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Quantification of Trace-Element Loading in the Upper Tenmile Creek Drainage Basin near Rimini, Montana, September 2011

Scientific Investigations Report 2019–5126

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

Cover photo. The Susie Lode adit discharge entering Tenmile Creek near Rimini, Montana. Photograph by Craig L. Bowers, U.S. Geological Survey, September 16, 2011.

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By Tom Cleasby and Sara L. Caldwell Eldridge

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Volume	
cubic meter (m^3)	6.290	barrel (petroleum, 1 barrel = 42 gal)
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
	Flow rate	
liter per second (L/s)	15.85	gallon per minute (gal/min)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8.$$

Datum

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Water-Year Definition

Water year is the 12-month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2011 is the period from October 1, 2010, through September 30, 2011.

Abbreviations

LRL	laboratory reporting level
NWIS	National Water Information System (U.S. Geological Survey database)
NWQL	National Water Quality Laboratory
RPD	relative percent difference
SCUFA	self-contained underwater fluorescence apparatus
USGS	U.S. Geological Survey

Quantification of Trace-Element Loading in the Upper Tenmile Creek Drainage Basin near Rimini, Montana, September 2011

By Tom Cleasby and Sara L. Caldwell Eldridge

Abstract

The principle sources of trace elements entering upper Tenmile Creek, Montana, during September 2011, four trace metals and the metalloid arsenic, were identified and quantified by combining and analyzing streamflow data determined from tracer injection with trace-element concentrations and related water-quality data determined from synoptic sampling. The study reach was along upper Tenmile Creek, beginning downstream from the city of Helena's diversion and extending 5,020 feet downstream. Results from the 2011 study, completed by the U.S. Geological Survey in cooperation with the Montana Department of Environmental Quality, were compared to results from a similar study conducted in 1998 to assess the effectiveness of mine reclamation and remediation work to reduce trace-element loading to upper Tenmile Creek, which has been ongoing throughout the drainage basin.

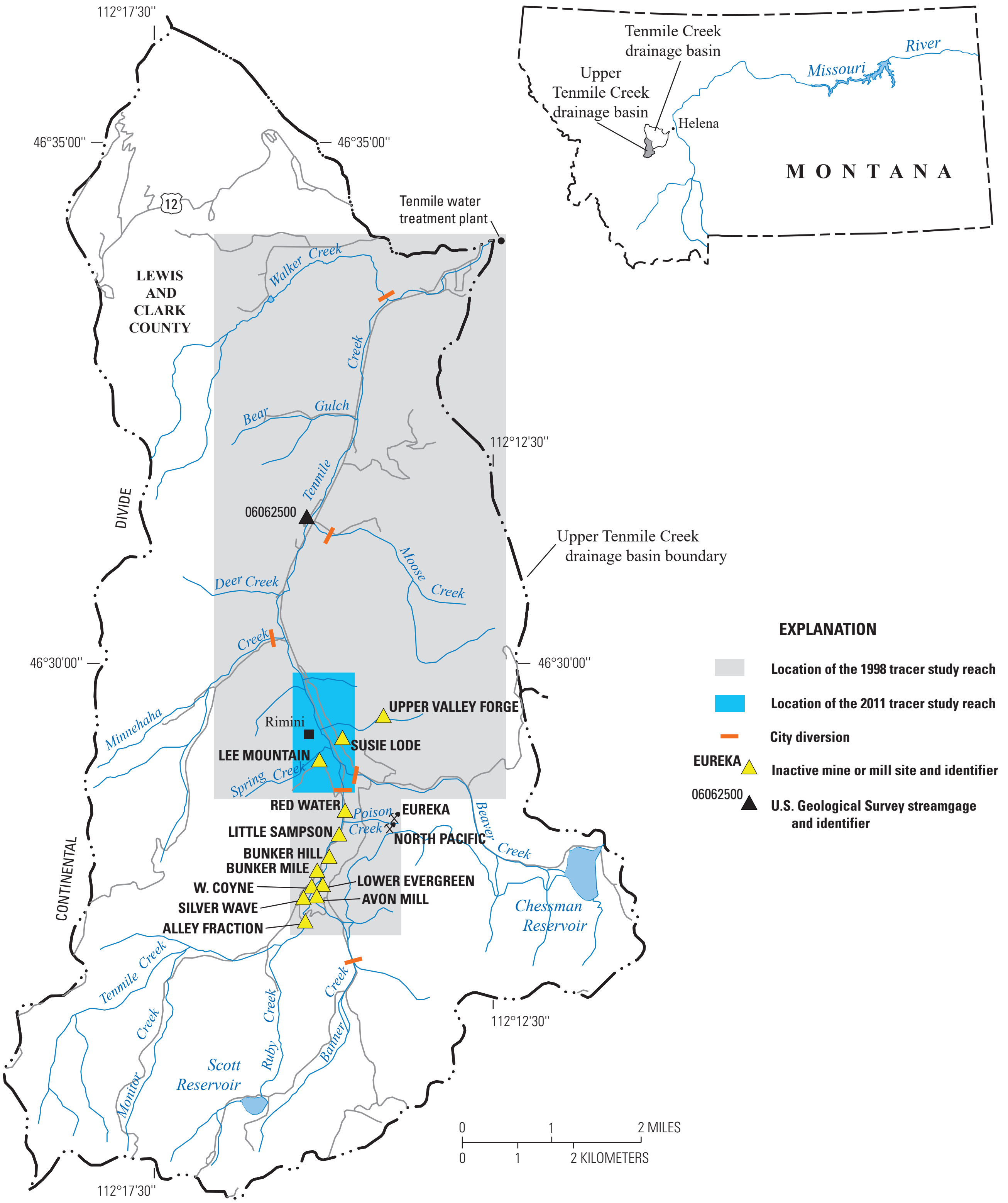
Main-stem concentrations of most trace elements analyzed were generally greater in 1998 than in 2011. However, the State of Montana human-health criteria for total-recoverable cadmium and arsenic were exceeded in parts of upper Tenmile Creek, and concentrations of cadmium and zinc exceeded the acute aquatic-life criteria at all main-stem sites during both studies. Total-recoverable copper concentrations observed in 2011 exceeded the chronic aquatic-life criterion upstream from the Lee Mountain adit, whereas, in 1998, all sites exceeded the acute aquatic-life criteria.

Direct comparison of loads from the 1998 and 2011 tracer studies were complicated by the differences in hydrologic conditions. Streamflow in 1998 was about 10 percent of the 2011 streamflow. The Lee Mountain Mine and Susie Lode adit were identified as major contributors of trace elements to upper Tenmile Creek in both studies. However, trace-element loading from the Lee Mountain Mine area was substantially reduced between 1998 and 2011. Total-recoverable loads of all trace elements showed substantial loss in 1998 but increased in 2011 downstream from the Susie Lode adit to the end of the study reach. This reach was one of the primary sources of trace-element loading to upper Tenmile Creek in 2011. This difference indicated that the streambed may act as a sink or a source for trace elements, depending on hydrologic conditions.

Introduction

The upper Tenmile Creek drainage basin in west-central Montana (defined in this report as that part of the Tenmile Creek basin upstream from the Tenmile Water Treatment plant), 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). Tailings and other artifacts from more than 100 years of mining are scattered throughout the drainage basin (Metesh and others, 1998). Many of these mining artifacts are sources of trace-element (trace metals; primarily cadmium, copper, lead, iron, zinc, and the metalloid arsenic) loads to upper Tenmile Creek (Cleasby and Nimick, 2002). In 1998, a trace-element loading study was conducted by the U.S. Geological Survey (USGS) using tracer techniques and synoptic water-quality samples in a 9.8-mile reach of upper Tenmile Creek near Rimini, Montana (fig. 1). Study results identified and quantified several substantial trace-element loading sources to upper Tenmile Creek in the nearly 1-mile subreach that flowed through the town of Rimini (Cleasby and Nimick, 2002). In 1999, the U.S. Environmental Protection Agency designated upper Tenmile Creek as a Federal superfund site (U.S. Environmental Protection Agency, 2002). Since the superfund designation, extensive remediation work has been completed throughout the drainage basin with the goal of reducing trace-element loading to upper Tenmile Creek. Remediation work within the stream reach sampled for this study included the removal of more than 50,000 cubic yards of contaminated mine waste from the Lee Mountain Mine and the Susie Lode and the removal of contaminated soils in residential properties and roads in the town of Rimini. The adit portals (a horizontal passage leading into a mine for access or drainage) for the Lee Mountain Mine and the Susie Lode have been opened and rehabilitated, and pilot scale treatment options have been explored.

The USGS, in cooperation with the Montana Department of Environmental Quality, initiated a study in 2011 to quantify trace-element loading in the upper Tenmile Creek drainage basin to help assess the effectiveness of mine reclamation and remediation work to reduce trace-element loading to



Base modified from U.S. Geological Survey digital data, 1:24,000, 1961–89 (streams);
U.S. Census Bureau digital data, 1:100,000, 1992 (roads)
Albers Equal Area Conic projection
Standard, parallels 46°00' N. and 48°00' N.
Central meridian 109° 30' W.
North American Datum of 1927

Figure 1. Locations of the study reaches, upper Tenmile Creek, Montana, 1998 and 2011.

upper Tenmile Creek. The 2011 study was performed using tracer injection and synoptic water-quality sample collection methods similar to the 1998 study within the approximately 1-mile subreach where the 1998 study identified substantial trace-element loading sources (fig. 2). Data collected in the 2011 study were used to estimate trace-element loadings from various sources in this subreach of the upper Tenmile Creek drainage basin and were compared to results of the 1998 trace-element loading study. The two principal objectives of this study were (1) to identify and quantify the primary sources of trace-element loads entering a 5,020-foot reach of upper Tenmile Creek and (2) to compare the 2011 results (current study) with results from the trace-element loading study conducted in 1998 to describe changes in the sources and overall transport of trace-element loads in upper Tenmile Creek after reclamation activity.

Purpose and Scope

The purposes of this report are to present the results of a trace-element study completed in September 2011 in the upper Tenmile Creek drainage basin and to provide a comparison of the 2011 results with results from a previous trace-element loading study conducted in 1998. Physical and chemical data collected at 19 upper Tenmile Creek main-stem sites, 8 surface-water inflow sites, and 8 groundwater sites during September 13–14, 2011, are presented to describe the loading and downstream transport of trace elements in the study reach of upper Tenmile Creek. Quality-assurance data are presented for samples collected concurrently.

Study Area

Tenmile Creek originates on the eastern side of the Continental Divide and flows about 12 miles toward the Ten Mile Water Treatment Plant west of Helena, Mont. (fig. 1), draining about 200 square miles of mountain and valley terrain (Parrett and others, 2001). The reach of interest for this study starts just upstream from Rimini, Mont., about 5 miles downstream from the headwaters, and ends just downstream from Rimini. With a population of less than 100 people, the Rimini community consists primarily of single-family homes and cottages. Hard-rock mining for gold, lead, copper, and zinc took place from the 1870s through the 1930s, and some intermittent activity transpired until 1953 (U.S. Environmental Protection Agency, 2002). Remnants from the mining take form as acid-mine drainage from flowing adits, tailings, and waste-rock piles scattered throughout the drainage basin and are potential sources of trace-element contamination. Trace elements from some of these sources have been mobilized throughout the drainage basin by surface-water movement, wind erosion, and groundwater leaching. Also, contaminated material has been moved from source sites and used as fill along roads and other areas within the drainage basin (U.S. Environmental Protection Agency, 2002).

Since the classification of upper Tenmile Creek as a superfund site on October 22, 1999, remediation of mining sites within the study reach included the removal of waste rock from the Lee Mountain Mine adit and the Susie Lode adit. Both adits were opened, and experimental treatment of the acid-mine drainage water was attempted at each site.
At the Lee Mountain Mine, the adit discharge was treated with lime to increase the pH and precipitate the trace elements before entering upper Tenmile Creek. As part of the treatment system at the Lee Mountain Mine, the land surface was re-contoured to direct as much of the mine drainage into the treatment system as possible. Before remediation, the drainage from the mine was diffuse, and discharge from the adit percolated into the ground and, depending on flow paths, traveled a considerable distance before seeping into upper Tenmile Creek (Cleasby and Nimick, 2002). The passive lime treatment was discontinued because of the costly maintenance needed to replenish the lime and remove the precipitate from the settling ponds. An experimental treatment system at the Susie Lode adit operated for a short time. However, this was discontinued because the adit was deemed unstable, and the operation of the treatment system was unsafe. More recently, waste rock, tailings, and fill used for roads and landscaping previously suspected of being trace-element loading sources have been removed and replaced with clean fill material.

Methods

This study was designed to provide a snapshot of the loading and downstream transport of trace elements in the study reach. Tracer injection was used to determine streamflow, and synoptic water-quality sampling was used to determine concentrations of trace elements and other constituents.

A reconnaissance of the study reach was conducted 1 week before the start of the tracer injection. Sites to be sampled were selected, marked with flagging, and their locations were determined using a handheld global position system (table 1, fig. 2) receiver. When possible, sites that were sampled in the 1998 trace-element loading study were included in the current study. Sampling sites were selected on upper Tenmile Creek upstream and downstream from surface-water inflows, tailing piles, and other mining-related features, which might provide trace-element loadings to the creek. Eight groundwater monitoring wells were sampled near the Lee Mountain Mine to evaluate trace-element loading from groundwater to upper Tenmile Creek (table 2, fig. 3). Two wells were located on the right bank (looking downstream) and six were on the left bank, where most of the disturbances from the Lee Mountain Mine were located. Three of the wells on the left bank were preexisting and located to the north of (downstream from) the Lee Mountain Mine adit (LMLB–4, 5, and 6). These three wells were installed during reclamation that included the recontouring of the Lee Mountain Mine adjacent to the left bank of upper Tenmile Creek (fig. 3).

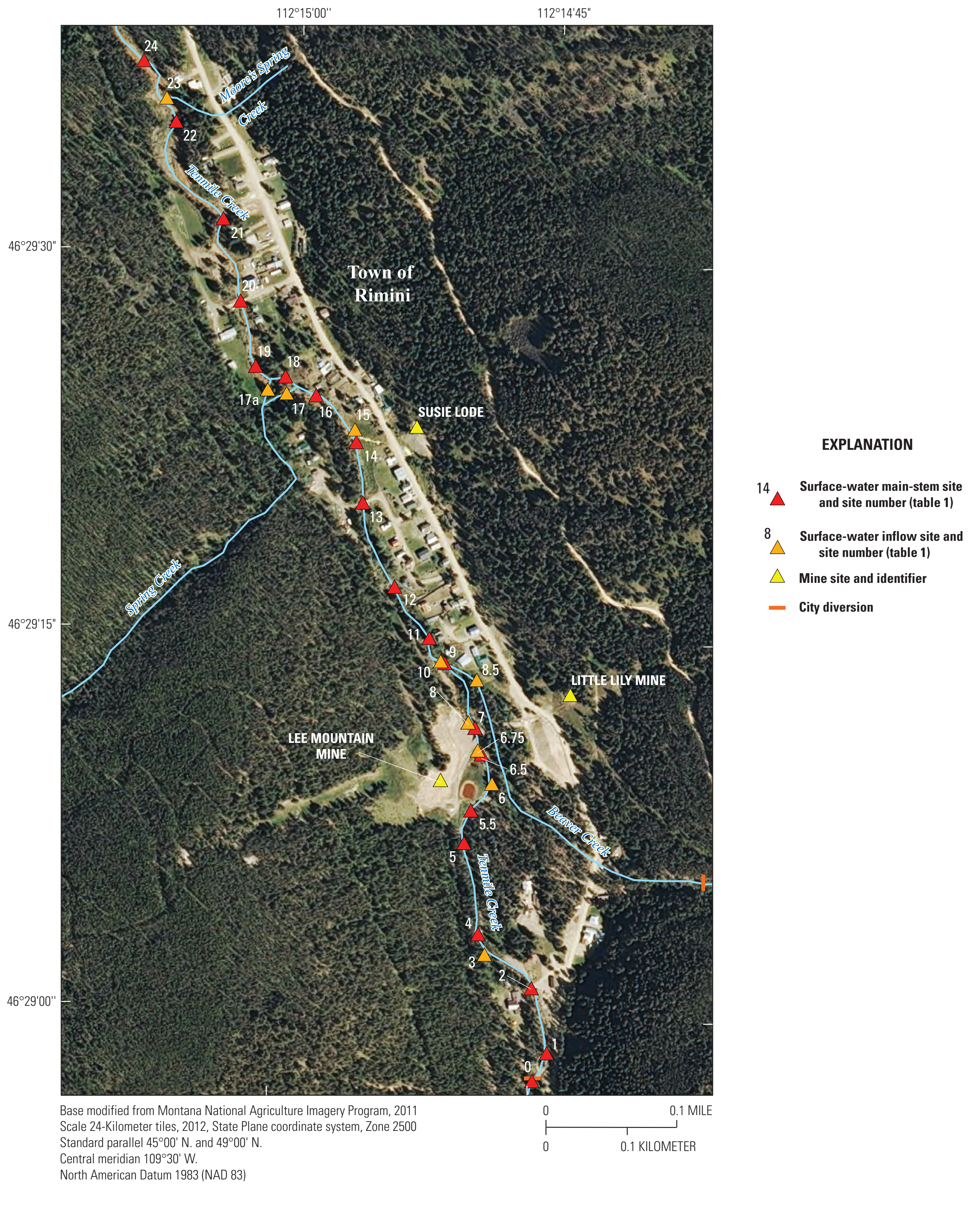


Figure 2. Locations of surface-water sites and selected mine sites, upper Tenmile Creek, Montana, 2011.

Table 1. Sampled surface-water sites, upper Tenmile Creek drainage basin, Montana, 2011.

