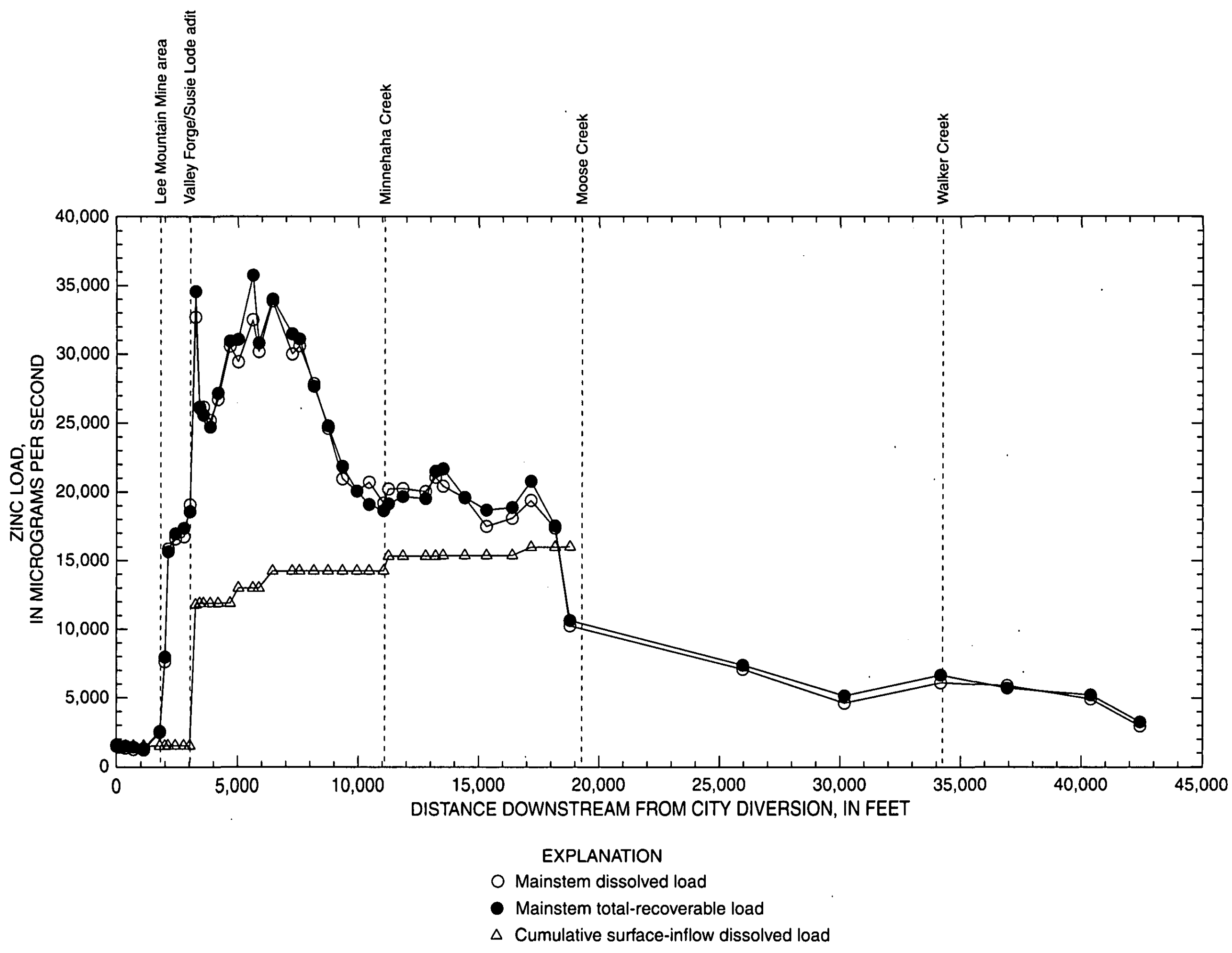


Figure 20. Instantaneous loads of dissolved and total-recoverable zinc in the lower study reach, Tenmile Creek, Montana, September 6, 1998.

ASSESSMENT OF METAL SOURCES

Although metal loading to the upper and lower study reaches of Tenmile Creek was studied separately because of the large difference in flows above and below the City Diversion, the results for both reaches can be combined to better understand metal loading in the watershed. Thus, loads for dissolved arsenic, cadmium, copper, and zinc, along with total-recoverable lead, were plotted for subreaches of Tenmile Creek (fig. 21). These graphs identify the incremental downstream changes in mainstem loads relative to potential source areas. The number of sites that were combined to define a subreach varied and were based on their proximity to a potential source or source area (for example, an inactive mine, a tailings pile, an adit discharge, or a tributary). By subtracting the load at the upstream end of each subreach from the load at the downstream end, the net gain or loss of loads in Tenmile Creek was determined for each subreach.

Loads are a function of streamflow and, therefore, when water is diverted, loads also are diverted. The streamflow in Tenmile Creek at site 36u (upper reach) upstream from the City Diversion was 185 L/s (table 1), whereas the streamflow at site 2 (lower reach) just downstream from the City Diversion was about 5 L/s (table 2). Thus, about 180 L/s of water were diverted. The large decrease in loads from sites 36u to 1 results from streamflow that was diverted from Ten-

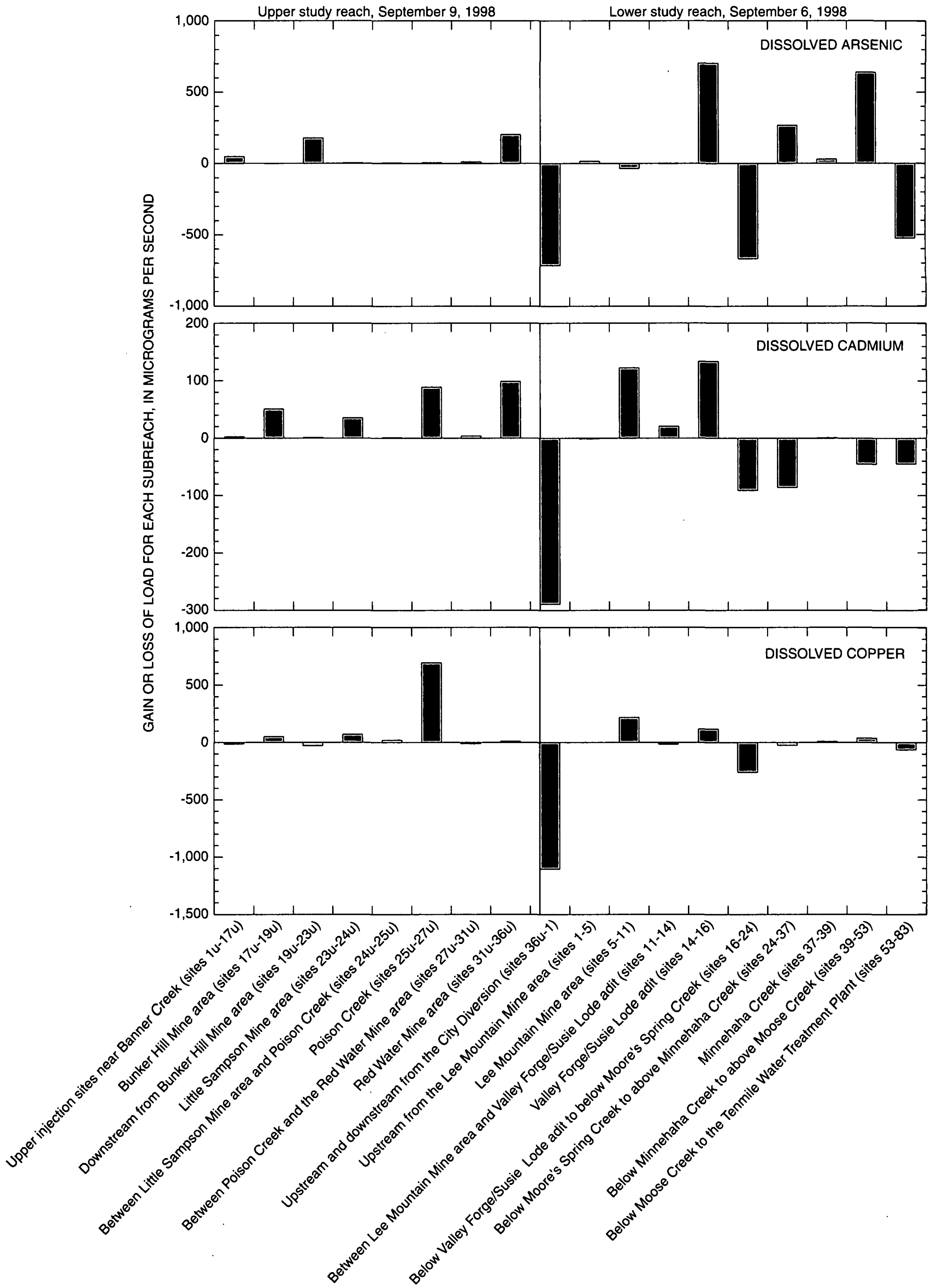


Figure 21. Net gain or loss of selected metal loads in Tenmile Creek, Montana, September 6 and 9, 1998. Most of the loss in metal loads in the subreach from site 36u (upper reach) to site 1 (lower reach) are due to a decrease in streamflow where water was diverted to the Tenmile Water Treatment Plant.

