Quantification and Simulation of Metal Loading to the Upper Animas River, Eureka to Silverton, San Juan County, Colorado, September 1997 and August 1998

By Suzanne S. Paschke, Briant A. Kimball, and Robert L. Runkel

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Conversion Factors, Vertical Datum, Acronyms, and Abbreviations

Multiply	By	To obtain
centimeter (cm)	0.3937	inch
cubic meter (m^3)	35.31	cubic foot (ft^3)
kilogram	2.205	pound
kilometer (km)	0.6214	mile
liter (L)	0.2642	gallon
liter per minute (L/min)	5.886×10^{-4}	cubic foot per second (ft^3/s)
liter per second (L/s)	0.0353	cubic foot per second (ft^3/s)
meter	3.281	foot
square meter (m^2)	10.76	square foot

Temperature in degrees Celsius (^{O}C) may be converted to degrees Fahrenheit (^{O}F) as follows:

$$^{O}F = (1.8 \times {}^{O}C) + 32$$

Vertical coordinate information is referenced to North American Vertical Datum of 1988 (NAVD 88). Horizontal coordinate information is referenced to North American Datum of 1927 (NAD 27) except as noted.

Acronyms and Abbreviations

kilogram per day (kg/d)

meters per second (m/s)

microsiemens per centimeter at 25 degrees Celsius (μS/cm)

micrometer (μm)

milligrams per liter (mg/L)

milliliter (mL)

milliliters per minute (mL/min)

AMD	acid mine drainage
ARD	acid rock drainage
ARSG	Animas River Stakeholders Group
BLM	Bureau of Land Management
CLATIN	OTIS input parameter for lateral inflow concentration
Ma	million years before present
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

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Abstract

Drainage from abandoned and inactive mines and from naturally mineralized areas in the San Juan Mountains of southern Colorado contributes metals to the upper Animas River near Silverton, Colorado. Tracer-injection studies and associated synoptic sampling were performed along two reaches of the upper Animas River to develop detailed profiles of stream discharge and to locate and quantify sources of metal loading. One tracer-injection study was performed in September 1997 on the Animas River reach from Howardsville to Silverton, and a second study was performed in August 1998 on the stream reach from Eureka to Howardsville. Drainage in the upper Animas River study reaches contributed aluminum, calcium, copper, iron, magnesium, manganese, sulfate, and zinc to the surface-water system in 1997 and 1998. Colloidal aluminum, dissolved copper, and dissolved zinc were attenuated through a braided stream reach downstream from Eureka. Instream dissolved copper concentrations were lower than the State of Colorado acute and chronic toxicity standards downstream from the braided reach to Silverton. Dissolved iron load and concentrations increased downstream from Howardsville and Arrastra Gulch, and colloidal iron remained constant at low concentrations downstream from Howardsville. Instream sulfate concentrations were lower than the U.S. Environmental Protection Agency's secondary drinking-water standard of 250 milligrams per liter throughout the two study reaches.

Elevated zinc concentrations are the primary concern for aquatic life in the upper Animas River. In the 1998 Eureka to Howardsville study, instream dissolved zinc load increased downstream from the Forest Queen mine, the Kittimack tailings, and Howardsville. In the 1997 Howardsville to Silverton study, there were four primary areas where zinc load increased. First, was the increase downstream from Howardsville and abandoned mining sites downstream from the Cunningham Gulch confluence, which also was measured during the 1998 study. The second affected reach was downstream from Arrastra Gulch, where the increase in zinc load seems related to a series of right-bank inflows with low pH and elevated dissolved zinc concentrations. A third increase in zinc load occurred 6,100 meters downstream from the 1997 injection site and may have been from ground-water discharge with elevated zinc concentrations based on mass-loading graphs and the lack of visible inflow in the reach. A fourth but lesser dissolved zinc load increase occurred downstream from tailings near the Lackawanna Mill.

Results of the tracer-injection studies and the effects of potential remediation were analyzed using the one-dimensional stream-transport computer code OTIS. Based on simulation results, instream zinc concentrations downstream from the Kittimack tailings to upstream from Arrastra Gulch would approach 0.16 milligram per liter (the upper limit of acute toxicity for some sensitive aquatic species) if zinc inflow concentrations were reduced by 75 percent in the stream reaches receiving inflow from the Forest Queen mine, the Kittimack tailings, and downstream from Howardsville. However, simulated zinc concentrations downstream from Arrastra Gulch were higher than approximately 0.30 milligram per liter due to numerous visible inflows and assumed ground-water discharge with elevated zinc concentrations in the lower part of the study reach. Remediation of discrete visible inflows seems a viable approach to reducing zinc inflow loads to the upper Animas River. Remediation downstream from Arrastra Gulch is more complicated because ground-water discharge with elevated zinc concentrations seems to contribute to the instream zinc load.

Introduction

The upper Animas River drains an extensively mineralized area of the San Juan Mountains near Silverton, Colorado. Gold deposits were first discovered in 1871 in Arrastra Gulch, and mining activity continued in the watershed at various levels of activity until the Sunnyside Mine was closed in 1991 (Church and others, 1997). The Animas River drainage basin contains more than 300 formerly producing metal mines that have affected water quality in the watershed (Church and others, 1997). Acid mine drainage (AMD) from abandoned and

inactive mines and mine-related wastes, as well as naturally occurring acid rock drainage (ARD) from mineralized areas, contributes acidic, metal-rich water to the upper Animas River.

Environmental characterization of the upper Animas River basin upstream from Silverton began in 1991 under the auspices of the Colorado Department of Public Health and Environment (Church and others, 1997). These initial studies showed seasonal and regional variation in water quality and noted several acidic tributaries upstream from Silverton. Although pH was variable, aluminum and iron concentrations in the acidic waters exceeded the solubility products of various iron and aluminum hydroxides, and iron- and aluminum-hydroxide-coated bed sediments were noted in many stream reaches. Additional reconnaissance sampling of water and bed sediments was conducted by Church and others (1997) during 1995 and 1996 to identify the sources, movement, and partitioning of metals in the upper Animas River. Results of that investigation indicated that most of the aluminum, arsenic, cadmium, copper, iron, lead, and zinc in the Animas River originated within the upper Animas River drainage basin upstream from Silverton (Church and others, 1997). Aquatic habitats in the upper Animas River and its tributaries are affected by the presence of acidic, metal-rich water and by aluminum and iron oxyhydroxide precipitates on bed sediments (Besser and others, 2001).

The Bureau of Land Management (BLM) and the Animas River Stakeholders Group (ARSG) are planning possible remedial actions along the upper Animas River to alleviate water-quality degradation. An evaluation of remedial actions requires a detailed understanding of the primary metal sources to the river and any instream geochemical processes controlling metal transport. River and tributary discharge measurements, which allow calculation of metal loads, are available for a few sites along the stream. However, a more detailed profile of discharge distribution and resultant metal loading is needed to evaluate specific locations for remedial actions.

The U.S. Geological Survey (USGS), in cooperation with the Bureau of Land Management, conducted two tracer-injection and synoptic-sampling studies during September 1997 and August 1998. The purpose of these studies was to provide an evaluation of metal loading to the upper Animas River and instream geochemical processes, which will aid in the selection of remedial alternatives. The principal objectives of the studies were to: (1) locate, identify, and quantify increases in metal loading, by surface and subsurface flow, to the upper Animas River between Eureka and Silverton, Colorado, using tracer-dilution methods; and (2) identify and describe any instream geochemical processes affecting metal concentrations and natural attenuation of metals in streamwater.

Purpose and Scope

The purpose of this report is to document quantification and simulation of metal loading to the upper Animas River

that was based on two tracer-injection and synoptic-sampling studies performed in 1997 and 1998. The methods used to calculate stream discharge and chemical mass loading from the collected data are described. Additionally, this report describes the computer simulations using the one-dimensional computer program OTIS (Runkel, 1998) to simulate the effects of potential remediation plans.

Study Area Description

The upper Animas River study area is in San Juan County in southwestern Colorado near Silverton. The study area encompasses the upper Animas River from the historical mining town of Eureka to the town of Silverton (fig. 1). The river and its major tributaries originate at an altitude of more than 3,000 meters (m). The watershed receives as much as 80–100 centimeters (cm) of annual precipitation principally as snow in winter (Yager and Bove, 2002), and the principal source of streamwater is snowmelt runoff, which usually occurs from May through July. Major tributaries to this reach of the upper Animas River include Eureka Gulch, Minnie Gulch, Maggie Gulch, Otto Gulch, Porcupine Gulch, Cataract Gulch, Cunningham Gulch, Hematite Gulch, Arrastra Gulch, Boulder Gulch, Blair Gulch, and Swansea Gulch (fig. 1).

Bedrock beneath much of the study area consists of Tertiary volcanic rocks of the Silverton caldera, underlain by Precambrian igneous and metamorphic rocks and Paleozoic sedimentary rocks that outcrop in the southern part of the study area (Luedke and Burbank, 1996a; 1996b; Yager and Bove, 2002). Tertiary volcanism in the San Juan volcanic field began between 35 and 30 million before present (Ma), and later caldera-related eruptions occurred between 28.2 and 27.6 Ma (Yager and Bove, 2002). Caldera-bounding ring and tangential radial fractures associated with the Silverton caldera provided pathways for later intrusive magmas and hydrothermal fluids, which contain gold and silver mineral deposits in the area (Yager and Bove, 2002). Subsequent uplift, erosion, and glaciation of the area in more recent geologic time resulted in surficial exposure of the hydrothermally altered rock, and continued weathering of the bedrock and derived surficial materials released acid and metals to surface and ground waters in the drainage basin prior to mining (Bove and others, 2000; Church and others, 2000; Mast and others, 2000).

Placer gold deposits were discovered in 1871 on Arrastra Creek upstream from Silverton, and hard-rock gold and silver mining activity spread rapidly through the area following the 1873 treaty with the Ute Indians (U.S. Geological Survey, 2000). Mining continued in the Animas River watershed at various levels of activity until 1991 when the Sunnyside Mine was closed (U.S. Geological Survey, 2000). More than 100 years of historical mining activity created many kilometers of underground workings and produced large volumes of waste rock. The mine workings provide pathways for ground water and surface water to react with mineralized rock
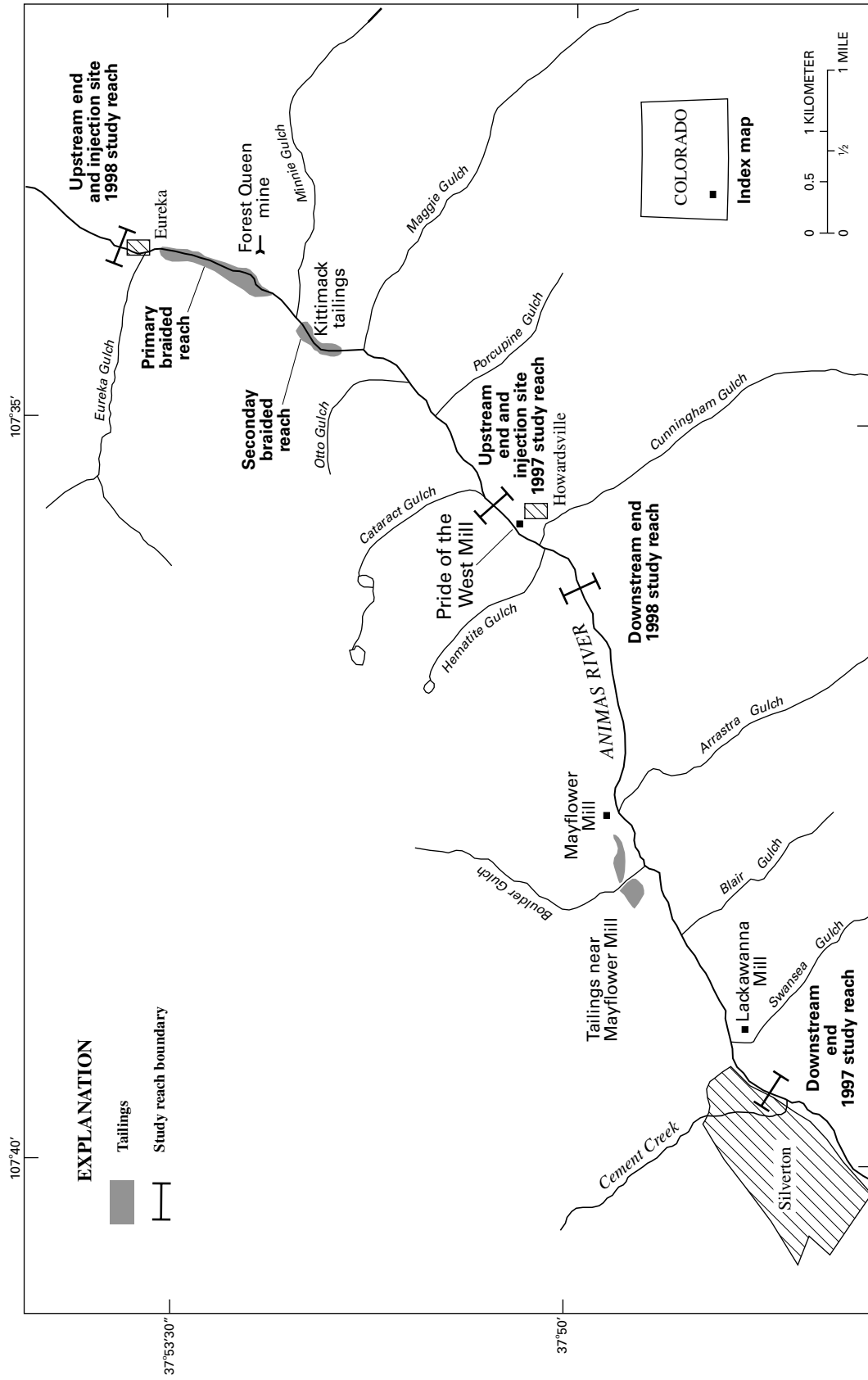
Figure 1. Location of study area and study reaches, upper Animas River, Colorado.

producing low-pH, metal-rich waters that flow from mine adits (U.S. Geological Survey, 2000). Ground-water and surface-water flow in and over waste rock piles also can contribute acidic metal-rich drainage to the Animas River and its tributaries. Mineralization and historical mining sites are present throughout the area, but several specific areas are possible contributors of metals to the Animas River: Eureka Gulch, the Forest Queen mine downstream from Eureka, the Kittimack tailings, mill tailings near Howardsville, Arrastra Gulch, mill tailings near the Mayflower Mill, and mill tailings near the Lackawanna Mill (fig. 1).

Study Methods

Metal loading to the upper Animas River was quantified by performing two tracer-injection and synoptic-sampling studies and by simulating study results with the one-dimensional solute-transport code OTIS (Runkel, 1998). One tracer-injection and synoptic-sampling study was performed on the upper Animas River reach from Howardsville to Silverton in September 1997, and a second study was performed on the stream reach from Eureka to Howardsville in August 1998 (fig. 1). This section of the report describes the methods used for tracer injection and synoptic sampling and for sampling and analyzing surface-water samples. Methods used for calculating discharge, traveltime, and mass loading also are described. A general overview of the one-dimensional computer code OTIS (Runkel, 1998) used for simulating solute transport also is provided.

Tracer-Injection and Synoptic-Sampling Methods

The methodology of tracer-injections studies was developed as part of the USGS Toxic Substances Hydrology Program to identify and enumerate sources of acid and metals to streams (Bencala and McKnight, 1987; Bencala and others, 1990; Broshears and others, 1995; Kimball and others, 1991; 1994; Kimball, 1997; Kimball and others, 1999a, 1999b, 1999c; Runkel and others, 1996; Walton-Day and others, 1999). As described in this section of the report, a tracer-injection study includes a tracer injection to quantify discharge (Kilpatrick and Cobb, 1985) and synoptic sampling to provide spatial concentration profiles of pH and inorganic constituents. Discharge and concentration data then are combined to develop mass-loading profiles for the stream.

Quantification of metal loads requires accurate discharge measurements and representative chemical concentrations. However, quantifying discharge in mountain streams by the traditional velocity-area method (Rantz, 1982) is complicated by streambed roughness and variability caused by pools and riffles (Jarrett, 1992). In addition, some percentage of discharge cannot be measured by the traditional method because

of flow through the streambed (hyporheic zone) (Bencala and Walters, 1983; Bencala and others, 1991; Harvey and Bencala, 1993; Zellweger and others, 1988). Because velocity-area discharge measurements cannot measure flow through the hyporheic zone, metal-loading calculations based on traditional discharge measurements may underestimate metal loads (Kimball, 1997; Zellweger and others, 1988). Application of the velocity-area method for quantifying metal loads also is limited by the time and personnel required to measure discharge at numerous stream sampling sites in a single day.

The tracer-injection study is an alternative method of estimating discharge in gaining mountain streams (Kilpatrick and Cobb, 1985). A tracer injection consists of continuously injecting an inert chemical tracer into the stream at a constant rate and concentration and measuring the downstream dilution of the tracer at various locations. Given sufficient time during a tracer injection, all parts of the stream including side pools and the hyporheic zone become saturated with tracer, and instream tracer concentrations will reach a plateau (Kimball, 1997). Downstream decreases in tracer plateau concentration indicate tracer dilution by surface- and ground-water inflow to the stream, and stream discharge is calculated from the downstream dilution. The downstream arrival, concentration plateau, and departure (upon cessation of the injection) of the tracer also are monitored at selected transport sites to compute stream velocities and other streamflow properties. Discharge computed from tracer concentrations accounts for both the surface and the hyporheic flow because the tracer follows the water through cobbled bed sediment. The tracer-injection method also allows discharge estimates at numerous locations in a short timeframe. Zellweger and others (1988) provide additional details of tracer-injection methods.

Synoptic sampling is a one-time detailed sampling of stream sites and all visible tributary inflows to the stream performed during the plateau period of the tracer injection. Synoptic sampling provides a description of the stream and tributary inflow chemistry during the tracer injection. By combining discharge, computed from the tracer injection, with synoptic metal concentrations, metal-loading profiles are developed for the stream using mass-balance calculations. Results of the tracer-injection study can identify where changes in stream load occur. However, study results do not identify specific pathways to the stream from particular sites, except for visible surface inflows. The detailed loading information provides insight to the key geochemical processes affecting stream pH and metal concentrations, and it provides the hydrologic framework for solute-transport simulations (Bencala, 1983; Bencala and others, 1988; Broshears and others, 1993; Broshears and others, 1996; Harvey and others, 1996; McKnight and Bencala, 1989; Runkel, 1998; Runkel and others, 1996; Runkel and others, 1999; Wagner and Harvey, 1997).

Both of the upper Animas River tracer-injection studies were conducted during fall base-flow (low-flow) conditions. Application of tracer-injection studies to low-flow condi-

tions is appropriate for two reasons. First, the mass-loading profiles developed for low-flow conditions reflect base-flow metal-loading conditions, which are present all year long. Remediation that addresses sources identified during low flow therefore will improve water quality during the entire year. Second, mass-loading profiles developed for low-flow conditions indicate those sources contributing to elevated instream concentrations during the winter months when conditions most toxic to aquatic organisms likely occur (Besser and Leib, 1999). During the low-flow winter months, dilution of metals is minimal, and toxicity standards based on metal concentrations are more likely exceeded (Besser and others, 2001). Testing during low-flow conditions also makes it possible to measure discharge and collect samples at many synoptic-sampling sites during the tracer plateau.

Successful implementation of a tracer-injection study requires that the injected tracer be transported through the stream system in a conservative manner unaffected by biogeochemical reactions. Potential tracers include dyes and inorganic salts. Dye tracers have the disadvantage of being unstable at low pH, and they adsorb to solids and organic matter in the hyporheic zone (Bencala and others, 1986). Chloride and bromide salts of sodium and lithium are suitable tracers in environments where naturally occurring chloride or bromide concentrations are low. Lithium works well in streams with low pH, and chloride and bromide work well in streams with higher pH (Bencala and others, 1990). Sodium chloride tracer was used for both of the upper Animas River tracer injections where stream pH was circumneutral.

Sampling and Analytical Methods

Surface-water samples were collected at downstream transport sites and synoptic-sampling sites during the tracer injection. Sampling sites are referenced by their distance in meters downstream from the injection, and inflow samples were referenced as being on the right or left streambank looking downstream.

Frequent surface-water samples were collected at the transport sites during the tracer injections to observe the arrival, plateau, and departure of the sodium-chloride tracer. Transport-site samples were collected as manual grab samples and with auto samplers and were filtered upon collection through 0.45-micrometer (µm) in-line capsule filters into polyethylene bottles. Transport-site samples were analyzed for chloride concentrations using ion chromatography (table 1) at the USGS laboratory in Salt Lake City, Utah, using analytical techniques and quality assurance procedures described by Kimball and others (1999a).

Synoptic samples were collected from instream and inflow sites during the tracer plateau. Instream and inflow samples were collected into polyethylene bottles, and water temperature was measured at each site upon sample collection. For the instream sites, samples were collected using equal-width integration (EWI) and a DH-81 sampler (Wilde

and others, 1998). Manual grab samples were collected at inflow sites. A temporary field laboratory was used to process the synoptic samples, measure pH and specific conductance, and filter the samples for the remaining analyses (table 1). To prevent photoreduction of iron, all samples were kept out of the light in dark plastic bags until processing at the temporary field laboratory.

Synoptic samples were analyzed for anions and iron speciation at the USGS laboratory in Salt Lake City, Utah. Chloride and sulfate concentrations were determined using ion chromatography (Kimball and others, 1999a), alkalinity was determined using Gran titration (Stumm and Morgan, 1981), and iron speciation was determined colorimetrically (table 1). Precision of the ion chromatography results was less than 5 percent for chloride analyses and less than 10 percent for sulfate analyses (Kimball and others, 1999a).

Dissolved and total-recoverable concentrations for aluminum, barium, calcium, cadmium, copper, iron, potassium, magnesium, manganese, sodium, silica, strontium, and zinc were determined by inductively coupled argon plasma atomic emissions spectrometry (ICP-AES, table1). The dissolved concentrations for instream samples were obtained by filtering samples through a tangential-flow filter apparatus with a 10,000-Dalton molecular-weight nominal pore size (Benoit and Rozan, 1999; Kimball and others, 1992; Moran and Moore, 1989). For inflow samples, dissolved concentrations were obtained from a 0.45-µm filtration using the same apparatus. For both instream and inflow samples, total-recoverable concentrations were obtained from an unfiltered sample. The colloidal concentration was calculated indirectly by subtracting the dissolved concentration from the total-recoverable concentration (Kimball and others, 1995). Synoptic samples for ICP-AES analyses were acidified at the field laboratory using 1 milliliter (mL) of ultrapure nitric acid. ICP-AES analyses of synoptic samples from the September 1997 tracer-injection study (Howardsville to Silverton study reach) were performed at the USGS laboratories in Boulder, Colorado, and ICP-AES analyses of synoptic samples from the August 1998 tracer-injection study (Eureka to Howardsville study reach) were performed at the Colorado School of Mines laboratories in Golden, Colorado. ICP-AES analytical techniques are described in Taylor (1982) and Garbarino and Taylor (1984a; 1984b), and quality-assurance procedures followed the methods described by Friedman and Erdmann (1982).

Discharge and Traveltime Calculations

During a tracer injection, the tracer reaches a steady plateau concentration in the stream, and discharge can be calculated by the amount of tracer dilution at each successive instream site by using the conservation of mass. If stream discharge increases downstream, the tracer will have successively lower downstream plateau concentrations. The synoptic sampling is conducted during the plateau period of the tracer injection, and tracer concentrations from the

Table 1.   Analytical methods for tracer and synoptic water samples collected during the Eureka to Howardsville tracer-injection study, August 1998, and the Howardsville to Silverton tracer-injection study, September 1997.

[μm, micrometer; ICP-AES, inductively coupled plasma atomic emissions spectrometry]

Analysis	Field treatment	Analytical method
Chloride tracer concentrations and sulfate	Filtered (0.45 μm), unacidified	Ion chromatography (Kimball and others, 1999a)
pH, specific conductance	Unfiltered, unacidified	Ion-sensitive electrode measured at field laboratory
Filtered ferrous iron	Filtered (0.45 μm), unacidified	Bipyridine, colorimetric method for ferrous iron
Filtered metal concentrations	Filtered (10,000 Dalton), acidified Filtered (0.45 μm), acidified	ICP-AES (Taylor, 1982; Garbarino and Taylor, 1984a; 1984b; Friedman and Erdmann, 1982)
Total-recoverable metal concentrations	Unfiltered, acidified	ICP-AES with standard U.S. Environmental Protection Agency digestion for total-recoverable concentrations (Taylor, 1982; Garbarino and Taylor, 1984a; 1984b; Friedman and Erdmann, 1982)

synoptic sampling are used to compute stream discharge as discussed herein.

Conservation of mass requires the load of tracer in the stream at B to be equal to the load at A, upstream from the injection, plus the load added by the injection (table 2, equation 1). In addition, by flow balance, the discharge at B must equal the discharge at A plus the discharge of the injection. Discharge at the downstream site B then is computed from the injection flow rate and concentration and the measured tracer concentrations at sites A and B (table 2, equation 2). Mass and flow balance relations also are used to develop a discharge equation for site C and all subsequent sites downstream based on the flow and measured tracer concentration computed for the upstream site B and the measured tracer concentration of any inflow between sites B and C (table 2, equation 3).

Inflow to the stream can include visible tributaries, seeps, springs, and diffuse ground-water inflow. Inflow discharge is computed as the difference in discharge between sites C and B (table 2, equation 4). If a visible tributary is present in the reach between two sites, calculated inflow discharge is assigned to the tributary inflow. If there is no visible inflow between two sites, calculated inflow discharge is assigned as unsampled ground-water inflow.

During the tracer injection, the arrival, plateau, and departure of tracer in the stream are monitored at several downstream transport sites, and the transport graphs are used to calculate traveltime between sites as well as stream-channel parameters used for solute-transport simulations. The tracer arrival time at a site (t_{50}) is defined as the time at which the instream tracer concentration reaches one-half of the plateau concentration (C_{50}) (Zellweger and others, 1988). Traveltime between two sites is the difference in arrival times.

Mass-Loading Calculations

Discharge values computed from a tracer-injection study are combined with synoptic-sampling results to compute mass-loading graphs for various constituents of interest. The constituent load at the downstream end of a stream segment includes the load from the upstream end plus the load contributed by all surface and subsurface inflows between the sites (table 2, equation 5). The sampled instream load (M_S) and the sampled inflow load (M_I) are two ways to consider the load of a stream segment (Kimball and others, 1999a). The sampled instream load at site C, M_C, is calculated as the product of the discharge (Q) and synoptic constituent concentration (C) at each stream sampling site (table 2, equation 5). The sampled instream load represents the effect of constituent sources in the watershed on the stream, and it is used to identify changes in constituent load because it can increase, decrease, or remain constant between stream sites. An increase generally indicates a source of constituent loading, and the magnitude of the increase compared to other stream segments ranks the sources in the context of the watershed. A decrease generally indicates a loss of metal from the water through chemical reactions such as precipitation or adsorption. Both reactions can result in loss to the streambed or a transformation from the dissolved phase to a colloidal solid phase.

The net change in sampled instream load between stream sites includes the instream load at site B plus the inflow load contributed by all the surface and subsurface inflow between sites B and C (table 2, equation 5). Because it is not possible to sample all the inflow affecting the stream, especially the diffuse ground-water inflow, the inflow concentration in equation 5 (table 2) represents an effective inflow concentra-

Table 2. Equations defining calculated quantities in tracer-injection studies (modified from Kimball and others, 1999a) [Subscripts correspond to sites illustrated in the diagram].
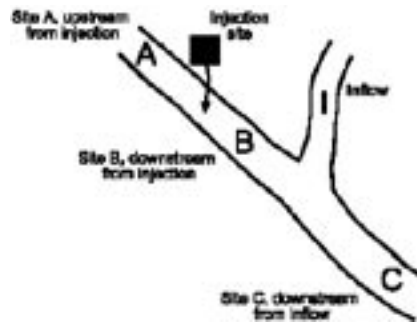
Calculated quantity	Tracer-dilution equations	Variables
(1) Mass balance downstream from the injection site	$M_B = C_B Q_B$ $\quad = C_A Q_A + C_{inj} Q_{inj}$ $Q_B = Q_A + Q_{inj}$	M_B, Load at site B C_B, Concentration at site B Q_B, Discharge at site B C_A, Concentration at site A Q_A, Discharge at site A C_{inj}, Concentration of injectate solution Q_{inj}, Discharge of injection pump
(2) Discharge at first site downstream from tracer injection	$Q_B = \dfrac{Q_{inj}\,(C_{inj} - C_A)}{(C_B - C_A)}$	All variables defined above
(3) Discharge at subsequent downstream sites	$Q_C = \dfrac{Q_B\,(C_B - C_I)}{(C_C - C_I)}$	Q_C, Discharge at downstream site C C_C, Concentration of tracer at site C C_I, Sampled inflow concentration of tracer
(4) Inflow discharge	$Q_I = Q_C - Q_B$	Q_I, Computed inflow discharge. If visible inflow is present in the reach, Q_I is assigned inflow discharge, otherwise, Q_I is assigned to unsampled ground-water discharge.
Solute-loading equations		
(5) Sampled instream load at subsequent stream sites	$M_C = C_C\,Q_C$ $\quad = C_B Q_B + C_I^{\,E}\,(Q_C - Q_B)$	M_C, Load at site C or subsequent sites downstream $C_I^{\,E}$, Effective inflow concentration
(6) Effective inflow concentration	$C_I^{\,E} = \dfrac{(C_C\,Q_C - C_B\,Q_B)}{(Q_C - Q_B)}$	All variables defined above
(7) Change in sampled instream load	$\Delta M_S = C_C\,Q_C - C_B\,Q_B$ $\quad = C_I^{\,E}\,(Q_C - Q_B)$	ΔM_S, Net change in load between sites B and C
(8) Change in sampled inflow load	$\Delta M_I - C_I\,(Q_C - Q_B)$	ΔM_I, Net change in load between sites B and C based on sampled inflow concentration C_I, Sampled inflow concentration

tion ($C_I{}^E$), which is a discharge-weighted mean concentration of all surface and subsurface inflow contributions within the stream segment (table 2, equation 6).

The change in instream load between two stream sites (ΔM_S) is defined as the downstream load minus the upstream load (table 2, equation 7), and the cumulative instream load is defined as the sum of the positive values of ΔM_S. Each negative value of ΔM_S indicates a stream segment where there is a net reduction in constituent load, and the cumulative instream load is held constant for a segment with a negative ΔM_S. The cumulative instream load represents the minimum total load added to the stream over the study reach. Comparison of ΔM_S to M_S indicates the extent of instream constituent attenuation along the study reach, because ΔM_S is greater than M_S when M_S is reduced by physical, chemical, or biological process.

The change in sampled inflow load, ΔM_I, represents the load contributed to the stream from visible inflows and is calculated for each stream reach as the product of the sampled inflow concentrations, C_I, and the change in discharge between stream sites, Q_I (table 2, equation 8). The change in sampled inflow load represents the net change in stream loading from the sampled inflow concentrations. For stream segments with no visible inflow, ΔM_I is set to zero. The cumulative inflow load is the sum of the values for ΔM_I along the study reach.

Table 3 presents probable explanations for the various relations between ΔM_S and ΔM_I. If ΔM_S and ΔM_I are nearly equal for a stream segment, then the sampled inflow concentrations, C_I, approximate the effective inflow concentrations,

$C_I{}^E$, and the sampled inflow loads account for the change in stream loading. If ΔM_S is greater than ΔM_I, then $C_I{}^E$ is greater than C_I, presumably because there is unsampled inflow such as ground-water discharge to the stream with high constituent concentrations. For colloidal constituent loads, if ΔM_S is greater than ΔM_I, chemical precipitation of colloidal material is indicated. For dissolved constituent loads, if ΔM_S is less than ΔM_I, then there has been a reduction in load by chemical reaction.

Solute-Transport Simulations

To interpret mass-loading calculations and simulate the effects of potential remediation plans in the basin, surface-water flow and zinc solute transport were simulated for the Eureka to Howardsville and the Howardsville to Silverton study reaches using the one-dimensional computer program OTIS (Runkel, 1998). A general overview of OTIS is provided in this section of the report. Details on the site-specific application of OTIS to the Eureka to Howardsville and Howardsville to Silverton study reaches are provided in subsequent sections.

OTIS is a computer code for simulating one-dimensional solute transport of a single solute in a stream based on the advection-dispersion equation with additional terms to account for transient storage, lateral inflow, first-order decay, and adsorption (Runkel, 1998). Transient storage refers to the temporary storage of streamwater in the stream and adjacent streambed, and OTIS accounts for transient stor-

Table 3.   Probable explanations for various cumulative stream-load relations (modified from Kimball and others, 1999a).

[ΔM_S, change in sampled instream load; M_I, change in sampled inflow load; <, less than; >, greater than]

Condition	Probable explanation
$\Delta M_S = \Delta M_I$	The sampled inflow concentrations approximate the effective inflow concentrations, and the sampled inflow load accounts for the change in sampled stream load.
$\Delta M_S > \Delta M_I$	The sampled stream load is greater than the sampled inflow load, and the sampled inflow load does not account for the change in sampled stream load. For dissolved constituents, ground-water discharge with elevated constituent concentrations is indicated. For colloidal constituents, transfer from the dissolved to the colloidal phase by chemical precipitation is indicated.
$\Delta M_S < \Delta M_I$	The sampled inflow load is greater than the sampled stream load indicating a loss of stream load through physical, chemical, or biological reaction or dilution by ground-water inflow.
$\Delta M_S < 0$	There is a net loss of load through physical, chemical, or biological reaction in the stream reach.

age by solving separate mass-balance equations for the main stream channel and the stream storage zone. The main channel is defined as the stream portion where advection and dispersion are the dominant transport processes, and the storage zone is defined as the stream portion where transient storage occurs. Advection and dispersion are not included in the storage zone, where downstream transport is negligible. Lateral inflow represents additional water coming into the main channel as overland flow, interflow, and ground-water discharge. Chemical reactions can be specified within the main channel, the storage zone, or both.

OTIS can be used in conjunction with data from field-scale tracer-injection studies to quantify the hydrologic parameters affecting surface-water flow (Runkel, 1998). The application of OTIS to tracer-injection results generally involves a trial-and-error process where estimates for the hydrologic parameters of channel cross-sectional area, transient storage cross-sectional area, and solute dispersion are adjusted to obtain an acceptable match between simulated and measured tracer concentrations for the tracer-transport sites and synoptic sampling. OTIS-P is a modified version of OTIS that couples OTIS with a nonlinear regression package to automate the hydrologic parameter-estimation process.

Once the hydrologic parameters are established for the conservative tracer, OTIS is used to simulate measured mass loading and solute transport for constituents of interest. For the two upper Animas River study reaches, the measured inflow concentrations (C_I) are used as lateral inflow values to simulate conservative solute transport for zinc. The simulated instream concentration profile is compared to the measured synoptic instream concentration profile to identify potential instream physical, chemical, or biological processes in the stream reach. If the simulated instream concentrations for a given constituent are higher than the measured synoptic instream concentrations, then removal of the constituent by physical, chemical, or biological processes is indicated. For the two upper Animas River study reaches, the effects of instream chemical reactions are simulated using first-order decay. The resulting OTIS simulations then are used to predict the effects of hypothetical remedial actions for the upper Animas River.

Metal Loading to the Upper Animas River, Eureka to Howardsville, Colorado, Study Reach, August 1998

The Eureka to Howardsville tracer-injection study started near the historical mining town of Eureka and ended downstream from Howardsville at the USGS gaging station 09358750 (referenced herein using the Colorado State gaging station number A53). This study reach encompassed a 7,250-m reach of the upper Animas River (fig. 2).

Tracer-Injection Study Objectives

There were three primary objectives for the Eureka to Howardsville tracer-injection study. The first objective was to identify and locate metal loading in the stream study reach. Although a tracer-injection study can help identify where load increases occur, it does not identify specific pathways to the stream from particular sites, except for visible surface inflows. Possible sources of metal loading include Eureka Gulch, the Forest Queen mine discharge, the Kittimack mill tailings, and tailings near Howardsville. The second objective was to determine (for low-flow conditions) if the stream reach is a net sink or source of metals to the downstream areas. This objective was accomplished by identifying and describing any instream physical, chemical, or biological processes affecting metal concentrations and natural attenuation. A third objective for the Eureka to Howardsville study was to characterize the effects of braided stream reaches on streamwater quality. There is a primary braided reach just downstream from Eureka from 786 to 2,030 m and a secondary braided reach near the Kittimack tailings from 3,150 to 3,435 m. Channel restoration is being considered for these braided reaches, and an understanding of 1998 conditions will aid in rechannelization planning.

Tracer-Injection Study Methods

The Eureka to Howardsville tracer-injection study was conducted August 11 through August 14, 1998. A solution containing 166,700 milligrams per liter (mg/L) of sodium chloride was injected into the upper Animas River at an average flow rate of 1.784 liters per minute (L/min). The injection started at 1000 hours on August 11, 1998, but the pump stopped at approximately 1200 hours the same day. The injection began again at 1002 hours on August 12, 1998 and ran continuously until 1930 hours on August 14, 1998 (table 4). For reporting results, time 0.0 is the beginning of experiment time, which was midnight on August 11, 1998, and subsequent times are reported as decimal hours.