[Surface-water inflow sites are **bold**. USGS, U.S. Geological Survey; ft, foot; ab, above; nr, near; bl, below; LB, left bank (looking downstream); RB, right bank (looking downstream); ---, number not assigned]

Site number[1] (fig. 2)	Station description	USGS station identification number	Distance downstream from injection site (ft)
0	Tenmile Creek ab City Diversion, nr Rimini, MT[2]	462853112144101	–50
1	Tenmile Creek bl City Diversion, at Rimini (injection site)	462902112144401	0
2	Tenmile Creek 365 ft bl City Diversion, at Rimini	462902112144101	365
3	**Tenmile LB seep 665 ft bl City Diversion, at Rimini**	**462903112144501**	**665**
4	Tenmile Creek 695 ft bl City Diversion at Rimini	462904112144501	695
5	Tenmile Creek 1,115 ft bl City Diversion, at Rimini	462907112144602	1,115
5.5	Tenmile Creek 1,215 ft bl City Diversion, at Rimini	462909112144501	1,215
6	**Tenmile RB discharge pipe 1,245 ft bl City Diversion**	**462910112144501**	**1,245**
6.5	Tenmile Creek 1,350 ft bl City Diversion, at Rimini	462911112144502	1,350
6.75	**Lee Mountain Mine adit discharge, at Rimini**	**462911112144601**	**1,400**
7	Tenmile Creek 1,780 ft bl City Diversion, at Rimini	462912112144601	1,780
8	**LB seep from Lee Mountain Mine[2]**	**---**	**1,800**
8.5	**Tenmile Creek RB seep 1,970 bl City Diversion, at Rimini**	**462914112144702**	**1,970**
9	Tenmile Creek 1,985 ft bl City Diversion, at Rimini	462914112144703	1,985
10	**Beaver Creek at mouth, at Rimini**	**462914112144801**	**2,000**
11	Tenmile Creek 2,120 ft bl City Diversion, at Rimini	462915112144801	2,120
12	Tenmile Creek 2,420 ft bl City Diversion, at Rimini	462917112145001	2,420
13	Tenmile Creek ab Susie Lode Adit, at Rimini	462920112145501	2,765
14	Tenmile Creek 3,015 ft bl City Diversion, at Rimini	462922112145301	3,015
15	**Susie Lode Adit discharge at mouth, at Rimini**	**462923112145301**	**3,040**
16	Tenmile Creek 3,250 ft bl City Diversion, at Rimini	462925112145501	3,250
17	**Spring Creek at Mouth, at Rimini**	**462921112145701**	**3,305**
18	Tenmile Creek 3,415 ft bl City Diversion, at Rimini	462925112145701	3,415
17a	**Spring Creek Fork[2]**	**---**	**3,500**
19	Tenmile Creek 3,575 ft bl City Diversion, at Rimini	462926112145801	3,575
20	Tenmile Creek 3,850 ft bl Spring Creek, at Rimini	462922112145401	3,850
21	Tenmile Creek 4,180 ft bl City Diversion, at Rimini	462932112150101	4,180
22	Tenmile Creek 4,675 ft bl City Diversion, at Rimini	462935112150401	4,675
23	**Moore's Spring Creek at mouth, at Rimini**	**462932112145801**	**4,890**
24	Tenmile Creek 5,020 ft bl City Diversion, at Rimini	462937112150501	5,020

[1]Sites identified as whole numbers were sampled in 1998 and 2011. Sites 5.5, 6.5, and 6.75 were only sampled in 2011. Site 17a is a fork of Spring Creek and was not sampled. Streamflow at 17a was combined with site 17 streamflow for load calculations.

[2]Not sampled in 2011.

The preexisting wells were constructed of 4-inch diameter polyvinyl chloride casing and were perforated along their entire length. Five wells, LMRB–1, LMRB–2, LMLB–1, LMLB–2, and LMLB–3, were hand-driven near upper Tenmile Creek (fig. 3). The large boulder substrate in the area constrained the locations of the hand-driven wells, and several attempts were made before the final wells were successfully installed. The new wells were constructed with 1.25-inch diameter galvanized pipe with perforations over the lower 0.1-foot of the pipe (just above the drive point). The six wells on the left bank were located downgradient from the Lee Mountain Mine adit.

Table 2. Sampled groundwater sites, upper Tenmile Creek drainage basin, Montana, 2011.

[USGS, U.S. Geological Society; ft, foot; in., inch; PVC, polyvinyl chloride]

Site number[1] (fig. 3)	USGS station identification number	Distance downstream from injection site (ft)	Well depth (ft)	Open interval top (ft)	Water level (ft)	Remarks
			Right stream bank wells[1]			
LMRB–1	462907112144601	1,115	3.9	3.7	2.20	85 ft from Tenmile Creek, 380 ft upstream from bridge, 1.25-in. diameter galvanized casing.
LMRB–2	462911112144501	1,700	5.3	5.1	1.12	50 ft from Tenmile Creek, 20 ft upstream from bridge, 1.25-in. diameter galvanized casing.
			Left stream bank wells[1]			
LMLB–1	462908112144601	1,145	9.5	9.3	6.89	10 ft from Tenmile Creek 380 ft upstream from bridge, 1.25-in. diameter galvanized casing.
LMLB–2	462909112144701	1,400	9.4	0	3.56	Near adit, 80 ft from Tenmile Creek, 220 ft upstream from bridge, 4-in. diameter PVC casing.
LMLB–3	462910112144601	1,600	13.3	0	8.04	135 ft from Tenmile Creek, 150 ft upstream from bridge, 4-in. diameter PVC casing.
LMLB–4	462913112144801	2,000	9.5	0	0.65	50 ft from Tenmile Creek, 200 ft downstream from bridge, located in shallow pit, 4-in. diameter PVC casing.
LMLB–5	462913112144701	2,000	4.3	4.1	0.51	Near Tenmile Creek, 200 ft downstream from bridge, 1.25-in. diameter galvanized casing.
LMLB–6	462914112144701	2,100	4.9	4.7	0.90	Near Tenmile Creek, 250 ft downstream from bridge, 1.25-in. diameter galvanized casing.

[1]Left-bank and right-bank designations refer to Tenmile Creek.

Figure 3. Locations of groundwater sites and selected mine sites, upper Tenmile Creek, Montana, 2011.

Streamflow Estimation

Streamflow can be determined using tracer injection and dilution. Streamflow measurements by tracer injection are recommended only for those sites where conventional methods cannot be accurately applied owing to shallow depths, extremely high velocities, excessive turbulence, or excessive hyporheic flow (Kilpatrick and Cobb, 1984). These conditions were present within the study reach of upper Tenmile Creek. Streamflow cannot be determined using tracer injection and dilution in a losing stream reach because the tracer concentration would remain constant through flow decreases. Tracer injection using Rhodamine WT dye as the tracer (Kilpatrick and Cobb, 1984; Wilson and others, 1986; Kimball, 1997; Cleasby and others, 2000; Cleasby and Nimick, 2002) was used to calculate streamflow. The tracer-injection rate, a tracer-solution dilution factor, and instream concentrations of the tracer at equilibrium were required to calculate streamflow at any location downstream from the injection point.

A tracer solution was prepared in a 50-gallon barrel by mixing 0.5-liters of Rhodamine WT dye (stock solution 2.0×10^{8} micrograms per liter [µg/L]) with about 140 liters of stream water before the tracer injection. Starting at 7:10 a.m. on September 13, 2011, and ending at 12:30 p.m. on September 14, 2011, this solution was injected continuously into upper Tenmile Creek surface-water sites at a rate of 92 milliliters per minute (0.00153 liters per second [L/s]) using a positive-displacement metering pump system. During the injection, three samples were collected from the premixed tracer solution to document the relative dye concentration in the injected tracer solution. These samples were collected in glass bottles and stored out of direct sunlight in a dark cooler. Samples were transported to the USGS Wyoming-Montana Water Science Center (Helena, Mont.), where they were diluted serially using de-ionized water. The diluted tracer samples were then analyzed with the stream samples using a Turner Design 10A bench fluorometer.

Throughout synoptic sampling and the tracer injections, instream dye concentrations were monitored continuously at two sites (7 and 24, fig. 2) downstream from the injection point to document the movement and equilibrium concentrations of the injected dye. At each tracer monitoring site, a calibrated self-contained underwater fluorescence apparatus (SCUFA) was placed near the centroid of streamflow. SCUFAs were programmed to measure and log dye concentrations every 10 minutes.

Additional streamflow measurements were made at selected upper Tenmile Creek sites and at all surface-water inflow sites using either traditional current-meter measurements (Rantz and others, 1982) or volumetric measurements using a calibrated collection container and stopwatch as described in Buchanan and Somers (1969).

For a continuous tracer injection to yield accurate results, the mass of the tracer must be conserved as it moves downstream. The duration of the injection must be enough to allow tracer concentrations to achieve an equilibrium or plateau throughout the entire study reach. Also, the reach length must be enough for complete lateral mixing of the dye. Once equilibrium plateau concentrations have been achieved through the entire reach, streamflow at any site downstream from the injection point can be calculated from the conservation of mass equation (eq. 1):

$$qC=Qc \tag{1}$$

where

- q is the tracer-injection rate, in liters per second, and is assumed to be very small relative to Q;
- C is the concentration of the injected tracer solution, in milligrams per liter. This is assumed to be large relative to c;
- Q is the streamflow, in liters per second; and
- c is the resulting plateau concentration of the tracer in the stream after dilution by Q in milligrams per liter.

Concentrations of C and c in equation 1 can be measured in any consistent concentration unit because C/c is a ratio (the units cancel out). To evaluate the relative concentrations of C and c, an injectate sample was retained from the mixed tracer solution. A three-step serial dilution was performed on the sample of the injectate tracer solution (C) by dilution to concentrations about equal to what was expected in the stream (c). The diluted injectate sample was analyzed at the same time as the stream sample, using the same fluorometer, and in the same laboratory conditions as the stream samples to cancel or minimize errors. This relative comparison method prevented errors, given that the concentration of the injectate solution was not known precisely. The relative ratio of fluorometer dial readings for the diluted injectate sample compared to the stream samples were used to calculate streamflow using equation 2:

$$Q=q\left(\frac{R}{r} \text{ x } \frac{1}{D}\right) \tag{2}$$

where

- Q is streamflow, in liters per second;
- q is the tracer-injection rate, in liters per second;
- R is the net fluorometer dial reading of the diluted injectate sample;
- r is the net fluorometer dial reading of the stream samples; and
- D is the dilution of the injectate sample.

The three-step serial dilution was conducted by diluting the injectate tracer solution by a factor of $2.052\text{x}10^{-5}$. The diluted sample was then analyzed simultaneously with the stream samples using the same fluorometer settings. The net fluorometer dial reading for the diluted injectate sample was 15.9.

Surface-Water-Quality Sampling

Synoptic water-quality samples were collected at 19 main-stem sites in upper Tenmile Creek and at 8 surface-water inflow sites on September 14, 2011, between 8:00 a.m. and 11:15 a.m. after the dye reached an equilibrium plateau as determined by the deployed SCUFAs. Two sampling crews collected water samples in an upstream direction. One crew started from the center of the study reach and worked toward the top of the study reach, and the other crew started at the bottom of the study reach and worked toward the middle of the study reach. Dip samples were collected at each site by dipping sample bottles at a single vertical near the centroid of streamflow (U.S. Geological Survey, 2006). Samples were processed, filtered, and preserved as described in Ward and Harr (1990), Horowitz and others (1994), and U.S. Geological Survey (variously dated). Quality assurance for processing water-quality samples was performed as described by U.S. Geological Survey (variously dated) and Lambing (2006). Onsite measurements of pH, specific conductance, and water temperature were made during collection of water samples according to the U.S. Geological Survey (variously dated). Onsite sample processing, including filtration and preservation, was completed according to procedures described by Ward and Harr (1990), Horowitz and others (1994), and the U.S. Geological Survey (variously dated).Water samples were analyzed for calcium, magnesium, and selected trace-element concentrations at the USGS National Water Quality Laboratory (NWQL) in Denver, Colorado, using methods described by Fishman (1993), Garbarino and Struzeski (1998), Hoffman and others (1996), and Garbarino and others (2006). Tracer concentrations were determined at the USGS laboratory in Helena, Mont., using a Turner Design 10A bench fluorometer following methods described in Wilson and others (1986).

Groundwater Sampling

Groundwater levels in each well were measured according to Cunningham and Schalk (2011) before sampling, and adjacent stream levels were marked for follow-up elevation surveys to document the gradient between groundwater and surface water at the time of sampling. The elevation of the wells and marked stream levels were surveyed using standard-differential leveling methods (Kenney, 2010).

Groundwater samples were collected from eight shallow wells on September 13, 2011, 1 day before the surface-water samples were collected. Before sampling, wells with enough water were purged using a peristaltic pump by evacuating three casing volumes of water. Low-yielding wells were pumped dry and allowed to recover. Sampling was performed as described by U.S. Geological Survey (variously dated). Groundwater samples were analyzed for water temperature, specific conductance, and pH following methods by U.S. Geological Survey (variously dated). Groundwater samples were analyzed for dissolved concentrations of calcium, magnesium, and selected trace elements at the NWQL using methods described previously for surface-water samples.

Quality Assurance/Quality Control

Data collection and analytical procedures used in this study incorporated practices designed to control, verify, and assess bias and variability in data that resulted from the collection, processing, shipping, and handling of samples. Quality-assurance procedures used for the collection and field processing of water samples were as described by Ward and Harr (1990), Horowitz and others (1994), Edwards and Glysson (1999), Lambing (2006), and the U.S. Geological Survey (variously dated). Standard procedures used by the NWQL for internal sample handling and quality assurance were as described by Friedman and Erdmann (1982), Jones (1987), and Pritt and Raese (1995).

Analytical results reported for primary (environmental) water samples were evaluated using quality-control samples collected and analyzed concurrently with primary samples. These quality-control samples consisted of three sets of sequential replicate samples and one blank sample (inorganic blank water; de-ionized water that was laboratory produced and that carries a certificate of analyte concentrations for each grade and lot of water produced) to provide quantitative information on the precision and bias of the overall field and laboratory processes. The total number of quality-control samples represented about 10 percent of the total number of all samples.

Precision of analytical results is affected by numerous sources of potential variability within the field and laboratory environments, including sample collection, sample processing, and sample analysis. To assess this variability, sequential replicate samples were collected and processed immediately after collecting the primary samples from the same site and were subjected to identical laboratory analyses as the primary samples. The relative percent differences (RPD) between the primary (*sample* 1) and replicate (*sample* 2) samples were calculated using equation 3:

$$RPD=|(sample\ 1-sample\ 2)/|(sample\ 1+sample\ 2)/2|\ |*100$$

Two surface-water replicates and one groundwater replicate were collected. RPDs were calculated for each constituent pair (31 total) and are reported in table 3. RPDs for most constituents were less than 20 percent and did not preclude the use of the data. Four out of 31 replicate pairs for filtered constituents showed RPDs greater than 20 percent, 3 of which occurred from 1 replicate pair. At surface-water site 24, the RPDs for dissolved copper, lead, and arsenic were 23.6 percent, 74.4 percent, and 67.3 percent, respectively. At groundwater site LMRB–1, the RPD for dissolved lead was 50.0 percent. All replicate pairs with RPDs exceeding 20 percent were re-analyzed, and the differences between sample concentrations were confirmed.

A field blank sample (inorganic blank water) was analyzed to identify the presence and magnitude of contamination that could bias analytical results. Field blanks were collected and processed in the same manner and using the same equipment as the environmental samples. A field blank with constituent

Table 3. Concentrations of water-quality constituents and the relative percent differences measured in primary and replicate samples from groundwater and surface-water sites in the upper Tenmile Creek drainage basin, Montana, September 2011.

[mg/L, milligram per liter; µg/L, microgram per liter]

Constituent	Primary sample	Replicate sample	Relative percent difference
Site LMRB–1[1]			
Calcium, dissolved, mg/L	9.59	9.65	0.62
Magnesium, dissolved, mg/L	2.29	2.27	0.88
Cadmium, dissolved, µg/L	1.04	1.03	0.97
Copper, dissolved, µg/L	2.1	2.1	0.00
Lead, dissolved, µg/L	0.20	0.12	50.00
Zinc, dissolved, µg/L	379	354	6.82
Arsenic, dissolved, µg/L	4.80	4.80	0.00
Site 6.75[1]			
Calcium, dissolved, mg/L	215	220	2.30
Magnesium, dissolved, mg/L	54.6	55.0	0.73
Cadmium, dissolved, µg/L	313	368	16.15
Cadmium, total-recoverable, µg/L	299	297	0.67
Copper, dissolved, µg/L	219	223	1.81
Copper, total-recoverable, µg/L	299	309	3.29
Lead, dissolved, µg/L	22.1	20.2	8.98
Lead, total-recoverable, µg/L	26.6	27.8	4.41
Zinc, dissolved, µg/L	67,900	64,500	5.14
Zinc, total-recoverable, µg/L	57,100	56,700	0.70
Arsenic, dissolved, µg/L	544	581	6.58
Arsenic, total-recoverable, µg/L	646	636	1.56
Site 24[1]			
Calcium, dissolved, mg/L	12.9	13.2	2.30
Magnesium, dissolved, mg/L	3.65	3.7	1.36
Cadmium, dissolved, µg/L	8.11	7.98	1.62
Cadmium, total-recoverable, µg/L	7.84	7.84	0.00
Copper, dissolved, µg/L	12.3	9.7	23.64
Copper, total-recoverable, µg/L	26.6	26.4	0.75
Lead, dissolved, µg/L	1.07	0.49	74.36
Lead, total-recoverable, µg/L	3.56	3.55	0.28
Zinc, dissolved, µg/L	1,410	1,260	11.24
Zinc, total-recoverable, µg/L	1,170	1,170	0.00
Arsenic, dissolved, µg/L	45.7	22.7	67.25
Arsenic, total-recoverable, µg/L	110	108	1.83

[1]Site numbers are defined on tables 1 and 2.

concentrations equal to or less than the laboratory reporting limit (LRL) for the analytical method indicates that the entire process of sample collection, field processing, and laboratory analysis is presumably free of contamination. In the 2011 study, one field blank sample was collected at surface-water site 13. Trace-element concentrations in this sample were less than the LRL except for total-recoverable arsenic (0.12 µg/L), which had an LRL of 0.10 µg/L. Because the arsenic concentration in the blank sample was near the LRL and was much less than the concentrations in all the environmental samples, it is assumed that no substantial bias was present in the environmental samples.

In addition to the use of quality-control samples submitted from the field, internal quality-assurance practices were performed systematically by the NWQL to provide quality control of analytical procedures in the laboratory (Pritt and Raese, 1995; Maloney, 2005). These internal practices include analyses of quality-control samples, such as calibration with standard samples, standard reference water samples, replicate samples, blank samples, or spiked samples at a proportion equivalent to at least 10 percent of the total number of collected samples. The NWQL participates in a blind sample program in which standard reference water samples prepared by the USGS Branch of Quality Systems are routinely inserted into the sample line for each analytical method at a frequency proportional to the number of collected samples (https://bqs.usgs.gov/). The laboratory also participates in external evaluation studies and audits with the National Environmental Laboratory Accreditation Program, U.S. Environmental Protection Agency, Environment Canada, and the USGS Branch of Quality Systems to assess analytical performance. Dissolved zinc at most sites in the current study exceeded the total-recoverable concentrations by as much as 20 percent. This anomaly may be due to matrix interference (a shift in analytical results caused by specific constituents, chemical components, or physicochemical properties in the matrix). The differences in the measured concentrations are usually within precision of the analytical methods. As such, it is assumed that most of the zinc is dissolved.

Quantification of Trace-Element Loading

Synoptic streamflow and concentrations of water-quality constituents are essential to develop a mass loading profile along a stream reach. Such a profile can reveal notable spatial differences in loads, identify the location of constituent sources, and indicate where geochemical reactions affect instream concentrations and loads. Load is the product of streamflow and constituent concentration, so accurate load estimations require accurate streamflow measurements. Using tracer injection to determine streamflow is a good alternative to traditional current-meter methods, which are hampered by irregular channel cross sections or turbulent flow typical of many mountain streams and do not account for shallow hyporheic flow. Another advantage of the tracer-injection method is that the information needed to calculate streamflow can be collected more quickly than individual current-meter measurements, minimizing potential fluctuations in streamflow and trace-element concentrations that can occur diurnally and complicate loading calculations.

Streamflow

Tracer-dye concentration data, collected continuously with the SCUFAs at surface-water sites 7 and 24 (1,780 and 5,020 feet (ft) downstream from the tracer-injection point), were used to graphically display the temporal variation of dye concentrations during the tracer injection as the dye moved downstream (fig. 4). Ideally, these graphs have three distinct periods that show the arrival, plateau, and departure of the injected tracer.