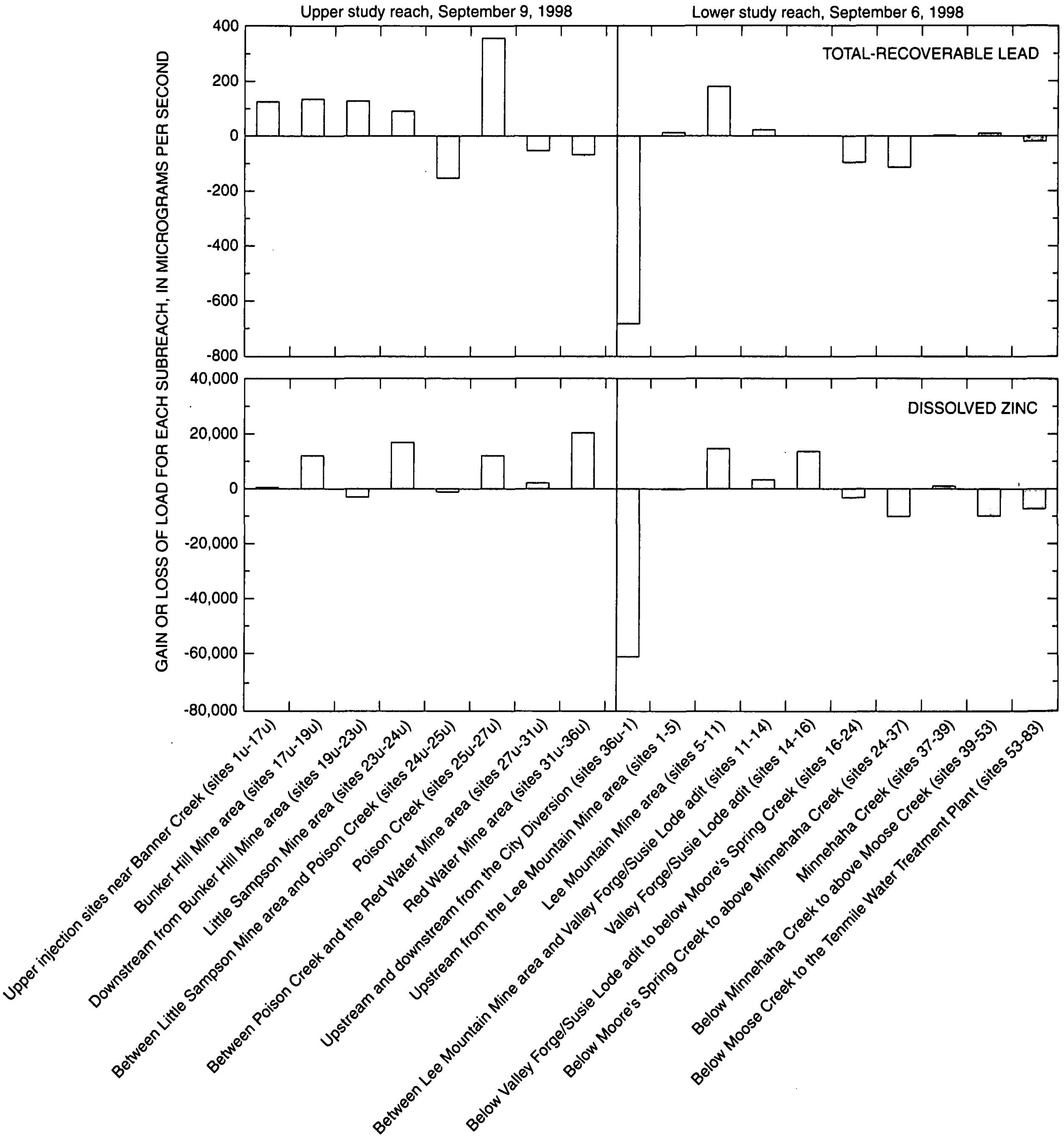


Figure 21. Net gain or loss of selected metal loads in Tenmile Creek, Montana, September 6 and 9, 1998. (Continued)

mile Creek to the Tenmile Water Treatment Plant (fig. 21). Other subreaches downstream from site 1 where net losses of loads occurred likely indicate areas of geochemical removal of the metal, or areas where Tenmile Creek naturally loses streamflow.

Net gains shown on figure 21 indicate that metal loads generally entered Tenmile Creek in six subreaches that were both relatively short and adjacent to an inactive mine. In each subreach, loads of at least three metals increased substantially. Four of the subreaches were in the upper study reach and included the subreaches bracketing the Bunker Hill Mine area (sites 17u to 19u), the Little Sampson Mine area (sites 23u to 24u), Poison Creek (sites 25u to 27u), and the Red Water Mine area (sites 31u to 36u). Two of the subreaches were in the lower study reach near the Lee Mountain Mine area (sites 5 to 11) and the Valley Forge/Susie Lode adit (sites 14 to 16). Comparison of the two study reaches indicates that sources in the lower study reach contributed more dissolved arsenic load to Tenmile Creek. About one-half of the dissolved cadmium that entered Tenmile Creek came from each study reach. In contrast, sources in the upper study reach contributed more copper, lead, and zinc to Tenmile Creek.

The importance of the six subreaches to metal loading is best illustrated by the loads of dissolved cadmium and zinc (fig. 21) which increased in Tenmile Creek in these six subreaches. The increase in dissolved cadmium load in these subreaches ranged from about 35 to 134 μg/s (fig. 21), with two of the largest increases occurring in the Lee Mountain Mine area and near the Valley Forge/Susie Lode adit. The increases in dissolved zinc load in the six subreaches were fairly similar, ranging from 12,100 to 20,380 μg/s. The largest increase was in the Red Water Mine area.

Dissolved arsenic loading increased substantially through only two of the six subreaches. The largest increase was about 700 μg/s from near the Valley Forge/Susie Lode adit (sites 14 to 16), and a smaller increase was from the Red Water Mine area. However, arsenic loading from stream reaches other than the six subreaches that were adjacent to obvious mining disturbances was substantial and larger than the load from the six subreaches. For example, the increase in dissolved arsenic load in the subreach between Minnehaha Creek and Moose Creek (sites 39 to 53) was almost as large as the increase near the Valley Forge/Susie Lode adit. On the basis of elevated concentrations of dissolved arsenic (51 μg/L) in the inflow sample from site 48 (a right-bank inflow which drains a marshy area in this subreach), it seems reasonable to assume that most of the arsenic load in this subreach came from ground water discharging to Tenmile Creek. Some dissolved arsenic loads entered Tenmile Creek below Moore's Spring Creek to above Minnehaha Creek (sites 24 to 37).

Dissolved copper loads increased through each of the same six subreaches, but the increases in each subreach ranged widely, in contrast to the generally similar loading of cadmium and zinc through each of the six subreaches. Increases in copper loads ranged from 10 to 694 μg/s through the subreaches. Poison Creek was the major source of dissolved copper (694 μg/s) and contributed more copper to Tenmile Creek than all of other source areas combined. The dissolved copper load increased slightly in the Lee Mountain Mine area and near the Valley Forge/Susie Lode adit.

Total-recoverable lead loads increased through five of the six subreaches, with the largest increase occurring near Poison Creek. These lead loads increased slightly in the subreaches near the Bunker Hill, Little Sampson, and Lee Mountain Mine areas, but lead loads decreased near the Red Water Mine area. Lead loads also increased upstream from the Bunker Hill Mine area between sites 1u and 17u in the upper study reach. These increases were contributed by Banner Creek and other areas apparently unrelated to historical mining along Tenmile Creek.

Metal loads entering Tenmile Creek in the lower study reach greatly increased mainstem concentrations owing to the small streamflow available for dilution. During this study, about 180 L/s of streamflow was being diverted from Tenmile Creek at the City Diversion at Rimini and about 152 L/s (table 8) was being diverted from the four tributaries (Beaver, Minnehaha, Moose, and Walker Creeks). If this flow had not been diverted, the additional flow would have diluted metal concentrations in Tenmile Creek. To estimate the hypothetical instream concentrations in Tenmile Creek that would result if no water were diverted, a simple mass-balance load profile for dissolved zinc was constructed. Estimated zinc loads (fig. 22) were calculated by combining the mainstem loads measured in Tenmile

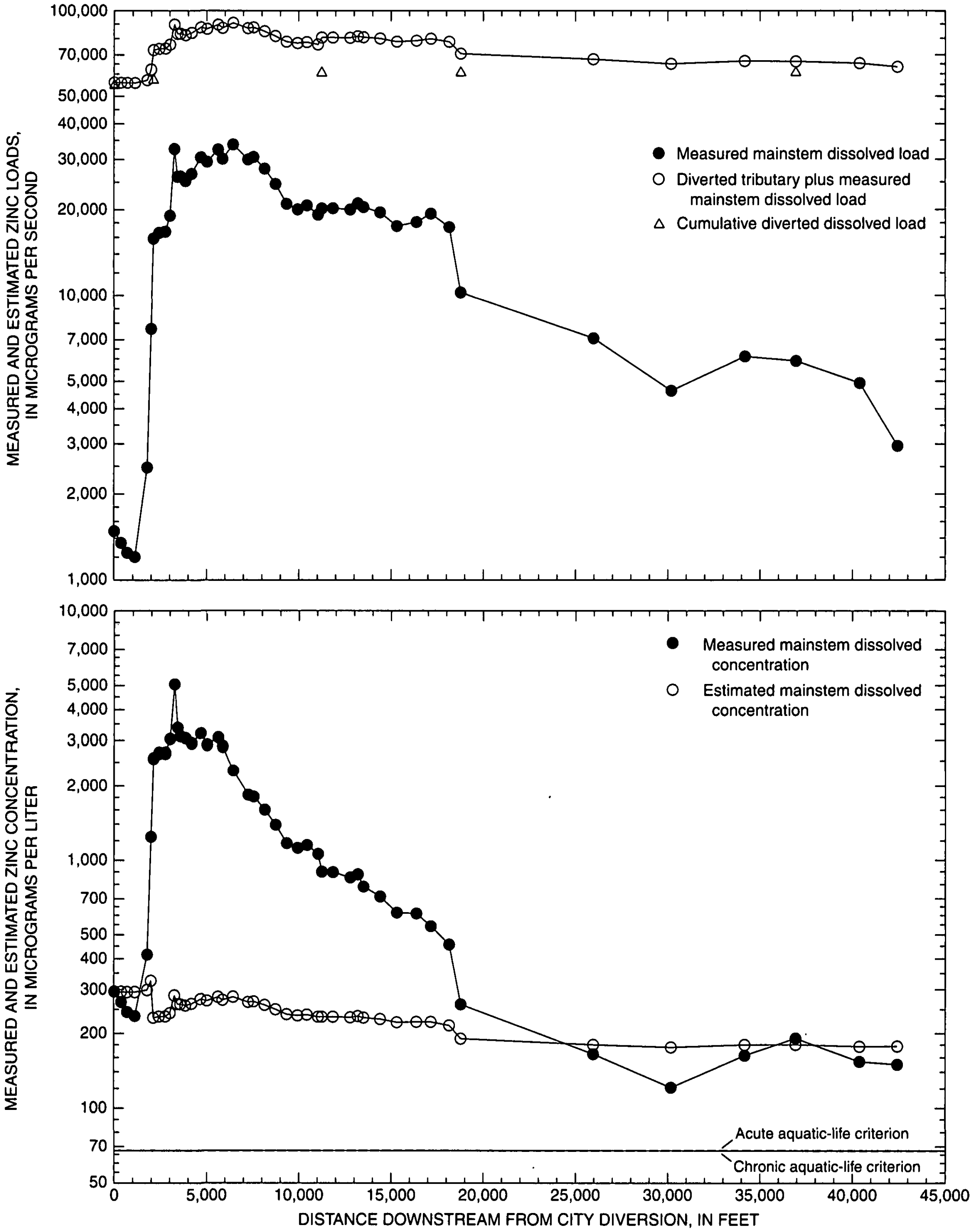


Figure 22. Measured and estimated dissolved-zinc loads (top) and measured and estimated dissolved-zinc concentrations (bottom) in the lower study reach, Tenmile Creek, Montana, September 6, 1998. Estimated zinc loads were calculated by combining measured mainstem loads with the diverted tributary loads. Estimated zinc concentrations were calculated by dividing estimated combined loads by combined streamflow.