The Eureka to Howardsville injection site was located approximately 347 m upstream from Eureka Gulch so inflow from Eureka Gulch could be quantified as tributary inflow. The arrival of the sodium-chloride pulse and the development of a plateau concentration were measured at four downstream locations, transport sites T1 through T4 (fig. 2). Transport site T1 was located upstream from Eureka Gulch at 282 m. Transport site T2 was located at 2,240 m, downstream from the braided reach, and site T3 was located at 5,467 m at the same location as the tracer injection for the Howardsville to Silverton tracer-injection study conducted in 1997. Transport site T4 was located at 6,993 m at the Howardsville gaging station A53.
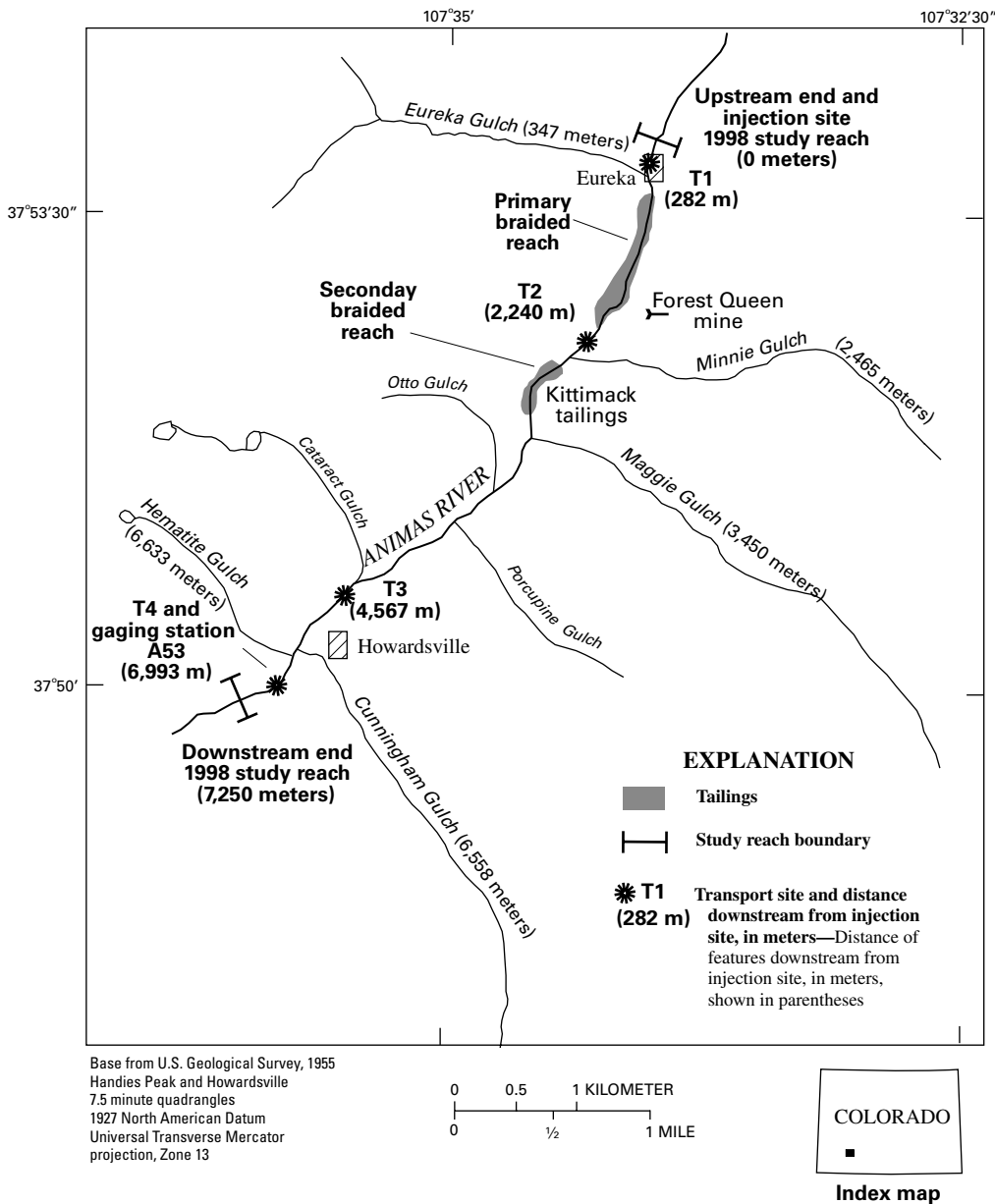
Figure 2.   Eureka to Howardsville study reach, upper Animas River, Colorado, August 1998.

Synoptic Sampling and Analyses

Synoptic samples were collected from 34 instream sites, including the 4 transport sites and 4 sites in the breaded reach at 1,618 m, and 17 inflows on August 14, 1998, during the plateau period of the tracer injection. Although there was rain before and after the synoptic sampling, there was no rain during the sampling, so steady-state conditions were achieved during the synoptic sampling. Instream sampling sites were located upstream and downstream from identified inflows to allow mass-balance calculations for each inflow, and additional sites were located in longer subreaches between inflows

to account for subsurface inflow. Seventeen inflow-sampling sites were chosen to represent the range of pH and specific conductance of water entering the stream. Although there were several sampling sites in the braided reach, only the samples upstream and downstream from the braided reach can account for the metal loading or loss that could occur in the braided reach. The instream sample at 786 m represents input to the braided reach, and the instream sample at 2,030 m represents output from the braided reach.

Instream and inflow water samples were analyzed in the field and laboratory for various constituents as presented in the

Table 4. Tracer-injection study sequence of events, upper Animas River, Eureka to Howardsville, Colorado, August 1998.

[mL/min, milliliters per minute]

Date	Clock time	Experiment time (hours)	Activity
08/09/1998– 08/10/1998			Stream reconnaissance and discharge measurements
08/11/1998	0000	0.0	Start of experiment time
	1000	10.0	Start of initial injection
	1800	18.0	Initial injection pump stopped
08/12/1998	1002	34.03	Started injection pump
	1115	35.25	Injecate sample, measured pump rate at 2,517 mL/min
	1135	35.58	Adjusted pump rate to approximately 1,833 mL/min
	1705	41.08	Injecate sample, measured pump rate at 1,783 mL/min
	1920	43.33	Finished refilling the tank with injectate solution
	1932	43.53	Injecate sample, measured pump rate at 1,817 mL/min
08/13/1998	1056	58.93	Finished refilling the tank with injectate solution
	1115	59.25	Measured pump rate at 1,725 mL/min
	1538	63.63	Measured pump rate at 1,800 mL/min
	1600	64.00	Finished refilling the tank with injectate solution
08/14/1998	1000 –1830	82.0 – 90.5	Synoptic sample collection
	1135	83.58	Injecate sample, measured pump rate at 1,790 mL/min
	1520	87.33	Measured pump rate at 1,767 mL/min
	1930	91.50	Stopped pumps

"Study Methods" section of this report. The analytical methods are listed in table 1.

Tracer-Injection Study Results

Chemical analyses results for chloride tracer concentrations at the Eureka to Howardsville transport and synoptic sites were used to compute traveltime, stream discharge, and chemical mass loading as discussed herein. The 1998 synoptic-sampling site locations are listed in table 5, field measurements and major ion concentrations are listed in Appendix 1, and ICP-AES synoptic-sampling results are listed in Appendix 2. Data are sorted in downstream order within groups of instream and inflow sites to emphasize the downstream changes.

Arrival Times

Information from the arrival and departure of tracer from the transport sites was used to calculate the traveltime between sites. Despite the complication caused by the pumps stopping on the first day of injection, the arrival times of the tracer at the downstream sites during the subsequent injection were not affected, and data from the restarted continuous injection are reported herein.

Data for transport sites T1 and T2 are used to demonstrate how arrival times of the chloride tracer were calculated and to discuss traveltime through the braided reach (fig. 3). At transport site T1, an abrupt chloride arrival is noted; indicating that the interval of time between sample collections was too large to discern a gradual tracer arrival. However, the tracer arrival curve is well defined at transport site T2. After the initial arrival of chloride tracer at sites T1 and T2, the plateau concentration decreased between 35 and 40 hours because of a decrease in the upstream tracer injection rate (table 4). A second decrease in the tracer plateau is noted at both sites T1 and T2 at approximately 75 hours because of a local rainstorm, which diluted the instream tracer concentrations. Because of variations in tracer plateau concentration at sites T1 and T2, an assumed average tracer plateau concentration for each site was used to compute the traveltime between sites. An average plateau concentration of 11.0 mg/L was assumed at site T1, and an average plateau concentration of 5.5 mg/L was assumed at T2, resulting in C_{50} values of 5.5 mg/L and 2.25 mg/L for sites T1 and T2, respectively. Interpolations of C_{50} arrival times

Table 5. Synoptic-sampling sites and discharge calculated from tracer-dilution, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.

[distance, distance downstream from injection site; L/s, liters per second; ft^3/s, cubic feet per second; --, not applicable]

Distance (meters)	Site name	Source	Inflow location	Discharge (L/s)	Discharge (ft^3/s)
0	Upstream from injection site	Stream	--	261	9.2
80	First site downstream from injection	Stream	--	261	9.2
282	T1 site—Upstream from Eureka Gulch	Stream	--	310	11.0
347	Eureka Gulch	Inflow	Right bank	162	5.7
586	Downstream from Eureka Gulch	Stream	--	472	16.7
786	Near right bank talus slope	Stream		473	16.7
906	Upstream from first braids	Stream		477	16.8
1,061	Upper braided reach	Stream		481	17.0
1,411	Left braid near Forest Queen	Stream	--	491	17.3
1,618	1618 Braids	Stream	--	496	17.5
1,918	Left braid upstream from Forest Queen	Stream	--	505	17.8
2,030	Upstream from Forest Queen inflow	Stream	--	706	25.0
2,090	Inflow from Forest Queen mine	Inflow	Left bank	80.2	2.8
2,240	T2 site—Downstream from end of braids	Stream	--	786	27.8
2,420	Upstream from Minnie Gulch	Stream	--	786	27.8
2,465	Minnie Gulch	Inflow	Left bank	90.3	3.2
2,860	Near braided area	Strean	--	877	31.0
3,150	Upstream from inflow near Kittimack	Stream	--	948	33.5
3,165	Upstream from Otto Gulch fan	Inflow	Right bank	104	3.7
3,400	Downstream from braids near Kittimack	Stream	--	1,052	37.2
3,405	Drains hillslope or alluvium	Inflow	Left bank	168	5.9
3,435	Upstream Maggie Gulch downstream Kittimack tailings	Stream	--	1,200	43.1
3,450	Maggie Gulch	Inflow	Right bank	80.5	2.8
3,665	Downstream from Maggie Gulch	Stream	--	1,301	46.0
3,905	Upstream from braided reach	Stream	--	1,328	46.9
3,954	Drains large area of willows	Inflow	Right bank	29.3	1.0
4,164	Near beaver ponds on left bank	Stream	--	1,357	48.0
4,189	Inflow from beaver ponds	Inflow	Left bank	84.2	3.0
4,430	Downstream from beaver ponds on left bank	Stream	--	1,441	50.9
4,670	Downstream from braids	Stream	--	1,560	55.1
4,970	Along smooth reach of stream	Strean	--	1,570	55.5
5,190	Upstream from beaver pond inflow	Strean	--	1,595	56.4
5,210	Drains beaver pond	Inflow	Right bank	0.8	0.03
5,407	Drains ponds	Inflow	Right bank	0.8	0.03
5,467	T3 site--Site of 1997 Howardsville injection	Inflow	Left bank	0.8	0.03
5,648	Drains upstream from tailings piles	Stream	--	1,597	56.4
6,038	Along tailings piles (1997 T1)	Inflow	Left bank	30.2	1.1
6,438	Inflow from Howardsville Mill	Stream	--	1,627	57.5

Table 5. Synoptic-sampling sites and discharge calculated from tracer-dilution, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.—Continued

[distance, distance downstream from injection site; L/s, liters per second; ft³/s, cubic feet per second; --, not applicable]

Distance (meters)	Site name	Source	Inflow location	Discharge (L/s)	Discharge (ft³/s)
6,528	Downstream from Howardsville Mill	Inflow	Left bank	15.7	0.6
6,558	Cunningham Gulch	Stream	--	1,662	58.7
6,618	Downstream from Cunningham Gulch	Inflow	Left bank	445	15.7
6,633	Hematite Gulch	Stream	--	2,107	74.4
6,753	Downstream from Hematite Gulch	Inflow	Right bank	65	2.3
6,993	T4 site—Howardsville gage	Stream	--	2,172	76.8
7,008	Drains left bank adit up hill	Inflow	Left bank	30.6	1.1
7,013	Drains old mill site	Inflow	Right bank	30.6	1.1
7,063	Also drains old mill site (?)	Inflow	Right bank	30.6	1.1
7,250	End of study reach	Stream	--	2,319	81.9
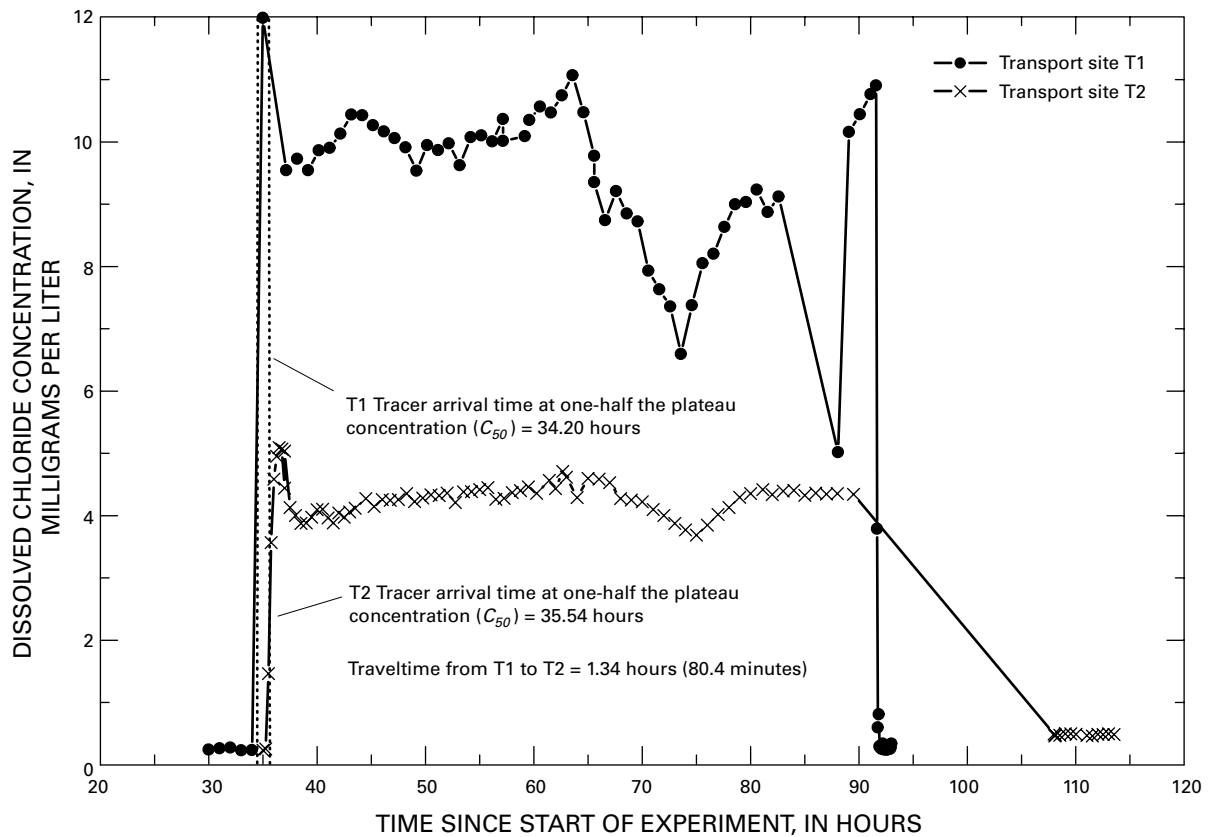
Figure 3. Dissolved chloride concentrations with time at transport sites T1 and T2, Eureka to Howardsville study reach, upper Animas River, Colorado, August 1998.

(t_{50} values) from figure 3 result in an arrival time of 34.2 hours for T1 and an arrival time of 35.54 hours for site T2.

The difference between the T1 and T2 arrival times is 1.34 hours (80.4 minutes) and represents the average travel-time from site T1 to site T2. Site T2 is located downstream from the braided reach of interest, and the traveltime calculated for this stream reach indicates relatively rapid flow of water through the braided reach. A stream velocity of 0.47 meter per second (m/s) was computed for the open stream channel from the injection site to site T1, and a stream velocity of 0.45 m/s was computed for the braided reach from site T1 to T2. This small difference in stream velocity between reaches indicates that the braided reach did not substantially reduce water flow velocity under low-flow conditions.

Discharge Profile

A detailed discharge profile for the 1998 Eureka to Howardsville study reach was developed using the chloride tracer concentrations that were measured in the synoptic samples and adjusted for analytical precision. Discharge calculations based on chloride concentrations for a given tracer-injection study depend on two conditions. First, the instream tracer concentration should be consistently higher than the inflow tracer concentrations, and this condition was generally met during the 1998 Eureka to Howardsville tracer-injection study (fig. 4). Second, the tracer concentration in the synoptic samples must represent the steady-state tracer-plateau concentration at that sampling site. For the 1998 Eureka to Howardsville study, the tracer-plateau chloride concentrations at the transport sites do match the synoptic-sampling chloride concentrations (fig. 4).

Concentrations of chloride, in a downstream direction, indicate the initial addition of the tracer and then the dilution due to surface and subsurface inflows (fig. 4). For a decrease of chloride to be considered a measurable change and not a product of analytical error, the decrease in concentration between stream samples must be higher than the precision of the chemical analyses. Error bars are indicated for chloride concentrations to show the precision of 1.75 percent for the 1998 data set (fig. 4). If a change in instream chloride concentration was lower than the precision of the analysis, the downstream chloride concentration was held constant for discharge calculations until a change higher than the precision of the analysis was measured.

The resulting profile of chloride concentration was used to calculate discharge according to the equations presented in table 2. Discharge results are presented in table 5 and in fig. 4. The total flow increase through the study reach was 2,058 L/s (72.7 ft^3/s), with visible tributary inflow contributing 1,449 L/s (51.1 ft^3/s) or about 70 percent of the total flow increase. By difference, unsampled ground-water inflow accounted for 609 L/s (21.6 ft^3/s) or about 30 percent of the total flow increase through the study reach. Cunningham Gulch (distance 6,558 m) was the largest tributary inflow,

accounting for 445 L/s (15.7 ft^3/s) or about 22 percent of the total flow increase. The change in flow through the braided reach was the difference in flow between sites at 2,030 m and 786 m and was 233 L/s (8.2 ft^3/s) or about 11 percent of the total flow increase. Eureka Gulch (586 m) contributed 162 L/s (5.7 ft^3/s) or about 8 percent of the total flow increase. Notable flow increases also occurred downstream from the Kitty Mack tailings at 3,405 m (168 L/s, 5.9 ft^3/s, 8 percent of total increase), Otto Gulch at 3,165 m (104 L/s, 3.7 ft^3/s, 5 percent of total increase), Minnie Gulch at 2,465 m (90 L/s, 3.2 ft^3/s, 4 percent of total increase), willows and beaver ponds at 4,189 m (84 L/s, 3.0 ft^3/s, 4 percent of total increase), Maggie Gulch at 3,450 m (80 L/s, 2.8 ft^3/s, 4 percent of total increase), and Hematite Gulch at 6,633 m (65 L/s, 2.3 ft^3/s, 3 percent of total increase).

A streamflow-gage measurement at the downstream monitoring site (gaging station A53) did not compare well with the discharge values calculated from tracer dilution (fig. 4). Similar to other streams, the volume of flow measured by tracer dilution was much higher than concurrent flowmeter measurements because of flow through streambed cobbles (Kimball, 1997; Kimball and others, 1999a, 1999c).

Synoptic-sampling and Mass-Loading Calculation Results

This section presents results for the 1998 Eureka to Howardsville synoptic-sampling results and mass-loading calculations for constituents of interest. Synoptic-sampling data are presented in Appendixes 1 and 2, and the data are contained in USGS digital database for the Animas River watershed Abandoned Mine Land Program (Sole and others, 2005). Although concentrations of many metals were determined in the study, constituents of interest in the Eureka to Howardsville reach of the upper Animas River included pH, aluminum, calcium, magnesium, copper, iron, manganese, zinc, and sulfate.

pH

Instream pH is an important chemical parameter used to evaluate ARD effects and instream chemical reactions because pH can control chemical reactions such as aluminum or iron hydroxide precipitation and adsorption of metals onto sediment. The downstream profile of instream and inflow pH values for the Eureka to Howardsville study reach is presented in figure 5. Instream pH values were near neutral, ranging from about 6.6 at 1,918 m to 7.6 at 3,905 m. There was no clear downstream trend to the instream pH values; however, instream pH did appear to be affected by inflow pH. Instream pH values decreased downstream from inflows with pH values lower than the stream (3,165-m inflow, 3,954-m inflow, and 6,438-m inflow), and instream pH values increased downstream from inflows with high pH values (Minnie Gulch, Maggie Gulch, beaver ponds at 5,210 m, Cunningham Gulch,
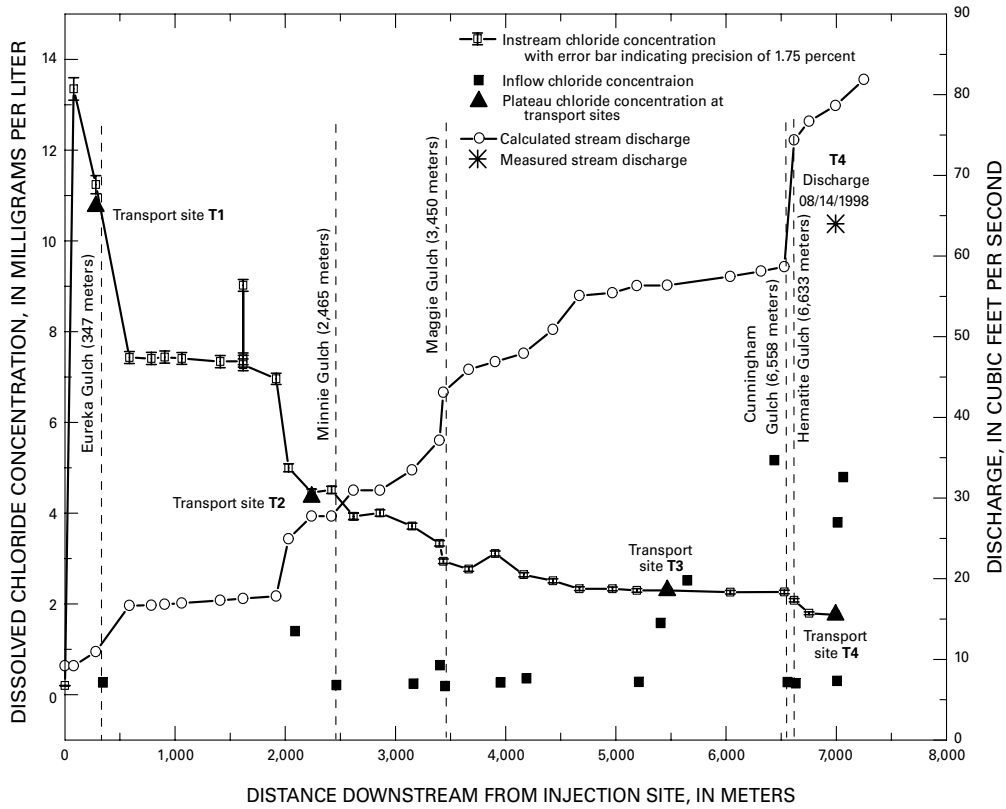
Figure 4.   Dissolved chloride concentrations and calculated discharges with distance downstream from the injection site, Eureka to Howardsville study reach, upper Animas River, Colorado, August 14, 1998.
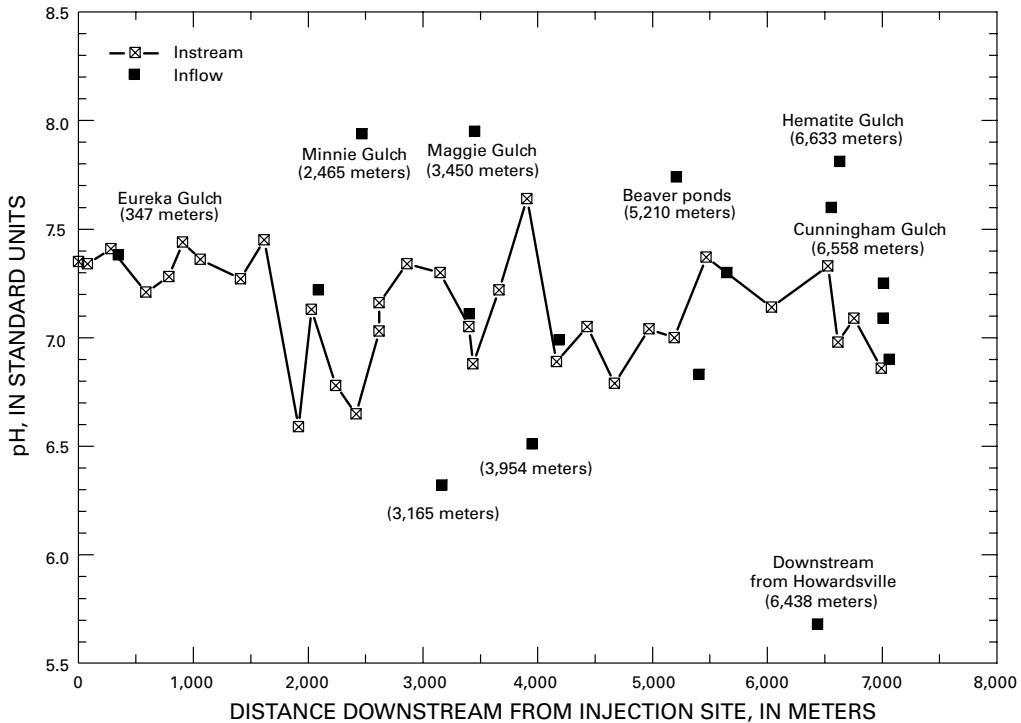
Figure 5.   Instream and inflow pH with distance from the injection site, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.

and Hematite Gulch) (fig. 5). The inflow sample from 6,438 m had the lowest pH of all sampled inflows (5.7), and there were no acidic inflows (pH lower than 5.0) identified during the synoptic sampling.

Aluminum

There was little variability in dissolved aluminum instream and inflow concentrations (Appendix 2). Instream aluminum concentrations ranged from 0.014 to 0.084 mg/L with a mean of 0.049 mg/L, and inflow aluminum concentrations ranged from 0.014 to 0.56 mg/L with a mean of 0.067 mg/L. The maximum dissolved aluminum inflow concentration of 0.56 mg/L occurred at 6,438 m.

Instream colloidal aluminum concentrations decreased downstream from Eureka to just upstream from Howardsville at 6,038 m (fig. 6). The maximum instream colloidal aluminum concentration of 0.226 mg/L occurred at the upstream end of the study reach near the injection site, indicating that colloidal aluminum was contributed to the Eureka to Howardsville study reach from sources upstream from Eureka. Instream colloidal aluminum concentrations decreased through the primary braided reach from a concentration of 0.172 mg/L at 786 m to a concentration of 0.077 mg/L at 2,030 m (fig. 6). Colloidal aluminum loss also occurred through a secondary braided reach where the colloidal aluminum concentration decreased from 0.088 mg/L at 3,150 m to 0.036 mg/L at 3,435 m (fig. 6). A graph of sampled instream load (fig. 7) also shows a loss of colloidal aluminum through the braided reaches and supports conclusions that the braided reaches contributed to attenuation of colloidal aluminum probably by settling and entrapment of colloidal particles through the shallow water. Downstream from transport site T3 at 5,467 m, colloidal aluminum concentrations increased slightly in response to inflows with elevated colloidal aluminum concentrations (fig. 6). The instream colloidal aluminum load also increased downstream from the inflow at 6,438 m (fig. 7).

Calcium and Magnesium

Calcium and magnesium concentrations in the upper Animas River for 1998 were controlled by the calcium and magnesium concentrations of surface-water inflows. Instream concentrations of calcium ranged from approximately 25 to 37 mg/L with a mean of 30 mg/L, and inflow calcium concentrations ranged from 27 to 96 mg/L with a mean of 43 mg/L. Instream calcium concentrations increased in a downstream direction, from approximately 26 mg/L at Eureka to approximately 37 mg/L at the downstream end of the study reach, in response to elevated inflow calcium concentrations (fig. 8).

Magnesium concentrations in the stream ranged from approximately 2.0 to 2.4 mg/L with a mean of 2.2 mg/L, and inflow magnesium concentrations ranged from approximately 1.9 to 8.8 mg/L with a mean of 3.0 mg/L. Magnesium concentrations increased slightly in the downstream direction from

2.2 mg/L at Eureka to 2.4 mg/L at the downstream end of the study reach. Inflow magnesium concentrations were similar to stream concentrations with the exception of the inflow at 6,438 m (fig. 9).

Copper

Instream dissolved copper concentrations were compared to acute and chronic toxicity standards for aquatic life. These standards were computed for each water sample as a function of hardness (the sum of calcium, magnesium, barium, and strontium concentrations in milligrams per liter as calcium carbonate) according to the following relations (Colorado Department of Public Health and Environment, written commun., 1997):

$$\text{Copper Acute Toxicity Standard} = 0.5* \frac{(e^{(0.9422*\ln(\text{hardness}) - 0.7703)})}{1,000}, \text{ and}$$

$$\text{Copper Chronic Toxicity Standard} = \frac{(e^{(0.8545*\ln(\text{hardness}) - 1.465)})}{1,000}.$$

Figure 10 presents a graph of instream and inflow dissolved copper concentrations for the Eureka to Howardsville 1998 synoptic sampling and the acute and chronic toxicity standards computed for each instream sample. The highest dissolved copper concentrations were in the upstream part of the study reach, indicating that dissolved copper was contributed by sources upstream from Eureka. Similar to colloidal aluminum, dissolved copper concentrations decreased through the primary braided reach downstream from Eureka from approximately 0.033 mg/L at 906 m to less than the method detection limit of 0.002 mg/L at 2,030 m (fig. 10). A graph of sampled instream copper load (fig. 11) also shows a loss of dissolved copper at the downstream end of the primary braided reach at 2,030 m. Adsorption of dissolved copper was the likely mechanism of copper attenuation through the primary braided reach.

Instream dissolved copper concentrations remained lower than both the acute and chronic toxicity standards downstream from the primary braided reach at 2,030 m to the end of the study reach (fig. 10), and the mass-loading graph for copper also indicates a relatively constant instream copper load downstream from the primary braided reach (fig. 11). An increase in copper load at the downstream end of the study reach (fig. 11) seems to be related to inflows from abandoned mines downstream from Hematite Gulch (6,633 m), although the instream dissolved copper concentrations remained lower than the acute and chronic toxicity standards downstream from Hematite Gulch (fig. 10). Dissolved copper was not detected in the 6,438-m inflow downstream from Howardsville in 1998.

Figure 6. Instream and inflow colloidal aluminum concentrations with distance from the injection site, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.

Figure 7. Sampled instream load, cumulative instream load, and cumulative inflow load of colloidal aluminum with distance from the injection site, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.
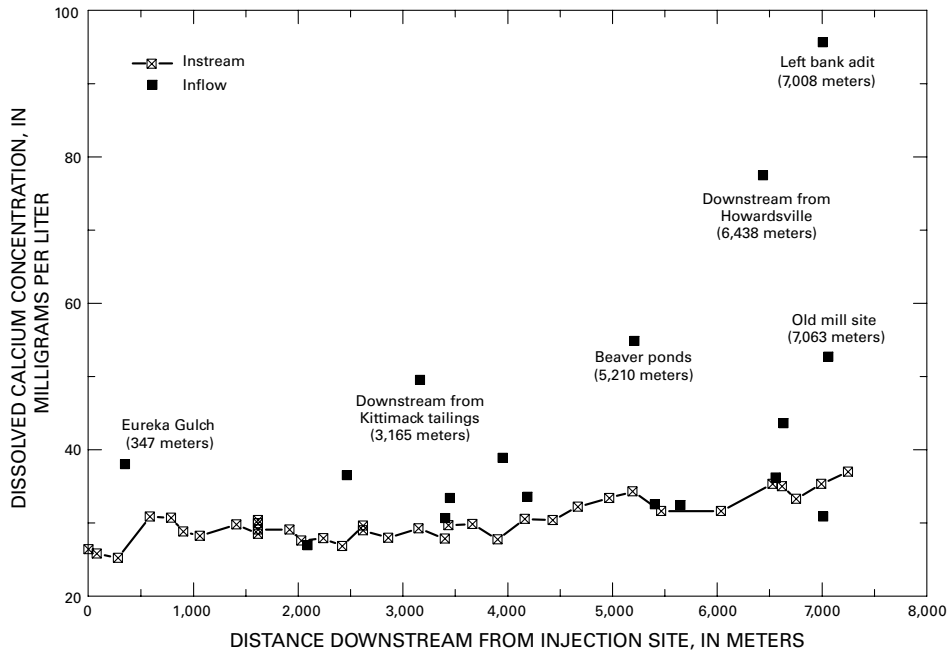
Figure 8.   Instream and inflow dissolved calcium concentrations with distance from the injection site, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.

Figure 9.   Instream and inflow dissolved magnesium concentrations with distance from the injection site, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.

Figure 10. Instream and inflow dissolved copper concentrations, copper acute toxicity standard, and copper chronic toxicity standard with distance from the injection site, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.

Figure 11. Sampled instream load, cumulative instream load, and cumulative inflow load of dissolved copper with distance from the injection site, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.

Iron

Instream dissolved and colloidal iron concentrations during the 1998 Eureka to Howardsville study generally were low or not detected upstream from Howardsville, where dissolved iron concentrations were less than 0.014 mg/L, and colloidal iron concentrations were less than 0.088 mg/L. There was essentially no change in the instream load, the cumulative instream load, or the cumulative inflow load for dissolved or colloidal iron upstream from Howardsville (figs. 12 and 13).

Downstream from Howardsville, the sampled instream load for dissolved iron increased because of the elevated iron concentration from the inflow at 6,438 m (11.7 mg/L) and then decreased downstream probably because iron colloids precipitated in the near-neutral pH streamwater (fig. 12). A second but smaller increase in the dissolved iron instream load occurred at 7,008 m where an adit inflow contributed additional dissolved (1.03 mg/L) and colloidal (1.13 mg/L) iron to the stream. Downstream from Howardsville, the dissolved iron cumulative inflow load was higher than the cumulative instream and sampled instream loads indicating chemical removal probably as precipitation of iron colloids (fig. 12).

The sampled instream load for colloidal iron increased downstream from Howardsville because of the elevated colloidal iron concentration from the inflow at 6,438 m (3.87 mg/L) and likely from precipitation of iron colloids from the dissolved iron. For colloidal iron, the cumulative instream load was higher than the cumulative inflow load (fig. 13), indicating that the source of iron colloids was instream chemical precipitation rather than inflow contributions. The decrease in the colloidal iron instream load between Howardsville and the adit drainage at 7,008 m likely reflects the settling of iron colloids onto the streambed.

Based on synoptic-sampling concentration data and mass-loading calculations, the inflow at 6,438 m was a substantial source of dissolved and colloidal iron to the upper Animas River from Eureka to Howardsville in 1998. This inflow drains the area of tailings near Howardsville and the Pride of the West Mill. Some of these tailings were relocated during 1997 and 1998, and the effects of tailings removal on stream inflow quality are undocumented. Inflow from a draining adit at 7,008 m was a secondary source of dissolved and colloidal iron to the study reach. The instream dissolved iron load downstream from each of these inflows first increased in response to the inflow and then decreased in response to precipitation of iron colloids in the near-neutral pH stream. The colloidal iron load increased downstream from each of these inflows in response to the elevated inflow concentrations of colloidal aluminum and the chemical precipitation of iron colloids.

Manganese

Instream dissolved manganese concentrations in the Eureka to Howardsville study reach ranged from 0.14 to 0.78 mg/L in 1998. The highest instream manganese con-

centration (fig. 14) was upstream from the injection site at 0 m (0.78 mg/L) indicating that dissolved manganese was contributed by sources upstream from Eureka. Downstream from Eureka to upstream from Howardsville, instream manganese concentrations decreased (fig. 14), and the cumulative instream manganese load remained relatively constant (fig. 15). Inflows dissolved manganese concentrations upstream from Howardsville ranged from less than the method detection limit of 0.01 to 0.26 mg/L and generally were lower than the instream manganese concentrations from Eureka to Howardsville. The highest manganese inflow concentration in the Eureka to Howardsville study reach in 1998 was from the inflow at 6,438 m (18.5 mg/L), and the second highest manganese inflow concentration was downstream from Howardsville at 7,008 m where visible drainage from an adit contributed 1.0 mg/L dissolved manganese to the upper Animas River.

The mass-loading graphs for dissolved manganese showed little increase in sampled instream load, cumulative instream load, or cumulative inflow load upstream from Howardsville (fig. 15). All three loads increased downstream from Howardsville in response to the elevated manganese concentrations from the inflows at 6,438 m and 7,008 m. The manganese cumulative inflow loads were higher than the cumulative instream loads downstream from Howardsville, indicating chemical removal of manganese possibly by precipitation of manganese oxyhydroxides.

Zinc

Instream dissolved zinc concentrations were compared to acute and chronic toxicity standards for aquatic life. These standards were computed for each water sample as a function of hardness (in milligrams per liter as calcium carbonate) according to the following relations (Colorado Department of Public Health and Environment, written commun., 1997):

$$\text{Zinc Acute Toxicity Standard} = \frac{(e^{(0.8473*1n(hardness)+0.8604)})}{1,000}, \text{ and}$$

$$\text{Zinc Chronic Toxicity Standard} = \frac{(e^{(0.8473*1n(hardness)+0.7614)})}{1,000}.$$

Instream dissolved zinc concentrations ranged from 0.27 to 0.54 mg/L and exceeded the acute and chronic aquatic-life standards along the entire study reach (fig. 16). The highest dissolved zinc concentrations were upstream from the primary braided reach, indicating that dissolved zinc was contributed by sources upstream from Eureka. Dissolved zinc concentrations decreased through the primary braided reach similar to colloidal aluminum and dissolved copper concentrations (fig. 16), and the graph of sampled instream zinc load (fig. 17) also shows slight dissolved zinc loss through the primary braided reach. Adsorption of dissolved zinc likely contributed to its attenuation through the braided reach.

