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Arsenic and Metal Loads and Source Areas in the Middle Fork Warm Springs Creek Watershed, Jefferson County, Montana, June 2001

Water-Resources Investigations Report 03-4153

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

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By Thomas E. Cleasby, Joanna N. Thamke, and David A. Nimick

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**Helena, Montana
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U.S. Department of the Interior

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CONVERSION FACTORS, VERTICAL DATUM, ABBREVIATED UNITS, AND ACRONYMS

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06309	liter per second (L/s)
mile (mi)	1.609	kilometer

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

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

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Abbreviated water-quality units and acronyms used in this report:

L	liter	RPD	relative percent difference
L/s	liters per second	NWQL	National Water Quality Laboratory, U.S. Geological Survey
mg/L	milligrams per liter	USDA Forest Service	U.S. Department of Agriculture Forest Service
mg/s	milligrams per second	USGS	U.S. Geological Survey
mL/min	milliliters per minute		
µg/L	micrograms per liter		
µg/s	micrograms per second		
µm	micrometer		

Arsenic and Metal Loads and Source Areas in the Middle Fork Warm Springs Creek Watershed, Jefferson County, Montana, June 2001

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Abstract

A constituent-loading study was conducted in the Middle Fork Warm Springs Creek watershed during low-flow conditions in late June 2001 to quantify arsenic and metal loads at various points in order to identify predominant source areas. Loads were calculated for 55 mainstem and inflow sites using stream-flow data and concentrations of arsenic and metals determined from synoptic sampling. Knowledge of the locations and relative importance of sources of arsenic and metals can aid resource managers in planning effective and cost-efficient remediation activities.

To improve resolution of incremental load increases, the watershed was divided into three subreaches based on stream-channel characteristics, flow, and possible metal sources. The upper subreach, from 0 to 3,220 feet, is an area that has been disturbed by previous mining activities and recent road development through waste-rock piles. The middle subreach, from 3,220 to 6,240 feet, had greater flow than the upper subreach, primarily from a right-bank tributary near the beginning of this subreach. Nearly 2,000 feet of the middle subreach flows through channel deposits of mill tailings that were derived from mining operations. The lower subreach, from 6,240 feet to the end of the study reach at 13,840 feet, had no obvious mining sources or other disturbances adjacent to the creek.

Mainstem concentrations of arsenic, cadmium, copper, lead, and zinc sharply increased near the uppermost part of the upper subreach. In the middle subreach, concentrations of all constituents were diluted by the large volume of water entering the Middle Fork Warm Springs Creek from the right-bank inflow at the beginning of the subreach. Downstream from this inflow, mainstem concentrations of cadmium, copper, and zinc remained mostly unchanged, and arsenic and

lead slightly increased. In the lower subreach, mainstem concentrations of cadmium gradually decreased, copper and zinc concentrations remained either mostly unchanged or slightly decreased, and mainstem concentrations of arsenic and lead steadily increased.

Throughout the entire study reach, the dissolved arsenic load increased by about 810 micrograms per second ($\mu\text{g/s}$) and total-recoverable arsenic load increased by more than 1,100 $\mu\text{g/s}$. Of this increase, approximately equal amounts of arsenic load entered the mainstem in each of the three subreaches. In the upper subreach, the largest surface inflow load of arsenic (109 $\mu\text{g/s}$ dissolved and 261 $\mu\text{g/s}$ total-recoverable) was measured at site 1,630, adit 4. In the middle subreach, the cumulative arsenic load from the sampled surface inflows only accounted for about 9 percent of the increase in the dissolved arsenic load through this subreach. Consequently, subsurface flow seeping into the mainstem probably is a substantial source of arsenic to the Middle Fork along the middle subreach. In the lower subreach, both dissolved and total-recoverable arsenic loads increased by more than 300 $\mu\text{g/s}$. Surface inflows only accounted for about 8 percent of this increase. A likely source of the remaining arsenic load increase in the lower subreach is subsurface flow or eroded mill tailings washed downstream from the middle subreach. Lead loads displayed a downstream pattern of increases similar to that of arsenic.

The largest loads of cadmium and zinc entered the mainstem in the first several hundred feet of the upper subreach and likely came from a combination of sources, such as adits and waste-rock piles, which are prevalent throughout this area. In this several hundred feet, the loads for dissolved and total-recoverable cadmium increased from about 1 $\mu\text{g/s}$ to about 40 $\mu\text{g/s}$, respectively, while dissolved and total-recoverable zinc loads increased from about 1 to about 7,500 $\mu\text{g/s}$,

respectively. No other major source area of cadmium or zinc was evident for the entire study reach, although smaller loads of zinc entered the mainstem near site 1,630 (about 2,100 $\mu\text{g/s}$) and site 7,510 (1,800 $\mu\text{g/s}$).

INTRODUCTION

The Middle Fork Warm Springs Creek watershed drains a highly mineralized area of the Elkhorn Mountains about 15 mi southeast of the city of Helena, Mont. (fig. 1). This area was extensively mined from the late-1890s to about 1939 with sporadic mining activity continuing into the late 1970s (Frontier Historical Consultants, 2001). Mining disturbances such as prospect pits, adits, waste-rock piles, and mill tailings are scattered throughout the watershed with some being near and in the stream channel. Recent road development through waste-rock piles may have increased erosion and transport of mine wastes. Acid drainage from these disturbances and natural weathering of mineralized rock has potentially affected the quality of water, aquatic habitat, and stream biota in this watershed. The generation of acid, mostly by oxidation of pyrite and other sulfide-rich ore exposed to the atmosphere either by natural weathering or mining operations, can liberate metals found within the mineralized rock. Arsenic and metal-rich waters can become a health risk to humans and can decrease the ability of a stream to support a healthy and diverse aquatic ecosystem. In severe cases, elevated arsenic and metal concentrations might degrade a stream's ability to sustain any appreciable aquatic life.

Periodic water samples collected in the Middle Fork Warm Springs Creek watershed have contained high trace-element concentrations (Montana Department of State Lands, 1995; Metesh and others, 1998; Olympus Environmental Science and Engineering, Inc., 1998; Klein and others, 2001). Although arsenic and metal concentrations have been shown to increase in the watershed downstream from mining development in this area, the specific source areas and transport pathways were not well understood. Possible sources of arsenic and metals to the Middle Fork are visible surface inflows, including seepage from waste-rock or tailings piles and discharge from adits, springs, and tributaries; and subsurface inflow of ground water. The relative contributions of arsenic and metals from mined areas and from unmined areas of natural mineralized rock have not previously been quantified. Further-

more, the importance of surface runoff and ground water as pathways for transporting arsenic and metals to the Middle Fork was unknown. Consequently, a constituent-loading study was undertaken using a design similar to other studies that have been useful in characterizing water quality in historically mined areas (Kimball, 1997; Kimball and others, 1999; Cleasby and others, 2000; Nimick and Cleasby, 2001; Cleasby and Nimick, 2002). By combining streamflow data and concentration data obtained by synoptic water-quality sampling, instantaneous loads can be determined at numerous locations and be used to construct detailed load profiles, thus allowing sources or source areas to be identified. With this information, resources managers can make informed, cost-efficient decisions in planning possible remediation activities.

Purpose and Scope

The purpose of this report is to quantify arsenic and metal loading to Middle Fork Warm Springs Creek and identify the principal source areas along the mainstem. Physical and chemical data were collected at 29 mainstem sites, 26 surface inflows, and 2 leachate pits along Middle Fork Warm Springs Creek corridor during low-flow conditions, June 2001 (fig. 1). A list of sites and a brief description of each site is presented in table 1 (back of report). The study reach was 13,840 ft (about 2.6 mi) in length and included all of Middle Fork Warm Springs Creek, about 3,220 ft of the left-bank headwater tributary upstream from the origin of Middle Fork Warm Springs Creek, and one site on Warm Springs Creek just downstream from the confluence of Middle Fork Warm Springs Creek and North Fork Warm Springs Creek (fig. 1). This study was conducted in cooperation with the U.S. Department of Agriculture Forest Service (USDA Forest Service).

Description of Study Area

The Middle Fork Warm Springs Creek watershed is a mixture of private and public lands. The watershed drains part of the Elkhorn Mountains about 15 mi southeast of the city of Helena, Mont. Middle Fork starts at the confluence of two unnamed tributaries and flows about 10,500 ft, where it joins with the North Fork to form Warm Springs Creek. For this report the left-bank (looking downstream) headwater tributary

upstream from the origin of Middle Fork Warm Springs Creek is, hereinafter, referred to as Middle Fork Warm Springs Creek and is considered part of the mainstem. The most upstream site sampled during this study was at an altitude of about 5,800 ft. The most downstream site in the study reach was at an altitude of about 4,760 ft on Warm Springs Creek, just downstream from the confluence of the Middle Fork and North Fork.

The study reach was divided into three subreaches based on stream-channel characteristics, flow, and observed potential metal sources. The upper subreach (from site 0 to site 3,220) is steep with a gradient of about 12 percent. The streambed is composed primarily of large cobbles and boulders. In many parts of the upper subreach, the stream channel is poorly defined and surface flow disappears under the coarse substrate of the channel. The area was highly disturbed by previous mining activities: between site 0 and site 240 streamflow was lost to shallow subsurface flow through a waste-rock pile (WR2), and between site 480 and site 790 streamflow was lost through a boulder field (fig. 1). Three mine sites, four adits, and numerous waste-rock piles (Olympus Environmental Science and Engineering, Inc., 1998) are located along the upper subreach near or in the channel. Recently, roads have been developed through waste-rock piles in the upper subreach.

The middle subreach (from site 3,220 to site 6,240) has a gradient of about 6 percent, which is one-half as steep as that in the upper subreach. The stream channel in the middle subreach is composed primarily of cobbles, gravels, sand, and silt. Streamflow in the middle subreach is much greater than that in the upper because of the relatively large contribution from the unnamed right-bank tributary just upstream from site 3,310. The stream in the middle subreach meanders through a relatively wide valley bottom and has characteristics of a pool-and riffle-type stream. More than 2,000 ft of the middle subreach flows through mill tailings between sites 3,680 and 6,240. A flotation mill was operated by the Newburgh Mine and Mill Company from 1934 to 1939. During the mill's operation, 67,352 tons of ore were processed (Roby and others, 1960). The lower reach (from site 6,240 to site 13,840) has the same general characteristics as the middle subreach except that no obvious mining sources are located adjacent to the creek.

The geology of the Middle Fork Warm Springs Creek watershed has been described by Greenwood and others (1990). Rocks within this area are predominantly quartz monzonite, with rhyolite capping the northern ridges of the watershed. Rhyolite porphyry plugs, dikes, and breccia also are present in the watershed, primarily on the northern ridges (Greenwood and others, 1990). The quartz monzonite of the Boulder batholith also can be found on the southern slopes of the watershed. According to Roby (1960), ore deposits in the Middle Fork Warm Springs Creek watershed are of two ages, late Cretaceous or early Tertiary and late Tertiary. The older deposits are east-trending quartz veins that include pyrite and chalcopyrite with some galena, sphalerite, and arsenopyrite. The ore of the younger deposits includes sulfides of iron, silver, copper, lead, and zinc.

Acknowledgments

Appreciation is extended to the individual landowners in the study area who allowed access to their property. In addition, several USDA Forest Service and U.S. Geological Survey (USGS) employees are acknowledged for their assistance with collection of water-quality and hydrologic data: Jack A. Kaiser and Melanie L. Scott of the USDA Forest Service; and Clarence L. Chambers, Kent A. Dodge, Cynthia J. Harksen, Adam N. Johnson, Philip L. Karper, John H. Lambing, and Andrew R. Skerda of the USGS.

METHODS OF DATA COLLECTION

During a reconnaissance of the study area, 57 synoptic-sampling sites were selected and marked with flagging. Locations of the sites were determined using a global positioning system. Sites were selected to provide a dense spatial resolution that bracketed all visible surface inflows to the mainstem, including all tributaries and seeps, and any streamside mine waste. To detect possible subsurface inflow, additional mainstem sites were selected in longer subreaches that had no visible surface inflow or mining disturbances. Locations of sampling sites were verified in the office by checking the latitude and longitude of each site on a topographic map. The upstream site (site 0) was located above the mining disturbances on Middle Fork Warm Springs Creek (fig. 1). Sampling sites were then num-