Creek (table 5) with the diverted tributary loads (table 8). Dissolved zinc concentrations then were estimated by dividing the combined load by the combined streamflow (mainstem flow plus tributary flow measured above the diversions, table 9) at each site. The constructed profile assumes that all measured flow from the upper Tenmile Creek study reach and the diverted tributaries would remain in the stream channel and not be lost through the streambed or banks.

Figure 22 demonstrates the substantial effect that current diversions have on zinc concentrations in Tenmile Creek, particularly near Rimini. The estimated dissolved zinc concentrations with no streamflow diversions ranged from about 325 μg/L just upstream from Beaver Creek to 177 μg/L at the downstream end of the study reach. The measured dissolved zinc concentrations ranged from 115 μg/L to 5,060 μg/L. The maximum estimated mainstem concentration was only 6 percent of the maximum measured concentration (5,060 μg/L). Because some of the load would likely be lost to geochemical sorption reactions, these estimated concentrations probably are too high, and actual zinc concentrations likely would be somewhat less. Although the estimated dissolved zinc concentrations are only a fraction of those measured during this study, the estimated concentrations would still exceed the acute aquatic-life criterion (67 μg/L) for zinc through the entire lower study reach. During this study, Beaver Creek would have provided the most water for dilution. The flow in Beaver Creek is regulated and varies depending on the amount of water released from Chessman Reservoir. During base-flow conditions, the total streamflow in the upper Tenmile Creek watershed is probably insufficient to dilute dissolved-zinc concentrations to values less than the aquatic-life criteria. But a substantial reduction in instream concentration could be achieved by reducing some of the metal loads that enter Tenmile Creek from the major sources identified by this study.

SUMMARY

The upper Tenmile Creek watershed in west-central Montana is typical of many headwater areas in the western United States where acid drainage from abandoned mine lands has affected the quality of water and aquatic resources. In addition to the effect of historical mining, streamflow in parts of the upper Tenmile Creek watershed is routinely depleted during low-flow periods by water diversions used to supply the municipal needs of the City of Helena. In response to efforts to improve water-quality and streamflow conditions, information was needed concerning specific sources of metal loading in the watershed and the potential ability of the Tenmile Creek channel to convey water during low-flow conditions.

The purpose of this report is to present the results of a metal-loading study conducted on two reaches of upper Tenmile Creek watershed during September 1998. These results identify the quality of water in Tenmile Creek, quantify metal loads entering Tenmile Creek, and identify the predominant source areas contributing those metals. A total of 87 sites on Tenmile Creek and 32 surface-inflow sites were sampled.

Metal loading data were collected during September 8-10, 1998, along the 1.8-mi reach of Tenmile Creek starting about 1,600 ft upstream from Banner Creek and ending at the City Diversion on Tenmile Creek (upper study reach). Metal loading data were collected during September 3-6, 1998, along an 8-mi reach of Tenmile Creek starting just downstream from the City Diversion and ending at the Tenmile Water Treatment Plant (lower study reach).

In the upper study reach, streamflow increased from 145 L/s near the injection site to 185 L/s at the City Diversion. Sampled surface inflows accounted for 36 L/s (90 percent) of the increase, leaving 4 L/s (10 percent) of the total increase attributable to unsampled seeps and subsurface flow.

In the lower study reach, streamflow in Tenmile Creek increased by 38 L/s from site 1 just downstream from the City Diversion to site 62, about 26,000 ft downstream from the City Diversion and about 2,000 ft upstream from Bear Creek. Streamflow decreased in Tenmile Creek from 42.9 to 32.0 L/s in the reach between site 62 and 81, about 2,000 ft upstream from the Tenmile Water Treatment Plant. In the 2,000-ft reach between site 81 and site 83 (Tenmile Creek at Tenmile Water Treatment Plant), streamflow decreased sharply from 32.0 L/s to 19.7 L/s. To verify streamflow gains and loses documented during this study, a second set of synoptic current-meter streamflow measurements was conducted on Tenmile Creek in 1999. The second set of measurements confirmed that Tenmile Creek gained streamflow from the City Diversion to about Walker Creek and lost streamflow downstream from Walker Creek to the Tenmile Water Treatment Plant.

Streamflow in the upper study reach was being augmented by releases from a storage reservoir and was much greater than that in the lower study reach, where the majority of the streamflow was being diverted to the Tenmile Water Treatment Plant. The small flow rate in the lower study reach offered little dilution capacity to metal loads entering Tenmile Creek, and source loads greatly influenced the mainstem concentrations.

Metal concentrations in all mainstem samples collected in the upper study reach were less than the State of Montana human-health standards and, therefore, pose little risk to human health during the low flows. In the lower study reach, concentrations of total-recoverable arsenic in almost 90 percent of stream samples exceeded the State of Montana human-health standard of 18 μg/L. Cadmium, lead, and zinc concentrations exceeded the human-health standards of 5 μg/L, 15 μg/L, and 2,100 μg/L, respectively, in several Tenmile Creek samples, downstream from the Lee Mountain Mine area and the Valley Forge/Susie Lode adit.

Metals concentrations exceeded the State of Montana aquatic-life criteria in both the upper and lower study reaches. Aquatic-life criteria were not exceeded in water from Tenmile Creek mainstem upstream from the Bunker Hill Mine area, except for total-recoverable lead. Copper concentrations exceeded the chronic criterion in several mainstem sites in the reach downstream from the Bunker Hill mine area to Poison Creek. Downstream from the Bunker Hill Mine area, all mainstem zinc concentrations exceeded the acute criteria. Downstream from Poison Creek (site 26u), mainstem cadmium and copper concentrations exceeded the acute criteria. Mainstem total-recoverable lead values exceeded the chronic aquatic-life criterion throughout the upper study reach.

Based on the concentrations measured during this study, aluminum, arsenic, cadmium, copper, iron, lead, and zinc have the potential to adversely affect the aquatic community in the lower study reach during low-flow conditions. In the lower study reach, almost all of the samples from Tenmile Creek upstream from Moose Creek had dissolved and total-recoverable cadmium concentrations that exceeded the chronic aquatic-life criterion of 1.4 μg/L. Dissolved and total-recoverable cadmium concentrations in samples from Tenmile Creek also exceeded the acute criterion (2.1 μg/L) from the Lee Mountain Mine area to just upstream from Moose Creek. Dissolved copper concentrations in samples collected from Tenmile Creek exceeded the chronic aquatic-life criterion (5.2 μg/L), starting at the Lee Mountain Mine and extending about 1,000 ft downstream from Moore's Spring Creek. Total-recoverable copper concentrations exceeded the chronic criterion, starting at the City Diversion and extending about 10,440 ft downstream. The acute aquatic-life criterion for copper (7.3 μg/L) was exceeded for dissolved copper from the Lee Mountain Mine area to just downstream from Moore's Spring Creek and for total-recoverable copper from the Lee Mountain Mine area to about 2,500 ft downstream from Moore's Spring Creek. Dissolved iron concentrations exceeded the chronic aquatic-life criterion (1,000 μg/L) in samples from five consecutive sites on Tenmile Creek just downstream from the Valley Forge/Suzie Lode adit. Total-recoverable iron concentrations exceeded the chronic criterion in a slightly longer reach from the Lee Mountain area to about 1,000 ft downstream from Moore's Spring Creek. Total-recoverable lead concentrations exceeded the chronic criterion from the City Diversion to just downstream from Minnehaha Creek. Dissolved and total-recoverable zinc concentrations in all samples from Tenmile Creek in the lower study reach exceeded both the chronic and acute aquatic-life criterion of 67 μg/L.

Metal loads generally enter Tenmile Creek in six short subreaches that are adjacent to inactive mines. Four of the six subreaches were in the upper study reach and were near the Bunker Hill Mine area, Little Sampson Mine area, Poison Creek, and Red Water Mine area. Two of the six substream reaches were in the lower study reach and were near the Lee Mountain Mine area and Valley Forge/Susie Lode adit. Comparison of the gain in loads from each study reach (the upper and lower) indicates that a greater amount of dissolved arsenic load entered Tenmile Creek along the lower study reach, with the largest dissolved arsenic load (731 μg/s) coming from the Valley Forge/Susie Lode adit. About one-half of the total cadmium load entered Tenmile Creek from each study reach. The increase in dissolved cadmium load in the subreaches ranged from about 35 to 134 μg/s. The two largest sources of dissolved cadmium entered Tenmile Creek near the Lee Mountain Mine area and the Valley Forge/Susie Lode adit. Poison Creek was the major source of dissolved copper and total-recoverable lead loads. The dissolved copper loading from Poison Creek (694 μg/s) contributed more copper to Tenmile Creek than all of the other sources combined. Gains in dissolved zinc load along the six subreaches ranged from 12,100 μg/s to 20,380 μg/s. The largest single source of dissolved zinc came from the Red Water Mine area.

Metal loads entering Tenmile Creek in the lower study reach greatly increased the mainstem concentrations owing to the small streamflow available for dilution. During this study, about 180 L/s of streamflow was being diverted from Tenmile Creek at the Tenmile City Diversion at Rimini and about 152 L/s was being diverted from four tributaries. If flow had not been diverted, the additional volume of relatively clean water from the tributaries would have diluted metal concentrations in Tenmile Creek. To estimate the hypothetical instream concentrations in Tenmile Creek that would result if no water were diverted, a simple mass-balance load profile for dissolved zinc was constructed by combining the mainstem loads measured in Tenmile Creek with the diverted tributary loads. From these loads, mainstem zinc concentrations were estimated. Estimated instream dissolved zinc concentrations in Tenmile Creek ranged from about 325 μg/L just upstream from Beaver Creek to 177 μg/L at the downstream end of the study reach. Although the estimated dissolved zinc concentrations are less than those that were measured during this study, they would still exceed the acute aquatic-life criterion for zinc along the entire lower study reach. During base-flow conditions, the volume of water in the upper Tenmile Creek watershed is probably insufficient to dilute dissolved zinc concentrations to values less than the aquatic-life criteria. A substantial reduction in mainstem concentration could be achieved by reducing the metal loads that enter Tenmile Creek from the six major sources identified by this study.