A generally stable plateau concentration indicates that the injected dye has reached equilibrium at a downstream site. As the tracer moves downstream during the plateau period, it becomes diluted by inflows. Therefore, in a gaining stream system, the magnitude of the plateau concentration decreases downstream as the instream flow increases. Tracer concentration data collected at sites 7 and 24 in this study were used to document that a relatively stable plateau concentration was reached before the collection of synoptic samples (fig. 4). Changes in tracer concentrations were observed during the plateau period possibly due to natural streamflow variations, changes in the tracer-injection rate, or measurement variability. Streamflow data from USGS streamgage 06062500 (U.S. Geological Survey, 2016) indicated that streamflow variations did occur during the study period, but it is likely that other factors also contributed to the observed changes in plateau concentrations.

Mean travel times through the upper Tenmile Creek system computed from the dye tracer response curve (fig. 4) indicated that the tracer achieved plateau concentrations at the two tracer-monitoring sites relatively quickly. Dye concentrations at surface-water site 7, which was 1,780 ft downstream from the injection point, reached a stable plateau in approximately 100 minutes and traveled at a mean rate of 0.30 feet per second. Plateau concentrations at surface-water site 24, which was 5,020 ft downstream from the injection point, were measured in about 240 minutes after the injection was initiated, and the mean travel time at this site in the lower reach was 0.35 feet per second. At 5,020 ft downstream from the injection point, the mean travel time for the entire study reach was about 0.35 feet per second. After termination of the tracer injections at sites 7 and 24, the times needed to reach the near baseline tracer concentrations were like the arrival times. However, the lingering presence of small dye concentrations at both sites indicated that some dye was being retained in slower moving pools or in hyporheic zones within the study reach.

Streamflow during the 2011 study was determined using the results of the fluorometric dial readings for dye samples collected at the 19 main-stem sites during the synoptic sampling and equation 3 (table 4; fig. 5). Streamflow data collected during the 1998 and 2011 trace-element loading studies are presented on figure 5 for comparisons.

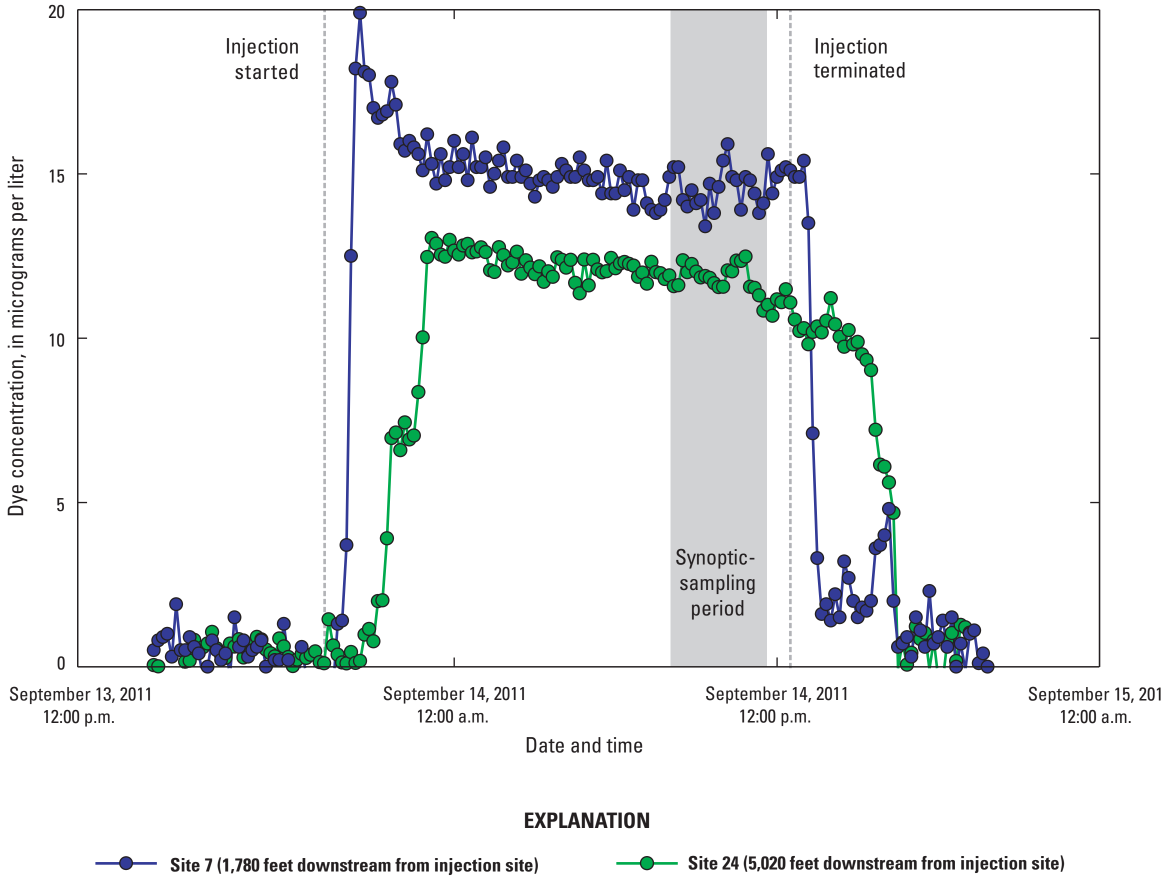


Figure 4 Time series of tracer dye concentrations at sites 7 and 24, upper Tenmile Creek, Montana, 2011.

In the 5,020-ft study reach, streamflow increased in upper Tenmile Creek from 57.8 L/s at the tracer-injection point (site 1) to 96.4 L/s at the end of the study reach (site 24), an increase of 38.6 L/s. Total surface inflows accounted for 5.75 L/s, or about 15 percent of the increase, leaving 32.9 L/s of the increase attributable to subsurface inflow. The largest increase in streamflow (12.3 L/s) occurred between sites 5.5 and 6.5 just upstream from the Lee Mountain Mine adit discharge. Although surface inflow at site 6 entered the creek between these main-stem sites, surface inflow accounted for only 0.057 L/s. The historic confluence of Beaver Creek and upper Tenmile Creek was once located in this area of large subsurface inflow. The Beaver Creek channel has since been moved and now flows parallel to upper Tenmile Creek for about 800 ft to its confluence with upper Tenmile Creek (surface-water inflow site 10). A berm composed of large cobbles and boulders was constructed along this 800-ft reach between Beaver Creek and upper Tenmile Creek; however, it is possible that substantial subsurface flows took place through the berm substrate. Site reconnaissance for the 2011 study indicated that surface flow was only in the lower 100 ft of Beaver Creek, indicating that upstream inflows to Beaver Creek were all subsurface flows.

Instantaneous streamflow was measured by current meter at four main-stem sites during synoptic sample collection. Three of these measurements were made at sites within the tracer study reach to confirm the streamflow calculated by tracer injection. Instantaneous streamflow also was measured at a main-stem site (surface-water site 0; table 1) just upstream from the city diversion to estimate flow diverted between surface-water sites 0 and 1 to the Ten Mile Water Treatment Plant and to calculate trace-element loads in upper Tenmile Creek upstream from the city diversion.

Current-meter measurements conducted near the top and middle of the study reach (surface-water sites 5 and 12) were both within 10 percent of the streamflow calculated by tracer injection (table 4), indicating agreement between the two methods and possibly a lack of hyporheic flow in the top and middle sections. The current-meter measurement conducted at the bottom of the study reach (surface-water site 24) was about 21 percent less than the tracer-calculated value. Because current-meter measurements do not measure hyporheic flow, the difference between the two methods indicated that there was more hyporheic flow near the bottom of the study reach. At the lower end of the reach, about 21 percent of the streamflow was subsurface hyporheic flow.

Table 4. Results of streamflow calculated by tracer injection, surface-water inflow, subsurface inflow, and associated water-quality analyses of samples collected from upper Tenmile Creek drainage basin, Montana, September 2011.

[Subsurface inflows were assigned point of inflow but occurred between upstream and downstream points within the reach. Sites were assigned short numbers (Site number), defined in table 1, and displayed on figure 2. Surface-water inflow sites are **bold.** ft, foot; mg/L, milligram per liter; L/s, liter per second; µS/cm, microseimen per centimeter; $CaCO_3$, calcium carbonate; µg/L, microgram per liter; ab, above; nr, near; --, no data; bl, below; E, estimated; LB, left bank (looking downstream); RB, right bank (looking downstream); <, less than]

Site	Distance downstream from injection site (ft)	Station description	Dye concentration (mg/L)	Tracer-calculated streamflow (L/s)
0	–50	Tenmile Creek ab City Diversion, at Rimini (36u)	--	--
1	0	Tenmile Creek bl City Diversion, at Rimini (injection site)[1]	20.1	E57.8
2	365	Tenmile Creek 365 ft bl City Diversion, at Rimini	20.5	57.8
3	**665**	**Tenmile LB seep 665 ft bl City Diversion, at Rimini**	--	--
4	695	Tenmile Creek 695 ft bl City Diversion at Rimini	20.0	59.3
5	1,115	Tenmile Creek 1,115 ft bl City Diversion , at Rimini	19.8	59.9
5.5	1,215	Tenmile Creek 1,215 ft bl City Diversion, at Rimini	19.8	59.9
6	**1,245**	**Tenmile RB discharge pipe 1,245 ft bl City Diversion**	--	--
6.5	1,350	Tenmile Creek 1,350 ft bl City Diversion, at Rimini	16.4	72.3
6.75	**1,400**	**Lee Mountain Mine adit discharge, at Rimini**	--	--
7	1,780	Tenmile Creek 1,780 ft bl City Diversion, at Rimini	16.2	73.2
8	**1,800**	**LB seep from Lee Mountain Mine**	--	--
8.5	**1,970**	**Tenmile Creek RB seep 1,970 bl City Diversion, at Rimini**	--	--
9	1,985	Tenmile Creek 1,985 ft bl City Diversion, at Rimini[2]	15.0	E73.6
10	**2,000**	**Beaver Creek at mouth, at Rimini**	--	--
11	2,120	Tenmile Creek 2,120 ft bl City Diversion, at Rimini	16.0	74.1
12	2,420	Tenmile Creek 2,420 ft bl City Diversion, at Rimini	15.9	74.6
13	2,765	Tenmile Creek ab Susie Lode Adit, at Rimini	15.2	78.0
14	3,015	Tenmile Creek 3,015 ft bl City Diversion, at Rimini	15.1	78.5
15	**3,040**	**Susie Lode Adit discharge at mouth, at Rimini**	--	--
16	3,250	Tenmile Creek 3,250 ft bl City Diversion, at Rimini	14.5	81.8
17	**3,305**	**Spring Creek at Mouth, at Rimini**	--	--
18	3,415	Tenmile Creek 3,415 ft bl City Diversion, at Rimini	14.1	84.1
17a	**3,500**	**Spring Creek Fork[2]**	--	--
19	3,575	Tenmile Creek 3,575 ft bl City Diversion, at Rimini	14.0	84.7
20	3,850	Tenmile Creek 3,850 ft bl Spring Creek, at Rimini	13.1	90.5
21	4,180	Tenmile Creek 4,180 ft bl City Diversion, at Rimini	13.1	90.5
22	4,675	Tenmile Creek 4,675 ft bl City Diversion, at Rimini	12.9	91.9
23	**4,890**	**Moore's Spring Creek at mouth, at Rimini**	--	--
24	5,020	Tenmile Creek 5,020 ft bl City Diversion, at Rimini	12.3	96.4

[1]A tracer-calculated streamflow could not be determined at this site because the dye was not fully mixed in Tenmile Creek. A streamflow value equal to the value at site 2 was used.

[2]The dye concentration at this site was anomalous; therefore, an estimated streamflow value equal to site 7 plus one-half of the difference from sites 7 to 11 was assigned to this site.

[3]Streamflow (0.23 L/s) at this site, a fork of Spring Creek, was added to site 17 to calculate loads for Spring Creek.

Table 4. Results of streamflow calculated by tracer injection, surface-water inflow, subsurface inflow, and associated water-quality analyses of samples collected from upper Tenmile Creek drainage basin, Montana, September 2011.—Continued

[Subsurface inflows were assigned point of inflow but occurred between upstream and downstream points within the reach. Sites were assigned short numbers (Site number), defined in table 1, and displayed on figure 2. Surface-water inflow sites are **bold**. ft, foot; mg/L, milligram per liter; L/s, liter per second; µS/cm, microseimen per centimeter; $CaCO_3$, calcium carbonate; µg/L, microgram per liter; ab, above; nr, near; --, no data; bl, below; E, estimated; LB, left bank (looking downstream); RB, right bank (looking downstream); <, less than]

Site	Current meter streamflow (L/s)	Surface inflow (volumetric, L/s)	Subsurface inflow (calculated, L/s)	Sample start time	pH (standard units)	Specific conductance (µS/cm)	Calcium, dissolved (mg/L)
0	83.5	--	--	--	--	--	--
[1]1	--	--	--	1115	6.8	75	7.82
2	--	--	--	1100	6.9	75	7.98
3	--	**0.057**	**1.44**	**1050**	**6.5**	**85**	**8.29**
4	--	--	--	1045	7.2	76	7.75
5	64.8	--	--	1035	6.9	76	7.83
5.5	--	--	--	1020	6.9	77	7.82
6	--	**0.057**	**12.3**	**1100**	**8.1**	**3,070**	**16.3**
6.5	--	--	--	0955	6.8	79	8.06
6.75	--	**0.41**	**0.49**	**0945**	**2.9**	**2,230**	**215**
7	--	--	--	0925	6.8	91	9.35
8	--	--	--	--	--	--	--
8.5	--	**0.085**	**0.32**	**0910**	**6.4**	**103**	**10.3**
[2]9	--	--	--	0855	6.7	92	9.53
10	--	**0.028**	**0.47**	**0845**	**6.8**	**113**	**11.0**
11	--	--	--	0835	6.6	95	9.63
12	71.4	--	--	0820	6.7	98	10.2
13	--	--	--	1010	6.6	95	9.89
14	--	--	--	1000	6.6	97	10.3
15	--	**0.91**	**2.39**	**0955**	**3.3**	**1,930**	**155**
16	--	--	--	0945	6.6	123	12.1
17	--	**3.26**	**2.34**	**0940**	**6.7**	**44**	**3.81**
18	--	--	--	0930	6.4	119	11.3
[3]17a	--	**0.23**	**0.37**	--	--	--	--
19	--	--	--	0915	6.6	119	11.5
20	--	--	--	0905	6.4	120	11.6
21	--	--	--	0850	6.9	123	11.6
22	--	--	--	0840	6.8	127	12.1
23	--	**0.71**	**3.79**	**0825**	**7.3**	**227**	**24.1**
24	76.5	--	--	0800	6.8	138	12.9

[1]A tracer-calculated streamflow could not be determined at this site because the dye was not fully mixed in Tenmile Creek. A streamflow value equal to the value at site 2 was used.

[2]The dye concentration at this site was anomalous; therefore, an estimated streamflow value equal to site 7 plus one-half of the difference from sites 7 to 11 was assigned to this site.

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Site	Magnesium, dissolved (mg/L)	Hardness, dissolved (mg/L as $CaCO_3$)	Cadmium, dissolved (µg/L)	Cadmium, total recoverable (µg/L)	Copper, dissolved (µg/L)	Copper, total recoverable (µg/L)
0	--	--	--	--	--	--
[1]1	1.80	26.9	1.22	1.22	2.63	3.09
2	1.83	27.5	1.22	1.20	2.72	3.09
3	**1.98**	**28.8**	**0.56**	**0.53**	**2.51**	**2.76**
4	1.80	26.8	1.18	1.16	2.57	3.11
5	1.83	27.1	1.19	1.15	2.64	2.97
5.5	1.83	27.1	1.18	1.15	2.53	2.92
6	**4.76**	**60.3**	**1.42**	**1.96**	**<1.0**	**323**
6.5	1.86	27.8	1.15	1.06	2.45	2.70
6.75	**54.6**	**761**	**313**	**299**	**219**	**299**
7	2.15	32.2	2.77	2.56	4.33	5.50
[2]8	--	--	--	--	--	--
8.5	**2.71**	**36.9**	**1.23**	**1.08**	**6.34**	**8.55**
[2]9	2.23	33.0	2.75	2.55	4.38	5.86
10	**2.99**	**39.9**	**0.62**	**0.54**	**7.21**	**9.12**
11	2.23	33.2	3.15	2.85	5.54	7.11
12	2.38	35.2	3.38	2.81	5.76	7.59
13	2.34	34.3	2.99	2.78	5.69	7.88
14	2.38	35.6	3.06	2.84	5.22	7.74
15	**60.5**	**636**	**506**	**476**	**1,520**	**1,490**
16	3.24	43.5	8.73	8.54	13.3	28.1
17	**1.03**	**13.7**	**0.85**	**0.87**	**6.53**	**8.33**
18	3.09	41.1	6.77	8.05	5.30	27.0
[3]17a	--	--	--	--	--	--
19	3.12	41.5	8.81	7.99	10.0	27.2
20	3.14	42.0	8.89	8.11	9.10	27.3
21	3.17	42	8.63	8.2	12.8	27.9
22	3.34	43.8	8.04	8.11	10.7	30.6
23	**7.68**	**91.7**	**6.39**	**5.91**	**5.76**	**6.68**
24	3.65	47.2	8.11	7.84	12.3	26.6

[1]A tracer-calculated streamflow could not be determined at this site because the dye was not fully mixed in Tenmile Creek. A streamflow value equal to the value at site 2 was used.

[2]The dye concentration at this site was anomalous; therefore, an estimated streamflow value equal to site 7 plus one-half of the difference from sites 7 to 11 was assigned to this site.

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Site	Lead, dissolved (µg/L)	Lead, total recoverable (µg/L)	Zinc, dissolved (µg/L)	Zinc, total recoverable (µg/L)	Arsenic, dissolved (µg/L)	Arsenic, total recoverable (µg/L)
0	--	--	--	--	--	--
[1]1	0.78	1.72	331	298	8.40	10.1
2	0.80	1.73	302	289	8.59	10.3
3	**0.35**	**0.76**	**185**	**164**	**10.4**	**10.7**
4	0.77	1.77	318	285	8.69	10.4
5	0.76	1.76	317	280	8.70	10.3
5.5	0.75	1.69	314	289	8.81	10.3
6	**0.04**	**43.9**	**95.7**	**134**	**28.0**	**25.1**
6.5	1.10	2.16	314	289	9.43	10.5
6.75	**22.1**	**26.6**	**62,200**	**57,100**	**544**	**646**
7	1.13	2.74	559	514	7.19	11.5
[2]8	**--**	**--**	**--**	**--**	**--**	**--**
8.5	**0.16**	**0.23**	**162**	**145**	**17.7**	**17.9**
[2]9	1.1	3.04	600	538	6.94	13.0
10	**0.25**	**0.52**	**185**	**168**	**20.7**	**21.4**
11	1.21	3.24	620	569	7.02	12.2
12	1.35	3.22	670	547	7.39	12.0
13	1.30	3.58	573	559	7.27	13.3
14	1.11	3.53	580	527	7.03	13.5
15	**20.9**	**46.9**	**41,500**	**41,800**	**2,980**	**8,430**
16	0.92	4.07	1,110	1,090	33.3	115
17	**0.09**	**0.36**	**72.5**	**71.5**	**8.99**	**9.29**
18	0.15	3.87	1,050	1,040	57.6	108
[3]17a	**--**	**--**	**--**	**--**	**--**	**--**
19	0.69	3.81	1,090	1,040	33.9	112
20	0.54	3.90	1,070	1,070	27.9	112
21	0.99	3.61	1,100	1,080	43.0	111
22	0.74	4.23	1,200	1,150	32.4	137
23	**0.15**	**1.18**	**1,040**	**969**	**61.2**	**59.6**
24	1.07	3.56	1,220	1,170	45.7	110

[1]A tracer-calculated streamflow could not be determined at this site because the dye was not fully mixed in Tenmile Creek. A streamflow value equal to the value at site 2 was used.

