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U.S. GEOLOGICAL SURVEY

**Determination of Chemical-Constituent Loads
During Base-Flow and Storm-Runoff Conditions Near
Historical Mines in Prospect Gulch, Upper Animas River
Watershed, Southwestern Colorado**

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CONVERSION FACTORS AND ABBREVIATED UNITS

<u>Multiply</u>	<u>By</u>	<u>To obtain</u>
Millimeter (mm)	25.4	inch (in)
Meter (m)	3.281	foot (ft)
Meter (m)	0.001	millimeter (mm)
Kilometer (km)	0.6214	mile (mi)
Cubic meter per second (m ³ /s)	35.31	cubic foot per second (ft ³ /s)
Gram (g)	0.002205	pound (lb)
Kilogram (kg)	2.205	pound (lb)
Liter (L)	0.0001	milliliter (ml)
Millimeter per minute (ml/min)		
Million years ago (Ma)		
MicroSiemens per centimeter at 25 degrees Celsius (μS/cm)		
Milligrams per liter (mg/L)		
Parts per million (ppm)		
Micron or micrometer (μm)		
Degree Celsius (°C)		

Determination of Chemical-Constituent Loads During Base-Flow and Storm-Runoff Conditions Near Historical Mines in Prospect Gulch, Upper Animas River Watershed, Southwestern Colorado

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Abstract

Prospect Gulch is a major source of iron, aluminum, zinc, and other metals to Cement Creek. Information is needed to prioritize remediation and develop strategies for cleanup of historical abandoned mine sites in Prospect Gulch. Chemical-constituent loads were determined in Prospect Gulch, a high-elevation alpine stream in southwestern Colorado that is affected by natural acid drainage from weathering of hydro-thermally altered igneous rock and acidic metal-laden discharge from historical abandoned mines. The objective of the study was to identify metal sources to Prospect Gulch. A tracer solution was injected into Prospect Gulch during water-quality sampling so that loading of geochemical constituents could be calculated throughout the study reach. A thunderstorm occurred during the tracer study, hence, metal loads were measured for storm-runoff as well as for base flow. Data from different parts of the study reach represents different flow conditions. The beginning of the reach represents background conditions during base flow immediately upstream from the Lark and Henrietta mines (samples PG5 to PG45). Other samples were collected during storm runoff conditions (PG100 to PG291); during the first flush of metal runoff following the onset of rainfall (PG303 to PG504), and samples PG542 to PG700 were collected during low-flow conditions.

During base-flow conditions, the percentage increase in loads for major constituents and trace metals was more than an order of magnitude greater than the corresponding 36 % increase in stream discharge. Within the study reach, the highest percentage increases for dissolved loads were 740 % for iron (Fe), 465 % for aluminum (Al), 500 % for lead (Pb), 380 % for copper (Cu), 100 % for sulfate (SO₄), and 50 % for zinc (Zn). Downstream loads near the mouth of Prospect Gulch often greatly exceeded the loads generated within the study reach but varied by metal species. For example, the study reach accounts for about 6 % of the dissolved-Fe load, 13 % of the dissolved-Al load, and 18 % of the dissolved-Zn load; but probably contributes virtually all of the dissolved Cu and Pb. The greatest downstream gains in dissolved trace-metal loads occurred near waste-rock dumps for the historical mines. The major sources of trace metals to the study reach were related to mining. The major source of trace metals in the reach near the mouth is unknown, however is probably related to weathering of highly altered igneous rocks, although an unknown component of trace metals could be derived from mining sources.

The late-summer storm dramatically increased the loads of most dissolved and total constituents. The effects of the storm were divided into two distinct periods; (1) a first flush of higher metal concentrations that occurred soon after rainfall began and (2) the peak discharge of the storm runoff. The first flush contained the highest loads of dissolved Fe, total and dissolved Zn, Cu, and Cd. The larger concentrations of Fe and sulfate in the first flush were likely derived from iron hydroxide minerals such as jarosite and schwertmanite, which are common on mine dumps in the Prospect Gulch drainage basin. Peak storm runoff contained the highest measured loads of total Fe, and of total and dissolved calcium, magnesium, silica and Al, which were probably derived from weathering of igneous rocks and clay minerals in the drainage basin.

INTRODUCTION

Problem

Prospect Gulch is a major source of iron, aluminum, zinc, and other metals to Cement Creek. Cement Creek, a tributary of the upper Animas River in southwestern Colorado (fig. 1), is known for its cloudy reddish-orange color, high metal content, and acidity. Efforts to improve water quality by reclaiming historical abandoned mine sites have targeted Prospect Gulch for further investigation and remediation. Likely sources of metals in Prospect Gulch from mining activity include flow from mine adits, surface drainage from historical abandoned mine sites, and ground-water seepage through waste-rock dumps. Metals also are derived from natural weathering of highly altered and mineralized volcanic bedrock.

This study was done in cooperation with the Bureau of Land Management (BLM) in order to identify sources of metals in Prospect Gulch. Several historical mines and waste-rock dumps in Prospect Gulch are located on Federal property, and information is needed by BLM to assess the relative importance of different point sources of metals. Information on sources and loading of metals will be used to prioritize remediation and to develop strategies for cleanup of selected sites.

Ground-water and surface water inflows with the highest concentrations of metals are often small in discharge, and hence, do not always produce the largest metal loads. Relying on metal concentrations of solid-phase samples from waste-rock dumps and water-quality samples from adit discharges to prioritize sites for cleanup can be misleading (Nash, 1999). A more diagnostic tool is the tracer-dilution method that can relate the metal loads in a stream to specific drainage areas that generate metals.

Because concentrations and loads of metals can change substantially with temporal and seasonal changes in stream discharge and ground-water inflows, metal loading data are needed over a full range of hydrologic flow regimes. For example, from a biological perspective the steady-state low or base-flow concentrations represent chronic exposure of aquatic organisms to metals, whereas the brief increases in the concentrations of metals during storm runoff can expose biota to short-term but acute levels of toxic metals.

Purpose and Scope

The purpose of this study was to use the tracer-dilution method (Kimball, 1997) to identify and quantify inflows of naturally occurring and mining-related (anthropogenic) metals along an 800-meter reach of Prospect Gulch that includes drainage from the Lark mine, the Henrietta mine, and the Joe and John mine sites (fig. 2). The test was conducted during September, which generally can be expected to have low or base-flow conditions in the absence of rainfall runoff. During the 7-hour tracer injection on

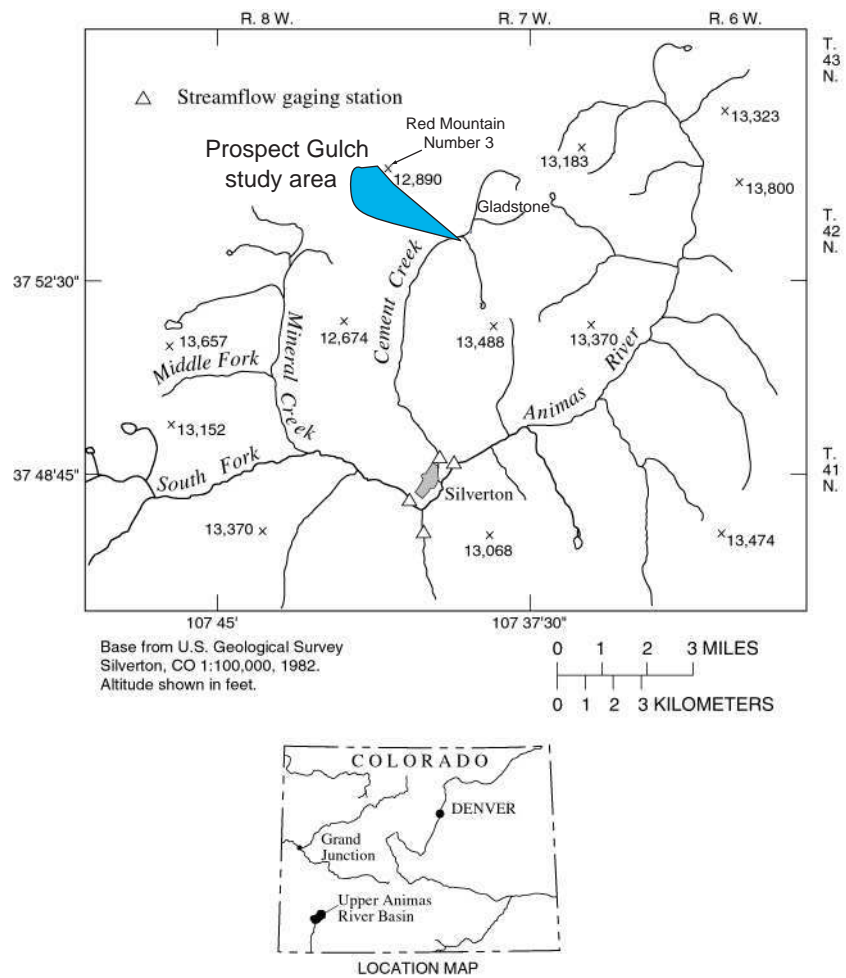


Figure 1. Location of Prospect Gulch study area, Upper Animas River Watershed, Southwestern Colorado.

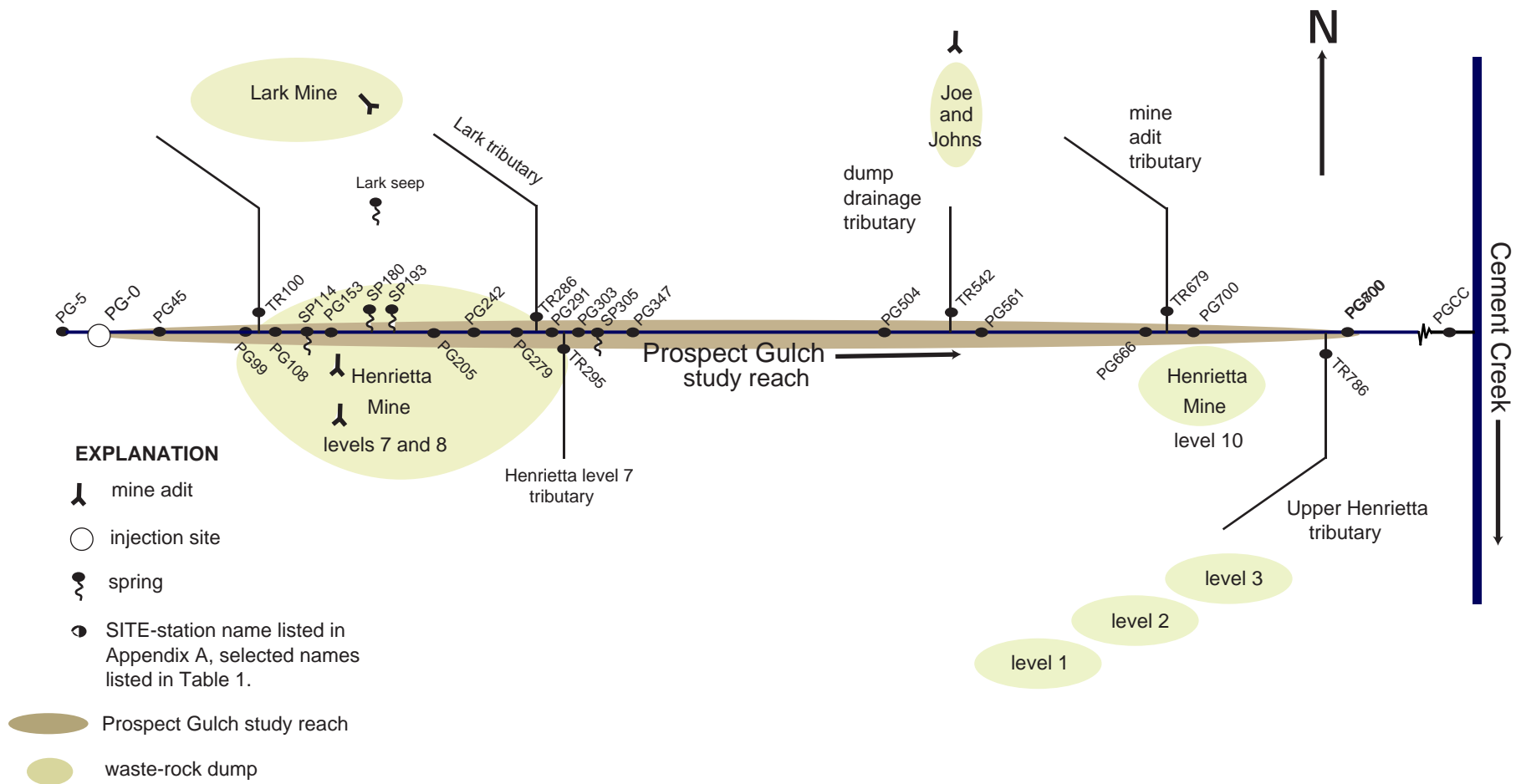


Figure 2. Location of study reach in Prospect Gulch, Upper Animas River Watershed, Southwestern Colorado

September 15, 1998, more than 35 water-quality samples were collected along the study reach and from adjacent springs and tributaries to calculate loads and identify inflows of chemical constituents under base-flow conditions. Because of adverse weather conditions that developed during the sampling period, however, the scope of the study was modified to include loads measured during storm-runoff conditions, as well as during base-flow conditions. Samples collected before and after the storm were used to indicate changes in metal loads with respect to different reaches along Prospect Gulch. Samples collected during the rainstorm indicate how metal loads change over the duration of a thunderstorm.

Starting under base-flow conditions, a sodium-chloride tracer solution was injected into Prospect Gulch. Concurrent synoptic water-quality sampling determined loading of geochemical constituents throughout the study reach. Because of the changes in discharge caused by the storm runoff, many of the samples collected could not be used to estimate detailed changes in base-flow loads of chemical constituents relative to specific historical mine sites. Enough data were collected during base-flow conditions, and before and after the storm, however, to indicate changes in metal loads (1) between the beginning and end of the study reach, and (2) between the end of the study reach and the mouth of Prospect Gulch above Cement Creek (site PGCC in [fig. 2](#)). Additional tracer work is planned for high-flow conditions during the summer of 1999.

The storm loads yielded valuable information about temporal changes in metal loads during storm runoff. In particular, the storm data indicate differences in the timing and magnitude of major-element and trace-metal loads throughout the hydrograph that is evidence of the dissolution of primary and secondary minerals in the drainage. Together, the base-flow and storm-runoff data indicate how metal loads change in time and space over the full range of hydrologic conditions likely to occur in an alpine stream on a rainy late-summer day.