**Figure 12.** Sampled instream load, cumulative instream load, and cumulative inflow load of dissolved iron with distance from the injection site, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.
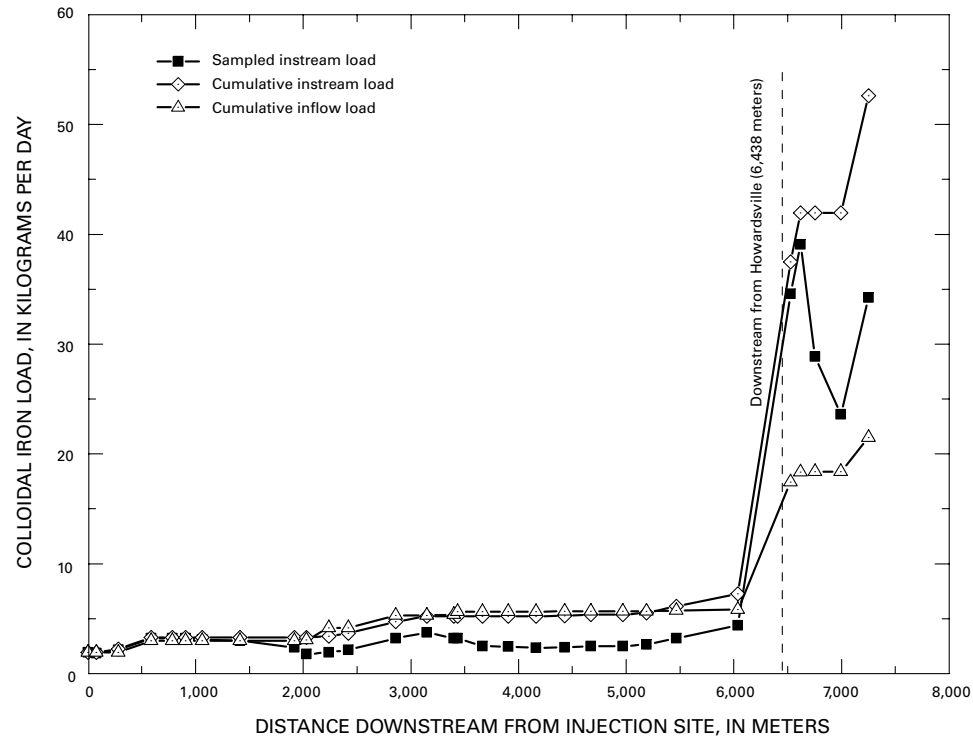
Figure 13. Sampled instream load, cumulative instream load, and cumulative inflow load of colloidal iron with distance from the injection site, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.
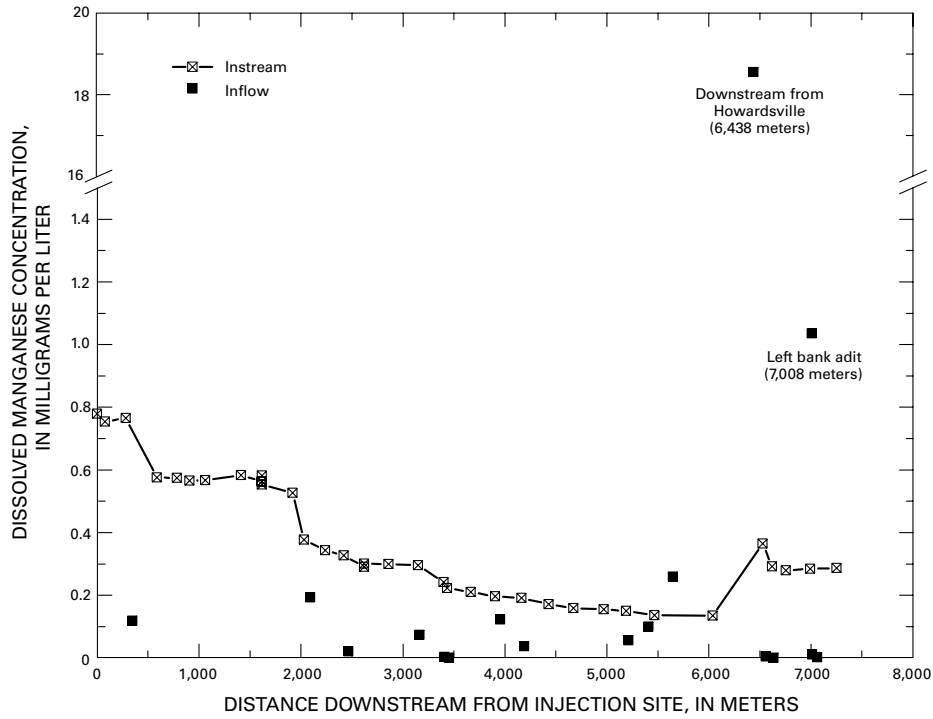
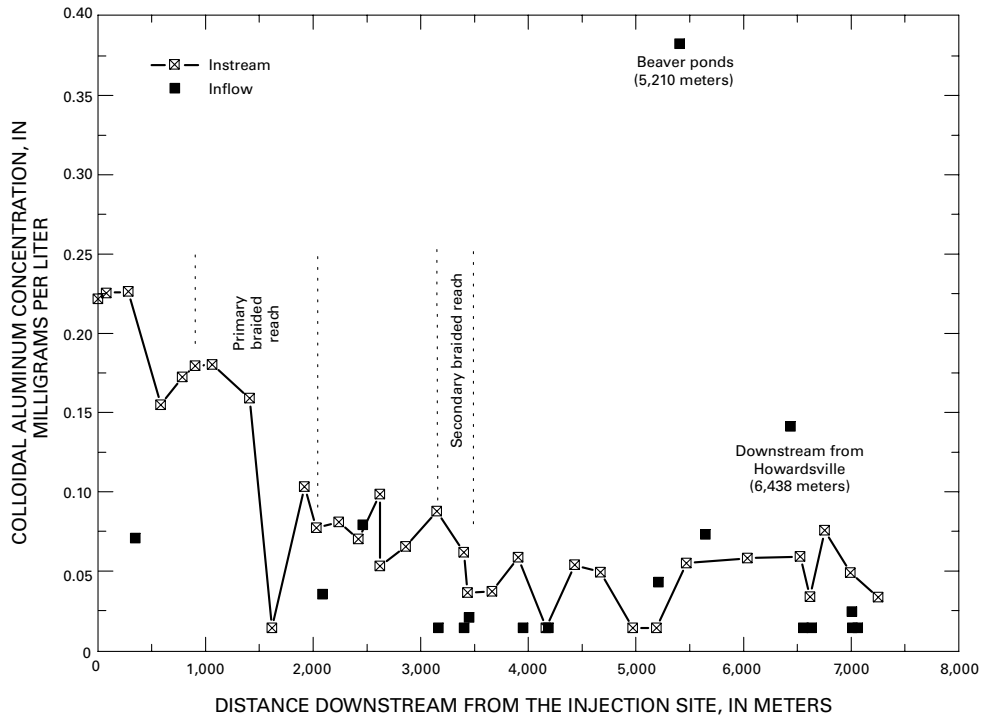**Figure 14.**   Instream and inflow dissolved manganese concentrations with distance from the injection site, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.
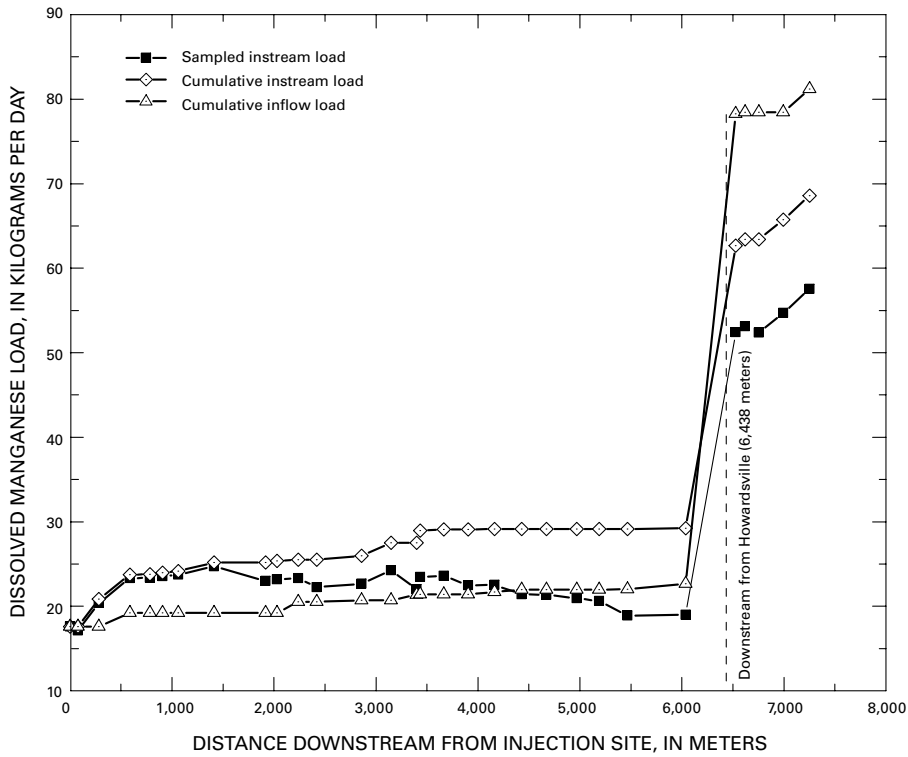
Figure 15.   Sampled instream load, cumulative instream load, and cumulative inflow load of dissolved manganese with distance from the injection site, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.
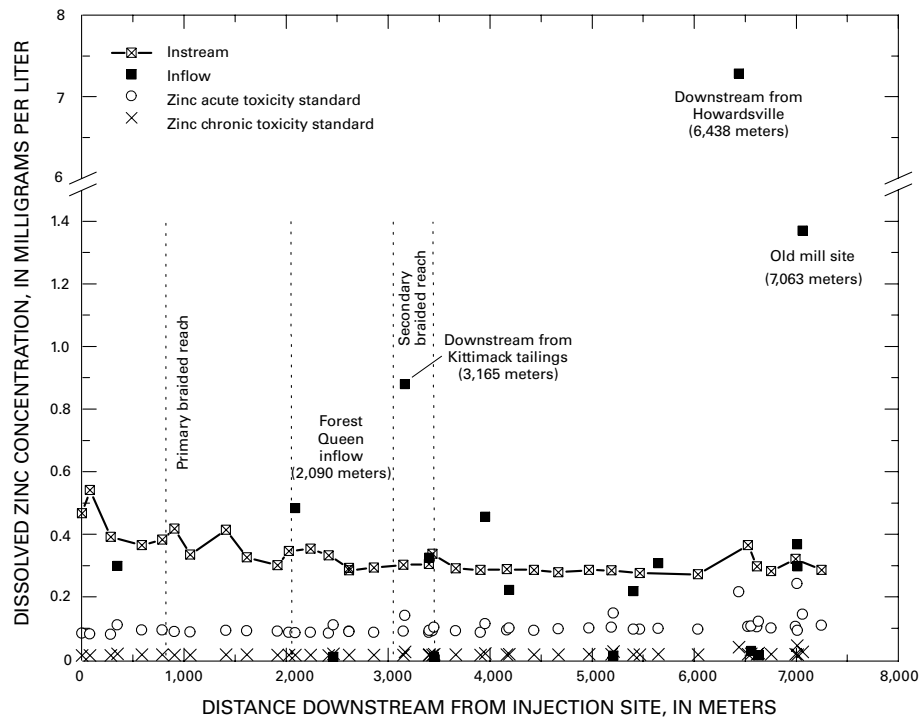
Figure 16. Instream and inflow dissolved zinc concentrations, zinc acute toxicity standard, and zinc chronic toxicity standard with distance from the injection site, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.

The zinc concentration of inflow samples varied more than instream zinc concentrations. Inflow zinc concentrations ranged from a minimum value of 0.008 mg/L to a maximum value of 7.3 mg/L for the inflow downstream from Howardsville at 6,438 m (fig. 16). Increases in the dissolved zinc sampled instream load, cumulative instream load, and cumulative inflow load are noted at approximately 2,000 m, 3,500 m, and 6,500 m downstream from the 1998 injection site (fig. 17). Corresponding increases in instream dissolved zinc concentrations also occurred in these reaches (fig. 16).

The dissolved zinc load increase at approximately 2,000 m apparently was the result of elevated dissolved zinc concentrations in unsampled inflow at the downstream end of the primary braided reach and the Forest Queen inflow at 2,090 m (0.48 mg/L). Zinc loading from unsampled inflow could be from ground-water and/or surface-water interaction with historical tailings dispersed from Eureka, which now are located in and downstream from the braided reach (Vincent and others, 1999). A smaller load increase at 2,090 m was attributed to visible inflow from the Forest Queen mine (fig. 2). However, in the fall of 1998, a wetland was constructed at the mouth of the Forest Queen mine, and dissolved zinc concentrations in the Forest Queen discharge to the Animas River had decreased to near detection limits (0.003 mg/L) in 2000 as a result of this remedial action (M.A. Mast, U.S. Geological Survey, oral commun., 2000).

Downstream from the Kittimack tailings, from approximately 3,000 to 3,500 m, the dissolved zinc loads again increased (figs. 16 and 17). This area included the secondary braided reach and is identified as a contributor of dissolved zinc to the Eureka to Howardsville study reach. The effects of remediating this area are addressed through solute-transport simulations later in the "Zinc Solute-Transport Simulations" section.

The large increases in dissolved zinc load and instream dissolved zinc concentration at approximately 6,500 m likely were the result of inflow downstream from Howardsville at 6,438 m, where the maximum dissolved zinc inflow concentration of 7.3 mg/L was measured. Some of the tailings near Howardsville were relocated during 1997 and 1998, and the effects of tailings removal on instream zinc concentrations are undocumented. Inflows downstream from Howardsville and Cunningham Gulch drain abandoned adits and other historical mining sites and contribute dissolved zinc to the upper Animas River including the inflow at 7,063 m (1.4 mg/L dissolved zinc). Summing all the positive changes in zinc load between stream sites provides a minimum estimate of the total mass of zinc entering the study reach, which was approximately 76 kilograms per day (kg/d) for low-flow conditions in 1998.
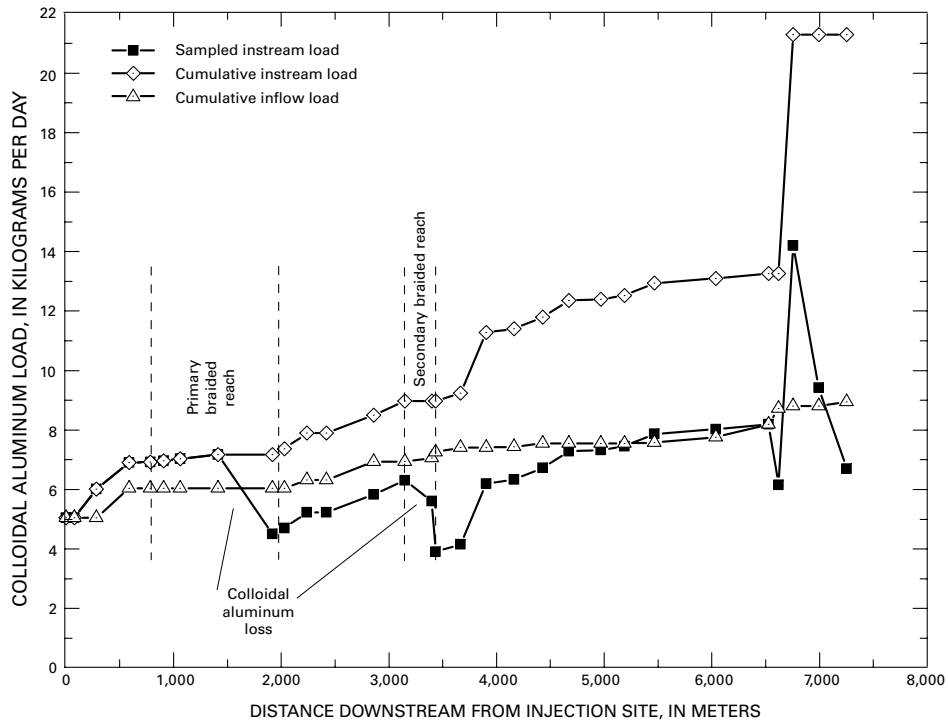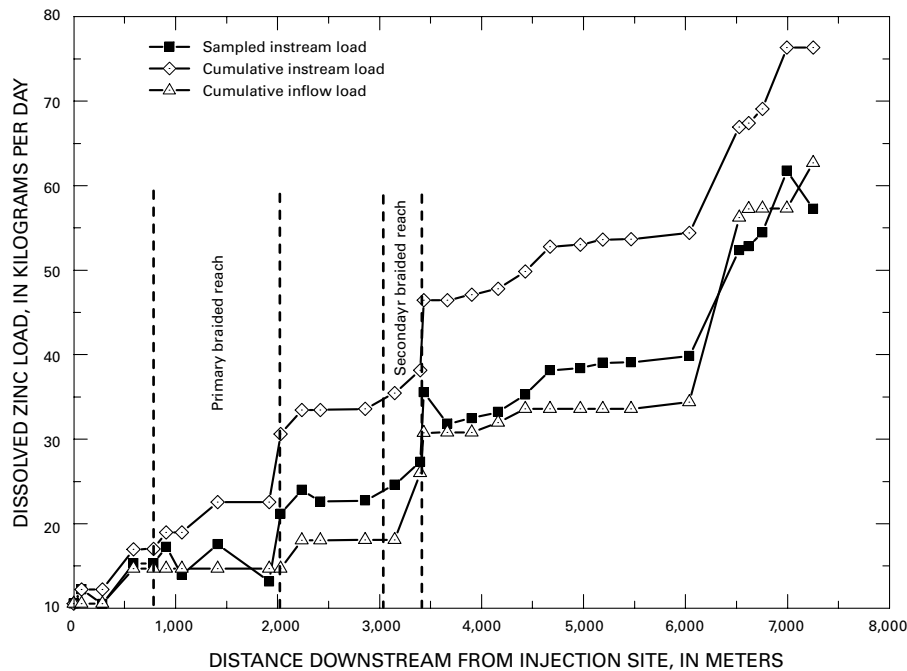
Figure 17.   Sampled instream load, cumulative instream load, and cumulative inflow load of dissolved zinc with distance from the injection site, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.

Sulfate

Instream sulfate concentrations ranged from 55 to 74 mg/L and were lower than the U.S. Environmental Protection Agency's (USEPA) secondary drinking-water standard of 250 mg/L (U.S. Environmental Protection Agency, 1992). A slight increase of instream sulfate concentration occurred downstream from the Eureka Gulch inflow, and concentrations remained nearly constant downstream from Eureka Gulch (fig. 18). Inflow sulfate concentrations in the study reach were more variable, ranging from 44 to 307 mg/L. The highest inflow sulfate concentrations were from Eureka Gulch at 347 m (90.7 mg/L), inflow downstream from the Kittimack tailings at 3,165 m (128 mg/L), inflow downstream from Howardsville at 6,438 m (307 mg/L), adit inflow at 7,008 m (266 mg/L), and inflow downstream from an old mill site at 7,063 m (108 mg/L) (fig. 18).

The mass-loading graphs for sulfate show increases in the sampled instream load, cumulative instream load, and cumulative inflow load from Eureka to Howardsville, indicating a general increase in instream and inflow sulfate load through the study reach. The sampled instream load and the cumulative instream load were approximately equal throughout the entire study reach, indicating no loss of sulfate because of chemical reaction (fig. 19).

Discussion of Sources and Loadings, Eureka to Howardsville Study Reach

Surface-water drainage in the Eureka to Howardsville study reach contributed aluminum, calcium, copper, iron, magnesium, sulfate, and zinc to the upper Animas River in 1998. Based on the 1998 synoptic-sampling results and mass-loading graphs, sources upstream from Eureka contributed aluminum, copper, manganese, and zinc to the Eureka to Howardsville study reach.

Colloidal aluminum, dissolved copper, and dissolved zinc were attenuated through the primary reach downstream from Eureka indicating that the braided reach is a sink for these metals. Colloidal aluminum attenuation through the primary braided reach likely was the result of physical processes such as particle settling and entrapment. Attenuation of dissolved copper and zinc through the primary braided reach likely was the result of adsorption of the dissolved constituents onto colloidal iron particles or streambed coatings. Instream colloidal aluminum concentrations were low downstream from the braided reaches to upstream from Howardsville (less than approximately 0.05 mg/L). The instream dissolved copper concentrations were lower than both the acute and chronic toxicity standards downstream from the primary braided reach to the end of the study reach.

Instream loads for colloidal aluminum, dissolved iron, colloidal iron, dissolved manganese, dissolved zinc, and dis-
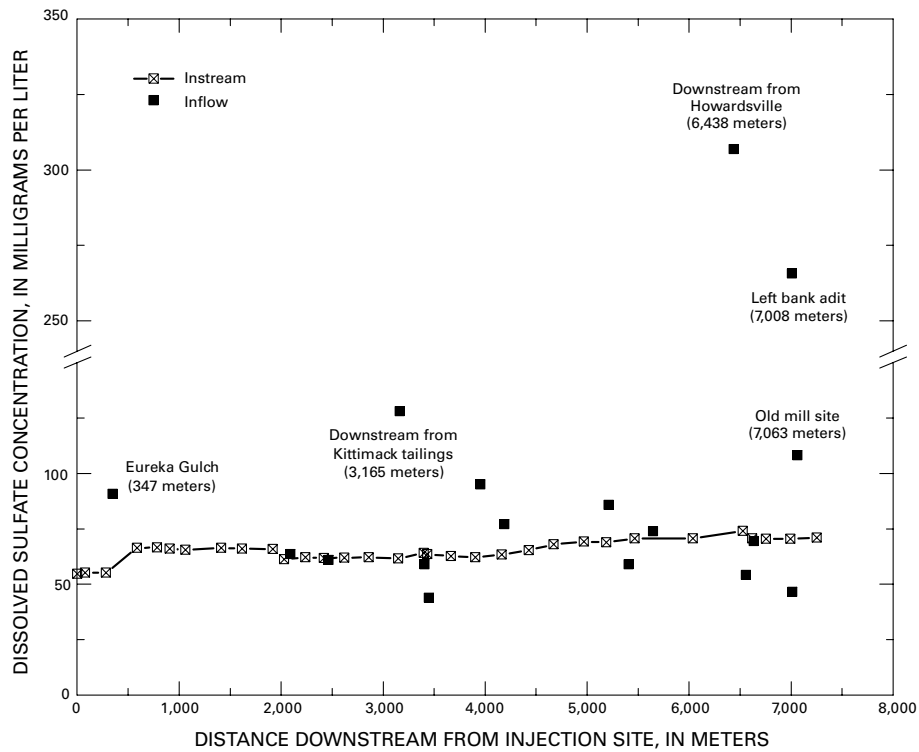
Figure 18. Instream and inflow dissolved sulfate concentrations with distance from the injection site, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.
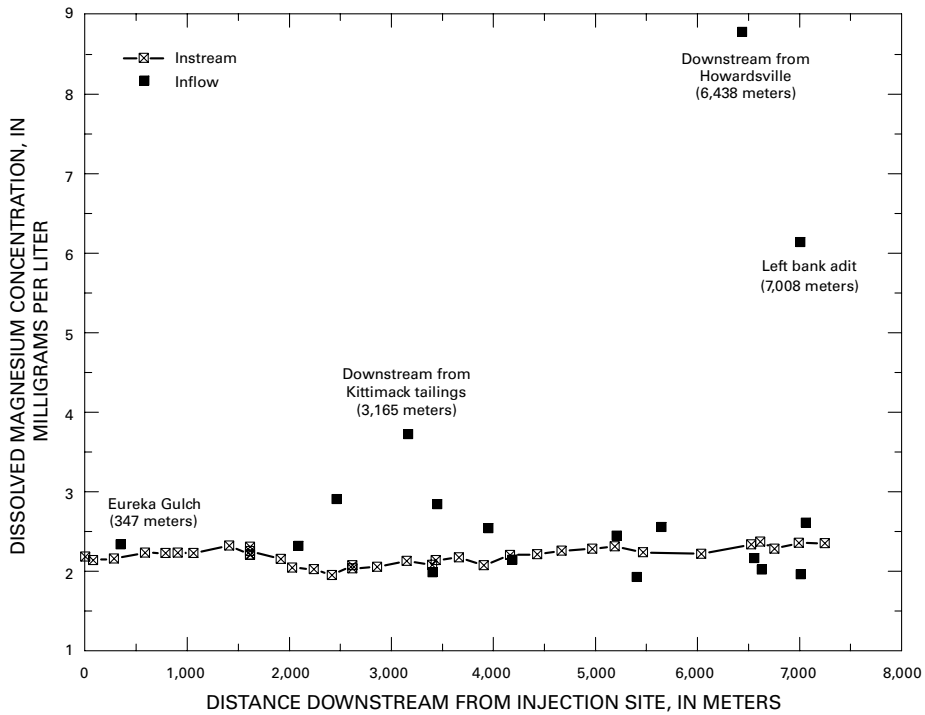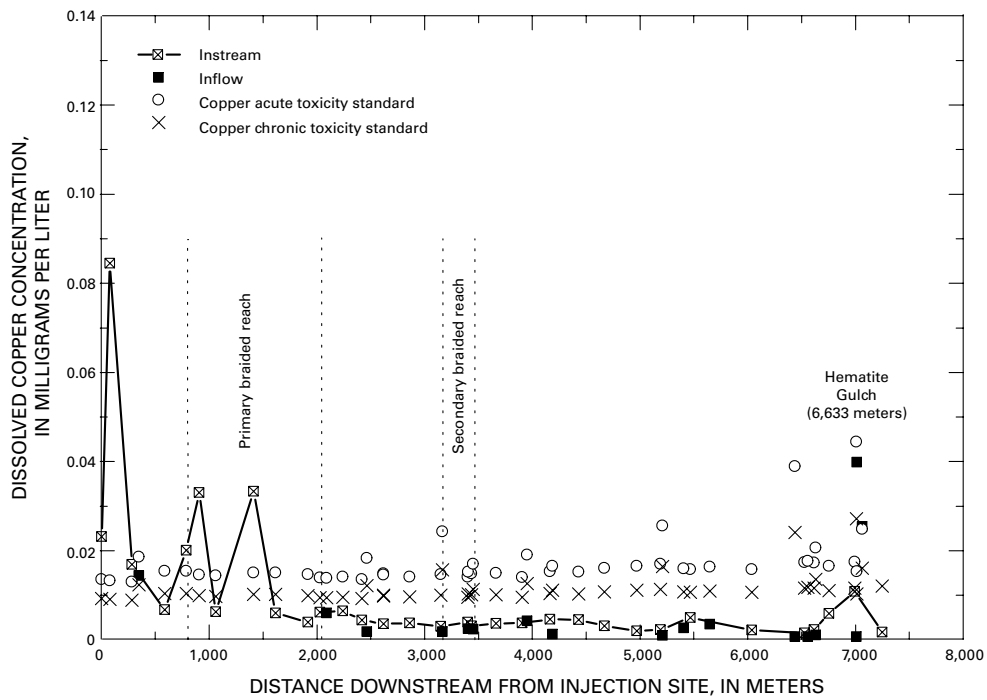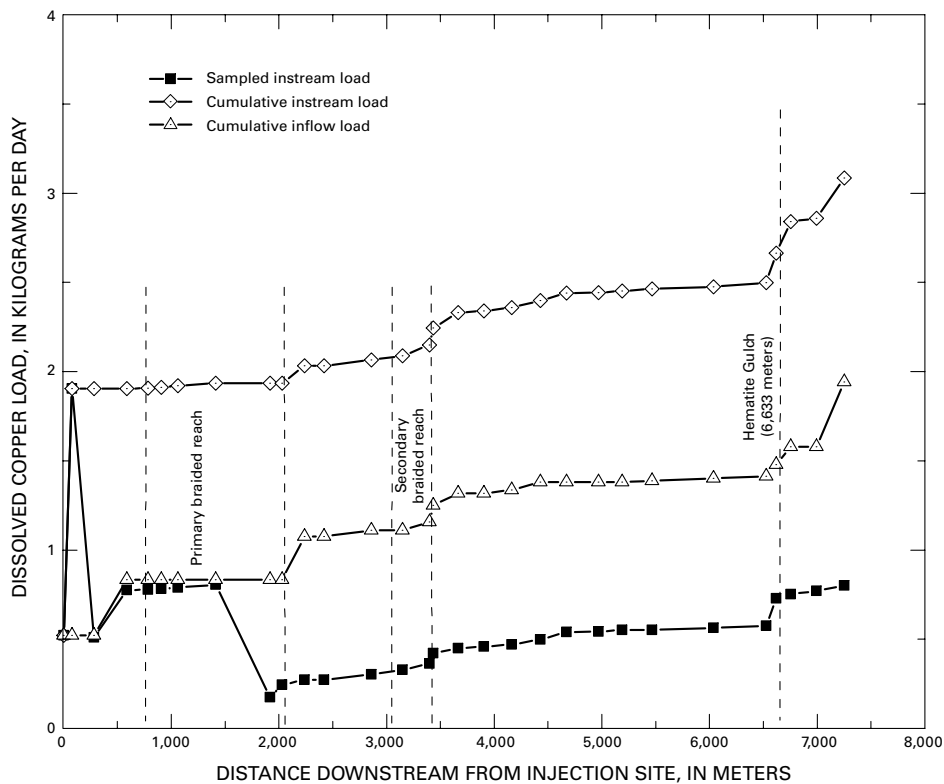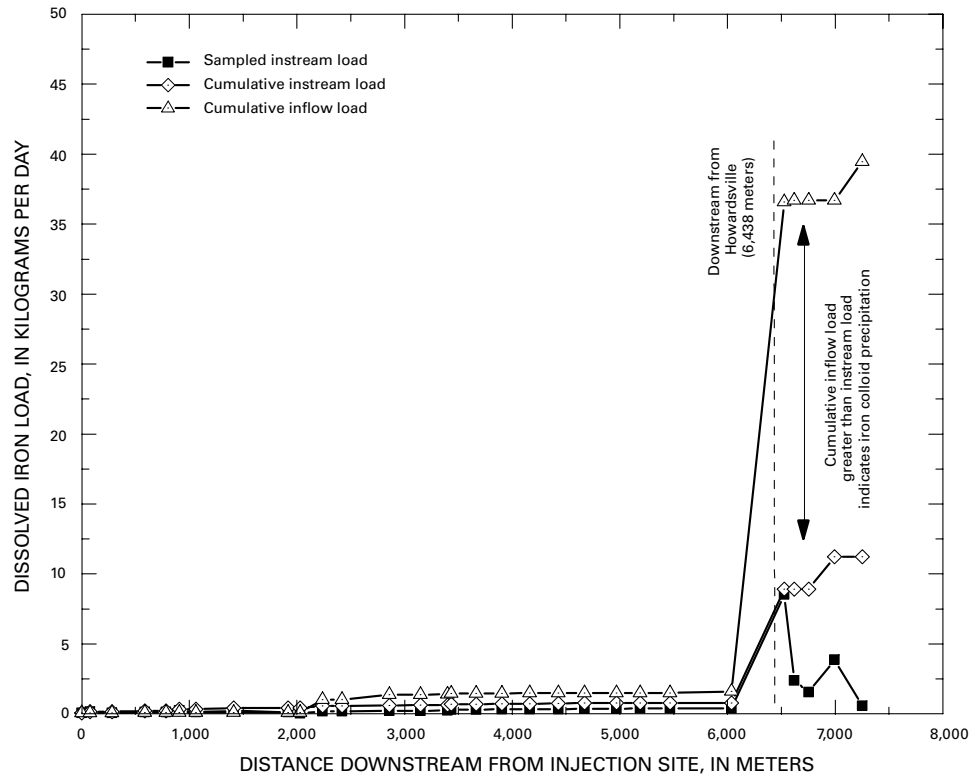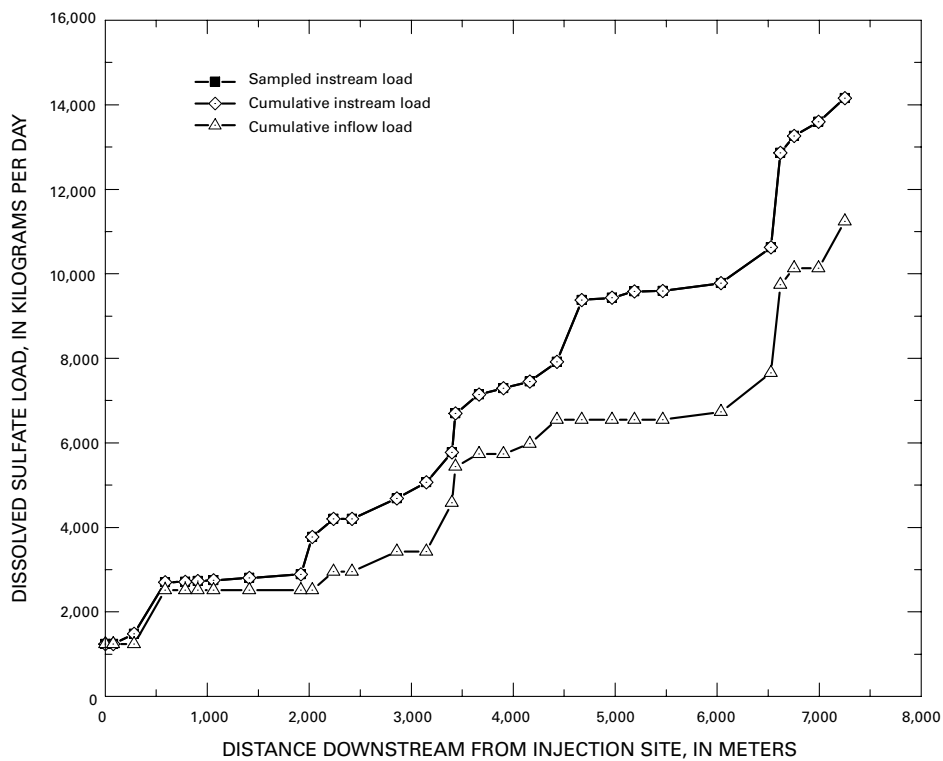

Figure 19. Sampled instream load, cumulative instream load, and cumulative inflow load of dissolved sulfate with distance from the injection site, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.

solved sulfate all increased substantially downstream from the inflow at 6,438 m. The inflow at 6,438 m drains the area of tailings near Howardsville and the Pride of the West Mill. Some of these tailings were relocated during 1997 and 1998, and the effects of tailings removal on streamwater quality are uncertain. Upstream from Howardsville, dissolved manganese was diluted by inflow, and dissolved and colloidal iron concentrations generally were low or not detected. Although instream sulfate loads increased in a downstream direction, instream sulfate concentrations were lower than the USEPA's secondary drinking-water standard of 250 mg/L.

Based on synoptic-sampling results, dissolved zinc was the primary constituent of concern in the Eureka to Howardsville study reach of the upper Animas River, and a cumulative instream zinc load of 76 kg/d was calculated for low-flow conditions in 1998. Increases in zinc load were measured downstream from Howardsville at 6,438 m (19 percent of the total load), downstream from the braided reach near the Forest Queen mine at 2,090 m (13 percent of the total load), near the Kittimack tailings at 3,165 m (12 percent of the total load), downstream from site T4 at 6,993 m (10 percent of the total load), and downstream from Eureka Gulch at 347 m (6 percent of the total load). Zinc loading from the upper Animas drainage upstream from the study area also was substantial (14 percent of the total load). A constructed wetland installed at the mouth of the Forest Queen mine in 1998 was successfully reducing zinc concentrations in the Forest Queen discharge to near detection limits (0.003 mg/L) in 2000.

Zinc Solute-Transport Simulations

To interpret mass-loading calculations and to evaluate the effects of potential remediation, one-dimensional surface-water transport of dissolved zinc was simulated for the Eureka to Howardsville study reach using OTIS. This section of the report describes the conservative and first-order decay simulations and the remediation simulations for the Eureka to Howardsville reach.

Conservative and First-Order Decay Simulations

The Eureka to Howardsville study reach was divided into 14 model reaches based on discharge calculations and mass-loading graphs. Main channel cross-sectional area, storage zone cross-sectional area, and storage-zone exchange coefficients were determined using OTIS-P simulations of the transport site data, and a uniform dispersion coefficient of 1.0 m was used for all model reaches. For each model reach, a lateral inflow discharge was computed based on the stream discharge profile, and lateral inflow concentrations were assigned to each model reach based on measured inflow concentrations for 1998 (table 6 and fig. 20).

Using lateral inflow concentrations representative of measured inflow concentrations (table 6), the conservative

(no decay) OTIS simulation computed instream zinc concentrations higher than the measured instream concentrations downstream from reach 2 (Eureka Gulch) (fig. 21). Consistent with the mass-loading graphs, this simulation result indicates removal of dissolved zinc from the stream. The loss of dissolved zinc likely was caused by zinc adsorption onto colloidal particles or streambed sediment and was represented as a first-order decay process using OTIS. First-order decay rates determined from best-fit trial and error simulations were assigned to model reaches 3, 5, 8, and 13 (table 6) to represent the decrease of sampled instream zinc load through these reaches (fig. 17). The OTIS result for instream zinc concentrations using measured lateral inflow concentrations and first-order decay is shown in figure 21 and is a reasonable match to the measured instream zinc concentrations.