[2]The dye concentration at this site was anomalous; therefore, an estimated streamflow value equal to site 7 plus one-half of the difference from sites 7 to 11 was assigned to this site.

[3]Streamflow (0.23 L/s) at this site, a fork of Spring Creek, was added to site 17 to calculate loads for Spring Creek.

The current-meter measurement conducted upstream from the city diversion (surface-water site 0) yielded a result of 83.5 L/s or about 30 percent more than the streamflow at surface-water site 1 (57.8 L/s) just downstream from the diversion, indicating that about 26 L/s of the streamflow in upper Tenmile Creek was being diverted to the treatment plant during the study.

Comparison of streamflow calculated by tracer injection determined in this study (fig. 5) and those observed in the 1998 trace-element loading study (Cleasby and Nimick, 2002) indicated that streamflow values were about an order of magnitude less in 1998. In the 1998 study, streamflow in upper Tenmile Creek upstream from the city diversion was 185 L/s, but about 5 L/s was measured in upper Tenmile Creek downstream from the city diversion. This small amount of streamflow in 1998 was evident throughout the study reach with minimal gains downstream to site 24.

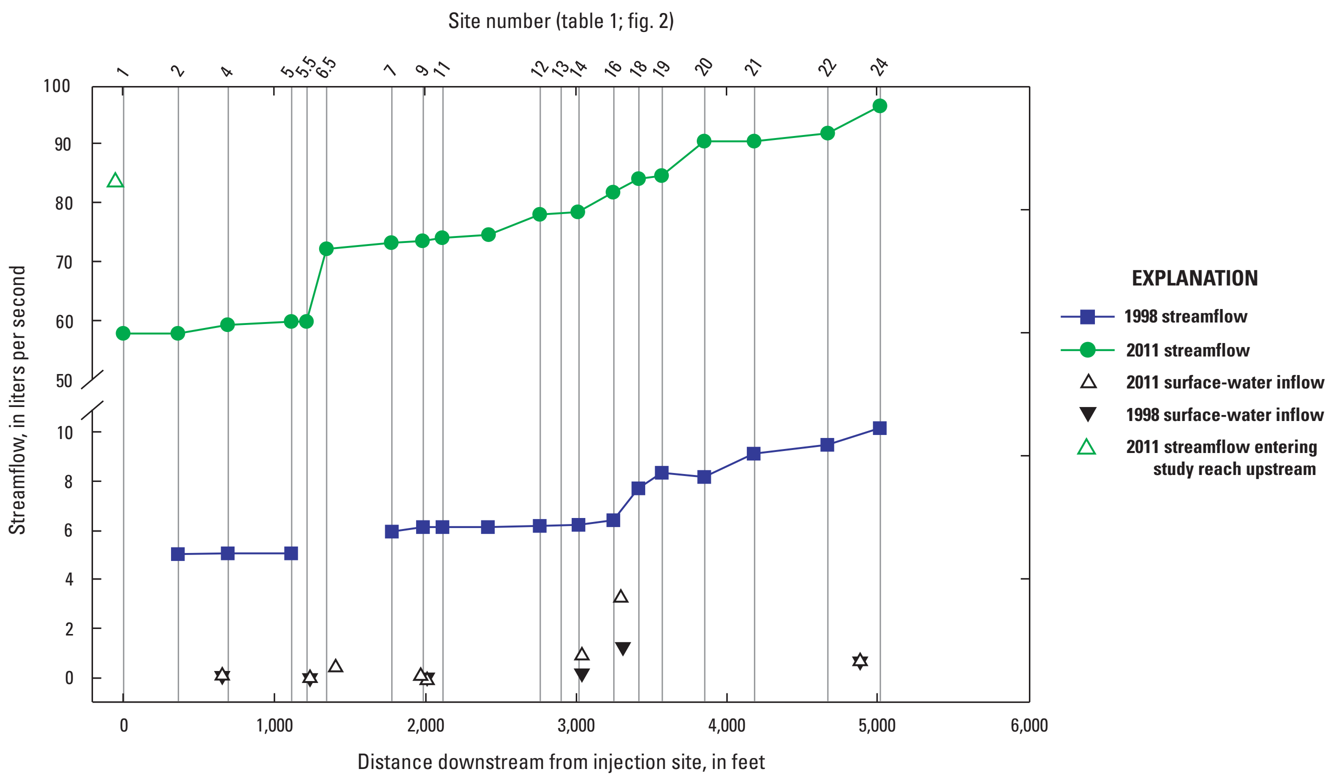

Figure 5. Streamflow calculated by tracer injection, upper Tenmile Creek drainage basin, Montana, 1998 and 2011.

Water Quality

Results of water-quality sampling in this study indicated that overall trace-element concentrations measured in 2011 were lower than those measured in 1998, but concentrations of trace elements originating from mine adits did not change substantially. The observed decreases in trace-element concentrations since 1998 were likely caused by dilution from increased streamflow rather than from reduced trace-element concentrations introduced from mining.

Synoptic water-quality samples were collected at the 19 main-stem sites in upper Tenmile Creek and the 8 surface-water inflow sites and were analyzed for physical properties, hardness (calcium and magnesium), and selected dissolved and total-recoverable trace-element concentrations. The groundwater samples were analyzed for the same suite of constituents as surface-water samples except for total-recoverable trace elements. It was assumed that dissolved concentrations would be about the same as total-recoverable concentrations because groundwater samples should not contain sediment. Results are listed in table 4 and table 5, and selected constituents are graphically displayed in figures 6 and 7. Water-quality data collected for the 2011 study also are available in the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2018). Results of the 1998 tracer study and applicable Montana water-quality standards for cadmium, copper, lead, zinc, and arsenic (Montana Department of Environmental Quality, 2017) also are shown in figure 7.

Two criteria levels for selected trace-element concentrations, chronic and acute, are established for freshwater habitats. Chronic criteria are established for the protection against long-term exposure to moderately elevated concentrations. If concentrations exceed the chronic criteria for long periods, detrimental effects on growth and reproduction might be seen in aquatic populations. Acute criteria are established for protection against short-term exposure to highly elevated concentrations that can be lethal to aquatic organisms. Because tolerance to trace-element exposure can vary among species, or between individuals within the same species, aquatic-life criteria are only general guidelines. The Montana criteria for trace-element toxicity are based on total-recoverable concentrations, but dissolved and total-recoverable trace-element concentrations are compared to the criteria in this report. Aquatic-life criteria for cadmium, copper, lead, and zinc vary with water hardness (Montana Department of Environmental Quality, 2017), with trace-element toxicity decreasing with increasing hardness. The aquatic-life criteria shown in figure 7 were calculated using a hardness of 35 milligrams per liter measured as calcium carbonate, the mean hardness measured at the main stem sites during the tracer injection. Overall, the State of Montana human-health criteria for total-recoverable cadmium and arsenic were exceeded in parts of upper Tenmile Creek.

Surface Water

The pH in upper Tenmile Creek remained relatively constant (ranging from 6.4 to 7.2) during the 2011 study compared to the pH during 1998, which ranged from 5.0 to 7.4 (fig. 6). During both studies, the pH was near neutral in the upper portion of the study reach from surface-water sites 1 through 10. In 1998, the main-stem pH declined to less than 5.5 downstream from surface-water site 11 (2,120 ft) and remained below 6.0 for an almost 1,300-ft reach of upper Tenmile Creek between surface-water sites 11 (2,120 ft) and 18 (3,415 ft). The area around Lee Mountain Mine and the Susie Lode adit contributed acidic water that depressed pH in this stream reach during the 1998 study. The Lee Mountain Mine adit was a diffuse source to upper Tenmile Creek in 1998. Discharge from this area was not channelized, and water percolated into the unconsolidated mine waste, seeping into upper Tenmile Creek over a broader reach. The small volume of streamflow in upper Tenmile Creek in 1998 resulted in little neutralization of the acidic inflows from these sources. Although pH values in the two acidic inflows were similar during both studies, they did not have a substantial effect on upper Tenmile Creek during 2011 because of the larger volume of streamflow. The pH increased downstream from Spring Creek during the 1998 study such that pH values at the most downstream site in 1998 and 2011 were roughly equivalent. The highest pH during both studies was measured at the surface-water inflow site 6 (1,245 ft). At site 6, the pH was over 8.0 during both studies. This inflow was a pipe with a small discharge.

The 2011 concentration profiles for cadmium, copper, and zinc through the study reach displayed similar patterns (fig. 7). Main-stem concentrations for these trace elements increased substantially in response to contributions from the Lee Mountain Mine adit (site 6.75) and the Susie Lode adit (site 15). Other than the two concentration increases attributed to discharge contributions from these adits, main-stem concentrations remained relatively unchanged. Dissolved concentrations increased about 6.5, 5, and 3 times over the entire study reach for cadmium, copper, and zinc, respectively. For these trace elements, main-stem dissolved and total-recoverable concentrations were roughly equivalent, indicating that they existed mostly in the dissolved form. The exception to this was that downstream from the Susie Lode adit discharge (surface-water inflow site 15), the increase in main-stem concentrations of total-recoverable copper (from 7.74 to 28.1 µg/L) was higher than it was for the dissolved concentrations (from 5.22 µg/L to 13.3 µg/L; table 4).

Table 5. Groundwater levels and results of water-quality analyses of groundwater samples collected at wells adjacent to upper Tenmile Creek, Montana, September 2011.

[USGS, U.S. Geological Survey; hh, hour; mm, minute; ft, foot; --, not determined; µS/cm, microsiemen per centimeter; mg/L, milligram per liter; µg/L, microgram per liter]

Site number table 2; fig. 3)[1]	USGS station identification number	Sample date	Sample time (hhmm)	Land surface elevation (ft)	Water level (ft)	Groundwater level elevation (ft)	Surface water elevation (ft)	Difference between groundwater level and adjacent stream level (ft)[2]
Right bank wells[1]								
LMRB–1	462907112144601	9/13/2011	0900	5,265	2.20	5,262.80	5,263.55	–0.75
LMRB-2	462911112144501	9/13/2011	1100	5,244	1.12	5,242.85	5,242.94	–0.08
Left bank wells[1]								
LMLB–1	462908112144601	9/13/2011	1000	5,270	6.89	5,262.83	5,263.61	–0.78
LMLB–2	462909112144701	9/13/2011	1200	5,261	3.56	5,257.24	--	--
LMLB–3	462910112144601	9/13/2011	1400	5,259	8.04	5,251.28	--	--
LMLB–4	462913112144801	9/13/2011	1500	5,242	0.65	5,241.01	--	--
LMLB–5	462913112144701	9/13/2011	1400	5,238	0.51	5,237.46	5,237.65	–0.19
LMLB–6	462914112144701	9/13/2011	1500	5,237	0.90	5,236.03	5,235.67	0.36

Site number table 2; fig. 3)[1]	pH (standard units)	Specific conductance (µS/cm)	Calcium, water, dissolved (mg/L)	Magnesium, water, dissolved (mg/L)	Cadmium, water, dissolved (µg/L)	Copper, water, dissolved (µg/L)	Lead, water, dissolved (µg/L)	Zinc, water, dissolved (µg/L)	Arsenic, water, dissolved (µg/L)
Right bank wells[1]									
LMRB–1	7.3	96	9.59	2.29	1.04	2.1	0.203	379	4.84
LMRB–2	6.2	107	9.66	2.54	2.48	0.55	0.218	1,330	25.0
Left bank wells[1]									
LMLB–1	6.9	366	40.3	13.1	1.75	1.41	0.116	5,630	36.1
LMLB–2	4.4	161	11.0	3.27	29.4	69.9	13.3	2,700	14.1
LMLB–3	3.2	608	23.0	5.56	91.6	296	534	7,200	199
LMLB–4	3.5	2,110	180	51.0	7,900	46,200	18.7	1,040,000	31.7
LMLB–5	7.0	322	31.8	9.21	0.751	0.54	3.4	4,400	277
LMLB–6	7.1	390	40.8	11.8	0.345	0.51	0.817	1,780	49.9

[1]Left bank and right bank are relative to Tenmile Creek facing downstream.

[2]Positive value indicates groundwater level higher than stream level and negative value (–) indicates groundwater level lower than stream level.

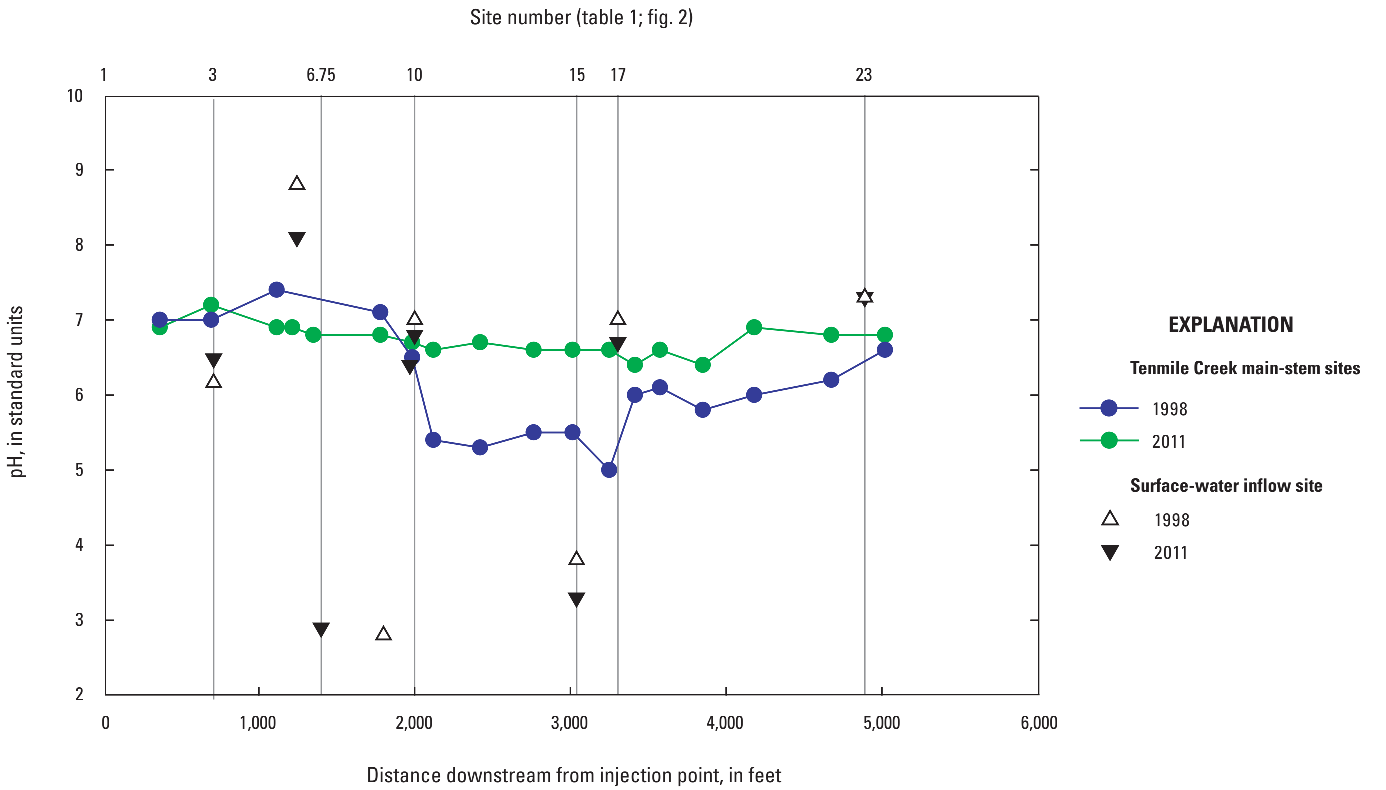

Figure 6. Values of pH measured in main-stem and inflow sites downstream from the tracer-injection point, upper Tenmile Creek drainage basin, Montana, 1998 and 2011.

Comparison between results of the 1998 and 2011 studies indicated that increases in main-stem trace-element concentrations after flowing through the Lee Mountain Mine area (downstream from inflow site 6.75) were substantially greater in 1998 than in 2011 (fig. 7). Concentrations of cadmium and zinc were approximately equal in both studies in the upper portion of the study reach from surface-water sites 1 to 5 upstream from the Lee Mountain Mine adit. However, main-stem copper concentrations in this area were about twice as high in 1998 as in 2011. In 1998, main-stem concentrations of cadmium, copper, and zinc steadily increased over an approximately 1,000-ft reach in the Lee Mountain Mine area from surface-water sites 5 to 11. In contrast, the 2011 increases in main-stem concentrations for theses trace elements occurred more as a point source from the channelized Lee Mountain Mine adit discharge at site 6.75 (table 4). In 1998, main-stem cadmium concentrations increased by about 17 times through this reach, copper increased by about 7 times, and zinc increased by about 11 times (Cleasby and Nimick, 2002). In 2011, concentrations of cadmium, copper, and zinc in this area increased by less than three times. At the time of the 1998 study, there was no surface-water inflow observed in the mine area, and the increases in trace-element concentrations were attributed to subsurface inflow.

Concentration profiles for lead were different than those for cadmium, copper, or zinc (fig. 7). In 2011, dissolved lead concentrations were relatively constant downstream from the Lee Mountain Mine adit (site 6.75). Downstream from the Susie Lode adit (site 15), concentrations decreased, and total-recoverable lead concentrations steadily increased from surface-water site 5 to the end of the study reach. This indicates that main-stem conditions may have favored the precipitation of lead downstream from site 5 to the end of the study reach. This partitioning from dissolved lead to particulate lead was expected because, at near-neutral pH, dissolved lead forms colloids and is converted to the particulate fraction (Hem, 1985).