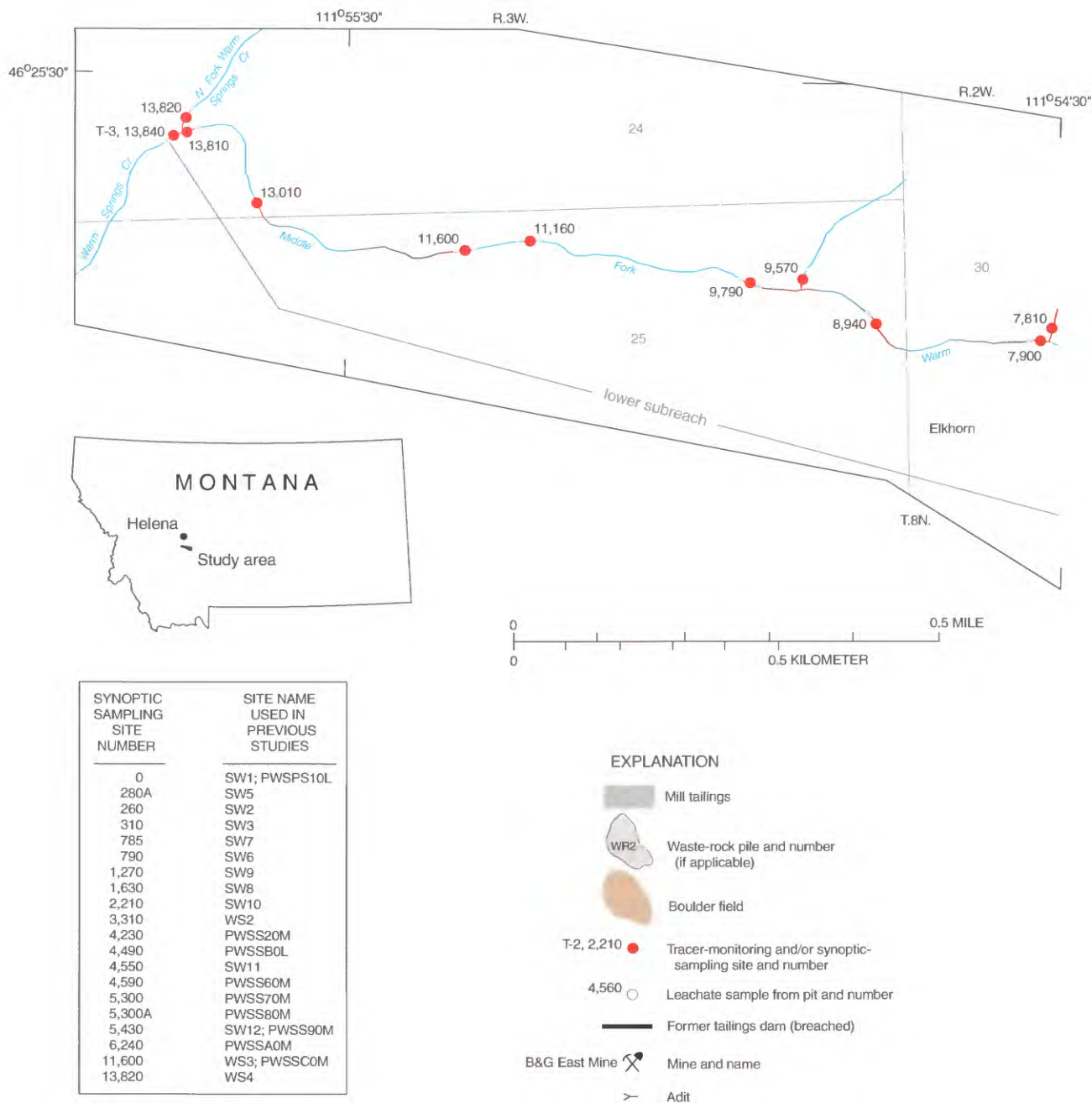
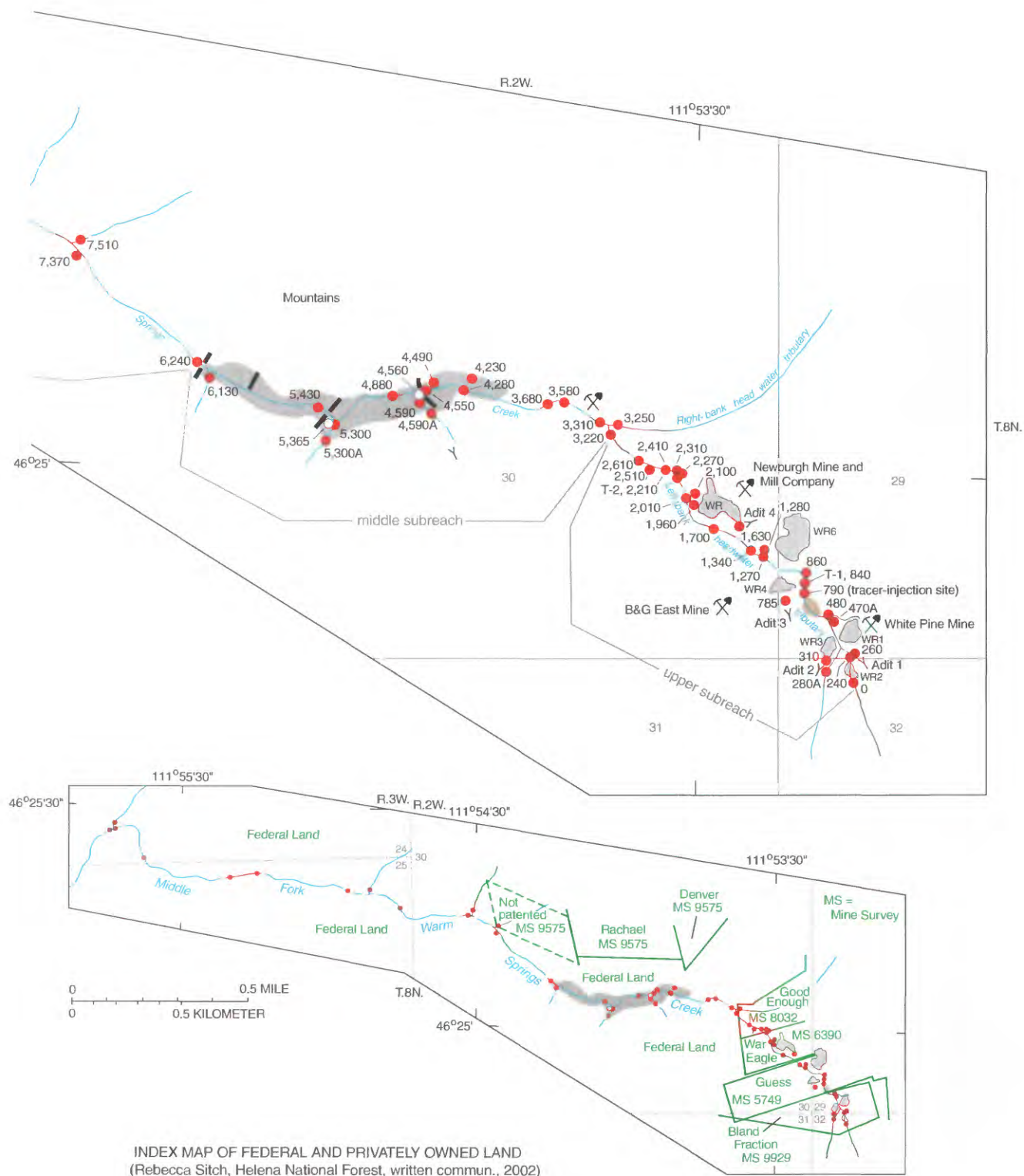


Figure 1. Middle Fork Warm Springs Creek watershed and location of synoptic-sampling sites, Montana.



Modified from Olympus Environmental Science and Engineering (1998).

bered as distance along the channel downstream from site 0, in feet. Samples at surface inflow sites 280A; 470A; 4,590A; and 5,300A were collected upstream from any obvious mining disturbance. Site descriptions and locations are presented in table 1. Right bank and left bank are terms used in this report to refer to the respective sides of the stream viewed while looking downstream.

Loads at various points along Middle Fork Warm Springs Creek and loads contributed by surface inflows were quantified by combining streamflow data with concentration data obtained from laboratory analysis of samples collected during this study. Downstream profiles of mainstem and surface-inflow loads provided the spatial information needed to identify the principal source areas contributing arsenic and metal loads to Middle Fork Warm Springs Creek.

Streamflow

Three methods were used to determine streamflow at sites during this study: current-meter measurements, volumetric measurements, and tracer-injection analysis. The first two methods are described by Buchanan and Somers (1969) and Rantz and others (1982). Tracer-injection methods are described in Kimball, 1997; Kimball and others, 1999; Cleasby and others, 2000; Nimick and Cleasby, 2001). Chloride was the tracer used to calculate streamflow for the tracer-injection method. An arbitrary flow value of 0.01 L/s was used for surface inflows (seeps) that were too small to accurately measure.

To document ambient chloride concentrations, samples were collected at sites downstream from the injection site (790) just prior to the start of the tracer injection (table 2, back of report). Samples were collected near the center of flow at each site and were filtered through a 0.45- μ m syringe filter.

Before the start of the tracer injection, an ample volume of tracer solution was prepared in a polyethylene tank by mixing approximately 550 pounds of sodium chloride (NaCl) with about 450 gallons of tap water. This mixture ratio produced a chloride concentration much higher than ambient concentrations in the stream, but less than the concentration at which the solution would be saturated with respect to NaCl. The tracer-injection site was located downstream from

obvious losing reaches observed during the reconnaissance. The tracer solution was injected continuously for about 121 hours into the mainstem at an average rate of about 223 mL/min. The tracer injection was started at 1225 hours on June 22, 2001, using a positive-displacement pump system controlled and monitored by an electronic data logger. The tracer injection ended at 1310 hours on June 27, 2001.

Water samples were collected at three sites (840; 2,210; and 13,840; also designated as tracer-monitoring sites T-1, T-2, and T-3, respectively; fig. 1) to document the downstream movement and concentration changes of the injected tracer. At each of the three sites, numerous chloride samples were collected during the study. Samples were collected prior to the arrival of the tracer and at multiple times during and after the tracer injection. These samples were collected manually or with automatic pumping samplers at a single point near midstream and were filtered through 0.45- μ m capsule filters.

Water Quality

Synoptic water samples for chemical analysis were collected on June 27, 2001, in acid-washed and stream-rinsed 3-L polyethylene bottles at each sampling site. To reduce the effect of load changes caused by diel variation, samples were collected throughout the study reach and processed as rapidly as possible using multiple teams of samplers. At each sampling site, water temperature was measured and samples were collected using grab methods at a single vertical near midstream where water was well mixed, but too shallow for depth-integrating sampling equipment.

Water-quality samples were transported to a central processing location near the middle of the study reach as soon as possible after collection. Values of pH were determined on an unfiltered aliquot of each sample. A second unfiltered aliquot was drawn for analysis of total-recoverable selected trace elements. A third aliquot was filtered through a 0.45- μ m capsule filter for the analysis of dissolved selected cations, arsenic, and selected metals. The latter two aliquots were preserved with ultra-pure nitric acid to a pH of less than 2. A fourth (filtered) aliquot was drawn for the analysis of dissolved chloride and sulfate. Sample processing, filtration, and preservation were performed according to procedures described by Ward and Harr (1990),

Horowitz and others (1994), and Wilde and others (1998). All samples were analyzed by the USGS National Water Quality Laboratory (NWQL) in Denver, Colo., using methods described by Fishman and Friedman (1989), Fishman (1993), Garbarino and Taylor (1996), Hoffman and others (1996), and Garbarino and Struzeski (1998). Water-quality data are presented in table 3 (back of report).

The USGS NWQL has developed a convention for reporting the presence of trace elements at low concentrations (Childress and others, 1999). These estimated values (indicated by a remark code "E" in this report) are smaller than a minimum concentration reliably reported by a given analytical method (the minimum reporting level), but larger than the method detection limit which was established to keep the possible occurrence of false negative or false positive error to 1 percent or less. The remark code "E" also is used to indicate quantitative uncertainty intermittently introduced by chemical interference or variable recovery efficiency (Furlong and others, 1996). Estimated values indicate that trace elements have been identified in a sample, but the reported concentration has more uncertainty than concentrations that are reported without the "E" remark code (concentrations higher than the minimum reporting level). "E" values or values less than the minimum reporting level (tables 3 and 4) were used directly for the calculation of loads throughout this report.

Quality Assurance

Data collection and analytical procedures used in this study incorporated practices designed to control, verify, and assess the quality of sample data. Methods and associated quality control for collection and field processing of water-quality samples are described by Horowitz and others (1994) and Wilde and others (1998).

The quality of analytical results reported for water-quality samples can be evaluated with data from quality-control samples that were submitted from the field and analyzed concurrently in the laboratory with routine samples. These quality-control samples consisted of replicates and field blanks, which provide quantitative information on the precision and bias of the overall field and laboratory process. In addition to quality-control samples submitted from the field, inter-

nal quality-assurance practices at the NWQL were performed systematically to provide quality control of analytical procedures (Pritt and Raese, 1995). These internal practices included analyses of quality-control samples such as calibration standards, standard-reference-water samples, replicate samples, deionized-water blanks, or spiked samples, at a proportion equivalent to at least 10 percent of the total samples analyzed.

Replicate samples were obtained in the field to provide data on precision (reproducibility) for samples exposed to all sources of variability. Precision of analytical results for field replicates is affected by many sources of variability within the field and laboratory environments, including sample collection, processing (filtration, preservation, transportation, and laboratory handling), and analysis. For this study, replicate samples were concurrently collected in the field at three sites (1,960, 4,590A, and 11,160) and analyzed separately. Analytical results for field replicates are presented in table 3. Precision of analytical results for any constituent can be determined from the relative percent difference (RPD) of the concentrations of the constituent in replicate analyses. The RPD is calculated for a constituent by dividing the absolute value of the difference between the two concentrations by the mean of the two concentrations and multiplying by 100. RPD for constituents that did not have concentrations reported as E values for dissolved and total-recoverable trace elements were all less than 13 percent, indicating good precision for analytical results.

Two field blanks were analyzed to identify the presence and magnitude of contamination that potentially could bias analytical results. A field blank is an aliquot of deionized water that is certified as essentially free of the measured trace elements and that is processed through the same sampling equipment used to collect stream samples. The blank is then subjected to the same processing (filtration, preservation, transportation, and laboratory handling) as stream samples. Blank samples were analyzed for the same constituents as those of stream samples to identify whether any detectable concentrations existed. Analytical results for field blanks are presented in table 3. Concentrations of all constituents were less than minimum reporting level, except for one total-recoverable zinc value of 3.2 µg/L. Consequently, analytical results for the environmental samples are assumed free of significant or

systematic bias from contamination associated with sample collection and processing.

TRACER-INJECTION AND SYNOPTIC-SAMPLING RESULTS

This tracer-injection and synoptic-sampling study was designed to determine streamflow and chemical quality at many mainstem and surface-inflow sites in a short period of time to create a nearly instantaneous measure of the transport of arsenic and selected metals in the study reach during low-flow conditions. Downstream changes in concentrations can be plotted as concentration profiles and reveal the locations of notable spatial differences that can indicate the effects of either significant load inputs or dilution by tributaries. Loads are calculated as the product of streamflow and concentration, and are used to quantify the mass of a constituent being transported per unit time. Load information also can be plotted as a downstream profile and used to identify abrupt increases that indicate locations of significant arsenic or metal source areas. Unlike concentration profiles, loads will not decrease as a result of dilution and, thus, provide a more accurate measure of downstream inputs of arsenic and metals. Because load calculations require both streamflow and concentration data, it is important that both components be accurately determined for detection of sources.

Streamflow

Streamflow was determined, in part, by tracer-injection methods, which are based on the principle of conservation-of-mass. The mass of the injected tracer, chloride for this study, is presumed to remain in solution as it travels downstream (not appreciably removed from the water column by sorption or biological uptake). After correcting for ambient instream chloride concentration, decreases in mainstem chloride concentration are attributed to dilution from inflows. The volume of water per unit time needed to achieve the measured chloride concentration for a given mass of injected tracer is calculated as the streamflow (tracer-calculated streamflow, table 2). Streamflow can only be determined by tracer-injection methods in a gaining stream reach where dilution effects on concentration can be translated to a quantifiable increase in flow. In a losing stream reach, the tracer concentration remains constant even though instream flow decreases. The

constant concentration implies no change in flow, thereby resulting in an overestimation of flow downstream from the losing reach.