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SUPPLEMENTAL DATA

Table 5. Water-quality data for synoptic samples collected in the upper study reach, Tenmile Creek, Montana, September 9, 1998

[Data in **bold print** are for samples from surface inflows. Abbreviations: ft, feet; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter. Symbols: <, less than minimum reporting level; --, no data]

Site number (see fig. 2)	Site description	Distance downstream from arbitrary measuring point (feet)	pH (standard units)	Specific conductance (µS/cm)	Sulfate, dissolved (mg/L as SO_4)	Aluminum, dissolved (µg/L as Al)	Aluminum, total recoverable (µg/L as Al)	Arsenic, dissolved (µg/L as As)	Arsenic, total recoverable (µg/L as As)
1u	Tenmile Creek, about 300 ft downstream from bridge, 44 ft upstream from tracer-injection site (small right-bank waste-rock pile from Alley Fraction Mine about 100 ft upstream)	485	7.05	24	5.56	76	217	2	3
2u	Tenmile Creek, downstream from tracer-injection site	985	6.89	41	5.58	69	331	2	3
3u	Tenmile Creek, upstream from Banner Creek (tracer-monitoring site 1)	1,575	7.03	41	5.65	73	186	2	3
4u	**Banner Creek, right-bank inflow**	**1,625**	**7.40**	**52**	**8.34**	**10**	**119**	**2**	**2**
5u	Tenmile Creek, downstream from Banner Creek	1,810	7.29	41	5.83	67	237	3	3
6u	**Left-bank adit (Silver Wave Mine)**	**1,850**	**6.94**	**156**	**14.2**	**<10**	**--**	**4**	**--**
7u	Tenmile Creek, downstream from adit	1,985	7.51	42	5.87	63	236	2	3
8u	Tenmile Creek (dry right-bank adit from W. Coyne Mine, about 200 ft upstream)	2,265	7.17	42	5.94	61	224	2	2
9u	Tenmile Creek, upstream from right-bank waste-rock pile (Lower Evergreen Mine site)	2,710	6.99	42	5.88	59	203	3	2
10u	Tenmile Creek, downstream from right-bank waste-rock pile	2,970	7.14	42	5.90	63	164	2	3
11u	**Left-bank inflow**	**3,060**	**7.21**	**36**	**5.57**	**24**	**143**	**4**	**6**
12u	Tenmile Creek, downstream from left-bank inflow	3,240	7.25	40	6.02	60	196	2	3
13u	**Right-bank seep**	**3,325**	**4.27**	**243**	**95.6**	**887**	**867**	**2**	**3**
14u	**Right-bank seep**	**3,400**	**5.00**	**114**	**45.6**	**431**	**563**	**16**	**61**
15u	Tenmile Creek, downstream from seeps	3,590	7.55	43	5.93	65	223	2	2
16u	**Left-bank adit (Bunker Mile Mine)**	**3,610**	**7.74**	**257**	**32.9**	**10**	**48**	**12**	**28**
17u	Tenmile Creek, downstream from adit discharge (tracer-monitoring site 2)	3,900	7.07	44	6.06	61	256	2	3
18u	**Right-bank seep at base of Bunker Hill Mine area**	**4,205**	**4.24**	**59**	**302**	**2,050**	**2,180**	**3**	**5**
19u	Tenmile Creek, downstream from Bunker Hill Mine area	4,445	7.10	44	6.58	63	229	2	3
20u	Tenmile Creek, downstream from bridge, road is next to stream	4,955	7.21	46	6.68	59	197	2	3
21u	Tenmile Creek	5,610	7.25	46	6.67	62	297	2	3
22u	**Right-bank inflow**	**6,140**	**6.82**	**161**	**37.9**	**<10**	**12**	**12**	**15**
23u	Tenmile Creek, upstream from Little Sampson Mine site	6,440	7.21	47	6.87	52	227	3	3
24u	Tenmile Creek, downstream from Little Sampson Mine site (tracer-monitoring site 3)	6,740	7.56	49	7.46	64	201	3	4
25u	Tenmile Creek, just upstream from Poison Creek	7,450	6.86	49	7.40	52	190	3	3
26u	**Poison Creek, right bank inflow**	**7,465**	**4.02**	**235**	**93.1**	**2,020**	**2,080**	**5**	**6**
26u	**Duplicate sample**	**7,465**	**3.98**	**235**	**92.8**	**2,120**	**2,100**	**5**	**6**
27u	Tenmile Creek, downstream from Poison Creek	7,470	7.61	51	8.47	76	220	3	4
28u	**Left-bank inflow from spring**	**7,880**	**7.09**	**100**	**25.6**	**13**	**113**	**12**	**13**
29u	Tenmile Creek, upstream from Red Water Mine site	8,020	7.41	52	8.71	74	213	3	4
30u	**Right-bank seeps**	**8,720**	**7.73**	**386**	**145**	**<10**	**<10**	**10**	**12**
31u	Tenmile Creek, upstream from Red Water Mine adit	8,895	7.27	53	8.75	74	230	3	4
32u	**Red Water Mine adit**	**8,900**	**7.28**	**470**	**182**	**<10**	**50**	**19**	**92**
33u	Tenmile Creek, downstream from adit discharge	9,035	7.34	57	9.80	72	216	3	5
34u	**Left-bank seep**	**9,045**	**7.02**	**74**	**18.4**	**<10**	**138**	**13**	**13**
35u	Tenmile Creek, downstream from Red Water Mine	9,455	7.21	57	10.1	69	261	3	5
36u	Tenmile Creek, upstream from City Diversion (tracer-monitoring site 4, spot injection and current-meter measurement)	10,165	7.70	57	10.1	67	189	4	5
36u	Duplicate sample	10,165	7.87	57	10.2	58	234	3	6
--	Field blank	--	5.97	3	--	<10	<10	<1	<1
--	Field blank	--	6.08	2	--	<10	<10	<1	<1

Table 5. Water-quality data for synoptic samples collected in the upper study reach, Tenmile Creek, Montana, September 9, 1998 (Continued)

Cadmium, dissolved (µg/L as Cd)	Cadmium, total recov-erable (µg/L as Cd)	Copper, dissolved (µg/L as Cu)	Copper, total recov-erable (µg/L as Cu)	Iron, dissolved (µg/L as Fe)	Iron, total recov-erable (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Lead, total recov-erable (µg/L as Pb)	Manga-nese, dissolved (µg/L as Mn)	Zinc, dissolved (µg/L as Zn)	Zinc, total recov-erable (µg/L as Zn)	Site number (see fig. 2)
<0.1	<1	2.3	2.4	98	274	<1	1	<4	<20	<10	1u
<.1	<1	2.1	2.5	94	279	1.1	1.1	<4	<20	<10	2u
<.1	<1	2.1	2.6	98	262	<1	1.2	<4	<20	10	3u
<.1	**<1**	**1.5**	**1.2**	**<10**	**92**	**<1**	**<1**	**<4**	**23**	**13**	**4u**
<.1	<1	1.7	2.4	81	255	<1	1.8	<4	<20	12	5u
.5	**--**	**2.3**	**--**	**<10**	**--**	**<1**	**--**	**<4**	**260**	**--**	**6u**
<.1	<1	1.8	2.4	76	256	<1	1.6	<4	<20	11	7u
<.1	<1	2.1	2.3	63	230	<1	1.1	<4	<20	12	8u
<.1	<1	2.1	2.7	59	213	<1	1.7	<4	<20	13	9u
<.1	<1	2	2.1	77	215	<1	1	<4	<20	13	10u
.3	**<1**	**<1**	**<1**	**36**	**119**	**<1**	**1**	**16**	**56**	**56**	**11u**
<.1	<1	2.3	2.4	78	221	<1	1.1	<4	<20	13	12u
31	**29**	**77**	**82**	**52**	**69**	**97**	**93**	**1,340**	**5,540**	**5,700**	**13u**
14	**13**	**50**	**52**	**213**	**626**	**21**	**39**	**1,110**	**1,910**	**1,800**	**14u**
.2	<1	2.1	2.4	94	280	<1	1.8	<4	24	19	15u
4	**3.9**	**1.5**	**3.9**	**<10**	**146**	**<1**	**2**	**522**	**451**	**431**	**16u**
<.1	<1	1.9	2.5	88	283	<1	1.6	<4	<20	21	17u
227	**218**	**213**	**206**	**23**	**100**	**55**	**67**	**1,970**	**38,600**	**39,000**	**18u**
.4	<1	2.2	2.9	102	311	1.1	2.4	5	93	83	19u
.4	<1	2.6	2.7	103	294	1.1	2.5	6	97	87	20u
.2	<1	2.5	2.6	97	296	1	3.4	5.8	77	85	21u
.2	**<1**	**1.6**	**2.2**	**87**	**130**	**2.9**	**6.7**	**17**	**119**	**136**	**22u**
.4	<1	2	2.8	72	257	<1	3.1	5.8	73	84	23u
.6	<1	2.4	3	101	262	<1	3.6	21	169	180	24u
.6	<1	2.5	2.8	87	230	1.1	2.7	17	162	172	25u
32	**32**	**352**	**358**	**339**	**348**	**91**	**93**	**775**	**3,980**	**4,210**	**26u**
33	**32**	**359**	**360**	**367**	**341**	**90**	**91**	**860**	**4,170**	**4,200**	**26u**
1.1	1	6.4	7.4	87	242	1.5	4.7	41	229	225	27u
.8	**<1**	**1.7**	**1.8**	**15**	**83**	**<1**	**<1**	**<4**	**1,310**	**1,260**	**28u**
1.1	1	6	7.5	95	267	1.1	4.2	39	229	241	29u
15	**15**	**1.8**	**2.4**	**<10**	**<10**	**<1**	**<1**	**<4**	**4,680**	**4,350**	**30u**
1.1	1.1	6.2	7.3	78	271	1	4.3	38	235	245	31u
52	**55**	**<1**	**27**	**990**	**6,340**	**<1**	**<1**	**4,650**	**9,920**	**10,300**	**32u**
1.5	1.5	6.1	7.5	108	325	1.3	4.4	76	333	312	33u
.5	**<1**	**1.2**	**1.4**	**<10**	**82**	**<1**	**<1**	**<4**	**523**	**530**	**34u**
1.6	1.5	6.3	7.8	92	301	1.3	4.4	75	335	324	35u
1.6	1.5	6.1	7.2	87	289	1.3	3.8	72	338	323	36u
1.6	1.6	5.5	7.8	46	296	<1	4	70	317	329	36u
<.1	<1	<1	<1	<10	<10	<1	<1	<4	<20	<10	--
<.1	<1	<1	<1	<10	<10	<1	<1	<4	<20	<10	--

Table 6. Water-quality data for synoptic samples collected in the lower study reach, Tenmile Creek, Montana, September 6, 1998

[Data in **bold print** are for samples from surface inflows. Abbreviations: ft, feet; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter. Symbols: <, less than minimum reporting level; --, no data]

