Distribution of pH Values and Dissolved Trace-Metal Concentrations in Streams

By Winfield G. Wright, William Simon, Dana J. Bove, M. Alisa Mast, and Kenneth J. Leib

Chapter E10 of
Integrated Investigations of Environmental Effects of Historical Mining in the Animas River Watershed, San Juan County, Colorado

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Chapter E10
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Abstract

The Animas River watershed study area contains nearly 5,400 inactive mines, prospect pits, and other mining-related features. Many of these features do not affect water-quality conditions. For this study, a subset of mines was selected representing draining mines, mine waste-rock piles, and permitted mine and mill sites that may affect the environment.

Dissolved trace-metal concentrations and pH values in streams throughout the watershed were highly variable and depended on factors such as hydrothermal alteration, acid-neutralizing capacity of the rocks, and mixing of different waters. Hydrothermal alteration was the primary influence on distribution of trace-metal concentrations, because the rocks in the Animas River watershed have a wide range of mineral assemblages. Many of the historical mines are located in highly mineralized and altered areas.

Spatial distribution maps prepared for this report display areas of hydrothermal alteration and locations of selected historical mine sites. They show color ranges for different pH values and dissolved trace-metal concentrations in study area streams, and they depict low-flow and high-flow conditions of the streams.

Because of the combined effects of hydrothermal alteration and historical mines, to attribute low pH values and high trace-metal concentrations to either source is difficult; however, several historical mines clearly affect the study area streams. Several non-mining related iron and manganese springs affect low pH values and high trace-metal concentrations, for example, near peak 3,792 m in Mineral Creek basin, in Cement Creek, and in California Gulch.

Introduction

Trace metals are inorganic chemicals usually occurring in small amounts in nature. In the Animas River watershed study area, however, trace metals such as aluminum, copper, iron, manganese, and zinc can occur in high concentrations due to the weathering of mineralized rocks and drainage from historical mines. These high concentrations can be harmful to the aquatic life in the Animas River and its tributaries (Besser and Brumbaugh, this volume, Chapter E18; Besser and others, this volume, Chapter D). High concentrations of copper and zinc in streams can be acutely toxic to fish and other aquatic life. High concentrations of aluminum and iron cause the precipitation of solids in zones where acidic and more neutral waters mix, and the precipitates can reduce productivity of food sources for aquatic life or prohibit the development or retention of suitable aquatic habitat. High manganese concentrations can be toxic to aquatic life and are pervasive in streams of the study area because of the abundance of manganese-related minerals (Bove and others, this volume, Chapter E3) and the high solubility of manganese at the pH range of streams in the study area (Garrels and Christ, 1965). The pH of stream water is an important control of trace metal solubility—where pH values are low, dissolved iron and aluminum concentrations generally are high; where pH values are high, iron and aluminum concentrations are low.

The study area has deep snowpack in the winter, and snowmelt runoff can increase streamflow by several orders of magnitude (Mast, Evans, and others, 2000; von Guerard and others, this volume, Chapter B), thereby diluting dissolved trace-metal concentrations in streams. Descriptions of climate, snowpack, annual streamflow, and the differences between low flow and high flow at selected sites can be found in Mast, Evans, and others (2000) and Leib and others (this volume, Chapter E11). Trace-metal precipitation and annual runoff in the study area exhibit some unusual characteristics that are not easily explained using accepted hydrologic and geochemical principles; some of these unusual characteristics are described in this chapter for the purposes of future investigation.

The presence of historical mines may contribute to or intensify the characteristics of pH and trace-metal distribution. Remediation of historical mines can bring about benefits to a watershed in the form of achieving levels of pH and trace-metal content closer to those of the undisturbed site. Effects of weathering of hydrothermally altered rocks on water

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quality as well as trace-metal discharges from large springs are also important to consider, however, in attempts to remediate historical mining areas. Better understanding of the complex sources of spatial distribution of pH values and trace-metal concentrations can be used to indicate areas that might benefit most from mine-site remediation.

Purpose and Scope

The purposes of this chapter are the following:

- Describe the distribution of pH values and selected trace-metal concentrations in streams during low and high flow

- Describe some of the unusual characteristics of trace-metal precipitation and annual runoff in the watershed

- Show photographic examples of features that result from high trace-metal concentrations in waters of the study area.

Spatial distribution maps are presented using water-quality data collected during 1991–99. For the low-flow distribution maps, the data do not reflect a single snapshot of pH values and trace-metal concentrations in streams due to the wide area covered and the large number of samples that constitute the low-flow data set. For the high-flow distribution maps, data from a synoptic sampling of the watershed are presented; however, fewer sites are represented by the high-flow data set because access to the high country during snowmelt runoff was difficult or impossible. Ranges of trace-metal concentrations in streams are indicated on the spatial distribution maps to provide a pictorial presentation of the water-quality conditions in the watershed.

Methods of Study

Sample Collection

Low-flow data were collected during 1991–99. These data do not represent a steady-state snapshot of conditions in the watershed. The primary goal of the low-flow data was to show the ranges of water-quality conditions in the high-altitude tributary streams as they are influenced by hydrothermal alteration and the presence of historical mines. The ranges of pH and trace-metal concentrations do not substantially vary between years during low flow. Because of snowmelt, the most important contrasts occur between low-flow and high-flow conditions. Most of the low-flow data were collected by the U.S. Geological Survey (USGS) during late summer (Wright and Janik, 1995; Mast, Evans, and others,

2000; Sole and others, this volume, Chapter G). A few of the samples were collected during late fall or mid-winter low-flow conditions. Data gaps were filled in by use of selected low-flow samples collected by the Colorado Department of Public Health and Environment (CDPHE) (Peter Butler, Robert Owen, and William Simon, Unpublished report to Colorado Water Quality Control Commission, Animas River Stakeholders Group, 2001), Schemel and others (2000), and Wirt and others (2001). Locations of the low-flow sampling sites are in figure 1, and the data are in table 1.

High-flow data were collected during June 23–25, 1992, by the CDPHE. These sites were not as numerous as the low-flow sites and do not include the high-altitude tributary streams. Because of the diurnal streamflow fluctuations during snowmelt runoff (Leib and others, this volume, Chapter E11), these high-flow samples do not necessarily represent a steady-state snapshot of conditions in the watershed. Locations of the high-flow sampling sites are shown in figure 2, and the data are listed in table 2.

Site numbers for data collected by the USGS are prefixed with UA (upper Animas River site), CC (Cement Creek site), MC (Mineral Creek site), and MS (mine site) (table 1). The USGS collected samples for seasonal analyses at mainstem streams where CDPHE site numbers were used (1996–99 sampling dates), and the sites are prefixed with COA (Colorado Animas River site), COC (Colorado Cement Creek site), and COM (Colorado Mineral Creek site) (table 1). Site numbers for other low-flow sites are prefixed with AR for Animas River (Schemel and others, 2000) and PG for Prospect Gulch (Wirt and others, 2001). Site numbers for high-flow data collected by the CDPHE are prefixed with COA (Colorado Animas River site), COC (Colorado Cement Creek site), and COM (Colorado Mineral Creek site) (table 2).

At sites where water-quality samples were collected by the USGS, field parameters (pH, specific conductance, water temperature, discharge, and dissolved oxygen) were measured at the time of sample collection. Samples were filtered using 0.45-μm (micrometer) filters and acidified using concentrated nitric acid for analysis of dissolved trace-metal concentrations. Samples were not collected for total (unfiltered) trace metals in the high-altitude tributary streams. Samples were analyzed within 6 months after collection by using inductively coupled plasma–atomic emission spectroscopy (ICP-AES). Sample collection methods and quality-assurance information for USGS data presented in this study are described in Mast, Evans, and others (2000). Methods for collection and analysis of CDPHE data are described in the internal document, "Guidance on Data Requirements and Data Interpretation Methods Used in Stream Standards and Classification Proceedings (July 1993)" (http://www.cdphe.state.co.us/wq/Assessment/assessment_practices_and_methods.htm accessed August 14, 2002).
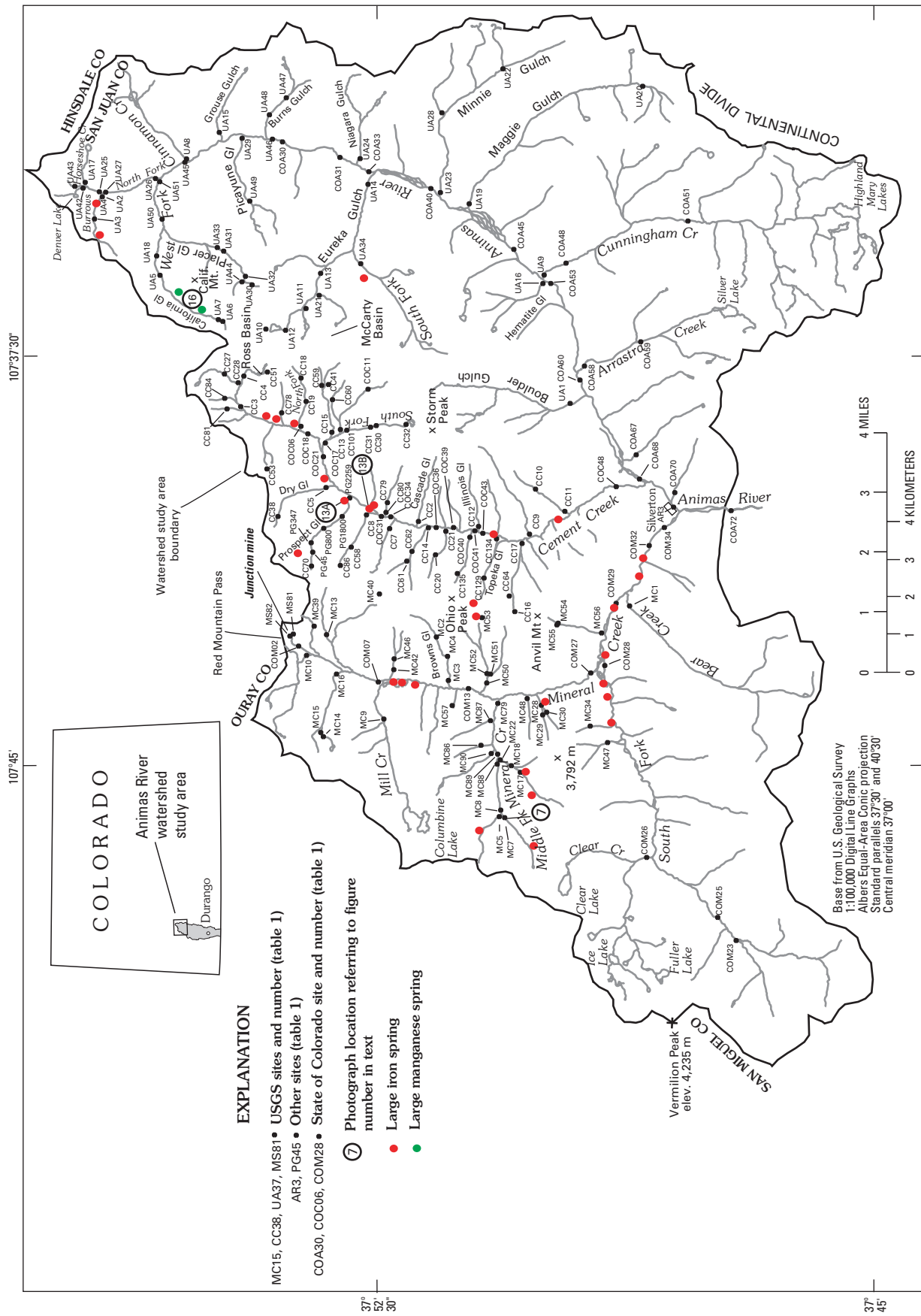
Figure 1.   Locations of water-quality sampling sites where data were collected for construction of low-flow distribution maps.

Table 1. Selected water-quality data for construction of the low-flow distribution maps.

[Some site names are informal place names used on local signage; ft³/s, cubic feet per second; SC, specific conductance; µS/cm, microsiemens per centimeter at 25°C; pH, s.u., standard units; temp., temperature; °C, degrees Celsius; Al, aluminum; Cu, copper; Fe, iron; Mn, manganese; Zn, zinc; Diss., dissolved; µg/L, micrograms per liter; <, less than; --, no data; BDL, below detection limit; data, unless otherwise indicated, are from Mast, Evans, and others, 2000]

Site number (fig. 1)	Site name	Date	Time	Stream-flow (ft³/s)	SC (µS/cm)	pH (s.u.)	Water temp. (°C)	Diss. Al (µg/L)	Diss. Cu (µg/L)	Diss. Fe (µg/L)	Diss. Mn (µg/L)	Diss. Zn (µg/L)
				Animas River basin								
UA1---	Boulder Gulch near mouth	9/26/97	14:00	5.00	93	7.45	7.4	63	<4	37	<3	25
UA2---	Burrows Creek upstream from North Fork	9/05/98	14:45	0.56	181	4.55	16.1	5,350	58	93	2,660	2,330
UA3---	Burrows Creek downstream from London mine	9/05/98	11:30	--	215	4.30	13.0	9,140	66	137	2,540	3,880
UA4---	Burrows Creek downstream from wetland	9/05/98	13:40	0.71	192	4.49	15.7	6,230	63	146	2,910	2,510
UA5---	California Gulch upstream from mines	8/18/98	14:00	1.74	135	4.9	13.5	3,220	16	67	9,670	1,540
UA6---	California Gulch upstream from Mountain Queen mine	8/11/98	14:00	0.52	474	6.63	6.4	<40	10	<30	19	44
UA7---	California Gulch downstream from Mountain Queen mine	8/11/98	15:30	0.65	365	6.55	8.8	109	12	<30	143	204
UA8---	Cinnamon Creek near mouth	9/08/98	10:45	2.32	174	7.32	7.4	<40	<4	<30	<3	<20
UA9---	Cunningham Creek near mouth	9/23/98	14:15	7.46	260	8.13	12.1	<40	<4	<30	<3	27
UA10--	Eureka Gulch upstream from mines	9/08/98	12:00	0.04	86	5.81	7.5	112	<4	<30	27	198
UA11--	Eureka Gulch upstream from sink holes	9/13/98	15:00	0.53	161	6.62	10.8	<40	<4	<30	21	220
[1a]UA12--	Eureka Gulch downstream from cut dike	9/08/98	14:00	0.06	254	6.45	9.7	63	5	<30	1,210	2,070
UA13--	Eureka Gulch downstream from Terry tunnel	9/13/98	13:00	2.17	148	6.28	11.3	96	10	<30	287	338
UA14--	Eureka Gulch near mouth	9/14/98	11:30	6.72	308	7.10	8.4	140	6	<30	161	373
UA15--	Grouse Gulch near mouth	9/06/98	12:45	1.76	228	6.97	9.9	<40	<4	<30	<3	<20
UA16--	Hematite Gulch near mouth	9/23/98	13:50	0.68	277	8.24	9.0	<40	<4	<30	<3	<20
UA17--	Horseshoe Creek near mouth	9/04/98	10:40	0.95	109	6.76	8.5	<40	<4	<30	<3	34
UA18--	Lower California Gulch	8/18/98	16:00	2.19	278	5.32	12.3	1,800	8	113	8,640	1,440
UA19--	Maggie Gulch near mouth	9/23/98	12:55	1.98	232	8.49	9.2	<40	<4	<30	<3	<20
UA20--	Maggie Gulch upstream from mines	10/03/98	15:00	0.65	193	6.81	7.0	42	<4	<30	25	<20
UA21--	McCarty Basin	9/13/98	16:30	0.37	109	6.67	9.3	57	<4	<30	17	29
UA22--	Minnie Gulch upstream from Esmeralda mine	9/29/98	13:30	1.21	185	8.15	8.4	<40	<4	35	<3	<20
UA23--	Minnie Gulch near mouth	9/23/98	12:05	2.71	253	8.42	7.4	77	<4	<30	23	<20
UA24--	Niagara Gulch near mouth	9/09/98	9:40	0.51	195	7.27	6.4	<40	<4	<30	<3	<20
UA25--	North Fork upstream from Burrows Creek	9/05/98	15:30	1.52	105	6.76	15.6	43	<4	<30	<3	44
UA26--	North Fork upstream from West Fork	9/06/98	11:30	2.60	114	5.99	10.7	55	9	<30	663	772
UA27--	North Fork downstream from Burrows Creek	9/05/98	16:15	1.88	121	5.41	15.5	360	17	54	920	840
UA28--	North fork Minnie Gulch	10/3/98	13:15	0.26	219	6.79	4.4	<40	<4	<30	<3	<20
UA29--	Picayune Gulch near mouth	9/09/98	8:30	1.09	386	6.86	6.7	62	<4	<30	11	<20
UA30--	Placer Gulch upstream from Gold Prince mine	9/23/98	13:30	0.05	171	7.34	6.4	<40	<4	<30	<3	256
UA31--	Placer Gulch upstream from Sunbank mine	9/28/98	14:30	0.53	184	6.40	9.7	92	6	<30	270	905
UA32--	Placer Gulch downstream from Gold Prince mine	9/23/98	16:30	0.41	141	6.61	9.5	57	<4	<30	736	839
UA33--	Placer Gulch downstream from Sunbank mine	9/28/98	15:30	0.63	195	5.93	9.4	362	21	704	1,180	1,210
[2b]COA33-	Animas River at Eureka	9/23/98	11:05	8.78	219	6.48	6.6	<40	<4	<30	971	573

Table 1.   Selected water-quality data for construction of the low-flow distribution maps.—Continued