Two surface inflows, site 1,280 and 1,960, had substantially higher chloride concentrations during the synoptic sampling compared to ambient concentrations measured prior to the tracer injection (table 2), indicating that some of the injected tracer was flowing into the subsurface near these inflows. Thus, streamflow probably also was flowing into the subsurface, indicating a losing stream reach between these sites. With this possible loss of injected tracer, streamflow just downstream from the injection site (790) could not be reliably calculated by the tracer-injection methods. Thus, streamflow for mainstem sites upstream from 2,210 was measured by a current meter.

Streamflow for mainstem sites downstream from site 2,210 was calculated using the synoptic chloride concentration at site 2,210 (36.1 mg/L) times the measured flow (5.52 L/s) to establish a new chloride injection load of 199.3 mg/s. Assuming this chloride load was conserved as it was transported downstream, then a decrease in chloride concentration represents an increase in streamflow, which can be calculated by dividing the load by the synoptic chloride concentration at downstream sites. For example, at site 3,220, the synoptic chloride concentration was 30.9 mg/L. Thus, the streamflow was determined by dividing 199.3 mg/s by 30.9 mg/L to calculate 6.45 L/s of streamflow (table 2).

Three tracer-monitoring sites located along the study reach (fig. 1, table 1) were sampled numerous times during this study. The first tracer-monitoring site was located at site 840 (T-1) and was as close to the tracer-injection site as possible. Additional tracer-monitoring sites were located at sites 2,210 (T-2) and 13,840 (T-3). Samples were collected hourly at tracer-monitoring sites T-1 and T-2; samples were collected every two hours at tracer-monitoring site T-3.

Information on the movement of the chloride tracer is gained by constructing temporal concentration profiles that show the change in chloride concentration with time at each tracer-monitoring site (fig. 2). Ideal temporal concentration profiles of an injected tracer have three distinct regions that show the arrival, plateau (or equilibrium) conditions, and departure of the

tracer. Chloride data from site 840 (T-1) are not shown on figure 2 because the chloride data were not used to calculate streamflow in the losing reach from site 840 to site 2,210.

Once the tracer has reached equilibrium at a site, a generally stable plateau concentration ideally will exist until the tracer injection is terminated. Therefore, in a gaining stream system, the plateau concentration decreases downstream as the result of dilution from inflows. Because equilibrium conditions are required for streamflow determinations and load comparisons, data from the tracer-monitoring sites are used to determine whether a relatively stable plateau concentration was reached at each site prior to and during collection of the synoptic water-quality samples. Chloride concentrations gradually increased during the plateau period at site 2,210 (T2) and site 13,840 (T3). The gradual increases likely indicated a steady decrease in streamflow during the 5-day plateau period due to hot, dry conditions; however, concentrations remained generally stable during the approximately 6-hour sampling period on June 27.

Instantaneous streamflow was determined at 25 mainstem and 25 inflow sites (fig. 3, table 2). Whenever possible, instantaneous streamflow was measured using volumetric or current-meter methods. However, streamflow at several surface inflows (seeps) was too small to be measured and was likely <0.01 L/s. These sites are listed as seeps in table 2. A value of 0.01 L/s was used for the load calculation at these inflows. Streamflow increased in the mainstem from 0.85 L/s at site 0 to 46.4 L/s at site 13,840, representing an overall net increase of 45.6 L/s. Measured and estimated surface inflows that entered the mainstem accounted for 34.2 L/s of this increase, with 11.4 L/s of the increase attributable to unmeasured subsurface inflows. Two inflows (sites 3,250 and 13,820) accounted for about 46 percent of the total increase in streamflow entering the mainstem during this study.

Water Quality

Synoptic water samples were collected at 29 mainstem sites, 26 inflow sites, and 2 near-stream pit sites where leachate water was obtained. These sam-

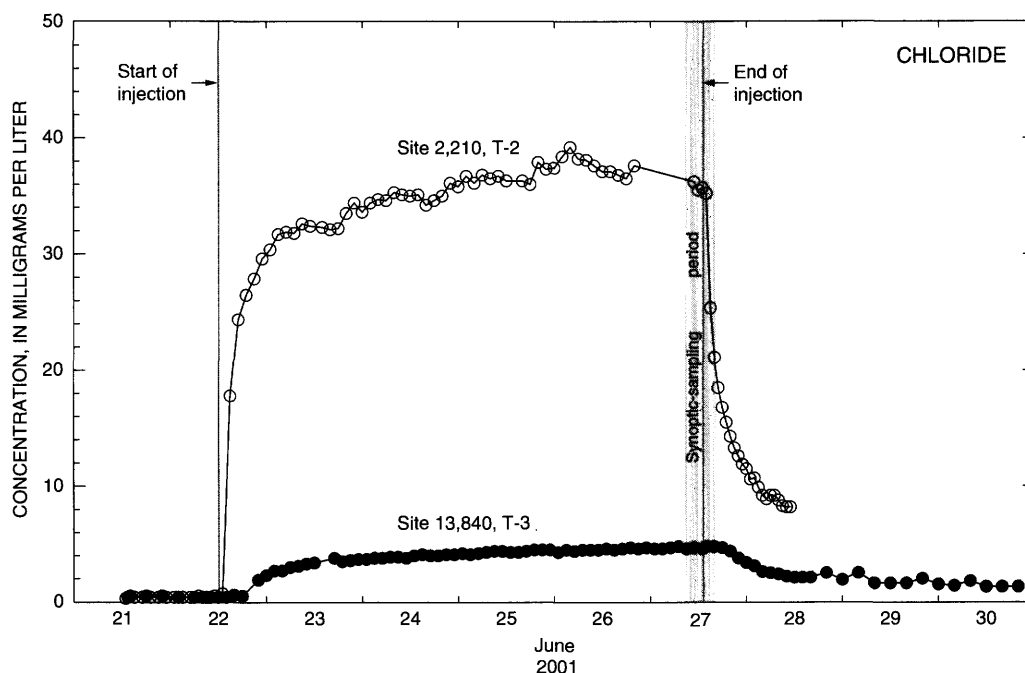


Figure 2. Temporal profiles of chloride concentration at two tracer-monitoring sites (2,210, T-2; and 13,840, T-3), Middle Fork Warm Springs Creek, Montana, June 21-30, 2001.

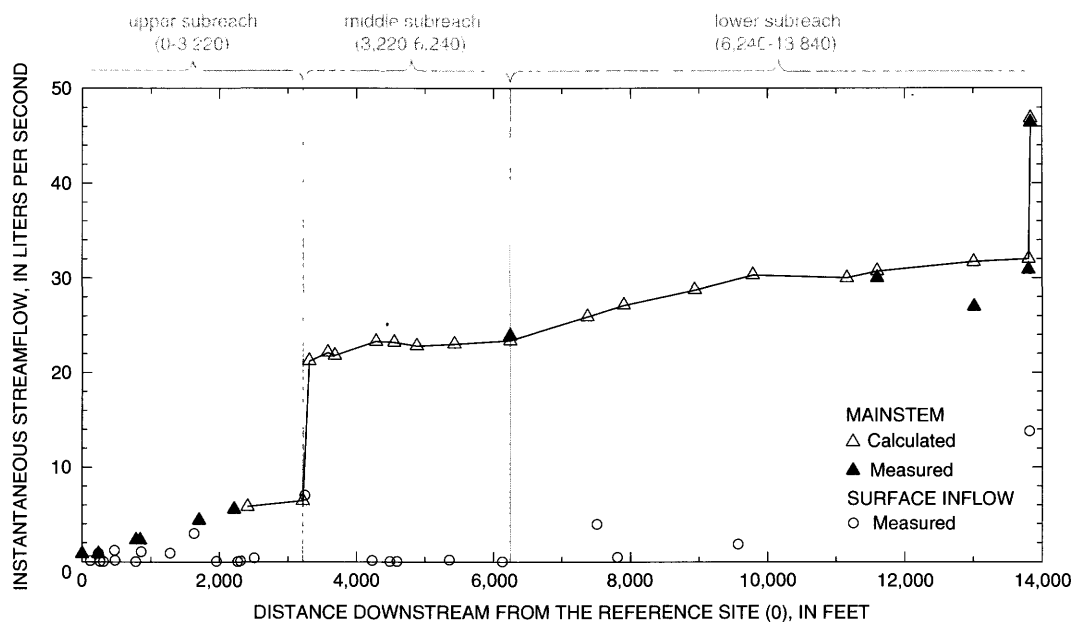


Figure 3. Downstream profile of streamflow at synoptic-sampling sites, Middle Fork Warm Springs Creek watershed, Montana, June 27, 2001.

ples were analyzed for pH, selected major ions, dissolved and total-recoverable arsenic, and selected dissolved and total-recoverable metals (table 3).

During the low-flow conditions of this study, pH values in the mainstem were near neutral to slightly basic (fig. 4, table 3) throughout the study reach, ranging from 7.45 (site 1,270) to 8.02 (site 7,900). Mainstem pH values remained relatively constant, except for a slight decrease between sites 240 and 1,700. Most surface inflows contributed near neutral or basic water to the mainstem, with most inflow pH values being lower than those in the mainstem. Two adits (adit 1 at site 260 and adit 2 at site 310) and one surface inflow flowing through the mill tailings area (site 4,590) contributed slightly acidic water, with pH values that ranged from 6.33 to 6.83.

Downstream concentration profiles for dissolved and total-recoverable arsenic, cadmium, copper, zinc, and total-recoverable lead show that mainstem concentrations at site 0 (upstream from mining disturbances) were low (fig. 5). Constituent concentrations sharply increased in the upper subreach (between site 240 and site 3,220). Mainstem concentrations of total-recover-

able arsenic and total-recoverable copper were highest at site 1,700, dissolved cadmium was highest at site 840, total-recoverable cadmium and dissolved and total-recoverable zinc were highest at site 790, and total-recoverable lead was highest at site 240. Downstream from site 790, dissolved and total-recoverable cadmium and zinc concentrations slightly decreased throughout the rest of the upper subreach. Total-recoverable lead concentrations decreased markedly from site 240 to site 790 and generally continued to decrease within the upper subreach. In the middle subreach (site 3,220 to site 6,240) all concentrations near the upstream end of the subreach were diluted by the right-bank tributary at site 3,250 (figs. 1 and 5). Downstream from this inflow, through the end of the study reach at site 13,840, mainstem concentrations of dissolved and total-recoverable cadmium decreased slightly, but steadily; dissolved and total-recoverable copper and zinc concentrations remained mostly unchanged; and arsenic and lead concentrations slightly increased. No abrupt shifts in concentration were observed for either the middle or lower subreaches below site 3,250. A gradual increase in concentration (about 15 $\mu\text{g/L}$) was measured in the middle subreach for arsenic.

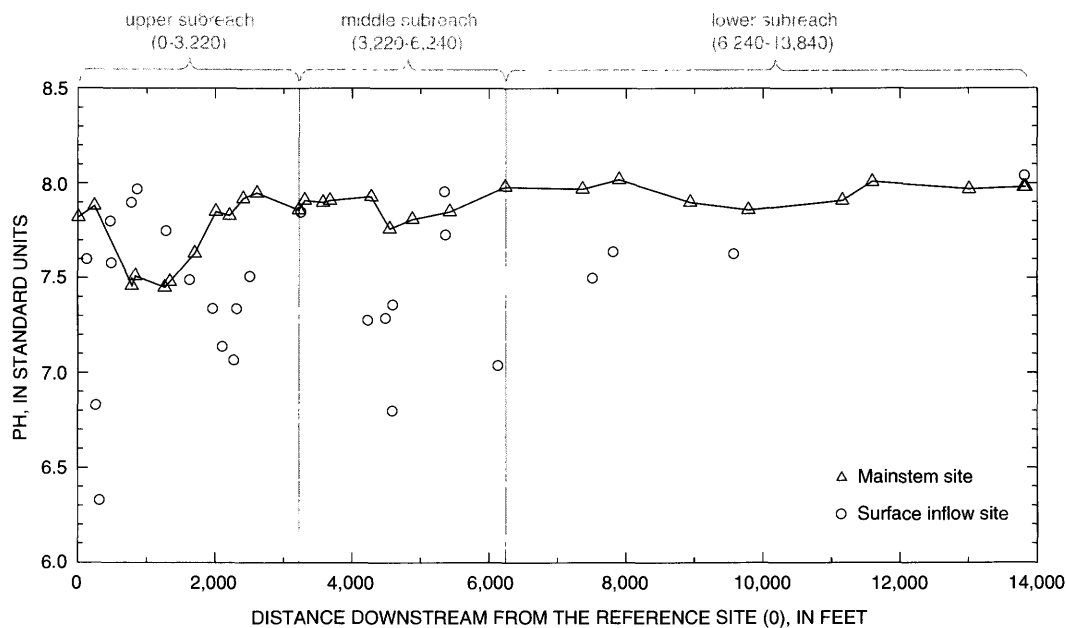


Figure 4. Downstream profile of pH in synoptic samples from Middle Fork Warm Springs Creek watershed, Montana, June 27, 2001.

Water-quality standards for surface water issued by the State of Montana (Montana Department of Environmental Quality, 2002) are compared to the total-recoverable concentration of arsenic and each metal. Human health standards and aquatic-life criteria are plotted on the concentration profiles (fig. 5) to illustrate spatial patterns of exceedance and non-exceedance.

The Montana human-health standard for total-recoverable arsenic ($18 \mu\text{g/L}$) was exceeded in numerous mainstem samples collected during this study (fig. 5). Although figure 5 shows the current (2002) Montana standard of $18 \mu\text{g/L}$, a proposed Federal standard of $10 \mu\text{g/L}$ is scheduled to go into effect January 2006 (U.S. Environmental Protection Agency, 2001). Water in samples from only 6 of 29 mainstem sites had concentrations below the current Montana human-health standard for arsenic. Arsenic concentrations exceeded the human-health standard at site 240 and from sites 1,270 to 3,220 in the upper subreach, and from site 4,280 in the middle subreach to the end of the lower subreach. Several inflow sites in the middle subreach also exceeded the arsenic standard. The proposed human-health standard for arsenic ($10 \mu\text{g/L}$) was exceeded at all mainstem sites downstream from site 0.

The human-health standard for total-recoverable cadmium ($5 \mu\text{g/L}$) was exceeded in the upper subreach between mainstem sites 790 and 2,410 (fig. 5). No exceedances of the human health standard for total-recoverable cadmium were observed in mainstem samples collected in the middle or lower subreaches, and only one inflow in the middle subreach exceeded the standard.