Physical setting

Prospect Gulch is a steep-gradient mountain stream that drains the southern flank of Red Mountain No. 3 (elevation 3,930 m or 12,890 ft), shown in [fig. 1](#). The stream is approximately 1.5 mi in length and joins Cement Creek one mile downstream of Gladstone. Cement Creek is a tributary of the Animas River in the San Juan Mountains of southwestern Colorado. Much of the Prospect Gulch drainage basin is above the tree line at about 3,536 m (11,600 ft). Non-forested areas consist of exposed bedrock or alpine vegetation on poorly developed soils. Average annual precipitation is about 114 cm (45 in) with 94 cm (37 in) occurring as snowfall (Sunnyside Gold Corporation, written commun., 1996, as cited in Herron and others, 1998).

The study area ([fig. 2](#)) is the reach of Prospect Gulch that begins just above the access road between the Henrietta mine (levels 7 and 8) and the Lark mine. There are portals into at least six levels of the Henrietta mine, including the 1, 2, 3, 7, 8, and 10 levels. In general, the portals or levels are approximately 100 ft apart in elevation. The names of levels used in this report are consistent with terms used by Herron and others (1998). Other notable historical mines within the Prospect Gulch drainage basin include

the Hercules mine and the Galena mine (located above the study reach); and the Joe and John mine (which is north of the study reach and east of the Lark mine).

The Prospect Gulch study reach begins just upstream from where the creek flows through a culvert under the access road from the Lark mine to the Henrietta mine levels 7 and 8 (designated as sampling site PG-0 on [fig. 2](#)). The study reach extends 800 m downstream from the tracer-injection site (PG-0) to a point (PG800) that is downstream from the waste-rock dump for Henrietta mine level 10. The streambed drops about 100 m (320 ft) in elevation over the length of the reach. The Lark, the Henrietta, and the Joe and John mine sites are all immediately adjacent or within about 250 ft of Prospect Gulch and its ephemeral tributaries.

The Galena and Hercules mines are adjacent to the creek in the watershed immediately upstream from the study reach. Between the upstream mines and the study reach, Prospect Gulch flows through a narrow bedrock channel, characterized by a series of small waterfalls. In this area, about 60 m upstream from site PG-0 at creek level, is a lens-like body of massive fine-grained pyrite, which is known to contain anomalous metal concentrations and could be a potential inflow of metals. Thus, although water entering the study reach has traveled through an area disturbed by mining, there are also naturally occurring metals present. This study does not attempt to determine the relative contributions of dissolved metals upstream from the study reach. Trace metals in stream flow at the upstream end of the study reach are probably derived from a mixture of drainage in contact with land disturbed by mining and natural exposures of hydro-thermally altered rocks. The geology and mineralogy of this area will be discussed in greater detail in the section to follow.

Below site PG-0 within the first 100 m of the study reach, Prospect Gulch flows through a steep run of large rocky talus and mining debris. This area may be the remains of an upper section of the Henrietta waste-rock dump that has been mostly washed away. Under base-flow conditions, a small tributary flows in from the north side at 100 m. The tributary is fed by a series of seeps from a boggy area to the north, upstream from the Lark mine that may be fault or fracture-controlled. The seep emerges near some mining debris and timbers at the upstream north edge of the Henrietta waste-rock dump. For the next 200 m, Prospect Gulch splits the main waste-rock dump from Henrietta mine levels 7 and 8 into two sections that are referred to as the north and south Henrietta waste-rock dumps. Small seeps enter the north side of the stream channel at 114, 180, 193, and 305 m below site PG-0. Large tributaries enter Prospect Gulch from both sides at 286 and 295 m. These tributaries were barely flowing on the day of the reconnaissance, but carried substantial runoff during the storm the next day. The reach from about 310 to 540 m has no springs, no major tributaries, and little evidence of mining activities. Bedrock is exposed in the stream channel near 504 m, and unlike the upper part of the study reach, no indications of ground-water inflow were observed in this area.

The lower part of the study reach includes the Joe and John mine site and the waste-rock dump for Henrietta mine level 10. There are no springs, but there are several important tributaries. A steep ravine that drains the waste-rock dump for the Joe and John

mine enters Prospect Gulch from the north side at 542 m. A second ravine that carries flow from the Joe and John mine adit enters the creek at 679 m. The south bank of Prospect Gulch cuts through the toe of the waste-rock dump for the Henrietta mine level 10 from approximately 685 to 695 m. The creek is narrow and cuts largely through bedrock in this reach. A steep avalanche chute enters Prospect Gulch from the south below the waste-rock dump at 786 m, and is here referred to as the Upper Henrietta tributary. The snow and debris from an avalanche were still present in this tributary at the time of the tracer study. The Upper Henrietta tributary might include some mine drainage from the Henrietta mine levels 1, 2, and 3, although the waste-rock dumps for these workings are considerably smaller than the waste-rock dumps for other mines in the study reach and, therefore, have not been sampled extensively.

Geology and Mineralogy of Prospect Gulch. Prospect Gulch lies within the Silverton caldera, which is described by Burbank and Luedke (1969), Lipman and others (1973 and 1976). Thick sequences of finely porphyritic dacitic-andesitic lavas comprise the dominant lithology within the Silverton caldera (Burbank and Luedke, 1969; Yager and others, 1998). These lavas are generally referred to as the Burns Member of the Silverton Volcanic Series (Lipman and others, 1973; Burbank and Luedke, 1969; Yager and others, 1998). This thick assemblage of lavas largely erupted along ring fracture zones of the earlier collapsed San Juan and Uncompaghe calderas, prior to collapse of the Silverton caldera at 27.6 Ma (Lipman and others, 1976). The volcano-stratigraphic units above the Burns Member vary considerably throughout the Silverton caldera and nomenclature seems to be a source of confusion to many past and present workers. Interbedded volcanoclastic sediments, mudflow breccias, and interbedded lavas are commonly noted to overlie the Burns Member within and around the Silverton caldera, and are commonly referred to as the Henson Member of the Silverton Volcanics (Burbank and Luedke, 1969; Lipman and others, 1973).

Caldera rocks in the Prospect Gulch area consist dominantly of massive andesitic and dacitic flows, flow breccias, and volcanoclastic sediments (Burbank and Luedke, 1969). The northern slopes of Prospect Gulch (fig. 3) encompass the margins of an extensive acid-sulfate hydrothermal system comprised of quartz-alunite \pm pyrophyllite-altered rocks (0.6 mi²), and paragenetically older but related quartz-sericite-pyrite (QSP) alteration (Bove and others, 1998). These altered rocks contain 8-10 volume percent pyrite and as much as 1,100 parts per million (ppm) Cu, 100 ppm molybdenum (Mo), 200 ppm zinc (Zn), 60 ppm Pb, as analyzed by energy dispersive X-ray fluorescence spectroscopy methods of Yager and Quick (1993). Weathering of highly altered rocks is believed to contribute substantially to the low pH and high metal loads in Prospect Gulch (Bove and others, 1998). In contrast, rocks in the southern part of the basin (fig. 3) represent a much weaker regional propylitic (PROP)(chlorite \pm epidote \pm calcite) event that was largely unaffected by a later generation of acid-sulfate altering fluids.

Ore minerals present within the major mines in Prospect Gulch (Lark, Galena Queen, Henrietta, Joe and John) are localized along large (>150 ft wide), mineralized fault structures and spatially associated hydrothermal breccia masses. These brecciated ores are mineralogically similar to the contemporaneous but more famous mineralized



ALTERATION ASSEMBLAGES

- Dickite
- Propylitic
- Quartz-Pyrophyllite-Alunite
- Quartz-Sericite-Pyrite
- Quartz-Alunite
- Silicified
- Weak Sericite

FAULTS

- Approximate
- Certain
- Inferred

% Mine shaft

Figure 3. Map of hydrothermal-alteration assemblages in Prospect Gulch watershed.

breccia deposits (ie. National Belle mine, Guston mine, etc.; Ransome, 1901; Fisher and Leedy, 1973) in the Red Mountain Pass area. Ore minerals may be present and exposed near the surface in ore-storage piles and can also be mixed with waste rock in dumps at the historical mine sites. Flow from mine adits is another possible pathway for water to come in contact with ore minerals. Representative samples obtained from waste-rock and ore dumps from three mines in Prospect Gulch (Galena Queen, Lark, and Henrietta) have been recently studied by petrographic microscope, X-ray diffraction, and electron microbeam. Thin sections from representative samples indicate that major ore minerals consist of pyrite, sphalerite, galena, enargite, and arsenic (As) and zinc (Zn)-rich tetrahedrite, in general decreasing order of abundance (table 1). Gangue and related minerals include alunite, pyrophyllite, quartz, anhydrite, and illite, with minor amounts of barite, diaspore, anglesite, and zunyite (Bove and others, 1998). Drainage from waste-rock piles and mine adits is a large potential source of metals to the Prospect Gulch study reach.

Relation of Prospect Gulch Water Chemistry to Drainage from Non-mined Areas and Areas Disturbed by Mining. Leaching of ore and gangue minerals and dissolution of natural and mine-related soluble salts contribute substantially to the stream metal loads within the Prospect Gulch drainage basin (Bove and others, 1998). Areas up-gradient from mining activity, such as the large zone of quartz-alunite-altered breccia on the north side of Prospect Gulch (fig. 3), are among the most naturally degraded waters in this area. These natural waters have been measured with pH as low as 3.3 and Ficklin Metal (FM) sum (Cu + Zn + Pb + Ni + Co + Cd) in micrograms per liter ($\mu\text{g/L}$) as high as 285 (Bove and others, 1998). In contrast, waters draining the weak sericitic/propylitic margins (fig. 3) of the acid-sulfate system are less degraded, with pH values from 3.4 to 3.8 and FM sums $< 10 \text{ mg/L}$. Waters influenced by propylitized rocks (mostly on the south side of basin) have the best water quality, on the basis of pH values > 6.0 and FM sums $< 70 \text{ mg/L}$. Recent studies (Bove and others, 1998) indicate that calcite within these propylitically-altered rocks buffer sulfate-rich waters that interacted with local acid-sulfate and sulfide-rich vein/breccia structures. In contrast, very little buffering occurs on the north side of the basin, where extreme acid-leaching by fluids left these rocks with inconsequential amounts of buffering material such as calcite (Bove and others, 1998). Mine-impacted waters in Prospect Gulch (which include mine adits and waters draining waste-rock dumps) had higher FM sums than their natural counterparts with a median pH value of 3.2 and FM sum of $4,300 \mu\text{g/L}$. On the basis of trace metals data on September 15, 1998 in appendix A, the FM sum at the beginning of the study reach (PG45) was $1,310 \mu\text{g/L}$. The FM sum at the end of the study reach (PG800) was $2,000 \mu\text{g/L}$. Near the mouth of Prospect Gulch (PGCC) the FM sum was $1,330 \mu\text{g/L}$.

Table 1. Electron microbeam analyses of ore minerals from Lark and Galena Queen waste dumps.

[Note: Sphalerite and tetrahedrite-tennantite were present in Lark ores; * in totals likely indicates Ag or Te, which were not analyzed; however, Ag was detected by energy dispersive spectroscopy; ND, not detected]

		Lark Mine Waste Dump Minerals				
Sample ID		LS298D_1_2	LS298D_2A_1	LS298D_1_7	LS298D_1_9	LS298D_2B_2
Mineral		galena	galena	enargite	pyrite	pyrite
	Element					
	Fe	ND	0.47	ND	46.77	45.84
	As	ND	ND	18.59	ND	ND
	S	13.39	13.33	32.11	53.32	53.54
	Sb	ND	ND	0.4	ND	ND
	Co	ND	ND	ND	0.09	0.1
	Cu	ND	ND	47.93	ND	0.53
	Zn	ND	ND	ND	ND	ND
	Pb	86.44	86.37	ND	ND	ND
	Se	ND	ND	ND	ND	ND
	Mn	ND	ND	ND	ND	ND
	Hg	ND	ND	ND	ND	ND
	Cd	ND	ND	ND	ND	ND
	Total	99.97	100.24	100.16	100.24	100.1

		Galena Queen Waste Dump Minerals						
Sample ID		QG398A_1A_1	QG398A_2A_1	QG398A_2A_2	QG398A_3B_8	QG398A_3Ba_15	QG398A_3_2	QG398A_3B_7
Mineral		galena	pyrite	tetrahedrite	tetrahedrite	tetrahedrite	sphalerite	sphalerite
	Element							
	Fe	ND	45.84	0.12	ND	ND	0.08	0.16
	As	ND	0.29	4.57	7.93	8.92	ND	ND
	S	13.39	53.99	26.23	26.47	26.6	32.77	33.33
	Sb	ND	ND	21.76	17.3	15.57	0.08	ND
	Co	ND	0.1	ND	ND	ND	ND	ND
	Cu	ND	ND	35.78	37.99	38.54	ND	0.41
	Zn	ND	ND	6.87	8.14	8.08	66.78	65.44
	Pb	86.12	ND	ND	ND	ND	ND	ND
	Se	ND	ND	ND	ND	ND	ND	ND
	Mn	ND	ND	ND	ND	ND	0.06	ND
	Hg	ND	ND	ND	ND	ND	ND	ND
	Cd	ND	ND	ND	ND	ND	ND	ND
	Total	99.69	100.54	95.51*	97.98*	97.92*	99.8	99.72

METHODS AND SAMPLING PLAN

Theory of Tracer-Dilution Techniques

The volume of flow (referred to as discharge) was calculated at each water-sampling site in Prospect Gulch using the tracer-dilution technique. This technique was chosen because of the difficulty and the error associated with traditional discharge-measurement techniques, such as current meters or flumes, when used in rocky steep-gradient channels. Tracer dilution recently has been applied elsewhere to characterize metal inflows in other mountain stream reaches affected by mine drainage, including St. Kevins Gulch near Leadville (Kimball, 1997), the upper Animas River upstream and downstream from Silverton, and Cement Creek (Kimball and others, 1999; Walton-Day and others, 1999). Discharge in mountain streams can be measured very precisely by adding a salt tracer, such as NaCl, to a stream; measuring the dilution of the tracer with distance downstream; and calculating discharge from the amount of dilution (Kimball, 1997). Ninety-nine percent pure NaCl, obtained locally in a 50-lb sack as salt, was used as the tracer solution because little chloride is present in the surface waters of Prospect Gulch, it is inexpensive and readily available, and has little effect on the stream environment at low concentrations. This technique is best described by the following equation:

$$Q_s = (C_i * Q_i) / (C_b - C_a) \quad (1)$$

where

Q_s = stream discharge, in cubic ft per second;

C_i = tracer concentration in the injection solution, in mg/L;

Q_i = rate of injection to the stream, in cubic ft per second;

C_b = tracer concentration downstream from injection point, in mg/L; and

C_a = tracer concentration upstream from injection point, in mg/L.

The tracer-dilution technique is used to measure base flow when streamflow is constant. However, the technique can be used during fluctuations in stream volume, such as diurnal changes resulting from daily fluctuations in temperature or runoff events from storms, if all tracer-dilution samples are obtained at the same time in a synoptic sampling. Even in streams where the quantity of runoff changes, such as during a storm, the volume of discharge can still be measured quite accurately, although the loads cannot be compared between sites.