Remediation Simulations

Two remediation alternatives were evaluated for the Eureka to Howardsville study reach using the first-order decay zinc solute-transport simulation described in the previous section. The first set of remediation simulations evaluated the effects of remediating inflow zinc concentrations in model reaches representing the Forest Queen mine inflow and unsampled inflow downstream from the braided reach in model reach 4 and inflow downstream from the Kittimack tailings in model reach 6. The second set of remediation simulations evaluates the effects of remediating inflow zinc concentrations in model reaches 4 and 6 in addition to inflow downstream from Howardsville in model reach 10.

To simulate remediation of stream reaches, the zinc lateral inflow concentrations were reduced from the measured inflow concentrations to hypothetical concentrations representative of inflow after remediation. Because these post-remediation concentrations are uncertain, remediation simulations of the Eureka to Howardsville study reach used a 50-percent reduction and then a 75-percent reduction in zinc concentrations for the lateral inflow concentrations of remediated reaches. A list of remediation simulations, zinc lateral inflow concentrations, and simulation results are presented in table 7.

The first set of remediation simulations address remediation of zinc concentrations in the model reaches representing the Forest Queen mine inflow and inflow below the Kittimack tailings (table 7, simulations 3 and 4). Model reach 4 represents the zinc inflow from the Forest Queen mine and unsampled inflow downstream from the braided reach, and model reach 6 represents the Kittimack tailings inflow. The zinc lateral inflow concentrations for these reaches were reduced by 50 percent and by 75 percent, and the simulations were run with first-order decay. Simulation results are shown in figure 22 and indicate that instream zinc concentrations downstream from the Kittimack tailings and upstream from Howardsville (end of model reach 7) would approach concentrations near 0.16 mg/L (fig. 22 and table 7) if zinc inflow

Table 6. OTIS setup and input parameters for zinc solute-transport model, upper Animas River, Eureka to Howardsville, Colorado.

[m, meters; m², square meters; m³/s-m, cubic meters per second per meter; mg/L, milligrams per liter; /s, per second; --, not applicable]

Model reach	Distance from injection site (m)	Reach length (m)	Main channel cross-sectional area (m²)	Lateral inflow rate (m³/s-m)	Lateral inflow concentration (mg/L)	First-order decay rate (/s)	Description (see figure 2)
1	282	282	0.65	1.767×10^{-4}	0.008	--	T1
2	586	304	1.20	5.329×10^{-4}	0.299		Downstream from Eureka Gulch
3	1,918	1,332	1.20	2.445×10^{-5}	0.008	4.0×10^{-5}	Downstream from braided reach
4	2,240	322	1.20	8.751×10^{-4}	0.483		T2 and downstream from Forest Queen mine
5	3,150	910	1.50	1.777×10^{-4}	0.008	2.5×10^{-5}	Upstream from Kittimack tailings
6	3,400	250	1.50	4.169×10^{-4}	0.879		Downstream from Kittimack tailings
7	3,435	35	1.50	4.806×10^{-3}	0.325		Downstream from flow increase at 3,405 m
8	4,670	1,235	1.50	2.754×10^{-4}	0.229	1.0×10^{-4}	Increase in flow from willows and beaver ponds
9	5,467	797	1.50	4.584×10^{-5}	0.115		T3 and upstream from Howardsville
10	6,528	1,061	3.00	6.112×10^{-5}	2.62		Downstream from Howardsville and upstream from Cunningham Gulch
11	6,618	90	3.00	4.947×10^{-3}	0.020		Downstream from Cunningham Gulch
12	6,993	375	3.00	3.217×10^{-4}	0.400		T4
13	7,250	257	3.00	3.570×10^{-4}	1.37	5.0×10^{-4}	End of study reach
14	7,350	100	3.00	--	--	--	Downstream boundary

concentrations were reduced by 75 percent in model reaches 4 and 6. An instream zinc concentration of 0.16 mg/L is the upper limit of acute toxicity for some sensitive aquatic species (Besser and others, 2001).

For the second set of remediation simulations, the effects of remediating model reaches representing the Forest Queen mine (model reach 4), inflow downstream from the Kittimack tailings (model reach 6), and inflow downstream from Howardsville (model reach 10) were evaluated (table 7,

simulations 5 and 6). The zinc lateral inflow concentrations for these reaches were reduced by 50 percent and by 75 percent, and the simulations were run with first-order decay. Simulation results are shown in figure 23 and indicate that instream zinc concentrations downstream from the Kittimack tailings and downstream from Howardsville would approach concentrations near 0.16 mg/L (fig. 23 and table 7) if zinc inflow concentrations were reduced by 75 percent in model reaches 4, 6, and 10.
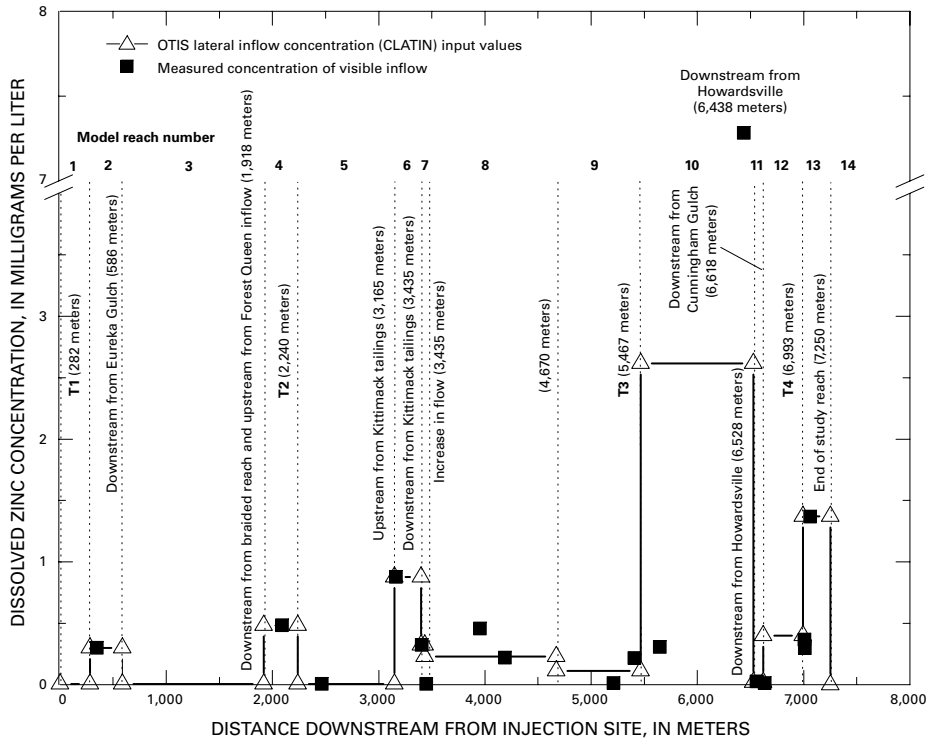
Figure 20.   OTIS lateral inflow concentrations and measured inflow concentrations for dissolved zinc with distance from the injection site, upper Animas River, Eureka to Howardsville, Colorado.
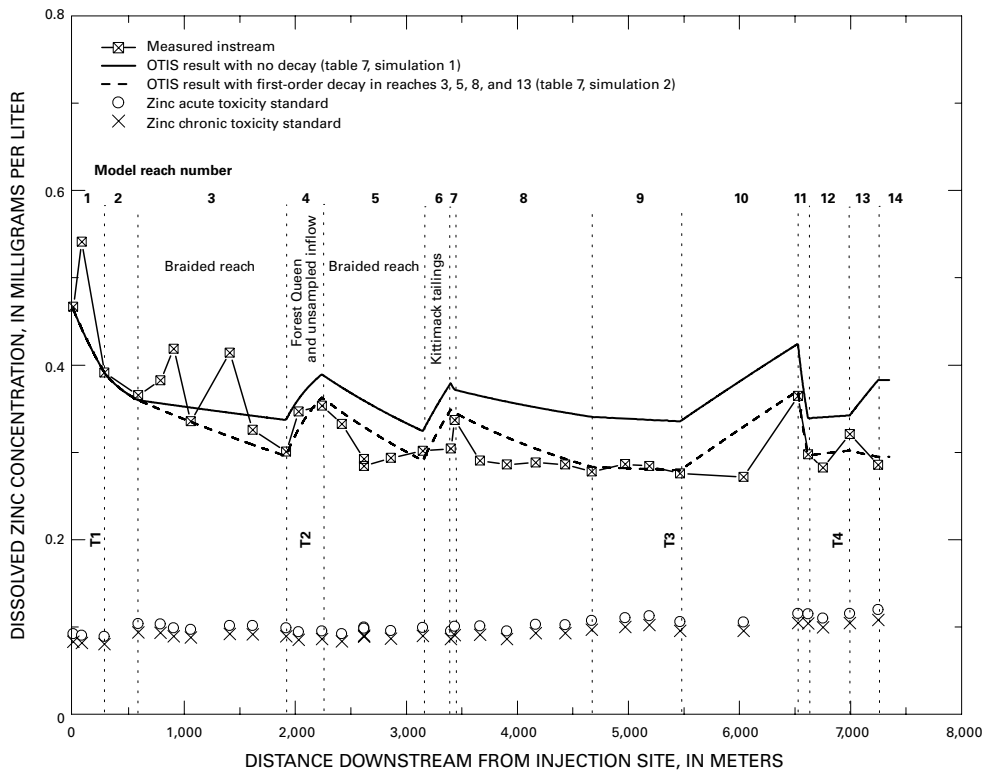
Figure 21.   OTIS results for conservative and first-order decay simulations, upper Animas River, Eureka to Howardsville, Colorado.

Table 7. OTIS results for zinc solute-transport and remediation simulations, upper Animas River, Eureka to Howardsville, Colorado.

[CLATIN, OTIS input parameter for lateral inflow concentration; m, meters; mg/L, milligrams per liter; %, percent]

Simulation number	OTIS input lateral inflow concentration (CLATIN) (mg/L)			OTIS result — computed instream zinc concentration (mg/L)		Description
	Reach 4	Reach 6	Reach 10	End of reach 7 (3,435 m)	End of study reach (7,250 m)	
1	0.483	0.879	2.615	0.372	0.383	Zinc CLATIN represents measured inflows with no decay.
2	0.483	0.879	2.615	0.346	0.295	Zinc CLATIN represents measured inflows with first-order decay in reaches 3, 4, 8, and 13.
3	0.242	0.440	2.615	0.255	0.259	Forest Queen and Kittimack remediation. 50% reduction in zinc CLATIN in reaches 4 and 6 with first-order decay in reaches 3, 5, 8, and 13.
4	0.121	0.220	2.615	0.165	0.238	Forest Queen and Kittimack remediation. 75% reduction in zinc CLATIN in reaches 4 and 6 with first-order decay in reaches 3, 5, 8 and 13.
5	0.242	0.440	1.308	0.255	0.229	Forest Queen, Kittimack, and Howardsville remediation. 50% reduction in zinc CLATIN in reaches 4, 6, and 10 with first-order decay in reaches 3, 5, 8, and 13.
6	0.121	0.220	0.654	0.165	0.191	Forest Queen, Kittimack, and Howardsville remediation. 75% reduction in zinc CLATIN in reaches 4, 6, and 10 with first-order decay in reaches 3, 5, 8 and 13.
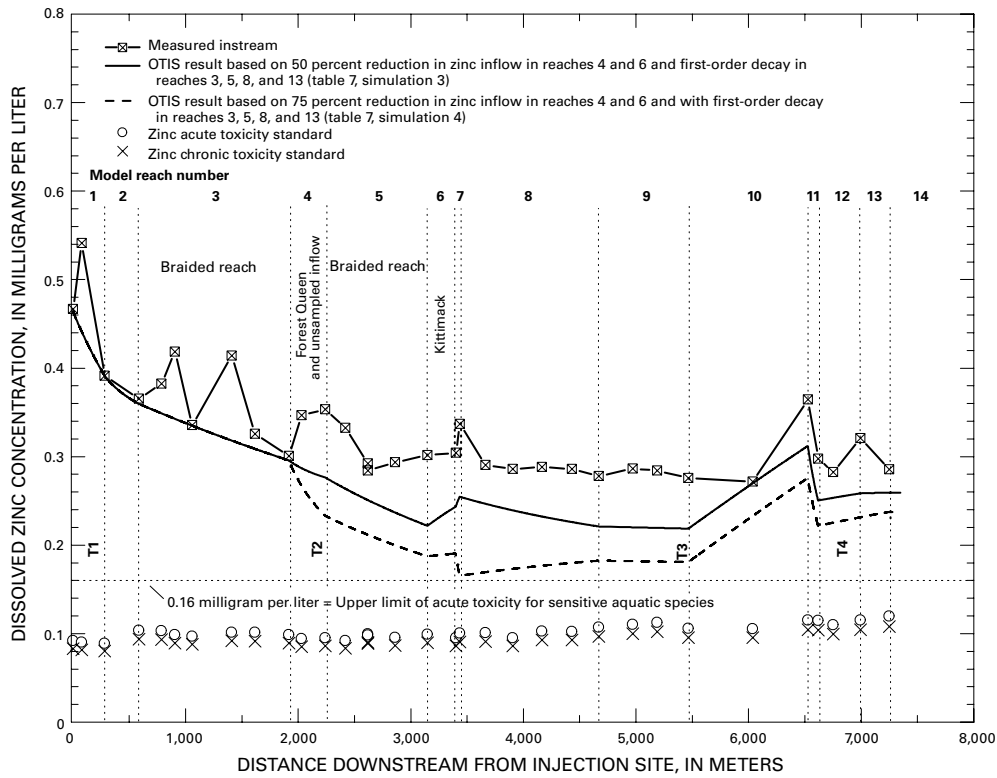
Figure 22.   OTIS results for remediation simulations 3 and 4, upper Animas River, Eureka to Howardsville, Colorado.
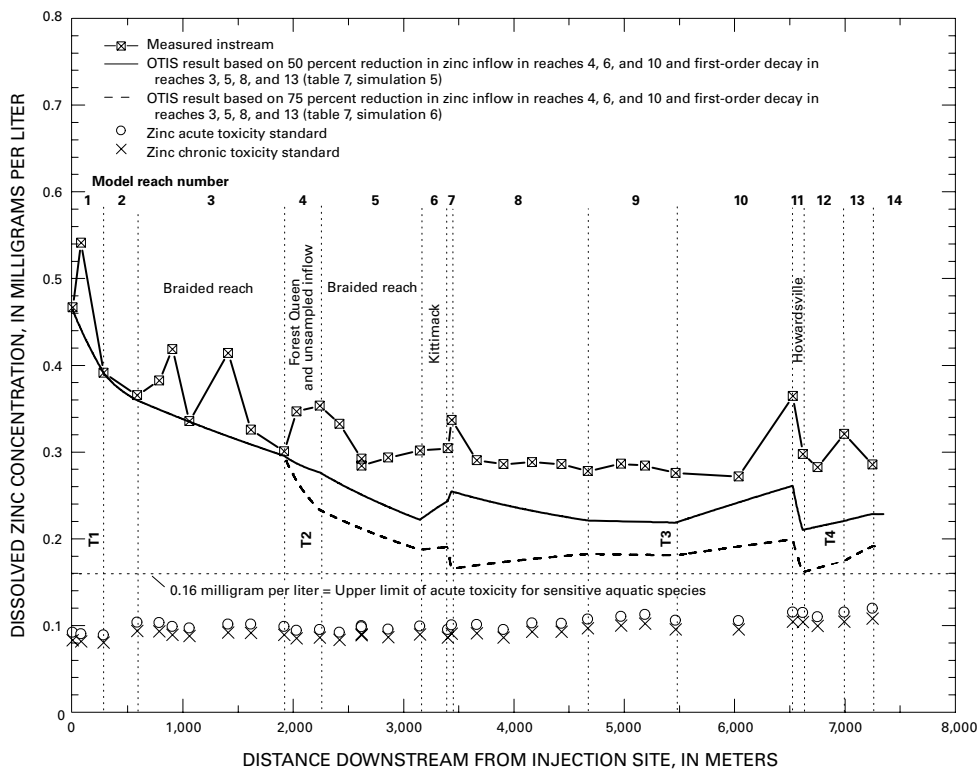
Figure 23.   OTIS results for remediation simulations 5 and 6, upper Animas River, Eureka to Howardsville, Colorado.

Metal Loading to the Upper Animas River, Howardsville to Silverton, Colorado, Study Reach, September 1997

The Howardsville to Silverton tracer-injection study started near the historical mining town of Howardsville and ended just upstream from Silverton at the USGS gaging station 09358000 (referenced herein using the Colorado State gaging station number A68). The study reach encompassed a 7,858-m reach of the upper Animas River (fig. 24).

Tracer-Injection Study Objectives

There were two primary objectives for the Howardsville to Silverton tracer-injection study. The first objective was to identify and locate where metal loading occurred in the study reach. Although a tracer-injection study can help identify where load increases occur, it does not identify specific pathways to the stream from particular sites, except for visible surface inflows. Potential sources of metal loading included the tailings near Howardsville, Arrastra Gulch, tailings near the Mayflower Mill, and tailings near the Lackawanna Mill. The second objective was to determine (for low-flow conditions) if the stream reach is a net sink or source of metals to the downstream areas. Identifying and describing any instream geochemical processes that affect metal concentrations and natural attenuation accomplished this objective.

Tracer-Injection Study Methods

The Howardsville to Silverton tracer-injection study began at 1206 on September 13, 1997, and ran continuously until 0900 on September 15, 1997 (table 8). A solution containing 128,200 mg/L of sodium chloride (or 77,760 mg/L of chloride) was injected into the upper Animas River at an average rate of 1.098 L/min. A leak in the injectate pool prior to the injection start likely resulted in elevated preinjection chloride concentrations at the transport sites. For reporting results, time 0.0 is the beginning of the experiment time, which was midnight on September 13, 1997, and subsequent times are reported as decimal hours.

The Howardsville to Silverton injection site was located approximately 180 m upstream from a ditch near Howardsville so that inflow near Howardsville and Cunningham Gulch could be quantified as tributary inflow to the stream. The arrival of the sodium-chloride pulse and the development of a plateau concentration were measured at six downstream locations, transport sites T1 through T6 (fig. 24). Transport site T1 was located upstream from a channelized stream reach at 595 m, and transport site T2 was located at 1,059 m, which is downstream from Howardsville and upstream from Cunning-

ham Gulch, to differentiate between these inflows. Transport site T3 was located upstream from a canyon in the river at 2,800 m, and transport site T4 was located upstream from Arrastra Gulch at 4,166 m. Transport site T5 was located at 6,038 m, and transport site T6 was located at 7,858 m at gaging station A68.

Synoptic Sampling and Analyses

Synoptic samples were collected from 41 instream sites, including the 6 transport sites, and 46 inflows on September 14, 1997, during the plateau period of the tracer injection. Instream sampling sites were located upstream and downstream from identified inflows to allow mass-balance calculations for each inflow, and additional sites were located in longer subreaches between inflows to account for subsurface inflow. Forty-six inflow sites were chosen to represent the range of pH and specific conductance of water entering the stream. Instream and inflow water samples were analyzed in the field and laboratory for various constituents as presented in the "Study Methods" section of this report. The analytical methods are listed in table 1.

Tracer-Injection Study Results

Chemical analyses results for chloride tracer concentrations at the Howardsville to Silverton transport and synoptic sites were used to compute traveltime, stream discharge, and chemical mass loading as discussed herein. The 1997 synoptic-sampling site locations are listed in table 9, field measurements and major ion concentrations are listed in Appendix 3, and the ICP-AES synoptic-sampling results are listed in Appendix 4. Data are sorted in downstream order within groups of stream and inflow sites to emphasize the downstream changes.

Arrival Times

Tracer arrival data and traveltime calculations for the six transport sites from Howardsville to Silverton are listed in table 10. The tracer sampling frequency provided well-defined tracer arrival graphs at sites T1, T2, T4, T5, and T6 (figs. 25a and 25b). A complete arrival curve was not obtained for site T3. However, a complete departure curve for site T3 was obtained, and the departure curve was used to compute traveltime between sites T2 and T3. Instream chloride concentrations increased to a maximum of 5.22 mg/L at sites T4, T5, and T6 from approximately 18 to 28 hours because of a rainstorm and the possible associated runoff of magnesium chloride road salts from the adjacent roadway.

The tracer moved quickly from the injection site upstream from Howardsville to the downstream transport site T6 (gaging station A68) at Silverton (table 10). The injection began at 12.1 hours, and the tracer arrival time at site T1 was
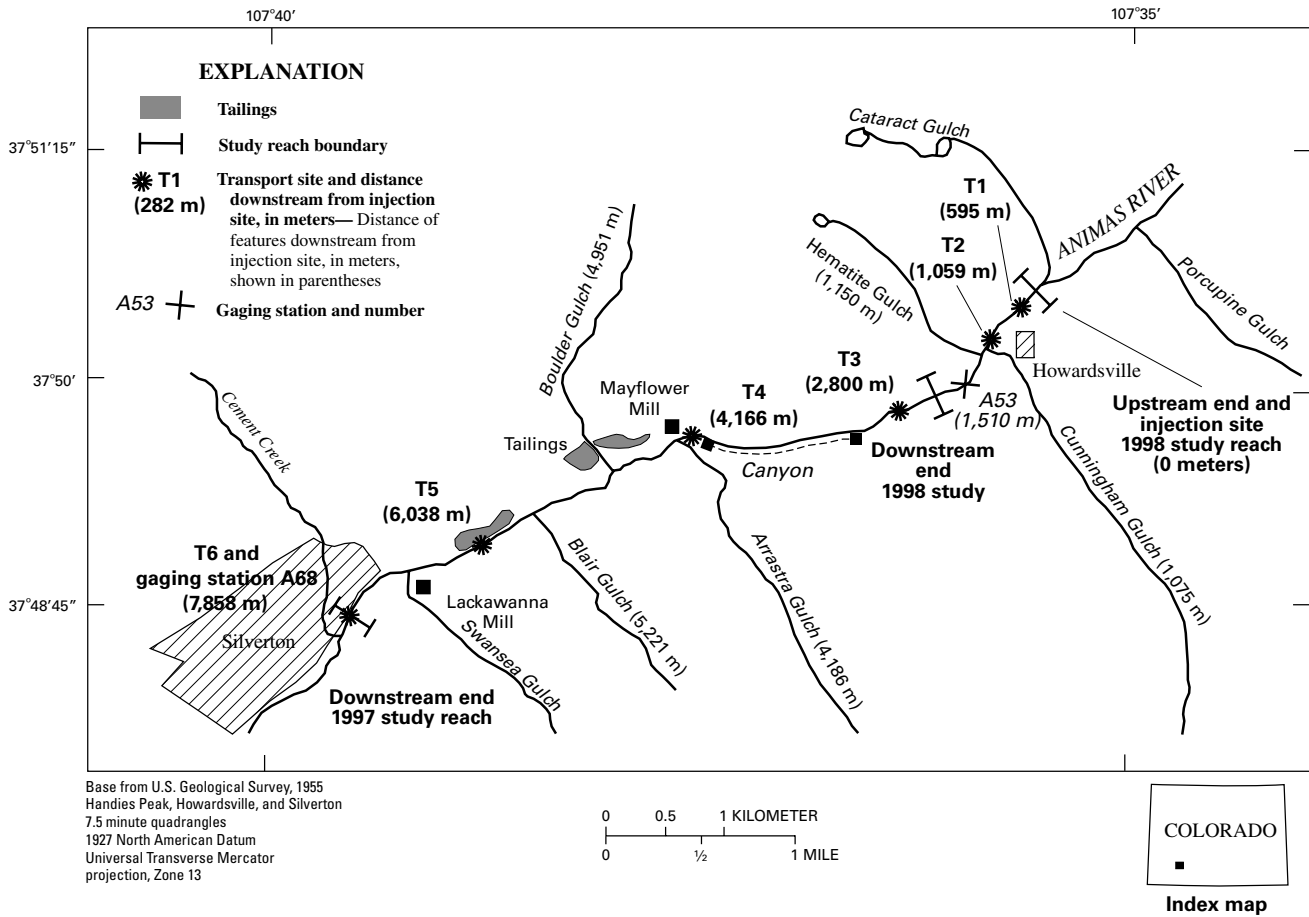
Figure 24. Howardsville to Silverton study reach, upper Animas River, Colorado, September 1997.

Table 8. Tracer-injection study sequence of events, upper Animas River, Howardsville to Silverton, Colorado, September 1997.

[mL/min, milliliters per minute]

Date	Clock time	Experimental time (hours)	Activity
09/12/1997			Stream reconnaissance and discharge measurements
09/13/1997	0000	0.0	Start of experimental time
	0900	9.0	Scheduled injection start, but injectate pool leaked
	1206	12.10	Started injection; measured pump rate of 1,075 mL/min
	1400	14.00	Measured pump rate at 1,100 mL/min
	1630	16.50	Measured pump rate at 1,100 mL/min
	1810	18.17	Measured pump rate at 1,100 mL/min
09/14/1997			Synoptic sampling
	0905	33.08	Measured pump rate at 1,080 mL/min; mixed more salt into pool
	1330	37.50	Measured pump rate at 1,070 mL/min
09/15/1997	0900	57.00	Stopped injection
	1100	59.00	Slug injection of remaining solution

Table 9.   Synoptic-sampling sites and discharge calculated from tracer-dilution, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.

[distance, distance downstream from injection sites; L/s, Liters per second; ft³/s, cubic feet per second; RB, right bank; LB, left bank; --, not applicable]

Distance (meters)	Site name	Source	Inflow location	Discharge (L/s)	Discharge (ft³/s)
0	Upstream from injection site	Stream	--	1,107	39.1
160	Downstream from injection site	Stream	--	1,107	39.1
181	Dredged ditch from Howardsville Ponds	Inflow	Left bank	1.6	0.05
213	Stream from beaver ponds	Inflow	Right bank	1.6	0.05
310	Downstream from RB ponds	Stream	--	1,110	39.2
315	RB seep from talus	Inflow	Right bank	0	0
595	T1—near construction	Stream	--	1,110	39.2
745	Drains beaver pond	Inflow	Right bank	35	1.2
905	Upstream from RB inflow	Stream	--	1,145	40.4
910	From cobble road bank RB	Inflow	Right bank	10.5	0.37
955	Upstream from Howardsville Mill	Stream	--	1,156	40.8
965	Mill discharge	Inflow	Left bank	14.4	0.51
1,059	T2—Downstream from Howardsville Mill	Stream	--	1,170	41.3
1,075	Cunningham Gulch	Inflow	Left bank	386	13.6
1,135	Downstream from Cunningham Gulch	Stream	--	1,556	54.9
1,150	Hematite Gulch	Inflow	Right bank	56.6	2.0
1,270	Downstream from bridge	Stream	--	1,612	56.9
1,510	At State gage (A53)	Stream	--	1,615	57.0
1,605	Draining LB adit—large inflow	Inflow	Left bank	6.4	0.23
1,648	RB road bank seep (old mill site)	Inflow	Right bank	6.4	0.23
1,665	RB seep beneath old road bank	Inflow	Right bank	6.4	0.23
1,725	Downstream from clean and dirty inflows	Stream	--	1,634	57.7
1,745	Water across road RB	Inflow	Right bank	88.6	3.1
1,925	At upper "campground" A	Stream	--	1,723	60.8
1,925	At upper "campground" B	Stream	--	1,723	60.8
2,050	LB spring inflow	Inflow	Left bank	3.6	0.13
2,110	Downstream from campground	Stream	--	1,726	61.0
2,125	Drains LB ponds with iron precipitate	Inflow	Left bank	3.7	0.13
2,360	LB inflow	Inflow	Left bank	3.7	0.13
2,361	LB rapid inflow from marsh	Inflow	Left bank	3.7	0.13
2,425	Swift inflow from marshy area	Inflow	Left bank	3.7	0.13
2,515	Upstream from draining adit	Stream	--	1,737	61.4
2,522	Drains old mining	Inflow	Left bank	16.9	0.60

Table 9. Synoptic-sampling sites and discharge calculated from tracer-dilution, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.—Continued

[distance, distance downstream from injection sites; L/s, Liters per second; ft³/s, cubic feet per second; RB, right bank; LB, left bank; --, not applicable]

Distance (meters)	Site name	Source	Inflow location	Discharge (L/s)	Discharge (ft³/s)
2,572	Downstream from adit	Stream	--	1,754	61.9
2,605	RB inflow from willows	Inflow	Right bank	0.3	0.01
2,709	RB inflow	Inflow	Right bank	0.3	0.01
2,800	T3—Truck park	Stream	--	1,754	61.9
3,040	Narrow chute within canyon	Stream	--	1,788	63.1
3,235	RB cascade across road	Inflow	Right bank	0.0	0.00
3,295	Downstream from first cableway	Stream	--	1,788	63.1
3,555	Mid canyon	Stream	--	1,788	63.1
3,682	RB drainage off grassy hillside	Inflow	Right bank	21.2	0.75
3,820	RB cascade from rocky bank	Inflow	Right bank	21.2	0.75
4,023	Between RB inflows in canyon	Stream	--	1,830	64.6
4,033	RB cascade from rocky bank	Inflow	Right bank	2.8	0.10
4,166	T4—upstream from Arrastra Gulch	Stream	--	1,833	64.7
4,186	Arrastra Gulch	Inflow	Left bank	218	7.7
4,190	Inflow from pipe RB	Inflow	Right bank	2.8	0.10
4,310	Downstream from Arrastra Gulch	Stream	--	2,053	72.5
4,334	From "pipe bridge"	Inflow	Right bank	3.2	0.11
4,353	Stream level spring RB	Inflow	Right bank	3.2	0.11
4,473	Downstream from river level spring	Stream	--	2,060	72.7
4,533	Marsh area RB	Inflow	Right bank	27.1	0.96
4,581	Downstream from LB abandoned mill	Stream	--	2,087	73.7
4,586	Ponded water RB	Inflow	Right bank	12.0	0.42
4,656	Upstream from Pinnacle Gap	Stream	--	2,099	74.1
4,816	Upstream from acid inflows	Stream	--	2,099	74.1
4,886	Seep w/acid algae	Inflow	Right bank	2.8	0.10
4,916	Downstream from acid inflows	Stream	--	2,102	74.2
4,951	Boulder Gulch	Inflow	Right bank	39.0	1.4
4,970	RB inflow—substantial	Inflow	Right bank	39.0	1.4
5,131	Downstream from Boulder Gulch	Stream	--	2,180	77.0

Table 9. Synoptic-sampling sites and discharge calculated from tracer-dilution, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.—Continued

[distance, distance downstream from injection sites; L/s, Liters per second; ft³/s, cubic feet per second; RB, right bank; LB, left bank; --, not applicable]

Distance (meters)	Site name	Source	Inflow location	Discharge (L/s)	Discharge (ft³/s)
5,161	Pond to stream LB with fish	Inflow	Left bank	14.2	0.50
5,221	Blair Gulch	Inflow	Left bank	14.2	0.50
5,306	Downstream from Blair Gulch	Stream	--	2,208	78.0
5,355	LB inflow from willow bog	Inflow	Left bank	0.3	0.01
5,356	Small ponds RB in cobbles	Inflow	Right bank	0.3	0.01
5,446	LB inflow near wells	Inflow	Left bank	0.3	0.01
5,536	Downstream from first of capped tailings	Stream	--	2,208	78.0
5,756	Upstream from drain from tails	Stream	--	2,233	78.3
5,766	Drains tailings RB in "ditch"	Inflow	Right bank	0.3	0.01
5,858	Seep along 60 m of grass	Inflow	Right bank	0.3	0.01
6,038	T5—Downstream from capped tailings	Stream	--	2,233	78.8
6,105	LB inflow from willows	Inflow	Left bank	24.2	0.86
6,288	Downstream from toe of Mayflower	Stream	--	2,257	79.7
6,528	Upstream from Lackawanna Bridge	Stream	--	2,257	79.7
6,768	Downstream from Lackawanna Bridge	Stream	--	2,257	79.7
7,008	Upstream from Lackawanna Mill	Stream	--	2,257	79.7
7,103	Discharge from Lackawanna Mill	Inflow	Left bank	0.00	0.00
7,163	LB inflow	Inflow	Left bank	0.30	0.01
7,283	Downstream from Lackawanna Mill	Stream	--	2,257	79.7
7,483	LB inflow	Inflow	Left bank	2.8	0.10
7,523	Among braids near town	Stream	--	2,257	79.7
7,688	RB drainage from Mayflower	Inflow	Right bank	7.1	0.25
7,858	T6—At bridge/gage A68 - end of study reach	Stream	--	2,264	79.9

Table 10. Tracer arrival data and traveltime calculations for transport sites downstream from the tracer-injection site, upper Animas River, Howardsville to Silverton, Colorado, September 1997.

[m, meters; m/s, meters per second; mg/L, milligrams per liter; NM, not measured (arrival time computed from departure curve for transport site T3)]

Transport site	Distance downstream from injection site (m)	Distance between transport sites (m)	Arrival time (t_{50}) (hours)	Traveltime from injection site (hours)	Traveltime between transport sites (hours)	Average velocity between transport sites (m/s)	Comments
T1	595	595	12.38	0.28	0.28	0.59	Injection start time = 12.1 hours
T2	1,059	464	12.60	0.50	0.22	0.59	
T3	2,800	1741	NM(13.4)	1.30	0.80	0.60	T3 traveltime computed from departure curve instead of arrival curve
T4	4,166	1,366	14.07	1.97	0.67	0.57	
T5	6,038	1,872	14.90	2.80	0.83	0.63	
T6	7,858	1,820	15.68	3.58	0.78	0.65	
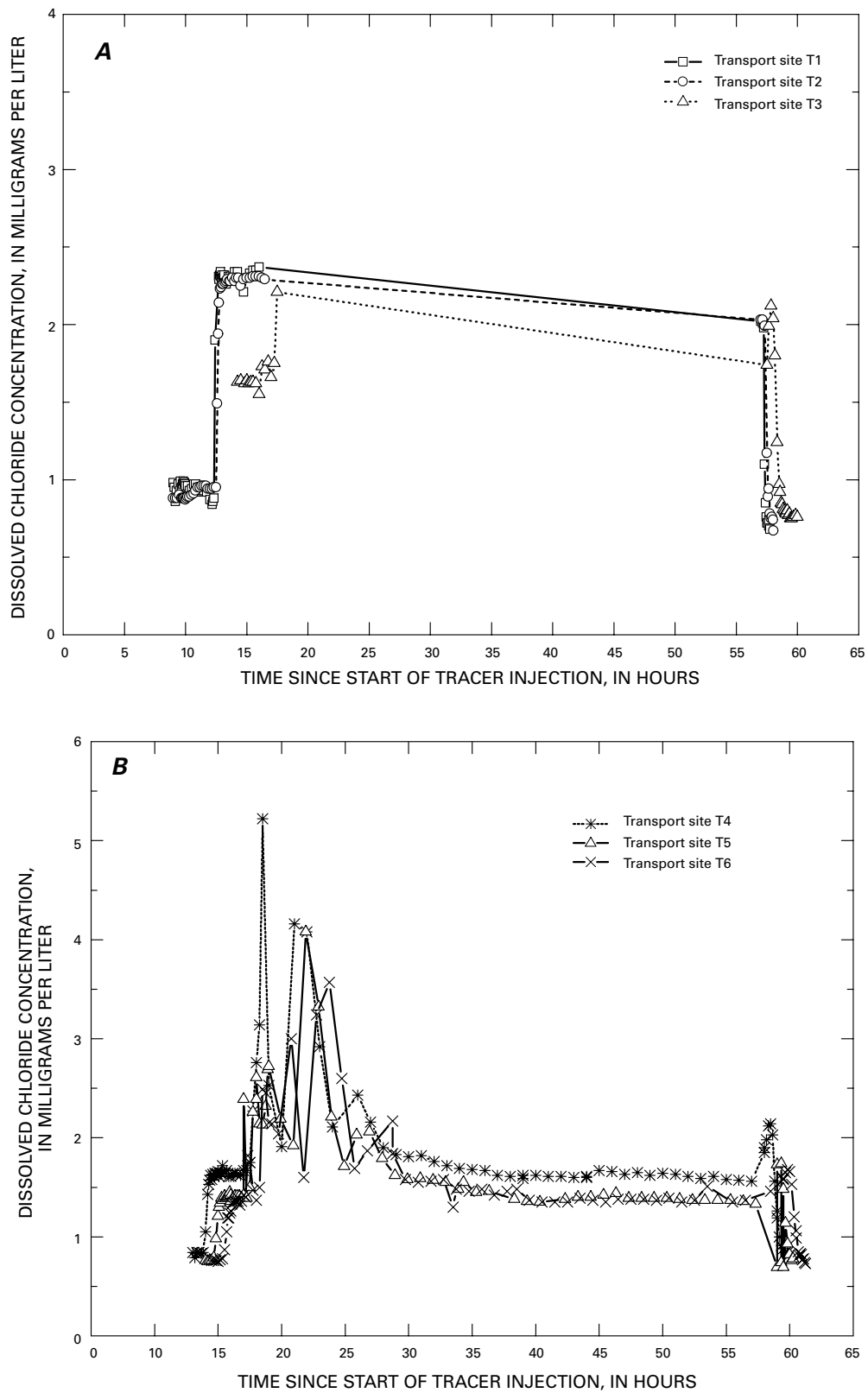
Figure 25. Dissolved chloride concentrations with time at (*A*) transport sites T1, T2, and T3, and (*B*) transport sites T4, T5, and T6, upper Animas River, Howardsville to Silverton, Colorado, September 1997.

12.38 hours, indicating a traveltime of 0.28 hour (16 minutes) and an average flow velocity of 0.59 m/s between the injection site and site T1. A similar traveltime (0.22 hour) and velocity (0.59 m/s) were measured for a similar distance between sites T1 and T2. The tracer arrival time at site T3, computed from the T3 departure curve, was 13.4 hours, indicating a traveltime of 1.3 hours from the injection site. The total traveltime from the injection site to site T6 was 3.58 hours. The average flow velocity generally increased downstream to a maximum value of 0.65 m/s between sites T5 and T6.