Site number (see fig. 3)	Site description	Distance downstream from injection site (feet)	pH (standard units)	Specific conductance (µS/cm)	Sulfate, dissolved (mg/L as SO_4)	Aluminum, dissolved (µg/L as Al)	Aluminum, total recoverable (µg/L as Al)	Arsenic, dissolved (µg/L as As)	Arsenic, total recoverable (µg/L as As)
1	Tenmile Creek, downstream from City Diversion	0	7.16	46	10.2	66	258	5	7
1	Ultrafiltrate sample	0	7.16	46	--	<10	--	8	--
2	Tenmile Creek, just downstream from bridge	365	7.05	161	9.89	54	196	7	9
3	**Inflow seep on left bank**	**665**	**6.26**	**99**	**15.4**	**15**	**139**	**15**	**18**
4	Tenmile Creek, downstream from left-bank seep	695	7.00	150	11.1	47	176	8	12
5	Tenmile Creek, upstream from mining reclamation on left bank--Lee Mountain Mine	1,115	7.42	145	10.2	54	232	8	10
6	**Sewage pipe on right bank--excessive algae growth in Tenmile Creek 50 ft downstream from pipe**	**1,245**	**8.83**	**1,830**	**43.5**	**44**	**--**	**9**	**--**
7	Tenmile Creek	1,780	7.06	115	18.2	67	184	10	12
8	**Left-bank seep from Lee Mountain Mine (Dug a pit and sampled tailings leachate seeping from pit)**	**1,800**	**2.79**	**2,500**	**1,680**	**46,500**	**43,700**	**1,900**	**1,900**
9	Tenmile Creek, just upstream from Beaver Creek, seeps from Beaver Creek on right bank and tailings on left bank	1,985	6.48	144	35.9	23	779	2	17
10	**Beaver Creek, right-bank inflow**	**2,000**	**6.95**	**336**	**123**	**<10**	**28**	**36**	**39**
11	Tenmile Creek, downstream from Beaver Creek	2,120	5.38	182	59.3	293	1,530	1	20
11	Ultrafiltrate sample	2,120	5.38	182	--	173	--	1	--
12	Tenmile Creek	2,420	5.34	187	62.0	296	1,450	<1	19
13	Tenmile Creek, at bridge just upstream from right-bank tailings	2,765	5.51	189	63.3	171	1,360	<1	19
14	Tenmile Creek, downstream from tailings	3,015	5.53	197	68.0	164	1,260	<1	18
14	Duplicate sample	3,015	5.54	197	67.4	154	1,050	<1	14
14	Ultrafiltrate sample	3,015	5.53	197	--	55	--	1	--
15	**Valley Forge/Suzie Lode adit right-bank inflow**	**3,040**	**3.82**	**2,190**	**1,580**	**4,870**	**4,720**	**3,550**	**5,400**
16	Tenmile Creek, downstream from the Valley Forge/Suzie Lode adit discharge and upstream from Spring Creek	3,250	4.97	322	137	479	1,400	110	230
16	Ultrafiltrate sample	3,250	4.97	322	--	523	--	132	--
17	**Spring Creek, left-bank inflow**	**3,305**	**7.00**	**50**	**12.1**	**23**	**107**	**8**	**9**
18	Tenmile Creek, downstream from upper fork of Spring Creek	3,415	6.00	229	92.7	59	1,100	47	135
19	Tenmile Creek, downstream from Spring Creek	3,575	6.09	211	82.2	29	910	38	110
20	Tenmile Creek, just downstream from bridge	3,850	5.85	210	83.7	25	803	27	100
20	Ultrafiltrate sample	3,850	5.85	210	--	27	--	14	--
21	Tenmile Creek	4,180	6.03	209	83.6	19	758	14	85
22	Tenmile Creek, downstream from swampy area	4,675	6.22	235	94.5	<10	621	4	71
22	Ultrafiltrate sample	4,675	6.23	235	--	22	--	5	--
23	**Moore's Spring Creek, right-bank inflow**	**4,890**	**7.27**	**267**	**110**	**33**	**866**	**7**	**84**
24	Tenmile Creek, downstream from Moore's Spring Creek	5,020	6.64	251	105	<10	538	4	65
25	Tenmile Creek, swampy area on right bank	5,620	6.75	265	113	<10	591	2	73
26	Tenmile Creek, 20 ft upstream from rip rap on right bank	5,865	6.86	260	108	<10	480	2	62
27	**Right-bank inflow draining swampy area**	**6,165**	**7.35**	**241**	**85.5**	**<10**	**27**	**29**	**38**
28	Tenmile Creek, downstream from swampy area (spot injection and current-meter measurement)	6,435	6.73	253	105	<10	247	4	38

Table 6. Water-quality data for synoptic samples collected in the lower study reach, Tenmile Creek, Montana, September 6, 1998 (Continued)

Cadmium, dissolved (µg/L as Cd)	Cadmium, total recov-erable (µg/L as Cd)	Copper, dissolved (µg/L as Cu)	Copper, total recov-erable (µg/L as Cu)	Iron, dissolved (µg/L as Fe)	Iron, total recov-erable (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Lead, total recov-erable (µg/L as Pb)	Manganese, dissolved (µg/L as Mn)	Zinc, dissolved (µg/L as Zn)	Zinc, total recov-erable (µg/L as Zn)	Site num-ber (see fig. 3)
1.4	1.4	4.9	6.7	76	288	1.0	4.4	66	295	315	1
<.1	--	8	--	<10	--	<1	--	<3	<20	--	1
1.3	1.4	5.3	6.4	75	239	1.3	4.3	47	268	294	2
.7	**<1**	**2.5**	**3.5**	**11**	**146**	**<1**	**6**	**<4**	**244**	**250**	**3**
1.3	1.3	5.3	7.1	49	267	<1	11	39	244	275	4
1.2	1.2	4.9	6.5	67	229	<1	6.8	35	235	256	5
<.1	**--**	**13**	**--**	**319**	**--**	**2.2**	**--**	**61**	**<20**	**--**	**6**
2.5	2.5	5.1	7.1	47	147	5.8	16	82	416	427	7
702	**698**	**860**	**906**	**129,000**	**140,000**	**65**	**84**	**30,800**	**79,900**	**82,500**	**8**
9.1	9.4	8.7	18	36	1,010	1.8	35	457	1,245	1,300	9
3.9	**4.1**	**12**	**23**	**<10**	**60**	**<1**	**1.6**	**475**	**2,120**	**2,220**	**10**
21	20	40	48	106	1,900	12	35	969	2,580	2,550	11
21	--	42	--	123	--	8.3	--	980	2,580	--	11
23	22	45	53	150	1,600	17	35	980	2,700	2,760	12
23	22	38	48	162	1,460	16	35	910	2,700	2,800	13
24	23	37	46	157	1,360	20	38	906	3,050	2,970	14
23	23	38	48	159	1,410	19	40	885	3,000	2,920	14
24	--	22	--	162	--	4.2	--	902	3,190	--	14
508	**466**	**272**	**260**	**143,000**	**147,000**	**3**	**7.1**	**18,300**	**49,900**	**48,600**	**15**
44	42	54	56	6,040	7,660	23	37	1,670	5,060	5,350	16
43	--	55	--	6,290	--	19	--	1,690	5,070	--	16
1.2	**1.2**	**7**	**8.8**	**12**	**44**	**<1**	**<1**	**<4**	**82**	**95**	**17**
29	28	27	40	3,590	5,150	2.7	27	1,090	3,380	3,390	18
26	25	20	36	2,810	4,180	1.1	20	967	3,070	3,010	19
25	25	18	32	2,470	3,840	<1	20	926	3,120	3,050	20
25	--	16	--	1,870	--	<1	--	904	3,020	--	20
25	25	16	32	1,900	3,500	<1	18	873	2,930	2,980	21
23	22	12	27	969	2,560	<1	14	770	3,210	3,250	22
21	--	14	--	933	--	<1	--	763	3,180	--	22
13	**16**	**7.3**	**33**	**<10**	**1,650**	**<1**	**24**	**513**	**1,650**	**2,080**	**23**
19	18	8.8	24	702	2,000	<1	14	608	2,890	3,050	24
20	20	6.5	24	332	2,050	<1	16	646	3,090	3,400	25
19	18	5.5	21	182	1,670	<1	11	589	2,850	2,910	26
1	**1**	**1.1**	**1.8**	**322**	**25**	**<1**	**<1**	**20**	**307**	**308**	**27**
15	14	4.3	13	33	874	<1	6.7	430	2,310	2,320	28

Table 6. Water-quality data for synoptic samples collected in the lower study reach, Tenmile Creek, Montana, September 6, 1998 (Continued)

Site number (see fig. 3)	Site description	Distance downstream from injection site (feet)	pH (standard units)	Specific conductance (µS/cm)	Sulfate, dissolved (mg/L as SO_4)	Aluminum, dissolved (µg/L as Al)	Aluminum, total recoverable (µg/L as Al)	Arsenic, dissolved (µg/L as As)	Arsenic, total recoverable (µg/L as As)
29	Tenmile Creek, upstream from lumber yard, stream is next to road	7,245	6.93	243	96.9	14	136	7	25
30	**Culvert from lumber yard, right-bank inflow**	**7,375**	**7.89**	**220**	**32.5**	**<10**	**33**	**24**	**37**
31	Tenmile Creek, downstream from culvert	7,545	6.92	242	95.7	<10	162	7	34
32	Tenmile Creek, just upstream from rip rap, stream is next to road	8,145	7.22	235	87.3	<10	131	10	23
33	Tenmile Creek, bedrock channel (spot injection and current-meter measurement)	8,735	7.30	232	84.4	11	93	11	25
34	Tenmile Creek, bedrock channel	9,335	7.46	230	82.8	<10	85	14	23
35	Tenmile Creek, about 40 ft upstream from power-line crossing	9,935	7.32	227	81.6	13	81	15	22
36	Tenmile Creek, at bridge to Minnehaha Creek	10,440	7.44	226	80.7	<10	76	15	23
37	Tenmile Creek, just upstream from Minnehaha Creek	11,040	7.72	224	78.5	14	64	17	25
38	**Minnehaha Creek, left-bank inflow**	**11,095**	**7.63**	**72**	**15.4**	**17**	**106**	**3**	**3**
39	Tenmile Creek, downstream from Minnehaha Creek	11,245	7.60	190	63.8	<10	77	15	18
40	Tenmile Creek, just downstream from old bridge piers	11,845	7.77	189	63.2	13	70	14	20
41	Tenmile Creek, just upstream from where stream and road converge	12,790	7.58	186	60.5	<10	61	17	20
42	Tenmile Creek, upstream from Deer Creek	13,200	7.60	186	60.6	<10	44	16	23
42	Duplicate sample	13,200	7.63	187	60.8	<10	46	16	20
43	**Deer Creek, left-bank inflow**	**13,285**	**7.92**	**83**	**9.07**	**<10**	**148**	**1**	**1**
44	Tenmile Creek, downstream from Deer Creek and upstream from bridge	13,510	7.66	177	52.4	<10	48	15	18
45	Tenmile Creek, downstream from bridge, steep right bank, channel disturbance on left bank	14,410	7.51	177	51.2	<10	65	18	21
46	Tenmile Creek, old road about 40 feet from creek on left bank	15,315	7.58	174	51.6	<10	28	19	20
47	Tenmile Creek	16,380	7.61	174	52.1	<10	34	19	20
48	**Right-bank inflow draining small marshy area**	**16,935**	**6.34**	**123**	**29.1**	**15**	**38**	**51**	**68**
49	**Right-bank inflow draining marshy area**	**16,985**	**6.87**	**147**	**43.6**	**<10**	**23**	**9**	**14**
50	Tenmile Creek, downstream from right-bank marshy area	17,160	7.12	170	49.8	<10	27	19	22
51	Tenmile Creek, just upstream from bridge	18,155	7.04	164	44.7	<10	17	23	24
52	**Left-bank inflow**	**18,685**	**6.91**	**105**	**9.70**	**<10**	**275**	**20**	**22**
53	Tenmile Creek, at USGS streamflow-gaging station 06062500 (spot injection and current-meter measurement)	18,780	7.41	156	44.0	10	19	25	27
53	Duplicate	18,780	7.31	157	43.6	<10	35	25	27
53	Ultrafiltrate sample	18,780	7.41	156	--	34	--	18	--
54	Tenmile Creek, upstream from Moose Creek	19,250	7.50	156	42.8	<10	38	28	25
55	Tenmile Creek, downstream from Moose Creek (no visible flow in Moose Creek on September 6, 1998, distance 19,270 feet from City Diversion)	19,485	7.64	157	43.3	<10	28	25	25
56	Tenmile Creek, 200 ft upstream from Moose Creek campground bridge	20,580	7.56	153	41.2	<10	34	25	26
57	Tenmile Creek	21,585	7.72	152	39.0	<10	21	28	30
58	Tenmile Creek, right bank is next to road	22,780	7.77	151	37.0	<10	21	27	27
59	Tenmile Creek, right bank is next to road just upstream from bridge	23,960	7.99	153	37.7	<10	25	26	30
60	Tenmile Creek, 1,000 ft downstream from bridge	25,125	7.85	153	37.7	<10	18	30	28
61	**Right-bank inflow**	**25,365**	**8.17**	**220**	**20.0**	**<10**	**35**	**1**	**1**