Field Sampling Methods

The choice of tracer is generally limited to anions (which tend to stay in solution), such as chloride, bromide, and sulfate, or to organic dyes (Zellweger, 1996). The tracer solution was mixed with stream water to a concentration approaching saturation level the night before the injection. Samples were taken throughout the day of tracer study to

ensure that the concentration of the tracer solution remained constant throughout the study. On the day of the injection, an ion-selective chloride probe was deployed at site PG700 (fig. 4) to track the arrival time of the tracer. The relative potential measured by the probe, measured in millivolts, was corrected by subtracting from a 300 millivolt datum. The chloride probe began logging values at 10:10 a.m. During the deployment of the probe, the injection apparatus was set up above the beginning of the study reach (site PG-5).

The injection apparatus included two high-capacity piston-core pumps driven by an electric motor that was powered by two deep cell marine batteries. Tracer solution (NaCl) was pumped from a reservoir through plastic tubing to a pre-pump filter capsule and then through the pump to the stream. Pumping of the tracer solution started at 9:07 a.m. and continued until 16:00 p.m. the same day. An injection rate of 117 milliliters per minute was maintained throughout the study. The injection rate was measured with a volumetric flask throughout the day to ensure proper pump operation and constant flux.

The tracer first arrived at site PG700 at 10:40 a.m., as monitored by the selective-ion probe. The tracer concentration stopped increasing at approximately 13:00 p.m. (fig. 4), indicating that tracer concentrations had reached a plateau, or steady state. Water sampling was conducted from 12:40 to 15:48 p.m. The injection pump was shut off as soon as sampling was completed. The tracer concentrations at site PG700 to begin to decline after approximately 3 hours (fig. 4). Results from the selective-ion probe were used only for monitoring tracer concentrations in the stream and were not used to calculate discharge because sample analysis is far more accurate for this purpose.

Selection of Sampling Locations

Prior to tracer injection, field reconnaissance was conducted in order to select appropriate tracer-dilution and water-quality sample sites, to estimate stream velocity in the study reach, and to measure discharge at the outflow of the study reach. The locations for tracer-dilution and water-quality samples were selected based on surface-water inflows and the surficial geology of the streambed. Station numbers were assigned according to the distance downstream from PG-0 in meters; for example, PG700 is 700 m downstream from PG-0. Specific conductivity and pH were used as guides when selecting samples sites in reaches where no tributaries were present. Tracer-dilution sites were selected along the main channel of Prospect Gulch, while water-quality samples were collected at the tracer-dilution sample sites as well as at springs and tributaries. All springs and tributaries in the study reach were bracketed in order to obtain discharge values above and below the inflow. Subtraction of discharge at bracketed sites yields a discharge value for the corresponding tributary or spring. The mean stream velocity for the sample reach over the length of the reach is used to estimate tracer arrival time. The arrival time dictates when synoptic sampling can begin. Discharge at the lowest site (PGCC) was measured with standard flow-metering equipment. This discharge was used to calculate the concentration of tracer solution needed in order to be detected in the stream.

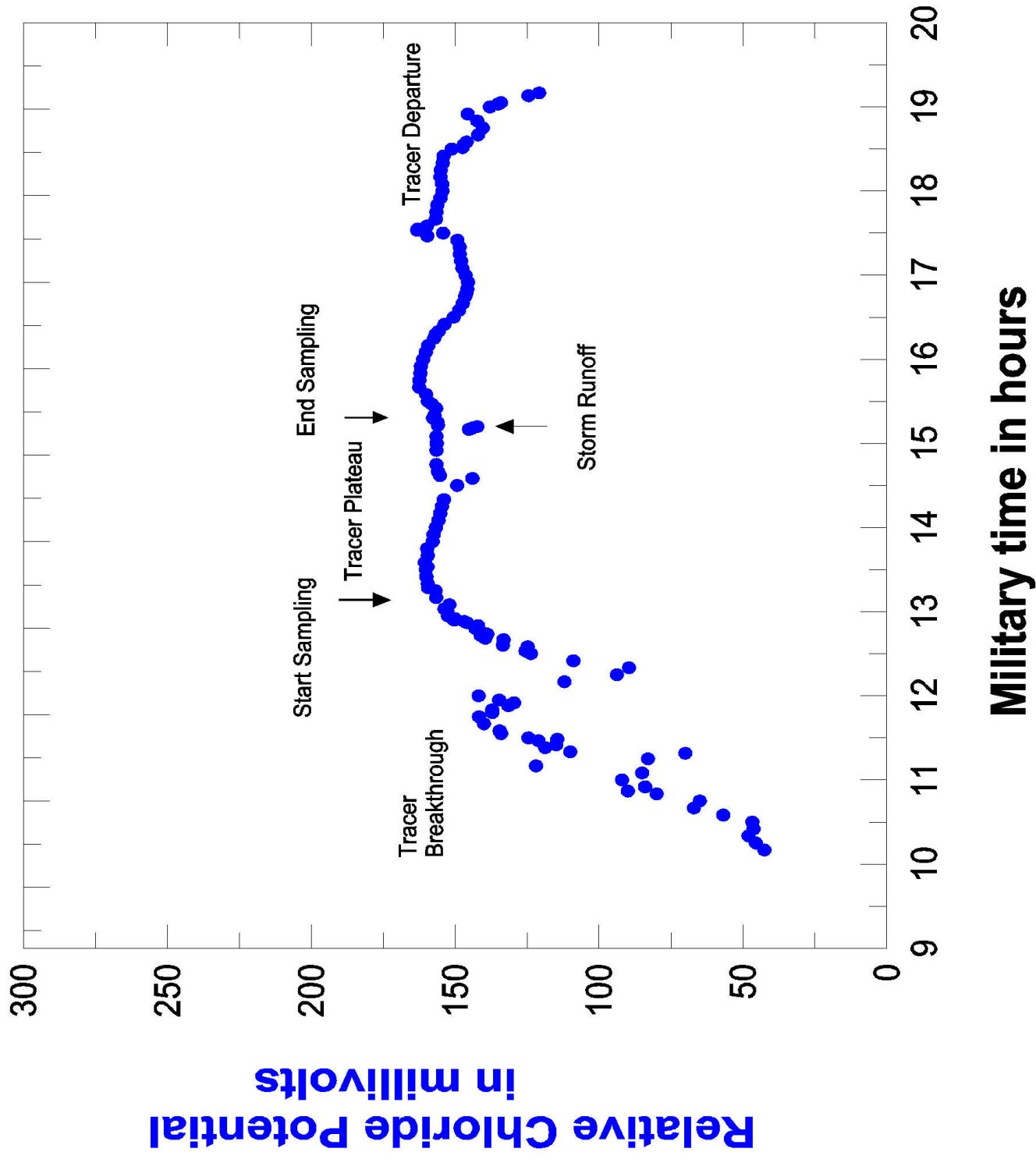


Figure 4. Chloride tracer concentration with time at downstream end of study reach (site PG700). Tracer was monitored using a chloride specific electrode with readings adjusted a 300 mV datum.

Monitoring of Tracer Concentrations and Timing of Weather Conditions

As soon as the relative chloride potential recorded by the selective-ion probe reached a plateau at about 13:00 p.m. (fig. 4), water sampling started at the downstream end of the study reach and proceeded upstream. A steady rain began at about 13:40 p.m. when the sampling crew was near 500 m. Discharge in the creek began to increase, and muddy water was observed at about 14:15 p.m. when sampling near 300 m. By the time the sampling crew reached the beginning of the reach near site PG45 at 15:50 p.m., the rain had stopped and discharge apparently returned or almost returned to base-flow conditions. Thus, only samples from site PG45 and the samples that were collected at or below 542 m (site PG542) could be used to accurately reflect total loads during base-flow conditions. For comparison at the same location, two samples were collected at site TR295 at 12:30 p.m. before the storm and at 14:21 p.m. during storm-runoff conditions.

Samples collected between 45 and 504 m were collected during the storm and could not be used for base-flow comparisons between the sites. The samples collected near the beginning of the reach (site PG45) seemed to approach initial conditions, however, and could be used to give a conservative estimate of the degree to which metal loads changed between the injection point and downstream from site PG504 during base-flow conditions.

Because the sampling crew was moving upstream while the peak storm discharge was moving downstream, samples from sites PG45 through PG305 (45 through 305 m below site PG-0) almost seem to be collected at a stationary location with the runoff pulse moving through. This is indicated by the shape of the rising and falling hydrograph (fig. 5). The prelude to storm runoff appears relatively flat (PG305 to PG504). In reality, discharge may have been increasing during the early part of the storm, or first flush, although discharge appears to be constant. In addition, the peak runoff samples were collected upstream from all of the major tributaries, therefore the peak discharge and the peak loads are probably considerably smaller than they would have been if they had been measured at the lower end of the reach. Although loads calculated during the storm cannot be used for comparisons between different parts of the study reach, they give a qualitative indication of the magnitude and timing of changes during a storm.

Analytical Accuracy of Tracer-Dilution Discharge Measurements

Chloride analyses were conducted using an ion chromatograph (IC) at a USGS laboratory in Denver, Colorado. Accuracy was determined using USGS standard reference water samples (Long and Farrar, 1995). A low-range standard of 25.8 mg/L was run four times and had a standard deviation of ± 1.4 mg/L. A high-range standard of 65 mg/L was run twice and had a standard deviation of ± 2.1 mg/L. Thus, the accuracy for the discharge measurements using the tracer-dilution technique was about ± 5 percent for low-range chloride concentrations and ± 3 percent for high-range chloride concentrations.

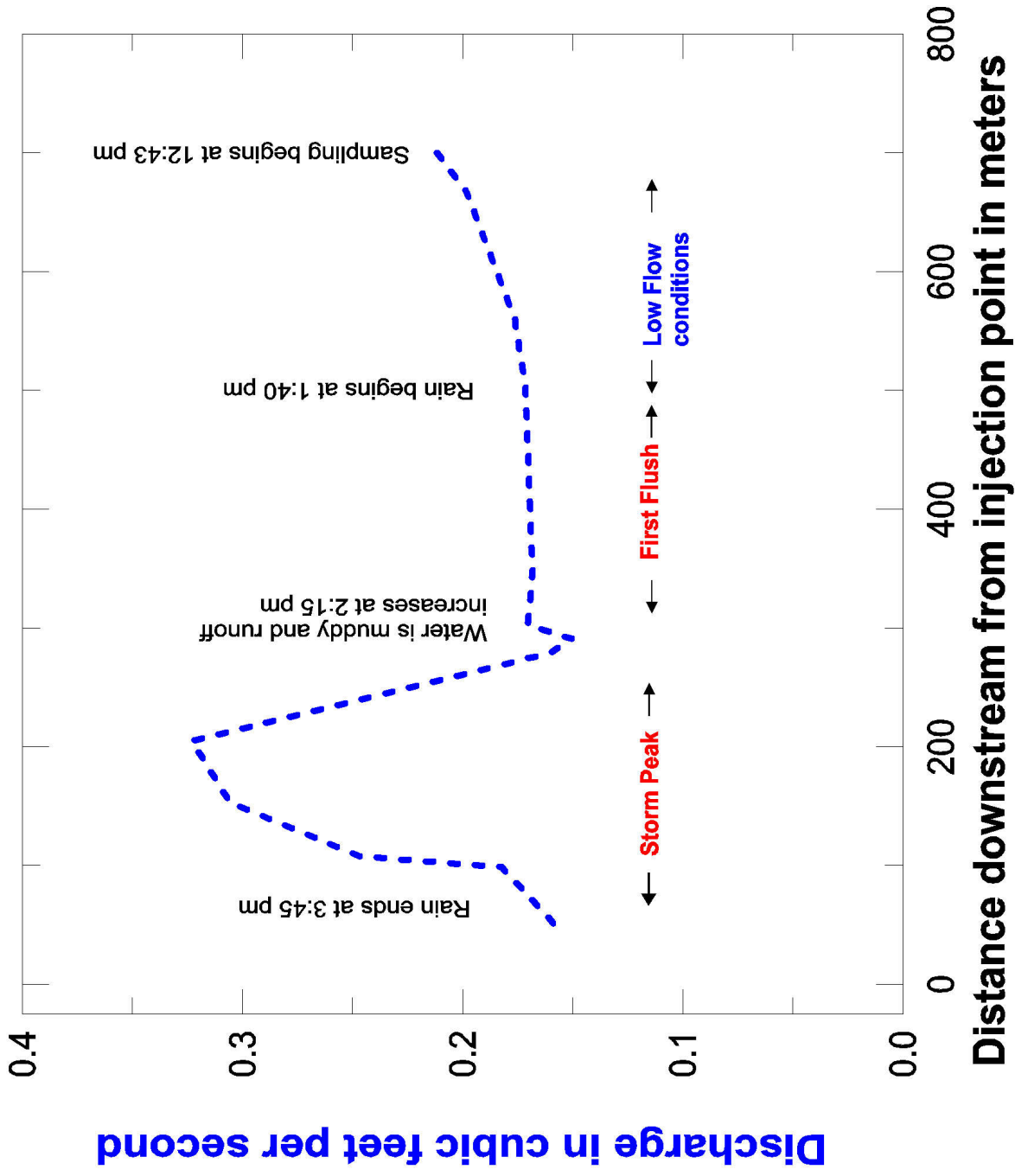


Figure 5. Stream discharge in Prospect Gulch during tracer-dilution study on September 15, 1998.

Water-Quality Sampling Techniques and Analytical Methods

Field measurements were made during field reconnaissance the day before the tracer test on September 14, 1998. Field measurements at 29 surface-water sites along Prospect Gulch included specific conductivity, pH, and water temperature. Field measurements collected on September 15, 1998 at two mine adits and two springs included the same parameters plus dissolved oxygen. Discharge in Prospect Gulch near the confluence of Cement Creek was measured using a pygmy current meter as described by Rantz and others (1982a and 1982b). Water-quality samples were collected at all sites using standard USGS methods similar to Wilde and Radtke (1998). A representative sample was collected at each site by immersing an open, hand-held open 1- or 2-L plastic bottle in the centroid of flow or at multiple verticals as described by Shelton (1994). The stream was generally less than one meter in width.

Filtering and processing was done in a controlled environment at the USGS field laboratory in Silverton, Colorado, using standard USGS equipment similar to Horowitz and others (1994). All samples were processed within a 12-hour time frame on the same day they were collected. Water samples collected for analysis of dissolved elements were filtered using a 0.45- μm cellulose plate filter housed in a 47-mm plastic filtering unit. Filtered and whole water samples were preserved with glass ampules of 70 percent ultra-pure nitric acid or hydrochloric acid in preservation chambers as described by Horowitz and others (1994). Whole water samples were digested in the laboratory with 6 ml of concentrated hydrochloric acid at 60°C for 8 hours according to the procedure of Hoffman and others (1996). The digested samples were filtered through a 0.45- μm polycarbonate filter into an acid-washed, pre-rinsed bottle prior to analysis.