Similar to the other measured trace elements, lead concentrations in upper Tenmile Creek substantially increased as it flowed through the Lee Mountain Mine area in 1998 (surface-water sites 5–11; fig. 7). This increase was not as large in 2011, although concentrations in the Lee Mountain Mine adit discharge (site 6.75) exceeded 20 μg/L for both dissolved and total-recoverable lead (table 4). The difference in upper Tenmile Creek lead concentrations between 1998 and 2011 was due to the difference in pH associated with smaller streamflow volumes in 1998. In 1998, downstream from the Susie Lode adit (site 15), where the main-stem pH increased (fig. 6),

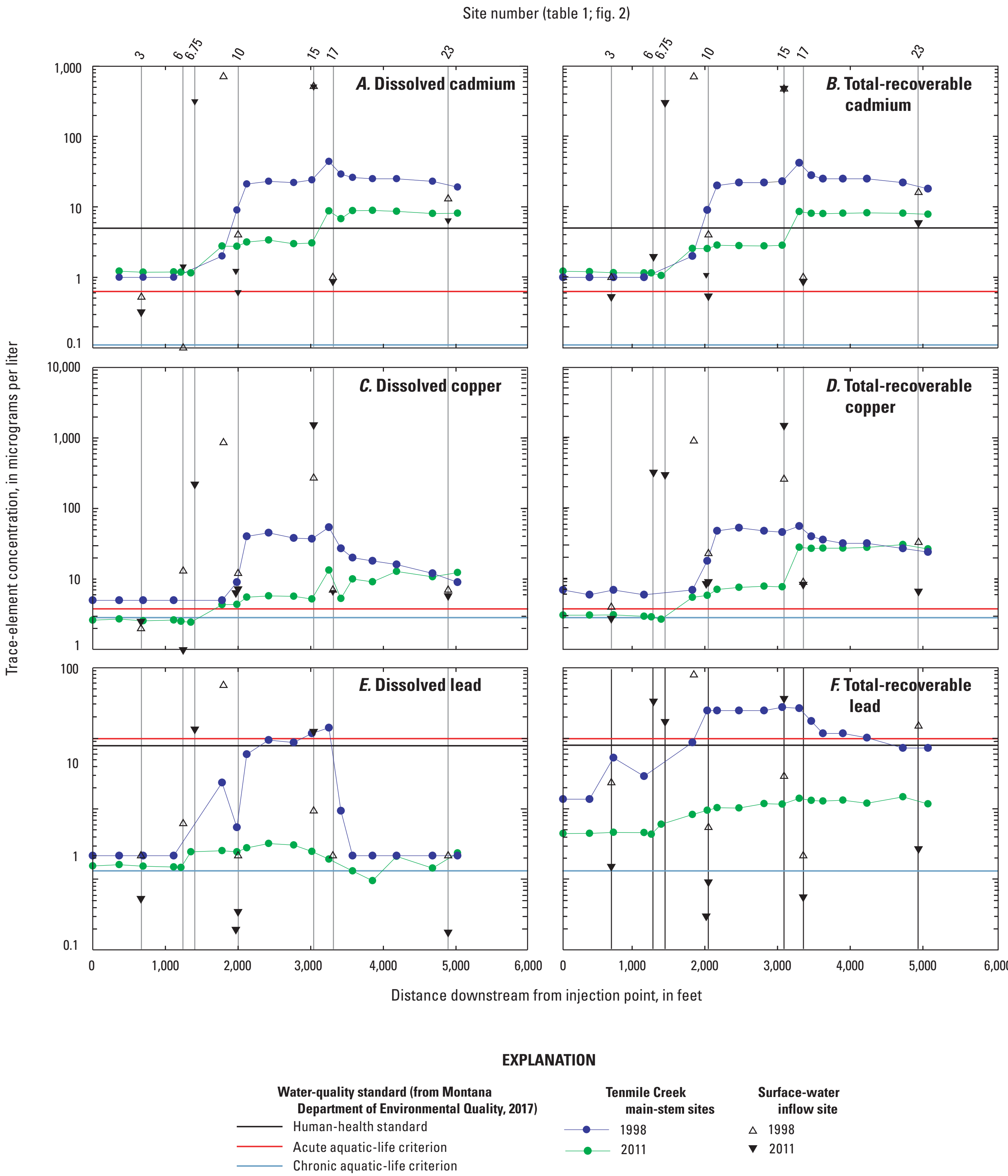

Figure 7a. Concentrations of *A*. dissolved cadmium, *B*. total-recoverable cadmium, *C*. dissolved copper, D. total-recoverable copper, *E*. dissolved lead, *F*. total-recoverable lead, *G*. dissolved zinc, *H*. total-recoverable zinc, *I*. dissolved arsenic, and *J*. total-recoverable arsenic measured in main-stem and inflow sites downstream from the tracer-injection point, upper Tenmile Creek drainage basin, Montana, 1998 and 2011.

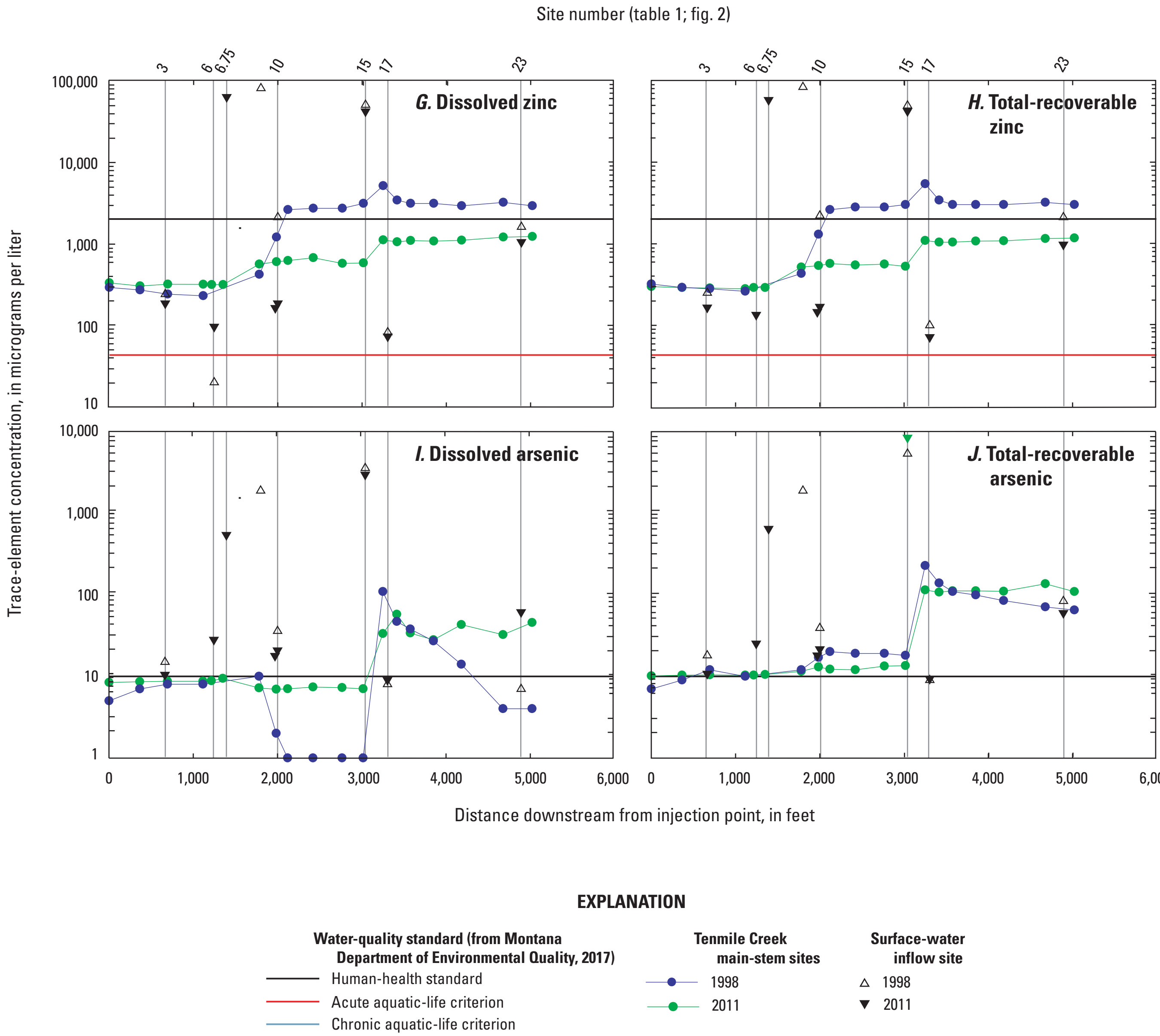

Figure 7b. Concentrations of *A*. dissolved cadmium, *B*. total-recoverable cadmium, *C*. dissolved copper, D. total-recoverable copper, *E*. dissolved lead, *F*. total-recoverable lead, *G*. dissolved zinc, *H*. total-recoverable zinc, *I*. dissolved arsenic, and *J*. total-recoverable arsenic measured in main-stem and inflow sites downstream from the tracer-injection point, upper Tenmile Creek drainage basin, Montana, 1998 and 2011.

dissolved lead concentrations decreased, and at the end of the study reach (site 24), dissolved lead concentrations were like those measured in 2011. Concentrations of total-recoverable lead at site 24 were about 4 times higher in 1998 than in 2011.

Dissolved and total-recoverable arsenic concentrations in 2011 were relatively low, except for one concentration peak from the Susie Lode adit discharge at site 15 (fig. 7). This source contributed most of the main-stem arsenic concentration, which increased by 5 times in the dissolved fraction and by 10 times in the total-recoverable arsenic fraction throughout the study reach. Downstream from this large increase, the concentrations of both dissolved and total-recoverable arsenic remained relatively constant.

Total-recoverable arsenic concentrations were similar between 1998 and 2011, but dissolved arsenic concentrations were much more variable between these years. In 1998, dissolved arsenic concentrations in upper Tenmile Creek decreased sharply as it flowed through the Lee Mountain Mine area (site 6.75), but not in 2011. This is the same stream reach where concentrations of cadmium, copper, and zinc increased in both years. This decrease in dissolved arsenic concentrations in 1998 was likely caused by adsorption and (or) coprecipitation of dissolved arsenic with visible iron particulates in the main stem of upper Tenmile Creek (Cleasby and Nimick, 2002). As previously mentioned, there was no surface inflow to upper Tenmile Creek in this reach during the 1998 study and arsenic, therefore, entered upper Tenmile Creek through diffuse subsurface inflow. The reclamation work done in this area after 1998 included re-contouring the mine area to concentrate and confine the diffuse subsurface flow into one conduit flowing into a lime treatment pond. Although the lime pond was not being maintained during the 2011 study, some iron particulates likely precipitated through oxidation, depending on the redox conditions, as the water was exposed to air converting ferrous iron into ferric iron as the water entered upper Tenmile Creek. Therefore, dissolved arsenic concentrations in 2011 may have been higher than in 1998 in the absence of iron colloids formed in the lime treatment pond flowing into upper Tenmile Creek from the Lee Mountain Mine area.

Trace-element concentrations in upper Tenmile Creek were lower, overall, in 2011 than in 1998. Dissolved and total-recoverable cadmium concentrations downstream from the Susie Lode adit (site 15) exceeded the human-health standard of 5 µg/L in 2011. The human-health standard of 10 µg/L for total-recoverable arsenic was exceeded at main-stem sites throughout the entire 5,020-ft study reach. Total-recoverable zinc concentrations in 2011 approached the human-health standard of 2,000 µg/L in the stream reach downstream from the Susie Lode adit but did not exceed it.

Exceedances of the calculated acute aquatic-life criteria were observed at several main-stem sites for total-recoverable lead (17.6 µg/L) in 1998, at several sites for total-recoverable copper (4.5 µg/L) in 2011, and at all sites for cadmium (0.63 µg/L) and zinc (43.2 µg/L) in both 1998 and 2011. In 2011, total-recoverable copper concentrations exceeded the acute aquatic-life criterion from site 7, just downstream from the Lee Mountain Mine adit discharge, to the end of the study reach, whereas, in 1998, the total-recoverable copper criterion was exceeded throughout the study reach. Main-stem dissolved and total-recoverable lead concentrations exceeded the chronic aquatic-life criterion throughout the study reach in 2011 except for site 20, where dissolved lead concentrations were lower than the criterion. In 1998, lead concentrations at all main-stem sites exceeded the chronic aquatic-life criterion (0.69 µg/L), and several sites exceeded the acute aquatic-life lead criterion, but concentrations were generally lower in 2011 than in 1998.

Groundwater

In 1998, a sample collected from along the left bank of upper Tenmile Creek in the Lee Mountain Mine area (site 8) contained the highest constituent concentrations of nearly all the samples collected that year (Cleasby and Nimick, 2002). Following that 1998 study, this area underwent substantial reclamation. In 2011, groundwater-levels were measured and water-quality samples were collected and analyzed for physical properties and dissolved trace-element concentrations from eight shallow wells in the Lee Mountain Mine area (table 5) to evaluate differences in diffuse trace-element loading from groundwater to upper Tenmile Creek between 1998 and 2011. Groundwater level and water-quality data collected during this study also are available in the NWIS database (U.S. Geological Survey, 2018).

Water levels were used to determine the general groundwater-flow gradient and to determine the interactions between the groundwater and surface water in the Lee Mountain Mine area. Upper Tenmile Creek is a moderately steep gradient stream as it flows through the Lee Mountain Mine area, dropping about 28 ft as it flows along the 985-ft reach from well LMLB–1 to LMLB–6 (fig. 3). Similarly, groundwater flows from areas of higher water-level elevation to areas of lower water-level elevation. Closely following the stream gradient, groundwater elevations declined in the downstream direction about 27 ft between the near-stream wells LMLB–1 and LMLB–6 (fig. 3; table 5), indicating down-valley groundwater flow as seen in many valley systems (Briar and Madison, 1992).

The degree of interaction between the groundwater and upper Tenmile Creek is dependent on the groundwater level and stream level, as well as the hydraulic conductivity of the streambed material and the adjacent alluvium. Groundwater levels on September 13, 2011, indicated that 4 of 5 near-stream wells had groundwater elevations that were 0.08 to 0.78 ft lower than the adjacent level in upper Tenmile Creek (table 5). These gradients indicated losing streamflow conditions (waterflow from upper Tenmile Creek to the groundwater) through that stream reach (between 1,115 ft and 2,000 ft downstream from the injection point). The most downstream well adjacent to the river (well LMLB–6; table 5) had a higher groundwater elevation relative to the surface water elevation in upper Tenmile Creek, indicating gaining streamflow conditions (waterflow from the groundwater to upper Tenmile Creek).

Trace-element concentrations in groundwater samples ranged from being like concentrations in upper Tenmile Creek to being extremely elevated (table 5). Concentrations in groundwater from the right-bank wells (LMRB–1 and LMRB–2) were generally lower than in those from the left-bank wells. Trace-element concentrations measured in LMRB–1 samples were like concentrations found in upper Tenmile Creek (surface-water site 5 is closest to LMRB–1; figs. 2–3; tables 4–5), and concentrations of cadmium and zinc in LMRB–2 samples were greater than concentrations in upper Tenmile Creek. The wells sampled on the left-bank side of upper Tenmile Creek had variable trace-element concentrations, and many concentrations were higher than concentrations measured in upper Tenmile Creek. The three wells that were in place before the study (LMLB–2, 3, and 4) were installed into the re-contoured fill material 50 to 135 ft away from the upper Tenmile Creek bank. The pH in water from these wells were all acidic (3.2–4.4), and trace-element concentrations in samples were generally elevated compared to the wells sampled immediately adjacent to the streambed, perhaps because the near-stream well concentrations were affected by flows from the stream to the adjacent groundwater. Concentrations of dissolved cadmium (7,900 µg/L), copper (46,200 µg/L), and zinc (1,040,000 µg/L) in LMLB–4 samples were, by far, the highest observed during this study.

Surface-water elevations in upper Tenmile Creek were higher than the groundwater elevations measured in nearby wells on both the left and right banks near the Lee Mountain Mine, indicating that upper Tenmile Creek may have been losing surface flow to the groundwater in this area. Under losing conditions, streamflows and trace-element concentrations from upper Tenmile Creek may have affected trace-element concentrations in the groundwater wells. Measured trace-element concentrations in the groundwater wells were greater than in upper Tenmile Creek, but groundwater concentrations could have been much greater if the creek was gaining rather than losing in this area. The down-valley gradient of the groundwater indicated that groundwater flows were toward upper Tenmile Creek farther downstream. The groundwater elevation of the farthest downstream well (LMLB–6) was greater than the adjacent surface-water elevations in upper Tenmile Creek, indicating that the creek was gaining in this area. Streamflows determined by dye tracer data indicated that upper Tenmile Creek gained 4.4 L/s between sites 11 and 14 (table 4); however, trace-element concentrations for these sites did not substantially increase. Long-term monitoring might be warranted to fully understand the groundwater/surface-water interactions and trace-element loading from the Lee Mountain Mine area under various hydrologic conditions.

Quantification of Trace-Element Loading

Estimation of trace-element load is critical for determining the mass of specific trace elements delivered to upper Tenmile Creek and for measuring the changes in trace-element loads following implementation of remediation or management actions. Load is the mass of a constituent transported downstream during a given period and is calculated as the product of a constituent concentration and streamflow. For chemically conservative constituents, inflows contribute their load in a cumulative manner to the overall load in the stream. Loads and instream concentrations are dependent on the volume of water transporting the constituent of interest. For comparative purposes, loads are commonly expressed in terms of mass transported per unit time (for example, micrograms per second (µg/s) for instantaneous loads or kilograms per year for annual loads). Instantaneous loads for dissolved and total-recoverable cadmium, copper, lead, zinc, and arsenic were calculated for the 19 main-stem and 8 surface-water inflow sites sampled during this study (table 6).

Loading profiles illustrate the longitudinal distribution of load and can be used to identify locations of important sources and sinks that contribute to or subtract from the overall constituent load. Main-stem segments where constituent loads are added to or removed from the water column can be identified by comparing the main-stem loads and the cumulative load from surface-water inflows. The profile of main-stem load represents the measured load at each main-stem sampling site. This load is the net result of contributions from the sampled and unsampled (groundwater and seeps) surface inflows, load loss from particulate deposition, and streamflow loss to groundwater. The main-stem load profile reflects the actual instream load and the net effect of all inputs and losses. The partitioning of elements between the dissolved and particulate fractions can be assessed by comparing the dissolved and total-recoverable (dissolved plus particulate) instream loads. Loads containing approximately equal portions of dissolved and total-recoverable fractions are considered mostly dissolved. Subtracting the dissolved load from the total-recoverable load provides an estimate of the instream particulate load, which is assumed to be primarily colloidal.

The cumulative surface-water inflow profile illustrates the sum of the load accrued from all the sampled surface-water inflows up to that location on the main stem. The cumulative surface-water inflow profile only represents the measured surface-water inflows and does not account for subsurface inflows. Loads from subsurface inflows can be calculated as the difference between the main-stem load and the cumulative surface-water inflow load. Less main-stem load than cumulative surface-water inflow load indicates load loss by geochemical precipitation, streambed deposition, or streamflow loss to groundwater.

Table 6. Instantaneous loads of trace elements measured in surface-water samples, upper Tenmile Creek drainage basin, Montana, September 2011.