Table 6. Water-quality data for synoptic samples collected in the lower study reach, Tenmile Creek, Montana, September 6, 1998 (Continued)

Cadmium, dissolved (µg/L as Cd)	Cadmium, total recoverable (µg/L as Cd)	Copper, dissolved (µg/L as Cu)	Copper, total recoverable (µg/L as Cu)	Iron, dissolved (µg/L as Fe)	Iron, total recoverable (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Lead, total recoverable (µg/L as Pb)	Manganese, dissolved (µg/L as Mn)	Zinc, dissolved (µg/L as Zn)	Zinc, total recoverable (µg/L as Zn)	Site number (see fig. 3)
11	11	4.3	9.2	<10	451	<1	3.3	322	1,840	1,930	29
<.1	**<1**	**<1**	**<1**	**58**	**300**	**<1**	**1.8**	**94**	**<20**	**14**	**30**
11	10	4	9.2	15	532	<1	6.1	299	1,810	1,840	31
9.8	8.9	4	6.5	<10	308	<1	2.3	239	1,600	1,590	32
8.4	7.9	3.9	6.3	<10	266	<1	1.5	196	1,390	1,400	33
7.5	7	3.6	5.6	<10	210	<1	1.5	150	1,170	1,220	34
6.2	6.4	3.3	5.6	<10	192	<1	1.7	131	1,120	1,120	35
6.2	6	3.1	5.4	<10	184	<1	1.5	123	1,150	1,060	36
5.9	5.8	3.6	4.9	<10	151	<1	1.5	99	1,060	1,030	37
1.5	**1.5**	**4.1**	**4.9**	**13**	**71**	**<1**	**<1**	**<4**	**245**	**243**	**38**
4.8	5.3	3.3	5	<10	116	<1	1.3	76	898	850	39
4.9	5	3.5	5	<10	128	<1	<1	71	895	870	40
5.0	4.9	3.4	4.7	<10	84	<1	1.1	46	852	830	41
4.8	4.9	3.7	4.5	<10	85	<1	1	45	877	895	42
4.8	4.8	3.6	4.6	<10	81	<1	1	45	876	895	42
<.1	**<1**	**<1**	**<1**	**<10**	**95**	**<1**	**<1**	**<4**	**<20**	**<10**	**43**
4.5	4.2	3.3	4.5	<10	87	<1	<1	38	782	830	44
3.7	4.1	2.8	4.6	<10	91	<1	2.8	29	714	715	45
3.2	3.5	3.1	3.7	<10	58	<1	<1	18	614	655	46
3.2	3.3	3.1	3.9	<10	61	<1	1.3	15	609	635	47
.2	**<1**	**<1**	**1.7**	**3,670**	**4,960**	**<1**	**4**	**942**	**71**	**75**	**48**
.8	**<1**	**2.4**	**2.7**	**<10**	**83**	**<1**	**3.1**	**12**	**125**	**143**	**49**
3.2	3	3.1	3.7	20	73	<1	<1	20	541	580	50
2.6	2.4	2.6	3.4	27	80	<1	<1	24	456	460	51
<.1	**<1**	**1.1**	**2.1**	**<10**	**181**	**<1**	**1.9**	**<4**	**<20**	**<10**	**52**
1.6	1.7	2.9	3.9	25	80	<1	<1	20	262	272	53
--	1.7	--	3.8	--	84	--	1	--	--	272	53
2.0	--	14	--	46	--	2.4	--	24	321	--	53
1.6	1.7	2.3	3.8	19	74	<1	<1	18	263	273	54
1.5	1.5	2.7	3.7	19	92	<1	<1	14	240	264	55
1.3	1.3	2.7	3.6	14	65	<1	<1	8.9	223	232	56
1.1	1.2	2.3	3.2	<10	43	<1	<1	7.6	198	210	57
1.1	1.1	2.2	3.1	<10	51	<1	<1	4.7	184	194	58
1.0	1.1	2.5	3.6	<10	40	<1	<1	4.4	166	185	59
1.1	1.1	2.7	3.2	<10	38	<1	<1	4.1	165	190	60
<.1	**<1**	**<1**	**1.1**	**<10**	**55**	**<1**	**<1**	**<4**	**<20**	**<10**	**61**

Table 6. Water-quality data for synoptic samples collected in the lower study reach, Tenmile Creek, Montana, September 6, 1998 (Continued)

Site number (see fig. 3)	Site description	Distance downstream from injection site (feet)	pH (standard units)	Specific conductance (µS/cm)	Sulfate, dissolved (mg/L as SO_4)	Aluminum, dissolved (µg/L as Al)	Aluminum, total recoverable (µg/L as Al)	Arsenic, dissolved (µg/L as As)	Arsenic, total recoverable (µg/L as As)
62	Tenmile Creek, valley is not as confined as it was upstream from this site, spot injection and current-meter measurement)	25,965	7.98	156	37.0	<10	18	27	24
63	**Right-bank inflow, draining pond**	**26,250**	**8.21**	**209**	**25.0**	**<10**	**126**	**1**	**1**
64	Tenmile Creek, just downstream from private bridge	26,500	7.77	158	36.1	<10	23	27	25
64	Ultrafiltrate sample	26,500	7.77	158	--	11	--	22	--
65	Tenmile Creek, upstream from Bear Gulch	27,215	7.71	161	35.5	<10	19	24	24
66	**Bear Gulch, left-bank inflow from culvert**	**27,220**	**8.00**	**215**	**36.9**	**<10**	**97**	**3**	**3**
67	Tenmile Creek, downstream from Bear Gulch	28,120	8.20	163	34.8	<10	15	26	23
68	Tenmile Creek, just downstream from bridge	29,080	8.23	166	35.3	<10	14	26	27
69	**Left-bank seep**	**29,585**	**6.80**	**156**	**36.3**	**<10**	**73**	**19**	**24**
70	Tenmile Creek (spot injection and current-meter measurement)	30,185	8.15	168	35.8	<10	18	25	24
71	Tenmile Creek	31,230	7.99	168	35.2	<10	15	25	24
72	Tenmile Creek, right-bank camping site	32,365	8.08	167	35.2	<10	12	26	23
73	Tenmile Creek, stream is next to road on right bank	33,415	8.00	168	35.6	<10	<10	24	23
74	Tenmile Creek, upstream from Walker Creek (spot injection and current-meter measurement)	34,175	7.89	167	35.3	<10	19	23	24
74	Ultrafiltrate sample	34,175	7.89	167	--	13	--	22	--
75	**Walker Creek, left-bank inflow**	**34,225**	**7.19**	**178**	**8.60**	**<10**	**371**	**2**	**3**
76	Tenmile Creek, downstream from Walker Creek	34,460	8.00	168	36.0	<10	15	24	27
77	Tenmile Creek	35,560	7.90	168	35.9	<10	13	26	22
78	Tenmile Creek, just downstream from bridge (spot injection and current-meter measurement)	36,935	7.77	168	35.4	<10	15	24	23
79	Tenmile Creek, downstream from private bridge	37,965	7.66	168	36.2	<10	<10	23	25
80	Tenmile Creek	39,000	7.84	169	34.7	<10	11	22	23
81	Tenmile Creek, at County bridge (spot injection and current-meter measurement)	40,390	7.76	171	36.0	<10	14	24	23
82	Tenmile Creek, downstream from County bridge	41,465	7.78	171	35.8	<10	<10	23	23
83	Tenmile Creek, at USGS streamflow-gaging station 06062750 (spot injection and current-meter measurement)	42,435	7.75	171	35.4	<10	14	23	24
83	Ultrafiltrate sample	42,435	7.75	171	--	19	--	21	--
--	Field blank	--	6.27	2.0	--	<10	<10	<1	<1
--	Field blank	--	5.88	2.0	--	<10	<10	<1	<1

Table 6. Water-quality data for synoptic samples collected in the lower study reach, Tenmile Creek, Montana, September 6, 1998 (Continued)