Aquatic-life criteria for chronic and acute toxicity for cadmium, copper, lead, and zinc vary with hardness, with metal toxicity decreasing as hardness increases. Chronic aquatic-life criteria for total-recoverable cadmium and zinc were exceeded in samples from many mainstem sites (fig. 5). Copper concentrations exceeded the chronic criterion at only two sites in the upper reach (sites 780 and 840). Cadmium concentrations exceeded the acute criterion in the upper subreach between mainstem sites 240 and 3,220; the chronic criterion was exceeded at all mainstem sites downstream from site 0. The chronic criterion for lead was exceeded; in the upper subreach between sites 790 to 1,700 the acute criterion for lead was exceeded at site 240. Exceedance of the total-recoverable lead criterion at site 0 could not be evaluated because the minimum

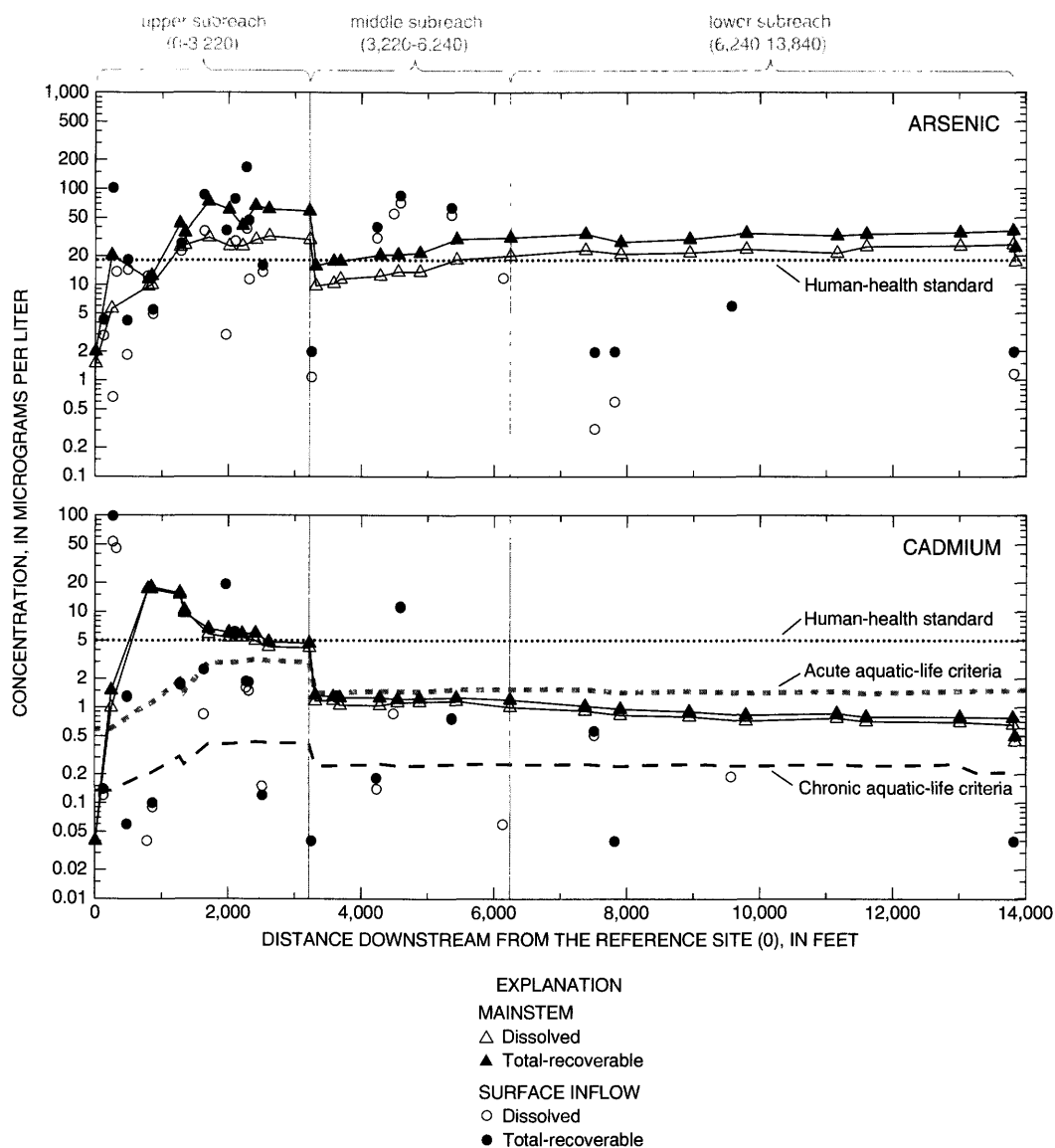


Figure 5. Downstream profiles of selected constituent concentrations in synoptic samples from Middle Fork Warm Springs Creek watershed, Montana, June 27, 2001. The State of Montana aquatic-life criteria are plotted for the mainstem and are hardness adjusted. For arsenic, the State of Montana human-health drinking-water standard is 18 micrograms per liter (Montana Department of Environmental Quality, 2002.) Estimated values or values equal to or less than the minimum reporting level are plotted at their estimated value or at the minimum reporting level.

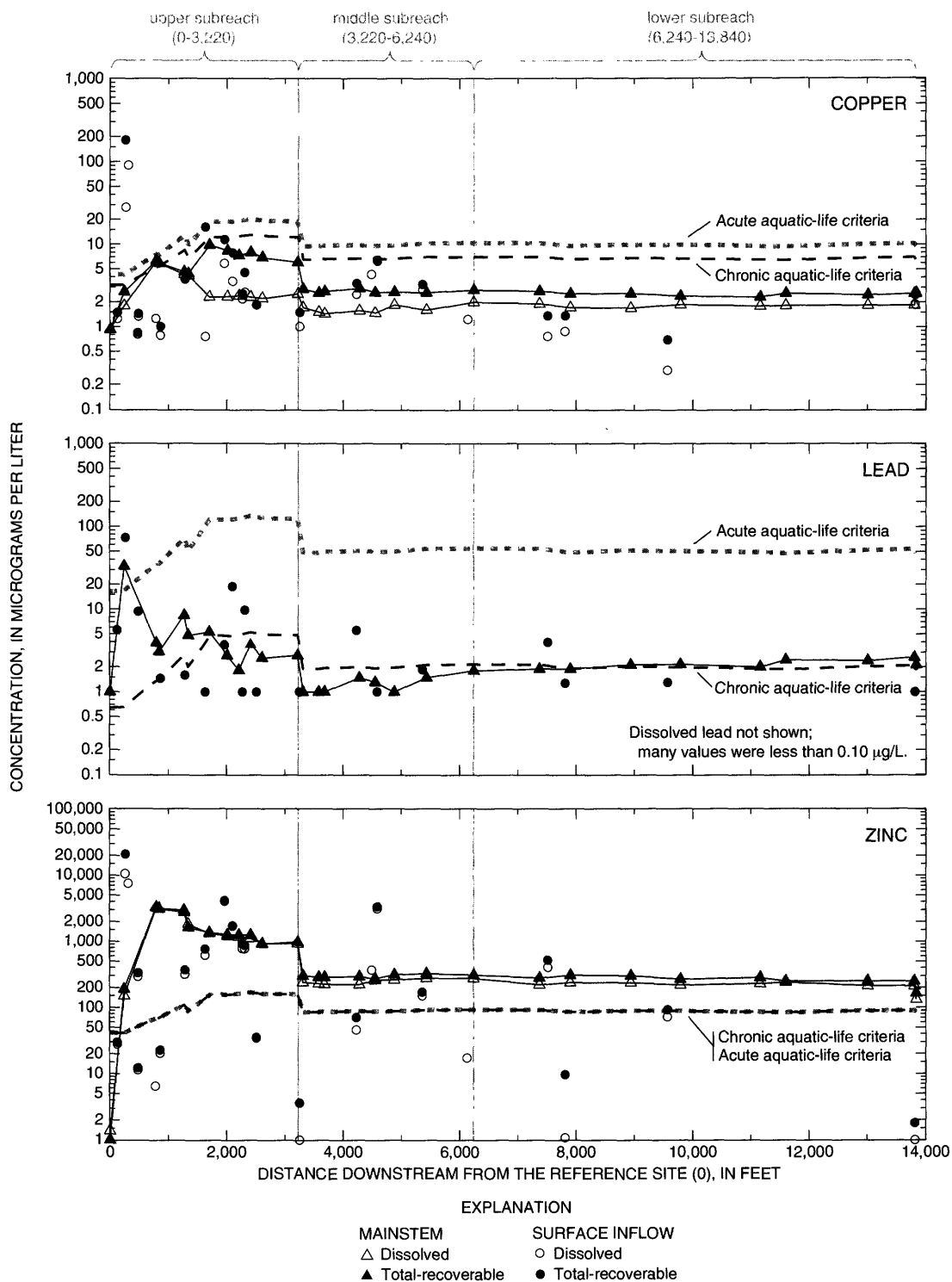


Figure 5. Downstream profiles of selected constituent concentrations in synoptic samples from Middle Fork Warm Springs Creek watershed, Montana, June 27, 2001 (Continued).

reporting level of <1 $\mu\text{g/L}$ exceeded the criteria. Concentrations of every mainstem sample downstream from site 0 exceeded the acute criterion for zinc.

Concentrations of arsenic, cadmium, copper, lead, and zinc in the surface inflows varied greatly throughout the study reach (fig. 5, table 3), with the greatest degree of variation occurring in the upper subreach. Total-recoverable concentrations of cadmium (99.6 $\mu\text{g/L}$), copper (184 $\mu\text{g/L}$), lead (74.1 $\mu\text{g/L}$), and zinc (21,000 $\mu\text{g/L}$) at inflow site 260 (adit 1) were higher than any other inflow in the study reach, and concentrations of total-recoverable arsenic (103 $\mu\text{g/L}$) were the second highest. Dissolved concentrations at nearby site 310 (adit 2) were the second highest of all inflows for cadmium (45.7 $\mu\text{g/L}$), copper (91.4 $\mu\text{g/L}$), and zinc (7,530 $\mu\text{g/L}$), and exceeded both dissolved and total-recoverable concentrations at all other inflow sites except site 260. The highest total-recoverable arsenic concentration was collected at inflow site 2,270 (168 $\mu\text{g/L}$). Concentrations in water from surface inflow sites 785 and 1,630 (adits 3 and 4, respectively) generally were lower than concentrations at sites 260 and 310 (adits 1 and 2, respectively). Site 785 (adit 3) had relatively low concentrations of all constituents analyzed during this study, except dissolved arsenic (12.3 $\mu\text{g/L}$). Concentrations at site 1,630 (adit 4) were high in total-recoverable arsenic (86.9 $\mu\text{g/L}$), cadmium (2.48 $\mu\text{g/L}$), copper (16.4 $\mu\text{g/L}$), and zinc (776 $\mu\text{g/L}$). The surface inflows draining waste-rock piles (sites 1,280; 1,960; and 2,100) all had high concentrations of total-recoverable arsenic, cadmium, copper, lead, and zinc. Total-recoverable zinc concentrations in these three surface inflows varied widely, ranging from 368 $\mu\text{g/L}$ to 4,250 $\mu\text{g/L}$. Surface inflows at sites 2,270 and 2,310 also had high concentrations of many of the constituents analyzed.

The right-bank surface inflow near the beginning of the middle subreach (site 3,250) had relatively low concentrations of all the constituents analyzed during this study. The large volume of streamflow (7.02 L/s, table 2) in this tributary and relatively low concentrations diluted the high concentrations contributed by inflows in the upper subreach, and can be seen as an abrupt drop in the concentration profiles for all constituents (fig. 5).

In the middle subreach, five surface inflows were sampled within the mill tailings area (sites 4,230,

4,490, 4,590, 5,300, and 6,130; fig. 1). Of those five inflows, site 4,590 (downstream from the first tailings dam) had the highest concentrations of arsenic, cadmium, copper, and zinc. Concentrations of dissolved cadmium and dissolved zinc at site 4,590 were about 13-fold and 8-fold greater, respectively, than any of the other inflows in the middle subreach. In addition to the samples that were collected in the depositional area of mill tailings at the mouth of inflow sites 4,590 and 5,300, a sample was collected upstream on each of these surface inflows (sites 4,590A and 5,300A) in an area above the margin of tailings deposition. Site 4,590A had high dissolved cadmium (7.32 $\mu\text{g/L}$), and dissolved zinc (1,940 $\mu\text{g/L}$) concentrations. Site 5,300A had relatively low concentrations of all the dissolved trace elements.

Two small pits were dug in the mill tailings area at sites 4,560 and 5,365 (fig. 1), and ground water leaching into the pits was sampled. Leachate water from site 4,560 had high concentrations of sulfate (103 mg/L), dissolved cadmium (5.18 $\mu\text{g/L}$), and dissolved zinc (1,960 $\mu\text{g/L}$). Concentrations of some trace elements in leachate water from site 4,560 were similar to concentrations determined at inflow sites 4,590 and 4,590A. Leachate water from site 5,365 (near the mouth of inflow site 5,300) had concentrations of dissolved cadmium (1.25 $\mu\text{g/L}$) and dissolved zinc (331 $\mu\text{g/L}$) that were more similar to the mainstem sites in this area than to the adjacent inflow. Dissolved arsenic (182 $\mu\text{g/L}$) and dissolved copper (9.25 $\mu\text{g/L}$) were significantly higher than mainstem concentrations.

Generally, surface inflows in the lower subreach (site 6,240 to 13,840) had low constituent concentrations. However, inflow site 7,510 had relatively high total-recoverable lead concentrations (3.98 $\mu\text{g/L}$) and high zinc concentrations (406 $\mu\text{g/L}$ for dissolved and 523 $\mu\text{g/L}$ for total-recoverable).

ARSENIC AND METAL LOADS

Load is the mass of a constituent transported downstream. Loads commonly are expressed as rates, or the mass transported per unit of time (for example, micrograms per second for an instantaneous load or kilograms per year for an annual load). Mainstem loads are the net result of load contributions from the sampled surface inflows and unsampled inflow (diffuse

subsurface flow and unsampled surface inflows), as well as load losses caused by streamflow loss, the formation and deposition of colloids, sorption, or other geochemical reactions. For chemically conservative constituents, loads are additive as inflows contribute their load to the load in the mainstem. If a constituent is removed from the water column, either by sorption to the streambed material or by a chemical reaction, it has the potential to later become re-suspended and transported if flow or geochemical conditions change. Thus, source areas and loading to a stream system might be different during varying hydrological conditions. The loads calculated for this study used data collected during low-flow conditions. To improve resolution and enhance the ability to identify trends in load changes, unrounded concentration values were used in load calculations. Instantaneous loads for dissolved and total-recoverable arsenic, cadmium, copper, and zinc and total-recoverable lead were calculated for 25 mainstem and 26 inflow sites (table 4, back of report). Loads were calculated using the minimum reporting level or estimated value at sites where concentrations were too low to be directly quantified (table 3).