Site number (fig. 1)	Site name	Date	Time	Stream-flow (ft³/s)	SC (µS/cm)	pH (s.u.)	Water temp. (°C)	Diss. Al (µg/L)	Diss. Cu (µg/L)	Diss. Fe (µg/L)	Diss. Mn (µg/L)	Diss. Zn (µg/L)
				Animas River basin—Continued								
UA34--	South fork Eureka Gulch	9/07/98	15:00	3.70	307	6.37	10.4	115	5	431	116	46
UA42--	Stream downstream from Denver Lake	9/04/98	12:35	0.26	63	7.15	18.0	<40	<4	<30	<3	<20
UA43--	Stream downstream from Lucky Jack mine	9/04/98	12:15	0.06	100	6.72	14.1	<40	<4	33	205	665
UA44--	Stream in Placer Gulch	9/23/98	12:00	0.24	100	4.86	6.4	2,200	5	<30	922	154
UA45--	Upper Animas River upstream from Cinnamon Creek	9/08/98	11:40	4.80	211	6.22	10.4	369	16	75	3,690	1,430
UA46--	Upper Animas River upstream from Silver Wing mine	9/30/98	14:00	10.4	228	6.68	10.2	65	4	<30	1,300	628
UA47--	Upper Burns Gulch	9/07/98	11:00	2.30	147	6.60	6.8	<40	<4	<30	<3	35
UA48--	Upper Burns Gulch	9/07/98	12:00	2.07	160	6.81	8.9	59	28	<30	45	790
[1a]UA49--	Upper Picayune Gulch	9/08/98	14:00	0.39	208	7.44	16.0	141	<4	<30	96	28
UA50--	West Fork Animas River downstream from Placer Gulch	8/19/98	12:00	0.31	180	5.75	10.0	606	7	112	4,700	1,070
UA51--	West Fork Animas River at Animas Forks	8/19/98	15:00	3.49	190	5.89	13.1	326	19	<30	4,260	1,390
[3c]COA60	Animas River downstream from Arrastra Creek	8/19/99	12:05	167	175	7.37	9.5	72	<4	<30	243	226
[4d]COA68	Animas River at Silverton	9/30/98	13:15	34	295	7.27	11	80	<4	<30	1,220	351
[5e]COA72	Animas River downstream from Silverton	9/30/98	11:00	111	440	6.73	7.5	77	<4	895	1,100	375
				Cement Creek basin								
CC2---	Cascade Gulch near mouth	9/04/97	16:20	0.50	243	7.96	7.0	<40	<4	<30	<3	<20
CC3---	Cement Creek upstream from Mogul mine	9/10/97	15:15	1.19	199	6.17	10.2	109	66	<30	745	1,200
CC4---	Cement Creek downstream from Ross Basin	9/10/97	10:15	0.40	189	6.82	8.1	76	23	<30	47	470
CC5---	Dry Gulch upstream from Eveline mine	9/26/97	9:30	0.27	89	3.89	7.3	907	36	155	64	91
CC7---	Fairview Gulch near mouth	9/26/97	12:15	0.71	113	7.50	7.2	<40	<4	<30	<3	<20
CC8---	Georgia Gulch near mouth	9/25/97	16:30	0.65	205	5.86	8.5	43	10	55	323	424
CC9---	Hancock Gulch near mouth	9/04/97	15:20	0.20	236	7.68	8.2	<40	<4	<30	<3	<20
CC10--	South fork, Hancock Gulch upstream from adit	8/29/97	14:15	0.20	233	6.93	4.7	<40	<4	<30	<3	<20
CC11--	South fork, Hancock Gulch at mouth	9/03/97	15:00	0.37	290	7.23	10.1	73	<4	<30	61	<20
CC12--	Illinois Gulch upstream from Yukon adit	9/04/97	17:00	0.05	162	7.91	8.4	<40	<4	<30	<3	<20
CC13--	Middle Fork Cement Creek near mouth	9/30/97	12:00	--	444	6.64	4.6	45	<4	71	575	278
CC14--	Minnesota Gulch near mouth	9/27/97	13:00	0.77	196	6.90	13.8	45	5	<30	364	147
CC15--	Near mouth of gulch in drainage from Minnehaha Basin	9/30/97	15:45	0.71	144	7.32	7.6	68	6	<30	15	72
CC16--	Niagara Gulch downstream from Irene mine	9/28/97	11:25	0.06	437	3.14	11.0	1,530	99	19,370	420	448
CC17--	Niagara Gulch near mouth	9/28/97	14:30	0.49	247	3.51	11.8	2,930	20	2,460	194	93
[6f]COC17-	South Fork Cement Creek at Gladstone	11/03/98	14:30	2.34	700	5.75	2.9	974	42	2,250	2,370	965

Table 1. Selected water-quality data for construction of the low-flow distribution maps.—Continued

Site number (fig. 1)	Site name	Date	Time	Stream-flow (ft^3/s)	SC (µS/cm)	pH (s.u.)	Water temp. (°C)	Diss. Al (µg/L)	Diss. Cu (µg/L)	Diss. Fe (µg/L)	Diss. Mn (µg/L)	Diss. Zn (µg/L)
				Cement Creek basin—Continued								
CC18--	North Fork Cement Creek upstream from Gold King	9/24/99	14:00	0.08	395	4.79	5.5	100	<4	<30	507	64
CC19--	North Fork Cement Creek upstream from upper Gold King	9/22/99	15:00	0.14	300	3.70	9.7	1,350	136	204	385	549
CC20--	Porcupine Gulch upstream from mines	9/29/97	14:30	0.21	168	6.99	8.7	<40	<4	37	<3	<20
CC21--	Porcupine Gulch near mouth	9/29/97	16:00	0.34	655	6.38	10.2	86	<4	3,220	4,760	930
CC27--	Creek upstream from Queen Anne adit	9/06/97	13:00	0.20	176	7.20	7.8	<40	<4	<30	<3	96
CC28--	Creek downstream from Queen Anne adit near mouth	9/10/97	12:45	0.30	252	5.19	8.9	1,110	55	<30	1,660	1,410
CC30---	South Fork Cement Creek upstream from Natalie/Occidental mine	10/17/96	14:00	0.48	191	5.36	3.8	168	8	<30	61	38
[7g]COC31	Cement Creek at Fairview Gulch bridge	11/03/98	15:15	10.7	1,010	4.04	6.0	6,560	34	16,310	1,910	957
CC31---	South Fork Cement Creek downstream from Big Colorado mine	10/17/96	11:30	1.78	603	5.78	3.8	932	17	4,800	1,180	381
CC32---	South Fork Cement Creek downstream from Velocity Lake	10/17/96	15:30	0.43	150	7.10	3.0	98	<4	<30	10	<20
CC38---	Spring in Dry Gulch	8/12/98	14:00	<0.01	50	4.45	13.1	232	7	50	18	<20
CC41---	Spring in Minnehaha Basin	9/30/97	13:25	0.54	173	6.82	1.4	<40	<4	<30	<3	<20
[8h]COC43	Cement Creek near Yukon tunnel	8/17/99	15:20	35.7	542	4.22	11	2,970	186	2,500	1,140	1,270
[9i]COC48	Cement Creek at Silverton	9/30/98	14:30	18	963	3.78	12	4,810	26	4,100	2,490	605
CC51---	Headwaters of Ross Basin	9/05/97	14:10	0.01	287	6.96	1.2	<40	<4	<30	4	237
CC53---	Spring near Corkscrew Pass	9/07/97	14:35	0.01	76	3.92	11.2	1,000	<4	<30	12	<20
CC58---	Stream downstream from Kansas City mine	9/25/97	15:30	0.03	775	3.30	8.4	3,110	619	6,600	10,800	3,950
CC59---	Stream downstream from Lead Carbonate Mill	9/30/97	12:30	0.01	565	3.06	16.8	4,690	380	7,450	1,210	3,880
CC60---	Stream in Middle Fork Cement Creek	9/30/97	10:00	0.33	63	6.52	6.9	<40	<4	<30	5	<20
CC61---	Stream in Minnesota Gulch	9/27/97	10:00	0.26	146	7.46	12.6	63	<4	<30	13	<20
CC62---	Stream in Minnesota Gulch	9/27/97	11:15	0.07	444	3.32	14.2	2,150	65	2,380	864	763
CC64---	Stream in Niagara Gulch	9/28/97	13:10	0.03	673	2.97	16.7	7,160	41	11,650	332	93
CC70---	Stream in upper Prospect Gulch	9/10/97	15:00	0.05	158	6.83	10.0	<40	<4	64	191	<20
CC78---	Stream near Adams mine	10/01/99	13:00	--	52	4.59	2.5	437	17	<30	61	74
CC79---	Telephone gulch upstream from adit	9/05/97	11:05	0.05	124	4.58	7.1	583	19	60	70	42
CC80---	Telephone gulch at mouth	9/05/97	12:15	0.03	160	4.28	10.0	1,750	31	33	149	56
CC81---	Tributary of upper Cement Creek	9/07/97	13:45	0.01	163	7.16	16.5	55	<4	<30	9	<20
CC84---	Tributary of upper Cement Creek	9/07/97	13:35	0.006	76	6.7	8.4	<40	<4	<30	<3	<20
CC86---	Upper Georgia Gulch	9/25/97	13:25	0.28	316	6.54	9.2	133	<4	<30	559	178
[10j]CC101--	South Fork Cement Creek upstream from Middle Fork	10/17/96	10:00	1.87	640	5.07	1.8	1,030	24	4,130	1,310	473
[10j]CC129--	Topeka Gulch upstream from mines	9/04/94	17:00	0.15	558	3.27	9	6,800	41	13,000	1,200	206
[10j]CC134--	Topeka Gulch at mouth	9/10/94	17:00	0.19	1,480	6.72	10.1	153	7	870	2,000	74
[10j]CC135--	Upper Ohio Gulch	9/30/94	14:00	0.001	980	3.34	9.4	11,000	336	2,300	9,900	1,200

Table 1. Selected water-quality data for construction of the low-flow distribution maps.—Continued

Site number (fig. 1)	Site name	Date	Time	Stream-flow (ft³/s)	SC (µS/cm)	pH (s.u.)	Water temp. (°C)	Diss. Al (µg/L)	Diss. Cu (µg/L)	Diss. Fe (µg/L)	Diss. Mn (µg/L)	Diss. Zn (µg/L)
				Mineral Creek basin								
MC1---	Bear Creek near mouth	9/27/97	14:30	--	135	7.51	8.6	78	<4	<30	7	<20
MC2---	Browns Gulch upstream from Brooklyn mine	9/18/99	10:40	0.80	281	4.62	4.0	9,110	18	405	569	55
MC3---	Browns Gulch near mouth	7/18/99	15:30	1.40	270	4.30	12.0	4,110	53	376	1,310	940
MC4---	Browns Gulch downstream from Brooklyn mine	9/18/99	12:15	1.04	349	4.01	5.6	8,110	67	829	1,470	749
MC5---	Creek draining Crystal Lake at mouth	8/27/98	16:35	0.40	204	6.84	12.9	59	<4	<30	<10	<20
[11k]COM07	Mineral Creek at Chattanooga	4/06/99	14:15	1.76	205	4.19	0.3	1,080	594	1,060	462	3,050
MC7---	Middle Fork Mineral Creek upstream from Paradise portal	8/27/98	16:15	1.76	566	6.86	9.8	100	<4	310	<10	52
MC8---	Middle Fork Mineral Creek downstream from Paradise portal	8/27/98	14:05	3.96	874	5.32	11.4	2,710	<4	14,640	26	164
MC9---	Mill Creek near mouth	8/26/99	11:00	3.83	89	7.69	9.9	<40	<4	<30	<3	<20
MC10--	Mineral Creek near Red Mountain Pass	8/25/99	9:40	3.14	77	7.33	8.5	<40	<4	<30	<3	<20
MC13--	North tributary to Big Horn Gulch downstream from mines	9/21/99	17:00	0.36	200	4.84	8.9	252	69	228	150	494
[12l]COM13	Mineral Creek at Burro Bridge	2/24/99	11:15	3.48	691	6.50	0.1	<40	129	<30	522	1,590
MC14--	Porphyry Gulch upstream from Bullion King mine	8/24/99	13:25	0.77	52	6.70	12.5	<40	<4	<30	4	<20
MC15--	Porphyry Gulch downstream from Bullion King mine	8/24/99	14:30	0.80	60	6.67	10.5	75	<4	<30	73	120
MC16--	Porphyry Gulch downstream from Highway 550	8/25/99	10:45	--	68	7.18	10.4	45	<4	<30	<3	35
MC17--	North-flowing tributary to Middle Fork Mineral Creek	10/02/98	9:30	0.86	1,369	3.74	1.4	51,530	22	76,650	1,770	302
MC18--	North-flowing tributary to Middle Fork Mineral Creek	10/02/98	10:30	0.84	1,785	3.74	2.6	71,430	<4	117,290	2,150	353
MC22--	North-flowing tributary to Middle Fork Mineral Creek	10/2/98	14:30	1.01	1,406	3.32	11.2	54,020	21	69,310	1,840	354
[13m]COM27	Mineral Creek upstream from South Fork	4/22/98	14:15	19.1	607	4.45	6.2	4,800	115	2,760	642	729
MC28--	Spring on lower Mineral Creek	8/12/98	16:30	0.002	465	3.59	8.3	11,880	147	33,520	1,180	445
MC29--	Spring on lower Mineral Creek	8/12/98	15:30	0.001	459	3.22	8.0	14,380	372	15,050	1,160	580
MC30--	Spring on lower Mineral Creek	8/28/97	17:30	0.001	576	3.02	15.8	7,650	80	4,260	772	314
MC34--	Spring near peak 3,792 m	8/28/97	11:30	--	675	2.70	10.0	1,630	193	16,200	22	<20
[14n]COM34	Mineral Creek at Silverton	9/25/97	12:30	181	203	6.82	7.6	44	<4	281	144	131
MC39--	Stream downstream from Congress mine	9/17/99	16:00	0.03	715	2.93	8.9	3,180	8,390	40,540	384	10,940
MC40--	Stream downstream from mine in US Basin	9/17/99	15:00	0.06	466	6.59	9.5	129	<4	134	3,970	353
MC42--	Stream east of Chattanooga beaver ponds	8/27/99	9:30	0.72	112	6.11	7.8	198	7	105	140	46
MC46--	Stream near Chattanooga beaver ponds	8/26/99	13:45	--	313	3.25	--	923	32	849	822	310
MC47--	Stream near peak 3,792 m	8/26/97	15:00	--	377	3.63	--	2,570	4	645	355	61
MC48--	Stream near peak 3,792 m	9/03/98	16:50	0.10	471	3.45	11.9	2,820	13	4,040	771	90
MC50--	Stream south of Browns Gulch	8/25/99	15:00	1.95	311	3.25	10.1	5,510	78	2,160	271	38
MC51--	Stream south of Browns Gulch	8/25/99	14:00	0.41	70	3.88	9.3	599	<4	211	46	29

Table 1. Selected water-quality data for construction of the low-flow distribution maps.—Continued

Site number (fig. 1)	Site name	Date	Time	Stream-flow (ft³/s)	SC (µS/cm)	pH (s.u.)	Water temp. (°C)	Diss. Al (µg/L)	Diss. Cu (µg/L)	Diss. Fe (µg/L)	Diss. Mn (µg/L)	Diss. Zn (µg/L)
				Mineral Creek basin—Continued								
MC52--	Stream south of Browns Gulch	8/25/99	14:30	1.62	355	3.21	9.4	6,640	100	2,950	331	76
MC53--	Stream southwest of Ohio Peak	8/09/99	12:00	--	1,035	2.61	9.8	14,800	44	36,790	4,130	186
MC54--	Upper Zuni Gulch	8/25/99	10:30	0.18	163	3.18	5.2	1,070	103	490	12	54
MC55--	Upper Zuni Gulch	8/25/99	10:00	0.05	17	5.53	6.9	74	<4	33	<3	<20
MC56--	Zuni Gulch near mouth	8/25/99	13:30	0.22	48	3.90	10.3	315	19	99	9	<20
MC57--	Spring downstream from mine northwest of Burro Bridge	9/13/99	17:00	0.36	241	6.24	4.6	71	<4	<30	7	25
MC79--	Middle Fork Mineral Creek at mouth	9/28/95	11:00	7.9	796	4.75	4.7	7,200	11	15,600	1,100	230
MC86--	Spring near Ophir Pass road	9/14/95	9:30	0.02	106	6.56	4.3	<1	<1	<1	<1	<1
MC87--	North tributary to Middle Fork Mineral Creek	9/19/95	17:00	0.09	180	6.78	13.6	<1	2	<1	<1	5
MC88--	Middle Fork Mineral Creek upstream from unnamed north-flowing tributary	9/20/95	10:30	5.6	778	6.39	6.7	120	5	10,400	990	72
MC89--	Middle Fork Mineral Creek downstream from unnamed north-flowing tributary	9/20/95	12:00	7.2	800	4.58	8.0	7,100	8	18,100	1,100	120
MC90--	North tributary to Middle Fork Mineral Creek	9/20/95	14:00	0.06	143	8.02	13.3	30	1	<1	4	<1
MS81--	Koehler tunnel (prior to remediation)	9/25/95	10:00	0.02	3,520	2.45	2.3	71,400	98,600	686,000	23,700	228,000
MS82--	Junction mine drainage downstream from red pool	9/25/95	10:30	0.15	3,310	2.50	2.5	70,300	61,100	494,000	20,300	157,000
	Colorado State sites (Unpub. report to Colorado Water Quality Control Commission, ARSG, 2001)											
COA30--	Animas River downstream from Burns Gulch	9/11/91	--	27	178	6.8	6.4	100	24	BDL	1,100	690
COA31--	Animas River upstream from Eureka	9/10/91	--	19	162	7.2	12.2	110	18	BDL	780	570
COA40--	Animas River upstream from Minnie Gulch	9/10/91	--	24	222	7.3	10.1	100	16	BDL	750	500
COA45--	Animas River downstream from Maggie Gulch	9/10/91	--	58	1,900	7.3	12.0	58	5	14	320	340
COA48--	Cunningham Creek near mouth	9/10/91	--	10.5	144	6.7	8.0	BDL	BDL	10	BDL	11
COA51--	Cunningham Creek	9/9/91	--	19.5	97	7.5	11.5	51	BDL	13	BDL	BDL
COA53--	Animas River downstream from Howardsville	9/10/91	--	88	160	7.0	7.0	86	BDL	45	230	270
COA58--	Arrastra Creek	9/10/91	--	13	160	7.8	7.8	BDL	BDL	BDL	BDL	120
COA59--	Upper Arrastra Creek	9/10/91	--	8.3	150	7.6	5.5	BDL	BDL	13	BDL	68
COA67--	Swansea Gulch	9/10/91	--	1.8	92	6.9	4.9	BDL	BDL	24	7	76
COA70--	Idaho Gulch	6/25/92	--	--	--	8.1	4.7	BDL	9	BDL	BDL	50
COC06--	North Fork Cement Creek at mouth	9/7/91	--	.18	353	3.1	6.5	8,400	1,400	16,000	2,200	4,200
COC11--	Upper Middle Fork Cement Creek	9/8/91	--	.30	227	8.4	5.5	BDL	BDL	BDL	BDL	12
COC18--	Cement Creek downstream from North Fork	9/8/91	--	2.4	376	3.8	6.6	2,700	360	1,300	2,000	3,100
COC21--	Cement Creek downstream from South Fork	9/8/91	--	9.8	575	5.5	7.9	1,600	91	950	2,600	1,800
COC34--	Cement Creek downstream from Cascade Gulch	9/7/91	--	12	735	4.2	9.0	3,900	64	6,200	1,900	1,000
COC36--	Cement Creek downstream from Minnesota Gulch	9/7/91	--	13	705	4.7	9.5	3,900	62	5,700	1,700	960