Cadmium, dissolved (µg/L as Cd)	Cadmium, total recoverable (µg/L as Cd)	Copper, dissolved (µg/L as Cu)	Copper, total recoverable (µg/L as Cu)	Iron, dissolved (µg/L as Fe)	Iron, total recoverable (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Lead, total recoverable (µg/L as Pb)	Manganese, dissolved (µg/L as Mn)	Zinc, dissolved (µg/L as Zn)	Zinc, total recoverable (µg/L as Zn)	Site number (see fig. 3)
1.0	1	2.5	3.1	<10	37	<1	<1	<4	165	172	62
<.1	**<1**	**<1**	**1.4**	**<10**	**177**	**<1**	**<1**	**<4**	**<20**	**<10**	**63**
1.0	1.1	2	3.6	11	38	<1	<1	6.5	181	165	64
<1.0	--	5.9	--	<10	--	<1	--	5.3	81	--	64
1.0	1	2	3	<10	50	<1	<1	7.1	165	169	65
<.1	**<1**	**<1**	**1.2**	**24**	**142**	**<1**	**<1**	**7**	**<20**	**<10**	**66**
.8	<1	2.2	3.2	10	41	<1	<1	7	154	146	67
.9	<1	2.4	2.8	11	36	<1	<1	6	115	124	68
.9	**<1**	**2**	**4.1**	**<10**	**107**	**<1**	**3.9**	**<4**	**200**	**181**	**69**
.8	<1	2.1	3.1	<10	44	<1	<1	4.1	121	135	70
.9	1	2.5	2.7	<10	27	<1	<1	<4	134	152	71
.9	1	2.8	3.2	<10	17	<1	<1	<4	149	158	72
1.0	1	2.3	2.8	<10	24	<1	<1	4.1	153	167	73
1.2	1	2.8	2.8	<10	38	<1	<1	5	163	178	74
<1.0	--	4.6	--	<10	--	<1	--	5.6	75	--	74
<.1	**<1**	**1.4**	**3.9**	**67**	**1,480**	**<1**	**1**	**659**	**<20**	**<10**	**75**
1.0	1.1	2.4	2.8	<10	24	<1	<1	5.4	173	181	76
1.0	1.1	2.4	3.4	<10	20	<1	<1	4.8	181	183	77
1.1	1.1	2.3	3.3	<10	26	<1	<1	4.8	191	185	78
1.0	1.1	2.4	2.9	<10	23	<1	<1	6.3	180	186	79
1.1	1.1	2.5	2.7	<10	18	<1	<1	5.5	166	181	80
.9	1	2.3	3.1	<10	19	<1	<1	4.8	154	163	81
1.0	1	2.7	2.7	<10	26	<1	<1	4.8	154	167	82
.9	1	2.5	2.8	<10	21	<1	<1	5.6	150	165	83
<1.0	--	4.5	--	<10	--	<1	--	9.1	65	--	83
<.1	<1	<1	<1	<10	<10	<1	<1	<4	<20	<10	--
<.1	<1	<1	<1	<10	<10	<1	<1	<4	<20	<10	--

Table 7. Instantaneous loads in the upper study reach, Tenmile Creek, Montana, September 9, 1998

[Data in **bold print** are loads from surface inflows. Abbreviations: µg/s, micrograms per second; mg/s, milligrams per second. Symbols: <, load is less than the value and was calculated using a minimum reporting level for each constituent; --, no data]

Site number (see fig. 2)	Sulfate load, dissolved (mg/s)	Aluminum load, dissolved (µg/s)	Aluminum load, total-recoverable (µg/s)	Arsenic load, dissolved (µg/s)	Arsenic load, total-recoverable (µg/s)	Cadmium load, dissolved (µg/s)	Cadmium load, total-recoverable (µg/s)	Copper load, dissolved (µg/s)
1u	806	11,000	31,500	290	435	<14.5	<145	334
2u	811	10,100	48,100	291	436	<14.5	<145	305
3u	823	10,600	27,100	291	437	<14.6	<146	306
4u	**193**	**<232**	**2,760**	**46.3**	**46.3**	**<2.32**	**<23.2**	**34.7**
5u	985	11,400	40,000	507	507	<16.9	<169	287
6u	**1.42**	**<1.0**	**--**	**.40**	**--**	**.05**	**--**	**.23**
7u	977	10,400	39,300	333	499	<16.7	<166	300
8u	999	10,200	37,700	336	336	<16.8	<168	353
9u	989	9,930	34,100	504	336	<16.8	<168	353
10u	992	10,600	27,600	336	504	<16.8	<168	336
11u	**1.91**	**8.40**	**49.0**	**1.37**	**2.06**	**.10**	**<.34**	**<.34**
12u	1,010	10,100	33,000	337	505	<16.8	<168	388
13u	**20.6**	**191**	**187**	**.43**	**.65**	**6.69**	**6.33**	**16.6**
14u	**9.84**	**93.1**	**122**	**3.45**	**13.2**	**3.02**	**2.72**	**10.7**
15u	1,000	10,900	37,700	338	338	33.8	<169	355
16u	**3.78**	**1.17**	**5.52**	**1.38**	**3.22**	**.46**	**.44**	**.17**
17u	1,020	10,300	43,300	338	507	<16.9	<169	321
18u	**30.2**	**205**	**218**	**.30**	**.50**	**22.7**	**21.8**	**21.3**
19u	1,110	10,700	38,700	338	507	67.6	<169	372
20u	1,130	9,940	33,300	338	508	67.6	<169	440
21u	1,140	10,500	50,600	341	511	34.1	<170	426
22u	**63.9**	**<16.9**	**20.3**	**20.2**	**25.3**	**.34**	**<1.69**	**2.70**
23u	1,180	8,990	39,000	516	516	68.8	<172	344
24u	1,290	11,200	34,900	520	694	104	<173	416
25u	1,290	9,010	33,200	524	524	105	<174	436
26u	**151**	**3,280**	**3,390**	**8.13**	**9.76**	**52.0**	**52.0**	**572**
27u	1,490	13,500	38,800	529	705	194	180	1,130
28u	**48.2**	**24.9**	**212**	**22.6**	**24.5**	**1.51**	**<1.88**	**3.20**
29u	1,550	13,200	37,900	534	712	196	<187	1,070
30u	**290**	**<20.0**	**20.0**	**20.0**	**24.0**	**30.0**	**30.0**	**3.60**
31u	1,580	13,300	41,400	540	720	198	191	1,120
32u	**439**	**<24.2**	**121**	**45.9**	**222**	**126**	**132**	**<2.42**
33u	1,790	13,000	39,400	548	913	274	276	1,110
34u	**37.2**	**<20.2**	**279**	**26.3**	**26.3**	**1.01**	**<2.02**	**2.43**
35u	1,860	12,800	48,200	554	923	295	280	1,160
36u	1,870	12,500	35,100	742	927	297	286	1,130

Table 7. Instantaneous loads in the upper study reach, Tenmile Creek, Montana, September 9, 1998 (Continued)

Copper load, total-recoverable (µg/s)	Iron load, dissolved (µg/s)	Iron load, total-recoverable (µg/s)	Lead load, dissolved (µg/s)	Lead load, total-recoverable (µg/s)	Manganese load, dissolved (µg/s)	Zinc load, dissolved (µg/s)	Zinc load, total recoverable (µg/s)	Site number (see fig. 2)
348	14,200	39,700	<145	145	<580	<2,900	<1,450	1u
364	13,700	40,600	160	160	<582	<2,910	<1,450	2u
379	14,200	38,200	<146	175	<583	<2,910	1,460	3u
27.8	**<232**	**2,100**	**<23.2**	**<23.2**	**<92.7**	**521**	**301**	**4u**
405	13,600	43,100	<169	304	<675	<3,380	2,030	5u
--	**<1.0**	**--**	**<.10**	**--**	**<.4**	**26.0**	**--**	**6u**
399	12,700	42,600	<166	266	<666	<3,330	1,830	7u
387	10,600	38,700	<168	185	<673	<3,360	2,020	8u
454	9,860	35,800	<168	286	<673	<3,360	2,190	9u
353	13,000	36,200	<168	168	<673	<3,360	2,190	10u
<.034	**12.2**	**40.8**	**<.34**	**<.34**	**5.44**	**19.2**	**19.2**	**11u**
404	13,100	37,200	<168	185	<674	<3,370	2,190	12u
17.7	**11.3**	**14.9**	**20.9**	**20.1**	**289**	**1,200**	**1,230**	**13u**
11.2	**45.9**	**135**	**4.49**	**8.42**	**238**	**413**	**390**	**14u**
405	15,900	47,300	<169	304	<676	3,880	3,210	15u
.45	**<1.15**	**16.8**	**<.11**	**.23**	**60.0**	**51.80**	**50.0**	**16u**
423	14,800	47,800	<169	270	<676	<3,380	3,550	17u
20.6	**2.33**	**10.0**	**5.50**	**6.70**	**197**	**3,860**	**3,900**	**18u**
490	17,300	52,500	186	405	842	15,500	14,000	19u
457	17,400	49,700	186	423	1,020	16,200	14,700	20u
443	16,600	50,400	170	579	990	12,900	14,500	21u
3.71	**147**	**219**	**4.89**	**11.3**	**29.1**	**201**	**229**	**22u**
482	12,300	44,200	<172	533	1,000	12,400	14,400	23u
520	17,400	45,400	<173	624	3,570	29,300	31,200	24u
489	15,100	40,200	192	471	2,940	28,100	30,000	25u
582	**551**	**566**	**148**	**151**	**2,890**	**6,470**	**6,850**	**26u**
1,300	15,300	42,600	264	828	7,260	40,200	39,600	27u
3.39	**27.8**	**156**	**<1.88**	**<1.88**	**<7.53**	**2,460**	**2,370**	**28u**
1,340	16,900	47,500	196	748	6,870	40,800	42,900	29u
4.80	**<20.0**	**<20.0**	**<2.00**	**<2.00**	**<8.00**	**9,350**	**8,700**	**30u**
1,310	14,000	48,800	180	774	6,800	42,320	44,100	31u
64.3	**2,390**	**15,300**	**<2.42**	**<2.42**	**11,240**	**24,000**	**24,770**	**32u**
1,370	19,700	59,300	237	803	13,790	60,600	56,900	33u
2.83	**<20.2**	**166**	**<2.02**	**<2.02**	**<8.10**	**1,060**	**1,070**	**34u**
1,440	16,900	55,500	240	812	13,890	61,600	59,800	35u
1,340	16,200	53,600	241	705	13,330	62,700	59,900	36u

Table 8. Instantaneous loads in the lower study reach, Tenmile Creek, Montana, September 6, 1998

[Data in **bold print** are loads from surface inflows. Abbreviations: µg/s, micrograms per second; mg/s, milligrams per second. Symbols: <, load is less than the value and was calculated using a minimum reporting level for each constituent; --, no data]