Major cation and trace-metal concentrations in the filtered and digested whole water samples were determined by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) in a USGS laboratory in Boulder, Colorado. The quality of the laboratory analyses was assessed through the analysis of laboratory blanks, sample duplicates, and USGS standard reference water samples (Long and Farrar, 1995). Field parameters and analytical data for both dissolved and total constituents are listed in [appendix A](#).

Major and minor elemental analyses of rock thin sections ([table 1](#)) were obtained with a JEOL 8900 electron microprobe at the U.S. Geological Survey in Denver, Colorado. The analyses were corrected using on-line ZAF correction procedures. Replicate analyses of secondary standards indicate a relative analytical precision of better than ± 1 percent (1σ) for major elements. For trace elements, analytical error is less than that for counting statistics where counting error is equal to one sigma or \pm square root of n over n , ($n = \text{net counts}$). Each element may have a different number of net counts based on differences in concentration.

RESULTS AND DISCUSSION

Changes in Chemical-Constituent Loads with Distance Downstream during Base-Flow Conditions

Specific conductivity and pH during field reconnaissance. Changes in pH and specific conductivity were used to select sampling sites for tracer-dilution and water-quality samples. Field parameters were measured before the start of tracer injection during field reconnaissance on September 14, 1998 (fig. 6). In the upper reach between 0 and 347 m, pH rapidly decreased from 4.8 to 3.2, and specific-conductivity values nearly tripled from 335 to 836 microSiemens per centimeter at 25 degrees Celsius ($\mu\text{S}/\text{cm}$). Below 347 m, pH remained fairly constant at about 3.2. The pH values for the four springs on the north side of the upper study reach were substantially lower than the values measured anywhere else in the Prospect Gulch study reach, and ranged from 2.6 to 3.1. The pH of water from these four springs draining waste-rock material was substantially lower than the pH of streams affected by natural acid drainage elsewhere in the drainage basin that generally have pH values greater than or equal to 3.3 (Bove and others, 1998). Three of the four springs had specific-conductivity values about twice the values of the adjacent stream. The exception was the specific conductivity for site SP114 near the upstream edge of the Henrietta waste-rock dump on the north bank, which was similar to that of the adjacent stream reach. Specific conductivity was 460 $\mu\text{S}/\text{cm}$ for site SP114 versus 440 $\mu\text{S}/\text{cm}$ for site PG108 in Prospect Gulch. The pH of spring SP114, however, was an order of magnitude lower than the stream (3.1 versus 4.2 standard pH units, respectively). The poorest ground-water quality was on the downstream edge of the Henrietta north and south waste-rock dumps (samples SP305 and TR295, respectively). Seeps near the mouth of the small tributary draining Henrietta mine levels 7 and 8 (site TR295) on the southern downstream edge of the waste-rock dump had the lowest pH value of 2.4 and highest specific conductivity of 2,160 $\mu\text{S}/\text{cm}$ (fig. 6).

In the lower study reach (PG347 to PG800), specific conductivity decreased from 836 to 630 $\mu\text{S}/\text{cm}$ (fig. 6), apparently because of dilution from ground-water inflows and base flow contributed by the Joe and John mine adit tributary and the Upper Henrietta tributary. In spite of the gradual increases in discharge from about 0.17 to 0.21 ft^3/s , pH does not change over this reach. At 786 m (site PG786), the Upper Henrietta tributary seems to have the best water-quality in the study reach; the pH was about 3.8 and the specific conductivity was 71 $\mu\text{S}/\text{cm}$. Water in the Upper Henrietta tributary may have come from melting snow at the time of the study. Metal concentrations for the Upper Henrietta tributary, listed in appendix A, were one or more orders of magnitude lower than the concentrations in samples collected in Prospect Gulch.

To summarize the results of the field reconnaissance, water quality in Prospect Gulch progressively deteriorated as the creek gained seepage from the rock-waste dumps for the Henrietta 7 and 8 levels, the Lark mine tributary (site TR286) and the tributary draining the Henrietta 7 and 8 levels (site TR295).

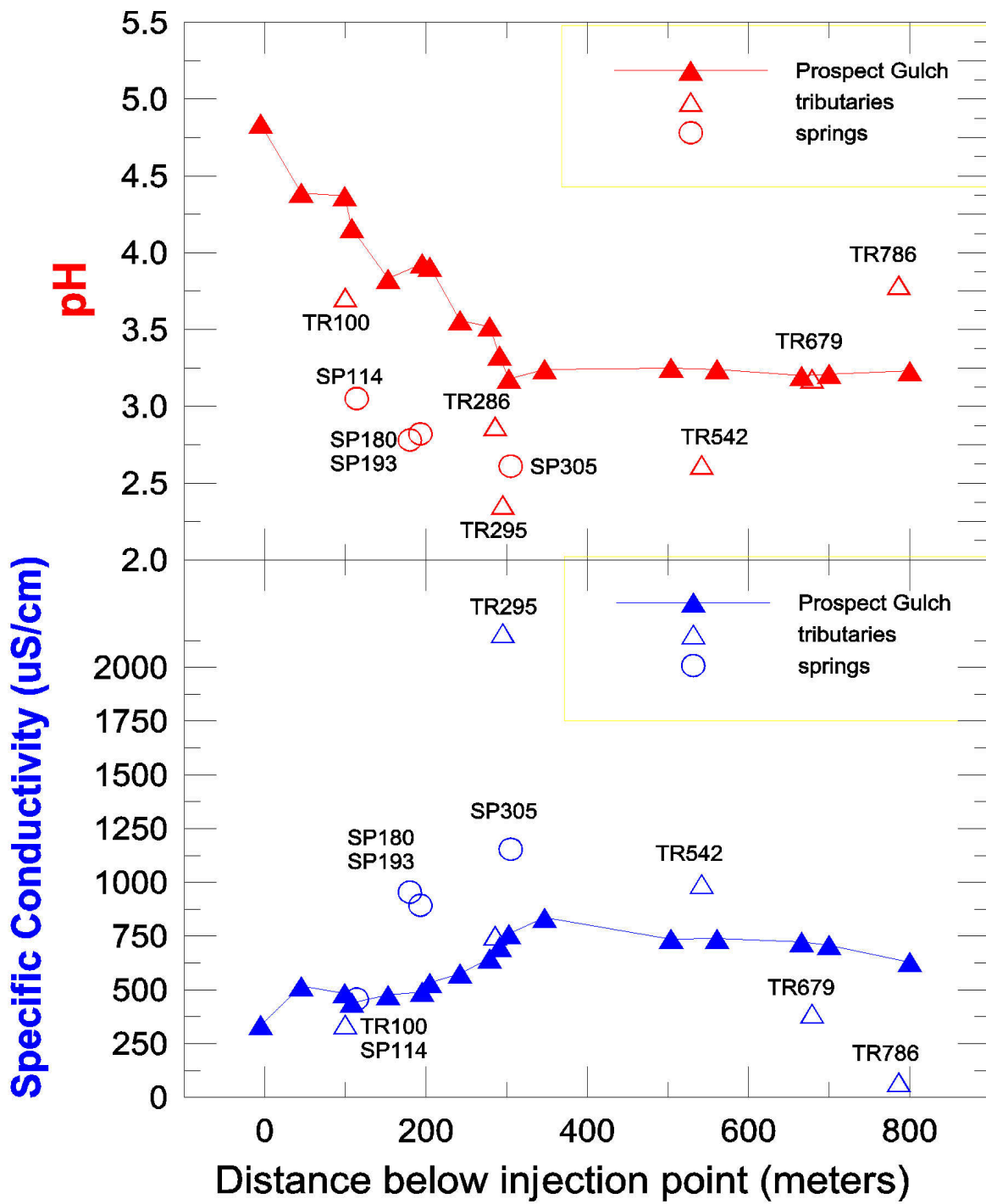


Figure 6. Specific conductivity and pH during base-flow conditions in Prospect Gulch, September 14, 1998

Because the creek is in contact with waste-rock dumps on both sides throughout the reach, decreasing pH and increasing specific conductivity from site PG45 to PG347 is largely attributed to ground-water flow in contact with the minerals present in waste-rock dumps. Downstream from the two tributaries affected by mine drainage (below site PG347), pH no longer decreased and specific conductivity no longer increased. In the lower end of the study reach, inflows from tributaries and ground water seemed to dilute the specific conductivity, whereas pH remained constant.

Chemical-constituent Loads on September 15, 1998. Loads of chemical constituents for selected sampling sites and base-flow sample conditions measured during the tracer-dilution study are given in [table 2](#) and [fig. 7](#).

Assuming that the stream had returned to base-flow conditions by the end of the storm, base flow increased between sites PG45 and PG700 by about 36 percent from 0.155 to 0.211 cubic feet per second (ft³/s) ([table 2](#) and [fig 7](#)). In the same reach, loads for dissolved constituents increased by 740 percent for iron (Fe), 465 percent for aluminum (Al), and 100 percent for sulfate (SO₄). Trace-metal loads for dissolved Pb, Cu, and Zn also increased 500, 380, and 50 percent, respectively. The increase in trace-metal loads through the study reach was generally more than an order of magnitude greater than the increase in base-flow.

The Colorado Division of Minerals and Geology (CDMG) estimated dissolved loads of trace metals in Prospect Gulch during base-flow conditions in October 1996 (Herron and others, 1998). Although the sampling sites in the two studies are not identical, comparisons were made between site PG700 with nearby CDMG site PG-18. Dissolved loads in lb/d of 1.63 for Zn, 5.71 for Fe, and 0.46 for Cu at site PG700 in this study are 2.2 to 3.5 times dissolved loads of 0.73 for Zn, 2.36 for Fe, and 0.13 for Cu in lb/d measured at PG-18 by the CDMG. Differences in the loads between the studies are reasonable given that the two studies used entirely different methods for determining discharge and the studies were conducted over one year apart, allowing for substantial seasonal and temporal differences in stream flow. In addition, variations in sampling locations, sampling methods and analytical methods may have contributed to the differences. As previously mentioned in the section on analytical accuracy, the tracer-dilution method for determining discharge is substantially more accurate than traditional methods for this type of irregular, small-volume stream channel.

The greatest increases in metal loading occur in the upper part of the reach from sites PG45 to PG561, with discharge increasing through the sub-reach by about 13 percent. Based on pH and Specific conductivity data collected during the reconnaissance ([fig. 6](#)), most of this loading probably occurs upstream from about 300 m, in the area where there are acidic ground-water inflows from waste-rock dumps on both sides of the creek. Dissolved loads in this sub-reach increased downstream by 670 percent for Fe, 330 percent for Al, and 170 percent for SO₄. Trace metal loads for dissolved Pb, Cu, and Zn increased by 50, 300, and 130 percent, respectively ([table 2](#)). In the lower end of the study reach from sites PG561 to PG700, dissolved trace-metal loads, particularly Pb,

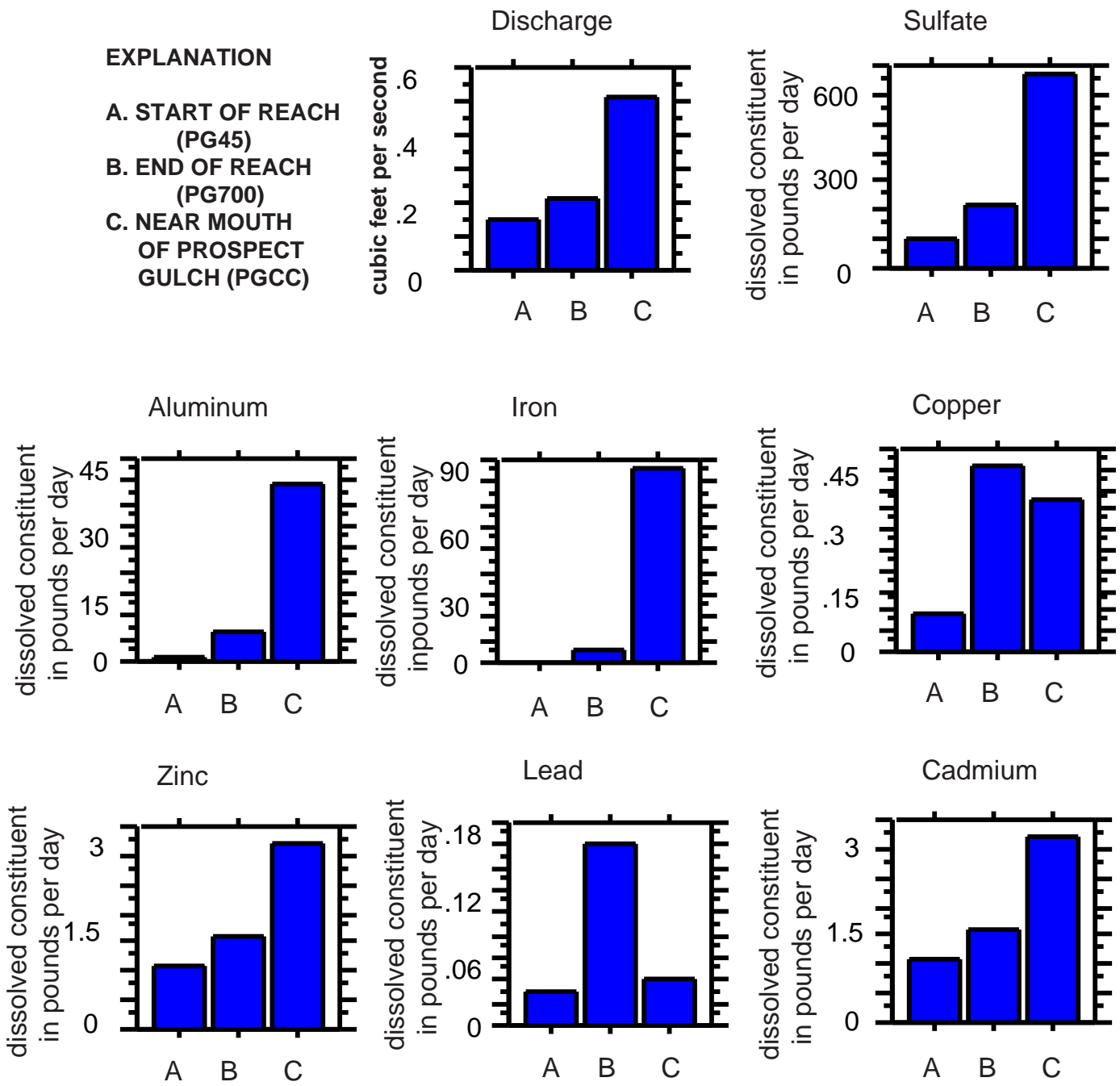


Figure 7. Comparison of dissolved chemical loads and discharge during base-flow conditions in Prospect Gulch.

seemed to increase in the vicinity of the waste-rock dump for Henrietta mine level 10. This result was unexpected based on constant pH and decreasing specific-conductivity values measured during reconnaissance (fig. 6). Although specific conductivity decreases above and below the waste dump from 737 to 629 $\mu\text{S}/\text{cm}$ under base-flow conditions, dissolved trace-metal loads from sites PG561 to PG700 generally increased (table 2). Trace-metal loading seemed to be greatest in the areas where waste-rock dump material is adjacent to the stream, where there is limited opportunity for attenuation of metals. Ground-water and surface-water drainage in contact with waste-rock dumps appears to be the major source of metal loading throughout the study reach.