Table 1.   Selected water-quality data for construction of the low-flow distribution maps.—Continued

Site number (fig. 1)	Site name	Date	Time	Stream-flow (ft³/s)	SC (µS/cm)	pH (s.u.)	Water temp. (°C)	Diss. Al (µg/L)	Diss. Cu (µg/L)	Diss. Fe (µg/L)	Diss. Mn (µg/L)	Diss. Zn (µg/L)
	Colorado State sites (Unpub. report to Colorado Water Quality Control Commission, ARSG, 2001)—Continued											
COC39--	Cement Creek downstream from Porcupine Gulch	9/7/91	--	19	945	4.0	10.5	4,000	72	5,500	1,800	1,000
COC40--	Ohio Gulch	9/7/91	--	1.4	970	2.9	9.5	18,000	330	25,000	530	1,000
COC41--	Cement Creek downstream from Ohio Gulch	9/7/91	--	18	650	4.0	10.3	4,900	85	5,800	2,000	960
COM02--	Mineral Creek at Red Mountain Pass	9/7/91	--	.50	2,600	2.6	8.5	67,000	62,000	490,000	17,000	180,000
COM23--	Upper South Fork Mineral Creek	9/6/91	--	6.7	167	7.0	9.0	BDL	BDL	10	26	13
COM25--	South Fork Mineral Creek downstream from Bandora mine	9/6/91	--	8.4	170	6.9	10.1	130	BDL	52	24	95
COM26--	Clear Creek, Ice Lake basin	9/6/91	--	5.7	126	7.8	10.1	BDL	BDL	BDL	BDL	BDL
COM28	South Fork Mineral Creek	9/6/91	--	23	217	7.6	12.7	87	BDL	330	18	9
COM29--	Mineral Creek downstream from South Fork	9/6/91	--	42	360	6.7	9.5	BDL	31	1,300	290	420
COM32--	Mineral Creek downstream from North Star mine	9/6/91	--	36	260	6.1	14.0	BDL	8	750	260	300
	Other sites											
AR3---	Animas River upstream from Mineral Creek confluence (Schemel and others, 2000)	9/19/96	10:00	69	420	6.9	--	48.5	--	558	1,110	514
PG45--	Prospect Gulch downstream from shaft mines (Wirt and others, 2001)	9/29/99	--	.38	356	5.0	--	750	83	290	290	810
PG347--	Prospect Gulch downstream from Lark mine (Wirt and others, 2001)	9/29/99	--	.55	556	3.4	--	3,500	360	5,000	460	1,400
PG800--	Prospect Gulch downstream from all mines (Wirt and others, 2001)	9/29/99	--	.58	496	3.8	--	3,900	340	5,400	480	1,700
PG1800	Prospect Gulch upstream from Red Spring (Wirt and others, 2001)	9/29/99	--	.72	497	3.4	--	4,400	360	4,300	500	1,700
PG2259	Prospect Gulch at mouth (Wirt and others, 2001)	9/29/99	--	1.2	583	3.5	--	10,000	230	20,000	610	1,500

[1a]Data for these sites are revised from Mast, Evans, and others (2000).

[2b]Site A33, table 24 (Mast, Evans, and others, 2000).

[3c]Site A60, table 24 (Mast, Evans, and others, 2000).

[4d]Table 21 (Mast, Evans, and others, 2000).

[5e]Table 20 (Mast, Evans, and others, 2000).

[6f]Site C17, table 24 (Mast, Evans, and others, 2000).

[7g]Site C31, table 24 (Mast, Evans, and others, 2000).

[8h]Site C43, table 24 (Mast, Evans, and others, 2000).

[9i]Table 22 (Mast, Evans, and others, 2000).

[10j]Sole and others (this volume).

[11k]Site M07, table 24 (Mast, Evans, and others, 2000).

[12l]Site, M13, table 24 (Mast, Evans, and others, 2000).

[13m]Site M27, table 24 (Mast, Evans, and others, 2000).

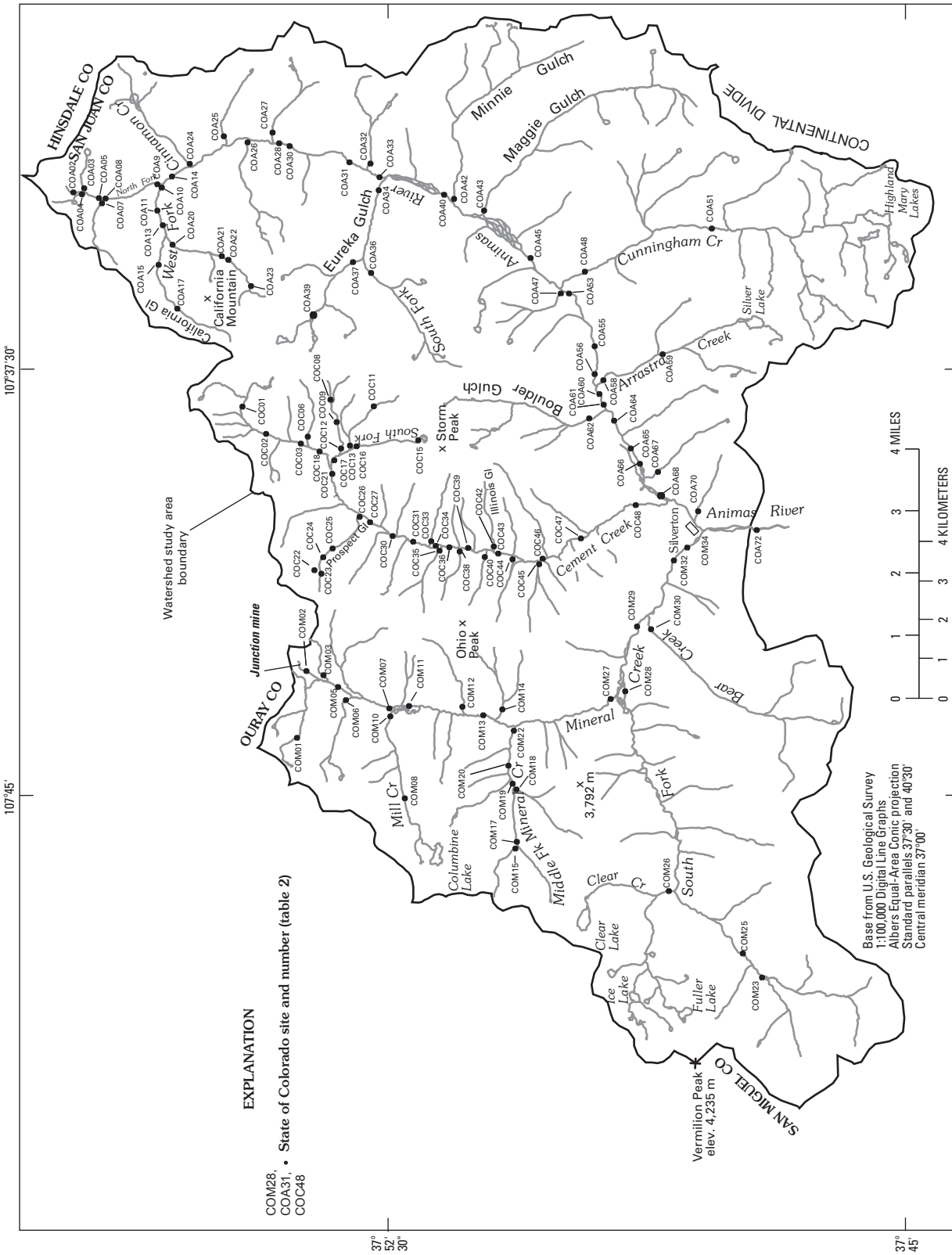[14n]Table 23 (Mast, Evans, and others, 2000).

Figure 2.   Locations of water-quality sampling sites where data were collected for construction of high-flow distribution maps.

Table 2.   Selected water-quality data for construction of the high-flow distribution maps.

[Some site names are informal place names used on local signage; ft³/s, cubic feet per second; SC, specific conductance; μS/cm, microsiemens per centimeter at 25°C; pH, s.u., standard units; temp., temperature; °C, degrees Celsius; Al, aluminum; Cu, copper; Fe, iron; Mn, manganese; Zn, zinc; Diss., dissolved; Tot., total; μg/L, micrograms per liter; --, no data; BDL, below detection limit]

Site number (fig. 2)	Site name	Date	Time	Stream-flow (ft³/s)	SC (μS/cm)	pH (s.u.)	Water temp. (°C)	Diss. Al (μg/L)	Diss. Cu (μg/L)	Tot. Fe (μg/L)	Diss. Mn (μg/L)	Diss. Zn (μg/L)
Colorado State sites (Colorado Department of Public Health and Environment, unpub. data, 1992)											
Animas River basin											
COA02	Downstream from Lucky Jack mine	6/25/92	--	--	--	6.88	18.6	130	4	--	--	850
COA03	Horseshoe Gulch	6/25/92	--	--	--	6.86	9.6	BDL	BDL	--	--	22
COA04	North Fork Animas River upstream from Horseshoe Creek	6/25/92	--	--	--	7.36	13.6	BDL	BDL	--	--	53
COA05	North Fork Animas River upstream from Burrows Creek	6/25/92	--	--	--	7.02	11.0	BDL	BDL	--	--	190
COA07	Burrows Creek	6/25/92	--	--	--	4.61	14.1	3,000	35	67	--	1,600
COA08	North Fork Animas River downstream from Burrows Creek	6/25/92	--	--	--	6.01	9.8	BDL	5	--	--	430
COA09	North Fork Animas River at Animas Forks	6/25/92	--	--	--	6.43	7.1	BDL	6	62	340	500
COA10	West Fork Animas River at Animas Forks	6/25/92	--	--	--	6.02	7.7	640	23	78	2,900	1,000
COA11	West Fork Animas River downstream from Frisco tunnel	6/25/92	--	--	--	5.88	7.6	730	20	--	--	960
COA13	West Fork Animas River downstream from Placer Gulch	6/25/92	--	--	--	6.05	9.1	790	20	--	--	960
COA14	North Fork Animas River downstream from Animas Forks	6/25/92	--	--	--	5.95	6.3	390	17	68	--	860
COA15	California Gulch downstream from Vermillion mine	6/25/92	--	--	--	5.78	11.2	1,700	17	--	--	990
COA17	California Gulch midway	6/25/92	--	--	--	5.89	9.6	2,100	15	--	--	1,100
COA20	Placer Gulch near mouth	6/25/92	--	--	--	6.38	8.6	88	22	--	1,900	950
COA21	Placer Gulch downstream from Sunbank mine	6/25/92	--	--	--	6.23	7.9	190	42	--	--	1,300
COA22	Placer Gulch upstream from Sunbank mine	6/25/92	--	--	--	6.20	6.2	100	36	--	--	1,300
COA23	Placer Gulch downstream from Gold Prince mine	6/25/92	--	--	--	5.06	2.0	BDL	9	--	--	1,100
COA24	Cinnamon Creek	6/25/92	--	--	--	7.71	5.1	BDL	BDL	--	--	BDL
COA25	Grouse Gulch	6/25/92	--	--	--	8.00	7.4	BDL	BDL	--	--	BDL
COA26	Picayune Gulch	6/25/92	--	--	--	7.66	9.8	BDL	BDL	--	--	14
COA27	Burns Gulch	6/25/92	--	--	--	7.54	6.4	76	27	BDL	--	710
COA28	Animas River downstream from Burns Gulch	6/25/92	--	--	--	7.35	6.3	53	6	--	--	490
COA30	Animas River downstream from Silver Wing mine	6/25/92	--	--	--	7.32	5.1	52	10	--	--	480
COA31	Animas River upstream from Eureka Gulch	6/25/92	--	--	--	7.11	4.1	59	--	--	--	470
COA32	Niagara Gulch	6/25/92	--	--	--	7.18	1.5	BDL	BDL	--	--	BDL
COA33	Animas River at Eureka	6/25/92	--	--	--	7.13	19.1	67	7	61	--	460
COA34	Eureka Gulch at mouth	6/25/92	--	--	--	7.50	6.3	94	11	92	--	550
COA36	South Fork Eureka Gulch	6/25/92	--	--	--	7.40	6.5	58	BDL	--	--	25
COA37	Eureka Gulch upstream from confluence with South Fork	6/25/92	--	--	--	7.44	7.7	87	13	--	--	890

Table 2. Selected water-quality data for construction of the high-flow distribution maps.—Continued

Site number (fig. 2)	Site name	Date	Time	Stream-flow (ft³/s)	SC (µS/cm)	pH (s.u.)	Water temp. (°C)	Diss. Al (µg/L)	Diss. Cu (µg/L)	Tot. Fe (µg/L)	Diss. Mn (µg/L)	Diss. Zn (µg/L)
	Colorado State sites (Colorado Department of Public Health and Environment, unpub. data, 1992) Animas River basin—Continued											
COA39	Eureka Gulch downstream from former Lake Emma	6/25/92	--	--	--	7.58	10.1	110	24	--	--	1,200
COA40	Animas River downstream from Eureka braided reach	6/25/92	--	--	--	7.02	25.3	55	8	--	800	590
COA42	Minnie Gulch	6/25/92	--	--	--	7.86	15.8	BDL	BDL	--	--	9
COA43	Maggie Gulch	6/25/92	--	--	--	7.80	20.7	51	BDL	--	--	13
COA45	Animas River downstream from Middleton braided reach	6/25/92	--	--	--	7.20	12.0	68	7	67	--	410
COA47	Hematite Gulch	6/25/92	--	--	--	7.65	14.0	BDL	BDL	--	--	10
COA48	Cunningham Creek near mouth	6/25/92	--	--	--	6.60	9.4	BDL	BDL	--	--	23
COA51	Cunningham Creek downstream from Highland Mary tailings	6/25/92	--	--	--	7.58	9.1	BDL	BDL	--	--	BDL
COA53	Animas River at Howardsville (gauging station)	6/25/92	--	--	--	7.25	9.0	BDL	5	--	--	240
COA55	Animas River	6/25/92	--	--	--	7.25	14.0	75	7	--	--	340
COA56	Animas River upstream from Arrastra Creek	6/25/92	--	--	--	7.25	5.0	BDL	8	80	--	360
COA58	Arrastra Creek at mouth	6/25/92	--	--	--	8.36	6.5	BDL	6	14	--	110
COA59	Arrastra Creek downstream from talus	6/25/92	--	--	--	8.48	3.9	BDL	5	--	--	68
COA60	Animas River downstream from Arrastra Creek	6/25/92	--	--	--	6.71	9.3	BDL	6	79	--	320
COA61	Animas River downstream from Mayflower Mill	6/25/92	--	--	--	6.59	6.3	BDL	6	--	--	350
COA62	Boulder Gulch	6/25/92	--	--	--	6.80	7.2	BDL	BDL	BDL	89	57
COA64	Animas River downstream from Boulder Gulch	6/25/92	--	--	--	6.83	7.0	51	7	64	--	340
COA65	Animas River downstream from mill tailings	6/25/92	--	--	--	6.54	6.0	BDL	5	70	--	350
COA66	Animas River downstream from Silver Lake campground	6/25/92	--	--	--	6.40	7.1	BDL	7	--	--	360
COA67	Swansea Gulch	6/25/92	--	--	--	8.25	5.4	BDL	BDL	56	--	68
COA68	Animas River at Silverton (gauging station)	6/25/92	--	421	--	7.60	5.5	50	7	260	--	310
COA70	Idaho Gulch	6/25/92	--	--	--	8.15	4.7	BDL	9	--	--	50
COA72	Animas River downstream from Silverton (gauging station)	6/23/92	--	965	--	7.40	8.0	BDL	7	78	350	240
	Cement Creek basin											
COC01	Cement Creek at upper Ross Basin	6/24/92	--	--	--	6.27	--	300	140	500	650	950
COC02	Cement Creek downstream from Ross Basin	6/24/92	--	--	--	4.88	18.1	420	140	--	BDL	1,100
COC03	Cement Creek upstream from North Fork	6/24/92	--	--	--	5.28	10.7	570	130	--	--	1,100
COC06	North Fork Cement Creek	6/24/92	--	--	--	3.20	10.0	13,000	2,100	45,000	--	6,900
COC08	Minnehaha Basin gulch downstream from Lead Carbonate mine	6/24/92	--	--	--	--	--	BDL	BDL	--	--	13
COC09	Minnehaha Basin gulch midway	6/24/92	--	--	--	7.30	7.2	100	9	--	--	87
COC11	Middle Fork Cement Creek downstream from Black Hawk mine	6/24/92	--	--	--	7.04	5.1	BDL	BDL	--	--	15