Discharge Profile

A detailed discharge profile for the Howardsville to Silverton study reach was developed using the chloride tracer concentrations measured in the synoptic samples. For the Howardsville to Silverton study reach, synoptic instream chloride concentrations generally were higher than the inflow chloride concentrations, and chloride concentrations decreased downstream due to dilution (fig. 26a). However, several inflow chloride concentrations were higher than instream chloride concentrations, and downstream increases of instream chloride concentrations were measured in the synoptic chloride profile. The inflows with higher chloride concentrations were located primarily on the right streambank, and some possibly were the result of runoff containing magnesium chloride road salts from the roadway, which also is located on the right streambank. For stream reaches where chloride was not an appropriate indicator of dilution because of higher inflow concentrations, the conservative ions strontium, manganese, and sulfate were used to calculate discharge.

For a decrease in chloride concentration to be considered a measurable change and not a product of analytical error, the decrease in concentration between instream samples must be higher than the precision of the chemical analyses. Error bars are indicated for chloride concentrations to show the precision of 1.83 percent for the 1997 data set (fig. 26a). If a change in instream chloride concentration was lower than the precision of the analysis, the downstream chloride concentration was held constant for discharge calculations until a change higher than the precision of the analysis was measured.

The synoptic-sampling profile of chloride concentration (fig. 26a), supplemented by strontium, manganese, and sulfate concentrations, was used to calculate discharge according to the relations presented in table 2. Discharge results are presented in table 9 and in figure 26b. The resulting discharge profile for the Howardsville to Silverton study reach indicates stream discharge ranged from 1,107 L/s (39.1 ft^3/s) at the injection site to 2,264 L/s (79.9 ft^3/s) at gaging station A68 (fig. 26b), and the total increase of discharge through the study reach was 1,157 L/s (40.8 ft^3/s). The largest inflow was Cunningham Gulch (1,075 m) with a computed inflow discharge of 386 L/s (13.6 ft^3/s) or 33 percent of the total flow increase. Arrastra Gulch (4,186 m) contributed 218 L/s (7.7 ft^3/s) or 19 percent of the total flow increase. The contributions from

Hematite Gulch (1,150 m) and Boulder Gulch (4,951 m) were 5 percent and 3 percent, respectively, of the total increase in stream discharge. Small surface inflows and ground-water seeps caused the remaining streamflow increase along the study reach. Discharge values computed from the synoptic-sampling results compare well with discharge measured at the six transport sites (fig. 26b).

The Howardsville to Silverton discharge values computed from the September 1997 tracer-injection study were higher than the discharge values computed from the August 1998 Eureka to Howardsville tracer-injection study. At the instream site immediately downstream from Cunningham Gulch, the 1997 computed discharge at site 1,135 m was 1,556 L/s (54.9 ft^3/s), whereas the 1998 computed discharge at this same site (6,618 m in 1998 study) was 2,107 L/s (74.4 ft^3/s) (table 5). The difference in discharge from 1997 to 1998 is attributed to seasonal variation.

Synoptic-Sampling and Mass-Loading Calculation Results

This section presents results for the 1997 Howardsville to Silverton synoptic-sampling results and mass-loading calculations for constituents of interest. Synoptic-sampling data are presented in Appendixes 3 and 4, and the data are contained in the USGS digital database for the Animas River watershed Abandoned Mine Land Program (Sole and others, 2005)

pH

The downstream profile of instream and inflow pH values for the 1997 Howardsville to Eureka study reach is presented in figure 27. Instream pH values were near neutral and ranged from a minimum of 7.4 at 4,581 m to a maximum of 7.8 at 3,295 m. Although there was no clear downstream trend for the instream pH values, instream pH did appear to vary with inflow pH. Instream pH values increased downstream from inflows with high pH values, such as those from Cunningham and Hematite Gulches, and instream pH values decreased downstream from inflows with pH values lower than the stream.

Based on the pH downstream profile, the study reach can be subdivided into sections with similar characteristics. First is the upper part of the stream from the injection site to Cunningham Gulch where the inflows at 181 m and 965 m had pH values of 6.9. These inflows lowered the instream pH to 7.4 upstream from Cunningham Gulch. The 1997 pH from the inflow downstream from Howardsville (965 m) was higher than the pH for this same inflow in the 1998 Eureka to Howardsville synoptic sampling (pH of 5.7 for the 6,438-m inflow). Instream pH increased to 7.7 downstream from Cunningham Gulch because of the high-pH inflow from Cunningham (8.0) and Hematite (8.1) Gulches.
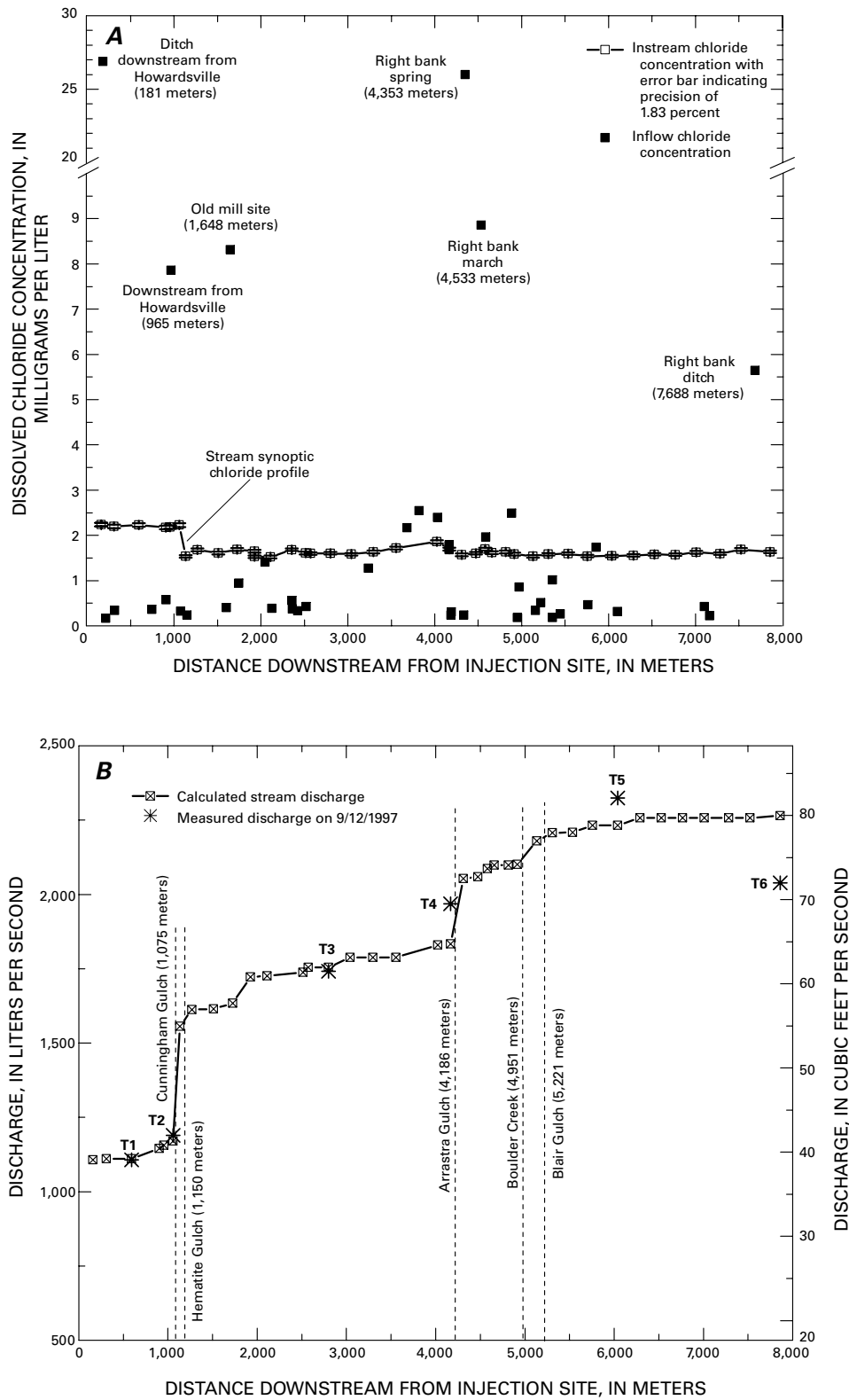
Figure 26. (*A*) Dissolved chloride concentrations, and (*B*) calculated discharge with distance downstream from the injection site, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.

Figure 27.   Instream and inflow pH with distance from the injection site, upper Animas River,
Howardsville to Silverton, Colorado, September 14, 1997.

The second area affected by low-pH inflows was from 1,605 to 2,572 m, where inflows with pH values lower than instream values lowered instream pH (fig. 27). The lowest inflow pH in this reach (4.8) was from ponds on the left bank at 2,125 m. Between the site at 2,572 m and site T4 at 4,166 m, the upper Animas River flows through a steep-walled canyon. The visible inflows in this reach are primarily from the right bank, with inflow pH values ranging from a minimum of 7.9 to a maximum of 8.2, and instream pH ranging from 7.7 to 7.8 (fig. 27).

A third area affected by AMD and ARD was downstream from 4,353 m, where a series of low-pH right bank inflows lowered the instream pH. The lowest inflow pH in the entire study reach emanated from a right bank spring at 4,353 m

(pH of 4.2), and additional right bank low-pH inflows were at 4,533 m (pH of 4.9) and 4,586 m (pH of 4.9) (fig. 27).

Aluminum

Instream dissolved aluminum concentrations were low and had little variability, although concentrations increased slightly downstream due to inflows with elevated dissolved aluminum concentrations. Instream dissolved aluminum concentrations ranged from less than the method detection limit of 0.01 to 0.98 mg/L. Inflow dissolved aluminum concentrations were more variable than instream concentrations and ranged from less than the method detection limit of 0.01 to 23.5 mg/L. The inflows with elevated dissolved aluminum concentrations included the right bank inflows downstream

from Arrastra Gulch. Dissolved aluminum was not elevated in the ditch upstream from Howardsville (0.060 mg/L at 181 m) or the inflow downstream from Howardsville (0.012 mg/L at 965 m). Instream colloidal aluminum concentrations also appeared to increase slightly in a downstream direction because of the inflow of elevated dissolved aluminum concentrations and the subsequent precipitation of aluminum oxyhydroxide.

Calcium and Magnesium

Calcium and magnesium concentrations in the upper Animas River for 1997 are controlled by the calcium and magnesium concentrations of surface-water inflows. Instream concentrations of calcium ranged from approximately 35 to 40 mg/L with a mean of 37 mg/L, and inflow calcium concentrations ranged from 12 to 344 mg/L with a mean of 81 mg/L. Instream calcium concentrations increased slightly in a downstream direction from about 36 mg/L at Howardsville to about 39 mg/L at gaging station A68 in response to elevated inflow calcium concentrations (fig. 28).

Instream magnesium concentrations had little variability and ranged from about 2.4 to 2.7 mg/L, generally increasing in a downstream direction. Inflow magnesium concentrations varied more than instream concentrations ranging from 0.8 to 35.3 mg/L (fig. 29). The inflows with elevated magnesium concentrations included the ditch upstream from Howardsville (10.6 mg/L), inflow downstream from Howardsville (7.55 mg/L), and a right bank ditch at 7,688 m (14.2 mg/L), as well as four right bank inflows downstream from Arrastra Gulch with magnesium concentrations ranging from 14.4 to 35.3 mg/L.

Copper

Instream dissolved copper concentrations were compared to acute and chronic toxicity standards for aquatic life. Figure 30 presents a graph of instream dissolved copper concentrations for the Howardsville to Silverton study reach 1997 synoptic sampling and the acute and chronic toxicity standards computed for each instream sample. Instream copper concentrations were near or estimated less than the method detection limit of 0.002 mg/L and were lower than the acute and chronic toxicity standards throughout the study reach (fig. 30). The maximum inflow copper concentrations were from the right bank inflows downstream from Arrastra Gulch (5.2 mg/L at 4,353 m; 0.36 mg/L at 4,533 m; 0.20 at 4,586 m; and 2.4 mg/L at 5,356 m).

Iron

Instream dissolved iron concentrations in the Howardsville to Silverton study reach generally were low or not detected except immediately downstream from Howardsville in 1997 (fig. 31). Instream colloidal iron also was not detected upstream from Howardsville (fig. 31). The dissolved iron concentration of inflow downstream from Howardsville (965 m) was 1.2 mg/L in 1997, which was an order of magnitude lower than the inflow dissolved iron concentration in 1998 (11.7 mg/L at 6,438 m in 1998 study). The maximum instream dissolved iron concentrations occurred immediately downstream from Howardsville at 1,059 m (0.13 mg/L) and downstream from Arrastra Gulch at 4,310 m (0.16 mg/L). Instream dissolved iron concentrations decreased and instream colloidal iron concentrations increased downstream from both the Howardsville and Arrastra Gulch inflows probably in response to iron oxyhydroxide precipitation.

The sampled instream, cumulative instream, and cumulative inflow loads for colloidal iron all increased downstream from Howardsville (fig. 32). The colloidal iron loads increased in response to the elevated inflow colloidal iron concentrations downstream from Howardsville (12.4 mg/L at 965 m) and the precipitation of iron oxyhydroxides from the elevated inflow dissolved iron concentrations. Downstream from Howardsville, the cumulative instream colloidal iron load was higher than the cumulative inflow load (fig. 32) indicating that mineral precipitation was a source of instream iron colloids. Downstream from Arrastra Gulch, from approximately 4,166 to 6,000 m, there was an increase of sampled instream colloidal iron load but no increase of cumulative inflow load, which indicates ground-water discharge of dissolved iron, possible precipitation of iron colloids, or both (fig. 32).

Based on synoptic-sampling concentration data and mass-loading calculations, inflow downstream from Howardsville at 965 m was a source of dissolved and colloidal iron to the upper Animas River reach from Eureka to Howardsville in 1998 and from Howardsville to Silverton in 1997. Inflow from a draining adit at 7,008 m in the Eureka to Howardsville study reach (1,605 m in the Howardsville to Silverton study reach) was a secondary source of dissolved and colloidal iron in both studies. The stream reach downstream from Arrastra Gulch and the right bank ditch inflow at 7,688 m were secondary sources of iron (fig. 31). The sampled instream dissolved iron load downstream from each of these inflows first increased in response to the inflow and then decreased as iron oxyhydroxides precipitated in the near-neutral pH stream.

Manganese

Instream manganese concentrations upstream from Howardsville decreased downstream due to dilution in 1998 (fig. 14). In contrast, instream dissolved manganese concentra-

Figure 28. Instream and inflow dissolved calcium concentrations with distance from the injection site, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.

Figure 29. Instream and inflow dissolved magnesium concentrations with distance from the injection site, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.
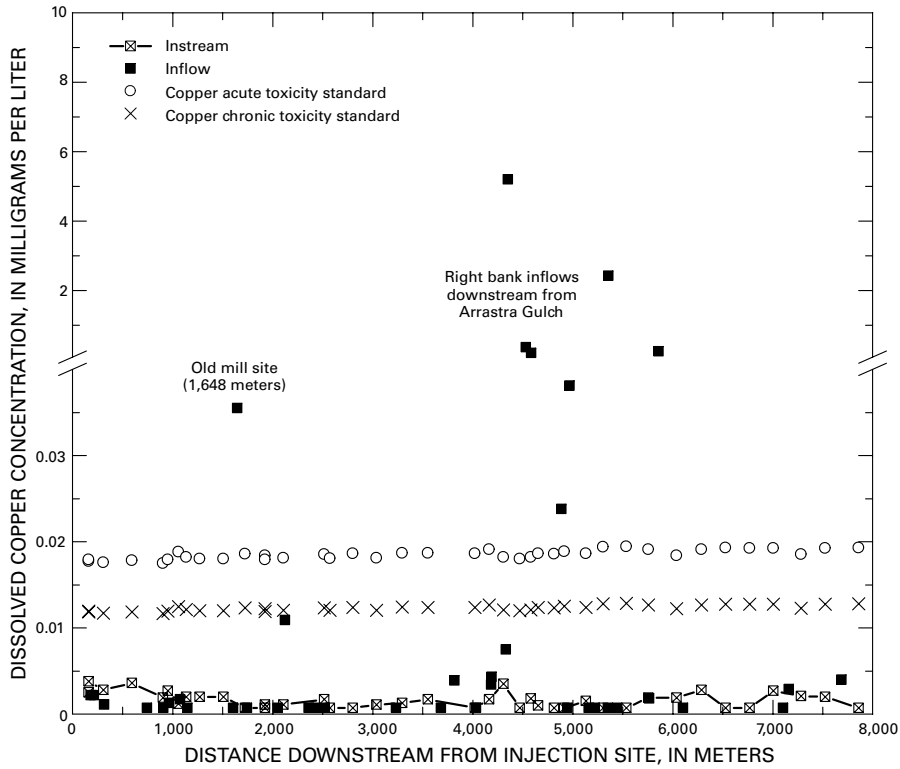
Figure 30. Instream dissolved copper concentrations, copper acute toxicity standard, and copper chronic toxicity standard with distance from the injection site, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.
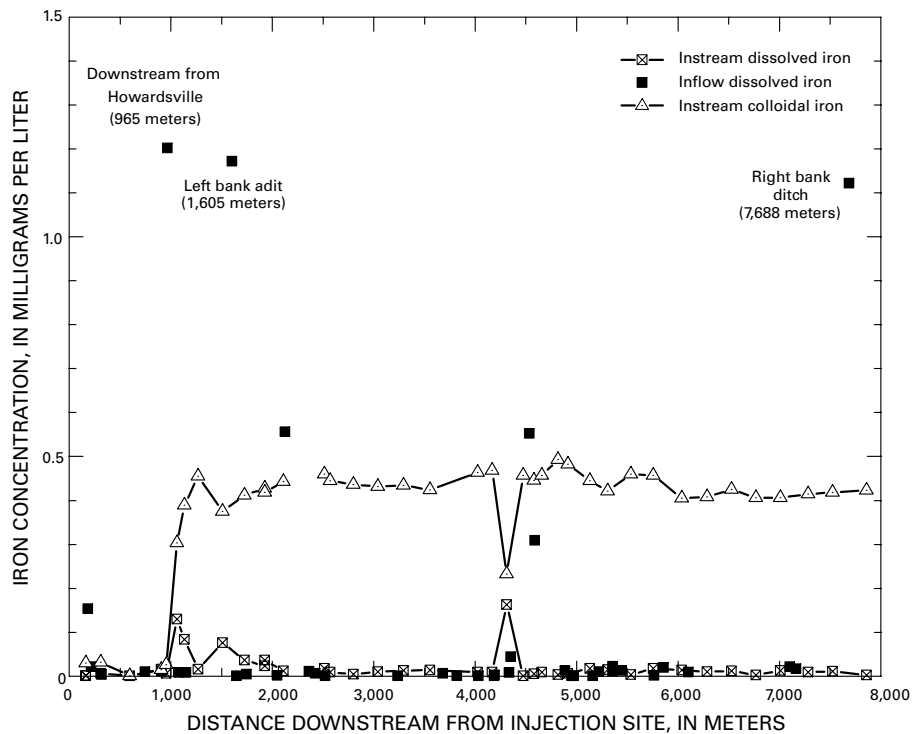
Figure 31. Instream and inflow dissolved iron concentrations and instream colloidal iron concentrations with distance from the injection site, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.
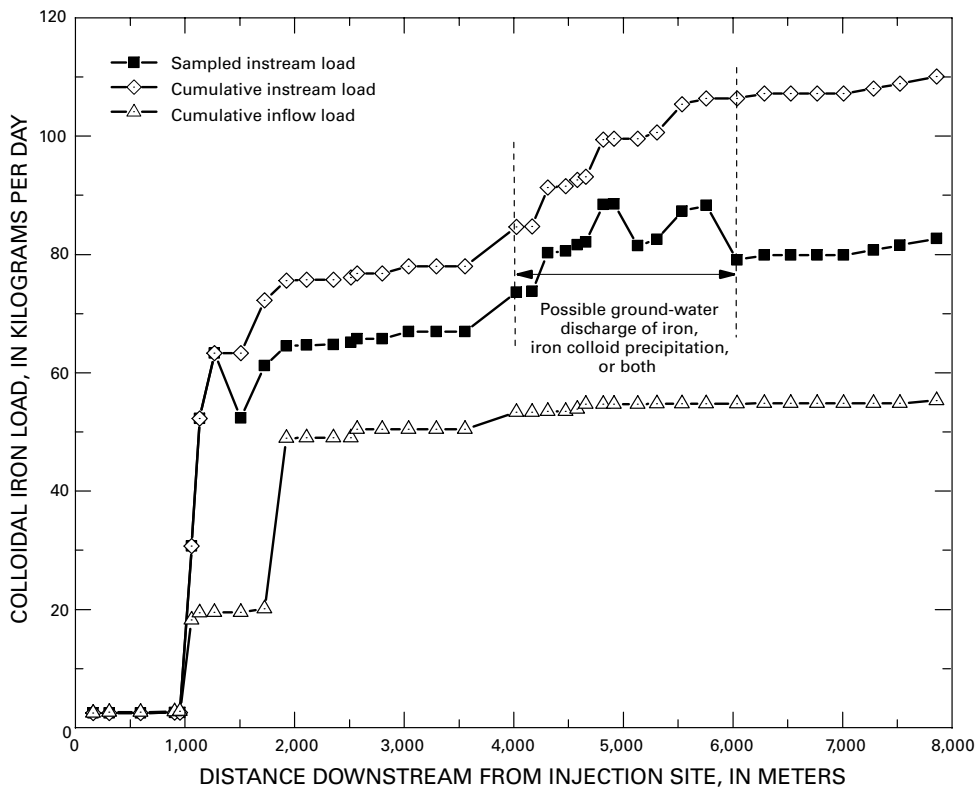
Figure 32. Sampled instream load, cumulative instream load, and cumulative inflow load of colloidal iron with distance from the injection site, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.

tions from the 1997 Howardsville to Silverton study ranged from 0.12 to 1.1 mg/L and generally increased in the downstream direction because of elevated inflow manganese concentrations (fig. 33). Inflow dissolved manganese concentrations ranged from less than the method detection limit of 0.001 to 284 mg/L (right bank marsh at 4,533 m). The dissolved manganese concentration from inflow downstream from Howardsville at 965 m was 15.9 mg/L during 1997, slightly lower than the manganese concentration measured for the inflow in 1998 (18.6 mg/L). Several right bank inflows downstream from Arrastra Gulch also had elevated manganese concentrations (55.5 mg/L at 4,353 m; 4.7 mg/L at 4,586 m; 75.6 mg/L at 4,886 m; 3.1 mg/L at 4,970 m; 34.4 mg/L at 5,858 m; and 39.7 mg/L at 7,688 m).

The mass-loading graphs for dissolved manganese reflect the downstream increase in manganese load caused by inflows with elevated manganese concentrations. Consistent with the Eureka to Howardsville study results for manganese, sampled instream, cumulative instream, and cumulative inflow loads generally did not increase upstream from Howardsville (figs. 15 and 34). All three manganese-loading graphs in figure 34 showed increases downstream from Howardsville. Immediately downstream from Howardsville, the sampled instream and cumulative instream manganese loads increased,

and this increase was greater than the cumulative inflow load increase for the same reach, indicating that ground-water inflow possibly contributed to the sampled instream manganese load. The sampled instream and cumulative instream manganese loads remained relatively constant downstream from Howardsville to Arrastra Gulch. A second increase in sampled instream and cumulative instream dissolved manganese loads occurred downstream from Arrastra Gulch where several right bank inflows had elevated manganese concentrations. However, the increases of sampled instream and cumulative instream manganese loads were greater than the increase of cumulative inflow load from approximately 5,000 to 6,500 m, again indicating that ground-water inflow possibly was contributing to the sampled instream manganese load downstream from Boulder Gulch.

Zinc

Instream dissolved zinc concentrations for 1997 were compared to acute and chronic toxicity standards for aquatic life. Instream dissolved zinc concentrations ranged from 0.24 to 0.45 mg/L, and exceeded the acute and chronic aquatic-life standards along the entire study reach (fig. 35). With a spatial distribution similar to manganese, dissolved zinc concentra-
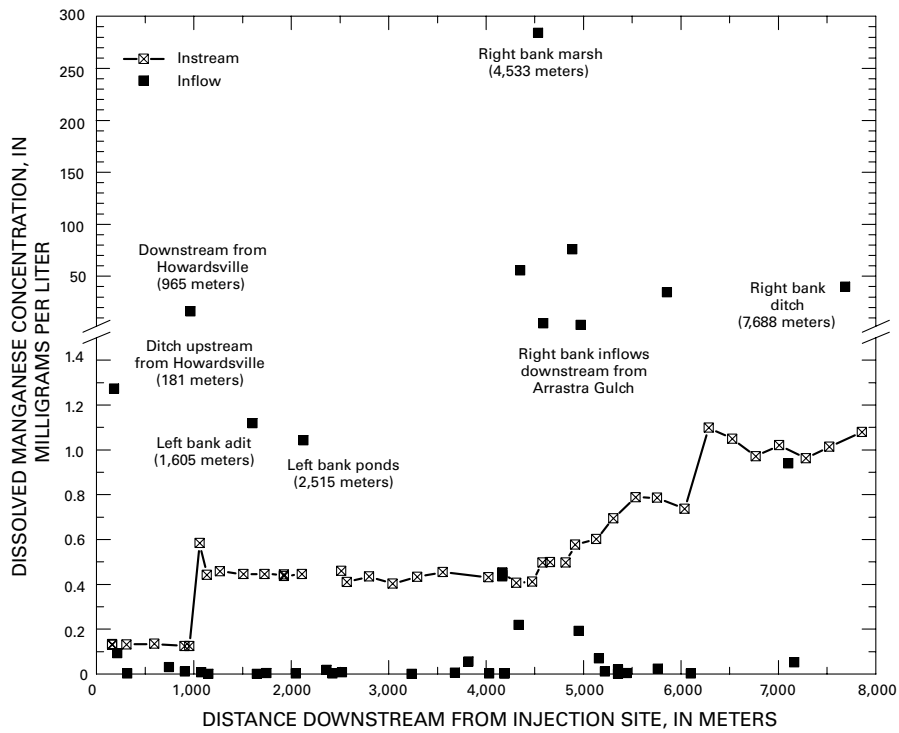
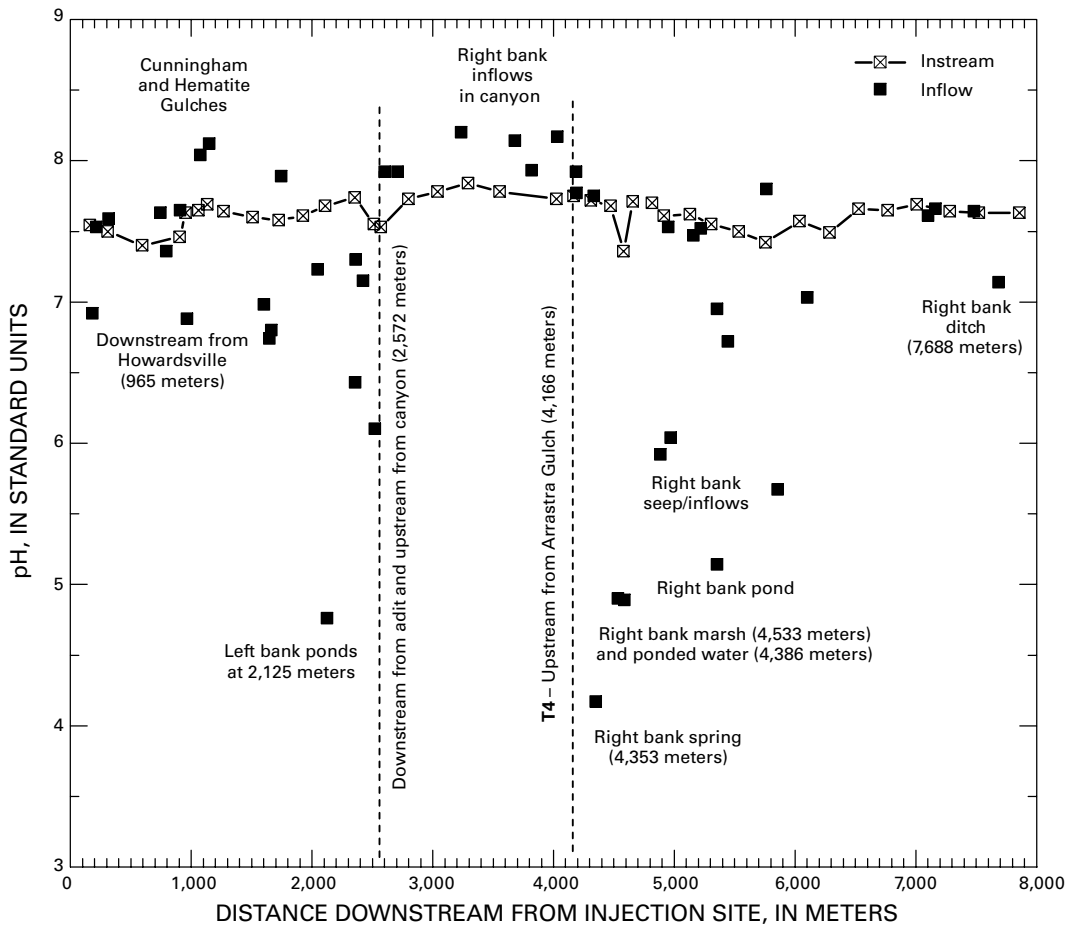**Figure 33.**   Instream and inflow dissolved manganese concentrations with distance from the injection site, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.
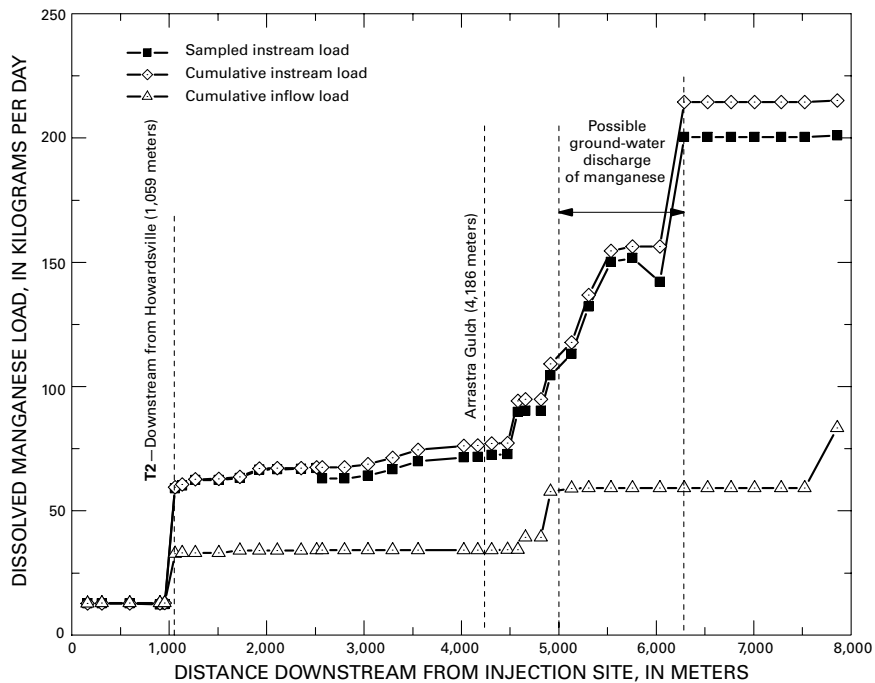
Figure 34.   Sampled instream load, cumulative instream load, and cumulative inflow load of dissolved manganese with distance from the injection site, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.
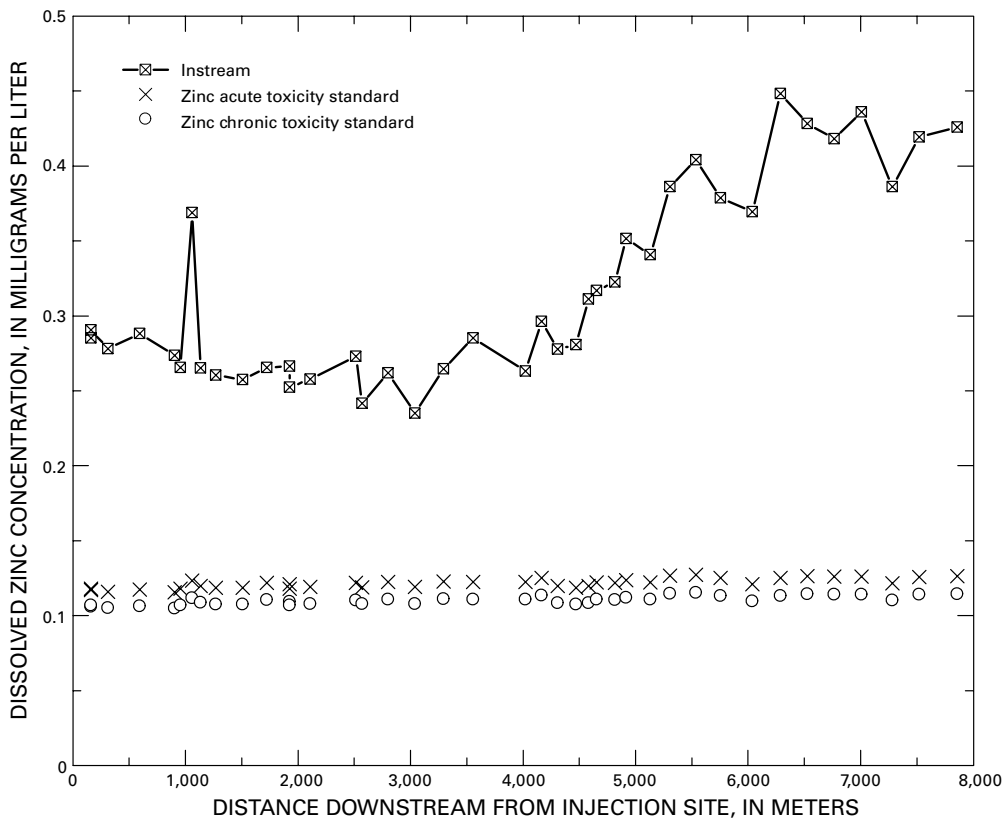
Figure 35.   Instream dissolved zinc concentrations, zinc acute toxicity standard, and zinc chronic toxicity standard with distance from the injection site, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.

tions generally increased in a downstream direction because of inflows with elevated zinc concentrations (fig. 36). The highest instream dissolved zinc concentrations were downstream from Howardsville and downstream from Arrastra Gulch.

The variability of zinc concentrations for inflow samples was much higher than for instream samples and ranged from 0.004 to 130 mg/L (right bank inflow at 4,353 m) (fig. 36). The highest inflow dissolved zinc concentrations were from right bank inflows downstream from Arrastra Gulch (130 mg/L at 4,353 m; 53.2 mg/L at 4,533; 9.3 mg/L at 4,586 m; 19.4 mg/L at 4,886 m; 3.8 mg/L at 4,970 m; 39.8 mg/L 5,356 m; and 12.7 mg/L at 5,858 m). The dissolved zinc concentration from inflow downstream from Howardsville (965 m) was 2.5 mg/L during 1997, which was considerably lower than the zinc concentration measured for the inflow in 1998 (7.3 mg/L).