[Surface-water inflow sites are **bold**. µg/s, microgram per second; ab, above; bl, below; ft, foot; LB, left bank (looking downstream); <, less than calculated load; RB, right bank (looking downstream)]

Site number (table 1; fig. 2)	Station description	Cadmium load, dissolved (µg/s)	Cadmium load, total recoverable (µg/s)	Copper load, dissolved (µg/s)	Copper load, total recoverable (µg/s)
0	Tenmile Creek ab City Diversion at Rimini[1]	102	102	225	264
1	Tenmile Creek bl City Diversion at Rimini (injection point)	70.5	70.5	152	179
2	Tenmile Creek 365 ft bl City Diversion at Rimini	70.6	69.4	157	179
3	**Tenmile LB seep 665 ft bl City Diversion at Rimini**	**0.03**	**0.03**	**0.14**	**0.16**
4	Tenmile Creek 695 ft bl City Diversion at Rimini	69.9	68.8	152	184
5	Tenmile Creek 1,115 ft bl City Diversion at Rimini	71.3	68.9	158	178
5.5	Tenmile Creek 1,215 ft bl City Diversion at Rimini	70.7	68.9	151	175
6	**Tenmile RB discharge pipe 1,245 ft bl City Diversion**	**0.08**	**0.11**	**<0.06**	**18.3**
6.5	Tenmile Creek 1,350 ft bl City Diversion at Rimini	83.1	76.6	177	195
6.75	**Lee Mountain Mine adit discharge at Rimini**	**128**	**123**	**89.9**	**123**
7	Tenmile Creek 1,780 ft bl City Diversion at Rimini	203	187	317	402
8.5	**Tenmile Creek RB seep 1,970 bl City Diversion at Rimini**	**0.10**	**0.09**	**0.54**	**0.73**
9	Tenmile Creek 1,985 ft bl City Diversion at Rimini	202	188	322	431
10	**Beaver Creek at mouth at Rimini**	**0.02**	**0.02**	**0.20**	**0.26**
11	Tenmile Creek 2,120 ft bl City Diversion at Rimini	233	211	410	527
12	Tenmile Creek 2,420 ft bl City Diversion at Rimini	252	210	429	566
13	Tenmile Creek ab Susie Lode Adit at Rimini	233	217	444	615
14	Tenmile Creek 3,015 ft bl City Diversion at Rimini	240	223	410	608
15	**Susie Lode Adit discharge at mouth at Rimini**	**459**	**431**	**1,380**	**1,350**
16	Tenmile Creek 3,250 ft bl City Diversion at Rimini	714	698	1,090	2,300
17	**Spring Creek at Mouth at Rimini**[2]	**2.98**	**3.04**	**22.8**	**29.1**
18	Tenmile Creek 3,415 ft bl City Diversion at Rimini	569	677	446	2,270
19	Tenmile Creek 3,575 ft bl City Diversion at Rimini	746	677	847	2,300
20	Tenmile Creek bl Spring Creek at Rimini	805	734	824	2,470
21	Tenmile Creek 4,180 ft bl City Diversion at Rimini	781	742	1,158	2,520
22	Tenmile Creek 4,675 ft bl City Diversion at Rimini	739	745	983	2,810
23	**Moore's Spring Creek at mouth at Rimini**	**4.52**	**4.18**	**4.08**	**4.73**
24	Tenmile Creek 5,020 ft bl City Diversion at Rimini	782	756	1,190	2,560

[1]Load values at site 0 were calculated using streamflow values that were measured using current meter methods and concentration data from site 1.

[2]Two forks of Spring Creek were entering Tenmile Creek (sites 17 and 17a; table 1). Only site 17 was sampled, and loads were computed by using the combined streamflow of both forks.

Table 6. Instantaneous loads of trace elements measured in surface-water samples, upper Tenmile Creek drainage basin, Montana, September 2011.—Continued

[Surface-water inflow sites are **bold**. µg/s, microgram per second; ab, above; bl, below; ft, foot; LB, left bank (looking downstream); <, less than calculated load; RB, right bank (looking downstream)]

Site number (table 1; fig. 2)	Station description	Lead load, dissolved (µg/s)	Lead load, total recoverable (µg/s)	Zinc load, dissolved (µg/s)	Zinc load, total recoverable (µg/s)
0	Tenmile Creek ab City Diversion at Rimini[1]	66.6	147	28,300	25,500
1	Tenmile Creek bl City Diversion at Rimini (injection point)	45.0	99.4	19,100	17,200
2	Tenmile Creek 365 ft bl City Diversion at Rimini	46.4	100	17,500	16,700
3	**Tenmile LB seep 665 ft bl City Diversion at Rimini**	**0.02**	**0.04**	**10.5**	**9.29**
4	Tenmile Creek 695 ft bl City Diversion at Rimini	45.9	105	18,800	16,900
5	Tenmile Creek 1,115 ft bl City Diversion at Rimini	45.4	105	18,900	16,800
5.5	Tenmile Creek 1,215 ft bl City Diversion at Rimini	44.8	101	18,800	17,300
6	**Tenmile RB discharge pipe 1,245 ft bl City Diversion**	**0.00**	**2.49**	**5.42**	**7.59**
6.5	Tenmile Creek 1,350 ft bl City Diversion at Rimini	79.5	156	22,700	20,900
6.75	**Lee Mountain Mine adit discharge at Rimini**	**9.06**	**10.9**	**25,500**	**23,400**
7	Tenmile Creek 1,780 ft bl City Diversion at Rimini	82.7	201	40,900	37,600
8.5	**Tenmile Creek RB seep 1,970 bl City Diversion at Rimini**	**0.01**	**0.02**	**13.8**	**12.3**
9	Tenmile Creek 1,985 ft bl City Diversion at Rimini	81.0	224	44,200	39,600
10	**Beaver Creek at mouth at Rimini**	**0.01**	**0.01**	**5.24**	**4.76**
11	Tenmile Creek 2,120 ft bl City Diversion at Rimini	89.7	240	45,900	42,200
12	Tenmile Creek 2,420 ft bl City Diversion at Rimini	101	240	50,000	40,800
13	Tenmile Creek ab Susie Lode Adit at Rimini	101	279	44,700	43,600
14	Tenmile Creek 3,015 ft bl City Diversion at Rimini	87.1	277	45,500	41,400
15	**Susie Lode Adit discharge at mouth at Rimini**	**18.9**	**42.5**	**37,600**	**37,900**
16	Tenmile Creek 3,250 ft bl City Diversion at Rimini	75.1	333	90,800	89,100
17	**Spring Creek at Mouth at Rimini[2]**	**0.32**	**1.27**	**253**	**250**
18	Tenmile Creek 3,415 ft bl City Diversion at Rimini	12.5	325	88,300	87,400
19	Tenmile Creek 3,575 ft bl City Diversion at Rimini	58.3	323	92,300	88,100
20	Tenmile Creek bl Spring Creek at Rimini	49.1	353	96,800	96,800
21	Tenmile Creek 4,180 ft bl City Diversion at Rimini	89.1	327	99,500	97,700
22	Tenmile Creek 4,675 ft bl City Diversion at Rimini	67.7	389	110,000	106,000
23	**Moore's Spring Creek at mouth at Rimini**	**0.11**	**0.84**	**736**	**686**
24	Tenmile Creek 5,020 ft bl City Diversion at Rimini	103	343	118,000	113,000

[1]Load values at site 0 were calculated using streamflow values that were measured using current meter methods and concentration data from site 1.

[2]Two forks of Spring Creek were entering Tenmile Creek (sites 17 and 17a; table 1). Only site 17 was sampled, and loads were computed by using the combined streamflow of both forks.

Table 6. Instantaneous loads of trace elements measured in surface-water samples, upper Tenmile Creek drainage basin, Montana, September 2011.—Continued

[Surface-water inflow sites are **bold**. µg/s, microgram per second; ab, above; bl, below; ft, foot; LB, left bank (looking downstream); <, less than calculated load; RB, right bank (looking downstream)]

Site number (table 1; fig. 2)	Station description	Arsenic load, dissolved (µg/s)	Arsenic load, total recoverable (µg/s)
0	Tenmile Creek ab City Diversion at Rimini[1]	719	864
1	Tenmile Creek bl City Diversion at Rimini (injection point)	486	584
2	Tenmile Creek 365 ft bl City Diversion at Rimini	497	596
3	**Tenmile LB seep 665 ft bl City Diversion at Rimini**	**0.59**	**0.61**
4	Tenmile Creek 695 ft bl City Diversion at Rimini	515	616
5	Tenmile Creek 1,115 ft bl City Diversion at Rimini	521	617
5.5	Tenmile Creek 1,215 ft bl City Diversion at Rimini	528	617
6	**Tenmile RB discharge pipe 1,245 ft bl City Diversion**	**1.59**	**1.42**
6.5	Tenmile Creek 1,350 ft bl City Diversion at Rimini	682	759
6.75	**Lee Mountain Mine adit discharge at Rimini**	**223**	**264**
7	Tenmile Creek 1,780 ft bl City Diversion at Rimini	526	842
8.5	**Tenmile Creek RB seep 1,970 bl City Diversion at Rimini**	**1.50**	**1.52**
9	Tenmile Creek 1,985 ft bl City Diversion at Rimini	511	957
10	**Beaver Creek at mouth at Rimini**	**0.59**	**0.61**
11	Tenmile Creek 2,120 ft bl City Diversion at Rimini	520	904
12	Tenmile Creek 2,420 ft bl City Diversion at Rimini	551	895
13	Tenmile Creek ab Susie Lode Adit at Rimini	567	1,040
14	Tenmile Creek 3,015 ft bl City Diversion at Rimini	552	1,060
15	**Susie Lode Adit discharge at mouth at Rimini**	**2,700**	**7,640**
16	Tenmile Creek 3,250 ft bl City Diversion at Rimini	2,730	9,400
17	**Spring Creek at Mouth at Rimini**[2]	**31.4**	**32.4**
18	Tenmile Creek 3,415 ft bl City Diversion at Rimini	4,840	9,080
19	Tenmile Creek 3,575 ft bl City Diversion at Rimini	2,870	9,480
20	Tenmile Creek bl Spring Creek at Rimini	2,520	10,100
21	Tenmile Creek 4,180 ft bl City Diversion at Rimini	3,890	10,000
22	Tenmile Creek 4,675 ft bl City Diversion at Rimini	2,980	12,600
23	**Moore's Spring Creek at mouth at Rimini**	**43.3**	**42.20**
24	Tenmile Creek 5,020 ft bl City Diversion at Rimini	4,400	10,600

[1]Load values at site 0 were calculated using streamflow values that were measured using current meter methods and concentration data from site 1.

[2]Two forks of Spring Creek were entering Tenmile Creek (sites 17 and 17a; table 1). Only site 17 was sampled, and loads were computed by using the combined streamflow of both forks.

The main-stem total-recoverable cadmium load in 2011 (fig. 8) increased from 70.5 µg/s at the injection point to 756 µg/s at the bottom of the study reach (table 7), a nearly elevenfold increase along the 5,020-ft study reach. Loads of dissolved and total-recoverable cadmium in the main-stem sites were generally equivalent (table 6), indicating that the dissolved fraction comprised nearly all the cadmium load in upper Tenmile Creek. About 81 percent of the increase in dissolved cadmium load in the upper Tenmile Creek study reach was accounted for by the incoming load from the two adits. The Lee Mountain Mine adit and Susie Lode adits contributed about 18 percent and 69 percent, respectively, of the 685 µg/s of load accrued in the reach. Diffuse total-recoverable cadmium loading also occurred in the 1,770-ft reach from site 16, 3,250 ft downstream from the injection point, to the end of the study reach. This reach accounted for about 8.5 percent of the cadmium loading within the entire study reach.

The main-stem copper load in 2011 increased almost eightfold, from 225 µg/s upstream from the injection point (site 0) to 1,190 µg/s at the end of the study reach, for dissolved copper and fourteenfold, from 264 µg/s to 2,560 µg/s, for total-recoverable copper (table 6; fig. 9). Unlike cadmium, the copper load was primarily in the dissolved form only in the upper portion of the study reach (from the injection point to 1,245 ft downstream from the injection point). Just downstream from the Lee Mountain Mine adit, about 1,400 ft downstream from the injection point, the total load was markedly dominated by the total-recoverable fraction. Downstream from the Susie Lode adit, about 3,040 ft downstream from the injection point to the end of the study reach, the total-recoverable load comprised more than one-half of the copper load in upper Tenmile Creek (fig. 9). The Susie Lode adit (near site 15) was the largest contributor of total-recoverable copper to the main stem during the study. This source accounted for most of the total-recoverable copper load introduced to the study reach. The Lee Mountain Mine adit accounted for only about 5 percent of the increase in the total-recoverable copper load. Other surface-water inflows accounted for only about 2 percent of the total-recoverable copper load entering the main stem during this study. About one-third of the total-recoverable copper load entering upper Tenmile Creek was from diffuse sources such as groundwater or re-mobilization of copper from the streambed. Two stream reaches, between 2,120 ft and 3,015 ft and between 3,250 ft and 5,020 ft downstream from the injection point, accounted for most of the diffuse load entering upper Tenmile Creek. A total-recoverable copper load increase of about 81 µg/s, or about 4 percent of the total reach accrual, occurred near Beaver Creek, between 2,120 ft and 3,015 ft downstream from the injection point, but the contribution from the surface inflow of Beaver Creek was less than 1 µg/s of this increase. The 1,770-ft stream reach between 3,250 ft downstream from the injection point to the end of the study reach contributed about 260 µg/s of the total-recoverable copper loading to upper Tenmile Creek.

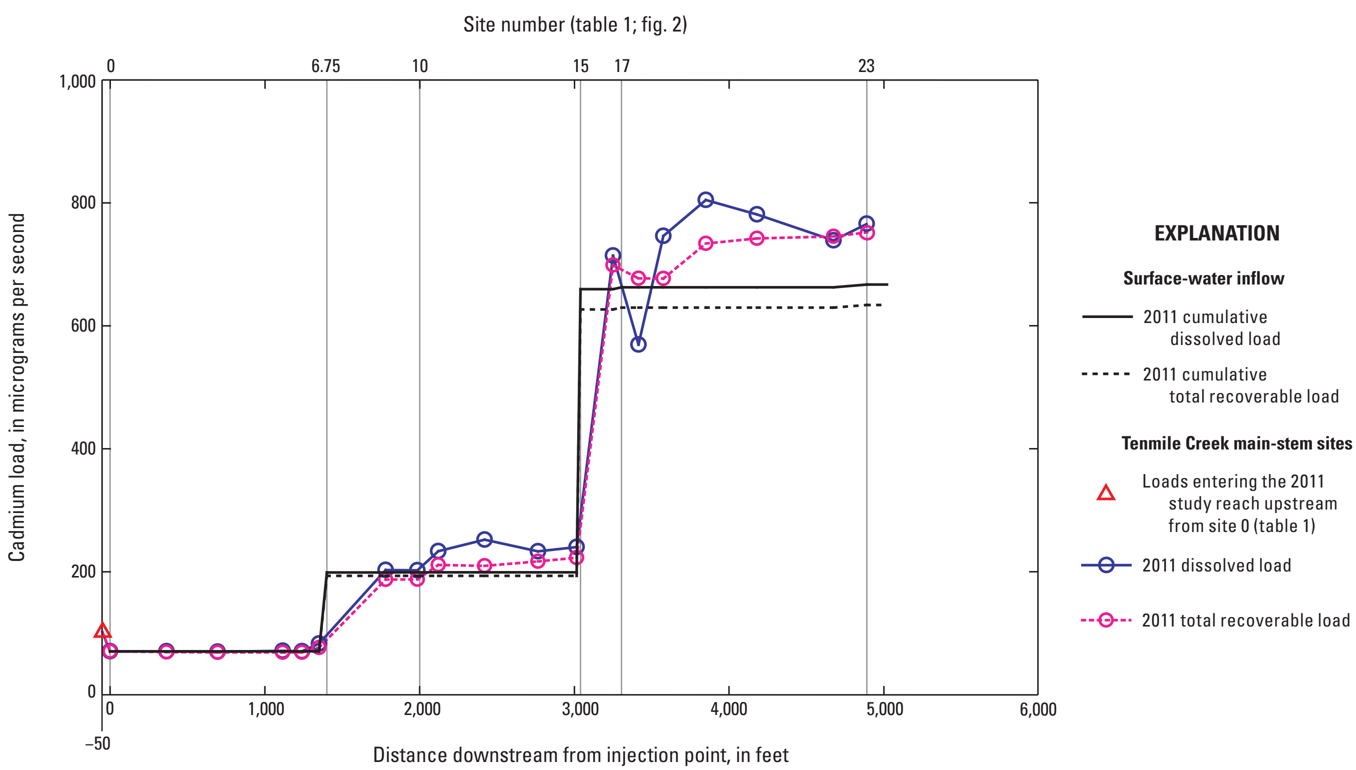

Figure 8. Tracer-calculated cadmium loads, upper Tenmile Creek drainage basin, Montana, September 2011.

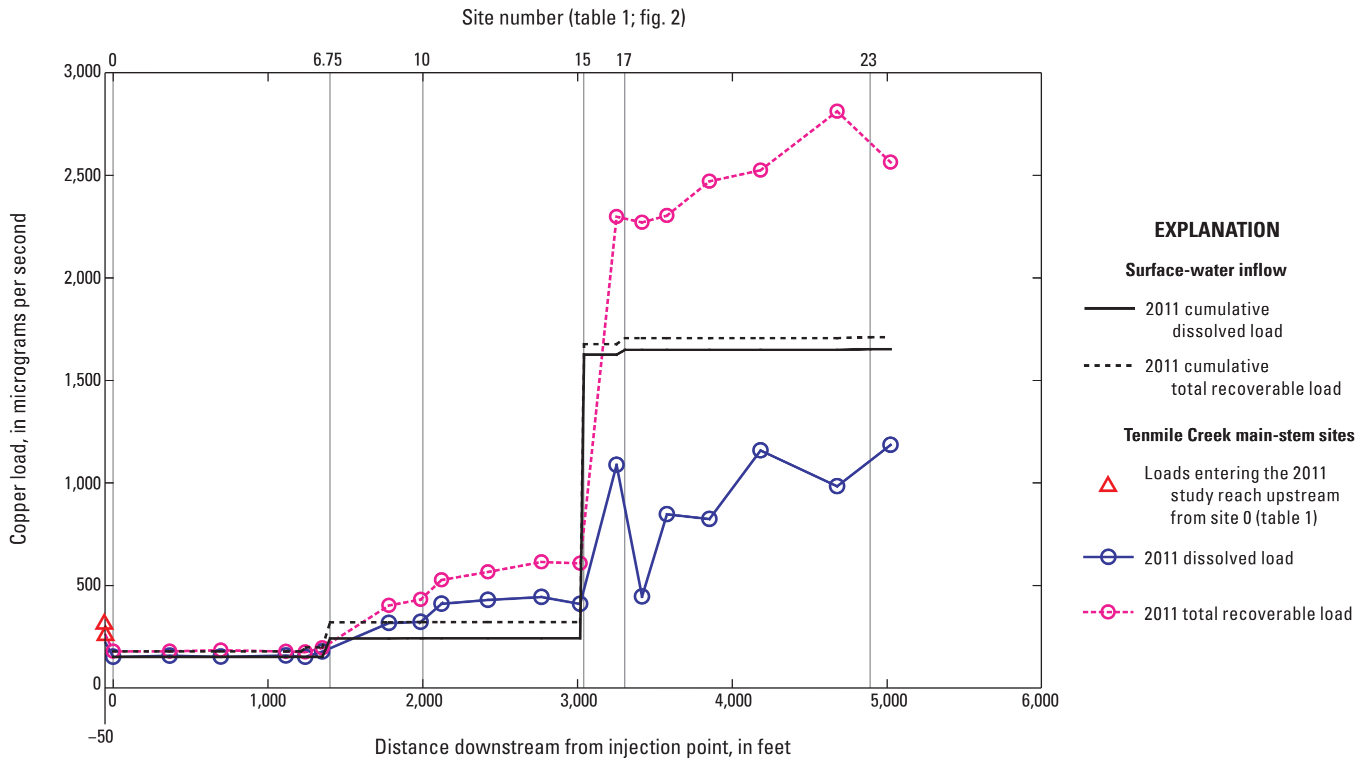

Figure 9. Tracer-calculated copper loads, upper Tenmile Creek drainage basin, Montana, September 2011.