Although trace-metal loads increased substantially in the 800-meter study reach, trace-metal loads near the mouth of Prospect Gulch (PGCC or bar “C” in fig. 7) generally were much larger. For example, the study reach contributed less than 6 percent of the dissolved-Fe load at sample site PGCC, 13 percent of the dissolved-Al load, and 18 percent of the dissolved-Zn load. In contrast, the discharge at site PGCC was only 2.4 times greater than at site PG700. Possible sources of dissolved metals downstream from the study reach include natural acidic drainage resulting from weathering of exposed altered rock, as evidenced by active ferricrete deposits and an iron bog in the reach, in addition to acid drainage that may be derived from areas disturbed by mining. In contrast with the study reach, the major source of metals to Prospect Gulch downstream from PG700 is thought to be from natural weathering processes. The study reach contributes about 40 percent of the dissolved (Cd) load and virtually all of the dissolved Pb-load and dissolved Cu-load. Dissolved Cu and Pb loads actually decrease between site PG700 and site PGCC by about 20 and 75 percent, respectively. The attenuation of Cu and Pb downstream from the study reach may be the result of natural processes that cause a slight increase in pH from 3.2 to 3.6 (fig. 6). For example, this attenuation may be caused by dilution from ground-water and surface-water inflows with higher pH or by exposure to geologic materials having a higher buffering capacity or ability to adsorb trace metals. Another possible explanation is that iron and aluminum precipitates may have removed dissolved Pb from solution. Unlike the study reach, in which metal loads increased and pH decreased because of drainage from waste-rock dumps, this lower reach near the mouth did not become more acidic. Although most metal loads substantially increased, the Cu and Pb loads actually decreased. Different types of source contributions and different types of weathering processes appear to be responsible in near the mouth of Prospect Gulch as opposed to the study reach.

Changes in Chemical-Constituent Loads Caused by Storm-Runoff Conditions

The late-summer storm on September 15, 1998 dramatically increased the loads of most dissolved and suspended constituents. The timing and magnitude of changes in loads varied greatly among different groups of chemical constituents (figs. 8 and 9; table 2). The effects of the storm were divided into two distinct periods; (1) a first flush of higher metal concentrations that occurred soon after rainfall began and (2) the peak discharge of the storm runoff.

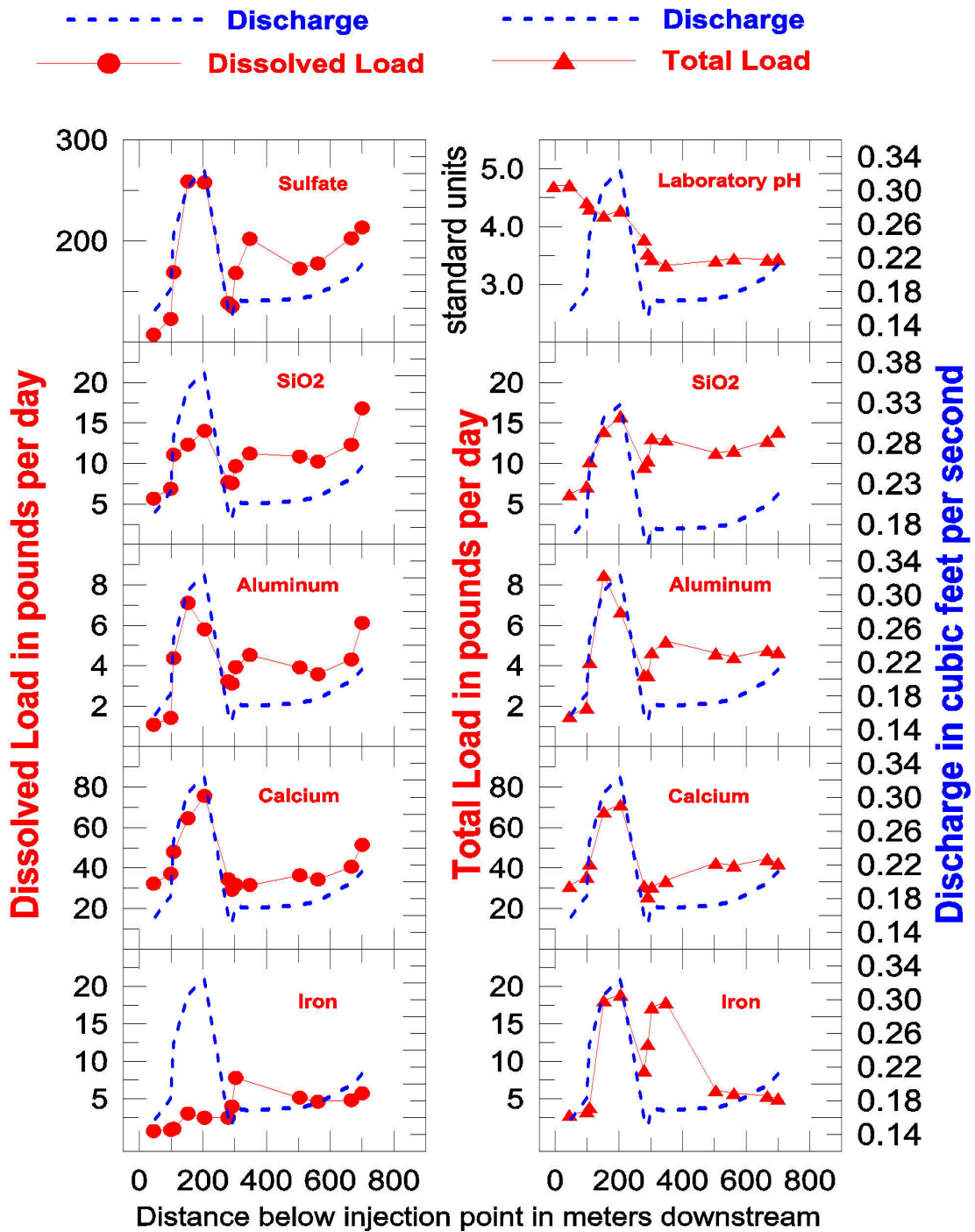


Figure 8a. Graphs showing chemical loads during first flush and peak runoff in Prospect Gulch, September 15, 1998

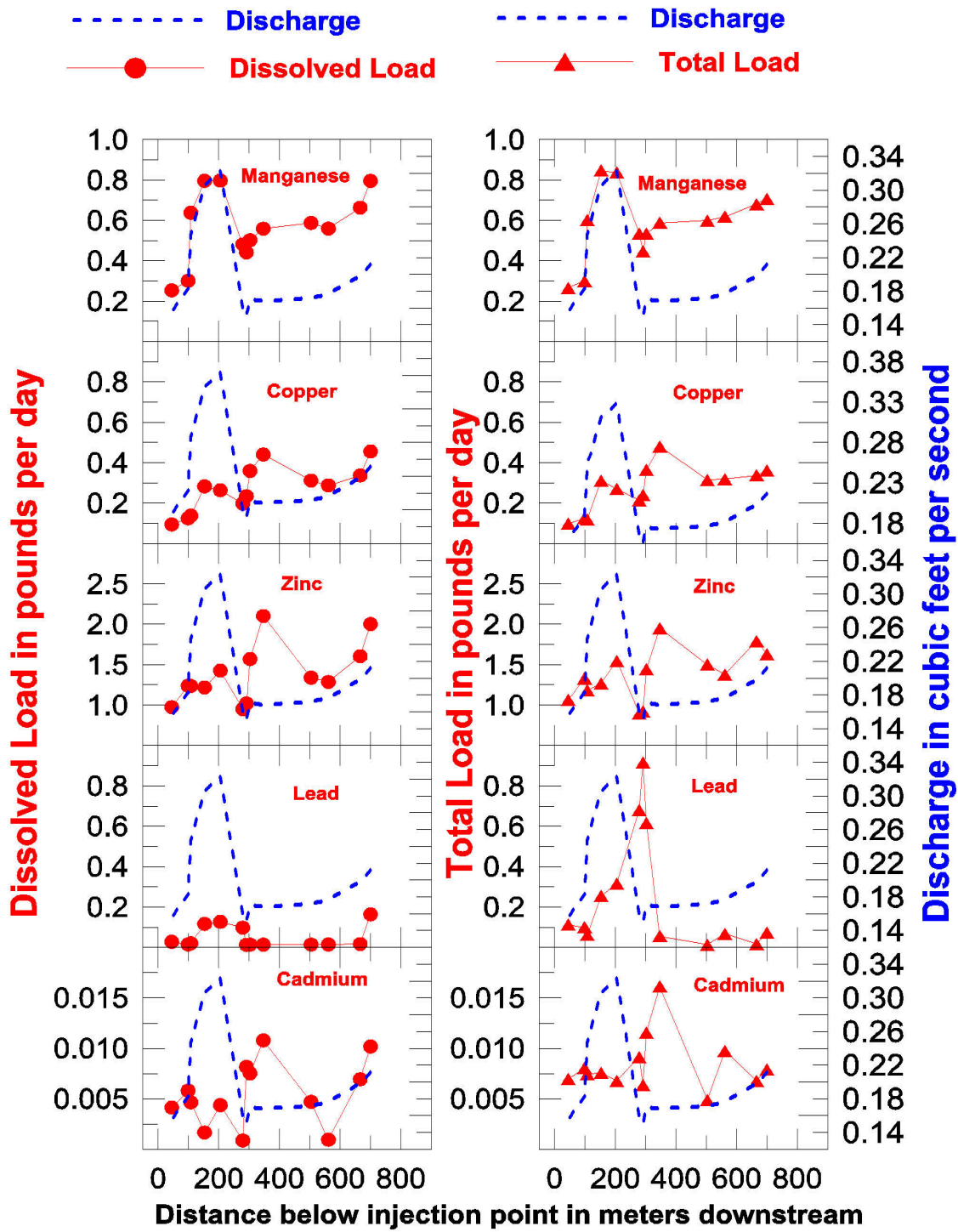


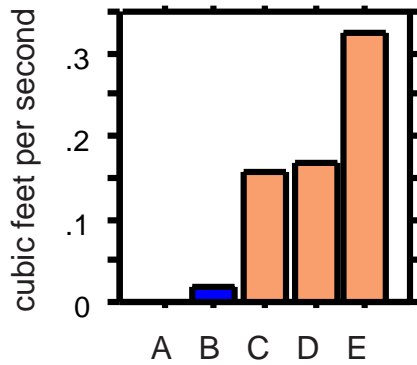
Figure 8b. Graphs showing chemical loads during first flush and peak runoff in Prospect Gulch, September 15, 1998 (continued).

EXPLANATION:

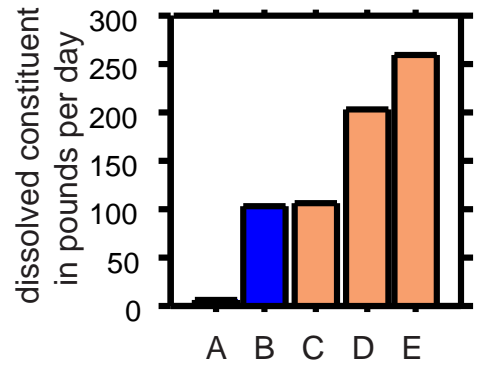
HENRIETTA TRIBUTARY
A. BASE FLOW (TR295)
B. PEAK FLOW (TR295)

PROSPECT GULCH
C. BASE FLOW (PG45)
D. FIRST FLUSH (PG347)
E. PEAK FLOW (PG205)

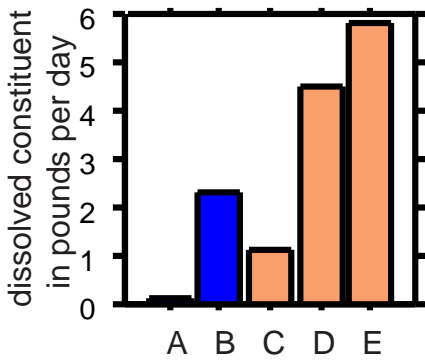
Discharge



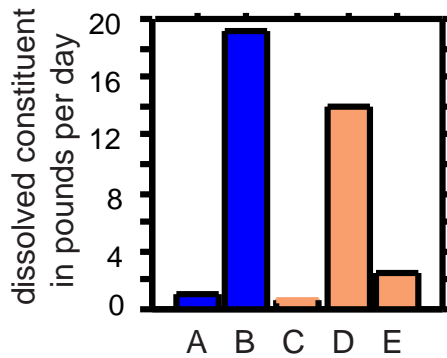
Sulfate



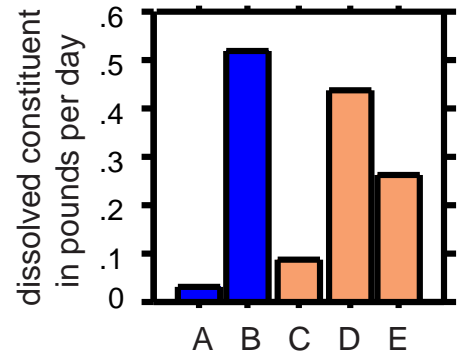
Aluminum



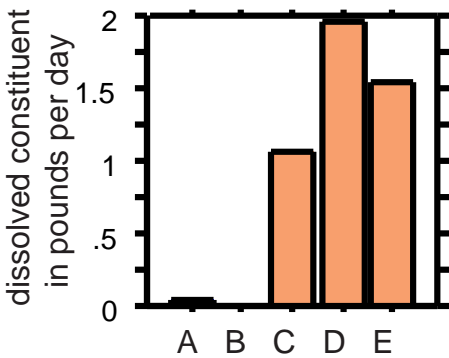
Iron



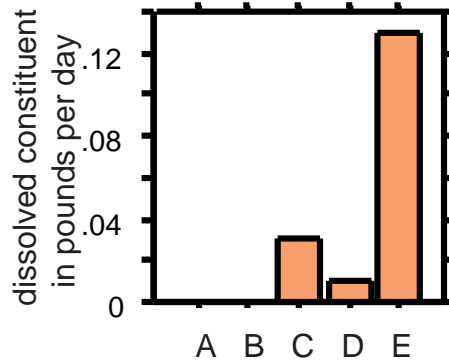
Copper



Zinc



Lead



Cadmium

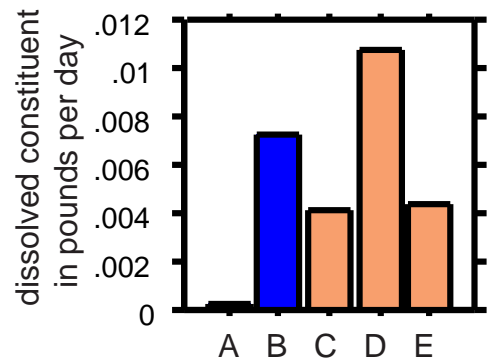


Figure 9. Comparison of dissolved chemical loads and discharge during storm runoff in Henrietta level 7 tributary and Prospect Gulch.