A downstream load profile for a stream can be developed using synoptic streamflow and water-quality data from many sites along a stream. Such a profile can graphically illustrate the spatial distribution of loads and reveal notable differences in loads between sites. Downstream profiles for mainstem loads of arsenic, cadmium, lead, and zinc calculated from samples collected from the mainstem of Middle Fork Warm Springs Creek during this study are shown in figures 6 and 7. Load profiles for arsenic and lead exhibited similar spatial patterns and were plotted together (fig. 6). Cadmium and zinc also shared some common spatial features (fig. 7). Large changes in load, especially over short distances, effectively identify the location of significant sources or sinks of constituents. Because streamflow is a component of the load equation and measurement errors of about 10 percent may occur in irregular, cobble stream channels, load differences of 10 percent or less between sites may not necessarily represent actual load inputs or losses. However, if a directional pattern persists over a long reach of stream, then the gain or loss of load is not varying randomly and likely represents actual change.

The dissolved arsenic load increased by about 810 $\mu\text{g/s}$ and the total-recoverable arsenic load increased by about 1,140 $\mu\text{g/s}$ along the entire length of the mainstem of Middle Fork Warm Springs Creek from site 0 to site 13,840 (fig. 6, table 4). About 23 percent (189 $\mu\text{g/s}$) of the dissolved arsenic load increase and 33 percent (378 $\mu\text{g/s}$) of the total-recoverable arsenic load increase entered the mainstem in the upper subreach, with most entering between sites 840 and 1,700. About 14 percent (113 $\mu\text{g/s}$) of the dissolved and about 26 percent (293 $\mu\text{g/s}$) of the total-recoverable arsenic load increase for the entire study reach was contributed to the mainstem in the 860 ft reach between these sites. Most of this increase was contributed from inflow site 1,630 (adit 4), which had the largest arsenic load (109 $\mu\text{g/s}$ dissolved and 261 $\mu\text{g/s}$ total-recoverable arsenic; table 4) of any inflow measured during this study.

A substantial percentage of the arsenic load increase for the study reach entered the mainstem in the middle subreach (between sites 3,220 to 6,240). About 34 percent (278 $\mu\text{g/s}$) of the dissolved arsenic load increase and 30 percent (346 $\mu\text{g/s}$) of the total-recoverable arsenic load increase was contributed to the mainstem in the middle subreach. The sharpest increase in mainstem dissolved and total-recoverable arsenic load in the middle subreach was near the lower end of the mill tailings between sites 4,880 and 5,430. In this 550-ft reach of stream the dissolved arsenic load increased by 103 $\mu\text{g/s}$ (13 percent of study reach increase) and the total-recoverable by 189 $\mu\text{g/s}$ (17 percent of study reach increase). The cumulative load from the surface inflow sites (3,250; 4,230; 4,490; 4,590; 5,300; and 6,130) in the middle subreach area could only account for 24 $\mu\text{g/s}$ (about 3 percent) of the increase in the dissolved arsenic load for the study reach. Consequently, the small volume of subsurface flow that is seeping into the mainstem along the middle subreach (fig. 3) probably is a substantial source of arsenic loading to the Middle Fork of Warm Springs Creek.

In the lower subreach (sites 6,240 to 13,840), both dissolved and total-recoverable arsenic loads increased by more than 300 $\mu\text{g/s}$ (about 40 percent of study reach increase). The cumulative arsenic loads

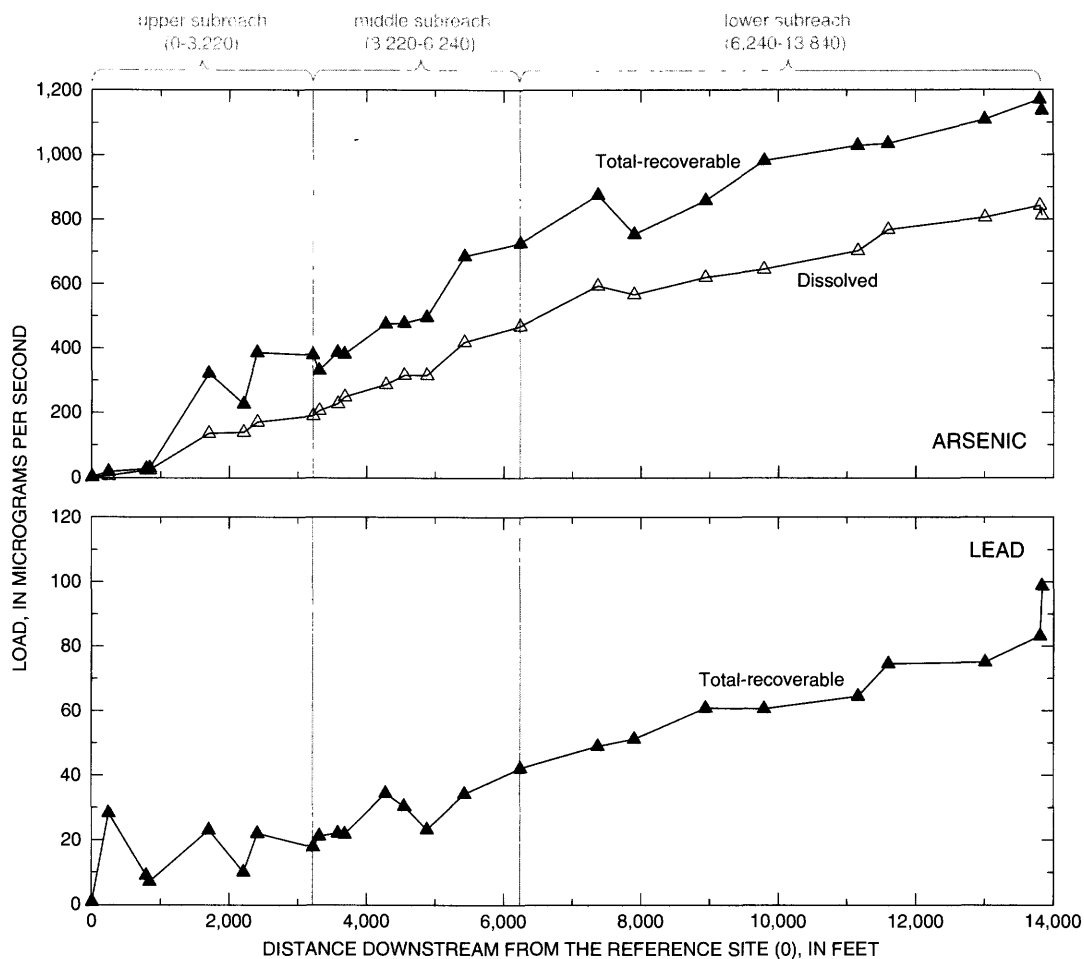


Figure 6. Instantaneous mainstem loads of arsenic and lead, Middle Fork Warm Springs Creek watershed, Montana, June 27, 2001.

from the surface inflows in the lower subreach (sites 7,510; 7,810; 9,570; and 13,820) could only account for 29 µg/s (about 4 percent of the study reach increase). Thus, additional sources of arsenic must be entering the mainstem. One possible source could be natural, diffuse subsurface flow that entered the mainstem in the lower subreach. However, most of the increase in streamflow through this area was accounted for by the surface inflows. Subsurface flow in this area was estimated to be only about 2.45 L/s. To achieve the loading increase through the lower subreach, the small amount of subsurface flow would need to have an average arsenic concentration of about 150 µg/L, which is much higher than concentrations in surface inflows. An alternative source of additional arsenic loading might be from the mill tailings that line the Middle Fork channel between sites 3,680 and 6,240 and pre-

sumably are migrating downstream. During high flow, tailings enriched with trace elements can erode and mix with stream sediment in the mainstem. Suspended in the water column, the mill tailings can be transported downstream and deposited in pools along the channel. The redeposited mill tailings can then become an instream source of trace-element loading to the mainstem, either by physical transport or geochemical dissolution.

The total-recoverable lead load increased by about 98 µg/s along the entire study reach of Middle Fork Warm Springs Creek (fig. 6, table 4). The total-recoverable lead load increased by about 27 µg/s (28 percent of study reach increase) between sites 0 to 240 where streamflow was diverted under a waste-rock pile (WR2, fig. 1) and lost to the subsurface. In the lower

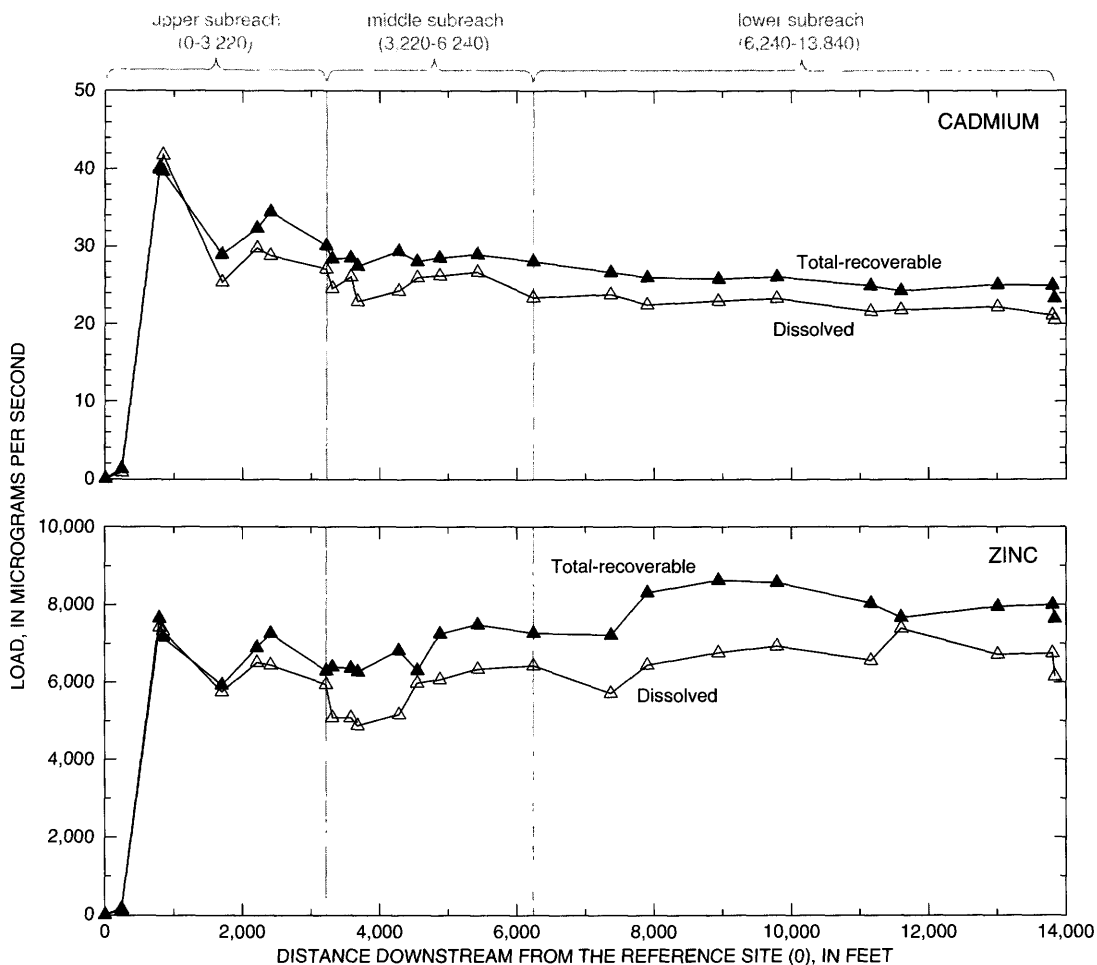


Figure 7. Instantaneous mainstem loads of cadmium and zinc, Middle Fork Warm Springs Creek watershed, Montana, June 27, 2001.

subreach, the total-recoverable lead load more than doubled with an increase of about 56 $\mu\text{g/s}$ (57 percent of study reach increase). The cumulative total-recoverable lead loads from the inflow sites through the lower subreach (sites 7,510; 7,810; 9,570; and 13,820) accounted for a little more than one-half of the load increase in the reach. Similar to the arsenic load, additional lead loading likely is derived either from the instream mill tailings that were transported downstream during high-flow events, or small volumes of enriched ground water.

The dissolved and total-recoverable cadmium loads had an overall net increase of about 20 $\mu\text{g/s}$ along the entire length of the Middle Fork Warm Springs Creek study reach (fig. 7, table 4). However, the cadmium load increased to a greater extent (from about 1 $\mu\text{g/s}$ to about 40 $\mu\text{g/s}$) between sites 240 and 790

(fig. 7) before gradually decreasing downstream. The cumulative loads of the surface inflow sites in this area (sites 260, 280A, 310, 480, and 785) were relatively small compared to the large mainstem load increase (table 4), accounting for only about 6 percent of the 39 $\mu\text{g/s}$ load increase over this 550 ft reach. Thus, most of the increase in cadmium load was attributed to unsampled sources. With only a small portion of the stream-flow increase between sites 240 and 790 not accounted for by surface inflows, the additional load originated from a source having highly elevated concentrations of cadmium. Site 260 (adit 1; 53.6 $\mu\text{g/L}$ dissolved and 99.6 $\mu\text{g/L}$ total-recoverable cadmium) and site 310 (adit 2; 45.7 $\mu\text{g/L}$ dissolved cadmium) had the two highest cadmium concentrations sampled during this study. Subsurface inflows entering near sites 260 and 310 might be sources of additional loads to the mainstem between sites 240 and 790.

Downstream from site 790, cadmium loads sharply decrease (between sites 840 and 1,700). This decrease in load might indicate a geochemical process, such as co-precipitation or adsorption to iron colloids, that removed cadmium from the water column, or might be the result of a loss in mainstem streamflow to ground water that is masked by tributary inflow.

The cumulative cadmium loads from surface inflows between mainstem sites 840 and 1,700 (sites 860; 1,280; and 1,630) are relatively large even though the cadmium load decreased in the mainstem through this area. Inflow site 1,630 (adit 4) had the largest cadmium load of any inflow (2.52 $\mu\text{g/s}$ for dissolved and 7.44 $\mu\text{g/s}$ for total-recoverable cadmium). At the time of this study, most of the flow at inflow site 1,630 (3 L/s) and, thus, most of the load that was discharged, did not enter the mainstem directly as surface inflow, but infiltrated into the waste-rock pile (WR) just downstream from site 1,630 (fig. 1). Flow that originated at site 1,630 likely entered the mainstem between sites 1,700 and 2,210 and caused the load increase between these sites. Mainstem cadmium loads downstream from site 2,210 generally decreased throughout the rest of the study reach, indicating that significant sources of cadmium (during low-flow conditions) are not present in the middle or lower subreaches, and that losses of cadmium load to instream geochemical processes occur even as the flow increases downstream.