Site number (see fig. 3)	Sulfate load, dissolved (mg/s)	Aluminum load, dissolved (µg/s)	Aluminum load, total recoverable (µg/s)	Arsenic load, dissolved (µg/s)	Arsenic load, total-recoverable (µg/s)	Cadmium load, dissolved (µg/s)	Cadmium load, total-recoverable (µg/s)	Copper load, dissolved (µg/s)
1	49.6	331	1,300	25.1	35.1	7.03	7.03	24.6
2	55.9	271	985	35.2	45.2	6.53	7.03	26.6
3	**1.06**	**1.03**	**9.58**	**1.03**	**1.24**	**.05**	**<.07**	**.17**
4	51.8	239	896	40.8	61.1	6.62	6.62	27.0
5	92.8	276	1,185	40.9	51.1	6.13	6.13	25.0
6	**.43**	**.44**	**--**	**7.69**	**--**	**<.01**	**--**	**.13**
7	214	399	1,100	59.6	71.5	14.9	14.9	30.4
9	364	141	4,780	12.3	104	55.8	57.7	53.4
10	**.88**	**<.07**	**.20**	**.26**	**.28**	**.03**	**.03**	**.09**
11	381	1,800	9,400	6.14	123	129	122	245
12	389	1,820	8,910	<6.15	117	141	135	276
13	422	1,060	8,430	<6.20	118	143	136	236
14	421	1,030	7,880	<6.25	112	150	144	231
15	**326**	**1,000**	**972**	**731**	**1,110**	**105**	**96.0**	**56.0**
16	599	3,090	9,040	710	1,480	284	271	349
17	**15.3**	**29.0**	**135**	**10.1**	**11.3**	**1.51**	**1.51**	**8.81**
18	646	455	8,490	363	1,040	224	216	208
19	689	210	6,740	226	839	210	210	151
20	686	238	7,470	312	903	213	205	164
21	862	173	6,910	128	775	228	228	149
22	995	<95.2	5,910	38.1	676	219	209	114
23	**73.1**	**<21.9**	**574**	**4.64**	**55.7**	**8.62**	**10.6**	**4.84**
24	1,150	<102	5,480	40.7	662	193	183	89.6
25	1,130	<105	6,210	21.0	767	210	210	68.3
26	1,110	<106	5,080	21.2	656	201	190	58.2
27	**348**	**<40.7**	**110**	**118**	**155**	**4.07**	**4.07**	**4.48**
28	1,420	<147	3,620	58.6	557	220	205	63.0
29	1,560	228	2,220	114	408	179	179	70.1
30	**19.5**	**<6.00**	**19.8**	**14.4**	**22.2**	**<.06**	**<.60**	**<.60**
31	1,480	<169	2,740	118	575	186	169	67.6
32	1,470	<174	2,280	174	400	170	155	69.6
33	1,460	195	1,650	195	442	149	140	69.0
34	1,460	<179	1,520	251	412	134	125	64.4
35	1,440	233	1,450	268	394	111	114	59.1
36	1,410	<180	1,370	270	414	112	108	55.8
37	1,150	253	1,160	308	452	107	105	65.2
38	**67.6**	**74.8**	**466**	**13.2**	**13.2**	**6.60**	**4.40**	**18.0**
39	1,420	<225	1,730	338	405	108	119	74.2
40	1,370	294	1,580	316	452	111	113	79.1
41	1,420	<235	1,430	400	470	118	115	79.9
42	1,460	<240	1,060	384	552	115	118	88.8
43	**19.0**	**<21.0**	**311**	**2.10**	**2.10**	**<.21**	**<2.10**	**<2.10**
44	1,340	<261	1,250	392	470	117	110	86.1
45	1,410	<274	1,781	493	575	101	112	76.7
46	1,480	<285	798	542	570	91.2	99.8	88.4
47	1,480	<297	1,010	564	594	95.0	98.0	92.1
48	**88.8**	**45.8**	**116**	**156**	**207**	**.61**	**<3.05**	**<3.05**
49	**133**	**<30.5**	**70.2**	**27.4**	**42.7**	**2.44**	**<3.05**	**7.32**
50	1,600	<358	967	680	788	114	107	111
51	1,670	<381	648	876	914	99.1	91.4	99.1
52	**9.70**	**<10.0**	**275**	**20.0**	**22.0**	**<.10**	**<1.0**	**1.10**
53	1,700	391	743	978	1,060	62.6	66.5	113
62	1,550	<429	772	1,160	1,030	42.9	42.9	107
70	1,340	<382	688	956	918	30.6	<38.2	80.3
74	1,350	<375	712	863	900	45.0	37.5	105
78	1,120	<309	463	741	710	34.0	34.0	71.0
81	1,150	<320	448	768	736	28.8	32.0	73.6
83	697	<197	276	453	473	17.7	19.7	49.2

Table 8. Instantaneous loads in the lower study reach, Tenmile Creek, Montana, September 6, 1998 (Continued)

Copper load, total-recoverable (µg/s)	Iron load, dissolved (µg/s)	Iron load, total-recoverable (µg/s)	Lead load, dissolved (µg/s)	Lead load, total-recoverable (µg/s)	Manganese load, dissolved (µg/s)	Zinc load, dissolved (µg/s)	Zinc load, total-recoverable (µg/s)	Site number (see fig. 3)
33.6	381	1,440	5.02	22.1	331	1,480	1,580	1
32.2	377	1,200	6.53	21.6	236	1,350	1,480	2
.24	**.76**	**10.1**	**<.07**	**<.41**	**.28**	**16.8**	**17.2**	**3**
36.2	250	1,360	<5.09	56.0	199	1,240	1,400	4
33.2	342	1,170	<5.11	34.7	179	1,200	1,310	5
--	**3.19**	**--**	**.02**	**--**	**.61**	**<.30**	**--**	**6**
42.3	280	876	34.6	95.4	489	2,480	2,540	7
110	221	6,200	11.0	215	2,800	7,640	7,980	9
.16	**.07**	**<.43**	**<.01**	**.01**	**3.39**	**15.1**	**15.9**	**10**
295	651	11,700	73.7	215	5,950	15,800	15,700	11
326	922	9,830	104	215	6,020	16,600	17,000	12
298	1,000	9,050	99.2	217	5,640	16,700	17,400	13
288	982	850	125	238	5,670	19,100	18,600	14
53.6	**29,400**	**30,300**	**.62**	**1.46**	**3,770**	**10,300**	**10,000**	**15**
362	39,000	49,500	148	239	10,800	32,700	34,600	16
11.1	**15.1**	**55.4**	**<1.26**	**<1.26**	**<5.04**	**103**	**120**	**17**
309	27,700	39,800	20.8	208	8,410	26,100	26,200	18
268	20,700	32,200	8.40	168	7,770	26,200	25,600	19
296	23,100	34,300	<9.03	164	7,940	25,200	24,700	20
292	17,300	31,900	<9.12	164	7,960	26,700	27,200	21
257	9,220	24,400	<9.52	133	7,330	30,600	30,900	22
21.9	**<6.63**	**1,090**	**<.66**	**15.9**	**340**	**1,090**	**1,380**	**23**
244	7,150	20,400	<10.2	142	6,190	29,400	31,000	24
252	3,490	21,600	<10.5	168	6,790	32,500	35,700	25
222	1,930	17,700	<10.6	116	6,230	30,200	30,800	26
7.32	**1,310**	**102**	**<4.07**	**<4.07**	**81.4**	**1,250**	**1,250**	**27**
190	484	12,800	<14.6	98.2	6,300	33,800	34,000	28
150	<163	7,350	<16.3	53.8	5,250	30,000	31,400	29
<.60	**34.8**	**180**	**<.60**	**1.08**	**56.4**	**<12.0**	**8.40**	**30**
155	254	8,990	<16.9	103	5,050	30,600	31,100	31
113	<174	5,360	<17.4	40.0	4,160	27,800	27,700	32
112	<177	4,710	<17.7	26.6	3,470	24,600	24,800	33
100	<179	3,760	<17.9	26.9	2,690	20,900	21,800	34
100	<179	3,440	<17.9	30.4	2,340	20,000	20,000	35
97.2	<180	3,310	<18.0	27.0	2,210	20,700	19,100	36
88.7	<181	2,730	<18.1	27.2	1,790	19,200	18,600	37
21.6	**57.2**	**312**	**<4.40**	**<4.40**	**<17.6**	**1,080**	**1,070**	**38**
112	<225	2,610	<22.5	29.3	1,710	20,200	19,100	39
113	<226	2,890	<22.6	<22.6	1,600	20,200	19,700	40
110	<235	1,970	<23.5	25.9	1,080	20,000	19,500	41
108	<240	2,040	<24.0	24.0	1,080	21,000	21,500	42
<2.10	**<21.0**	**200**	**<2.10**	**<2.10**	**<8.40**	**<42.0**	**<21.0**	**43**
117	<261	2,270	<26.1	<26.1	992	20,400	21,700	44
126	<274	2,490	<27.4	73.1	795	19,600	19,600	45
105	<285	1,650	<28.5	<28.5	513	17,000	18,700	46
116	<297	1,810	<29.7	38.6	446	18,100	18,800	47
5.18	**11,200**	**15,100**	**<3.05**	**12.2**	**2,870**	**216**	**229**	**48**
8.24	**<30.5**	**253**	**<3.05**	**9.46**	**36.6**	**381**	**436**	**49**
132	716	2,610	<35.8	<35.8	716	19,400	20,800	50
130	1,030	3,050	<38.1	<38.1	914	17,400	17,500	51
2.10	**<10**	**181**	**<1.0**	**1.90**	**<4.00**	**<20.0**	**<10.0**	**52**
152	978	3,130	<39.1	<39.1	782	10,200	10,600	53
133	<429	1,590	<42.9	<42.9	<172	7,080	7,380	62
118	<382	1,680	<38.2	<38.2	157	4,630	5,160	70
105	<375	1,420	<37.5	<37.5	188	6,110	6,680	74
102	<309	802	<30.9	<30.9	148	5,900	5,710	78
99.2	<320	608	<32.0	<32.0	154	4,930	5,220	81
55.2	<197	414	<19.7	<19.7	110	2,960	3,250	83

Table 9. Water-quality data for selected tributaries in the lower study reach, Tenmile Creek, Montana, September 4, 1998

[Data are for sites where water is diverted for municipal supply. Abbreviations: L/s, liter per second; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius. Symbol: <, less than minimum reporting level]

Station name	Streamflow, instantaneous (L/s)	pH (standard units)	Specific conductance (µS/cm)	Arsenic, dissolved (µg/L as As)	Arsenic, total recoverable (µg/L as As)	Cadmium, dissolved (µg/L as Cd)	Cadmium, total-recoverable (µg/L as Cd)	Copper, dissolved (µg/L as Cu)
Beaver Creek above City Diversion, near Rimini	124	7.5	51	3	6	<1	<1	70
Minnehaha Creek above City Diversion, near Rimini	14.5	7.7	71	2	3	1.5	1	4.4
Moose Creek above City Diversion, near Rimini	9.03	8.0	172	<1	<1	<1	<1	<1.0
Walker Creek above City Diversion, near Rimini	5.08	8.0	186	1	1	<1	<1	1.2

Station name	Copper, total-recoverable (µg/L as Cu)	Iron, dissolved (µg/L as Fe)	Iron, total-recoverable (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Lead, total-recoverable (µg/L as Pb)	Manganese, dissolved (µg/L as Mn)	Zinc, dissovled (µg/L as Zn)	Zinc, total-recoverable (µg/L as Zn)
Beaver Creek above City Diversion, near Rimini	140	200	1,100	<1	<1	77	20	41
Minnehaha Creek above City Diversion, near Rimini	6	11	90	<1	<1	<4	237	240
Moose Creek above City Diversion, near Rimini	<1	110	290	<1	<1	<3	<20	<10
Walker Creek above City Diversion, near Rimini	2	61	290	<1	<1	11	<20	<10

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