First Flush. An interesting phenomenon was observed in the 35 minutes between the time that rainfall began and the time that discharge began to increase rapidly. Loads of dissolved Fe and total and dissolved Zn, Cu, and Cd from site PG504 to site PG291 quickly rose and fell shortly before the onset of the rapid increase in runoff (fig. 8). These increases in trace-metal loads are the consequence of short-term increases in metals concentrations, given that the discharge of the stream did not change substantially during this time. Total and dissolved SO₄, SiO₂, and Al loads also increased substantially, although loads of these constituents were higher during peak runoff. At the same time, total and dissolved loads of major cations (notably Ca and Mg) did not change substantially. These measurements were interpreted as representing a scenario in which highly soluble material that is first and easiest to dissolve from the ground surface near the stream temporarily increases the concentrations of metals, referred to here as a “first flush” of salts. Because discharge apparently did increase during the first flush, the increase in loads of dissolved constituents must be derived in or near the streambed from the dissolution of salts or pore-waters having higher concentrations of metals. Miller and Drever (1977) made a similar observation in a study of the North Fork of the Shoshone River in Wyoming during and following a storm in which salinity increased at the onset of the storm. Drever (1982) reported how soils that are not continuously wet generally contain salts that form when water containing dissolved ions evaporates in the soil zone. During the early part of a storm, these salts are dissolved and flushed into the stream. During the later part of the storm, any remaining salts carried by the runoff are diluted by the higher discharge. Although concentrations of constituents are diluted by storm runoff, the loads of the most common constituents are generally higher than during base-flow conditions because the discharge is higher.

Rainfall patterns may affect the concentrations of salts in the soil and the magnitude of the first flush in any given runoff event. Kennedy (1971) and Kennedy and Malcolm (1977) studied how soluble salts in the soil would be flushed by fall storms into the Mattole River of northern California. Later in the rainy season, the salts would be washed out of the soil and would no longer affect stream chemistry. If the storm were the first storm or the most extensive storm following a period of extended dry conditions, higher loads of trace metals would be likely than if the storm were in the later part of a wet season. On the day of the tracer study, 0.37 centimeter (cm; 0.15 in) of rain fell at a nearby rain gage in Silverton. In the two weeks before the tracer study, a total of 1.65 cm (0.65 in) fell near the gage, 0.97 cm (0.38 in) falling in the three days before the tracer study (data from Colorado Climate Center, Colorado State University). Rainfall patterns can vary locally by substantial amounts, and the Prospect Gulch drainage basin may have actually received a larger or smaller amount of rainfall than occurred at the gage on any given day. In any case, the previous storms were not large enough to entirely remove the salts, or soils dried out enough for the salts to reform between storms. In general, loads were greatest for most dissolved trace metals such as Cu, Zn, and Cd during the first flush than during the remainder of the storm.

The large amounts of Fe and sulfate in the first flush were likely derived from iron hydroxide minerals (such as jarosite [KFe₃(SO₄)₂(OH)₆] and schwertmanite [Fe₈O₈(OH)_{5.5}(SO₄)_{1.25}]), which commonly occur in the drainage basin on the mine dumps.

These iron hydroxides can form under acid conditions (Bigham and others, 1996) and are secondary weathering products of iron sulfide minerals, such as pyrite. Iron hydroxides are important because they tend to strongly adsorb trace metals such as Cd, Cu, Pb, and Zn that were released in large amounts during the first flush. The mine dumps in the study reach are in close proximity to the creek with little soil or vegetation to adsorb soluble trace metals.

Peak Runoff. The peak runoff contained the highest loads of major constituents measured in the study reach, including dissolved and total calcium (Ca), magnesium (Mg), and Al (fig. 9). Total and dissolved loads of manganese (Mn) and silica (SiO₂) also increased substantially, and total Fe was higher at the peak of runoff than during the first flush. This increase in total Fe was consistent with field observations that the runoff became muddy with reddish brown sediment at about the same time that discharge increased rapidly. The highest load for dissolved Pb of 0.1 pound per day (lb/day) occurred during peak runoff, however the highest load for total Pb (0.9 lb/day) occurred before peak runoff. In most surface waters, Pb tends to sorb onto particulate matter, although Hem (1992, p.143) reported that acidic waters that are poorly buffered can dissolve considerable amounts of Pb. The dissolved Pb may have been leached from Fe hydroxides and fine-grained sediments that were suspended by the storm runoff. Ca, Mg, and Al were probably derived from weathering of igneous rocks and clay minerals (for example, illite and sericite) in the drainage basin.

The tributary for the Henrietta 7 and 8 levels (site TR295) was sampled before and during the storm. Although concentrations of dissolved constituents generally did not change substantially, the peak-runoff loads in the tributary were generally 1 to 2 orders of magnitude higher than the loads representing base-flow conditions (fig. 9 and table 2). Discharge in the tributary was at least 20 times higher during peak runoff. Additional work is needed to identify the specific mineral components that account for the greatest changes in water chemistry in this tributary and in the main channel during storm runoff conditions.

CONCLUSIONS

Loads for major and trace metals increased with distance downstream throughout the study reach during base-flow conditions. Temporal variations during storm-runoff conditions increased loads by at least one or more orders of magnitude above base-flow conditions. Interpretation of Prospect Gulch tracer results yielded the following conclusions:

1. During base-flow conditions (fig. 7), the increases in metal loads through the study reach were generally more than an order of magnitude greater than the increase in stream discharge. For example, base flow increased by 36 percent from sites PG45 to PG700, compared with dissolved-load increases of 100 percent for sulfate, 465 percent

for Al, and 740 percent for Fe. Trace-metal loads for dissolved Zn, Cu, and Pb increased by 50, 380, and 500 percent, respectively. Ground-water seeps in the stream channel near all three waste-rock dumps appear to be the major source of metal loading throughout this reach. Seeps were present near the mouths of tributaries draining the Lark No. 3 mine and the Henrietta 7 and 8 mine levels (TR-286 and TR295). A small amount of base flow was contributed from the two tributaries that receive drainage from the John and Joe mines (less than 0.02 ft³/s, combined), which has a corresponding increase in the loads.

2. During base-flow conditions, the metal loads near the mouth of Prospect Gulch (site PGCC) were generally substantially higher than loads generated within the study reach (sites PG45 to PG700) as shown in [fig. 7](#). For example, the study reach accounted for about 6 percent of the dissolved-Fe load, 13 percent of the dissolved-Al load, and 18 percent of the dissolved-Zn load near the mouth—but contributed virtually all of the dissolved Cu and Pb. Dissolved Cu and Pb loads actually decrease between the study reach and the mouth of Prospect Gulch by about 20 and 75 percent, respectively. The major source of metals near the mouth of Prospect Gulch has yet to be identified.

3. During base-flow conditions, water quality in Prospect Gulch progressively deteriorated in the upper part of the study reach ([fig. 6](#)) where the creek gains ground-water inflow emanating from the north and south waste dumps and the two tributaries draining the Lark mine and the Henrietta 7 and 8 levels. Seeps along the edge of the waste-rock dump had substantially lower pH values. The pH values were 0.5 to 1.1 unit lower than the adjacent reach of the creek. The pH of the seeps (2.6 to 3.1) is also substantially lower than the pH of other streams affected by natural acid drainage elsewhere in the drainage basin that generally have pH values greater than or equal to 3.3

The uppermost seep or spring on the north side of the waste-rock dump (site SP114) had water quality similar to the creek on the basis of specific conductivity (460 versus 440 $\mu\text{S}/\text{cm}$, respectively), although pH was approximately 1.0 standard unit lower. The seep on the southern downstream end of the waste-rock dump (site TR295) had the worst water quality compared with the adjacent reach of the creek (2.4 standard pH units and 2,160 $\mu\text{S}/\text{cm}$, respectively). Deteriorating water quality in this reach is predominantly due to ground-water flow in contact with the minerals present in waste-rock dumps.

4. Although brief in duration, the first flush of salts during the early rainstorm contained the highest concentrations and highest loads of dissolved Fe and total and dissolved Zn, Cu, and Cd that were measured in the study reach during the tracer injection. The highly soluble materials dissolved in the first flush were likely derived from iron hydroxide minerals such as jarosite and schwertmanite, which are common on mine dumps in the Prospect Gulch drainage basin.

5. Peak storm runoff contained the highest loads of major elements in the study reach, including dissolved and total Ca, Mg, and Al, which were probably derived from clay minerals and igneous rocks in the drainage basin. Total and dissolved loads of Mn and SiO₂ also increased substantially, and the total-Fe load was slightly higher at maximum discharge than during the first flush. Although discharge (and loads) increased by 1 to 2 orders of magnitude at Henrietta & and 8 level tributary (TR-295), there was little if any change in the metal concentrations between base-flow and peak-runoff conditions.

6. In general, metal loading in the study reach increased the most where waste-rock dump material was adjacent to the stream. Increases in dissolved major and trace-element loads were greatest near the north and south waste-rock dumps for Henrietta levels 7 and 8. The next largest increases in loads of total and dissolved Pb occurred in the lower part of the reach near the waste-rock dump for Henrietta level 10. Increases in dissolved loads of major elements and trace metals near the waste-rock dump for Henrietta level 10 were unexpected on the basis of field pH and specific conductivity.

Table 2. Loads of chemical constituents in Prospect Gulch during base-flow and storm-runoff conditions, September 15, 1998.

[Q, discharge; ft³/s, cubic feet per second; dis., dissolved; tot., total; lb/d, pounds per day; ND, not determined]

Sample Site (shown in fig. 2)	Q ft ³ /s	Time	Distance down- stream from	Metals in pounds per day									
				PG-0	SO4 (dis.)	Ca (dis.)	Ca (tot.)	Mg (dis.)	Mg (tot.)	SiO2 (dis.)	SiO2 (tot.)	Al (dis.)	Al (tot.)
Samples collected during base-flow conditions													
PGCC (upstream from Cement Creek)	0.515	1716			672.4	87.8	ND	20.9	ND	112.3	ND	39.3	ND
PG700	0.211	1305	700		213.4	51.4	42.3	7.5	6.6	16.8	14.0	6.1	4.7
TR679	0.014	1310	679		7.9	0.6	0.6	0.1	0.1	2.3	2.2	0.4	0.4
PG666	0.198	1315	666		202.6	40.6	44.5	6.3	6.8	12.3	12.8	4.3	4.8
PG561	0.176	1325	561		177.8	34.3	41.3	5.4	6.3	10.2	11.6	3.6	4.4
TR542	0.005	1325	542		6.1	0.1	0.1	0.1	0.1	1.0	0.9	0.2	0.2
TR295	0.001	1230	295		5.4	0.2	0.3	0.1	0.1	0.3	0.3	0.1	0.1
Samples collected during the first flush													
PG504	0.171	1335	504		172.8	36.4	42.6	5.7	6.3	10.9	11.3	3.9	4.6
PG347	0.168	1410	347		202.2	31.6	33.7	5.3	5.6	11.2	13.0	4.5	5.2
PG303	0.170	1420	303		168.3	31.6	30.8	4.7	5.1	9.7	13.1	3.9	4.7
TR295	0.020	1421	295		102.8	3.8	ND	1.7	ND	5.9	ND	2.3	ND
PG291	0.150	1424	291		135.3	29.2	26.1	4.2	4.2	7.6	10.4	3.1	3.5
Samples collected during peak runoff													
PG279	0.161	1435	279		138.7	34.5	31.4	4.9	4.7	7.7	9.6	3.2	3.6
PG205	0.323	1450	205		257.9	75.6	71.3	9.6	9.5	14.0	15.9	5.8	6.7
Average of SP180 & SP193	0.017				22.1	2.5	2.7	0.5	0.6	1.6	1.7	0.6	0.6
PG153	0.306	1500	153		258.9	64.6	67.9	8.8	9.0	12.3	14.0	7.1	8.5
SP114	0.059	1525	114		27.1	1.2	1.2	0.3	0.4	5.1	5.7	0.5	0.7
PG108	0.247	1525	108		169.1	48.0	42.2	6.6	6.0	11.1	10.3	4.4	4.2
TR100	0.064	1534	100		46.6	8.9	7.4	2.4	2.1	4.3	3.7	2.9	2.4
PG99	0.182	1538	99		123.0	37.1	35.9	4.3	4.2	6.9	7.2	1.4	1.9
Samples collected after the storm													
PG45	0.155	1547	45		107.3	32.2	31.1	3.7	3.7	5.7	6.2	1.1	1.5

Table 2. Loads of chemical constituents in Prospect Gulch during base-flow and storm-runoff conditions, September 15, 1998.