Table 2. Selected water-quality data for construction of the high-flow distribution maps.—Continued

Site number (fig. 2)	Site name	Date	Time	Stream-flow (ft³/s)	SC (μS/cm)	pH (s.u.)	Water temp. (°C)	Diss. Al (μg/L)	Diss. Cu (μg/L)	Tot. Fe (μg/L)	Diss. Mn (μg/L)	Diss. Zn (μg/L)
					Cement Creek basin—Continued							
COC12	Minnehaha Gulch at mouth	6/24/92	--	--	--	7.28	6.7	120	10	230	--	140
COC13	Middle Fork Cement Creek at mouth	6/24/92	--	--	--	6.52	6.2	67	15	180	--	230
COC15	South Fork Cement Creek downstream from Velocity Lake	6/24/92	--	--	--	6.27	12.7	91	BDL	--	--	35
COC16	South Fork Cement Creek upstream from Middle Fork	6/24/92	--	--	--	6.12	13.0	120	10	--	--	260
COC17	South Fork Cement Creek at Gladstone	6/24/92	--	--	--	6.16	14.1	63	11	1,600	--	340
COC18	Cement Creek downstream from North Fork	6/24/92	--	--	--	3.78	8.2	1,600	300	4,100	--	1,600
COC21	Cement Creek downstream from Gladstone	6/24/92	--	--	--	5.17	6.7	890	160	--	1,900	1,000
COC22	Prospect Gulch downstream from Red Mountain 3	6/24/92	--	--	--	3.38	5.3	3,300	12	--	--	46
COC23	Prospect Gulch upstream from Galena Queen mine	6/24/92	--	--	--	6.13	8.6	BDL	27	--	--	460
COC24	Prospect Gulch downstream from Galena Queen mine	6/24/92	--	--	--	4.45	12.3	660	43	--	--	360
COC25	Prospect Gulch downstream from Lark mine	6/24/92	--	--	--	3.07	8.8	1,700	240	--	--	850
COC26	Prospect Gulch at mouth	6/24/92	--	--	--	3.76	5.3	3,100	310	9,400	--	950
COC27	Cement Creek downstream from Prospect Gulch	6/24/92	--	--	--	4.90	8.5	1,400	170	4,000	1,700	1,000
COC30	Cement Creek downstream from Georgia Gulch	6/24/92	--	--	--	4.37	11.9	1,900	160	--	--	1,000
COC31	Cement Creek downstream from Fairview Gulch	6/24/92	--	--	--	4.47	8.7	1,900	150	--	--	960
COC33	Cascade Gulch	6/24/92	--	--	--	7.55	6.7	BDL	BDL	--	--	BDL
COC34	Cement Creek downstream from Cascade Gulch	6/24/92	--	--	--	4.90	8.9	1,700	140	--	--	870
COC35	Minnesota Gulch	6/24/92	--	--	--	7.28	9.7	110	BDL	500	--	85
COC36	Cement Creek downstream from Minnesota Gulch	6/24/92	--	--	--	4.85	6.5	1,700	140	4,800	--	860
COC38	Porcupine Gulch	6/24/92	--	--	--	6.98	11.9	220	23	--	--	810
COC39	Cement Creek downstream from Porcupine Gulch	6/24/92	--	--	--	5.11	5.9	1,800	140	--	--	920
COC40	Ohio Gulch	6/24/92	--	--	--	3.74	7.3	2,400	39	--	--	280
COC42	Illinois Gulch	6/24/92	--	--	--	7.59	10.0	76	BDL	--	--	59
COC43	Cement Creek downstream from Illinois Gulch	6/24/92	--	--	--	5.72	9.0	1,400	130	4,500	1,500	840
COC44	Topeka Gulch	6/24/92	--	--	--	4.55	11.4	1,300	12	--	--	130
COC45	Niagara Gulch	6/24/92	--	--	--	3.75	12.0	860	11	--	--	39
COC46	Cement Creek downstream from Niagara Gulch	6/24/92	--	--	--	5.05	11.0	1,500	120	4,600	--	850
COC47	Cement Creek upstream from large spring	6/24/92	--	--	--	5.05	9.0	1,500	120	--	--	790
COC48	Cement Creek at Silverton (gauging station)	6/23/92	--	98	--	5.00	5.0	1,700	110	5,000	1,100	720

Table 2. Selected water-quality data for construction of the high-flow distribution maps.—Continued

Site number (fig. 2)	Site name	Date	Time	Stream-flow (ft³/s)	SC (µS/cm)	pH (s.u.)	Water temp. (°C)	Diss. Al (µg/L)	Diss. Cu (µg/L)	Tot. Fe (µg/L)	Diss. Mn (µg/L)	Diss. Zn (µg/L)
					Mineral Creek basin							
COM01	Mineral Creek at headwaters	6/23/92	--	--	--	7.04	10.0	BDL	BDL	14	BDL	8
COM02	Tributary downstream from Junction mine	6/23/92	--	--	--	2.81	14.4	14,000	14,000	160,000	3,000	40,000
COM03	Tributary downstream from Congress mine	6/23/92	--	--	--	3.58	20.2	680	1,100	5,000	130	1,400
COM05	Mineral Creek upstream from Porphyry Gulch	6/23/92	--	--	--	3.90	14.7	870	900	8,000	200	2,600
COM06	Porphyry Gulch	6/23/92	--	--	--	6.95	11.1	BDL	BDL	BDL	BDL	57
COM07	Mineral Creek at Chattanooga	6/23/92	--	--	--	6.65	9.1	91	140	2,300	100	880
COM08	Mill Creek downstream from Silver Queen mine	6/23/92	--	--	--	7.06	10.8	BDL	BDL	--	--	13
COM10	Mill Creek at Chattanooga	6/23/92	--	--	--	7.48	6.6	BDL	BDL	30	--	14
COM11	Mineral Creek downstream from Chattanooga	6/23/92	--	--	--	6.89	9.0	BDL	51	--	--	540
COM12	Browns Gulch	6/23/92	--	--	--	4.70	9.1	1,100	42	1,200	--	700
COM13	Mineral Creek downstream from Browns Gulch	6/23/92	--	--	--	6.65	9.4	BDL	34	--	--	490
COM14	Tributary draining southwest Ohio Peak	6/23/92	--	--	--	3.70	11.0	2,700	38	--	--	22
COM15	Middle Fork Mineral Creek downstream from Ophir Pass	6/23/92	--	--	--	6.87	7.0	62	BDL	--	--	BDL
COM17	Middle Fork Mineral Creek downstream from Governor mine	6/23/92	--	--	--	6.80	--	180	BDL	--	--	25
COM18	Unnamed north-flowing tributary of Middle Fork Mineral Creek	6/23/92	--	--	--	4.11	5.6	9,500	9	--	--	110
COM19	Middle Fork Mineral Creek downstream from unnamed north-flowing tributary	6/23/92	--	--	--	5.74	7.4	1,200	BDL	--	--	83
COM20	Middle Fork Mineral Creek upstream from Bonner mine	6/23/92	--	--	--	5.82	10.3	370	BDL	--	--	31
COM22	Middle Fork Mineral Creek at mouth	6/23/92	--	--	--	5.72	11.2	2,200	4	4,200	240	47
COM23	South Fork Mineral Creek at headwaters	6/23/92	--	--	--	7.10	--	BDL	BDL	--	--	BDL
COM25	South Fork Mineral Creek downstream from Bandora mine	6/23/92	--	--	--	7.13	--	BDL	BDL	--	25	45
COM26	Clear Creek (Ice Lakes)	6/23/92	--	--	--	7.25	--	BDL	BDL	--	--	BDL
COM27	Mineral Creek upstream from South Fork	6/23/92	--	--	--	6.40	9.0	140	34	2,100	--	340
COM28	South Fork Mineral Creek at mouth	6/23/92	--	--	--	7.35	12.0	77	BDL	160	9	11
COM29	Mineral Creek downstream from large springs and Zuni Gulch	6/23/92	--	--	--	6.95	11.0	53	10	--	--	120
COM30	Bear Creek	6/23/92	--	--	--	7.00	18.8	BDL	BDL	--	--	13
COM32	Mineral Creek downstream from North Star mine	6/23/92	--	--	--	6.72	16.3	82	10	840	--	110
COM34	Mineral Creek at Silverton (gauging station)	6/23/92	--	379	--	7.20	8.0	BDL	8	190	74	110

Selection of Mines that May Affect the Environment

Inactive mines can be sources of trace-metal loading to streams of the study area (Jim Herron, Bruce Stover, and Paul Krabacher, Unpublished Lower Animas River reclamation feasibility report, Upper Animas River Basin, Colorado Division of Minerals and Geology, 2000; Unpub. report to Colorado Water Quality Control Commission, ARSG, 2001; Wirt and others, 2001; Nash and Fey, this volume, Chapter E6; Wright, Kimball, and Runkel, this volume, Chapter E23). From features indicated on USGS topographic maps (C.L. Rich, U.S. Geological Survey, written commun., 2002), nearly 5,400 inactive mines, prospect pits, and other mining-related features lie in the Animas River watershed study area (fig. 3), but not all of the sites contribute to environmental degradation (Unpub. Lower Animas River reclamation feasibility report, CDMG, 2000; Unpub. report to Colorado Water Quality Control Commission, ARSG, 2001; Church, Mast, and others, this volume, Chapter E5). The wide distribution of these features does not adequately describe the effects of historical mines on the environment because many of the features are prospect pits or small mines that have little, if any, environmental effect. Therefore, only a subset of mines thought to have some effect on stream-water quality is presented in this chapter.

As part of the mine-site ranking process by the Animas River Stakeholders Group, 33 draining mines and 32 waste-rock piles were identified and ranked as large contributors to water-quality degradation (table 3) (Unpub. report to Colorado Water Quality Control Commission, ARSG, 2001). In addition to the high-ranking mine sites, seven permitted mine and mill sites are undergoing remediation or have been remediated (table 3). The permitted sites are generally some of the large mine and mill sites that may contribute metal loads to streams, yet they were not included as part of the ARSG ranking process due to ongoing regulatory activities. To better show the effects of mine sites on the distribution of pH values and trace-metal concentrations, only the high-ranking draining mines, waste-rock piles, and permitted mine and mill sites are shown on the spatial distribution maps (fig. 3, and section, "Data Presentation"). More information about the mine-ranking process can be obtained through the ARSG Website, http://www.waterinfo.org/arsg/ (accessed August 15, 2002).

Geologic Setting

Because water quality is related to geology, a short synopsis of bedrock geology, hydrothermal alteration, and mineralization of the study area is presented here to establish a geologic framework for the reader for interpretation of the variation of pH and trace metals in surface water. More detailed descriptions of the geology and alteration of the watershed are found in other chapters of this volume (Yager and Bove, this volume, Chapter E1; Bove and others, this volume). The study area lies within the western part of the San Juan volcanic field, which includes the San Juan, Uncompahgre, and Silverton calderas (Lipman and others, 1976; Bove and others, 2000). The Silverton caldera, a large collapsed volcanic depression, nested within the larger San Juan caldera, formed in response to the eruption of the 27.7-Ma Crystal Lake Tuff (Lipman and others, 1976; Bove and others, this volume). Within the Silverton caldera, the Crystal Lake Tuff is mostly absent due to erosion, and the dominant volcanic rock units are a thick sequence of finely porphyritic dacitic-andesitic lavas and volcaniclastic rock (Silverton Volcanics) (Burbank and Luedke, 1969; Yager and Bove, this volume).

The Eureka graben, which is the downdropped, northeast-trending fault zone along the crest of the uplifted dome of the coalesced San Juan–Uncompahgre calderas, was an important host to mineralization that postdates these calderas by about 5–15 Ma (Lipman and others, 1976). Although altered and mineralized rocks are in close spatial association with the San Juan, Uncompahgre, and Silverton calderas, alteration and mineralization were rarely contemporaneous with caldera formation (Lipman and others, 1976; Slack and Lipman, 1979). The San Juan–Uncompahgre caldera cycle thus provided a favorable structural environment for later mineralization. Most mineralization and associated hydrothermal alteration in this area were temporally and genetically associated with three major episodes of high-level magmatism between about 27 and 10 Ma.

Major Events of Mineralization, Alteration, and Igneous Intrusion

More than 90 volume percent of the rocks in the study area were affected by low-grade regional metamorphism or propylitic alteration, the result of thermal events associated with the San Juan–Uncompahgre and Silverton calderas (Burbank and Luedke, 1969; Bove and others, this volume). The timing of these events preceded most ore mineralization and later episodes of more intense hydrothermal alteration by several million years (Lipman and others, 1976; Bove and others, 2001). The propylitic mineral assemblage contains varying amounts of chlorite, epidote, calcite, and illite, in the presence of fresh to weakly altered primary feldspar crystals. The regional propylitic event was followed by three major periods of magmatism, which were related to most mineralization and hydrothermal alteration in the area (Bove and others, this volume). Hydrothermal activity related to these magmatic episodes superimposed more intense hydrothermal alteration assemblages upon the previously propylitically altered rocks.

The earliest of these magmatic events was associated with 26–25 Ma quartz-monzonite intrusive activity, which was related to subeconomic porphyry copper-molybdenum mineralization in the area between Middle and South Forks Mineral Creek (Ringrose and others, 1986; Bove and others, this volume). The center of the most intense hydrothermal alteration
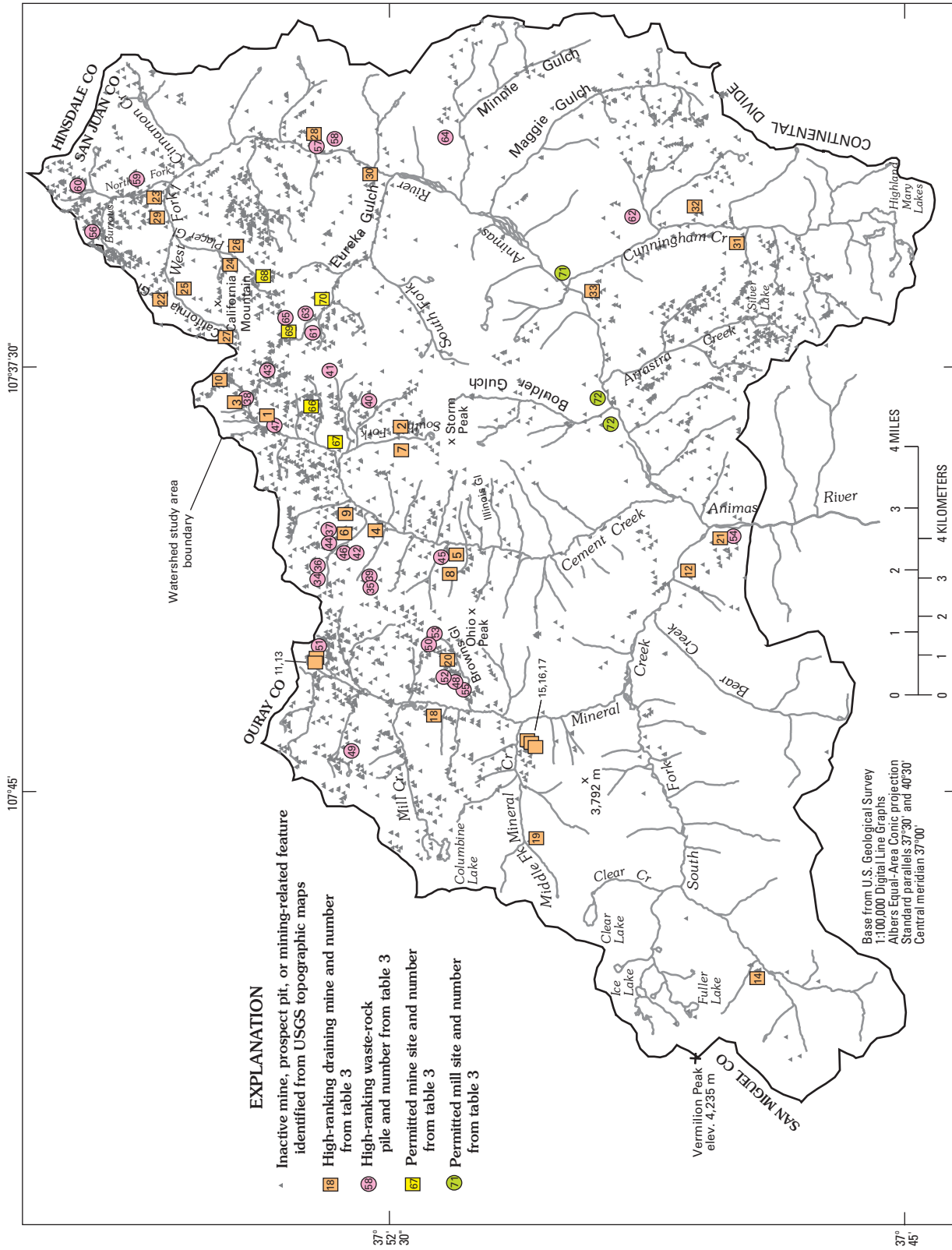
Figure 3.   Locations of inactive mines, prospect pits, and mining-related features identified from topographic maps, high-ranking draining mines and waste-rock piles, and permitted sites (Unpub. report to Colorado Water Quality Control Commission, ARSG, 2001; Church, Mast, and others, this volume).