Increases in the dissolved zinc loads corresponded to increases of instream dissolved zinc concentrations. Zinc load increases occurred downstream from Howardsville, through the reach with right bank inflows downstream from Arrastra Gulch, and downstream from Boulder Gulch (4,951 m) (fig. 37). Sampled instream load and cumulative instream load for dissolved zinc were higher than the cumulative inflow load

immediately downstream from Howardsville, indicating that ground-water discharge possibly contributed dissolved zinc to the river in this area (table 11). From downstream of Howardsville to the reach immediately upstream from Arrastra Gulch at 4,166 m, the instream zinc load increased 7.6 kg/d from surface inflows and ground-water discharge (table 11 and fig. 37). The largest instream zinc load increase was observed downstream from Arrastra Gulch (4,186 m) from surface inflows and apparent ground-water discharge (table 11). For reaches where the sampled instream load and cumulative instream load increased but cumulative inflow load remained constant, unsampled inflow, possibly from ground-water discharge, is indicated. Possible ground-water discharge is evident for several reaches downstream from 5,131 to 7,523 m (table 11 and fig. 37). The instream zinc load increase of 15.3 kg/d from 6,038 to 6,288 m probably is caused by ground-water discharge with elevated zinc concentrations, because no visible inflows occurred in this reach (table 11 and fig 36). The loading graphs (fig. 37) also indicate locations downstream from Boulder Gulch where the dissolved zinc sampled instream load decreases possibly in response to zinc adsorption onto iron colloids or stream sediment. The total sampled instream load for dissolved zinc was approximately 83 kg/d, and the
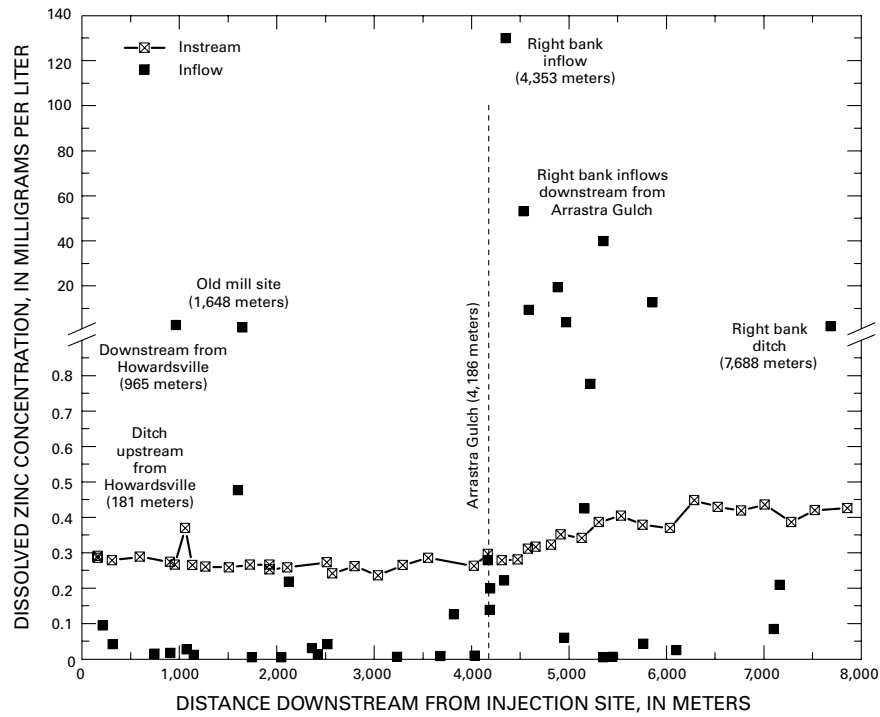
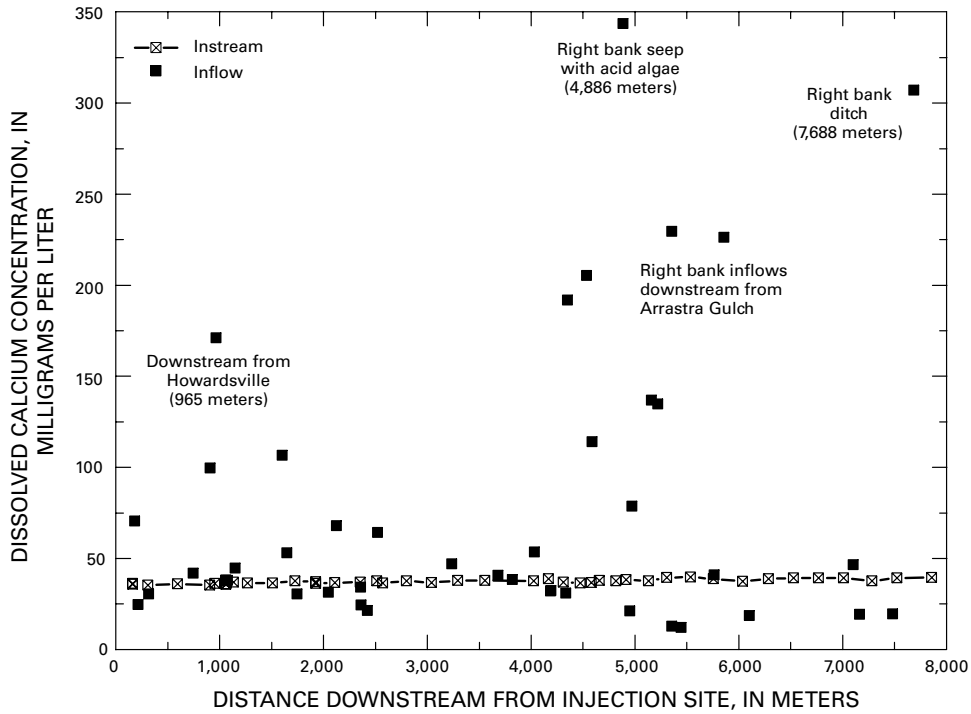**Figure 36.**   Instream and inflow dissolved zinc concentrations with distance from the injection site, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.
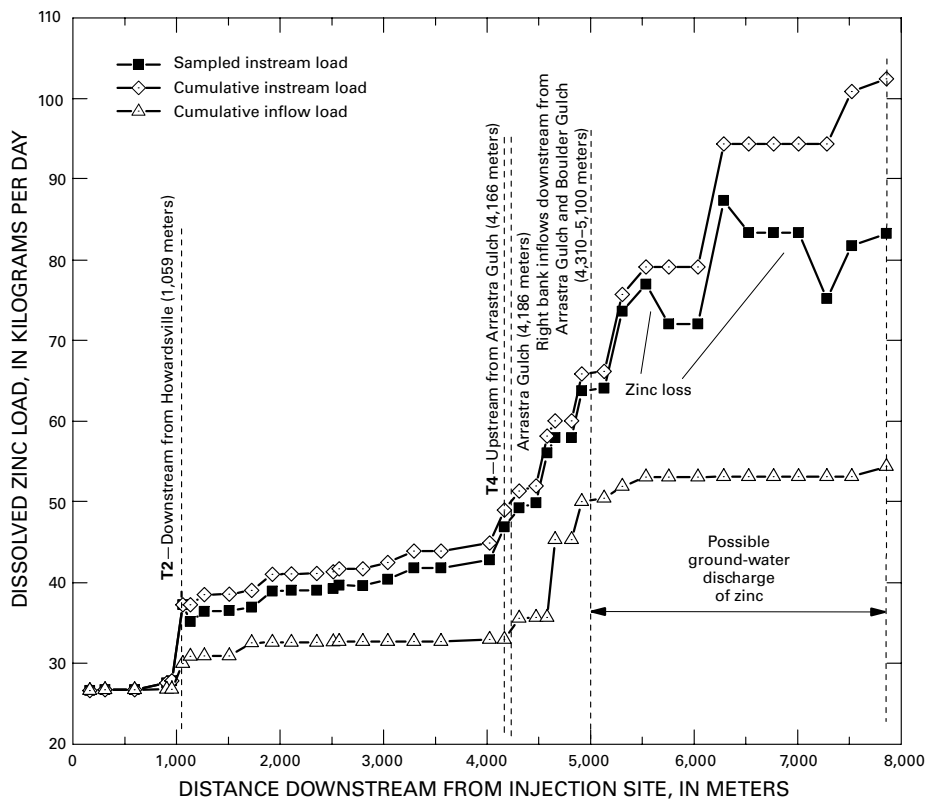
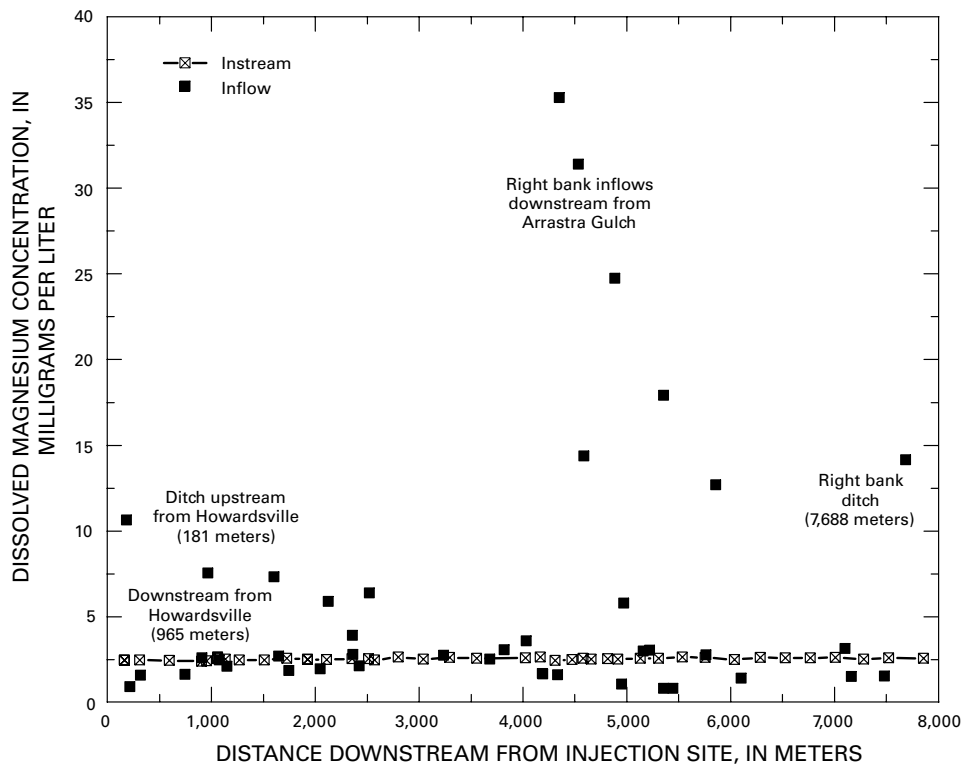**Figure 37.**   Sampled instream load, cumulative instream load, and cumulative inflow load of dissolved zinc with distance from the injection site, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.

**Table 11.**   Zinc loads calculated from tracer-dilution results, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.

[Distance, distance downstream from injection site; kg/d, kilograms per day; RB, right bank; LB, left bank]

Distance (meters)	Stream reach name	Instream zinc load (kg/d)	Cumulative instream zinc load (kg/d)	Cumulative inflow zinc load (kg/d)	Change in instream zinc load (kg/d)	Change in inflow zinc load (kg/d)	Possible explanation
160	Downstream from injection site–B	26.7	26.7	26.7	26.7	0.0	
310	Downstream from RB ponds	26.7	26.7	26.8	0.1	0.1	
595	T1—near construction	26.7	26.7	26.8	0.0	0.0	
905	Upstream from RB inflow	27.6	27.6	26.8	0.8	0.0	
955	Upstream from Howardsville Mill	27.8	27.8	26.8	0.3	0.0	
1,059	T2—Downstream from Howardsville Mill	37.3	37.3	30.0	9.4	3.2	Ground-water discharge
1,135	Downstream from Cunningham Gulch	35.2	37.3	30.9	-2.1	0.9	Zinc loss—adsorption
1,270	Downstream from bridge	36.5	38.6	30.9	1.3	0.1	
1,510	At State gage (A53)	36.5	38.6	30.9	0.1	0.0	
1,725	Downstream from clean/ dirty inflows	37.0	39.0	32.6	0.4	1.7	Surface inflow
1,925	At upper "campground"	39.0	41.1	32.6	2.0	0.0	Unsampled inflow
2,110	Downstream from campground	39.1	41.1	32.6	0.1	0.0	
2,515	Upstream from draining adit	39.3	41.4	32.7	0.2	0.0	
2,572	Downstream from adit	39.7	41.8	32.7	0.4	0.1	
2,800	T3—Truck park	39.7	41.8	32.7	0.0	0.0	
3,040	Narrow chute within canyon	40.4	42.5	32.7	0.8	0.0	
3,295	Downstream from first cableway	41.8	43.9	32.7	1.4	0.0	
3,555	Mid canyon	41.8	43.9	32.7	0.0	0.0	
4,023	Between RB inflows in canyon	42.8	44.9	33.0	1.0	0.2	
4,166	T4—Upstream from Arrastra Gulch	46.9	49.0	33.0	4.1	0.0	
4,310	Downstream from Arrastra Gulch	49.3	51.4	35.6	2.4	2.6	Surface inflow
4,473	Downstream from river level spring	49.9	52.0	35.7	0.7	0.1	
4,581	Downstream from LB abandoned mill	56.1	58.2	35.7	6.2	0.0	Ground-water discharge
4,656	Upstream from Pinnacle Gap	58.0	60.1	45.3	1.9	9.6	Surface inflow
4,816	Upstream from acid inflows	58.0	60.1	45.3	0.0	0.0	
4,916	Downstream from acid inflows	63.8	65.9	50.1	5.8	4.7	Surface inflow
5,131	Downstream from Boulder Gulch	64.1	66.2	50.5	0.3	0.4	Surface inflow
5,306	Downstream from Blair Gulch	73.6	75.7	51.9	9.5	1.5	Ground-water discharge
5,536	Downstream from first of capped tailings	77.0	79.1	53.1	3.4	1.2	Ground-water discharge
5,756	Upstream from drain from tailings	72.1	79.1	53.1	-4.9	0.0	Zinc loss—adsorption
6,038	T5—Downstream from capped tailings	72.1	79.1	53.1	0.0	0.0	
6,288	Downstream from toe of Mayflower	87.4	94.4	53.1	15.3	0.0	Ground-water discharge
6,528	Upstream from Lackawanna Bridge	83.4	94.4	53.1	-4.0	0.0	Zinc loss—adsorption
6,768	Downstream from Lackawanna Bridge	83.4	94.4	53.1	0.0	0.0	
7,008	Upstream from Lackawanna Mill	83.4	94.4	53.1	0.0	0.0	
7,283	Downstream from Lackawanna Mill	75.2	94.4	53.1	-8.2	0.0	Zinc loss—adsorption
7,523	Among braids near town	81.7	100.9	53.1	6.5	0.0	Ground-water discharge
7,858	T6—At bridge/gage A68	83.3	102.4	54.4	1.5	1.3	Surface inflow

total cumulative load for zinc was approximately 102 kg/d at gaging station A68 (table 11).

Sulfate

Dissolved sulfate concentrations in the upper Animas River for 1997 were controlled by the sulfate concentrations of surface-water inflows. Instream sulfate concentrations ranged from 63.5 to 85.3 mg/L and were lower than the USEPA's secondary drinking-water standard of 250 mg/L. Instream sulfate concentrations increased downstream from Howardsville, and concentrations remained relatively constant downstream from Cunningham Gulch (fig. 38).

Inflow sulfate concentrations in the study reach were more variable than instream concentrations and ranged from 12.8 to approximately 1,400 mg/L. Inflows with elevated sulfate concentrations in the upper part of the study reach included the ditch upstream from Howardsville at 181 m (212 mg/L), right bank drainage at 910 m (243 mg/L), inflow downstream from Howardsville at 965 m (549 mg/L), adit inflow at 1,605 m (256 mg/L) (7,008 m in the Eureka to Howardsville study reach), inflow from an old mill site at 1,648 m (116 mg/L) (7,063 m in the Eureka to Howardsville study reach), and abandoned mining sites at 2,125 m (222 mg/L) and 2,522 (224 mg/L) (fig. 38). In the lower part

of the study reach, the right bank inflows downstream from Arrastra Gulch contributed elevated sulfate concentrations to the stream. Inflows with the highest sulfate concentrations in this area were the right bank inflows at 4,353 m (1,053 mg/L); 4,533 m (1,353 mg/l); 4,886 m (1,408 mg/L); 5,356 m (1,378 mg/L); 5,858 m (861 mg/L); and the ditch at 7,688 m (1,103 mg/L).

The mass-loading graphs for sulfate show the sampled instream load, the cumulative instream load, and the cumulative inflow load as approximately equal, indicating little to no sulfate loss or gain due to chemical reaction. The sulfate cumulative instream load was approximately equal to the cumulative inflow load upstream from Blair Gulch (5,221 m) indicating that instream concentrations were a result of the measured inflow concentrations (fig. 39). However, downstream from approximately 5,500 m, the sulfate cumulative instream load curve is slightly greater than the cumulative inflow load curve (fig. 39), indicating that the measured inflow load did not account for the entire instream load with the remainder probably resulting from ground-water discharge with elevated sulfate concentrations.
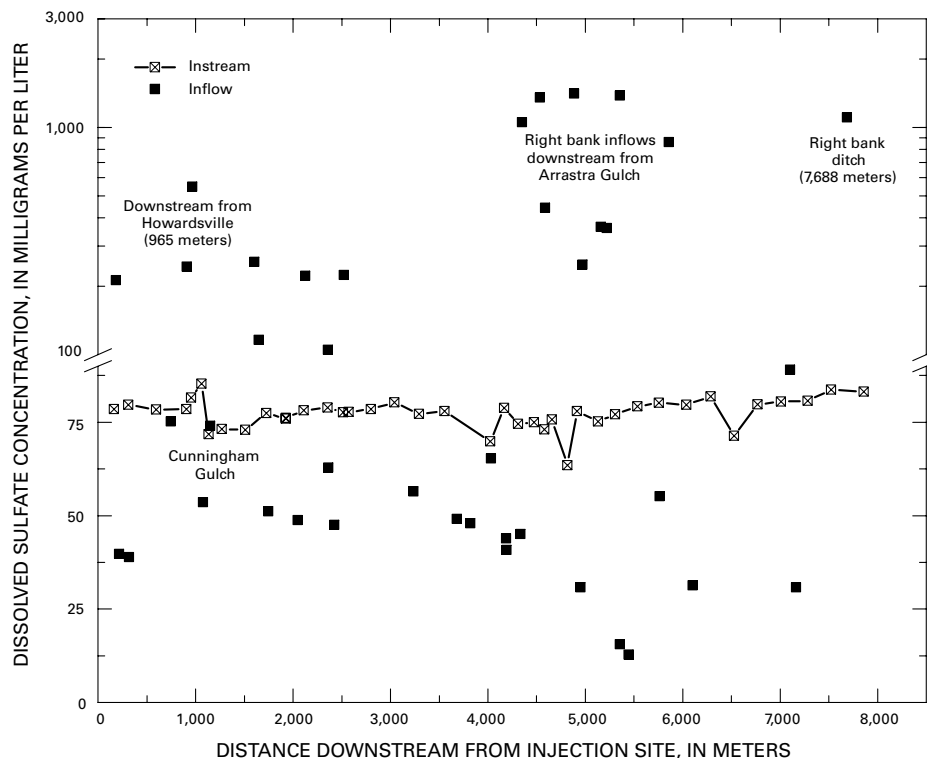
Figure 38. Dissolved sulfate concentrations with distance from the injection site, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.
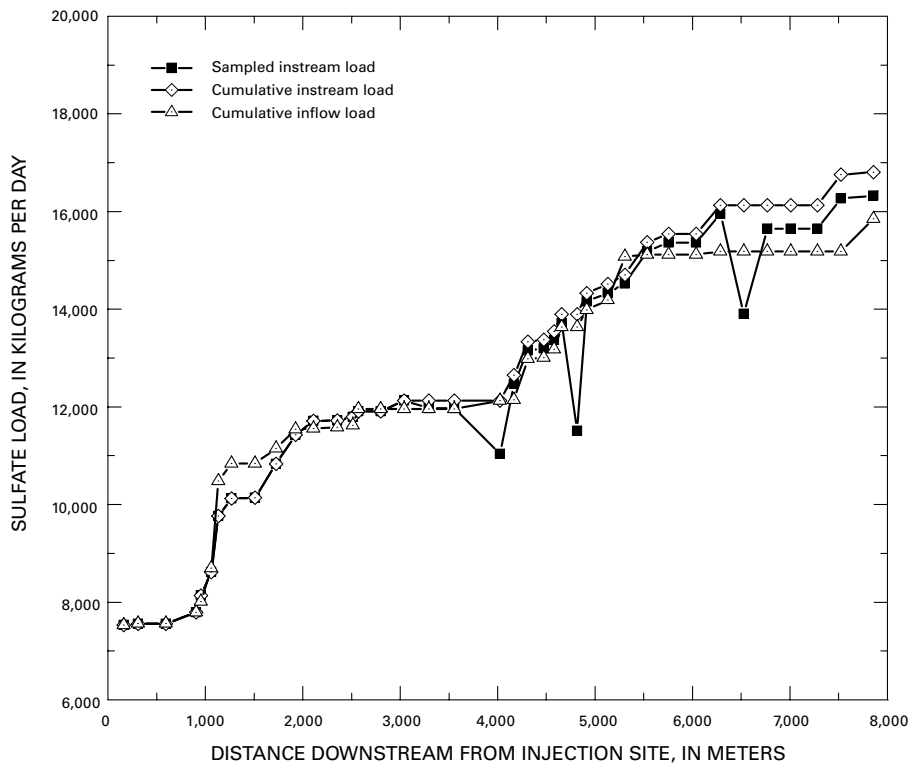
Figure 39. Sampled instream load, cumulative instream load, and cumulative inflow load of dissolved sulfate with distance from the injection site, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.

## Discussion of Sources and Loadings Howardsville to Silverton Study Reach

Surface-water drainage in the Howardsville to Silverton study reach contributed aluminum, copper, iron, manganese, zinc, and sulfate to the upper Animas River surface-water system in 1997. Instream dissolved and colloidal aluminum concentrations generally were low and near detection limits. Dissolved iron concentrations and loads increased downstream from Howardsville and Arrastra Gulch, and colloidal iron remained constant at low concentrations downstream from Howardsville. The concentrations and mass loads of instream dissolved manganese and zinc increased substantially downstream from Arrastra Gulch to the end of the study reach from surface and subsurface inflows, and instream dissolved zinc concentrations exceeded acute and chronic aquatic-life standards along the entire reach. Instream dissolved copper concentrations were lower than the acute and chronic toxicity standards throughout the study reach, and instream sulfate concentrations were lower than the USEPA's secondary drinking water standard of 250 mg/L throughout the study reach.

Based on the 1997 synoptic-sampling results and mass-loading graphs, there were four primary areas where metal concentrations and loads increased within the Howardsville to

Silverton study reach. The first increase was the reach downstream from Howardsville to downstream from Cunningham Gulch where the sampled instream loads of dissolved and colloidal iron, dissolved manganese, dissolved zinc, and dissolved sulfate all increased in a downstream direction during 1997 and 1998. The second increase was downstream from Arrastra Gulch, from approximately 4,186 to 5,900 m, where sampled instream loads of colloidal iron, dissolved manganese, dissolved zinc, and dissolved sulfate increased. The load increases in this reach appear to result from a series of right bank inflows downstream from the Mayflower Mill tailings with low pH and elevated constituent concentrations. A third increase of sampled instream loads occurred at approximately 6,100 m where load increases were measured for colloidal iron, dissolved manganese, dissolved zinc, and dissolved sulfate. The source of these load increases may have been from discharge of ground water with elevated constituent concentrations, based on mass-loading graphs and the lack of visible inflow in the reach. A fourth but lesser load increase for dissolved zinc and dissolved sulfate occurred at the end of the study reach, near the Lackawanna Mill, from approximately 7,283 to 7,850 m.

Based on the 1997 synoptic-sampling results, dissolved zinc is the primary constituent of concern in the Howardsville to Silverton study reach of the upper Animas River, and the

total cumulative load for zinc was approximately 102 kg/d at gaging station A68. Listed below are locations where instream dissolved zinc load increased and the percentage of the total load attributed to the reach:

- Downstream from tailings near the Mayflower Mill (15 percent),
- Downstream from Blair Gulch (9 percent),
- Downstream from Howardsville (9 percent),
- Downstream from tailings near the Lackawanna Mill (6 percent),
- Downstream from abandoned mill at 4,581 m (6 percent),
- Downstream from acidic inflows at 4,916 m (6 percent), and
- Downstream from Arrastra Gulch (4 percent).

A substantial dissolved zinc load also was contributed from the upper Animas drainage upstream from the study area (26 percent of the total load).

The 1997 Howardsville to Silverton study reach overlaps with the 1998 Eureka to Silverton study reach from a point upstream from Howardsville to a point downstream from Cunningham Gulch. Although seasonal variability was not specifically addressed by the studies, a general relation between constituent concentrations and stream discharge is noted in the overlapping part of the two data sets. Stream discharge near Howardsville was lower in 1998 than in 1997, the pH values were higher in 1997 than in 1998, and dissolved iron, manganese, zinc, and sulfate concentrations were lower in 1997 than in 1998. These observations indicate chemical constituents were diluted in 1997 relative to 1998, and that the effects of metal-rich inflow on water quality were greater at low flow.

Zinc Solute-Transport Simulations

To interpret mass-loading calculations and to evaluate the effects of potential remediation, one-dimensional surface-water transport of dissolved zinc was simulated for the Howardsville to Silverton study reach using OTIS. This section of the report describes the conservative and first-order decay simulations and the remediation simulations for the Howardsville to Silverton reach.

Conservative and First-Order Decay Simulation Results

The Howardsville to Silverton study reach was divided into 15 model reaches based on discharge calculations and mass-loading graphs. Main-channel cross-sectional area, storage-zone cross-sectional area, and storage-zone exchange coefficients were determined using OTIS-P simulations of the transport site data. A uniform dispersion coefficient of 1.0 m

was used for all model reaches. For each model reach, a lateral inflow discharge was computed based on the stream discharge profile. Upstream from Arrastra Gulch, lateral inflow concentrations were assigned to model reaches 1 through 7 based on measured inflow concentrations for 1997 (table 12 and fig. 40). Downstream from Arrastra Gulch, lateral inflow concentrations and first-order decay rates were adjusted as discussed herein to obtain a reasonable match between simulated and measured instream zinc concentrations.

Numerous low-pH inflows with elevated zinc concentrations occurred in model reach 8 downstream from Arrastra Gulch (fig. 40), and a flow-weighted average dissolved zinc inflow concentration of 42 mg/L was computed for reach 8. Using a lateral inflow concentration of 42 mg/L also required using a first-order decay constant in reach 8 to achieve a match between simulated and measured instream dissolved zinc concentrations. However, no dissolved zinc loss was indicated for reach 8 based on the sampled instream load graph (fig. 37). Therefore, the lateral inflow concentration for dissolved zinc in reach 8 was adjusted by trial-and-error to a value of 4.5 mg/L, and first-order decay was not simulated for this reach, to achieve a match between simulated and measured instream dissolved zinc concentrations (figs. 40 and 41).

Model reach 9 represents Boulder Gulch inflow. Using the lateral inflow rate and lateral inflow concentration representative of Boulder Gulch (0.06 mg/L), simulated zinc concentrations for reach 9 matched the measured instream zinc concentrations, so first-order decay was not simulated for this reach (table 12, fig. 41).

Instream concentrations and sampled instream load for dissolved zinc increased through model reaches 10, 12, and 14; however, there was little to no increase in the cumulative inflow load through these reaches (fig. 37). Unsampled inflow is indicated in these reaches, and the increase in instream zinc concentrations in this stream reach may be attributed to ground-water discharge with elevated zinc concentrations. Lateral inflow concentrations for model reaches 10, 12, and 14 therefore were increased by trial-and error to obtain a match between simulated and measured instream zinc concentrations. For model reach 10, a flow-weighted average inflow zinc concentration of 1.04 mg/L was computed for the visible inflows in the reach. However, using a lateral inflow concentration of 1.04 mg/L in reach 10 resulted in simulated zinc concentrations for the reach that were lower than the measured instream zinc concentrations. Consistent with the mass-loading graphs, this result indicates that effective lateral inflow zinc concentrations in reach 10 were higher than measured inflow concentrations. A lateral inflow concentration of 5.0 mg/L was used for model reach 10 to obtain a match between simulated and measured instream zinc concentrations (table 12 and fig. 40). The only visible inflow in model reach 12 had a low zinc concentration of 0.024 mg/L. However, measured instream zinc concentrations increased through reach 12. Ground-water discharge with elevated zinc concentrations again is indicated, and a lateral inflow concentration of

Table 12. OTIS setup and input parameters for zinc solute-transport model, upper Animas River, Howardsville to Silverton, Colorado.

[m, meters; m², square meters; m³/s-m, cubic meters per second per meter; mg/L, milligrams per liter; /s, per second; --, not applicable]

Model reach	Distance from injection site (m)	Reach length (m)	Main channel cross-sectional area (m²)	Lateral inflow rate (m³/s-m)	Lateral inflow concentration simulation (mg/L)	First-order decay rate (/s)	Description
1	595	595	1.713	5.24×10^{-6}	0.94	--	T1
2	955	360	1.730	1.25×10^{-4}	0.02	--	Upstream from Howardsville
3	1,059	104	1.730	1.39×10^{-4}	5.00	--	T2 — Downstream from Howardsville
4	1,135	76	2.816	5.08×10^{-3}	0.03	--	Downstream from Cunningham Gulch
5	2,800	1,665	2.816	1.19×10^{-4}	0.48	--	T3
6	4,166	1,366	2.740	5.76×10^{-5}	0.01	--	T4 — Upstream from Arrastra Gulch
7	4,310	144	2.851	1.53×10^{-3}	0.20	--	Downstream from Arrastra Gulch
8	4,916	606	2.851	7.99×10^{-5}	4.50	--	Downstream from right bank acid inflows and Boulder Gulch
9	5,131	215	2.851	3.68×10^{-4}	0.06	--	Downstream from Boulder Gulch
10	5,536	405	2.851	6.99×10^{-5}	5.00	--	Downstream from Blair Gulch
11	6,038	502	2.851	4.74×10^{-5}	6.38	4.0×10^{-4}	T5
12	6,288	250	3.188	9.74×10^{-5}	7.20	--	Downstream from zinc concentration increase
13	7,283	995	3.188	8.54×10^{-8}	0.20	1.0×10^{-4}	Downstream from zinc loss
14	7,858	575	3.188	1.23×10^{-6}	10.0	--	T6 — End of study reach
15	7,958	100	3.188	--	--	--	Downstream boundary
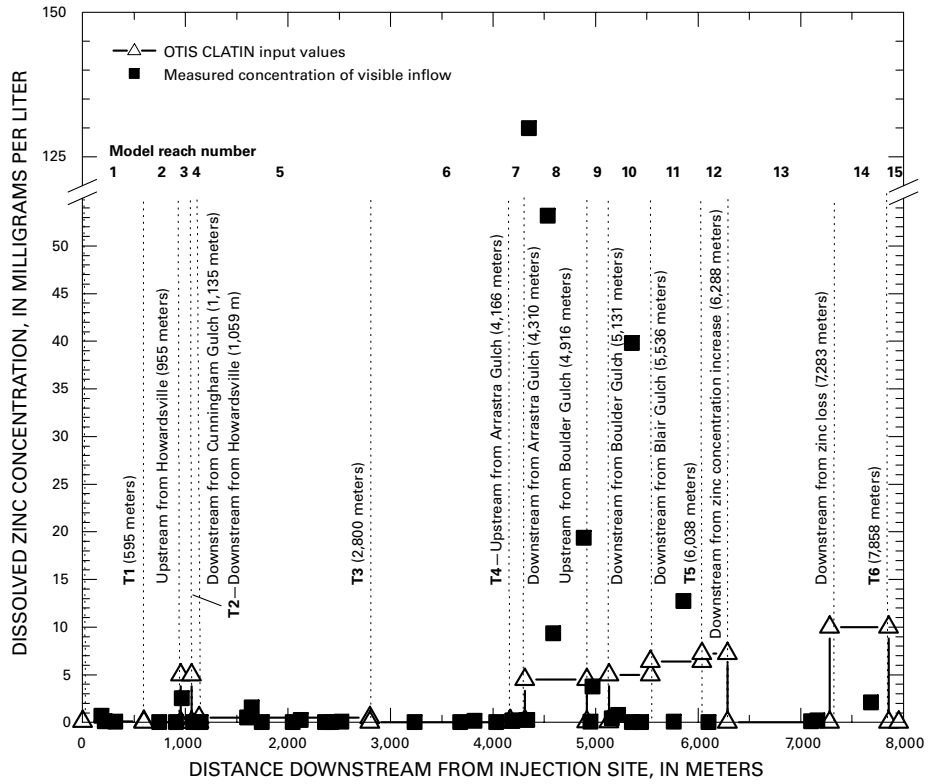
Figure 40. OTIS lateral inflow concentrations and measured inflow concentrations for dissolved zinc with distance from the injection site, upper Animas River, Howardsville to Silverton, Colorado.
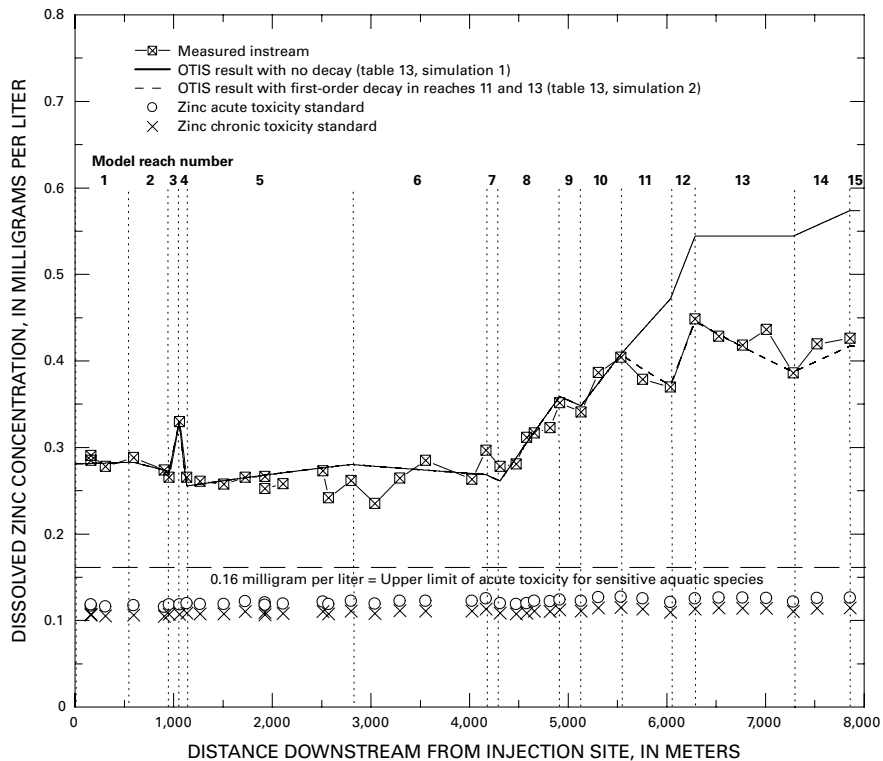
Figure 41. OTIS results for conservative and first-order decay simulations, upper Animas River, Howardsville to Silverton, Colorado.

7.2 mg/L was used for model reach 12 to obtain a match between simulated and measured instream zinc concentrations (table 12 and fig. 40). In model reach 14, a lateral inflow concentration of 10.0 mg/L was used to obtain a match between simulated and measured instream zinc concentrations (table 12 and fig. 40).

Using the lateral inflow concentrations listed in table 12, the conservative OTIS simulation computed instream zinc concentrations higher than the measured instream concentrations downstream from Blair Gulch (model reach 10) (fig. 41). Consistent with the mass-loading graphs, this simulation result indicates that chemical removal of dissolved zinc from some stream reaches likely is caused by zinc adsorption onto iron colloids or streambed sediment. Loss of a dissolved constituent is represented as a first-order process in OTIS, and first-order decay rates were assigned to model reaches 11 and 13 to represent the decrease of sampled instream zinc load through these reaches (table 12). The flow-weighted average zinc concentration of the two visible inflows in model reach 11 was 6.38 mg/L (table 12 and fig. 40). A first-order decay rate of 4.0×10^{-4}/s was assigned to model reach 11 to obtain a match between simulated and measured instream zinc concentrations (table 12 and fig. 41). In model reach 13, the flow-weighted average zinc concentration for the two inflows was 0.20 mg/L, and a first-order decay rate of 1.0×10^{-4}/s was assigned to obtain a match between simulated and measured instream zinc concentrations (table 12 and fig. 41).

Remediation Simulations

Two remediation alternatives were evaluated for the Howardsville to Silverton study reach using the first-order decay zinc transport simulation described in the previous section. To simulate remediation of stream reaches, the zinc lateral inflow concentrations were reduced from the model inflow concentrations to hypothetical concentrations representative of inflow after remediation. Because these post-remediation concentrations are uncertain, remediation for the Howardsville to Silverton study reach was simulated using a 50-percent reduction and then a 75-percent reduction in zinc lateral inflow concentrations of remediated reaches. A list of remediation simulations, zinc lateral inflow concentrations, and simulation results are presented in table 13.

The first set of remediation simulations addresses reducing zinc inflow concentrations in the model reach representing the inflow downstream from Howardsville (model reach 3). The zinc lateral inflow concentration for reach 3 (5.0 mg/L) was reduced by 50 percent and by 75 percent, and the simulations were run with first-order decay (table 13, simulations 3 and 4). A third simulation evaluated reducing the dissolved zinc upstream boundary condition from 0.28 to 0.19 mg/L to represent a 75-percent reduction in zinc concentrations from the Forest Queen mine and Kittimack tailings inflows (table 13, simulation 5). This simulation is similar to those presented for the Eureka to Howardsville 1998 study (table 7,

simulations 5 and 6) and is repeated here for the 1997 data set to examine the effects of remediation on stream reaches downstream from Howardsville. Results from simulations 3, 4, and 5 indicate that instream zinc concentrations downstream from Howardsville to upstream from Arrastra Gulch would approach concentrations near 0.16 mg/L if zinc inflow concentrations were reduced by 75 percent in the stream reaches receiving inflow from the Forest Queen mine, the Kittimack tailings, and downstream from Howardsville (fig. 42).

For the second set of remediation simulations, the anticipated effects of reducing zinc inflow concentrations in model reach 12 in addition to the upstream model reaches were evaluated (table 13, simulations 6 and 7). Remediation of the upstream inflows was represented using an upstream boundary condition of 0.19 mg/L zinc, a 75-percent reduction in zinc lateral inflow concentration for model reach 3, and then a 50- and a 75-percent reduction in zinc lateral inflow concentration for model reach 12. These simulations represent the effects of remediating reaches receiving inflow from the Forest Queen mine, Kittimack tailings, inflow downstream from Howardsville, presumed ground-water discharge in model reach 12, and include first-order decay in model reaches 11 and 13. Results of simulations 6 and 7 indicate that instream zinc concentrations would be higher than approximately 0.20 mg/L downstream from Arrastra Gulch because of visible inflows and ground-water discharge with elevated zinc concentrations in the lower part of the study reach (fig. 43).

SUMMARY

Drainage from abandoned and inactive mines and naturally mineralized areas in the San Juan Mountains of southern Colorado contributes metals to the upper Animas River near Silverton, Colorado. The Bureau of Land Management (BLM) and the Animas River Stakeholders Group (ARSG) are planning possible remedial actions along the upper Animas River to alleviate water-quality degradation, and tracer-injection studies and associated synoptic sampling were performed along two reaches of the upper Animas River to locate and quantify the sources of metal loading. One tracer-injection study was performed in September 1997 on the Animas River reach from Howardsville to Silverton, and a second study was performed in August 1998 on the stream reach from Eureka to Howardsville. Detailed profiles of stream discharge and chemical mass loading were obtained from the tracer-injection and synoptic-sampling studies. The one-dimensional stream transport computer code OTIS was used to evaluate results of the tracer-injection studies and to evaluate potential effects of remediation.