[Q, discharge; ft³/s, cubic feet per second; dis., dissolved; tot., total; lb/d, pounds per day; ND, not determined]

Sample Site (shown in fig. 2)	Metals in pounds per day								Metals in pounds per day				
	Cd (dis.)	Cd (tot.)	Cu (dis.)	Cu (tot.)	Fe (dis.)	Fe (tot.)	Mn (dis.)	Mn (tot.)	Pb (dis.)	Pb (tot.)	Sr (dis.)	Sr (tot.)	Zn (dis.)
Samples collected during base-flow con													
PGCC (upstream from Cement Creek)	0.0137	ND	0.37	ND	86.94	ND	1.99	ND	0.04	ND	1.34	ND	3.20
PG700	0.0102	0.0079	0.46	0.36	5.71	5.03	0.80	0.71	0.16	0.07	1.09	0.89	1.63
TR679	0.0012	0.0010	0.02	0.02	0.14	0.16	0.01	0.01	0.01	0.01	ND	ND	0.28
PG666	0.0069	0.0068	0.34	0.34	4.80	5.37	0.66	0.68	0.02	0.02	0.86	0.95	1.79
PG561	0.0010	0.0098	0.29	0.32	4.60	5.74	0.56	0.62	0.01	0.07	0.73	0.88	1.38
TR542	0.0011	0.0010	0.02	0.02	0.44	0.47	0.02	0.02	ND	ND	ND	ND	0.18
TR295	0.0003	0.0004	0.03	0.03	0.95	1.03	0.01	0.01	ND	ND	ND	ND	0.05
Samples collected during the first flush													
PG504	0.0047	0.0049	0.31	0.32	5.13	6.13	0.59	0.60	0.01	0.01	0.78	0.91	1.50
PG347	0.0108	0.0161	0.44	0.48	14.04	17.90	0.56	0.59	0.01	0.05	0.67	0.71	1.95
PG303	0.0075	0.0116	0.36	0.36	7.78	17.23	0.50	0.53	0.01	0.62	0.67	0.66	1.44
TR295	0.0073	ND	0.52	ND	19.18	ND	0.25	ND	ND	ND	0.03	ND	ND
PG291	0.0082	0.0064	0.23	0.24	3.96	12.32	0.44	0.45	0.01	0.92	0.63	0.57	0.92
Samples collected during peak runoff													
PG279	0.0009	0.0091	0.20	0.21	2.48	8.79	0.48	0.54	0.10	0.68	0.74	0.68	0.90
PG205	0.0044	0.0068	0.26	0.27	2.46	18.92	0.80	0.84	0.13	0.32	1.75	1.66	1.55
Average of SP180 & SP193	0.0011	0.0011	0.06	0.06	1.22	1.48	0.07	0.07	0.01	0.01	0.05	0.05	0.21
PG153	0.0016	0.0075	0.28	0.31	3.03	18.10	0.80	0.85	0.12	0.25	1.44	1.54	1.27
SP114	0.0030	0.0030	0.02	0.02	1.77	3.77	0.04	0.05	0.32	0.50	0.01	0.02	0.52
PG108	0.0046	0.0075	0.14	0.12	0.99	3.87	0.64	0.60	0.02	0.06	1.05	0.93	1.18
TR100	0.0003	0.0003	0.01	0.01	0.12	0.24	0.37	0.33	0.01	0.01	0.08	0.07	0.04
PG99	0.0058	0.0080	0.13	0.12	0.82	3.33	0.30	0.30	0.01	0.10	0.91	0.88	1.33
Samples collected after the storm													
PG45	0.0041	0.0070	0.09	0.10	0.68	2.85	0.25	0.27	0.03	0.11	0.78	0.76	1.06

Table 2. Loads of chemical constituents in Prospect Gulch during base-flow and storm-runoff conditions, September 15, 1998.

[Q, discharge; ft³/s, cubic feet per second; dis., dissolved; tot., total; lb/d, pounds per day; ND, not determined]

Sample Site (shown in fig. 2)	Zn (tot.)
Samples collected during base-flow con	
PGCC (upstream from Cement Creek)	ND
PG700	2.00
TR679	0.29
PG666	1.60
PG561	1.28
TR542	0.23
TR295	0.05
Samples collected during the first flush	
PG504	1.34
PG347	2.10
PG303	1.57
TR295	1.08
PG291	1.02
Samples collected during peak runoff	
PG279	0.95
PG205	1.43
Average of SP180 & SP193	0.21
PG153	1.22
SP114	0.52
PG108	1.24
TR100	0.05
PG99	1.24
Samples collected after the storm	
PG45	0.97

References Cited

- Bigham, J.M., Schwertmann, Udo, and Pfab, G., 1996, Influence of pH on mineral speciation in a bioreactor simulating acid mine drainage: *Applied Geochemistry*, v. 11, p. 845-849.
- Bove, D.J., 1988, Evolution of the Red Mountain alunite deposit, Lake City caldera, San Juan Mountains, Colorado, Unpub. M.A. thesis, University of Colorado, Boulder, 179 p.
- Bove, D.J. and Hon, K., 1992, Geology and alteration map and drill-core logs of the Red Mountain area, near Lake City, Hinsdale County, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-2286.
- Bove, D.J., Rye, R.O., and Hon, K., 1990, Evolution of the Red Mountain alunite deposit: U.S. Geological Survey Open-File report 90-0235, 30 p.
- Bove, D.J., Wright, W.G., Mast, M.A., and Yager, D.B., 1998, Natural contributions of acidity and metals to surface waters of the upper Animas River watershed, Colorado; *in* von Guerard P. and Nimick, D.A. eds., *Science for watershed decisions on abandoned mine lands: Review of preliminary results*, Denver, Colorado; February 4-5, 1998: U.S. Geological Survey Open-File report 98-297, 71 p.
- Burbank, W.S., and Luedke, R.G., 1969, Geology and ore deposits of the Eureka and adjoining districts San Juan Mountains, Colorado: U.S. Geological Survey Professional Paper 535, 73 p.
- Drever, J.I., 1982, *The geochemistry of natural waters*: Englewood Cliffs, N.J., Prentice Hall, p. 182-194.
- Fisher, F.S., and Leedy, W.P., 1973, Geochemical characteristics of mineralized breccia pipes in the Red Mountain district, San Juan Mountains, Colorado: U.S. Geological Survey Bulletin 1381, 43 p.
- Gray, J.E., and Coolbaugh, M.F., 1994, Geology and geochemistry of Summitville, Colorado: An epithermal acid-sulfate deposit in a volcanic dome: *Economic Geology*, v. 89, p. 1906-1923.
- Hem, J.D., 1992, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254, 263 p.
- Herron, Jim, Stover, Bruce, and Krabacher, Paul, 1998, Cement Creek reclamation feasibility report, Upper Animas River Basin: Denver, Colo., Colorado Division of Minerals and Geology, 137 p.

- Hoffman G.L., Fishman, M.J., and Garbarino, J.R., 1996, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—in-bottle acid digestion of whole-water samples: U.S. Geological Survey Open-File Report 96-225, 28 p.
- Horowitz, A.J., Demas, C.R., and Fitzgerald, K.K., 1994, U.S. Geological Survey protocol for the collection and processing of surface-water samples for the subsequent determination of inorganic constituents in filtered water: U.S. Geological Survey Open-File report 94-539, 157 p.
- Kennedy, V.C., 1971, Silica variation in stream water with time and discharge, *in* Nonequilibrium systems in natural water chemistry, American Chemical Society Advanced Chemistry Series 106, p. 94-130.
- Kennedy, V.C., and Malcolm R.L., 1977, Geochemistry of the Mattole River of northern California: U.S. Geological Survey Open-file report 78-205, 324 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., Runkel, R.L., Bencala, K.E., and Walton-Day, Katherine, 1999, 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—Contamination from hardrock mining: U.S. Geological Survey Water-Resources Investigations Report 99-4018A, in press.
- Lipman, P.W., Fisher, F.S., Mehnert, H.H., Naeser, C.W., Luedke, R.G., and Steven, T.A., 1976, Multiple ages of mid-Tertiary mineralization and alteration in the western San Juan Mountains, Colorado: *Economic Geology*, v. 71, p. 571-588.
- Lipman, P.W., Steven, T.A., Luedke, R.G., and Burbank, W.S., 1973, Revised volcanic history of the San Juan, Uncompahgre, Silverton, and Lake City calderas in the western San Juan Mountains, Colorado: U.S. Geological Survey *Journal of Research*, v. 1, p. 627-642.
- Lipman, P.W., Steven, T.A., and Mehnert, H.H., 1970, Volcanic history of the San Juan Mountains, Colorado—as indicated by potassium-argon dating: *Geological Society of America Bulletin*, v. 81, p. 2329-2352.
- Long, H.K. and Farrar, J.W., 1995, Report on the U.S. Geological Survey's evaluation program for standard reference samples distributed in May 1995—T-135 (trace constituents), M-134 (major constituents), N-45 (nutrients), N-46 (nutrients), P-24

- (low ionic strength), Hg-20 (mercury), and SED-5 (bed material): U.S. Geological Survey Open-File Report; 95-395, 135 p.
- Miller, W.R., and Drever, J.I., 1977, Water chemistry of a stream following a storm, Absaroka Mountains, Wyoming: Geological Society of America Bulletin, v. 88, p. 286-290.
- Nash, J.T., 1975, Fluid-inclusion study of vein, breccia pipe, and replacement ores, northwestern San Juan Mountains, Colorado: Economic Geology, v. 70, 1038-1049 p.
- Nash, J.T., 1999, Geochemical Investigations and Interim Recommendations for Priority Abandoned Mine Sites, BLM Lands, Upper Animas Watershed, San Juan County, Colorado U.S. Geological Survey Open-File report 99-323, 45 p.
- Ransom, F.L, 1901, A report on the economic geology of the Silverton quadrangle, Colorado: U.S. Geological Survey Bulletin 182, 265 p.
- Rantz, S.E., and others, 1982a and 1982b, Measurement and Computation of Streamflow—v. 1, Measurement of stage; v. 2, Computation of discharge: U.S. Geological Survey Water-Supply Paper 2175, v. 1, 284 p.; v. 2, 346 p.
- Shelton, L.R., 1994, Field guide for collection and processing stream-water samples for the National Water-Quality Assessment Program: U.S. Geological Survey Open-File Report 94-455, 42 p.
- Sylvester, M.A., Kister, L.R., and Garrett, W.B., eds., 1990, Guidelines for the collection, treatment, and analysis of water samples: Menlo Park, CA, U.S. Geological Survey Western Region Field Manual, 144 p.
- Walton-Day, Katherine, Runkel, R.L., Kimball, B.E., and Bencala, 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 Substances Hydrology Program—Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999: Volume 1—Contamination from hardrock mining: U.S. Geological Survey Water-Resources Investigations Report 99-4018A, in press.
- Wilde, F.D., and Radtke, D.B., 1998, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A6, sections 6.0,6.0.1, 6.0.2, 6.0.2.A, and 6.0.2B.
- Yager, D.B., and Quick, J.E., 1993, SuperXap Manual: U.S. Geological Survey Open-File Report 93-12, 45 p.

Yager, D.B., Lunk, K., Luedke, R.G., Bove, D.J., O'Neil, M.J., and Sole. T.C., 1998, Digital geologic compilations of the upper Animas River and Boulder River watersheds: Geographic information systems technology used as a scientific interpretation tool; *in* von Guerard P. and Nimick, D.A. eds., Science for watershed decisions on abandoned mine lands: Review of preliminary results, Denver, Colorado; February 4-5, 1998: U.S. Geological Survey Open-File report 98-297, 71 p.

Zellweger, G.W., 1993, Tracer injections in small streams—why and how we do them: Proceedings of the Toxic Substances Hydrology Program, U.S. Geological Survey Water-Resources Investigations report 94-4015, v. 2, p. 765-768.

Appendix A. Field properties and analytical results for dissolved and total constituents from base-flow tracer study, Prospect Gulch, September 14-15, 1998

[ft³/s, cubic feet per second; µS/cm, microSiemens per centimeter at 25 degrees Centigrade; SC, specific conductivity; mg/L, micrograms per liter; dis., dissolved; tot., total; <, less than]

Site Designation	Time	Instantaneous			Water								
		Discharge (ft ³ /s)	Field SC (µS/cm)	Field pH	Temperature (°C)	SO4 (dis.) (mg/L)	Ferrous (mg/L)	Ca (dis.) (mg/L)	Mg (dis.) (mg/L)	Na (dis.) (mg/L)	K (dis.) (mg/L)	SiO2 (dis.) (mg/L)	Al (dis.) (mg/L)
PGCC	1716	0.515	590	3.61		242		31.58	7.52	1.40	2.33	40.41	14.136
PG800	1243		629	3.23	11.6	190	1.73	44.04	6.45	28.48	0.38	14.27	5.174
TR786	1300		71	3.79	12.8	11	0.19	0.65	0.21	0.13	0.08	1.52	0.123
PG700	1305		708	3.21	11.4	187	1.85	45.08	6.58	51.76	0.48	14.73	5.366
TR679	1310		391	3.18	10.0	105	0.48	7.83	1.97	0.50	0.93	30.81	5.669
PG666	1315		723	3.20	11.4	190	1.88	38.03	5.93	33.97	0.48	11.55	4.040
PG561	1325		737	3.24	11.0	187	1.78	36.05	5.68	33.89	0.49	10.77	3.764
TR542	1325		993	2.62	9.3	227	0.38	3.68	4.54	1.62	0.31	36.15	6.049
PG504	1335		736	3.25	10.4	187	1.61	39.35	6.12	40.51	0.49	11.77	4.236
PG347	1410		836	3.24	9.1	223	1.59	34.87	5.88	35.60	0.47	12.38	4.999
SP305	1414		1154	2.61	9.3	360	1.32	25.26	7.62	1.52	0.49	35.28	12.199
PG303	1420		759	3.18	8.8	183	1.18	34.31	5.07	45.27	0.56	10.51	4.278
TR295	1421		2160	2.36	9.5	953	2.80	35.24	15.42	2.46	0.08	54.38	21.573
PG291	1424		701	3.33	8.9	167	1.20	36.10	5.17	45.81	0.59	9.34	3.840
PG291 replicate	1425		702	3.33	8.9	167	1.19	36.89	5.39	47.45	0.57	9.52	3.827
TR286	1435		753	2.87	9.6	190		6.79	2.51	0.64	1.31	13.14	6.174
PG279	1435		647	3.52	9.0	160	0.95	39.79	5.62	47.26	0.57	8.90	3.720
PG242	1439		575	3.56	9.2	148	0.83	39.50	5.52	39.22	0.58	8.42	3.682
PG205	1450		532	3.91	9.5	148	1.28	43.41	5.49	33.24	0.61	8.05	3.330
LS195	1453		583	3.41	9.8	173	1.74	43.30	5.89	26.85	0.55	9.73	4.293
RS195	1453		490	3.93	9.6	158	1.90	44.24	5.63	25.31	0.69	7.91	4.038
SP193	1500		893	2.82	10.0	220		26.77	5.54	1.49	0.40	17.59	5.825
SP180	1515		954	2.78	10.0	263		28.40	6.31	0.98	0.66	17.71	6.208
PG153	1500		476	3.83	9.1	157		39.16	5.31	22.03	0.67	7.48	4.307
SP114	1525		457	3.05	14.6	85		3.82	1.07	0.63	5.58	16.09	1.433
PG108	1525		440	4.16	10.5	127		36.07	4.98	32.95	0.63	8.32	3.288
TR100	1534		339	3.71	10.0	135		25.79	6.94	0.44	0.51	12.36	8.531
PG99	1538		484	4.37	10.4	125		37.73	4.32	41.86	0.63	6.99	1.441
PG45	1451					150		43.04	5.00	32.40	0.66	6.75	3.438
PG45	1547		517	4.39	10.4	128		38.44	4.35	46.90	0.64	6.75	1.292
PG45	1548		518	4.39	10.4	127		38.93	4.46	43.59	0.63	6.76	1.268
PG-5	1042		335	4.84	9.7	152		49.89	5.64	1.12	0.54	7.21	0.623
PG-5	1401					162		46.63	5.27	0.98	0.57	6.74	0.694
TR295 Hen. Seep	1230	0.001	2010	2.44	9.0	1000		34.89	15.42	1.70	0.94	53.82	21.879
Lark Seep	1100	0.001	3140	2.20	8.2	1967		6.01	10.90	1.28	0.04	74.64	22.093
Blank QA	0001						0.00		<0.15	<0.01	<0.10	<.01	<0.20

Appendix A. Field properties and analytical results for dissolved and total constituents from base-flow tracer study, Prospect Gulch, September 14-15, 1998