The main-stem total-recoverable lead load in 2011 (fig. 10) increased by nearly 3.5-fold, from 99.4 µg/s to 343 µg/s, in the 5,020-ft study reach. As predicted by the near-neutral pH, lead in the main stem was primarily in the particulate form (fig. 10). The main-stem total-recoverable lead load in the upper portion of the study reach, between the injection point to 1,215 ft downstream from the injection point, was relatively constant. Downstream from this reach, the total-recoverable lead load steadily increased through the end of the study reach. The total-recoverable lead load entering upper Tenmile Creek from surface-water inflows accounted for about 24 percent of the total load increase (table 6; fig. 10), indicating that 76 percent of the total-recoverable lead load entered the main stem through lead-rich bed material. This contribution from surface-water inflows was mostly from the Lee Mountain Mine adit (about 4.5 percent) and the Susie Lode adit (17 percent). The right-bank discharge entering upper Tenmile Creek from a small pipe at 1,245 ft downstream from the injection point had very little discharge and a relatively high total-recoverable lead concentration of 43.9 µg/L (table 4). However, the load contribution from this source was only 2.49 µg/s (table 6), or about 4.5 percent of the lead entering the main stem between 1,215 and 1,350 ft downstream from the injection point.

The main-stem dissolved zinc load in 2011 (fig. 11) increased by more than sixfold over the study reach, from 19,100 µg/s to 118,000 µg/s. The dissolved and total-recoverable zinc loads in the main-stem sites were generally equal, indicating that the zinc load was primarily dissolved. The primary sources of zinc and their relative contributions to the load in upper Tenmile Creek were like those for cadmium, but zinc loads were more than 2 orders of magnitude larger than cadmium loads. About 64 percent of the increase in the dissolved zinc loads to upper Tenmile Creek was from the two adits. The Lee Mountain Mine adit contributed about 26 percent of the 5,020-ft study reach accrual, whereas the Susie Lode adit contributed about 38 percent. From 3,250 ft downstream from the injection point to the end of the study reach, about 27 and 25 percent, respectively, of the dissolved and total-recoverable zinc load was accrued. The load in the downstream reach could not be attributed to surface inflows. Rather, the load likely entered through groundwater.

The total-recoverable arsenic load in 2011 (fig. 12) increased by more than eighteenfold, from 584 µg/s to 10,600 µg/s (table 7), proportionately, the largest increase observed. The Susie Lode adit was the primary source of arsenic, accounting for more than 76 percent of the increase in the total-recoverable arsenic load in the study reach. As with zinc, the total-recoverable arsenic load in the main-stem increased dramatically 3,250 ft downstream from the injection point. However, the dissolved load, originating almost entirely from the Susie Load adit, accounted for about one-half of the total-recoverable load downstream from the adit.

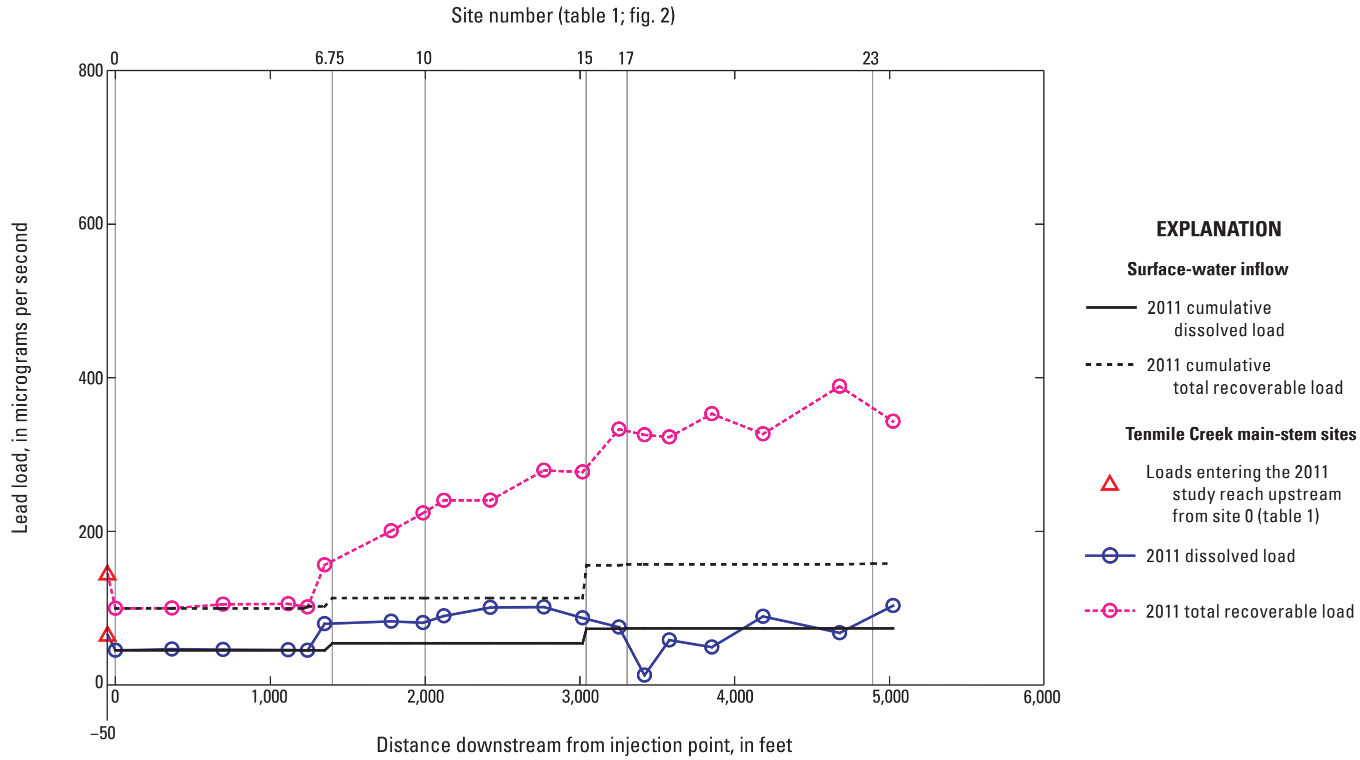

Figure 10. Tracer-calculated lead loads, upper Tenmile Creek drainage basin, Montana, September 2011.

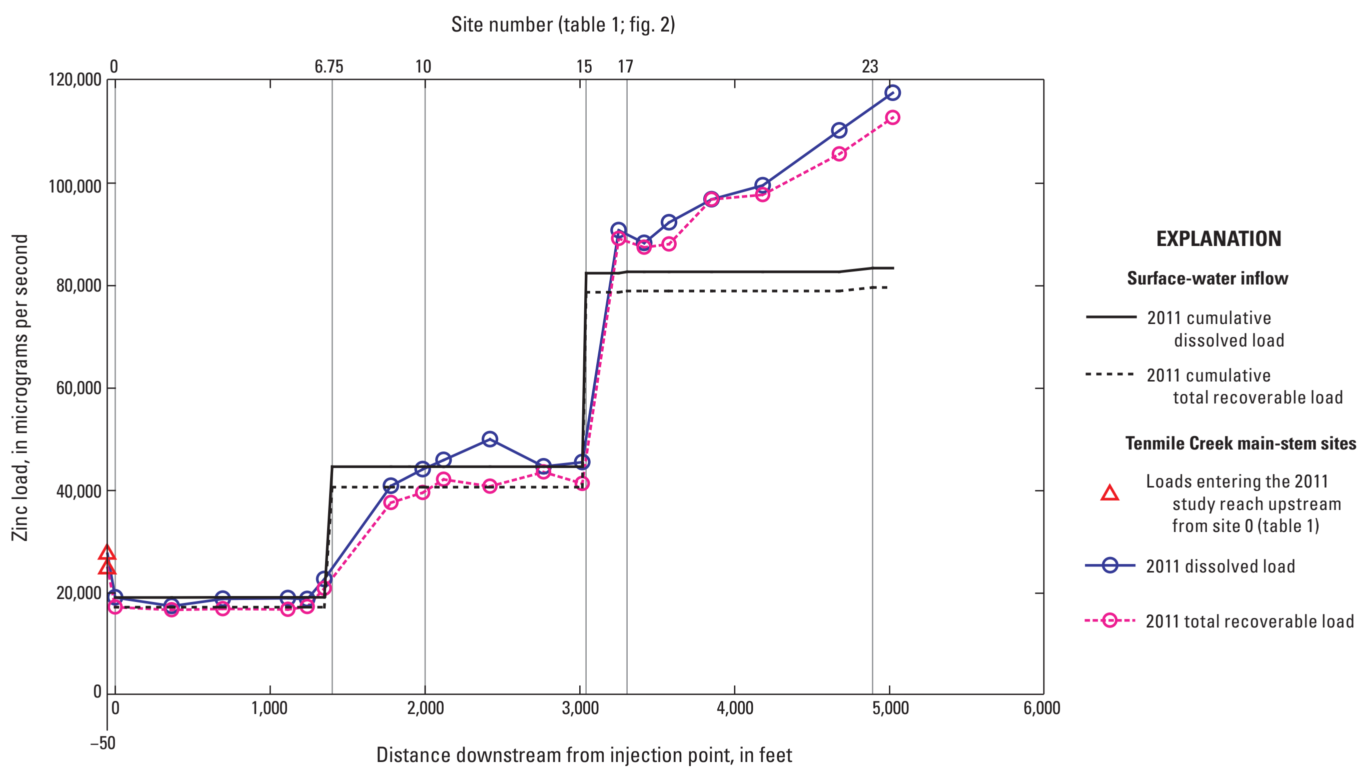

Figure 11. Tracer-calculated zinc loads, upper Tenmile Creek drainage basin, Montana, September 2011.

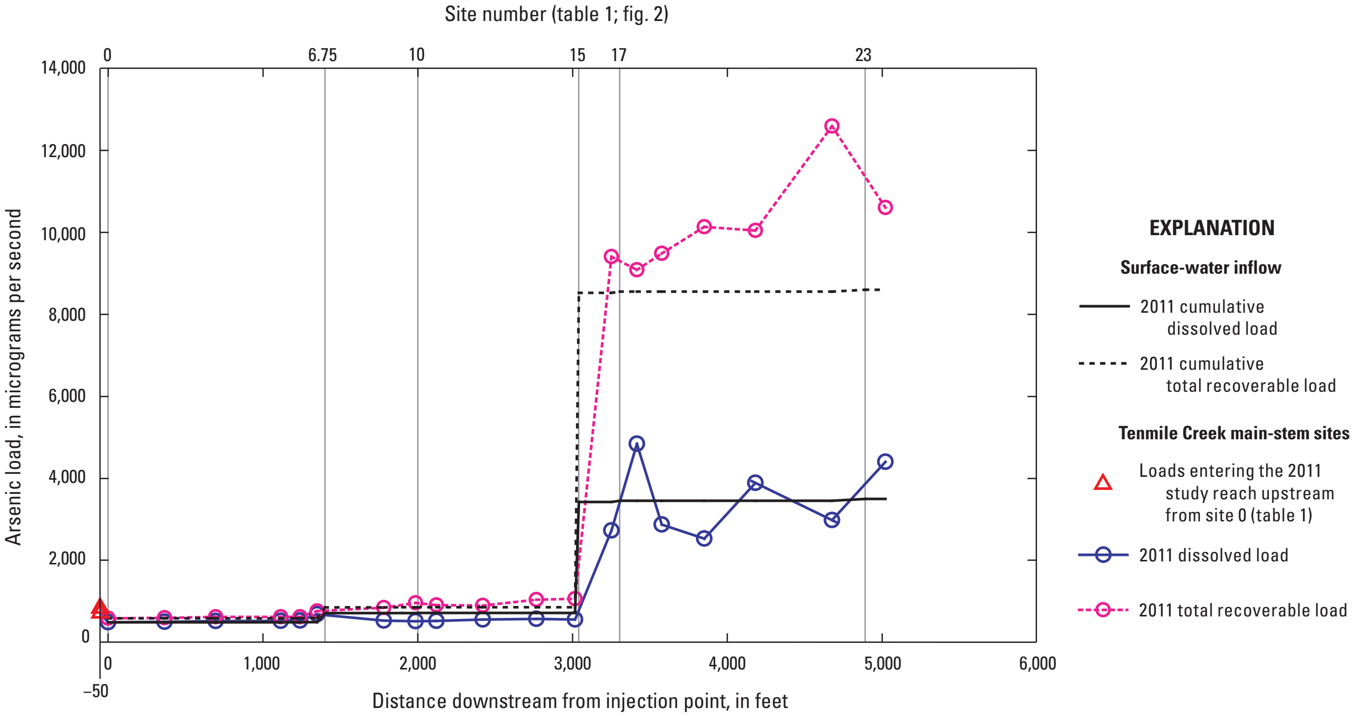

Figure 12. Tracer-calculated arsenic loads, upper Tenmile Creek drainage basin, Montana, September 2011.

Comparison of Relative Sources and Sinks of Trace-Element Loads between 2011 and 1998

Comparison of trace-element loads measured in the current study (2011) with those measured in 1998 was complicated by differences in hydrologic conditions between these years. In 1998, the streamflow in the study reach ranged from 5.0 L/s at site 1 to 10.2 L/s at site 24 (Cleasby and Nimick, 2002). In 2011, the streamflow ranged from 57.8 L/s at site 1 to 96.4 L/s at site 24 (table 4). Furthermore, at the USGS streamgage upper Tenmile Creek near Rimini (06062500), the mean daily streamflow measured in water year 2011 was 40.2 cubic feet per second, much higher than the mean daily streamflow of 17.1 cubic feet per second measured in water year 1998 (U.S. Geological Survey, 2016). The mean daily streamflow for the period of record from 1915 to 2011 was 17.0 cubic feet per second, indicating that streamflow conditions in 1998 were about average and that 2011 conditions were well above average. The smaller streamflow volume and extremely dry antecedent conditions in 1998 resulted in trace-element loads that were substantially less than loads in 2011. In contrast, 2011 was wetter than normal, and the streamflow and discharge from the mine adits and other sources were much larger.

A comparison of the differences of cumulative total-recoverable loads within the study reach, which is the cumulative downstream sum of all the sampled surface-water inflows, can be made between the two years. Subsurface inflows are not included in the determination of cumulative load, so the cumulative surface-water inflow load represents the minimum loading to the stream. Direct comparison of instantaneous loads and cumulative instantaneous loads of total-recoverable trace elements measured in 1998 versus 2011 (table 7) indicated that, although trace-element concentrations measured in 2011 were less than those measured in 1998, instantaneous, total-recoverable trace-element loads were larger in 2011 at every site sampled in both years. Considering the total cumulative instream total-recoverable loads, copper and arsenic showed the largest increases in 2011 over 1998 (table 7); the total cumulative load of total-recoverable copper increased by 560 percent, and the total cumulative load of total-recoverable arsenic increased by 735 percent across the study reach.

Upstream from the study reach at site 0 (fig. 2.), a portion of the streamflow and loads were diverted (city diversion) to the Ten Mile Water Treatment Plant in both 1998 and 2011. Streamflow and loads upstream from the city diversion included the accumulation of all upstream sources. It is possible that streamflow in upper Tenmile Creek could have been augmented from storage in Scott Reservoir or from Banner Creek (fig. 1). These upstream sources of water could have been diverted into or away from upper Tenmile Creek. The origin and relative amount of the water entering upper Tenmile Creek from these upstream sources was unknown during this study. The 1998 loads were described in Cleasby and Nimick (2002), and the 2011 loads are listed in table 6.

Between sites 1 and 5, there was relatively little loading of streamflow and trace elements in both 1998 and 2011. Losses of total-recoverable cadmium, copper, and zinc loads, and small gains in total-recoverable lead and arsenic loads, were observed in both studies (table 7). Small contributions of total-recoverable lead to upper Tenmile Creek were observed at sites 1, 2, 4, and 5 in 2011, but, in 1998, only site 4 within this area showed a gain in the total-recoverable lead load. Losses in total-recoverable zinc also were found at these sites in 1998, but a substantial gain in the total-recoverable zinc load was observed at site 4 in 2011. Increases in total-recoverable arsenic were measured at sites 2 and 4 in both years, and the arsenic contributions to upper Tenmile Creek were greater in 2011.

Between the Lee Mountain Mine area and the Susie Lode adit (sites 7–14), trace-element loading in upper Tenmile Creek decreased between 1998 and 2011 for total-recoverable lead, increased slightly for total-recoverable cadmium, and increased substantially for total-recoverable copper, zinc, and arsenic. In 2011, instantaneous loads of total-recoverable cadmium, copper, zinc, and arsenic increased substantially just below the Lee Mountain Mine adit (at site 7). Despite overall gains in loads, small losses in some reaches were observed between sites 11 and 14 in the total-recoverable copper and arsenic loads between Lee Mountain Mine and Suzie Load adits in 1998, and greater losses were observed in 2011 for zinc and arsenic loads, primarily between sites 11 and 14.

In 1998, the Susie Lode adit (site 15) was the primary source of total-recoverable cadmium, zinc, and arsenic. During the 2011 study, the Susie Lode adit also was a primary source of these trace elements and copper. In 2011, the instantaneous load at site 16 (the next site downstream from the Susie Lode adit) increased from 223 µg/s (site 14) to 698 µg/s for total-recoverable cadmium, from 608 µg/s (site 14) to 2,300 µg/s for total-recoverable copper, from 41,400 µg/s (site 14) to 89,100 µg/s for total-recoverable zinc, and from 1,060 µg/s (site 14) to 9,400 µg/s for total-recoverable arsenic. A small increase in total-recoverable lead was observed at site 16 in 2011, and this increase was very slight at this site in 1998 (table 7). Trace-element loads generally decreased in 1998 from site 18 to the end of the study reach at site 24 for total-recoverable cadmium, copper, lead, and arsenic. Loads of total-recoverable zinc in 1998 also decreased in this area between sites 16 and 22, but then notably increased again between sites 20 and 24. In 2011, instantaneous loads increased overall downstream from site 16 for total-recoverable cadmium, copper, and zinc. However, relatively large decreases were observed in 2011 at the most downstream site in the study reach (site 24) for instantaneous loads of total-recoverable copper, lead, and arsenic.

The most notable differences in trace-element loadings between 1998 and 2011 was in the reach downstream from the Susie Lode adit from site 16 to site 24 at the bottom of the study area (table 7). In 1998, all the total-recoverable trace-element loads indicated substantial losses, whereas, in 2011, all trace-element loads downstream from the Susie Lode adit increased. This increase in 2011 from 1998 conditions indicated that there were substantial contributions from trace-element sources in this area, through surface-water inflows or from resuspension of channel sediments, and the two surface-water inflows in this reach, Spring Creek and Moore's Spring Creek, contributed relatively small loads to upper Tenmile Creek. The load losses downstream from the Susie Lode adit in 1998 and the load gains in 2011 reflected differences in the hydrologic conditions between these years. In 1998, the streambed appeared to have acted as a sink, with dissolved trace elements precipitating from solution and sediment-associated trace elements falling out of the water column. In 2011, the increased stream velocity re-suspended the accumulated sediment and associated trace elements, which caused the reach downstream from the Susie Lode adit to act as a source of trace elements to the stream. Notably, the reach downstream from the Susie Lode adit contributed less than one-half of the total streamflow in 1998 and about 15 percent in 2011, indicating that groundwater discharge to upper Tenmile Creek during low streamflow conditions in this area was an important source of trace-element free water.

Table 7. Instantaneous loads and cumulative instantaneous loads (in micrograms per second) of total-recoverable trace elements measured in main-stem surface-water samples, upper Tenmile Creek, Montana, 1998 and 2011.