Tributary drainage in the upper Animas River study reaches contributed aluminum, calcium, copper, iron, magnesium, manganese, sulfate, and zinc to the surface-water system in 1997 and 1998. Based on the 1998 synoptic-sampling results and mass-loading graphs, sources upstream from

Table 13.   OTIS results for zinc solute-transport and remediation simulations, upper Animas River, Howardsville to Silverton, Colorado.

[CLATIN, OTIS input parameter for lateral inflow concentrations; m, meters; mg/L, milligrams per liter; %, percent]

Simulation number	OTIS CLATIN (mg/L)		OTIS result —computed instream zinc concentration (mg/L)		Description
	Reach 3	Reach 12	End of reach 6 (4,166 m)	End of study reach 6 (4,166 m)	
1	5.0	7.2	0.269	0.574	Zinc CLATIN represents measured inflows with adjusted values in reaches 10, 11, 12 and 14 for ground-water discharge and no decay.
2	5.0	7.2	0.269	0.417	Zinc CLATIN represents measured inflows with adjusted values in reaches 10, 11, 12 and 14 for ground-water inflow and first-order decay in reaches 11 and 13.
3	2.5	7.2	0.249	0.406	Howardsville remediation. 50% reduction in zinc CLATIN in reach 3 and first-order decay in reaches 11 and 13.
4	1.25	7.2	0.239	0.401	Howardsville remediation. 75% reduction in zinc CLATIN in reach 3 and first-order decay reaches 11 and 13.
5	1.25	7.2	0.184	0.371	Howardsville remediation. 75% reduction in zinc CLATIN in reach 3 with first-order decay in reaches 11 and 13 and upstream boundary = 0.19 mg/L.
6	2.5	3.6	0.194	0.343	Reach 12 remediation. 50% reduction in zinc CLATIN in reaches 3 and 12 with first-order decay in reaches 11 and 13 and upstream boundary = 0.19 mg/L.
7	1.25	1.8	0.184	0.321	Reach 12 remediation. 75% reduction in zinc CLATIN in reaches 3 and 12 with first-order decay in reaches 11 and 13 and upstream boundary = 0.19 mg/L.

Figure 42. OTIS results for remediation simulations, 3, 4, and 5, upper Animas River, Howardsville to Silverton, Colorado.
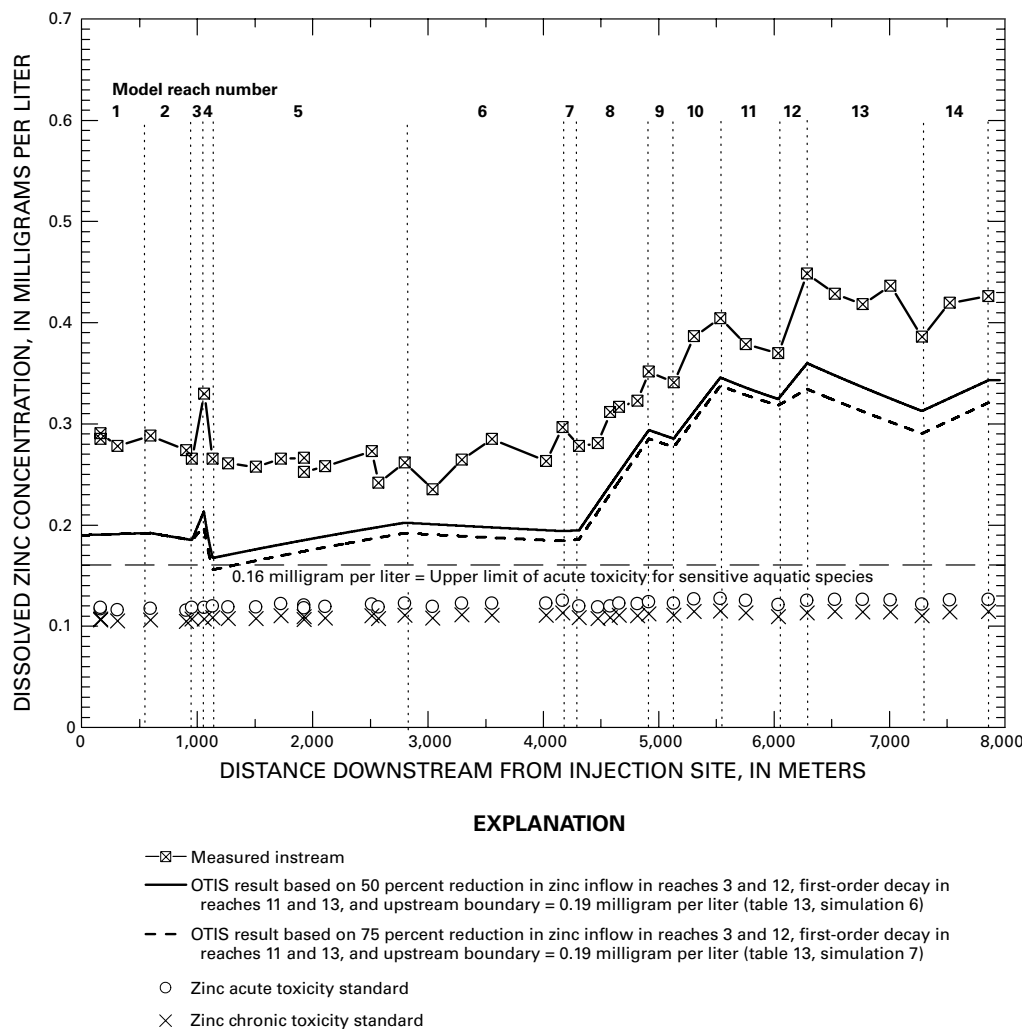
Figure 43. OTIS results for remediation simulations 6 and 7, upper Animas River, Howardsville to Silverton, Colorado.

Eureka contributed aluminum, copper, manganese, and zinc to the upstream end of the study reaches. Colloidal aluminum, dissolved copper, and dissolved zinc were attenuated through a braided reach downstream from Eureka. Instream copper concentrations were lower than the State of Colorado acute and chronic toxicity standards downstream from the braided reach to Silverton. Dissolved iron load and concentrations increased downstream from Howardsville and Arrastra Gulch, and colloidal iron remained constant at low concentrations downstream from Howardsville. Dissolved manganese was diluted by inflows downstream from Eureka, but the sampled instream manganese load increased downstream from Howardsville and downstream from Arrastra Gulch to Silverton. Instream sulfate concentrations were lower than the U.S. Environmental Protection Agency's secondary drinking-water standard of 250 milligrams per liter (mg/L) throughout the study reaches.

Elevated zinc concentrations are the primary concern for aquatic life in the upper Animas River. In the Eureka to

Howardsville 1998 study, the sampled instream dissolved zinc load increased downstream from the Forest Queen mine, the Kittimack tailings, and Howardsville. In the Howardsville to Silverton 1997 study, there were four primary areas where zinc load increased. First was the increase downstream from Howardsville and abandoned mining sites downstream from Cunningham Gulch, which also was measured during the 1998 study. The second increase was downstream from Arrastra Gulch, from approximately 4,186 meters (m) to downstream from the 1997 injection site at 5,900 m where the sampled instream zinc load increased because of a series of right bank inflows with pH values lower and dissolved zinc concentrations higher than those of the stream. A third increase of sampled instream dissolved zinc load occurred at approximately 6,100 m and may have been from ground-water discharge with elevated zinc concentrations, based on mass-loading graphs and the lack of visible inflow in the reach. A fourth but lower zinc load increase occurred near the end of the study reach

and downstream from tailings near the Lackawanna Mill, from approximately 7,283 to 7,850 m.

The 1997 Howardsville to Silverton study reach overlaps with the 1998 Eureka to Silverton study reach from a point upstream from Howardsville to a point downstream from Cunningham Gulch. Although seasonal variability was not specifically addressed by these studies, a general relation between constituent concentrations and stream discharge was noted in the overlapping part of the two data sets. River discharge near Howardsville was lower in 1998 than in 1997, instream pH values were higher in 1997 than in 1998, and instream dissolved iron, manganese, sulfate, and zinc concentrations were lower in 1997 than in 1998. These observations indicate that instream chemical constituents were diluted in 1997 relative to 1998, and that the effects of metal-rich inflow on water quality were greater at low flow.

Zinc solute transport in the river was simulated for both study reaches to interpret mass-loading calculations and to evaluate potential effects of remediation. Using lateral inflow concentrations representative of measured inflow concentrations, the conservative simulations computed instream zinc concentrations higher than the measured instream concentrations downstream from Eureka Gulch and downstream from Arrastra Gulch. Consistent with the mass-loading graphs, these simulation results indicate chemical removal of dissolved zinc from some stream reaches. The loss of dissolved zinc likely was caused by zinc adsorption onto iron oxyhydroxide colloids or streambed sediment and was represented as a first-order decay process using OTIS. First-order decay rates were assigned to selected reaches in both simulations to represent zinc adsorption, and lateral inflow zinc concentrations were adjusted to represent ground-water discharge of elevated zinc concentrations downstream from Arrastra Gulch in the Howardsville to Silverton simulations. The simulated results for instream zinc concentrations provided reasonable matches to the measured instream zinc concentrations for both study reaches.

Two remediation alternatives were evaluated for each study reach using the first-order decay zinc transport simulations. For the Eureka to Howardsville study reach, one set of simulations evaluated remediation of model reaches representing the Forest Queen mine inflow and inflow downstream from the Kittimack tailings, and the second set of simulations evaluated remediation of the model reach representing inflow downstream from Howardsville in addition to the Forest Queen mine inflow and inflow downstream from the Kittimack tailings. For the Howardsville to Silverton study reach, one set of simulations evaluated remediation of the model reach representing the inflow downstream from Howardsville, and the second set of simulations evaluated remediation of ground-water inflow in model reach 12. Based on simulation results, instream zinc concentrations downstream from the Kittimack tailings to upstream from Arrastra Gulch might approach 0.16 mg/L (the upper limit of acute toxicity for some sensitive aquatic species) if zinc inflow concentrations were

reduced by 75 percent in the stream reaches receiving inflow from the Forest Queen mine, the Kittimack tailings, and downstream from Howardsville. However, simulated zinc concentrations downstream from Arrastra Gulch were higher than approximately 0.20 mg/L because of numerous visible inflows and assumed ground-water discharge with elevated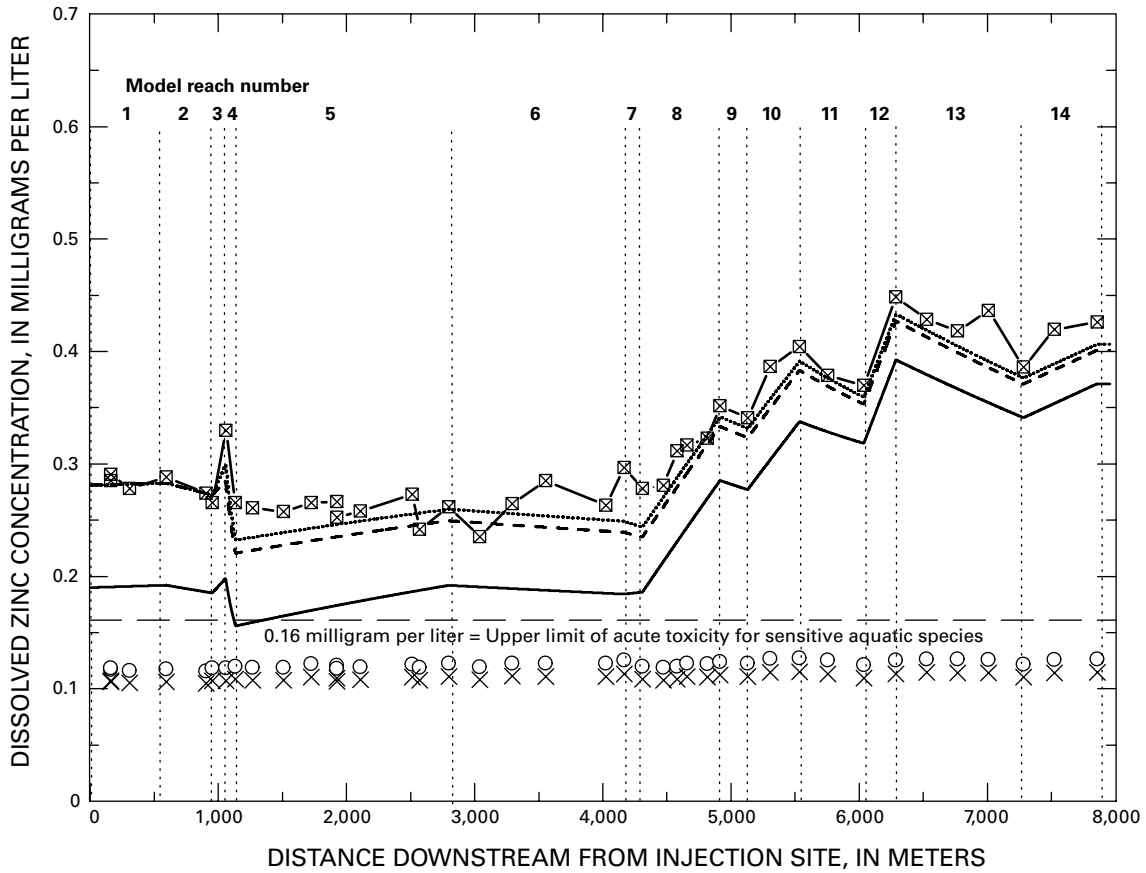 zinc concentrations in the lower part of the study reach. Removal of zinc from discrete visible inflows such as the Forest Queen mine discharge seems a viable approach to reducing zinc inflow loads to the upper Animas River. Remediation downstream from Arrastra Gulch is more complicated because ground-water discharge with elevated zinc concentrations seems to contribute to the instream zinc load.

REFERENCES

Bencala, K.E., 1983, Simulation of solute transport in a mountain pool-and-riffle stream with a kinetic mass transfer model for adsorption: Water Resources Research, v. 19, no. 3, p. 732–738.

Bencala, K.E., Kimball, B.A., and McKnight, D.M., 1991, Use of variation in solute concentration to identify interactions of the substream zone with instream transport: U.S. Geological Survey Water-Resources Investigations Report 91–4034, p. 377–379.

Bencala, K.E., and McKnight, D.M., 1987, Identifying instream variability — Sampling iron in an acidic stream in Averett, R.C. and McKnight, D.M. eds., Chemical quality of water and the hydrologic cycle: Chelsea, Mich., Lewis Publishers, Inc., p. 255–269.

Bencala, K.E., McKnight, D.M., and Zellweger, G.W., 1990, Characterization of transport in an acidic and metal-rich mountain stream based on a lithium tracer injection and simulations of transient storage: Water Resources Research, v. 26, p. 989–1000.

Bencala, K.E., McKnight, D.M., Zellweger, G.W., and Goad, Julie, 1986, The stability of rhodamine WT dye in trial studies of solute transport in an acidic and metal-rich stream: U.S. Geological Survey Water-Supply Paper 2310, p. 87–95.

Bencala, K.E., McKnight, D.M., Zellweger, G.W., and Kimball, B.A., 1988, Monitoring acidic streams for transport studies: U.S. Geological Survey Open-File Report 87–764, p. 119–124.

Bencala, K.E., and Walters, R.A., 1983, Simulation of solute transport in a mountain pool-and-riffle stream — A transient storage model: Water Resources Research, v. 19, no. 3, p. 718–724.

Benoit, Gaboury, and Rozan, T.F., 1999, The influence of size distribution on the particle concentration effect and trace metal partitioning in rivers: Geochimica et Cosmochimica Acta, v. 63, p. 113–127.

Besser, J.M., Brumbaugh, W.G., May, T.W., Church, S.E., and Kimball, B.A., 2001, Bioavailability of metals in stream food webs and hazards to brook trout (Salvelinus fontinalis) in the upper Animas River watershed, Colorado: Archive of Environmental Contamination and Toxicology, v. 40, p. 48–59.

Besser, J.M., and Leib, K.J., 1999, Modeling frequency of occurrence of toxic concentrations of zinc and copper in the Upper Animas River, *in* Morganwalp, D.W., and Buxton, H.T., eds., U.S. Geological Survey Toxic Substances Hydrology Program—Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999, v. 1, Contamination from Hardrock Mining: U.S. Geological Survey Water-Resources Investigations Report 99–4018A, p. 75–81.

Bove, D.J., Mast, M.A., Wright, W.G., Verplank, P.L., Meeker, G.P., and Yager, D.B., 2000, Geologic control on acidic and metal-rich waters in the southeast Red Mountains area near Silverton, Colorado: Proceedings of the Fifth International Conference on Acid Rock Drainage, Society of Mining, Metallurgy, and Exploration, Inc., Littleton, Colorado, v. 1, p. 523–533.

Broshears, R.E., Bencala, K.E., Kimball, B.A., and McKnight, D.M., 1993, Tracer-dilution experiments and solute-transport simulations for a mountain stream, Saint Kevin Gulch, Colorado: U.S. Geological Survey Water-Resources Investigations Report 92–4081, 18 p.

Broshears, R.E., Runkel, R.L., and Kimball, B.A., 1995, Interpreting spatial profiles of concentration in acid mine drainage streams *in* Hotchkiss, W.R., Downey, J.S., Gutentag, E.D., and Moore, J.E., eds., Water resources at risk: Denver, Colorado, American Institute of Hydrology, p. LL–10 to LL–21.

Broshears, R.E., Runkel, R.L., Kimball, B.A., Bencala, K.E., and McKnight, D.M., 1996, Reactive solute transport in an acidic stream — Experimental pH increase and simulation of controls on pH, aluminum, and iron: Environmental Science and Technology, v. 30, p. 3016–3024.

Church, S.E., Kimball, B.A., Fey, D.L., Ferderer, D.A., Yager, T.J., and Vaughn, R.B., 1997, Source, transport, and partitioning of metals between water, colloids, and bed sediments of the Animas River, Colorado: U.S. Geological Survey Open-File Report 97–151, 135 p.

Church, S.E., Fey, D.L., and Blair, R., 2000, Premining bed sediment geochemical baseline in the Animas River watershed, southwestern Colorado: Proceedings of the Fifth International Conference on Acid Rock Drainage, Society of Mining, Metallurgy, and Exploration, Inc., Littleton, Colorado v. 1, p. 499–512.

Friedman, L.C., and Erdmann, D.E., 1982, Quality assurance practices for the chemical and biological analyses of water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations of the U.S. Geological Survey, book 5, chap. A6, 164 p.

Garbarino, J.R., and Taylor, H.E., 1984a, Totally automated inductively-coupled plasma spectrometer for routine water quality testing: Spectrochimica Acta, 38B, p. 323.

Garbarino, J.R., and Taylor, H.E., 1984b, Trace analysis *in* Lawrence, J.R., ed., Recent developments and applications of ICP emission spectroscopy to trace elemental analysis of water: Academic Press, v. 4., 186.

Harvey, J.W., and Bencala, K.E., 1993, The effect of streambed topography on surface-subsurface water exchange in catchments: Water Resources Research, v. 29, p. 89–98.

Harvey, J.W., Wagner, B.J., and Bencala, K.E., 1996, Evaluating the reliability of the stream tracer approach to characterize stream-subsurface exchange: Water Resources Research, v. 32, no. 8, p. 2441–2451.

Jarrett, R.D., 1992, Hydraulics of mountain river, *in* Yen, B.C., ed., Channel flow resistance centennial of Manning's formula, International Conference of the Centennial of Manning's and Kuichling's Rational Formula: Littleton, Colorado, Water Resources Publications, p. 287–298.

Kilpatrick, F.A., and Cobb, E.D., 1985, Measurement of discharge using tracers: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A16, 52 p.

Kimball, B.A., 1997, Use of tracer injections and synoptic sampling to measure metal loading from acid mine drainage: U.S. Geological Survey Fact Sheet 245–96, 4 p.

Kimball, B.A., Broshears, R.E., Bencala, K.E., and McKnight, D.M., 1991, Comparison of rates of hydrologic and chemical processes in a stream affected by acid mine drainage, *in* Mallard, G.E., and Aronson, D.A., eds., U.S. Geological Survey Toxic Substances Hydrology Program — Proceedings of the technical meeting, Monterey, California, March 11-15, 1991: U.S. Geological Survey Water-Resources Investigations Report 91–4034, p. 407–412.

Kimball, B.A., Broshears, R.E., Bencala, K.E., and McKnight, D.M., 1994, Coupling of hydrologic transport and chemical reactions in a stream affected by acid mine drainage: Environmental Science and Technology, v. 28, p. 2065–2073.

Kimball, B.A., Callender, E., and Axtmann, E.V., 1995, Effects of colloids on metal transport in a river receiving acid mine drainage, upper Arkansas River, Colorado: Applied Geochemistry, v. 10, p. 285–306.

Kimball, B.A., McKnight, D.M., Wetherbee, G.A., and Harnish, R.A., 1992, Mechanisms of iron photoreduction in metal-rich, acidic streams, St. Kevin Gulch, Colorado, USA: Chemical Geology, v. 96, p. 227–239.

Kimball, B.A., Nimick, D.A., Gerner, L.J., and Runkel, R.L., 1999a, Quantification of metal loading in Fisher Creek by tracer injection and synoptic sampling, Park County, Montana, August 1997: U.S. Geological Survey Water-Resources Investigations Report 99–4119, 40 p.

Kimball, B.A., Runkel, R.L., Bencala, K.E., and Walton-Day, Katherine, 1999b, Use of tracer-injection and synoptic-sampling studies to quantify effects of metal loading from mine drainage, *in* Morganwalp, D.W., and Buxton, H.T., eds., U.S. Geological Survey Toxic Substances Hydrology Program—Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999—Volume 1 of 3—Contamination from Hardrock Mining: U.S. Geological Survey Water-Resources Investigations Report 99–4018A, p. 31–36.

Kimball, B.A., Runkel, R.L., and Gerner, L.J., 1999c, Quantification of metal loading in French Gulch, Summit County, Colorado, using a tracer-injection study, July 1996: U.S. Geological Survey Water-Resources Investigations Report 98–4078, 38 p.

Luedke, R.G., and Burbank, W.S., 1996a, Preliminary geologic map of the Silverton 7.5 minute quadrangle, San Juan and Hinsdale Counties, Colorado: U.S. Geological Survey Open-File Report 96–275, 20 p.

Luedke, R.G., and Burbank, W.S., 1996b, Preliminary geologic map of the Howardsville 7.5 minute quadrangle, San Juan and Hinsdale Counties, Colorado: U.S. Geological Survey Open-File Report 96–278, 19 p.

Mast, M.A., Verplank, P.L., Yager, D.B., Wright, W.G., and Bove, D.J., 2000, Natural sources of metals to surface waters in the upper Animas River watershed: Proceedings of the Fifth International Conference on Acid Rock Drainage, Society of Mining, Metallurgy, and Exploration, Inc., Littleton, Colorado, v. 1, p. 513–522.

McKnight, D.M., and Bencala, K.E., 1989, Reactive iron transport in an acidic mountain stream in Summit County, Colorado — A hydrologic perspective: Geochimica et Cosmochimica Acta, v. 53, p. 2225–2234.

Moran, S.B., and Moore, R.M., 1989, The distribution of colloidal aluminum and organic carbon in coastal and open ocean water off Nova Scotia: Geochimica et Cosmochimica Acta, v. 53, p. 2519–2527.

Rantz, S.E., compiler, 1982, Measurement and computation of streamflow — Volume I, Measurement of stage and discharge: U.S. Geological Survey Water-Supply Paper 2175, 284 p.

Runkel, R.L., 1998, One-dimensional transport with inflow and storage (OTIS) — A solute transport model for streams and rivers: U.S. Geological Survey Water-Resources Investigations Report 98–4018, 73 p.

Runkel, R.L., Kimball, B.A., McKnight, D.M, and Bencala, K.E., 1999, Reactive solute transport in streams — A surface complexation approach for trace metal adsorption: Water Resources Research, v. 35, no. 2, p. 3829–3840.

Runkel, R.L., McKnight, D.M, Bencala, K.E., and Chapra, S.C., 1996, Reactive solute transport in streams, 2. Simulation of a pH modification experiment: Water Resources Research, v. 32, no. 2, p. 419–430.

Sole, T.C., Granitto, Matthew, Rich, C.L., Litke, D.W., and Pelltier, R.T., 2005, Digital databases and CD-ROM for the Animas River watershed, Chapter G *in* Church, S.E., von Guerard, Paul, and Finger, S.E., eds., U.S. Geological Survey Professional Paper 1651, 27 p., 6 plates, 1 DVD.

Stumm, W. and J.J. Morgan, 1981, Aquatic Chemistry: New York, Wiley-Interscience, 780 p.

Taylor, H.E., 1982, Atomic emission spectrometric methods, *in* Fishman, M.J., and Bradford, W.L., eds., A supplement to methods for the determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Open-File Report 82–272, 136 p.

U.S. Environmental Protection Agency, 1992, Secondary Drinking Water Regulations: Guidance for Nuisance Chemicals: U.S. Environmental Protection Agency Report 810/K–92–001, http://www.epa.gov/safewater/consumer/2ndstandards.html, accessed February 8, 2005.

U.S. Geological Survey, 2000, Interim report on the scientific investigations in the Animas River watershed, Colorado, to facilitate remediation decisions by the U.S. Bureau of Land Management and the U.S. Forest Service, March 29, 2000 meeting, Denver, Colorado: U.S. Geological Survey Open-File Report 00–245, 34 p.

Vincent, K.R., Church, S.E., and Fey, D.L., 1999, Geomor-
phological context of metal-laden sediments in the Animas
River floodplain, Colorado, *in* Morganwalp, D.W., and
Buxton, H.T., eds., U.S. Geological Survey Toxic Sub-
stances Hydrology Program—Proceedings of the Technical
Meeting, Charleston, South Carolina, March 8-12, 1999—
Volume 1 of 3—Contamination from Hardrock Mining:
U.S. Geological Survey Water-Resources Investigations
Report 99–4018A, p. 99–105.

Wagner, B.J., and Harvey, J.W., 1997, Experimental design for
estimating parameters of rate-limited mass transfer — Anal-
ysis of stream tracer studies: Water Resources Research,
v. 33, no. 7, p. 1731–1741.

Walton-Day, Katherine, Runkel, R.L., Kimball, B.A., and Ben-
cala, K.E., 1999, Application of the solute-transport models
OTIS and OTEQ and implications for remediation in a
watershed affected by acid mine drainage, Cement Creek,
Animas River Basin, Colorado, *in* Morganwalp, D.W., and
Buxton, H.T., eds., U.S. Geological Survey Toxic Sub-
stances Hydrology Program—Proceedings of the Technical
Meeting, Charleston, South Carolina, March 8-12, 1999—
Volume 1 of 3—Contamination from Hardrock Mining:
U.S. Geological Survey Water-Resources Investigations
Report 99–4018A, p. 37–46.

Wilde, F.D., Radtke, D.B., Gibs, Jacob, and Iwatsubo, R.T.,
eds., 1998, National field manual for the collection of water-
quality data, selection of equipment for water sampling:
U.S. Geological Survey Techniques of Water-Resources
Investigations, book 9, chap. A2, variously paged.

Yager, D.B., and Bove, D.J., 2002, Generalized geologic map
of part of the upper Animas River watershed and vicinity,
Silverton, Colorado: U.S. Geological Survey Miscellaneous
Field Studies Map MF–2377.

Zellweger, G.W., Bencala, K.E., McKnight, D.M., Hirsch,
R.M., and Kimball, B.A., 1988, Practical aspects of tracer
experiments in acidic, metal-enriched streams, *in* Mallard,
G.E., ed., U.S. Geological Survey Toxic Substances
Hydrology Program — Surface-Water Contamination:
U.S. Geological Survey Open-File Report 87–764,
p. 125–130.

APPENDIXES

Appendix 1. Field measurements and major ion concentrations for synoptic water samples, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.

[Source, 0=stream, 1=inflow; Distance, distance downstream from injection site; Temp, water temperature in degrees Celsius; pH, in standard units; SC, specific conductance, in microsiemens per centimeter at 25 degrees Celsius; Alkalinity, in milligrams per liter calcium carbonate; all major ion concentrations in milligrams per liter; method detection limits in milligrams per liter listed in parentheses below constituent names; 1,618A, 1,618B, 1,618C, and 1,618D, instream samples collected from individual braids listed from left bank to right bank of main channel looking downstream; --, not measured]

Source	Distance (meters)	Time	Temp	pH	SC	Calcium (0.02)	Magnesium (0.001)	Sodium (0.20)	Chloride (0.30)	Sulfate (0.09)	Alkalinity
0	0	--	12.0	7.35	165	26.4	2.18	0.92	0.20	54.7	21.7
0	80	1855	12.5	7.34	210	25.8	2.14	8.72	13.35	55.2	34.4
0	282	1845	13.1	7.41	210	25.2	2.16	7.35	11.24	55.2	22.5
0	586	1830	11.9	7.21	220	30.9	2.23	5.44	7.43	66.4	20.5
0	786	1825	11.9	7.28	205	30.7	2.23	5.46	7.41	66.5	20.0
0	906	1820	12.1	7.44	225	28.8	2.23	5.49	7.44	66.0	21.3
0	1,061	1815	15.9	7.36	215	28.2	2.23	5.42	7.41	65.5	21.6
0	1,411	1800	14.9	7.27	185	29.8	2.32	5.60	7.34	66.5	--
0	1,618A	1740	13.0	6.98	210	30.0	2.20	5.30	7.35	66.1	36.8
0	1,618B	1750	12.9	7.45	225	29.1	2.25	5.92	9.02	66.1	20.2
0	1,618C	1750	12.8	7.27	210	30.4	2.31	5.74	7.40	66.1	35.7
0	1,618D	1755	14.4	7.17	210	28.5	2.21	5.25	7.27	66.1	23.0
0	1,918	1720	14.0	6.59	220	29.1	2.15	4.98	6.96	65.9	37.0
0	2,030	1700	11.7	7.13	185	27.6	2.04	4.03	5.00	61.3	--
0	2,240	1640	11.9	6.78	145	27.9	2.03	3.35	4.45	62.2	33.2
0	2,420	1630	12.2	6.65	145	26.9	1.95	4.14	4.51	61.8	30.8
0	2,620	1605	13.0	7.03	145	29.0	2.04	3.44	3.93	61.9	20.7
0	2,620	1610	12.7	7.16	150	29.6	2.07	3.55	3.93	61.9	20.9
0	2,860	1555	13.4	7.34	185	28.0	2.05	4.56	4.00	62.2	24.5
0	3,150	1540	13.8	7.30	190	29.3	2.13	4.67	3.72	61.7	20.0
0	3,400	1513	13.5	7.05	195	27.8	2.08	2.78	3.33	64.0	36.6
0	3,435	1505	13.4	6.88	195	29.7	2.14	3.90	2.94	63.5	35.0
0	3,665	1450	12.5	7.22	195	29.8	2.17	3.96	2.77	62.6	23.8
0	3,905	1435	12.0	7.64	190	27.8	2.07	2.53	3.11	62.2	22.5
0	4,164	1415	11.9	6.89	150	30.6	2.20	2.46	2.64	63.4	22.1
0	4,430	1400	11.6	7.05	200	30.4	2.21	3.12	2.51	65.3	23.8
0	4,670	1345	12.1	6.79	155	32.2	2.26	2.31	2.33	67.9	22.6
0	4,970	1333	12.5	7.04	210	33.4	2.28	2.71	2.33	69.3	23.4
0	5,190	1320	12.4	7.00	215	34.3	2.31	2.77	2.30	68.9	23.0
0	5,467	1240	11.1	7.37	210	31.6	2.24	2.85	2.30	70.6	24.6
0	6,038	1215	11.4	7.14	215	31.6	2.22	2.41	2.26	70.7	24.3
0	6,528	1145	10.7	7.33	220	35.3	2.34	2.73	2.26	74.0	23.9
0	6,618	1135	10.9	6.98	220	35.0	2.37	2.29	2.08	70.7	24.3
0	6,753	1115	10.5	7.09	145	33.3	2.28	2.40	1.80	70.4	29.2
0	6,993	1105	10.5	6.86	220	35.3	2.35	2.14	1.76	70.4	27.7
0	7,250	1024	9.4	7.13	235	37.0	2.35	2.77	1.84	71.0	31.1
1	347	1845	12.3	7.38	230	38.0	2.34	1.23	0.27	90.7	37.6
1	2,090	1705	10.5	7.22	175	26.9	2.32	1.47	1.35	63.6	32.7
1	2,465	1625	11.2	7.93	225	36.5	2.91	2.40	0.21	61.0	47.6
1	3,165	1540	12.4	6.32	240	49.5	3.72	2.24	0.24	128	24.3
1	3,405	1525	8.0	7.11	175	30.7	1.99	1.60	0.65	58.9	20.6
1	3,450	1500	13.5	7.95	195	33.4	2.84	2.60	0.19	43.8	52.8
1	3,954	1426	10.8	6.51	245	38.9	2.54	1.76	0.27	94.9	34.6
1	4,189	1415	12.0	6.99	165	33.5	2.14	1.45	0.36	77.1	11.7
1	5,210	1317	15.4	7.74	315	54.8	2.45	3.33	0.28	85.8	65.7
1	5,407	1307	17.9	6.83	210	32.5	1.93	2.07	1.58	58.9	28.8
1	5,648	1235	13.7	7.30	210	32.4	2.55	2.79	2.52	73.8	20.9
1	6,438	1151	15.5	5.68	610	77.5	8.78	2.77	5.17	307	--
1	6,558	1140	10.5	7.60	210	36.2	2.16	1.79	0.28	54.1	46.4
1	6,633	1128	9.3	7.81	245	43.6	2.02	2.44	0.25	69.3	50.7
1	7,008	1052	7.9	7.09	540	95.7	6.14	5.21	0.30	266	23.1
1	7,013	1045	10.1	7.25	185	30.9	1.96	2.48	3.79	46.6	27.1
1	7,063	1038	9.6	6.90	300	52.7	2.61	3.43	4.79	108	30.3

Appendix 2.   Inductively coupled plasma-atomic emissions spectrometry (ICP-AES) results for synoptic water samples,
upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.