[ft³/s, cubic feet per second; [ft³/s, cubic feet per second; μS/cm, microSiemens per centimeter at 25 degrees Centigrade; SC, specific conductivity; mg/L, micrograms per liter; Diss., dissolved; <, less than]

Site Designation	As (dis.) (mg/L)	Ba (dis.) (mg/L)	Be (dis.) (mg/L)	Cd (dis.) (mg/L)	Cr (dis.) (mg/L)	Cu (dis.) (mg/L)	Fe (dis.) (mg/L)	Li (dis.) (mg/L)	Mn (dis.) (mg/L)	Mo (dis.) (mg/L)	Ni (dis.) (mg/L)	Pb (dis.) (mg/L)	Se (dis.) (mg/L)	Sr (dis.) (mg/L)
PGCC		0.018	<0.001	0.005	<0.015	0.134	31.293	0.010	0.715	<0.010	0.038	<0.030		0.484
PG800		0.041	0.005	0.009	<0.015	0.389	4.611	<0.006	0.683	<0.010	<0.020	<0.030		0.939
TR786		0.020	<0.001	<0.002	<0.015	0.043	0.170	<0.006	0.027	<0.010	<0.020	<0.030		0.006
PG700		0.043	0.005	0.009	<0.015	0.399	5.005	<0.006	0.697	<0.010	<0.020	0.143		0.957
TR679		0.049	<0.001	0.016	<0.015	0.291	1.825	0.007	0.195	0.017	0.020	0.090		0.059
PG666		0.036	<0.001	0.006	<0.015	0.316	4.501	<0.006	0.622	<0.010	<0.020	<0.030		0.806
PG561		0.031	<0.001	<0.002	<0.015	0.302	4.833	<0.006	0.589	0.038	<0.020	<0.030		0.767
TR542		0.017	0.002	0.041	<0.015	0.881	16.182	<0.006	0.842	<0.010	<0.020	<0.030		0.045
PG504		0.036	<0.001	0.005	<0.015	0.337	5.552	<0.006	0.636	<0.010	<0.020	<0.030		0.839
PG347		0.032	0.002	0.012	<0.015	0.486	15.481	<0.006	0.617	<0.010	<0.020	<0.030		0.735
SP305		0.014	<0.001	0.022	<0.015	1.599	31.752	0.018	1.012	<0.010	<0.020	<0.030		0.394
PG303		0.046	<0.001	0.008	<0.015	0.391	8.464	<0.006	0.546	<0.010	<0.020	<0.030		0.725
TR295		<0.002	<0.001	0.068	<0.015	4.820	177.768	0.047	2.349	<0.010	<0.020	<0.030		0.302
PG291		0.049	<0.001	0.010	<0.015	0.289	4.885	<0.006	0.545	<0.010	<0.020	<0.030		0.772
PG291 replicate		0.047	<0.001	<0.002	<0.015	0.296	4.970	<0.006	0.543	<0.010	<0.020	0.064		0.785
TR286		0.127	<0.001	0.018	<0.015	1.044	24.515	0.012	0.361	<0.010	<0.020	0.214		0.057
PG279		0.039	<0.001	<0.002	<0.015	0.228	2.859	0.015	0.555	<0.010	<0.020	0.112		0.854
PG242		0.040	<0.001	0.002	<0.015	0.218	1.815	0.008	0.525	<0.010	<0.020	0.045		0.870
PG205		0.040	<0.001	0.003	<0.015	0.151	1.409	0.008	0.457	0.012	<0.020	0.072		1.005
LS195		0.037	<0.001	0.002	<0.015	0.289	3.590	0.008	0.533	0.014	<0.020	0.113		0.988
RS195		0.040	<0.001	<0.002	<0.015	0.186	1.995	0.008	0.470	<0.010	<0.020	0.070		1.021
SP193		0.023	<0.001	0.009	<0.015	0.522	8.033	0.015	0.739	<0.010	<0.020	0.183		0.522
SP180		0.006	<0.001	0.014	<0.015	0.792	18.644	0.015	0.826	<0.010	<0.020	<0.030		0.535
PG153		0.037	<0.001	<0.002	<0.015	0.172	1.835	0.008	0.482	<0.010	<0.020	0.070		0.872
SP114		0.050	<0.001	0.009	<0.015	0.060	5.570	<0.006	0.130	<0.010	<0.020	0.992		0.035
PG108		0.042	<0.001	0.003	<0.015	0.103	0.742	0.008	0.479	<0.010	<0.020	<0.030		0.790
TR100		0.056	0.001	<0.002	<0.015	0.020	0.351	0.008	1.077	<0.010	<0.020	<0.030		0.234
PG99		0.037	<0.001	0.006	<0.015	0.127	0.835	0.008	0.306	<0.010	0.028	<0.030		0.920
PG45		0.034	<0.001	<0.002	<0.015	0.194	1.833	0.008	0.372	<0.010	<0.020	0.062		1.028
PG45		0.036	<0.001	0.005	<0.015	0.113	0.814	0.008	0.302	<0.010	<0.020	0.033		0.931
PG45		0.037	<0.001	0.003	<0.015	0.114	0.793	0.008	0.307	<0.010	<0.020	0.035		0.947
PG-5		0.036	<0.001	<0.002	<0.015	0.066	0.388	0.008	0.367	<0.010	<0.020	<0.030		1.224
PG-5			0.034	<0.001	0.005	<0.015	0.068	0.271	0.337	<0.010	<0.020	<0.030		1.143
TR295 Hen. Seep	0.051	<0.002	<0.001	0.058	<0.015	4.904	176.760	0.052	2.255	<0.010	<0.020	<0.030	0.002	0.298
Lark Seep	0.167	<0.002	<0.001	0.170	<0.015	5.798	317.574	<0.006	0.939	<0.010	<0.020	<0.030	0.003	0.052
Blank QA	<0.040		<0.002	<0.001	<0.002	<0.015	<0.004	<0.030	<0.006	<0.003	0.014	<0.020	<0.030	

Appendix A. Field properties and analytical results for dissolved and total constituents from base-flow tracer study, Prospect Gulch, September 14-15, 1998

[ft³/s, cubic feet per second; [ft³/s, cubic feet per second; μS/cm, microSiemens per centimeter at 25 degrees Centigrade; SC, specific conductivity; mg/L, micrograms per liter; Diss., dissolved; <, less than]

Site Designation	V (dis.) (mg/L)	Zn (dis.) (mg/L)	Ca (tot.) (mg/L)	Mg (tot.) (mg/L)	Na (tot.) (mg/L)	SiO2 (tot.) (mg/L)	Al (tot.) (mg/L)	Ba (tot.) (mg/L)	Be (tot.) (mg/L)	Cd (tot.) (mg/L)	Cr (tot.) (mg/L)	Cu (tot.) (mg/L)	Fe (tot.) (mg/L)	Li (tot.) (mg/L)
PGCC	0.013	1.152												
PG800	<0.004	1.598	34.59	5.55	20.14	12.58	3.657	0.044	<0.001	0.012	<0.015	0.326	4.146	<0.006
TR786	<0.004	0.032	0.70	0.29	0.15	2.65	0.435	0.027	<0.001	<0.002	<0.015	0.050	0.936	<0.006
PG700	<0.004	1.755	37.10	5.79	33.99	12.23	4.109	0.043	<0.001	0.007	<0.015	0.316	4.410	<0.006
TR679	<0.004	3.864	7.44	1.87	0.49	29.40	5.403	0.055	<0.001	0.013	<0.015	0.274	2.119	0.007
PG666	<0.004	1.503	41.76	6.40	35.73	12.02	4.473	0.041	<0.001	0.006	<0.015	0.317	5.033	<0.006
PG561	<0.004	1.351	43.40	6.59	40.52	12.20	4.658	0.045	<0.001	0.010	<0.015	0.335	6.033	<0.006
TR542	<0.004	8.664	3.22	4.29	0.57	34.66	5.581	0.041	<0.001	0.036	<0.015	0.768	17.279	<0.006
PG504	<0.004	1.449	46.14	6.86	42.47	12.25	5.003	0.042	<0.001	0.005	<0.015	0.342	6.631	<0.006
PG347	<0.004	2.318	37.16	6.13	45.60	14.29	5.740	0.048	<0.001	0.018	<0.015	0.531	19.735	<0.006
SP305	<0.004	6.054	24.26	7.52	1.20	32.64	11.621	0.023	<0.001	0.023	<0.015	1.402	31.359	<0.006
PG303	<0.004	1.705	33.44	5.54	41.62	14.29	5.075	0.106	<0.001	0.013	<0.015	0.396	18.729	<0.006
TR295	<0.004	10.000												
PG291	<0.004	1.257	32.16	5.14	40.47	12.83	4.382	0.110	<0.001	0.008	<0.015	0.298	15.210	<0.006
PG291 replicate	<0.004	1.281	33.77	5.35	41.15	14.06	4.867	0.112	<0.001	0.010	<0.015	0.294	16.155	<0.006
TR286	<0.004	4.499	7.05	2.78	0.66	16.25	7.514	0.179	<0.001	0.029	<0.015	1.029	33.478	<0.006
PG279	<0.004	1.093	36.19	5.41	49.09	11.07	4.105	0.092	<0.001	0.011	<0.015	0.248	10.140	<0.006
PG242	<0.004	1.057	38.23	5.66	34.71	10.75	4.522	0.095	<0.001	0.006	<0.015	0.217	12.615	<0.006
PG205	<0.004	0.818	40.94	5.43	28.43	9.10	3.831	0.062	<0.001	0.004	<0.015	0.155	10.857	<0.006
LS195	<0.004	1.134	37.31	5.28	22.55	9.49	3.890	0.048	<0.001	0.010	<0.015	0.260	11.841	<0.006
RS195	<0.004	0.788	41.45	5.46	23.14	8.88	4.665	0.059	<0.001	0.005	<0.015	0.183	14.975	<0.006
SP193	<0.004	2.344	28.80	5.68	1.24	18.71	5.954	0.040	<0.001	0.010	<0.015	0.507	12.547	<0.006
SP180	<0.004	3.055	29.75	6.64	0.91	18.60	6.384	0.010	<0.001	0.015	<0.015	0.822	19.796	<0.006
PG153	<0.004	0.738	41.20	5.45	23.11	8.48	5.152	0.061	<0.001	0.005	<0.015	0.190	10.980	<0.006
SP114	<0.004	1.642	3.81	1.29	0.75	18.04	2.350	0.099	<0.001	0.009	<0.015	0.068	11.829	<0.006
PG108	<0.004	0.928	31.69	4.48	23.29	7.72	3.144	0.042	<0.001	0.006	<0.015	0.091	2.909	<0.006
TR100	<0.004	0.147	21.55	6.01	0.32	10.71	6.995	0.053	<0.001	<0.002	<0.015	0.016	0.706	<0.006
PG99	<0.004	1.260	36.47	4.26	38.35	7.31	1.976	0.040	<0.001	0.008	<0.015	0.127	3.388	<0.006
PG45	<0.004	0.869												
PG45	<0.004	1.160	37.15	4.36	43.30	7.37	1.794	0.045	<0.001	0.008	<0.015	0.118	3.396	<0.006
PG45	<0.004	1.153	37.47	4.38	42.58	7.35	1.737	0.044	<0.001	0.006	<0.015	0.118	3.294	<0.006
PG-5	<0.004	0.844	48.11	5.38	0.99	7.03	0.938	0.037	<0.001	<0.002	<0.015	0.068	0.726	<0.006
PG-5	<0.004	0.754												
TR295 Hen. Seep	<0.004	9.773	48.35	16.92	2.20	61.05	23.376	0.012	<0.001	0.067	<0.015	5.216	190.275	0.041
Lark Seep	<0.004	28.882												
Blank QA	<0.003	0.005	<0.020											

Appendix A. Field properties and analytical results for dissolved and total constituents from base-flow tracer study, Prospect Gulch, September 14-15, 1998

[ft³/s, cubic feet per second;

Site Designation	Mn (tot.) (mg/L)	Mo (tot.) (mg/L)	Ni (tot.) (mg/L)	Pb (tot.) (mg/L)	Sr (tot.) (mg/L)	V (tot.) (mg/L)	Zn (tot.) (mg/L)
PGCC							
PG800	0.651	0.065	<0.020	<0.030	0.724	<0.004	1.570
TR786	0.034	<0.010	<0.020	<0.030	0.011	<0.004	0.025
PG700	0.620	0.032	<0.020	0.063	0.782	<0.004	1.429
TR679	0.189	<0.010	<0.020	0.074	0.057	0.004	3.727
PG666	0.639	<0.010	<0.020	<0.030	0.889	<0.004	1.678
PG561	0.650	<0.010	<0.020	0.071	0.926	<0.004	1.447
TR542	0.787	0.032	<0.020	<0.030	0.045	<0.004	6.853
PG504	0.649	0.024	<0.020	<0.030	0.985	<0.004	1.624
PG347	0.648	<0.010	<0.020	0.060	0.787	<0.004	2.150
SP305	0.974	0.038	<0.020	<0.030	0.384	<0.004	5.415
PG303	0.581	0.037	<0.020	0.671	0.722	<0.004	1.565
TR295							
PG291	0.554	0.078	<0.020	1.131	0.698	<0.004	1.140
PG291 replicate	0.552	0.050	<0.020	1.080	0.736	<0.004	1.151
TR286	0.377	0.059	<0.020	0.483	0.073	<0.004	4.184
PG279	0.618	0.051	<0.020	0.785	0.787	<0.004	1.034
PG242	0.549	<0.010	<0.020	0.535	0.844	<0.004	1.063
PG205	0.481	0.015	<0.020	0.182	0.950	<0.004	0.889
LS195	0.519	0.043	<0.020	0.203	0.832	<0.004	1.088
RS195	0.465	0.011	<0.020	0.206	0.963	<0.004	0.863
SP193	0.726	0.028	<0.020	0.251	0.544	<0.004	1.978
SP180	0.887	0.052	<0.020	<0.030	0.561	<0.004	2.699
PG153	0.514	<0.010	<0.020	0.154	0.932	<0.004	0.770
SP114	0.147	<0.010	<0.020	1.573	0.051	0.004	1.639
PG108	0.452	0.015	<0.020	0.046	0.697	0.006	0.887
TR100	0.951	<0.010	<0.020	<0.030	0.196	<0.004	0.105
PG99	0.305	<0.010	<0.020	0.101	0.890	<0.004	1.352
PG45							
PG45	0.317	<0.010	<0.020	0.134	0.907	<0.004	1.266
PG45	0.325	<0.010	<0.020	0.123	0.914	<0.004	1.268
PG-5	0.363	<0.010	<0.020	<0.030	1.193	<0.004	0.812
PG-5							
TR295 Hen. Seep	2.614	0.063	<0.020	<0.030	0.462	<0.004	9.739
Lark Seep							
Blank QA							