[The adits are indicated at their relative site locations, but loads from these sites were not included. Surface-water inflow sites or sites sampled only in 2011 are not included. Cumulative loads from 1998 include sites 0–24 in the lower reach. Sites were assigned short numbers (Site number), defined in table 1, and displayed on figure 2 (2011 only). bl, below; NA, data not available; ft, foot; ab, above]

Site	Station description	Load 1998	Load difference 1998	Cumulative load 1998	Load 2011	Load difference 2011	Cumulative load 2011
		Cadmium					
1	Tenmile Creek bl City Diversion at Rimini (injection point)	7.03	NA	NA	70.5	NA	NA
2	Tenmile Creek 365 ft bl City Diversion at Rimini	7.03	0.00	7.03	69.4	−1.12	70.5
4	Tenmile Creek 695 ft bl City Diversion at Rimini	6.62	−0.41	7.03	68.8	−0.64	70.5
5	Tenmile Creek 1,115 ft bl City Diversion at Rimini	6.13	−0.49	7.03	68.9	0.10	70.6
6.8	Lee Mountain Mine adit			Lee Mountain Mine adit			
7	Tenmile Creek 1,780 ft bl City Diversion at Rimini	14.9	8.77	15.8	187	118	189
9	Tenmile Creek 1,985 ft bl City Diversion at Rimini	57.7	42.8	58.6	188	0.33	189
11	Tenmile Creek 2,120 ft bl City Diversion at Rimini	122	64.3	123	211	23.5	213
12	Tenmile Creek 2,420 ft bl City Diversion at Rimini	135	13.0	136	210	−1.65	213
13	Tenmile Creek ab Susie Lode Adit at Rimini	136	1.00	137	217	7.31	220
14	Tenmile Creek 3,015 ft bl City Diversion at Rimini	144	8.00	145	223	6.15	226
15	Susie Load adit			Susie Load adit			
16	Tenmile Creek 3,250 ft bl City Diversion at Rimini	271	127	272	698	475	702
18	Tenmile Creek 3,415 ft bl City Diversion at Rimini	216	−55.0	272	677	−21.4	702
19	Tenmile Creek 3,575 ft bl City Diversion at Rimini	210	−6.00	272	677	−0.25	702
20	Tenmile Creek bl Spring Creek at Rimini	205	−5.00	272	734	57.3	759
21	Tenmile Creek 4,180 ft bl City Diversion at Rimini	228	23.0	295	742	8.14	767
22	Tenmile Creek 4,675 ft bl City Diversion at Rimini	209	−19.0	295	745	3.23	771
24	Tenmile Creek 5,020 ft bl City Diversion at Rimini	183	−26.0	295	756	10.3	781
	Percent increase in 2011 (versus 1998) at site 24	NA	NA	NA	NA	NA	165

Table 7. Instantaneous loads and cumulative instantaneous loads (in micrograms per second) of total-recoverable trace elements measured in main-stem surface-water samples, upper Tenmile Creek, Montana, 1998 and 2011.—Continued

[The adits are indicated at their relative site locations, but loads from these sites were not included. Surface-water inflow sites or sites sampled only in 2011 are not included. Cumulative loads from 1998 include sites 0-24 in the lower reach. Sites were assigned short numbers (Site number), defined in table 1, and displayed on figure 2 (2011 only). bl, below; NA, data not available; ft, foot; ab, above]

Site	Station description	Load 1998	Load difference 1998	Cumulative load 1998	Load 2011	Load difference 2011	Cumulative load 2011
				Copper			
1	Tenmile Creek bl City Diversion at Rimini (injection point)	33.6	NA	NA	179	NA	NA
2	Tenmile Creek 365 ft bl City Diversion at Rimini	32.2	−1.40	33.6	179	0.10	179
4	Tenmile Creek 695 ft bl City Diversion at Rimini	36.2	4.00	37.6	184	5.65	184
5	Tenmile Creek 1,115 ft bl City Diversion at Rimini	33.2	−3.00	37.6	178	−6.52	184
6.8	Lee Mountain Mine adit			Lee Mountain Mine adit			
7	Tenmile Creek 1,780 ft bl City Diversion at Rimini	42.3	9.10	46.7	402	225	409
9	Tenmile Creek 1,985 ft bl City Diversion at Rimini	110	67.7	114	431	28.8	437
11	Tenmile Creek 2,120 ft bl City Diversion at Rimini	295	185	299	527	95.5	533
12	Tenmile Creek 2,420 ft bl City Diversion at Rimini	326	31.0	330	566	39.1	572
13	Tenmile Creek ab Susie Lode Adit at Rimini	298	−28.0	330	615	48.7	621
14	Tenmile Creek 3,015 ft bl City Diversion at Rimini	288	−10.0	330	608	−6.92	621
15	Susie Load adit			Susie Load adit			
16	Tenmile Creek 3,250 ft bl City Diversion at Rimini	362	74.0	404	2,300	1,692	2,313
18	Tenmile Creek 3,415 ft bl City Diversion at Rimini	309	−53.0	404	2,270	−30.0	2,313
19	Tenmile Creek 3,575 ft bl City Diversion at Rimini	268	−41.0	404	2,300	30.0	2,343
20	Tenmile Creek bl Spring Creek at Rimini	296	28.0	432	2,470	170	2,513
21	Tenmile Creek 4,180 ft bl City Diversion at Rimini	292	−4.00	432	2,520	50.0	2,563
22	Tenmile Creek 4,675 ft bl City Diversion at Rimini	257	−35.0	432	2,810	290	2,853
24	Tenmile Creek 5,020 ft bl City Diversion at Rimini	244	−13.0	432	2,560	−250	2,853
	Percent increase in 2011 (versus 1998) at site 24	NA	NA	NA	NA	NA	165

Table 7. Instantaneous loads and cumulative instantaneous loads (in micrograms per second) of total-recoverable trace elements measured in main-stem surface-water samples, upper Tenmile Creek, Montana, 1998 and 2011.—Continued

[The adits are indicated at their relative site locations, but loads from these sites were not included. Surface-water inflow sites or sites sampled only in 2011 are not included. Cumulative loads from 1998 include sites 0-24 in the lower reach. Sites were assigned short numbers (Site number), defined in table 1, and displayed on figure 2 (2011 only). bl, below; NA, data not available; ft, foot; ab, above]

Site	Station description	Load 1998	Load difference 1998	Cumulative load 1998	Load 2011	Load difference 2011	Cumulative load 2011
		Lead					
1	Tenmile Creek bl City Diversion at Rimini (injection point)	22.1	NA	NA	99.4	NA	NA
2	Tenmile Creek 365 ft bl City Diversion at Rimini	21.6	−0.50	22.1	100	0.63	100
4	Tenmile Creek 695 ft bl City Diversion at Rimini	56.0	34.4	56.5	105	4.87	105
5	Tenmile Creek 1,115 ft bl City Diversion at Rimini	34.7	−21.3	56.5	105	0.46	105
6.8	Lee Mountain Mine adit	Lee Mountain Mine adit					
7	Tenmile Creek 1,780 ft bl City Diversion at Rimini	95.4	60.7	117	201	95.1	201
9	Tenmile Creek 1,985 ft bl City Diversion at Rimini	215	120	237	224	23.2	224
11	Tenmile Creek 2,120 ft bl City Diversion at Rimini	215	0	237	240	16.3	240
12	Tenmile Creek 2,420 ft bl City Diversion at Rimini	215	0	237	240	0.02	240
13	Tenmile Creek ab Susie Lode Adit at Rimini	217	2.00	239	279	39.1	279
14	Tenmile Creek 3,015 ft bl City Diversion at Rimini	238	21.0	260	277	−2.08	279
15	Susie Load adit	Susie Load adit					
16	Tenmile Creek 3,250 ft bl City Diversion at Rimini	239	1.00	261	333	55.6	335
18	Tenmile Creek 3,415 ft bl City Diversion at Rimini	208	−31.0	261	325	−7.38	335
19	Tenmile Creek 3,575 ft bl City Diversion at Rimini	168	−40.0	261	323	−2.76	335
20	Tenmile Creek bl Spring Creek at Rimini	164	−4.00	261	353	30.3	365
21	Tenmile Creek 4,180 ft bl City Diversion at Rimini	164	0	261	327	−26.2	365
22	Tenmile Creek 4,675 ft bl City Diversion at Rimini	133	−31.0	261	389	62.0	427
24	Tenmile Creek 5,020 ft bl City Diversion at Rimini	142	9.00	270	343	−45.6	427
	Percent increase in 2011 (versus 1998) at site 24	NA	NA	NA	NA	NA	58

Table 7. Instantaneous loads and cumulative instantaneous loads (in micrograms per second) of total-recoverable trace elements measured in main-stem surface-water samples, upper Tenmile Creek, Montana, 1998 and 2011.—Continued

[The adits are indicated at their relative site locations, but loads from these sites were not included. Surface-water inflow sites or sites sampled only in 2011 are not included. Cumulative loads from 1998 include sites 0-24 in the lower reach. Sites were assigned short numbers (Site number), defined in table 1, and displayed on figure 2 (2011 only). bl, below; NA, data not available; ft, feet; ab, above]

Site	Station description	Load 1998	Load difference 1998	Cumulative load 1998	Load 2011	Load difference 2011	Cumulative load 2011
		Zinc					
1	Tenmile Creek bl City Diversion at Rimini (injection point)	1,580	NA	NA	17,200	NA	NA
2	Tenmile Creek 365 ft bl City Diversion at Rimini	1,480	−100	1,580	16,700	-500	17,200
4	Tenmile Creek 695 ft bl City Diversion at Rimini	1,400	−80.0	1,580	16,900	200	17,400
5	Tenmile Creek 1,115 ft bl City Diversion at Rimini	1,310	−90.0	1,580	16,800	−100	17,400
6.8	Lee Mountain Mine adit	Lee Mountain Mine adit					
7	Tenmile Creek 1,780 ft bl City Diversion at Rimini	2,540	1,230	2,810	37,600	20,800	38,200
9	Tenmile Creek 1,985 ft bl City Diversion at Rimini	7,980	5,440	8,250	39,600	2,000	40,200
11	Tenmile Creek 2,120 ft bl City Diversion at Rimini	15,700	7,720	15,970	42,200	2,600	42,800
12	Tenmile Creek 2,420 ft bl City Diversion at Rimini	17,000	1,300	17,270	40,800	−1,400	42,800
13	Tenmile Creek ab Susie Lode Adit at Rimini	17,400	400	17,670	43,600	2,800	45,600
14	Tenmile Creek 3,015 ft bl City Diversion at Rimini	18,600	1,200	18,870	41,400	−2,200	45,600
15	Susie Load adit	Susie Load adit					
16	Tenmile Creek 3,250 ft bl City Diversion at Rimini	34,600	16,000	34,870	89,100	47,700	93,300
18	Tenmile Creek 3,415 ft bl City Diversion at Rimini	26,200	−8,400	34,870	87,400	−1,700	93,300
19	Tenmile Creek 3,575 ft bl City Diversion at Rimini	25,600	-600	34,870	88,100	700	94,000
20	Tenmile Creek bl Spring Creek at Rimini	24,700	-900	34,870	96,800	8,700	102,700
21	Tenmile Creek 4,180 ft bl City Diversion at Rimini	27,200	2,500	37,370	97,700	900	103,600
22	Tenmile Creek 4,675 ft bl City Diversion at Rimini	30,900	3,700	41,070	106,000	8,300	111,900
24	Tenmile Creek 5,020 ft bl City Diversion at Rimini	31,000	100	41,170	113,000	7,000	118,900
	Percent increase in 2011 (versus 1998) at site 24	NA	NA	NA	NA	NA	189

Table 7. Instantaneous loads and cumulative instantaneous loads (in micrograms per second) of total-recoverable trace elements measured in main-stem surface-water samples, upper Tenmile Creek, Montana, 1998 and 2011.—Continued

[The adits are indicated at their relative site locations, but loads from these sites were not included. Surface-water inflow sites or sites sampled only in 2011 are not included. Cumulative loads from 1998 include sites 0-24 in the lower reach. Sites were assigned short numbers (Site number), defined in table 1, and displayed on figure 2 (2011 only). bl, below; NA, data not available; ft, feet; ab, above]

Site	Station description	Load 1998	Load difference 1998	Cumulative load 1998	Load 2011	Load difference 2011	Cumulative load 2011
		Arsenic					
1	Tenmile Creek bl City Diversion at Rimini (injection point)	35.1	NA	NA	584	NA	NA
2	Tenmile Creek 365 ft bl City Diversion at Rimini	45.2	10.1	45.2	596	11.9	596
4	Tenmile Creek 695 ft bl City Diversion at Rimini	61.1	15.9	61.1	616	20.8	616
5	Tenmile Creek 1,115 ft bl City Diversion at Rimini	51.1	−10.0	61.1	617	0.24	616
6.8	Lee Mountain Mine adit	Lee Mountain Mine adit					
7	Tenmile Creek 1,780 ft bl City Diversion at Rimini	71.5	20.4	81.5	842	225	841
9	Tenmile Creek 1,985 ft bl City Diversion at Rimini	104	32.5	114	957	115	957
11	Tenmile Creek 2,120 ft bl City Diversion at Rimini	123	19.0	133	904	−52.8	957
12	Tenmile Creek 2,420 ft bl City Diversion at Rimini	117	−6.00	133	895	−9.23	957
13	Tenmile Creek ab Susie Lode Adit at Rimini	118	1.00	134	1,040	145	1,102
14	Tenmile Creek 3,015 ft bl City Diversion at Rimini	112	−6.00	134	1,060	19.9	1,122
15	Susie Load adit	Susie Load adit					
16	Tenmile Creek 3,250 ft bl City Diversion at Rimini	1,480	1,368	1,502	9,400	8,340	9,462
18	Tenmile Creek 3,415 ft bl City Diversion at Rimini	1,040	−440	1,502	9,080	−320	9,462
19	Tenmile Creek 3,575 ft bl City Diversion at Rimini	839	−201	1,502	9,480	400	9,862
20	Tenmile Creek bl Spring Creek at Rimini	903	64.0	1,566	10,100	620	10,482
21	Tenmile Creek 4,180 ft bl City Diversion at Rimini	775	−128	1,566	10,000	−100	10,482
22	Tenmile Creek 4,675 ft bl City Diversion at Rimini	676	−99.0	1,566	12,600	2,600	13,082
24	Tenmile Creek 5,020 ft bl City Diversion at Rimini	662	−14.0	1,566	10,600	−2,000	13,082
	Percent increase in 2011 (versus 1998) at site 24	NA	NA	NA	NA	NA	735

Summary and Conclusions

The upper Tenmile Creek drainage basin in west-central Montana is typical of many headwater areas in the Western United States where acid drainage from mine lands has affected water quality. In 1998, a trace-element loading study, using tracer techniques and synoptic water-quality sampling, was conducted in a 9.8-mile reach of the creek near Rimini, Montana. Results of the 1998 study identified and quantified substantial loads of trace elements entering the approximately 1-mile reach of upper Tenmile Creek that flows through the town of Rimini. Following remediation work that had been ongoing since 1998, a follow-up study was conducted in 2011 by the U.S. Geological Survey in cooperation with the Montana Department of Environmental Quality within the 1-mile subreach of upper Tenmile Creek that flows through Rimini.

The two principal objectives of the current (2011) study were to identify and quantify the principal sources of trace-element loads entering a subreach of upper Tenmile Creek and to compare these results to those from 1998. Physical and chemical data were collected from 19 main-stem sites, 8 surface-water inflow sites, and 8 groundwater monitoring wells on September 13 and 14, 2011. Trace-element loads in upper Tenmile Creek and surface-water inflow sites were quantified using streamflow data calculated using an injected dye tracer and water-quality data. Groundwater samples were collected to evaluate the diffuse loading to upper Tenmile Creek. Within the study reach that flows through Rimini, Mont., acid-mine drainage from the Lee Mountain Mine adit and the Susie Lode adit were identified as trace-element sources in the 1998 study.

In this study, streamflow in upper Tenmile Creek increased from 57.8 liters per second (L/s) at the tracer-injection point to 96.4 L/s at the lower end of the 5,020-foot study reach. Surface-water inflows accounted for about 15 percent of the increase, and subsurface inflow accounted for the rest. Current-meter measurements conducted in upper Tenmile Creek just upstream from the study reach indicated that about 26 L/s of the 83.5 L/s streamflow in this area was diverted to the treatment plant. In 1998, streamflow upstream from the city diversion was 185 L/s, however only about 5 L/s was measured in upper Tenmile Creek downstream from the city diversion. Throughout the entire study reach, streamflow in 1998 was about an order of magnitude less than the streamflow measured during the 2011 study.

Main stem trace-element concentrations were generally higher in 1998 than in 2011, but exceedances of the State of Montana human-health criteria were observed in upper Tenmile Creek in both studies. In 2011, the total-recoverable cadmium standard was exceeded downstream from the Susie Lode adit to the end of the study area but indicated a slight improvement over 1998. The standard for total-recoverable arsenic was exceeded throughout the study reach in both years. Total-recoverable zinc concentrations were less than the human-health standard for all sites in 2011 and were greater than the standard downstream from Beaver Creek through the end of the study reach in 1998. Throughout the study reach, acute aquatic-life criteria were exceeded at all main stem sites for cadmium and zinc in 1998 and 2011. Downstream from the Lee Mountain Mine adit, total-recoverable copper concentrations exceeded the chronic aquatic criterion in 2011, and main-stem concentrations exceeded the acute aquatic criterion throughout the study reach in 1998. Most main-stem sites exceeded the chronic aquatic-life criterion for lead in both years, and several sites also exceeded the acute criterion in 1998.

Groundwater level and water-quality data collected in the Lee Mountain area in 1998 indicated that a left-bank seep near the Lee Mountain Mine had the highest measured constituent concentrations of nearly all the samples collected that year. In 2011, trace-element concentrations in groundwater samples ranged from being like upper Tenmile Creek to being much greater than upper Tenmile Creek. Trace-element concentrations in wells from the right bank were generally lower than in those from the left bank. The pH in left-bank wells adjacent to the Lee Mountain Mine adit were acidic, and trace-element concentrations in left-bank wells were generally elevated compared to the right-bank wells adjacent to the streambed.

Loading over the entire study reach in 2011 increased elevenfold for total-recoverable cadmium, fourteenfold for total-recoverable copper, 3.5-fold for total-recoverable lead, sixfold for total-recoverable zinc, and eighteenfold for total-recoverable arsenic. The largest source of trace elements was the Susie Lode adit, and the second largest source of trace-element loading to upper Tenmile Creek was the Lee Mountain Mine adit. Diffuse loading in the 1,770-feet stream reach just upstream from Spring Creek to the end of the study reach also contributed large amounts of total-recoverable cadmium, copper, zinc, and arsenic to upper Tenmile Creek.

Direct comparisons of trace-element loading to upper Tenmile Creek between 1998 and 2011 were complicated by the difference in hydrologic conditions. Streamflow throughout the study reach during the 1998 study was about 10 percent of the 2011 streamflow. However, analysis of the relative contributions of different sources to the total loading showed that the Lee Mountain Mine area and the Susie Lode adit were major trace-element contributors to upper Tenmile Creek in both years. The most notable difference in trace-element loading between 1998 and 2011 was the difference in loading between the Susie Lode adit and the end of the study reach. In 1998, all the total-recoverable trace-element loads showed a substantial loss in this reach despite the contribution of a larger proportion of the streamflow relative to 2011. In the current (2011) study, all the total-recoverable trace-element loads increased in this reach. Differences in trace-element loading between 1998 and 2011 in this reach indicated that the streambed may act as either a source or sink for trace elements, depending on hydrologic conditions.

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