Table 3.   Selected draining mines, waste-rock piles, and permitted mine and mill sites in the Animas River watershed study area.

[Unpub. report to Colorado Water Quality Control Commission, ARSG, 2001]

Map No. (fig. 3)	Mine or site name	Map No. (fig. 3)	Mine or site name
	Draining mines		**Waste-rock piles**
1	Mogul mine	34	Galena Queen mine, shaft
2	Natalie/Occidental mine	35	Kansas City #2 mine
3	Grand Mogul mine	36	Hercules mine, shaft
4	Mammoth tunnel	37	Upper Joe & Johns mine
5	Anglo-Saxon mine	38	Grand Mogul mine – East
6	Joe & Johns mine	39	Kansas City #1 mine
7	Big Colorado mine	40	Black Hawk mine
8	Porcupine mine	41	Lead Carbonate Mill
9	Eveline mine	42	Henrietta mine (level 3)
10	Columbia mine	43	Ross Basin mine
11	Koehler tunnel	44	Lark mine
12	North Star mine	45	Pride of the Rockies mine
13	Longfellow mine (Junction mine)	46	Henrietta mine (level 7)
14	Bandora mine	47	Mogul mine
15	Upper Bonner mine	48	Brooklyn mine
16	Bonner mine	49	Bullion King mine
17	Lower Bonner mine	50	Unnamed shaft mine, upper Browns Gulch
18	Ferricrete mine	51	Congress mine, shaft
19	Governor mine (Paradise portal)	52	Brooklyn mine, upper waste-rock pile
20	Brooklyn mine	53	Unnamed mine, upper Browns Gulch
21	Little Dora mine	54	Little Dora mine
22	Vermillion mine	55	Brooklyn mine, lower waste-rock pile
23	Columbus mine	56	Ben Butler mine
24	Lower Comet mine	57	Silver Wing mine
25	Unnamed mine	58	Tom Moore mine
26	Sound Democrat mine	59	Eagle mine
27	Mountain Queen mine	60	Lucky Jack mine
28	Silver Wing mine	61	Clipper mine
29	Frisco tunnel	62	Buffalo Boy mine
30	Senator mine	63	Ben Franklin mine
31	Royal Tiger mine	64	Caledonia mine
32	Pride of the West mine	65	Sunnyside mine
33	Little Nation mine		
			Permitted mine sites
	Permitted mill sites	66	Upper Gold King mine
71	Pride of the West Mill tailings	67	American tunnel
72	Mayflower Mill tailings	68	Gold Prince mine
		69	Sunnyside mine
		70	Terry tunnel

and mineralized rock was near peak 3,792 m (fig. 1), between Middle and South Forks Mineral Creek. In the vicinity of peak 3,792 m, quartz-molybdenite stockwork veins associated with intense quartz-sericite-pyrite (QSP) altered rock are cut by molybdenite-bearing quartz stockwork veinlets; these veinlets were postdated by base-metal veins, which are present mostly on the margins of the porphyry system (R.T. McCusker, Unpublished Mount Moly progress report, 1979–1980, Drill holes 1–6, 1982). The base-metal veins contain silver and some gold in sulfide ores consisting mainly of galena, sphalerite, and pyrite with lesser tetrahedrite-tennantite and chalcopyrite (Ringrose and others, 1986). A pervasive area of QSP-altered rock (3.5 km^2) is centered roughly on the summit and is zoned outward into weak sericite-pyrite (WSP) and then propylitic alteration assemblages. The weak sericite-pyrite assemblage is characterized by partial replacement of plagioclase by sericite, whereas biotite and pyroxene are altered to chlorite, sericite, and fine opaque minerals. The rocks are typically less silicified than QSP-altered rocks, and contain fewer quartz-sulfide stockwork veinlets.

Intrusion of high-level dacite porphyry in the Red Mountain Pass and Ohio Peak–Anvil Mountain areas at 23 Ma caused significant mineralization and formed extensive zones of acid-sulfate altered rock (>40 km^2 total). The Red Mountain Pass area was developed for silver-copper-lead-arsenic ores hosted within breccia pipes and brecciated fault zones (Burbank and Luedke, 1969; Bove and others, this volume). Although the Ohio Peak–Anvil Mountain system is very similar in size and style of alteration, it is largely devoid of economic mineral deposits (Bove and others, this volume). Zones of acid-sulfate altered rock were localized along fault and hydrothermal breccia zones and permeated outward into intensely altered wallrock (Bove and others, this volume). These acid-sulfate centers are composed mainly of quartz, alunite, pyrophyllite, dickite, and as much as 30 volume percent pyrite. Broad expanses of QSP-altered rock, very similar in character to that mapped in the area of peak 3,792 m, are generally present between individual acid-sulfate zones. Larger areas of QSP-altered rock are particularly well exposed on the highly dissected margins of the acid-sulfate systems. Propylitically altered rocks surround the Red Mountain Pass and Ohio Peak–Anvil Mountain acid-sulfate systems.

Post-20 Ma vein mineralization produced most of the economically important vein minerals in the study area and appears to have been closely tied to intrusion of high-silica alkali rhyolite (Lipman and others, 1976; Bove and others, this volume). Veins are mostly a polymetallic variety (silver, lead, zinc, copper, ±gold) and formed as fracture- or fissure-fillings (Bove and others, this volume). Many of these veins in the Eureka graben area are especially rich in manganese silicate gangue minerals (Bove and others, this volume). Zones of hydrothermally altered rock related to these post-20 Ma veins consist of narrow envelopes that are superimposed over regional propylitically altered rock (Bove and others, this volume). In some areas with high vein concentrations, the associated alteration zones can be locally pervasive.

Hydrothermal Alteration

Mineral types and abundances strongly affect water quality; for details on the minerals included in the alteration assemblages, see Bove and others (this volume). The study area has five types of hydrothermal alteration assemblages: regional propylitic alteration (PROP); weak sericite-pyrite alteration (WSP); vein-related quartz-sericite-pyrite alteration (V-QSP); quartz-sericite-pyrite alteration (QSP); and acid-sulfate alteration (AS). The PROP alteration is characterized by an earlier formed regional propylitic assemblage that affected most rocks within the Animas River watershed study area and vicinity. It is distinguished largely by the absence of pyrite, quartz, and chlorite veinlets and the scarcity of finely disseminated pyrite. Examples of QSP alteration occur in the peak 3,792 m and Red Mountain Pass areas. An example of WSP alteration occurs in the area where QSP-altered rock grades outward into WSP-altered rock and finally into propylitized (PROP) rock (Ringrose and others, 1986; Bove

and others, 1998). Hydrothermal propylitic alteration that formed in association and peripheral to the peak 3,792 m hydrothermal system is characterized by the presence of veins and fractures filled with pyrite, chlorite, magnetite, and quartz. Examples of AS alteration are indicated in the Topeka Gulch and Ohio Peak areas (locations, figs. 1, 4). The V-QSP alteration style is illustrated throughout the Animas River watershed study area where relatively narrow (1–3 ft) quartz base-metal veins are present on the periphery of the other hydrothermal systems (Bove and others, this volume). These veins contain silver and some gold in sulfide ores of pyrite, sphalerite, galena, fine-grained tetrahedrite-tennantite, and chalcopyrite in a gangue of quartz, with lesser manganese silicates, barite, and carbonates.

Undisturbed Sources

Weathering of rocks that have been hydrothermally altered and not disturbed by mining contributes to the low pH and observed trace-metal loads in the study area (Wright and Janik, 1995; Bove and others, 2000; Mast, Verplanck, and others, 2000; Unpub. Lower Animas River reclamation feasibility report, CDMG, 2000; Mast and others, this volume, Chapter E7). Metal and acid loading from these rocks is considered an undisturbed or background source. Background sources enter streams as diffuse ground-water inflow and in springs. Background iron and manganese springs (fig. 1) have a considerable effect on water quality of the study area. Information about iron springs, iron bogs, and ferricrete deposits can be found in Stanton, Yager, and others (this volume, Chapter E14), Verplanck and others (this volume, Chapter E15), and Wirt and others (this volume, Chapter E17). Trace-metal loading from diffuse ground-water sources in the Cement Creek basin is described in Walton-Day and others (2000), Wirt and others (2001), and Kimball and others (2002).

Data Presentation

Spatial distribution maps are used in this report to describe the distribution of pH values, dissolved aluminum, dissolved copper, dissolved iron, dissolved manganese, and dissolved zinc for low-flow and high-flow conditions. The spatial distribution maps display colors that represent the ranges of pH values and dissolved trace-metal concentrations for sites throughout the watershed. Colors represent the range of the entire data set to show major contrasts between different areas of the watershed. The blue and light-blue colors represent lower trace-metal concentrations and higher pH values; the green, orange, and red colors represent higher trace-metal concentrations and lower pH values. Dissolved iron and manganese concentrations were not available in the CDPHE high-flow data set; therefore, high-flow spatial distribution maps are not shown for these constituents.

Water-quality standards for protection of aquatic life in the study area were recommended by the ARSG to the State of Colorado, and the standards were adopted in 2002 (Colorado Department of Public Health and Environment, Stream Classifications and Water-Quality Standards, http://www.cdphe.state.co.us/op/regs/waterregs/100234wqccsanjuanriverbasintables.pdf, accessed September 18, 2003). The standards are either the State of Colorado table value standards, which are closely based on the national water-quality criteria, or the ARSG's model of the achievable ambient dissolved metal concentration for a partic-ular reach after restoration of historical mines. The standards are different for each segment of the watershed (Unpub. report to Colorado Water Quality Control Commission, ARSG, 2001), and the standard for most of the metals varies by hard-ness concentration. Because of the prevalence of naturally occurring dissolved constituents in waters of the study area, and the concentrations expected in surface waters after restora-tion of inactive mine sites, the ARSG-proposed standards may exceed the national criteria in certain stream reaches. The color ranges on the distribution maps, therefore, do not reflect toxicity thresholds or water-quality standards in the watershed study area because some of the thresholds and standards are exceeded throughout most of the area.

Distribution of pH Values and Dissolved Trace-Metal Concentrations

The distribution of pH and dissolved trace-metal con-centrations differs greatly in streams throughout the Animas River watershed study area and depends on many factors, such as geologic setting, the presence and size of historical mines, and mixing of acidic and more neutral waters. Because of the deep snowpack that accumulates during the winter and melts during the spring, streamflow in the study area exhibits large seasonal differences. This affects the distribution of pH values and trace-metal concentrations contrasted between low flow (late summer and middle winter) and high flow (snowmelt runoff during May through July). In some areas, the presence of historical mines does not affect low pH values and high trace-metal concentrations in streams. In other areas, the pres-ence of historical mines does affect low pH values and high trace-metal concentrations in streams.

pH Values

Although no national water-quality criteria exist for pH values in water, the State of Colorado has a statewide stan-dard of pH 6.5–9.0 for protection of aquatic life. Below about pH 5.5, more sensitive invertebrate taxa begin to decrease or disappear. Whether effects of acidity on invertebrates are caused by response to the direct toxicity of extremely low

pH or whether they have a more indirect cause, the effects of acidification on algal food resources, is not clear (Sutcliffe and Hildrew, 1989). About 50 percent of European lakes with pH below 5.1 are fishless. Populations of salmonid fishes (trout and char) are relatively sensitive to the effects of acidification. Freshly fertilized eggs are the most sensitive life stage, and survival of brown trout eggs can be reduced in the pH range of 4.2–5.1. However, adult and juvenile salmonids (across a range of species and test waters) can typically tolerate short exposures to pH between 4.2 and 5.1. Toxic effects of pH are strongly ameliorated by increased calcium concentrations in the range of 100–400 eq/L (equivalents per liter) (Brown and Sadler, 1989).

The geology in a watershed plays an important role in determining the pH of streams. Low pH values in streams are related to acid-generating minerals such as pyrite (FeS_2) and chalcopyrite ($CuFeS_2$), whereas neutral to alkaline pH values occur where these sulfide minerals generally are absent or where minerals such as calcite, with significant acid-neutralizing capacity, are abundant (Plumlee and others, 1993; U.S. Environmental Protection Agency, 1994). Low pH values (less than 4.5) were primarily found in streams drain-ing highly altered or mineralized bedrock. Some streams also were affected by historical mines. Low pH values in streams of the study area generally coincide with high concentrations of dissolved trace metals, because acidic conditions contribute to trace-metal mobilization and transport (Moran and Wentz, 1974, p. 23; Kimball and others, 1994; Broshears and others, 1996). In contrast, high pH values are associated with areas where rocks have substantial acid-neutralizing capacity and commonly coincide with low concentrations of some trace metals, such as aluminum and iron; however, higher pH values do not exclude the presence of some trace metals such as zinc and manganese, which have high solubilities in circumneu-tral waters (Stumm and Morgan, 1981, p. 242–243). Mixing of low- and high-pH streams contributes to the precipitation of some trace metals from the dissolved phase into the solid phase, for instance, aluminum and iron. Other trace metals such as copper may adsorb to the precipitated solids (Church and others, 1997; Schemel and others, 2000). Therefore, the concentrations of dissolved trace metals can decrease through mixing of waters having different pH.

During low flow, streams that primarily drain intensely altered rocks have notably lower pH. For example, rocks in the peak 3,792 m area between Middle and South Forks Mineral Creek contain as much as 5 volume percent pyrite (Bove and others, this volume), and figure 4 shows clearly that during low flow, pH values in streams draining that area are very low. Low pH values also were present in streams draining the east and west sides of Ohio Peak (fig. 4). Extremely low pH values of 2.45 and 2.50 were measured in water from the Koehler tunnel and Longfellow mine at the headwaters of Mineral Creek (MS81 and MS82 in fig. 1 and table 1), and low pH values were prevalent throughout most of Prospect Gulch (table 1; labeled in fig. 1); Wirt and others (2001) concluded that the lower reaches of Prospect Gulch are largely affected by ground-water discharge from undisturbed sources.
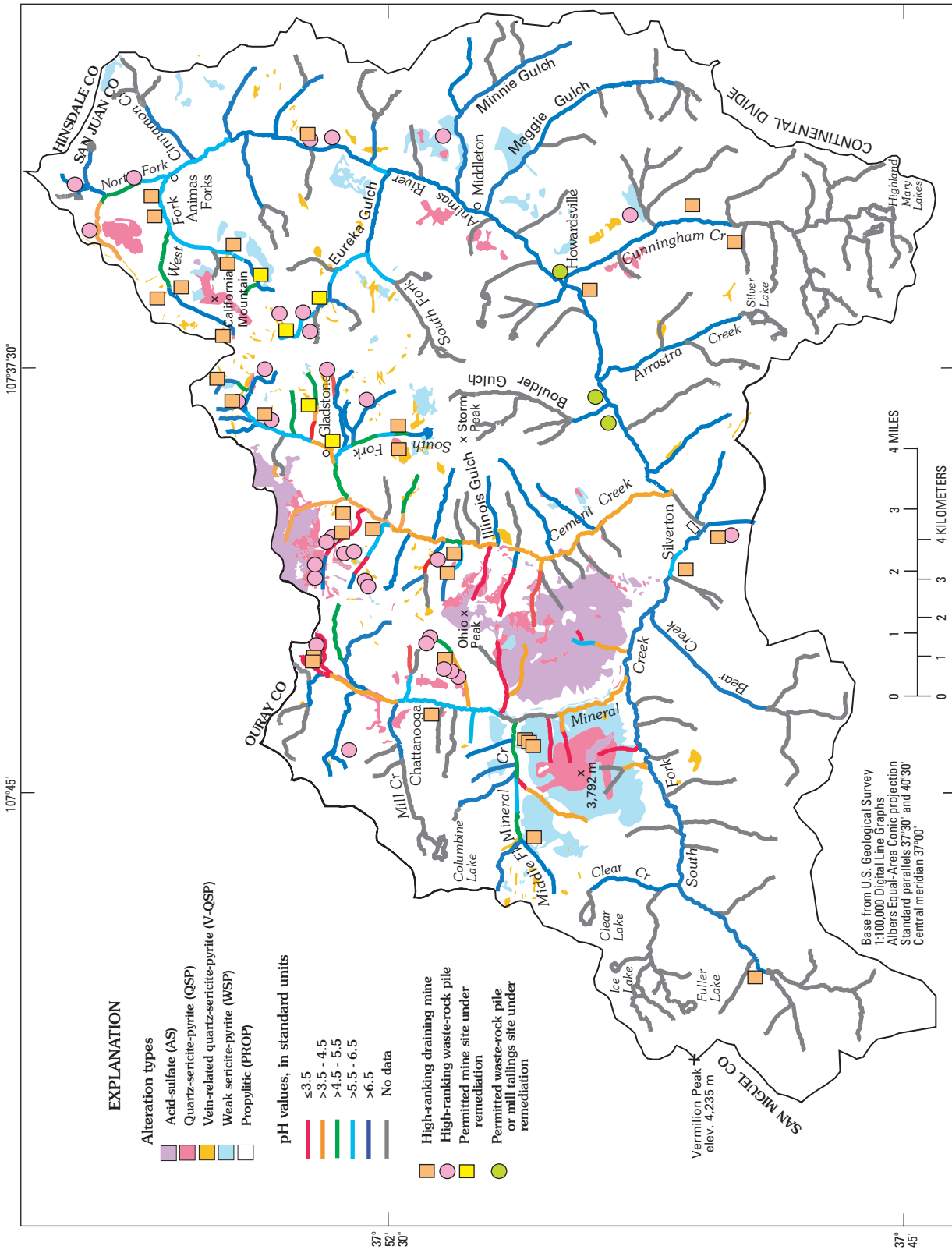
Figure 4. Distribution of pH values in streams during low flow.