Zinc loads had an overall net increase of 6,150 $\mu\text{g/s}$ for dissolved, and 7,640 $\mu\text{g/s}$ for total-recoverable along the entire study reach of Middle Fork Warm Springs Creek (fig. 7, table 4). Like cadmium, most of the zinc loads entered the mainstem between sites 240 and 790 (fig. 7). Also similar to cadmium, the cumulative zinc loads from the surface inflow sites in this area (sites 260, 280A, 310, 480, and 785) were relatively small (451 $\mu\text{g/s}$) compared to the load increase in the mainstem, accounting for only about 7 percent of the load increase through this 550 ft reach (table 4). To achieve the observed mainstem load increase between sites 240 and 790, the subsurface inflow not accounted for by measured surface inflows had to come from a source with highly elevated concentrations of zinc. Site 260 (adit 1; 10,610 $\mu\text{g/L}$ dissolved and 20,980 $\mu\text{g/L}$ total-recoverable zinc) and site 310 (adit 2; 7,530 $\mu\text{g/L}$ dissolved) had the two highest zinc concentrations sampled during this study. Subsurface inflows originating from the adit areas near sites 260 and 310 are likely sources of the additional loads to the mainstem between sites 240 and 790.

The mainstem dissolved zinc load decreased by about 1,570 $\mu\text{g/s}$ between sites 840 and 1,700. The cumulative dissolved zinc loads from the inflow sites (sites 860; 1,280; and 1,630) between these mainstem sites was about 2,160 $\mu\text{g/s}$. Similar to cadmium, even though zinc loading from the surface inflows was large between these two sites, the load decrease in the mainstem indicates substantial geochemical removal or a mainstem streamflow loss to ground water. Inflow site 1,630 (adit 4) had the largest zinc load of any inflow (1,850 $\mu\text{g/s}$ for dissolved and 2,380 $\mu\text{g/s}$ for total-recoverable zinc).

The mainstem zinc load increased between sites 1,700 and 2,210 to a greater extent than accounted for by surface inflows. A least part of this additional load may be from subsurface flow originating from the adit area near site 1,630 which presumably seeped into the mainstem between these sites.

Mainstem zinc loads downstream from site 2,210 were more variable than the cadmium loads (fig. 7). The dissolved zinc load decreased at inflow site 3,250. A possible explanation for this decrease was a chemical reaction caused by the mixing of the two waters that converted a portion of the dissolved zinc into a colloidal fraction that subsequently settled to the streambed. Dissolved zinc loads increased from 4,880 to 6,440 $\mu\text{g/s}$ through the remainder of the middle subreach (sites 3,680 to 6,240). Downstream from the middle subreach, the total-recoverable zinc load substantially increased (about 1,100 $\mu\text{s/s}$) between sites 7,370 and 7,900, likely as the result of inflow from site 7,510, which had the second largest zinc load of all inflows sampled during this study (table 4). Zinc loads remained relatively stable downstream from site 7,900 indicating a lack of any substantial source of zinc.

ARSENIC AND METAL SOURCE AREAS

On the basis of downstream load profiles, arsenic and lead loads generally enter the mainstem at a gradual rate throughout the entire length of Middle Fork Warm Springs Creek. An exception, however, occurred where arsenic loads sharply increased between mainstem sites 840 and 1,700. Most of the arsenic load between sites 840 and 1,700 entered the mainstem near two inflows, site 1,280 (drainage from a waste-rock pile), and site 1,630 (discharge from adit 4). Mill tailings that have been transported downstream also are a likely source of arsenic loading in the middle

and lower part of the study reach. Lead displayed generally similar patterns of gradual increase in load, with sporadic increases and decreases occurring in the upper subreach. Areas contributing the most significant amounts of arsenic and lead loads to the mainstem during low flow that could be targeted for remediation are difficult to assess. If all of the increase in arsenic load through the area of mill tailings in the middle subreach were eliminated by removal (219 $\mu\text{g/s}$ dissolved and 343 $\mu\text{g/s}$ total-recoverable), estimated arsenic concentrations (about 13 $\mu\text{g/L}$ dissolved and 17 $\mu\text{g/L}$ total-recoverable) at the downstream end of the study reach would be near or less than the current (2002) State of Montana human-health standard of 18 $\mu\text{g/L}$. A similar decrease in lead loads in the middle and lower subreaches would likely occur with tailings removal.

Most of the cadmium and zinc loads entered the mainstem between sites 240 and 790. Cadmium and zinc loads in the upper subreach were likely caused by subsurface inflow from a combination of sources, such as the adits and the waste-rock piles that are prevalent in the upper subreach. If cadmium and zinc loads in the upper reaches of the study could be eliminated or substantially reduced, concentrations of these trace elements in the mainstem would likely decrease accordingly. Sources of cadmium and zinc in the middle and lower subreaches are small compared to what is entering the Middle Fork in the upper subreach. Consequently, in contrast to arsenic and lead, removing the mill tailings in the middle subreach probably would have little effect on the reduction of cadmium and zinc concentrations.

Two inflows (site 1,630 and site 7,510) have the largest individual detrimental effects on the water quality in the Middle Fork mainstem. Site 1,630 (adit 4) had the largest loads of dissolved and total-recoverable arsenic, cadmium, and zinc and total-recoverable copper of any inflow sampled during this study. The effects of loads from site 1,630 (adit 4) to the mainstem loading was not directly measurable because most of the flow infiltrated underneath the waste-rock pile downstream from the mouth of the adit. Presumably, that water entered the mainstem at a downgradient location. Site 7,510, a right-bank inflow downstream from the middle subreach where mill tailings line the channel, had the largest total-recoverable lead load and the second largest dissolved and total-recoverable zinc and dissolved cadmium loads. Although substantial as

individual sources, the loads from these two inflows were relatively small compared to the cumulative loads from sources upstream from site 790.

SUMMARY

The Middle Fork Warm Springs Creek watershed is located about 15 mi southeast of Helena, Mont. This area was extensively mined from the late 1890s to about 1939 with sporadic mining activity continuing into the late 1970s. Mining disturbances are scattered throughout the watershed. Although arsenic and metal concentrations increase in the watershed downstream from mining development, the relative contributions of arsenic and metals from mine areas and from areas of mineralized rock have not previously been quantified. Furthermore, the importance of surface runoff and ground water as pathways for transporting arsenic and metals to the Middle Fork was unknown. Therefore, a constituent-loading study was conducted during June 21-27, 2001, to quantify loads and identify source areas contributing arsenic and metals to the Middle Fork Warm Springs Creek watershed during low-flow conditions. Knowledge of the main source of arsenic and metals can aid resource managers in planning effective and cost-efficient remediation activities.

The study reach was 13,840 ft (approximately 2.6 mi) in length and included all of Middle Fork Warm Springs Creek, about 3,220 ft of the left-bank headwater tributary upstream from the origin of Middle Fork Warm Springs Creek, and one site on Warm Springs Creek just downstream from the confluence of Middle Fork Warm Springs Creek and North Fork Warm Springs Creek. Physical and chemical data were collected at 29 mainstem sites, 26 surface inflow sites, and 2 leachate pits. Loads at various points were quantified using streamflow data (calculated by tracer-injection methods or measured by current-meter or volumetric methods) and water-quality data. During this low-flow study, streamflow increased by 45.6 L/s throughout the study reach. Measured and estimated surface inflows accounted for 34.2 L/s of this increase, with 11.4 L/s of the increase attributable to unmeasured subsurface inflows. Two surface inflows accounted for about 46 percent of the total increase in streamflow entering the mainstem during this study, the right-bank headwater tributary at the origin of Middle Fork Warm Springs Creek and North Fork Warm Springs Creek.

The study reach was divided into three sub-reaches based on stream-channel characteristics, flow, and possible metal sources. The upper subreach (from site 0 to site 3,220) is steep and the streambed is composed primarily of large cobbles and boulders. The area was disturbed from previous mining activities: between site 0 and site 240 streamflow infiltrated to the subsurface through a waste-rock pile, and between site 480 and site 790 streamflow infiltrated through a boulder field. The gradient in the middle subreach between site 3,220 to site 6,240 decreases and the channel is composed primarily of cobbles, gravels, sand, and silt. Streamflow in the middle subreach is much larger than that in the upper subreach because of the relatively large contribution from the right-bank headwater tributary near site 3,310. More than 2,000 ft of the mainstem flows through an extensive deposit of mill tailings between sites 3,680 and 6,240. The lower subreach (from site 6,240 to site 13,840) has the same general characteristics as the middle subreach, except that no obvious mining-related sources are located adjacent to the creek.

Mainstem concentrations of dissolved and total-recoverable arsenic, cadmium, copper, and zinc in water and total recoverable lead at site 0 (upstream from mining disturbances) were low. Constituent concentrations sharply increased in the upper subreach between site 240 and site 3,220. The highest mainstem concentrations in water for most of these constituents were determined within this portion of the upper subreach. In the middle subreach (from site 3,220 to site 6,240) all concentrations near the upstream end of the subreach were diluted by a right-bank tributary at site 3,250. Downstream from this inflow, mainstem concentrations of cadmium steadily decreased; copper and zinc concentrations remained mostly unchanged; arsenic and lead concentrations steadily increased. In the lower subreach (from site 6,240 to 13,840) dissolved and total-recoverable cadmium, copper, and zinc concentrations either remained mostly unchanged or decreased, whereas dissolved and total-recoverable arsenic and total-recoverable lead concentrations steadily increased.

Montana human-health standards for total-recoverable arsenic and cadmium were exceeded in numerous mainstem samples collected during this study. Arsenic concentrations in water from only 6 of 29 mainstem sites were less than the Montana current

human-health standard of 18 µg/L. The human-health standard for total-recoverable cadmium (5 µg/L) was exceeded in the upper subreach between mainstem sites 790 and 2,410.

Montana aquatic-life criteria for chronic toxicity were exceeded in water samples from many mainstem sites for total-recoverable cadmium, lead, and zinc. Cadmium concentrations exceeded the acute criterion in the upper subreach between mainstem sites 240 to 3,220 and the chronic criterion was exceeded at all mainstem sites downstream from site 0. Concentrations at only two mainstem sites, 790 and 840, exceeded the chronic criterion for copper. The chronic criterion for total-recoverable lead was exceeded in the upper subreach between sites 790 and 1,700; the acute criterion for lead was exceeded at site 240. Concentrations of every mainstem water sample downstream from site 0 exceeded the acute criterion for zinc.

The dissolved arsenic load increased by about 810 µg/s and total-recoverable arsenic load increased by about 1,140 µg/s throughout the entire study reach. Of this increase, approximately equal amounts of arsenic loads entered the mainstem in each of the three subreaches. In the upper subreach, the largest load of arsenic was measured at site 1,630 (adit 4), which had the largest arsenic load (109 µg/s dissolved and 261 µg/s total-recoverable) of any inflow measured during this study. In the middle subreach, the cumulative arsenic load from the surface inflows sampled could only account for about 3 percent of the increase in the dissolved arsenic load for the study. Consequently, a small volume of subsurface flow seeping into the mainstem along the middle subreach probably is a substantial source of arsenic loading to the Middle Fork Warm Springs Creek. In the lower subreach, both dissolved and total-recoverable arsenic increased by more than 300 µg/s (about 40 percent of study reach increase). Surface inflows only accounted for about 4 percent of the study reach increase. A likely source of the remaining arsenic load is an instream deposit of mill tailings washed downstream from the extensive channel deposits along most of the middle subreach. Similar to arsenic, the increase in lead load in the lower subreach could also be derived from instream deposits of mill tailings.

The largest cadmium and zinc loads entered the mainstem between sites 240 and 790. Most of the cad-

mium and zinc loads in the upper subreach were likely caused by subsurface inflow from a combination of sources, such as the adits and the waste-rock piles that are prevalent in the upper subreach. In the first several hundred feet of the upper subreach, the loads for dissolved and total-recoverable cadmium increased from about 1 µg/s to about 40 µg/s. Loads of cadmium and zinc entering the mainstem in the middle and lower subreaches are small compared to those entering in the upper subreach.

Two inflows (site 1,630 and site 7,510) have the largest individual detrimental effects on the water quality in the mainstem. Site 1,630 (adit 4) had the largest loads of arsenic, cadmium, and zinc and total-recoverable copper of any inflow sampled during this study. Site 7,510, a right-bank inflow downstream from the mill tailings, had the largest lead load and the second largest dissolved and total-recoverable zinc and dissolved cadmium loads. The loads from these two inflows were relatively small compared to the cumulative loads from sources upstream from site 790.

Removal of mill tailings in the middle subreach sufficient to eliminate the arsenic loads quantified in this study could decrease arsenic concentrations to levels near the State of Montana human-health standard of 18 µg/L. Additional removal of tailings that have been washed downstream during high flow and deposited in pools in the lower subreach would probably decrease arsenic concentrations further. Tailings removal also would likely decrease lead concentrations in the middle and lower subreaches. Cadmium and zinc loads are primarily derived from the adits and waste rock piles in the upper subreach; consequently, elimination or substantial reduction of loads from these sources would decrease concentrations accordingly. Cadmium and zinc sources in the middle and lower subreaches are small compared to those in the upper subreach. Consequently, in contrast to arsenic and lead, removal of mill tailings in the middle subreach probably would have little effect on reducing cadmium and zinc concentrations.