[Source, 0=stream, 1=inflow; Distance, distance downstream from injection site; Silica as SiO2; all concentrations in milligrams per liter;
method detection limits in milligrams per liter listed in parentheses below constituent names; 1,618A, 1,618B, 1,618C, and 1,618D, instream
samples collected from individual braids listed from left bank to right bank of main channel looking downstream; < constituent not detected;
E, estimated concentration less than method detection limit]

Source	Distance (meters)	Aluminum, dissolved (0.01)	Aluminum, colloidal (0.01)	Barium, dissolved (0.002)	Cadmium, dissolved (0.001)	Copper, dissolved (0.002)	Copper, colloidal (0.002)	Iron, dissolved (0.003)	Iron, colloidal (0.003)
0	0	0.066	0.222	0.0119	0.0021	0.0232	<0.002	<0.003	0.085
0	80	0.060	0.225	0.0114	0.0030	0.0845	<0.002	0.008	0.075
0	282	0.074	0.226	0.0116	0.0026	0.0170	<0.002	<0.003	0.088
0	586	0.084	0.155	0.0117	0.0024	0.0068	0.0037	<0.003	0.078
0	786	0.065	0.172	0.0119	0.0018	0.0201	<0.002	<0.003	0.078
0	906	0.053	0.180	0.0112	<0.001	0.0330	<0.002	0.006	0.073
0	1,061	0.053	0.180	0.0120	0.0024	0.0063	0.0058	<0.003	0.081
0	1,411	0.065	0.159	0.0121	0.0018	0.0334	<0.002	0.005	0.072
0	1,618A	0.076	0.134	0.0113	0.0021	0.0060	0.0030	<0.003	0.062
0	1,618B	0.079	0.130	0.0125	0.0035	0.141	<0.002	0.014	0.049
0	1,618C	0.053	0.014	0.0118	0.0028	0.0046	<0.002	0.005	<0.003
0	1,618D	0.077	0.117	0.0112	0.0020	0.0078	<0.002	<0.003	0.049
0	1,918	0.083	0.103	0.0109	0.0019	0.0040	0.0036	<0.003	0.055
0	2,030	0.059	0.077	0.0116	0.0017	0.0062	<0.002	<0.003	0.032
0	2,240	0.039	0.081	0.0118	<0.001	0.0065	<0.002	<0.003	0.029
0	2,420	0.048	0.070	0.0110	<0.001	0.0044	<0.002	<0.003	0.032
0	2,620	0.067	0.053	0.0152	<0.001	0.0036	<0.002	<0.003	0.048
0	2,620	0.058	0.098	0.0161	0.0015	0.0036	<0.002	<0.003	0.061
0	2,860	0.055	0.065	0.0162	<0.001	0.0038	<0.002	<0.003	0.044
0	3,150	0.037	0.088	0.0168	<0.001	0.0030	<0.002	<0.003	0.045
0	3,400	0.035	0.062	0.0157	0.0020	0.0040	<0.002	<0.003	0.034
0	3,435	0.053	0.036	0.0185	<0.001	0.0031	<0.002	<0.003	0.031
0	3,665	0.035	0.037	0.0199	<0.001	0.0037	<0.002	<0.003	0.023
0	3,905	0.021	0.059	0.0189	<0.001	0.0038	<0.002	<0.003	0.021
0	4,164	0.032	0.014	0.0195	<0.001	0.0046	<0.002	<0.003	<0.003
0	4,430	0.031	0.054	0.0199	<0.001	0.0045	<0.002	<0.003	0.023
0	4,670	0.028	0.049	0.0196	<0.001	0.0032	<0.002	<0.003	0.021
0	4,970	0.053	0.014	0.0195	<0.001	0.0020	<0.002	<0.003	0.015
0	5,190	0.046	0.014	0.0197	<0.001	0.0023	<0.002	<0.003	0.019
0	5,467	0.024	0.055	0.0184	<0.001	0.0050	<0.002	<0.003	0.023
0	6,038	0.014	0.058	0.0184	0.0017	0.0022	<0.002	<0.003	0.031
0	6,528	0.040	0.059	0.0183	<0.001	0.0015E	<0.002	0.059	0.240
0	6,618	0.036	0.034	0.0242	<0.001	0.0023	<0.002	0.013	0.213
0	6,753	0.014	0.076	0.0237	<0.001	0.0060	<0.002	0.008	0.152
0	6,993	0.026	0.049	0.0236	0.0015	0.0109	<0.002	0.020	0.121
0	7,250	0.041	0.033	0.0232	0.0017	0.0018E	0.0012E	<0.003	0.171
1	347	0.064	0.071	0.0121	0.0017	0.0144	<0.002	<0.003	0.076
1	1,940	0.154	0.014	0.0150	0.0020	0.0070	<0.002	0.029	<0.003
1	2,090	0.025	0.035	0.0093	0.0031	0.0060	0.0034	0.130	0.163
1	2,465	0.057	0.079	0.0485	<0.001	0.0018E	<0.002	0.049	0.144
1	3,165	0.085	0.014	0.0161	0.0028	0.0019E	<0.002	<0.003	0.008
1	3,405	0.028	0.014	0.0267	0.0018	0.0025	<0.002	<0.003	0.019
1	3,450	0.014	0.021	0.0468	<0.001	0.0023	<0.002	<0.003	<0.003
1	3,954	0.023	0.014	0.0247	0.0019	0.0043	<0.002	<0.003	<0.003
1	4,189	0.014	0.014	0.0182	<0.001	0.0013E	<0.002	<0.003	0.796
1	5,210	0.014	0.043	0.0105	<0.001	0.0010E	0.0015E	0.037	0.070
1	5,407	0.014	0.383	0.0110	<0.001	0.0027	0.0251	<0.003	0.796
1	5,648	0.031	0.073	0.0167	<0.001	0.0036	<0.002	0.036	0.041
1	6,438	0.563	0.141	0.0298	0.0091	<0.002	0.0225	11.7	3.87
1	6,558	0.023	0.014	0.0434	<0.001	<0.002	<0.002	<0.003	0.024
1	6,633	0.014	0.014	0.0019E	<0.001	0.0011E	<0.002	<0.003	<0.003
1	7,008	0.023	0.024	0.0093	0.0021	<0.002	<0.002	1.03	1.13
1	7,013	0.026	0.014	0.0043	0.0034	0.0399	0.0048	<0.003	0.040
1	7,063	0.032	0.014	0.0101	0.0100	0.0254	0.0018E	<0.003	<0.003

Appendix 2. Inductively coupled plasma-atomic emissions spectrometry (ICP-AES) results for synoptic water samples, upper Animas River, Eureka to Howardsville, Colorado, August 14, 1998.—Continued

[Source, 0=stream, 1=inflow; Distance, distance downstream from injection site; Silica as SiO2; all concentrations in milligrams per liter; method detection limits in milligrams per liter listed in parentheses below constituent names; 1,618A, 1,618B, 1,618C, and 1,618D, instream samples collected from individual braids listed from left bank to right bank of main channel looking downstream; < constituent not detected; E, estimated concentration less than method detection limit]

Source	Distance (meters)	Manganese, dissolved (0.001)	Manganese, colloidal (0.001)	Silica, dissolved (0.009)	Silica, colloidal (0.009)	Strontium, dissolved (0.0005)	Strontium, colloidal (0.0005)	Zinc, dis-solved (0.003)	Zinc, colloidal (0.003)
0	0	0.779	<0.001	3.94	0.449	0.172	<0.0005	0.467	<0.003
0	80	0.754	0.005	4.03	0.227	0.165	<0.0005	0.541	<0.003
0	282	0.766	0.016	4.01	0.436	0.167	0.0049	0.391	0.0270
0	586	0.576	0.006	4.11	0.689	0.241	0.0035	0.365	0.0185
0	786	0.574	0.013	4.25	0.604	0.244	0.0029	0.382	<0.003
0	906	0.566	0.012	4.54	0.215	0.239	0.0088	0.418	<0.003
0	1,061	0.567	0.007	4.69	0.058	0.244	<0.0005	0.335	0.0293
0	1,411	0.583	<0.001	4.67	0.136	0.248	<0.0005	0.414	<0.003
0	1,618A	0.552	0.013	4.49	0.021	0.238	0.0022	0.302	0.0217
0	1,618B	0.582	<0.001	4.71	0.021	0.248	<0.0005	0.339	<0.003
0	1,618C	0.562	0.018	4.61	0.156	0.242	0.0067	0.651	<0.003
0	1,618D	0.564	0.023	4.41	0.383	0.237	0.0069	0.326	0.0233
0	1,918	0.527	<0.001	4.35	0.269	0.232	0.0011	0.301	0.0130
0	2,030	0.377	0.007	4.90	0.160	0.232	0.0042	0.347	0.0136
0	2,240	0.343	<0.001	5.13	0.031	0.242	<0.0005	0.353	0.0019E
0	2,420	0.327	0.018	4.95	0.176	0.227	0.0117	0.332	0.0266
0	2,620	0.301	0.059	4.81	1.23	0.265	0.0528	0.292	0.0679
0	2,620	0.290	0.010	4.60	0.662	0.254	0.0097	0.284	0.0189
0	2,860	0.299	0.004	5.08	0.258	0.263	0.0048	0.294	0.0134
0	3,150	0.296	<0.001	5.23	0.021	0.276	<0.0005	0.302	0.0078
0	3,400	0.242	0.008	5.33	0.152	0.261	0.0081	0.304	0.0132
0	3,435	0.222	<0.001	5.61	0.134	0.284	<0.0005	0.337	<0.003
0	3,665	0.210	<0.001	5.52	0.076	0.290	<0.0005	0.291	0.0107
0	3,905	0.196	0.015	5.25	0.505	0.270	0.0216	0.286	0.0265
0	4,164	0.192	<0.001	5.62	0.021	0.288	0.0037	0.288	<0.003
0	4,430	0.172	0.003	5.65	0.021	0.292	0.0039	0.286	0.0071
0	4,670	0.158	0.004	5.86	0.021	0.305	0.0046	0.278	0.0159
0	4,970	0.154	<0.001	5.87	0.050	0.311	<0.0005	0.286	<0.003
0	5,190	0.149	<0.001	5.77	0.292	0.318	<0.0005	0.284	<0.003
0	5,467	0.137	0.004	5.90	0.021	0.306	0.0069	0.276	0.0087
0	6,038	0.135	0.004	5.94	0.178	0.312	0.0045	0.272	0.0186
0	6,528	0.365	0.011	5.82	0.561	0.324	0.0079	0.364	0.0238
0	6,618	0.292	0.005	5.99	0.033	0.341	<0.0005	0.298	0.0118
0	6,753	0.279	0.011	5.95	0.021	0.345	0.0034	0.282	0.0130
0	6,993	0.284	<0.001	5.95	0.021	0.346	<0.0005	0.321	<0.003
0	7,250	0.287	<0.001	5.68	0.483	0.348	<0.0005	0.286	0.0103
1	347	0.118	0.005	5.58	0.228	0.398	0.0197	0.299	0.0095
1	1,940	0.562	<0.001	6.15	0.021	0.281	<0.0005	0.728	<0.003
1	2,090	0.193	0.005	6.79	0.146	0.228	<0.0005	0.483	0.0094
1	2,465	0.021	0.008	6.44	0.413	0.504	0.0161	0.008	<0.003
1	3,165	0.073	0.003	11.9	0.021	0.405	0.0046	0.879	0.0027E
1	3,405	0.003	0.006	6.39	0.344	0.304	0.0014	0.325	<0.003
1	3,450	<0.001	<0.001	4.99	0.021	0.378	<0.0005	0.008	<0.003
1	3,954	0.122	0.002	8.38	0.021	0.367	0.0039	0.456	<0.0
1	4,189	0.038	0.002	6.90	0.245	0.328	0.0084	0.222	0.0063
1	5,210	0.056	0.013	6.62	0.058	0.646	<0.0005	0.012	0.0059
1	5,407	0.100	0.314	9.24	5.10	0.336	0.0085	0.218	0.0732
1	5,648	0.259	<0.001	6.69	0.085	0.304	<0.0005	0.308	<0.003
1	6,438	18.6	0.419	15.0	0.363	0.516	<0.0005	7.28	0.4317
1	6,558	0.005	0.001	5.23	0.200	0.363	0.0090	0.026	<0.003
1	6,633	<0.001	0.001	5.99	0.139	0.596	0.0086	0.013	<0.003
1	7,008	1.04	<0.001	20.9	0.021	0.885	<0.0005	0.368	<0.003
1	7,013	0.011	0.009	7.47	0.120	0.307	<0.0005	0.298	<0.003
1	7,063	0.001	<0.001	10.1	0.168	0.596	0.0192	1.37	0.0232

Appendix 3. Field measurements and major ion concentrations for synoptic water samples, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.

[Source, 0=stream, 1=inflow; Distance, distance downstream from injection site; Temp, water temperature, in degrees Celsius; pH, in standard units; SC, specific conductance, in microsiemens per centimeter at 25 degrees Celsius; Alkalinity, in milligrams per liter calcium carbonate; all major ion concentrations in milligrams per liter, method detection limits in milligrams per liter listed in parentheses below constituent names; --, not measured]

Source	Distance (meters)	Sample Time	Temp	pH	SC	Calcium (0.20)	Magnesium (0.001)	Sodium (0.20)	Chloride (0.30)	Sulfate (0.09)	Alkalinity
0	160	1815	9.5	7.55	203	35.9	2.44	2.53	2.24	78.6	21.8
0	310	1755	10.0	7.50	228	35.4	2.47	2.30	2.20	79.7	--
0	595	1735	11.0	7.40	230	36.0	2.45	2.53	2.23	78.4	23.0
0	905	1710	11.8	7.46	229	35.3	2.40	2.48	2.17	78.5	21.4
0	955	1701	12.0	7.63	232	36.3	2.41	10.2	2.18	81.5	23.3
0	1,059	1645	12.0	7.65	244	37.6	2.62	2.15	2.41	89.6	0.00
0	1,135	1630	12.5	7.69	229	36.9	2.52	2.32	1.53	71.8	29.0
0	1,270	1615	--	7.64	235	36.4	2.48	2.29	1.68	73.2	32.8
0	1,510	1610	--	7.60	234	36.5	2.47	2.31	1.61	73.0	30.4
0	1,725	1555	--	7.58	235	37.6	2.56	2.31	1.69	77.4	28.0
0	2,110	1525	--	7.68	235	36.6	2.49	2.79	1.52	78.2	28.1
0	2,515	1450	--	7.55	237	37.6	2.54	2.21	1.61	77.6	--
0	2,572	1442	--	7.53	240	36.6	2.47	2.13	1.60	77.7	27.8
0	2,800	1430	12.5	7.73	239	37.7	2.64	2.32	1.60	78.5	29.7
0	3,040	1420	12.5	7.78	238	36.6	2.52	2.12	1.58	80.4	29.9
0	3,295	1410	--	7.84	237	37.8	2.62	2.24	1.63	77.2	38.4
0	3,555	1405	11.5	7.78	238	37.8	2.58	3.22	1.72	78.0	29.8
0	4,023	1335	--	7.73	237	37.7	2.61	2.19	1.86	69.9	28.2
0	4,166	1320	--	7.75	238	38.8	2.65	2.93	1.69	78.8	22.7
0	4,310	1300	9.5	7.72	232	36.9	2.46	2.56	1.57	74.6	--
0	4,473	1240	9.0	7.68	232	36.4	2.48	2.15	1.60	75.0	29.6
0	4,581	1200	8.0	7.36	232	36.8	2.56	3.30	1.70	73.1	31.1
0	4,656	1150	--	7.71	234	37.8	2.52	2.32	1.62	75.7	2.62
0	4,816	1145	8.0	7.70	233	37.6	2.56	2.15	1.63	63.5	23.7
0	4,916	1125	8.0	7.61	236	38.4	2.52	2.18	1.59	78.0	30.2
0	5,131	1115	7.5	7.62	231	37.7	2.58	2.11	1.54	75.2	26.4
0	5,306	1100	7.5	7.55	237	39.5	2.58	3.48	1.58	77.2	32.8
0	5,536	1040	7.0	7.50	239	39.6	2.64	3.64	1.60	79.2	31.9
0	5,756	1030	7.0	7.42	239	38.8	2.61	3.50	1.54	80.2	31.9
0	6,038	1018	7.0	7.57	239	37.4	2.49	2.18	1.54	79.7	26.2
0	6,288	1005	7.0	7.49	244	38.8	2.61	4.78	1.56	81.9	33.1
0	6,528	1000	7.0	7.66	245	39.3	2.60	2.11	1.58	71.3	29.8
0	6,768	948	7.0	7.65	244	39.3	2.59	2.20	1.57	79.7	26.0
0	7,008	938	7.0	7.69	243	39.2	2.62	2.34	1.63	80.6	30.0
0	7,283	925	7.0	7.64	243	37.6	2.52	2.10	1.60	80.7	32.7
0	7,523	915	7.0	7.63	243	39.2	2.61	4.60	1.69	83.7	32.9
0	7,858	900	7.0	7.63	250	39.4	2.57	1.91	1.64	83.2	35.0
1	181	1805	18.0	6.92	443	70.4	10.6	2.10	26.9	212	3.73
1	213	1800	12.5	7.53	134	24.5	0.93	2.21	0.17	39.8	29.6
1	315	1750	6.5	7.59	183	30.5	1.59	2.32	0.34	38.9	44.6
1	745	1730	9.5	7.63	245	41.8	1.62	2.32	0.36	75.3	33.8
1	795	1725	12.0	7.36	--	--	--	1.59	78.0	21.1	--
1	910	1710	9.0	7.65	482	99.6	2.60	2.42	0.58	243	54.4
1	965	1700	18.0	6.88	839	171	7.55	1.25	7.86	549	22.9
1	1,075	1645	--	8.04	211	37.9	2.47	2.42	0.32	53.6	44.4
1	1,150	1620	9.5	8.12	259	44.6	2.10	2.35	0.23	74.1	52.8
1	1,605	1605	11.0	6.98	456	107	7.33	4.79	0.40	256	22.4
1	1,648	1605	9.5	6.74	297	52.9	2.69	2.35	8.31	116	31.5
1	1,665	1600	9.5	6.80	267	--	--	--	1.76	80.5	29.1
1	1,745	1550	11.0	7.89	191	30.4	1.85	1.86	0.94	51.1	40.7
1	2,050	1535	8.5	7.23	194	31.4	1.94	2.38	1.40	48.7	34.6
1	2,125	1520	11.0	4.76	354	67.8	5.87	4.65	0.39	222	0.00
1	2,360	1510	11.0	6.43	246	34.1	3.91	3.30	0.56	105	4.34
1	2,361	1510	9.5	7.30	177	24.4	2.80	2.43	0.37	62.9	24.1
1	2,425	1500	10.0	7.15	152	21.3	2.14	2.29	0.33	47.5	29.0

Appendix 3.   Field measurements and major ion concentrations for synoptic water samples, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.—Continued

[Source, 0=stream, 1=inflow; Distance, distance downstream from injection site; Temp, water temperature, in degrees Celsius; pH, in standard units; SC, specific conductance, in microsiemens per centimeter at 25 degrees Celsius; Alkalinity, in milligrams per liter calcium carbonate; all major ion concentrations in milligrams per liter, method detection limits in milligrams per liter listed in parentheses below constituent names; --, not measured]

Source	Distance (meters)	Sample Time	Temp	pH	SC	Calcium (0.20)	Magnesium (0.001)	Sodium (0.20)	Chloride (0.30)	Sulfate (0.09)	Alkalinity
1	2,522	1445	9.0	6.10	383	64.2	6.38	2.21	0.42	224	3.08
1	2,605	1440	14.5	7.92	291	--	--	--	1.63	77.2	63.1
1	2,709	1430	14.0	7.92	315	--	--	--	1.58	80.4	66.6
1	3,235	1415	12.5	8.20	276	46.9	2.75	2.24	1.28	56.4	78.5
1	3,682	1400	15.5	8.14	245	40.8	2.53	2.41	2.17	49.1	64.2
1	3,820	1350	13.0	7.93	240	38.3	3.06	2.24	2.54	48.0	64.5
1	4,033	1325	9.5	8.17	295	53.4	3.59	2.34	2.39	65.3	72.8
1	4,186	1310	--	7.92	184	32.1	1.68	9.31	0.23	43.9	41.6
1	4,190	1305	6.5	7.77	187	32.2	1.65	2.39	0.31	40.8	32.4
1	4,334	1255	--	7.75	187	30.8	1.62	2.54	0.23	45.0	40.8
1	4,353	1245	12.0	4.17	1,543	192	35.3	1.20	26.0	1,053	0.00
1	4,533	1225	14.5	4.90	1,929	205	31.4	6.83	8.85	1,353	0.00
1	4,586	1200	10.5	4.89	710	114	14.4	5.28	1.96	442	0.00
1	4,886	1135	12.5	5.92	1,824	344	24.7	6.65	2.49	1,408	18.0
1	4,951	1120	8.5	7.53	126	21.1	1.07	2.25	0.18	30.8	27.1
1	4,970	1125	9.5	6.04	478	78.7	5.78	5.23	0.85	249	10.8
1	5,161	1110	9.5	7.47	687	137	3.00	7.26	0.33	364	44.6
1	5,221	1107	8.0	7.52	673	135	3.04	2.43	0.51	360	50.0
1	5,355	1055	7.0	6.95	80	12.8	0.81	2.44	0.18	15.5	30.3
1	5,356	1055	11.0	5.14	691	230	17.9	1.01	1.01	1,378	0.00
1	5,446	1045	7.0	6.72	75	12.1	0.81	1.88	0.26	12.8	23.1
1	5,766	1045	8.0	7.80	236	40.8	2.77	2.24	0.47	55.2	59.9
1	5,858	1025	11.0	5.67	242	226	12.7	1.25	1.74	861	8.85
1	6,105	1010	6.5	7.03	120	18.5	1.41	2.34	0.32	31.3	21.9
1	7,103	935	9.0	7.61	272	46.4	3.13	4.45	0.42	89.1	44.8
1	7,163	935	6.0	7.66	123	19.3	1.50	2.27	0.22	30.8	26.4
1	7,483	915	7.5	7.64	129	19.6	1.54	1.20	0.30	33.5	26.8
1	7,688	905	10.5	7.14	1,522	307	14.2	1.22	5.64	1,103	35.2

Appendix 4. Inductively coupled plasma-atomic emissions spectrometry (ICP-AES) results for synoptic water samples, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.

[Source, 0=stream, 1=inflow; Distance, distance downstream from injection site; Silica as SiO2; all concentrations in milligrams per liter; method detection limits in milligrams per liter listed in parentheses below constituent names; <, constituent not detected; E, estimated concentration less than method detection limit; --, not measured]

Source	Distance (meters)	Aluminum, dissolved (0.01)	Aluminum colloidal (0.01)	Barium, dissolved (0.002)	Cadmium, dissolved (0.001)	Copper, dissolved (0.002)	Copper, colloidal (0.002)	Iron, dissolved (0.003)	Iron, colloidal (0.003)
0	160	0.006E	0.083	0.0208	0.0018	0.0038	0.0020E	0.002E	0.030
0	310	0.031	0.036	0.0207	0.0014	0.0028	0.0006E	0.006	0.032
0	595	0.009E	0.001E	0.0205	0.0018	0.0036	<0.002	<0.003	<0.003
0	905	0.036	0.026	0.0203	0.0013	0.0019E	<0.002	0.016	0.015
0	955	0.005E	0.057	0.0198	0.0018	0.0027	0.0012E	0.007	0.026
0	1,059	0.017	0.039	0.0200	0.0012	0.0012E	0.0031	0.130	0.304
0	1,135	0.015	0.040	0.0304	0.0012	0.0020E	0.0021	0.084	0.389
0	1,270	0.011	0.051	0.0276	0.0013	0.0020E	0.0014E	0.016	0.455
0	1,510	0.012	0.062	0.0277	0.0012	0.0020E	0.0012E	0.076	0.375
0	1,725	0.010E	0.064	0.0278	0.0018	<0.002	0.0025	0.036	0.412
0	1,925	0.011	0.051	0.0272	0.0013	<0.002	0.0029	0.023	0.428
0	1,925	0.022	0.036	0.0267	0.0011	0.0011E	0.0028	0.037	0.419
0	2,110	0.025	0.042	0.0269	0.0012	0.0011E	0.0023	0.012	0.443
0	2,515	0.024	0.065	0.0268	0.0014	0.0017E	0.0020E	0.017	0.460
0	2,572	0.033	0.033	0.0261	0.0018	<0.002	0.0035	0.009	0.445
0	2,800	0.022	0.070	0.0275	0.0012	<0.002	0.0030	0.005	0.436
0	3,040	0.035	0.039	0.0255	0.0016	0.0011E	0.0029	0.010	0.431
0	3,295	0.035	0.048	0.0268	<0.001	0.0013E	0.0025	0.013	0.434
0	3,555	0.017	0.069	0.0265	0.0017	0.0017E	0.0027	0.014	0.424
0	4,023	0.038	0.075	0.0260	0.0012	<0.002	0.0016E	0.009	0.464
0	4,166	0.023	0.087	0.0272	0.0014	0.0017E	0.0022	0.009	0.468
0	4,310	0.027	0.069	0.0262	0.0017	0.0035	0.0050	0.163	0.233
0	4,473	0.009E	0.098	0.0257	0.0016	<0.002	0.0041	<0.003	0.457
0	4,581	0.017	0.102	0.0264	0.0020	0.0018E	0.0020E	0.005	0.446
0	4,656	0.039	0.057	0.0262	0.0012	0.0010E	0.0030	0.009	0.457
0	4,816	0.049	0.092	0.0260	0.0013	<0.002	0.0021	0.004	0.493
0	4,916	0.041	0.065	0.0263	0.0011	<0.002	0.0034	0.007	0.482
0	5,131	0.021	0.079	0.0267	0.0015	0.0015E	0.0024	0.018	0.445
0	5,306	0.041	0.072	0.0264	0.0018	<0.002	0.0037	0.015	0.421
0	5,536	0.052	0.095	0.0265	0.0011	<0.002	0.0027	0.004	0.460
0	5,756	0.021	0.109	0.0261	0.0015	0.0019E	0.0038	0.018	0.457
0	6,038	0.040	0.070	0.0244	0.0015	0.0019E	0.0028	0.014	0.406
0	6,288	0.041	0.083	0.0261	0.0016	0.0028	0.0034	0.010	0.409
0	6,528	0.054	0.071	0.0253	0.0018	<0.002	0.0057	0.012	0.425
0	6,768	0.055	0.056	0.0260	0.0015	<0.002	0.0049	0.002E	0.406
0	7,008	0.043	0.079	0.0261	0.0021	0.0027	0.0021	0.013	0.406
0	7,283	0.034	0.106	0.0247	0.0015	0.0021	0.0028	0.009	0.414
0	7,523	0.041	0.101	0.0260	0.0017	0.0020E	0.0020E	0.011	0.419
0	7,858	0.058	0.081	0.0249	0.0017	<0.002	0.0047	0.003E	0.423

Appendix 4. Inductively coupled plasma-atomic emissions spectrometry (ICP-AES) results for synoptic water samples, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.—Continued

[Source, 0=stream, 1=inflow; Distance, distance downstream from injection site; Silica as SiO2; all concentrations in milligrams per liter; method detection limits in milligrams per liter listed in parentheses below constituent names; <, constituent not detected; E, estimated concentration less than method detection limit; --, not measured]

Source	Distance (meters)	Aluminum, dissolved (0.01)	Aluminum colloidal (0.01)	Barium, dissolved (0.002)	Cadmium, dissolved (0.001)	Copper, dissolved (0.002)	Copper, colloidal (0.002)	Iron, dissolved (0.003)	Iron, colloidal (0.003)
1	181	0.060	0.698	0.0211	0.0045	0.0022	0.0149	0.154	0.925
1	213	0.018	0.003E	0.0057	<0.001	0.0022	0.0020E	0.021	0.054
1	315	<0.01	0.003E	0.0039	0.0011	0.0011E	0.0012E	0.003	0.007
1	745	0.006E	0.014	0.0042	<0.001	<0.002	0.0006E	0.010	0.024
1	910	0.002E	0.079	0.0032	0.0013	<0.002	<0.002	0.011	0.074
1	965	0.012	0.329	0.0286	0.0038	0.0013E	0.0070	1.202	12.382
1	1,075	0.017	0.026	0.0508	<0.001	0.0017E	<0.002	0.008	0.038
1	1,150	0.013	0.011	0.0023	<0.001	<0.002	<0.002	0.008	0.011
1	1,605	0.051	0.010E	0.0111	0.0031	<0.002	<0.002	1.172	0.732
1	1,648	0.002E	0.016	0.0108	0.0122	0.0355	0.0068	<0.003	0.006
1	1,745	0.007E	3.975	0.0029	<0.001	<0.002	0.0092	0.004	3.775
1	2,050	0.002E	0.001E	0.0031	<0.001	<0.002	<0.002	0.001E	<0.003
1	2,125	1.323	0.001E	0.0111	<0.001	0.0109	0.0070	0.556	0.036
1	2,360	0.329	--	0.0140	0.0040	0.0180	--	0.222	--
1	2,361	0.060	0.064	0.0106	0.0018	<0.002	<0.002	0.011	<0.003
1	2,425	<0.01	0.031	0.0131	<0.001	<0.002	<0.002	0.007	0.048
1	2,522	0.565	0.454	0.0101	0.0035	<0.002	0.0008E	<0.003	1.016
1	3.235	<0.01	0.190	0.0035	<0.001	<0.002	<0.002	<0.003	0.225
1	3,682	0.035	0.001E	0.0071	<0.001	<0.002	<0.002	0.006	<0.003
1	3,820	0.020	1.392	0.0080	0.0021	0.0039	0.0056	<0.003	1.54
1	4,033	0.022	0.071	0.0068	0.001E	<0.002	<0.002	<0.003	0.119
1	4,186	0.021	0.020	0.0254	0.0016	0.0034	<0.002	<0.003	0.006
1	4,190	0.016	0.004E	0.0315	0.0021	0.0043	0.0012E	0.002E	0.011
1	4,334	0.026	0.001E	0.0304	0.0025	0.0075	<0.002	0.008	<0.003
1	4,353	23.5	11.695	0.0153	0.610	5.20	0.0604	0.044	9.81
1	4,533	9.76	0.403	0.0162	0.188	0.358	0.0677	0.552	0.170
1	4,586	2.43	0.524	0.0190	0.0370	0.203	0.0454	0.309	0.776
1	4,886	0.394	0.001E	0.0209	0.0458	0.0238	<0.002	0.013	0.006
1	4,951	0.046	0.001E	0.0077	<0.001	<0.002	0.0020E	<0.003	0.009
1	4,970	0.145	0.001E	0.0088	0.0131	0.0381	0.0040	<0.003	0.025
1	5,161	0.004E	0.018	0.0257	0.0021	<0.002	0.0010E	<0.003	0.026
1	5,221	0.030	0.001E	0.0251	0.0029	<0.002	<0.002	0.010	0.025
1	5,355	0.046	0.023	0.0151	<0.001	<0.002	<0.002	0.011	0.050
1	5,356	20.0	0.001E	0.0193	0.1244	2.42	<0.002	0.023	0.084
1	5,446	0.037	0.200	0.0133	<0.001	<0.002	<0.002	0.013	0.523
1	5,766	0.055	0.226	0.0052	0.0013	0.0018E	0.0069	0.002E	0.388
1	5,858	1.74	0.892	0.0156	0.0555	0.248	0.0460	0.020	0.957
1	6,105	0.015	0.015	0.0080	<0.001	<0.002	<0.002	0.009	0.013
1	7,103	<0.01	0.035	0.0299	0.0017	<0.002	0.0017E	0.022	0.112
1	7,163	0.025	0.032	0.0257	0.0017	0.0029	0.0010E	0.017	0.135
1	7,483	0.015	--	0.0290	0.0020	0.0020E	--	0.009	--
1	7,688	0.067	0.170	0.0306	0.0144	0.0040	0.0107	1.12	0.772

Appendix 4. Inductively couple plasma-atomic emissions spectrometry (ICP-AES) results for synoptic water samples, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.—Continued

[Source, 0=stream, 1=inflow; Distance, distance downstream from injection site; Silica as SiO2; all concentrations in milligrams per liter; method detection limits in milligrams per liter listed in parentheses below constituent names; <, constituent not detected; E, concentration estimated less than method detection limit; --, not measured]

Source	Distance (meters)	Manganese, dissolved (0.001)	Manganese, colloidal (0.001)	Silica, dissolved (0.009)	Silica, colloidal (0.009)	Strontium, dissolved (0.0005)	Strontium, colloidal (0.0005)	Zinc, dissolved (0.003)	Zinc, colloidal (0.003)
0	160	0.134	0.0010E	6.56	<0.009	0.354	<0.0005	0.291	<0.003
0	310	0.131	0.0060	6.38	0.205	0.348	0.3562	0.278	0.0158
0	595	0.135	<0.001	6.55	<0.009	0.352	--	0.288	<0.003
0	905	0.124	<0.001	6.23	0.778	0.353	<0.0005	0.274	0.0079
0	955	0.125	0.0005E	6.35	0.158	0.363	0.366	0.266	0.0062
0	1,059	0.585	<0.001	6.67	<0.009	0.370	0.3700	0.369	0.0298
0	1,135	0.442	0.0020	6.20	0.052	0.371	0.371	0.265	0.0276
0	1,270	0.458	0.0076	6.08	0.163	0.371	0.375	0.261	0.0436
0	1,510	0.446	0.0040	6.06	0.255	0.371	0.376	0.258	0.0444
0	1,725	0.446	0.0040	6.27	<0.009	0.385	0.374	0.266	0.0379
0	1,925	0.444	<0.001	6.30	<0.009	0.380	0.375	0.266	0.0345
0	1,925	0.437	0.0115	5.90	0.377	0.367	0.383	0.252	0.0556
0	2,110	0.446	<0.001	6.16	0.235	0.373	0.375	0.258	0.0492
0	2,515	0.459	0.0157	6.63	0.335	0.381	0.387	0.273	0.0558
0	2,572	0.410	0.0301	5.96	0.705	0.374	0.383	0.242	0.0620
0	2,800	0.435	0.0034	6.62	<0.009	0.386	0.380	0.262	0.0410
0	3,040	0.403	0.0338	6.26	0.254	0.364	0.385	0.235	0.0642
0	3,295	0.433	0.0146	6.60	0.200	0.382	0.381	0.265	0.0443
0	3,555	0.454	<0.001	6.68	0.178	0.384	0.383	0.285	0.0139
0	4,023	0.431	0.0193	6.52	0.467	0.379	0.385	0.263	0.0586
0	4,166	0.453	<0.001	6.76	<0.009	0.389	0.387	0.296	0.0268
0	4,310	0.407	<0.001	6.25	0.732	0.390	<0.0005	0.278	<0.003
0	4,473	0.412	0.0288	6.21	0.622	0.387	0.385	0.281	0.0635
0	4,581	0.497	<0.001	6.54	0.034	0.388	0.384	0.311	0.0223
0	4,656	0.499	0.0030	6.42	0.080	0.389	0.382	0.317	0.0402
0	4,816	0.497	0.0252	6.26	0.446	0.387	0.392	0.323	0.0555
0	4,916	0.576	0.0220	6.23	0.376	0.392	0.395	0.352	0.0437
0	5,131	0.601	0.0501	5.94	0.593	0.397	0.395	0.341	0.0569
0	5,306	0.693	<0.001	6.69	<0.009	0.409	0.388	0.386	0.0152
0	5,536	0.787	<0.001	6.58	0.091	0.412	0.401	0.404	0.0371
0	5,756	0.786	<0.001	6.52	0.456	0.407	0.402	0.379	0.0685
0	6,038	0.737	0.0224	6.39	0.260	0.387	0.399	0.370	0.0498
0	6,288	1.10	<0.001	6.67	<0.009	0.410	0.407	0.448	0.0217
0	6,528	1.05	0.0339	6.35	0.441	0.400	0.407	0.428	0.0550
0	6,768	0.972	0.0184	6.38	0.231	0.399	0.400	0.418	0.0375
0	7,008	1.02	0.0020	6.60	0.354	0.410	0.407	0.436	0.0427
0	7,283	0.962	0.0515	6.10	0.707	0.389	0.409	0.386	0.0735
0	7,523	1.01	<0.001	6.36	0.262	0.410	0.398	0.420	0.0398

Appendix 4. Inductively couple plasma-atomic emissions spectrometry (ICP-AES) results for synoptic water samples, upper Animas River, Howardsville to Silverton, Colorado, September 14, 1997.—Continued

[Source, 0=stream, 1=inflow; Distance, distance downstream from injection site; Silica as SiO2; all concentrations in milligrams per liter; method detection limits in milligrams per liter listed in parentheses below constituent names; <, constituent not detected; E, concentration estimated less than method detection limit; --, not measured]

Source	Distance (meters)	Manganese, dissolved (0.001)	Manganese, colloidal (0.001)	Silica, dissolved (0.009)	Silica, colloidal (0.009)	Strontium, dissolved (0.0005)	Strontium, colloidal (0.0005)	Zinc, dissolved (0.003)	Zinc, colloidal (0.003)
0	7,858	1.08	0.0584	6.33	0.478	0.403	0.421	0.426	0.0591
1	181	1.27	0.0583	21.9	1.29	0.652	0.645	0.645	0.0424
1	213	0.092	0.0183	4.29	<0.009	0.278	0.275	0.094	0.0033
1	315	0.003	0.0029	7.24	0.101	0.303	0.305	0.0411	0.0062
1	745	0.030	0.0022	7.79	0.075	0.472	0.474	0.0142	0.0017E
1	910	0.011	<0.001	12.8	0.551	1.49	1.55	0.0161	<0.003
1	965	15.9	0.5434	6.83	3.43	0.592	0.591	2.53	2.37
1	1,075	0.007	<0.001	5.51	<0.009	0.399	0.369	0.0267	<0.003
1	1,150	<0.001	0.0013	6.11	0.259	0.622	0.619	0.0106	0.0017E
1	1,605	1.12	<0.001	26.4	<0.009	0.992	0.792	0.476	<0.003
1	1,648	<0.001	<0.001	9.99	0.131	0.653	0.656	1.54	0.0173
1	1,745	0.003	0.1647	7.80	16.8	0.332	0.351	0.0040	0.0446
1	2,050	0.0010E	<0.001	7.63	<0.009	0.332	--	0.0043	<0.003
1	2,125	1.04	<0.001	30.9	<0.009	<0.0005	0.551	0.218	<0.003
1	2,360	0.249	--	21.2	--	0.0010	--	0.533	--
1	2,361	0.0181	0.0140	17.9	0.380	0.205	0.0010	0.0293	<0.003
1	2,425	0.0021	0.0066	16.0	<0.009	0.161	0.165	0.0115	0.0024E
1	2,522	0.0072	0.0158	25.1	2.26	0.704	0.711	0.0409	0.0024E
1	3,235	<0.001	0.0117	9.59	0.75	0.488	0.503	0.0056	0.0080
1	3,682	0.0054	<0.001	7.80	<0.009	0.373	--	0.0078	<0.003
1	3,820	0.0556	0.0152	8.12	5.76	0.344	0.353	0.126	<0.003
1	4,033	0.0025	0.0014	9.41	<0.009	0.526	0.488	0.0089	<0.003
1	4,186	0.0018	0.0006E	4.69	<0.009	0.457	0.449	0.138	0.0087
1	4,190	0.0021	<0.001	4.69	<0.009	0.457	0.435	0.199	<0.003
1	4,334	0.218	<0.001	4.53	0.171	0.441	0.447	0.221	<0.003
1	4,353	55.5	2.09	38.5	40.6	1.23	1.24	130	8.15
1	4,533	284	<0.001	33.8	0.292	0.989	0.971	53.2	<0.003
1	4,586	4.70	<0.001	31.0	0.921	0.564	0.557	9.32	<0.003
1	4,886	75.6	<0.001	16.5	0.093	2.04	2.02	19.4	<0.003
1	4,951	0.193	0.0115	3.98	0.092	0.211	0.210	0.0594	0.0109
1	4,970	3.11	<0.001	6.60	<0.009	<0.0005	<0.0005	3.77	<0.003
1	5,161	0.070	0.0007E	13.0	<0.009	1.23	1.21	0.424	0.0167
1	5,221	0.012	<0.001	12.3	0.075	1.16	1.15	0.776	0.0247
1	5,355	0.019	<0.001	5.83	0.279	<0.0005	<0.0005	0.0041	<0.003
1	5,356	<0.001	210	30.5	<0.009	<0.0005	2.08	39.8	<0.003
1	5,446	0.0032	0.131	5.98	1.02	<0.0005	<0.0005	0.0047	0.0098
1	5,766	0.0231	0.0120	10.4	0.532	0.455	0.429	0.0425	0.0181
1	5,858	34.4	0.960	24.6	4.18	2.13	2.19	12.7	0.6015
1	6,105	0.0012	0.0017	8.09	0.213	<0.0005	<0.0005	0.0239	0.0019E
1	7,103	0.940	<0.001	11.5	<0.009	<0.0005	<0.0005	0.0835	0.0037
1	7,163	0.0510	0.0094	4.86	0.226	<0.0005	<0.0005	0.2087	0.0240
1	7,483	0.0070	--	4.92	--	0.0010	--	0.395	--
1	7,688	39.7	1.07	15.5	0.087	3.75	3.79	2.08	0.0142