The most noteworthy effects of acid rock drainage were observed in the mainstem of Cement Creek (fig. 4), where pH values ranged from 3.9 to 5.5 downstream from Gladstone, despite the inflow of several high-pH streams draining the west slopes of Storm Peak (fig. 4). Metal-loading studies done in Cement Creek attributed the low-pH, high-metal waters throughout the length of the stream to diffuse ground-water inflows (Walton-Day and others, 2000; Kimball and others, 2002). Several large, low-pH iron springs in the Cement Creek basin likely are surface expressions of this ground water (fig. 1).

During low flow, high pH values (greater than 6.5) were measured in most of the Animas River upstream from Silverton, except for a few of the headwater streams in the North Fork and West Fork Animas River subbasins (fig. 4). The Animas River upstream from Silverton drains propylitically altered rocks that contain calcite within the rock matrix (Bove and others, this volume), and calcite dissolution likely maintains the high pH values. High pH values also were measured in South Fork Mineral Creek, which drains sedimentary rocks containing calcite.

During high flow, many streams had higher pH values compared to those of low flow, including Mineral Creek, lower Cement Creek, and the Animas River downstream from Silverton. Streams affected by historical mining and geologic alteration still had relatively low pH values (less than 4.5). These included upper Mineral Creek (COM02, COM03, and COM05), north-flowing Red tributary (informal name) of Middle Fork Mineral Creek (COM18), tributary draining southwest Ohio Peak (COM14), North Fork Cement Creek (COC06), Cement Creek below North Fork (COC18), Prospect Gulch (COC26), Ohio Gulch (COC40), and Niagara Gulch (COC45) (figs. 2 and 5; table 2).

Aluminum

Aluminum binds with organic and inorganic ligands to form compounds that are soluble in acidic and basic solutions (aluminum is amphoteric) and quite insoluble in circumneutral solutions. Aluminum is listed as a nonpriority pollutant in surface water; it has a continuous concentration standard of 87 µg/L (micrograms per liter) and a maximum concentration standard of 750 µg/L (U.S. Environmental Protection Agency, 2002). Recent work has noted that colloidal aluminum may be the form most toxic to fish (Witters and others, 1996), and freshly formed aluminum-hydroxide precipitates may be the most toxic to trout. The toxicity of aluminum to brook trout is generally thought to be greatest at pH 5.0–5.5 (Cleveland and others, 1986; Mount and others, 1988). Water-quality standards for aluminum in the Animas River watershed have numeric values that vary by month, ranging from 700 µg/L in July to 3,550 µg/L in February (Unpub. report to Colorado Water Quality Control Commission, ARSG, 2001). Many of the aluminum concentrations in the study area exceeded the

standards; therefore, the colors for the distribution of dissolved aluminum were divided arbitrarily to show the stream segments with the highest dissolved aluminum concentrations (fig. 6).

During low flow, concentrations of dissolved aluminum ranged from a high of 71,400 µg/L in the north-flowing Red tributary of Middle Fork Mineral Creek (MC18, undisturbed site) and 71,400 µg/L in water from the Koehler tunnel to 77 µg/L at the outflow of the watershed study area (COA72) (fig. 6; table 1). Many stream segments and tributaries had aluminum concentrations that were below the detection limit (table 1). The distribution of high dissolved aluminum concentrations (green, orange, and red colors on the distribution map) reflects the weathering of hydrothermally altered rocks and low-pH waters in the study area.

A possible control on the aluminum chemistry of waters in the study area could be the leaching of aluminum from common aluminosilicate minerals in sulfuric acid solutions generated by the oxidation of sulfide minerals (Nordstrom and Ball, 1986, p. 55). An example illustrating aluminum precipitation that results from high dissolved aluminum concentrations is shown in drainage from the Governor mine, also called Paradise portal (fig. 7). The white precipitate has been identified as aluminum hydroxysulfate, or basaluminite (Carlson-Foscz, 1991), and the precipitation of the aluminum is generally attributed to mixing of acidic water from deeper in the mine with near-surface, circumneutral ground water (D.K. Nordstrom, oral commun., 1995). Many other streams in the study area also have these aluminum precipitates, such as Middle Fork Mineral Creek (MC79), Mineral Creek downstream from the confluence with Middle Fork, Burrows Creek (UA2), California Gulch (UA18), and West Fork Animas River at Animas Forks (UA51) (fig. 1; table 1). Aluminum precipitates are not everywhere accompanied by high dissolved aluminum concentrations. For example, the dissolved aluminum concentration was relatively low at site UA51 (326 µg/L, table 1); however, the mixing of acidic and more neutral waters causes aluminum precipitation that coats the streambed with a white material. Aluminum colloids also may be transported from mixing zones and deposited at downstream locations (Schemel and others, 2000, p. 1004); these processes occur at numerous locations throughout the watershed.

During high flow, dissolved aluminum concentrations were generally not as high as during low flow. Dissolved aluminum concentrations ranged from 14,000 µg/L at the headwaters of Mineral Creek, and 13,000 µg/L in water from North Fork Cement Creek, to below the detection limit at the outflow of the study area (fig. 8; table 2). Some stream segments had relatively high dissolved aluminum concentrations during high flow, including Burrows Creek, California Gulch, Prospect Gulch, most of Cement Creek, and the north-flowing Red tributary of Middle Fork Mineral Creek (fig. 8; table 2).

Dissolved aluminum concentrations are highly dependent on pH, and dissolved aluminum is not conservative (dissolved phase is pH dependent) in the hydrologic system (Stumm and
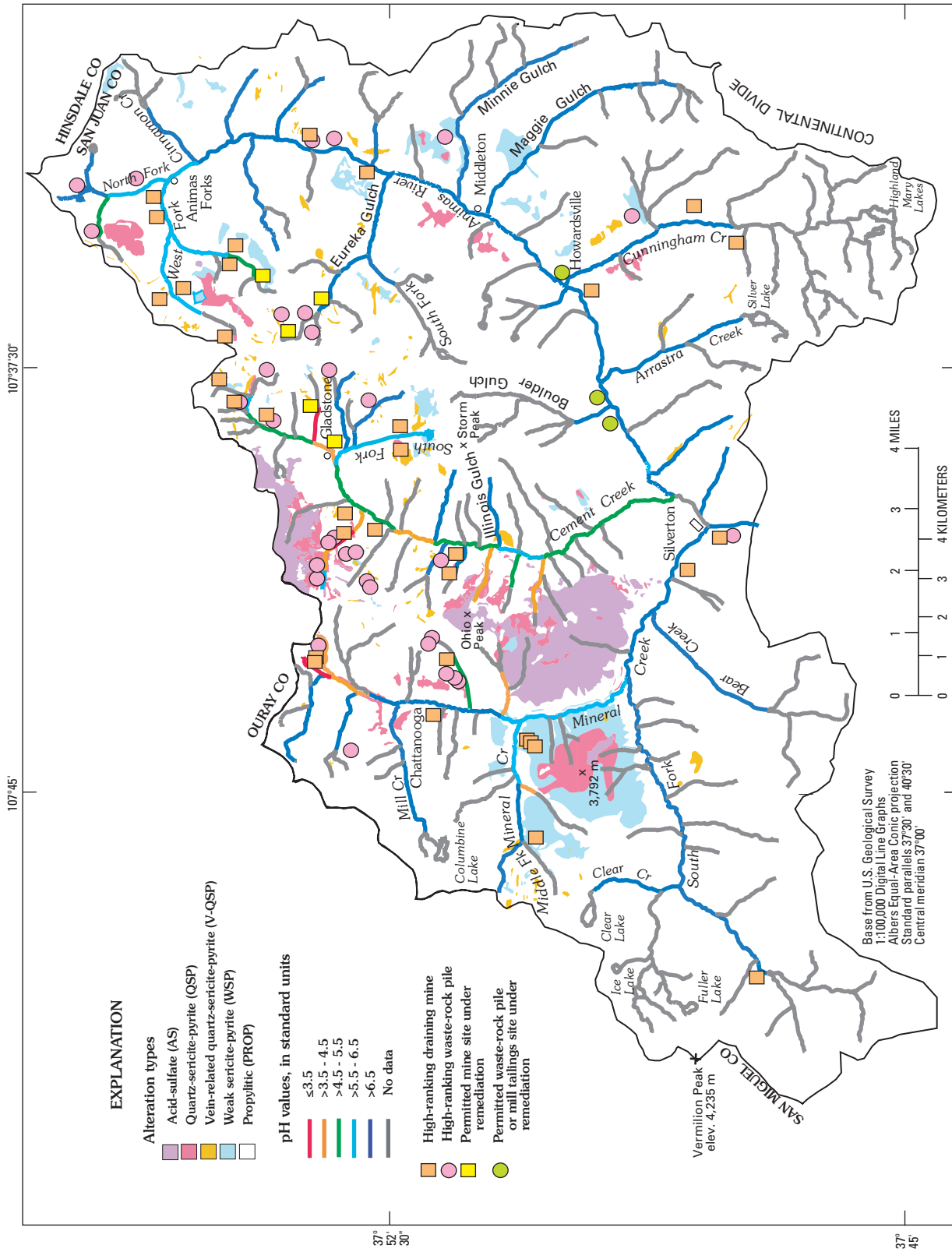
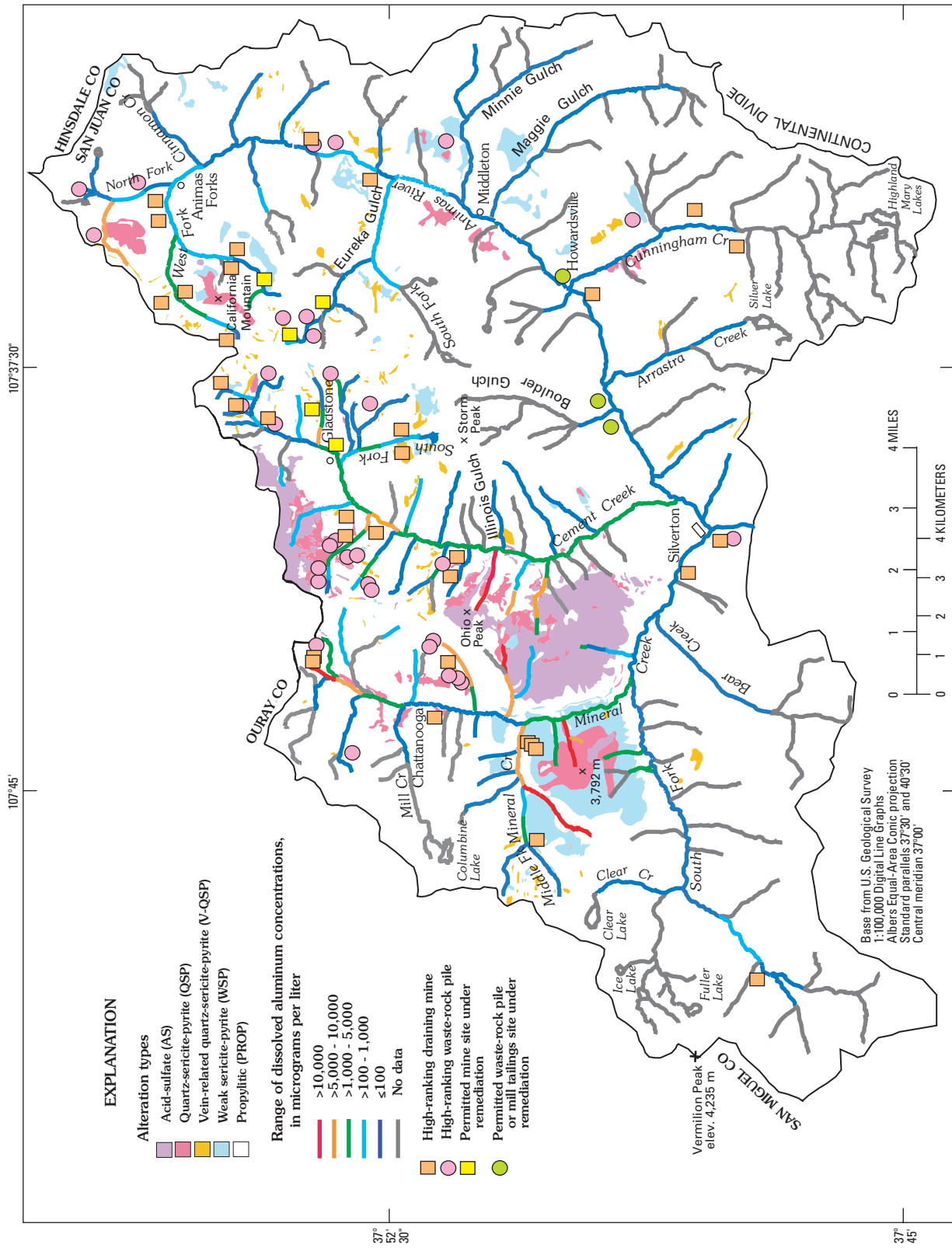**Figure 5.** Distribution of pH values in streams during high flow.

Figure 6.   Distribution of dissolved aluminum concentrations in streams during low flow.

Figure 7.   Aluminum hydroxysulfate precipitates in discharge from Governor mine (Paradise portal), Middle Fork Mineral Creek subbasin.

Morgan, 1981; Nordstrom and Ball, 1986; Schemel and others, 2000). Aluminum is soluble in acidic solutions, and the pH-dependent precipitation of aluminum colloids is illustrated by comparison of some of the dissolved and total-recoverable aluminum concentrations. For example, precipitated aluminum colloids are reflected by the difference between the dissolved aluminum concentration (0.45-µm filtration) and the total-recoverable aluminum concentration (unfiltered). In water from the Animas River downstream from Silverton (COA72) where the mean pH was 6.4, the mean dissolved aluminum concentration was 262 µg/L and the mean total-recoverable aluminum was 1,260 µg/L (Mast, Evans, and others, 2000). In water from Cement Creek (COC48) where the mean pH was 4.2, the mean dissolved aluminum concentration was

3,080 µg/L, and the mean total-recoverable aluminum was 12,940 µg/L. In water from a spring located in lower Mineral Creek (site MS57 in Mast, Evans, and others, 2000) where the mean pH was 2.9, the mean dissolved aluminum concentration was 10,260 µg/L, and the mean total-recoverable aluminum concentration was 10,270 µg/L.