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DATA

Table 1. Field descriptions of synoptic-sampling sites, Middle Fork Warm Springs Creek watershed, Montana, June 2001

[Mainstem refers to sites on Middle Fork Warm Springs Creek, plus sites on left-bank headwater tributary, upstream from the origin of Middle Fork Warm Springs Creek. Site numbers followed by an "A" designate inflow sites that are upstream from the confluence of the mainstem. The terms left and right bank refer to the side of the creek viewed while looking downstream. Site number indicates distance downstream from the reference site (0), in feet. Abbreviations: ft, feet; T, tracer-monitoring site; WR, waste-rock pile; ID, identification]

Site number (fig. 1)	Site name used in previous studies	General site description	Station ID ¹
0	² SW1 ³ PWSPS10L	Mainstem, upstream from adits, waste-rock piles, mill tailings, and mines	462446111531501
280A	² SW5	Left-bank inflow, upstream from mines, about 260 ft upstream from confluence of mainstem	462447111531801
240		Mainstem, downstream from WR2	462448111531701
260	² SW2	Right-bank inflow originating from adit No. 1	462448111531601
310	² SW3	Left-bank inflow originating from adit No. 2	462448111531901
470A		Right-bank inflow, originating from WR1 (flowing into site 480)	462450111531701
480		Right-bank inflow just downstream from WR1, about 50 ft upstream from confluence of mainstem	462450111531702
785	² SW7	Left-bank inflow originating from adit No. 3, about 50 ft west of tracer-injection site	462451111532101
790	² SW6	Mainstem, tracer-injection site	462452111532001
840		Mainstem, about 50 ft downstream from tracer-injection site, WR4 adjacent to left bank, tracer-monitoring site T-1	462452111532002
860		Right-bank inflow	462452111532003
1,270	² SW9	Mainstem, downstream from WR4 and WR6	462454111532301
1,280		Right-bank inflow, originating from WR6	462455111532301
1,340		Mainstem, downstream from right-bank inflow	462455111532401
1,630	² SW8	Right-bank inflow, adit No. 4	462456111532701
1,700		Mainstem, downstream from adit No. 4	462456111532801
1,960		Right-bank inflow, drainage from WR	462457111533001
2,010		Mainstem, downstream from right-bank inflow	462458111533002
2,100		Right-bank inflow, drainage from WR	462458111533003
2,210	² SW10	Mainstem, just upstream from road crossing, tracer-monitoring site T-2	462459111533101
2,270		Right-bank inflow, upstream from culvert	462459111533102
2,310		Right-bank inflow, downstream from culvert	462459111533103
2,410		Mainstem, just downstream from road crossing	462459111533201
2,510		Left-bank inflow	462500111533401
2,610		Mainstem, downstream from left-bank inflow	462500111533501
3,220		Mainstem, just upstream from right-bank inflow	462502111533701
3,250		Right-bank headwater tributary	462502111533702
3,310	⁴ WS2	Mainstem, just upstream from mine shaft on right bank, beginning of Middle Fork Warm Springs Creek	462502111533801
3,580		Mainstem, downstream from mine shaft, small waste-rock pile across the road on left bank	462504111534201
3,680		Mainstem, upstream from road crossing	462506111534301
4,230	³ PWSS20M	Right-bank inflow, about 200 ft downstream from road crossing	462505111535101
4,280		Mainstem, downstream from right-bank inflow, site 4,230	462505111535102
4,490	³ PWSSB0L	Right-bank inflow, some ferricrete deposits on streambed	462504111535401
4,550	² SW11	Mainstem, upstream from first tailings dam	462504111535501
4,560		Left-bank leachate pit	462504111535502
4,590	³ PWSS60M	Left-bank inflow, water originates near an adit about 600 ft from creek bank	462459111540501
4,590A		Left-bank inflow (same inflow as 4,590), upstream from tailings, about 300 ft upstream from confluence with mainstem	462503111535601
4,880		Mainstem, downstream from first tailings dam	462503111535801
5,300	³ PWSS70M	Left-bank inflow, upstream from second tailings dam	462502111535301
5,300A	³ PWSS80M	Left-bank inflow (same inflow as 5,300), upstream from tailings, about 300 ft upstream from confluence with mainstem	462503111540301
5,365		Left-bank leachate pit	462503111540302
5,430	² SW12 ³ PWSS90M	Mainstem, downstream from second tailings dam	462503111540501
6,130		Left-bank inflow	462505111541401

Table 1. Field descriptions of synoptic-sampling sites, Middle Fork Warm Springs Creek watershed, Montana, June 2001 (Continued)

Site number (fig. 1)	Site name used in previous studies	General site description	Station ID ¹
6,240	³ PWSSA0M	Mainstem, just downstream from fourth tailings dam	462505111541601
7,370		Mainstem, upstream from right-bank inflows	462513111542701
7,510		Right-bank inflow	462513111542901
7,810		Right-bank inflow	462516111543201
7,900		Mainstem, downstream from right-bank inflows	462515111543301
8,940		Mainstem	462516111544701
9,570		Right-bank inflow	462519111545501
9,790		Mainstem, downstream from right-bank inflow	462518111545801
11,160		Mainstem	462521111551701
11,600	³ PWSSC0M ⁴ WS3	Mainstem	462521111552101
13,010		Mainstem	462523111554001
13,810	⁴ WS4	Mainstem, upstream from North Fork Warm Springs Creek	462526111554601
13,820		North Fork Warm Springs Creek, right-bank inflow to Middle Fork	462527111554601
13,840		Warm Springs Creek downstream from confluence of Middle and North Fork Warm Springs Creek, tracer-monitoring site T-3	462527111554701

¹Fifteen-digit station-identification number is a unique identifier that represents the approximate latitude and longitude location of the site (first 13 digits), plus a sequence number (last two digits).

²Site numbers from Olympus Environmental Science and Engineering, Inc., 1998.

³Site numbers from Metesh and others, 1998.

⁴Site numbers from Klein and others, 2001.

Table 2. Dissolved chloride concentration and streamflow at synoptic-sampling sites, Middle Fork Warm Springs Creek watershed, Montana, June 2001

[Site numbers followed by an "A" designate inflow sites that are upstream from the confluence with the mainstem. Site number indicates distance downstream from reference site (0), in feet. Sites in **bold type** indicate inflow sites. Abbreviations: E, estimated; L/s, liters per second; mg/L, milligrams per liter. Symbol: --, no data]

Site number (fig. 1)	Dissolved chloride concentration (mg/L)		Instantaneous streamflow (L/s)	
	Ambient, pre-tracer injection (June 22, 2001)	Synoptic, during tracer injection (June 27, 2001)	Tracer-calculated (June 27, 2001)	Measured (June 27, 2001)
0	--	0.21	--	0.85
240	--	.25	--	.85
260 ¹	--	.74	--	.03
280A	--	.09	--	.11
310 ¹	--	.31	--	seep ²
470A	--	.09	--	.14
480	--	.14	--	1.19
785 ¹	--	.33	--	seep ²
790	0.33	1.22	--	2.32
840	.29	129	--	2.32
860	.26	.19	--	1.05
1,270	.28	115	--	--
1,280	.26	7.89	--	.91
1,340	.28	66.6	--	--
1,630 ¹	.37	.35	--	3.00
1,700	.31	37.9	--	4.36
1,960	.36	3.56	--	.03
2,010	.26	36.4	--	--
2,100	.16	.12	--	seep ²
2,210	.31	36.1	--	5.52
2,270	.28	.25	--	--
2,310	.23	.59	--	.06
2,410	.31	34.3	5.81	--
2,510	.29	.28	--	.36
2,610	.27	³ 21.6	--	--
3,220	.30	30.9	6.45	--
3,250	.37	.33	--	7.02
3,310	.35	9.42	21.2	--
3,580	.34	9.00	22.1	--
3,680	.34	9.13	21.8	--
4,230	.34	.19	--	.14
4,280	.27	8.56	23.3	--
4,490	.24	E.06	--	seep ²
4,550	.29	8.58	23.2	--
4,590	.30	.13	--	seep ²
4,590A	--	.44	--	seep ²
4,880	.27	8.57	23.2	--
5,300	.33	.14	--	.20
5,300A	--	.20	--	seep ²
5,430	.39	8.66	23.7	--
6,130	.90	.45	--	seep ²
6,240	.38	8.50	23.4	23.9
7,370	.41	7.68	25.9	--
7,510	.49	.28	--	3.96
7,810	.25	.10	--	.46
7,900	.25	7.35	27.1	--
8,940	.38	6.94	28.7	--
9,570	.40	.30	--	1.83
9,790	.37	6.58	30.3	--
11,160	.36	6.36	30.3	--
11,600	.38	6.49	30.7	30.0
13,010	.37	6.29	31.7	26.8
13,810	.37	6.22	32.0	30.9
13,820	.44	.50	--	13.8
13,840	.42	4.28	46.6	46.4

¹Adit.

²Inflows that are listed as seeps were assigned a streamflow value of 0.01 L/s for load calculations.

³Sample was collected after the tracer-injection ended; thus, the synoptic-chloride concentration could not be used to estimate streamflow.

Table 3. Water-quality data for synoptic samples, Middle Fork Warm Springs Creek watershed, Montana, June 27, 2001

[Site numbers followed by an "A" designate inflow sites that are upstream from the confluence with the mainstem. Site number indicates distance downstream from the reference site (0), in feet. Unrounded arsenic and metal concentrations, shown below, were used to improve the resolution of the calculated loads.

Sites in **bold type** indicate inflow sites. Abbreviations: °C, degrees Celsius; E, estimated; µg/L, micrograms per liter; mg/L, milligrams per liter.

Symbols: <, less than; --, no data]

Site number (fig. 1)	Time	Water temperature (°C)	pH, field (standard units)	Hardness (mg/L as CaCO ₃)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO ₄)	Arsenic, dissolved (µg/L as As)	Arsenic, total recoverable (µg/L as As)
0	1310	5.5	7.82	28.2	8.67	1.58	0.21	6.93	1.50	E1.4
240	1330	5.5	7.88	28.7	8.79	1.64	.25	8.47	5.60	20.2
260	1340	5.5	6.83	89.5	28.6	4.38	.74	104	.67	103
280A	1318	5.0	7.60	35.4	10.5	2.23	.09	10.9	2.93	4.31
310	1425	9.5	6.33	56.2	16.2	3.81	.31	60.8	13.6	--
470A	1420	8.0	7.80	32.1	9.60	1.99	.14	8.38	1.84	4.24
480	1408	9.5	7.58	34.7	10.4	2.12	.09	12.7	14.3	18.2
785	1605	12.5	7.90	275	86.7	14.1	.33	133	12.3	--
790	1220	7.0	7.46	51.4	15.4	3.16	1.22	43.7	9.65	11.4
840	0820	6.5	7.51	52.0	15.7	3.10	129	42.3	10.0	12.4
860	1215	8.0	7.97	33.7	9.92	2.16	.19	8.83	4.95	5.51
1,270	0830	7.0	7.45	90.0	26.5	5.76	115	56.4	24.8	43.3
1,280	0835	8.0	7.75	41.3	12.2	2.63	7.89	83.9	22.4	26.9
1,340	0844	7.5	7.48	69.4	20.4	4.46	66.6	41.9	25.9	35.0
1,630	0851	7.5	7.49	241	67.8	17.3	.35	112	36.3	86.9
1,700	0902	7.5	7.63	137	39.2	9.58	37.9	69.5	31.1	73.8
1,960	0911	5.0	7.34	274	71.5	23.2	3.56	218	2.98	37.0
1,960¹	0912	5.0	7.34	257	66.6	21.9	3.30	217	2.89	38.6
2,010	0918	8.0	7.85	136	38.7	9.55	36.4	70.5	25.2	60.7
2,100	0920	9.0	7.14	299	76.4	26.2	.12	232	28.5	78.7
2,210	0932	8.0	7.83	140	39.8	9.97	36.1	75.0	25.2	41.1
2,270	0958	8.5	7.07	324	82.2	28.9	.25	246	38.4	168
2,310	1008	14.5	7.34	424	104	39.7	.59	315	11.4	47.2
2,410	0945	13.5	7.92	148	40.8	11.1	34.3	82.3	29.4	66.5
2,510	1238	8.0	7.51	49.0	14.3	3.24	.28	20.1	13.6	15.9
2,610	1517	12.0	7.95	142	39.8	10.3	21.6	84.0	32.1	61.6
3,220	1050	10.0	7.86	139	39.2	10.0	30.9	77.9	29.5	58.7
3,250	1055	10.5	7.85	36.4	10.7	2.35	.33	10.2	1.08	E1.4
3,310	1045	10.5	7.91	67.0	18.7	4.90	9.42	28.3	9.72	15.6
3,580	1040	10.5	7.90	66.4	19.0	4.62	9.00	30.4	10.3	17.5
3,680	1030	10.5	7.91	67.6	18.9	4.94	9.13	28.5	11.4	17.5
4,230	1010	12.5	7.28	34.8	10.1	2.32	.19	12.3	30.8	40.0
4,280	1000	10.0	7.93	69.3	19.7	4.91	8.56	28.3	12.3	20.4
4,490	0955	11.5	7.29	65.1	19.9	3.70	E.06	28.7	55.3	--
4,550	0945	10.0	7.76	67.9	19.4	4.73	8.58	31.0	13.6	20.6
4,560	0920	12.5	6.65	114	32.2	8.15	.33	103	52.3	135
4,590	0930	11.5	6.80	102	28.6	7.39	.13	91.1	71.6	85.2
4,590A	0935	6.0	7.37	89.1	25.2	6.36	.44	75.1	.80	E1.0

Table 3. Water-quality data for synoptic samples, Middle Fork Warm Springs Creek watershed, Montana, June 27, 2001 (Continued)