Four possible controls on the aluminum chemistry in waters of the study area are (1) the leaching rate of aluminum from aluminosilicate minerals, (2) the solubility of aluminum sulfate minerals (basaluminite, jurbanite, and alunite) known to exist under these conditions (Nordstrom, 1982; Nordstrom and Ball, 1986), (3) the solubility of gibbsite and amorphous aluminum hydroxide minerals (Sullivan and Drever, 2001), and (4) the importance of organically bound
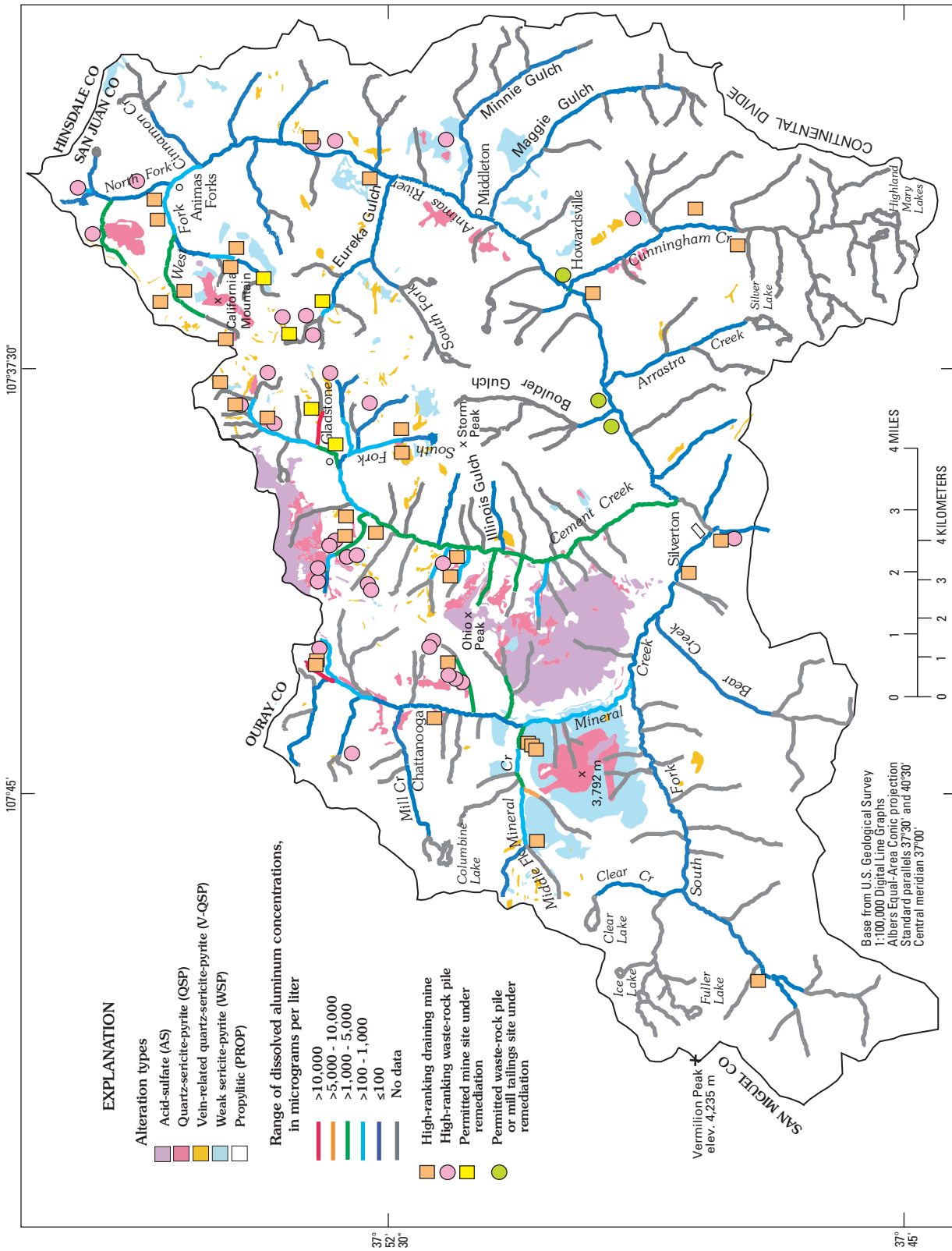
Figure 8.   Distribution of dissolved aluminum concentrations in streams during high flow.

dissolved aluminum (Nordstrom and Ball, 1986). Regarding solubility controls, aluminum should begin precipitating from the dissolved to the solid phase at about pH 4.5 and should not be present in the dissolved phase by about pH 5.5. In the study area, however, aluminum appears to be present in the dissolved phase to about pH 6.2 (fig. 9). The cause of this is uncertain, except for the possibility that the solubility of aluminum complexes is not following theoretical relations in the waters of the study area, or possibly aluminum colloids were passing through the 0.45-μm filtration apparatus.

Copper

Chronic toxicity of copper is an important factor limiting the distribution and abundance of brook trout populations in the study area (Besser and others, 2001; Besser and Brumbaugh, this volume). Survival of aquatic species exposed to copper and other divalent metals decreases when the concentration of metal bound to gills or other permeable body surfaces exceeds a threshold concentration. Chronic (long-term) toxicity occurs when threshold concentrations are achieved at internal target

EXPLANATION

◆ **Animas River downstream from Silverton**

■ **South Fork Cement Creek at Gladstone**

▲ **Mineral Creek at Chattanooga**

● **Mineral Creek at Silverton**
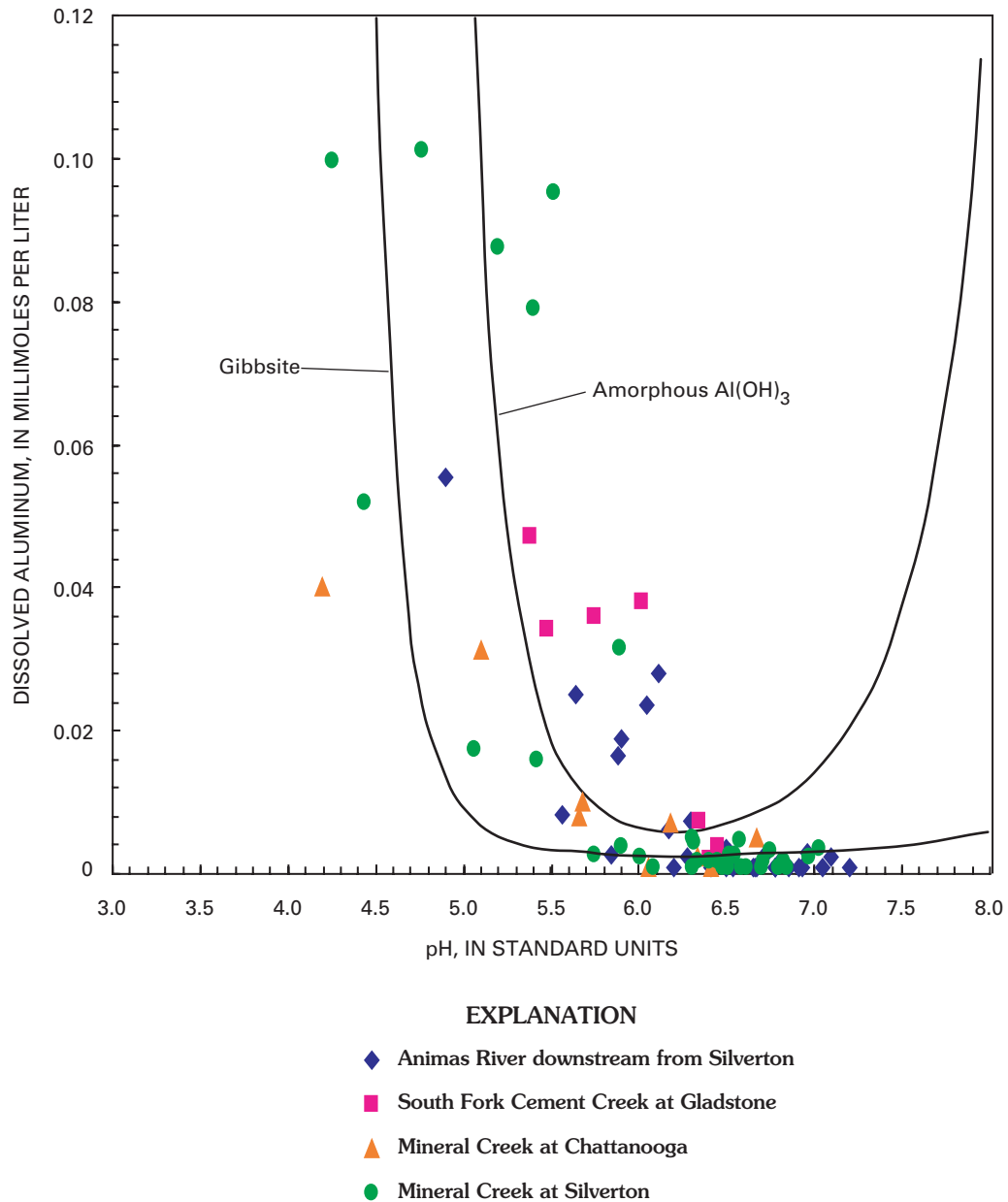
Figure 9.   Relation of pH values to dissolved aluminum concentrations in selected streams, compared to solubility lines for gibbsite (log K=9.35) and amorphous Al(OH)$_3$ (log K=10.8) (Sullivan and Drever, 2001).

organs. In acute (7 day) toxicity tests with copper in test waters with water quality similar to that of the Animas River, median lethal concentrations (LC50) of 35 and 75 µg/L were determined for fathead minnows and amphipods, respectively. Chronic (30 day) tests with early life stages of brook trout determined an LC50 (29 µg/L) similar to those for fathead minnows, but significant decreases in growth occurred at copper concentrations as low as 8 µg/L (Besser and Leib, this volume, Chapter E19). Copper is listed as a priority pollutant in surface water; it has a continuous concentration standard of 9 µg/L and a maximum concentration standard of 13 µg/L (U.S. Environmental Protection Agency, 2002). Copper standards for the Animas River downstream from Silverton are hardness-dependent concentrations; for hardness values ranging from 20–120 mg/L as $CaCO_3$, the chronic standard ranges from 2.9 to 13.8 µg/L, respectively (Unpub. report to Colorado Water Quality Control Commission, ARSG, 2000). Many of the dissolved copper concentrations in the study area exceeded the standards for aquatic life; therefore, the colors for the distribution of dissolved copper were divided arbitrarily to show the stream segments with the highest dissolved copper concentrations (fig. 10).

Dissolved copper concentrations in streams of the watershed were generally related to the presence of copper-bearing minerals such as chalcopyrite ($CuFeS_2$) and enargite (Cu_3AsS_4), and the highest dissolved copper concentrations generally were downstream from mines that worked these deposits. During low flow, dissolved copper concentrations ranged from 98,600 µg/L in water from the Koehler tunnel, to 8,390 µg/L in the stream downstream from the Congress mine, and 372 µg/L in water from a non-mining affected spring (site MC29) (fig. 10; table 1). In areas where copper minerals are not in abundance, such as the Animas River upstream from Silverton and parts of South Fork Mineral Creek, the dissolved copper concentrations were low and frequently below the analytical detection limit (<4 µg/L). Dissolved copper concentrations were elevated in water from a few non-mining affected streams and springs (MC29, MC52, and CC135, figs. 1 and 10; table 1); however, those dissolved copper concentrations were low compared to the concentrations from mining-affected sites, demonstrating the effect that mines can have on weathering of copper minerals. The distribution of high dissolved copper concentrations (green, orange, and red colors on the distribution map) reflects the weathering of hydrothermally altered rocks in the study area.

During high flow, the contrast in distribution of dissolved copper concentrations between low flow and high flow was not systematic. During snowmelt runoff, dissolved trace-metal concentrations typically decrease due to dilution (Sullivan and Drever, 2001). In Cement Creek, dissolved copper concentrations were higher during high flow, whereas dissolved copper concentrations were lower in Mineral Creek and in other parts of the watershed (figs. 2 and 11; table 2). For example, in the Animas River downstream from Silverton, the dissolved

copper concentrations decreased during snowmelt runoff. In Cement Creek, the dissolved copper concentrations increased during snowmelt runoff (fig. 12); the causes of this opposite response are uncertain. It is possible that small colloidal particles may have passed through the 0.45 µm filters; however, several replicate analyses were done on samples from Cement Creek filtered through 0.1 µm filters, and the results were the same as the 0.45 µm filtered analyses.

Dissolved copper is not conservative in the hydrologic system and partitions to solids by instream processes, particularly downstream from mixing zones of low- and high-pH waters (Church and others, 1997; Nordstrom, Alpers, and others, 1999). Copper adsorbs readily to particulates and is transported in the sediment and colloidal phases (Schemel and others, 2000). In the presence of iron and aluminum precipitates, copper concentrations can decrease with increasing pH values (Smith, 1994). The partitioning of dissolved copper is illustrated by comparing some of the dissolved and total-recoverable copper concentrations. For example, in water from the Animas River downstream from Silverton (COA72) where mean pH was 6.4 (during all seasons), the mean dissolved copper concentration was 13 µg/L and the mean total-recoverable copper was 27 µg/L (Mast, Evans, and others, 2000). In water from Cement Creek (COC48) where mean pH was 4.2, the mean dissolved copper concentration was 68 µg/L and the mean total-recoverable copper was 144 µg/L (Mast, Evans, and others, 2000). In water from the Joe and Johns mine, located in Prospect Gulch (site MS19 in Mast, Evans, and others, 2000), the pH value on March 14, 1997, was 2.54, the dissolved copper concentration was 597 µg/L, and the total-recoverable copper concentration was 605 µg/L (Mast, Evans, and others, 2000). These examples illustrate how low pH values correlate with high dissolved copper concentrations in water of the study area.

Iron

Iron is the main component of the colloidal material that forms in the streams of the study area. Therefore, the iron colloids may act to cover the food sources for aquatic life, can precipitate on fish gills, and can reduce the quantity and quality of habitat for benthic invertebrates and for spawning of trout. Toxicity data for iron are limited, and effects of aqueous iron on brook trout have been reported to vary widely under different test conditions (Besser and Leib, this volume). The toxicity of particulate iron to brook trout is low, and the standard method for separation of dissolved metals (0.45 µm filtration) does not adequately remove iron colloids (Church and others, 1997); therefore, dissolved iron concentrations tend to be overestimated. The toxicity of iron in stream water may best be represented by concentrations of dissolved ferrous iron (Fe^{2+}), which is the predominant species in highly acidic streams, such as Cement Creek and upper Mineral Creek
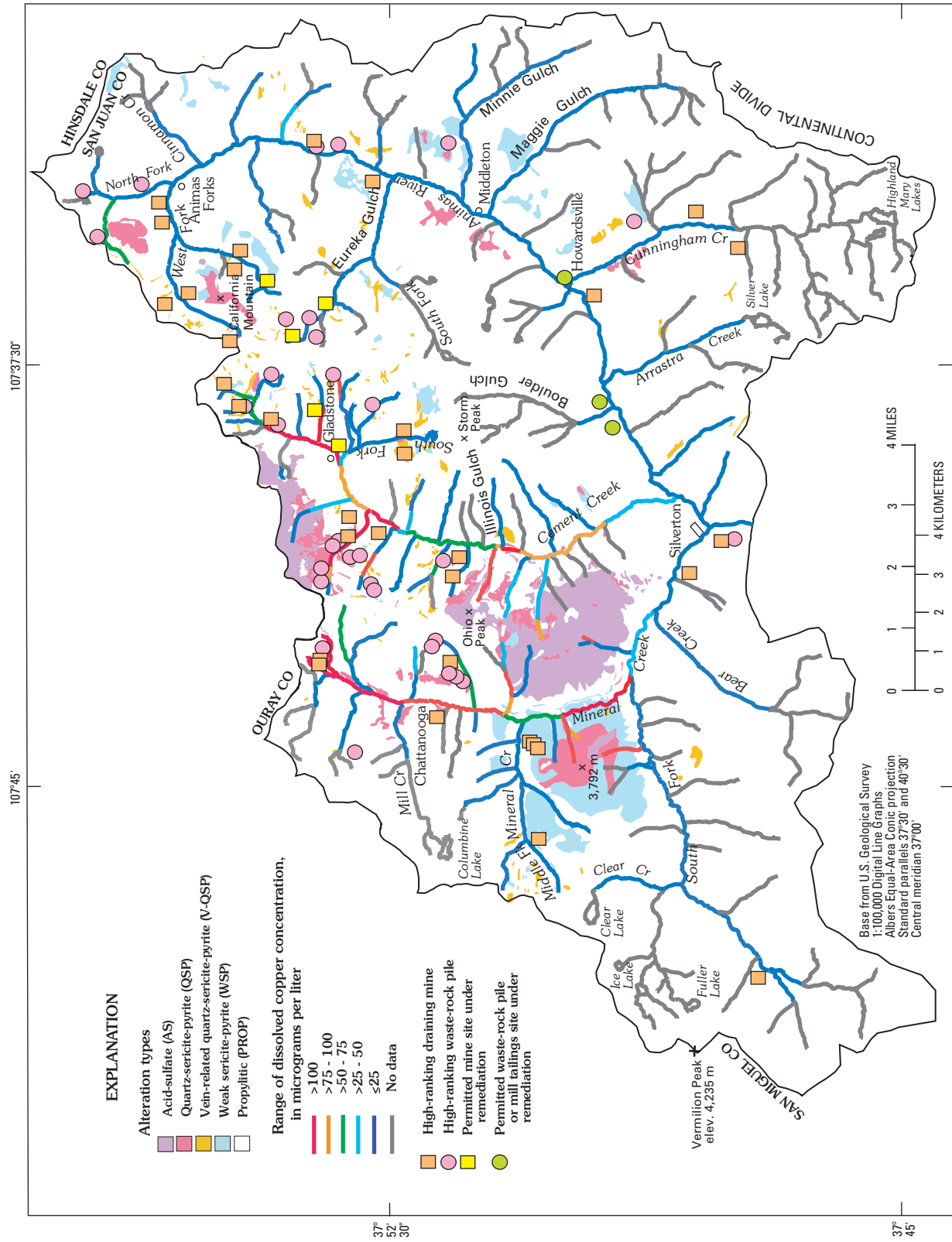
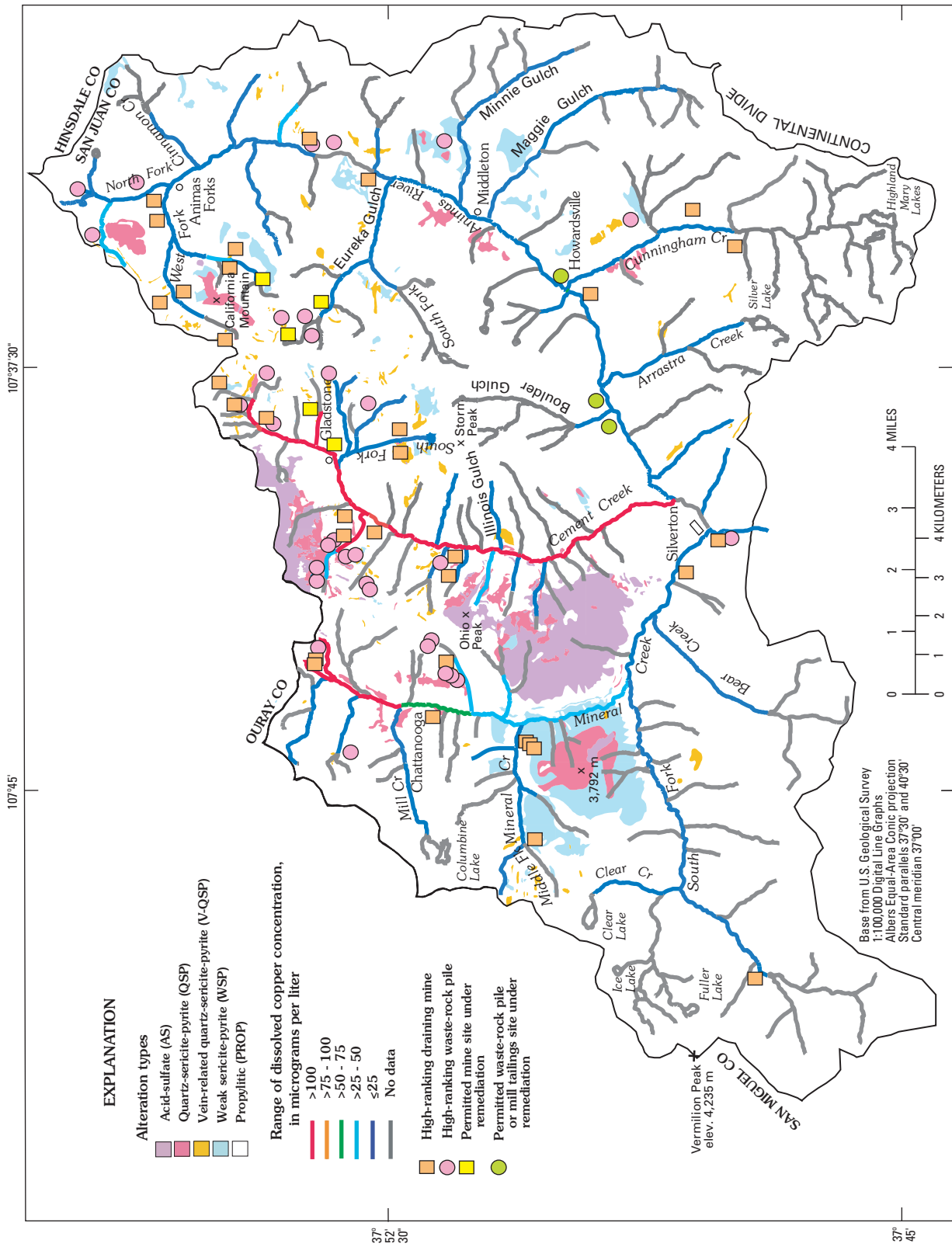**Figure 10.**   Distribution of dissolved copper concentrations in streams during low flow.