Cadmium, dissolved (µg/L as Cd)	Cad- mium, total recov- erable (µg/L as Cd)	Copper, dissolved (µg/L as Cu)	Copper, total recov- erable (µg/L as Cu)	Iron, dis- solved (µg/L as Fe)	Iron, total recov- erable (µg/L as Fe)	Lead, dis- solved (µg/L as Pb)	Lead, total recov- erable (µg/L as Pb)	Zinc, dis- solved (µg/L as Zn)	Zinc, total recov- erable (µg/L as Zn)	Site number (fig. 1)
<0.04	<0.04	0.93	0.92	E5.0	E13.2	E0.058	<1	1.37	<1	0
.99	1.50	1.80	2.66	E6.5	245	.463	33.3	150	189	240
53.6	99.6	28.2	184	<10	1,490	.805	74.1	10,600	21,000	260
.12	.14	1.24	1.48	E6.2	162	1.03	5.61	28.1	29.8	280A
45.7	--	91.4	--	E7.3	--	.244	--	7,530	--	310
.06	.06	.81	.85	E9.3	99.8	.161	--	11.3	12.3	470A
1.29	1.31	1.34	1.44	10.6	56.8	3.27	9.40	293	333	480
E.04	--	1.25	--	<10	--	E.06	--	6.5	--	785
17.2	17.3	6.20	6.33	27.6	62.8	1.36	3.89	3,200	3,300	790
18.0	17.1	5.88	5.95	26.7	47.2	1.59	3.06	3,160	3,090	840
.09	.10	.79	1.01	12.6	79.8	.241	1.46	20.3	22.8	860
15.6	15.0	4.32	4.65	11.3	144	.611	8.42	2,960	2,760	1,270
1.72	1.77	3.78	3.81	E9.8	62.2	.233	1.58	316	368	1,280
10.3	9.67	4.18	4.41	E9.3	83.5	.434	4.81	1,820	1,620	1,340
.84	2.48	.77	16.4	221	1,300	<.08	<1	615	776	1,630
5.82	6.64	2.31	9.86	177	763	.222	5.29	1,320	1,360	1,700
19.7	19.3	5.89	11.4	<10	635	<.08	3.70	4,100	4,250	1,960
19.4	19.5	6.09	11.1	<10	644	<.08	3.32	4,110	4,350	1,960¹
5.36	6.08	2.31	8.40	65	545	.111	2.75	1,200	1,260	2,010
5.79	6.16	3.60	7.93	<10	719	<.08	18.9	1,700	1,730	2,100
5.40	5.86	2.40	7.38	57.0	439	.249	1.82	1,180	1,250	2,210
1.61	1.87	2.20	2.53	167	1,210	<.08	<1	780	928	2,270
1.49	1.84	2.65	4.56	E6.1	891	.129	9.85	776	875	2,310
4.96	5.93	2.31	8.06	82.1	652	.140	3.79	1,110	1,250	2,410
.15	.12	1.87	1.85	E7.0	46.8	E.08	<1	35.2	34.4	2,510
4.28	4.84	2.22	6.96	82.3	444	.148	2.56	931	915	2,610
4.20	4.67	2.51	6.09	55.0	403	.120	2.76	923	977	3,220
<.04	<.04	1.01	1.50	<10	336	<.08	<1	<1	3.62	3,250
1.16	1.34	1.73	2.89	19.1	322	E.05	<1	240	302	3,310
1.18	1.29	1.52	2.60	17.4	312	.226	<1	230	288	3,580
1.05	1.26	1.45	2.70	19.1	300	E.06	<1	224	288	3,680
.14	.18	2.50	3.40	25.6	621	.424	5.60	45.9	70.4	4,230
1.04	1.26	1.58	2.95	13.0	347	<.08	1.48	222	293	4,280
.86	--	4.34	--	13.4	--	.104	--	370	--	4,490
1.12	1.21	1.48	2.62	18.6	308	E.06	1.31	258	272	4,550
5.18	5.44	5.75	11.4	21.8	888	1.02	43.9	1,960	2,040	4,560
11.1	11.3	6.54	6.32	11.2	31.4	.104	<1	3,140	3,370	4,590
7.32	7.38	1.92	1.96	<10	52.5	<.08	<1	1,940	1,920	4,590A

Table 3. Water-quality data for synoptic samples, Middle Fork Warm Springs Creek watershed, Montana, June 27, 2001 (Continued)

Site number (fig. 1)	Time	Water temperature (°C)	pH, field (standard units)	Hardness (mg/L as CaCO ₃)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO ₄)	Arsenic, dissolved (µg/L as As)	Arsenic, total recoverable (µg/L as As)
4,590A ¹	0936	6.0	7.37	95.2	26.8	6.85	.46	74.9	.83	<2
4,880	0910	9.5	7.81	68.6	19.6	4.77	8.57	32.5	13.6	21.4
5,300	0836	10.5	7.73	84.6	25.6	5.02	.14	35.9	53.7	63.7
5,300A	0900	9.5	7.96	98.7	30.8	5.30	.20	38.8	2.24	2.20
5,365	0845	14.0	7.38	189	54.2	13.1	E.06	98.0	182	--
5,430	0830	9.5	7.85	72.7	20.7	5.07	8.66	33.2	18.2	29.8
6,130	0820	11.5	7.04	58.1	17.2	3.67	.45	15.6	11.8	--
6,240	0815	9.5	7.98	73.1	21.0	5.00	8.50	33.5	20.0	31.0
7,370	1025	11.0	7.97	72.7	20.7	5.07	7.68	32.4	22.9	33.8
7,510	1020	10.5	7.50	19.6	6.42	.88	.28	9.09	.31	<2
7,810	1005	10.5	7.64	21.2	6.33	1.31	.10	6.51	.60	E1.1
7,900	1000	10.0	8.02	67.5	19.0	4.89	7.35	28.8	20.9	27.8
8,940	0950	10.0	7.90	70.0	20.1	4.82	6.94	29.7	21.6	29.9
9,570	0940	9.0	7.63	25.0	7.43	1.60	.30	8.70	5.70	6.00
9,790	0930	10.0	7.86	67.1	19.3	4.62	6.58	29.9	21.3	32.4
11,160	0910	10.0	7.91	69.2	19.8	4.77	6.65	28.9	23.4	34.3
11,160 ¹	0911	10.0	7.91	70.0	20.1	4.81	6.36	28.8	24.1	32.2
11,600	0905	10.5	8.01	65.8	18.9	4.54	6.49	30.2	25.0	33.7
13,010	0855	10.5	7.97	70.0	20.1	4.81	6.29	28.7	25.4	35.0
13,810	0840	10.5	7.98	71.3	20.4	4.91	6.22	28.6	26.3	36.6
13,820	0835	11.0	8.04	58.4	17.0	3.86	.50	12.8	1.17	E1.4
13,840	0825	10.5	7.98	66.4	19.1	4.52	4.28	24.5	17.4	24.2
Field blanks										
--	1600	--	6.09	--	<.01	<.008	<.08	<.1	<.2	<2
--	1500	--	6.11	--	<.01	<.008	<.08	<.1	<.2	<2

¹Replicate sample.

Table 3. Water-quality data for synoptic samples, Middle Fork Warm Springs Creek watershed, Montana, June 27, 2001 (Continued)

Cadmium, dissolved (µg/L as Cd)	Cad- mium, total recov- erable (µg/L as Cd)	Copper, dissolved (µg/L as Cu)	Copper, total recov- erable (µg/L as Cu)	Iron, dis- solved (µg/L as Fe)	Iron, total recov- erable (µg/L as Fe)	Lead, dis- solved (µg/L as Pb)	Lead, total recov- erable (µg/L as Pb)	Zinc, dis- solved (µg/L as Zn)	Zinc, total recov- erable (µg/L as Zn)	Site number (fig. 1)
7.32	7.25	1.70	1.77	<10	46.6	<.08	<1	1,900	1,890	4,590A¹
1.13	1.23	1.86	2.66	19.4	302	E.06	<1	262	313	4,880
.76	.78	2.82	3.30	32.1	83.3	E.05	1.87	150	170	5,300
.05	.07	.92	.83	<10	34.2	<.08	<1	25.3	29.1	5,300A
1.25	--	9.25	--	16.6	--	.384	--	331	--	5,365
1.16	1.26	1.61	2.62	25.5	349	E.06	1.49	276	326	5,430
.06	--	1.24	--	19.8	--	.185	--	17.4	--	6,130
1.10	1.23	2.10	2.80	20	310	E.04	1.80	275	311	6,240
.92	1.03	1.92	2.72	18.7	283	<.08	1.89	221	279	7,370
.51	.57	.77	1.38	<10	653	.177	3.98	406	523	7,510
<.04	<.04	.89	1.37	18.3	609	E.04	1.28	1.08	9.68	7,810
.83	.96	1.73	2.54	15.9	308	.081	1.89	238	307	7,900
.80	.90	1.70	2.55	E9.8	308	.094	2.12	236	301	8,940
.15	.19	.70	1.10	E6.0	200	E.06	1.30	72.0	92.1	9,570
.77	.86	1.79	2.30	E6.9	260	.143	2.00	229	283	9,790
.72	.83	1.87	2.38	E6.1	244	<.08	2.15	219	268	11,160
.73	.79	1.73	2.43	E8.5	245	<.08	2.26	223	272	11,160 ¹
.71	.79	1.82	2.56	11.2	237	.112	2.43	241	250	11,600
.70	.79	1.82	2.44	E8.1	219	E.04	2.37	212	251	13,010
.66	.78	1.82	2.52	E5.7	222	E.05	2.60	211	250	13,810
<.04	E.02	1.88	2.44	10.1	190	E.05	<1	<1	1.80	13,820
.44	.50	2.55	2.59	E6.1	231	.086	2.12	132	164	13,840
Field blanks										
<.04	<.04	<.2	<.6	<10	<14	<.08	<1	<1	<1	--
<.04	<.04	<.2	<.6	<10	<14	<.08	<1	<1	3.24	--

Table 4. Instantaneous loads of arsenic, cadmium, copper, lead, and zinc, Middle Fork Warm Springs Creek watershed, Montana, June 27, 2001

[Site numbers followed by an "A" designate inflow sites that are upstream from the confluence with the mainstem. Site number indicates distance downstream from the reference site (0), in feet. Abbreviations: µg/s, micrograms per second; E, estimated: Symbols: <, less than, --, no data]

Site number (fig. 1)	Arsenic load, dissolved (µg/s as As)	Arsenic load, total recoverable (µg/s as As)	Cadmium load, dissolved (µg/s as Cd)	Cadmium load, total recoverable (µg/s as Cd)	Copper load, dissolved (µg/s as Cu)	Copper load, total recoverable (µg/s as Cu)	Lead load, total-recoverable (µg/s as Pb)	Zinc load, dissolved (µg/s as Zn)	Zinc load, total-recoverable (µg/s as Zn)
Mainstem sites									
0	1.28	E1.19	<0.03	<0.03	0.79	0.78	<0.85	1.16	<0.85
240	4.76	17.2	.84	1.28	1.53	2.26	28.3	128	161
790	22.4	26.4	39.9	40.1	14.4	14.7	9.02	7,420	7,660
840	23.2	28.8	41.8	39.7	13.6	13.8	7.10	7,330	7,170
1,700	136	322	25.4	29.0	10.1	43.0	23.1	5,760	5,930
2,210	139	227	29.8	32.3	13.2	40.7	10.0	6,510	6,900
2,410	171	386	28.8	34.5	13.4	46.8	22.0	6,450	7,260
3,220	190	379	27.1	30.1	16.2	39.3	17.8	5,950	6,300
3,310	206	331	24.6	28.4	36.7	61.3	<21.2	5,090	6,400
3,580	228	387	26.1	28.5	33.6	57.5	<22.1	5,080	6,360
3,680	249	382	22.9	27.5	31.6	58.9	<21.8	4,880	6,280
4,280	287	475	24.2	29.4	36.8	68.7	34.5	5,170	6,830
4,550	316	478	26.0	28.1	34.3	60.8	30.4	5,990	6,310
4,880	316	496	26.2	28.5	43.2	61.7	<23.2	6,080	7,260
5,430	419	685	26.7	29.0	37.0	60.3	34.3	6,350	7,500
6,240	468	725	23.4	28.1	46.8	65.5	42.1	6,440	7,280
7,370	593	875	23.8	26.7	49.7	70.4	49.0	5,720	7,230
7,900	566	753	22.5	26.0	46.9	68.8	51.2	6,450	8,320
8,940	620	858	23.0	25.8	48.8	73.2	60.8	6,770	8,640
9,790	645	982	23.3	26.1	54.2	69.7	60.6	6,940	8,570
11,160	702	1,030	21.6	24.9	56.1	71.4	64.5	6,570	8,040
11,600	768	1,030	21.8	24.3	55.9	78.6	74.6	7,400	7,680
13,010	805	1,110	22.2	25.0	57.7	77.3	75.1	6,720	7,960
13,810	842	1,170	21.1	25.0	58.2	80.6	83.2	6,750	8,000
13,840	811	1,140	20.5	23.3	119	121	98.8	6,150	7,640
Surface inflow sites									
260 ¹	.02	3.09	1.61	2.99	.85	5.52	2.22	318	629
280A	.32	.47	.01	.02	.14	.16	.62	3.09	3.28
310 ¹	E.14	--	E.46	--	E.91	--	--	E75.3	--
470A	2.19	5.05	.07	.07	.96	1.01	--	13.4	14.6
480	2.00	2.55	.18	.18	.19	.20	1.32	41.0	46.6
785 ¹	E.12	--	E.00	--	E.01	--	--	E.07	--
860	5.20	5.79	.09	.11	.83	1.06	1.53	21.3	23.9
1,280	20.4	24.5	1.57	1.61	3.44	3.47	1.44	288	335
1,630 ¹	109	261	2.52	7.44	2.31	49.2	<3.00	1,850	2,380
1,960	.09	1.11	.59	.58	.18	.34	.11	123	128
2,100	E.29	E.79	E.06	E.06	E.04	E.08	E.19	E17.0	E17.3
2,270	.38	1.68	.02	.02	.02	.03	<.01	7.80	9.28

Table 4. Instantaneous loads of arsenic, cadmium, copper, lead, and zinc, Middle Fork Warm Springs Creek watershed, Montana, June 27, 2001 (Continued)

Site number (fig. 1)	Arsenic load, dissolved (µg/s as As)	Arsenic load, total recoverable (µg/s as As)	Cadmium load, dissolved (µg/s as Cd)	Cadmium load, total recoverable (µg/s as Cd)	Copper load, dissolved (µg/s as Cu)	Copper load, total recoverable (µg/s as Cu)	Lead load, total-recoverable (µg/s as Pb)	Zinc load, dissolved (µg/s as Zn)	Zinc load, total-recoverable (µg/s as Zn)
Surface inflow sites (Continued)									
2,310	.68	2.83	.09	.11	.16	.27	.59	46.6	52.5
2,510	4.90	5.72	.05	.04	.67	.67	<.36	12.7	12.4
3,250	7.58	E9.83	<.28	<.28	7.09	10.5	<7.02	<7.02	25.4
4,230	E4.31	E5.6	E.02	E.03	E.35	E.48	E.78	E6.43	E9.86
4,490	.55	--	.01	--	.04	--	--	3.70	--
4,590	E.72	E.85	E.11	E.11	E.07	E.06	E.01	E31.4	E33.7
4,590A	.01	E.01	E.07	E.07	E.02	E.02	E.01	E19.4	E19.2
5,300	10.7	12.7	.15	.16	.56	.66	.37	30.0	34.0
5,300A	E.02	E.02	E.00	E0.0	E.01	E.01	E.01	.25	.29
6,130	E.12	--	E.00	--	E.01	--	--	E.17	--
7,510	1.23	<7.92	2.02	2.26	3.05	5.46	15.8	1,610	2,070
7,810	.28	E.51	<.02	<.02	.41	.63	.59	.50	4.45
9,570	11.0	11.0	.35	.37	.55	1.28	2.38	132	169
13,820	16.1	19.3	<.55	<.25	25.9	33.7	<13.8	<13.8	24.8

¹Adit.