Figure 11.   Distribution of dissolved copper concentrations in streams during high flow.
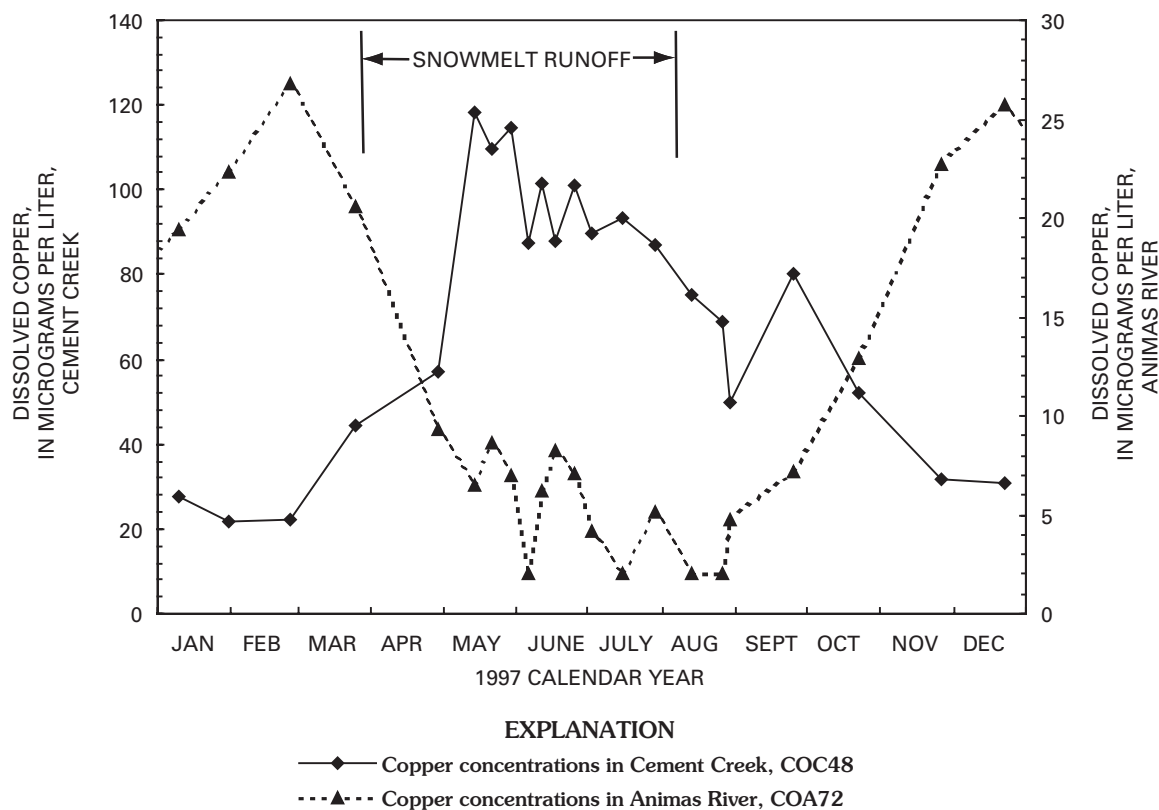
Figure 12. Dissolved copper concentrations in Cement Creek and in Animas River downstream from Silverton showing opposite responses to snowmelt runoff during April–September 1997.

(Besser and Leib, this volume). Iron is listed as a nonpriority pollutant in surface water; it has a continuous concentration standard of 1,000 μg/L (U.S. Environmental Protection Agency, 2002). Iron standards for chronic toxicity for the Animas River downstream from Silverton have numeric values that vary by month, ranging from 1,220 to 3,776 μg/L (Unpub. report to Colorado Water Quality Control Commission, ARSG, 2000). Many of the dissolved iron concentrations in the study area exceeded the standards for aquatic life; therefore, the colors for the distribution of dissolved iron were divided arbitrarily to show the stream segments with the highest dissolved iron concentrations.

Solubility of iron in streams is dependent on pH: iron is soluble at low pH values (less than about 3.2) and insoluble at higher pH values (Nordstrom and Alpers, 1999). However, iron also can be solubilized by sunlight through a process called photoreduction (McKnight and others, 1988). Iron precipitates as orange, red, or yellow solids under several conditions: (1) ground water with high ferrous-iron concentrations and low pH can discharge at springs or mine entrances and the ferrous iron oxidizes to ferric iron, which precipitates orange- or red-colored iron oxyhydroxides; (2) low-pH water with high dissolved iron concentration mixes with high-pH water, resulting in the precipitation of orange iron oxyhydroxides or yellow iron sulfate (for example, schwertmannite

(Bigham and others, 1996)); (3) ferrous iron is solubilized by photoreduction of ferric iron colloids in the stream, and reprecipitates as an orange oxyhydroxide. The iron oxyhydroxides and iron sulfates can be transported with the stream in a colloidal or sediment form, and iron colloids contribute to degradation of both water quality and habitat. Ground water discharging from springs or diffusely from the soil zone can form ferricrete deposits (Hanshaw, 1974). Because of the pervasive presence of iron sulfide minerals, dissolved and colloidal iron are major contributors to water-quality degradation in the Animas River watershed study area (Church and others, 1997; Schemel and others, 2000). Large iron springs and ferricrete deposits are present in many locations throughout the watershed (fig. 1); some of the iron springs are quite large and contribute to trace-metal loading in the study area. Figure 13 shows photographs of two large iron springs.

During low flow, dissolved iron concentrations ranged from 686,000 μg/L in water from the Koehler tunnel, to 117,000 μg/L in the north-flowing Red tributary of Middle Fork Mineral Creek (undisturbed site), and 25,000 μg/L in water from Ohio Gulch. The distribution of dissolved iron concentrations greater than 1,000 μg/L (green, orange, and red colors) reflects the weathering of hydrothermally altered rocks in the study area. In the Animas River upstream from Silverton, where hydrothermally altered rocks are less

Figure 13.   Iron oxyhydroxide precipitates in discharge from undisturbed springs. *A*, spring in lower Prospect Gulch (site CC29, Mast, Evans, and others, 2000); *B*, springs in Cement Creek downstream from confluence with Prospect Gulch (site CC1, Mast, Evans, and others, 2000).
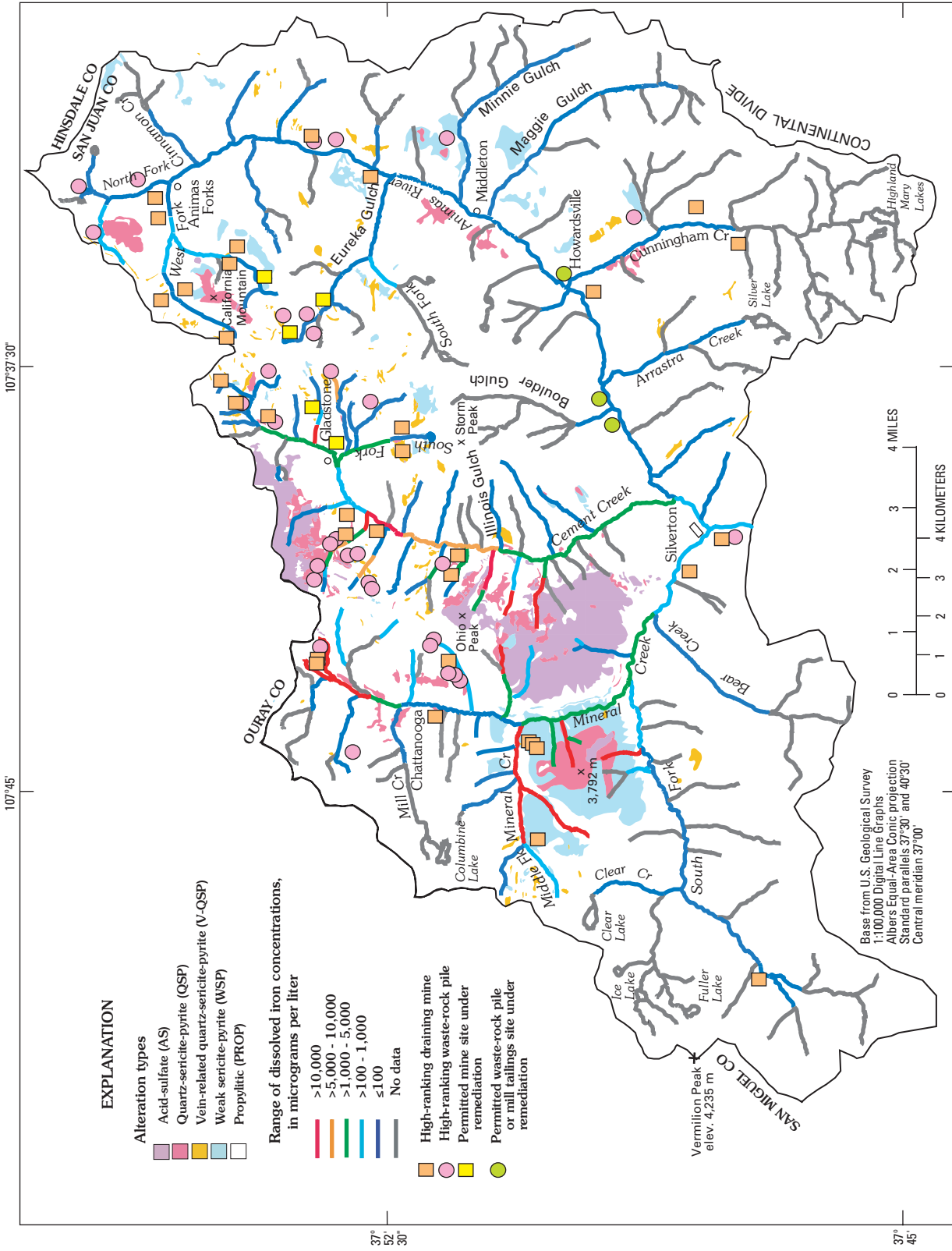
Figure 14.   Distribution of dissolved iron concentrations in streams during low flow.

abundant, dissolved iron concentrations were below detection limit in many stream segments. The dissolved iron high-flow data coverage was not nearly as complete as the low-flow data coverage; therefore, dissolved iron distribution maps are not shown for high-flow conditions.

Dissolved iron is highly dependent on pH and is not conservative in the hydrologic system. The pH-dependent precipitation of iron solids is illustrated by a comparison of some of the dissolved and total-recoverable iron concentrations. For example, in water from the Animas River downstream from Silverton (COA72) where the mean pH was 6.4, the mean dissolved iron concentration was 894 µg/L and the mean total-recoverable iron was 2,180 µg/L. In water from Cement Creek (COC48) where the mean pH was 4.2, the mean dissolved iron concentration was 3,590 µg/L and the mean total-recoverable iron was 49,240 µg/L. In water from a spring in lower Mineral Creek (site MS57 in Mast, Evans, and others, 2000) where the mean pH was 2.9, the mean dissolved iron concentration was 6,560 µg/L and the mean total-recoverable iron concentration was 6,980 µg/L. These examples illustrate how low pH values correlate with high dissolved iron concentrations in water of the study area.

Manganese

Manganese does not have a national water-quality criterion for surface water. The chronic aquatic life standards for manganese established for the Animas River at Silverton have numeric values that vary by month, and the values range from 1,000 to 2,700 µg/L (Unpub. report to Colorado Water Quality Control Commission, ARSG, 2000). Many of the dissolved manganese concentrations in the study area exceeded the chronic standards for aquatic life; therefore, the colors for the distribution of dissolved manganese were divided arbitrarily to show the stream segments with the highest dissolved manganese concentrations (fig. 15).

The distribution of high dissolved manganese concentrations (greater than 1,000 µg/L) was generally related to the presence of deposit-related minerals such as pyroxmangite ($MnSiO_3$), huebnerite or manganese tungstate ($MnWO_4$), and rhodochrosite ($MnCO_3$) (Bove and others, this volume); however, dissolved manganese concentrations were relatively high in many stream reaches of the study area because of manganese transport downstream from source areas. Manganese is soluble and can be transported long distances downstream from its source (Hem and Lind, 1994; Kimball and others, 1995). In addition, mill tailings piles that have large accumulations of tailings processed from manganese-rich ores also are sources from which manganese can be leached into streams. These factors contributed to the persistent presence of manganese in streams of the study area.

During low flow, dissolved manganese concentrations ranged from 23,700 µg/L in water from the Koehler tunnel, to 2,150 µg/L in the north-flowing Red tributary of Middle Fork Mineral Creek (undisturbed site M18, which is away from the influence of mine water), and 9,900 µg/L in upper Ohio Gulch

(table 1). The distribution of high manganese concentrations (green, orange, and red colors on the distribution map) reflects the weathering of hydrothermally altered rocks. The dissolved manganese data coverage for high flow was not nearly as complete as the coverage for low flow; therefore, dissolved manganese distribution maps are not shown for high-flow conditions.

One of the highest dissolved manganese concentrations was 56,010 µg/L in a seep below the waste-rock pile at the Yukon tunnel (site CC100 in Mast, Evans, and others, 2000; Yager and Bove, this volume), located east of site COC43 in Cement Creek (fig. 1). This site was a tungsten mine, and the primary deposit-related mineral was huebnerite ($MnWO_4$). In many other areas where high dissolved manganese concentrations were present in the water, the huebnerite (or tungsten) was not the target economic mineral, and other manganese phases were present as a gangue mineral. For example, the Sunnyside mine, which consists of more than 166 km of underground tunnels between upper Eureka Gulch and Gladstone (fig. 15), contained an abundance of pyroxmangite ($MnSiO_2$); and mines that were developed in "Sunnyside-type" deposits (Casadevall and Ohmoto, 1977) tended to have elevated dissolved manganese concentrations in mine drainage. The high concentrations of manganese downstream from Gladstone (fig. 15) may have been affected by development of Sunnyside-type deposits.

High dissolved manganese concentrations were present in stream reaches affected by conditions not related to mining. Manganese concentrations in California Gulch (sites UA5 and UA18, fig. 1) were largely affected by springs on the west side of California Mountain. For example, site UA37 had a dissolved manganese concentration of 74,670 µg/L (Mast, Evans, and others, 2000; Yager and Bove, this volume), and the "undisturbed" occurrence of manganese is evident in this area because of the thick, black manganese-rich ledges (called manganocrete (Verplanck and others, this volume, Chapter E15)) that are present along the east bank of California Gulch (fig. 16).

Dissolved manganese generally is conservative in the hydrologic system at all pH ranges (Garrels and Christ, 1965). Schemel and others (2000) showed that manganese transport from the Animas River, Cement Creek, and Mineral Creek to the Animas River downstream of Silverton agreed within 4 percent. Comparing the dissolved and total-recoverable manganese concentrations in the study area can illustrate other examples of the persistence of dissolved manganese. For example, in water from the Animas River at Eureka on September 23, 1998 (site COA33), the dissolved manganese concentration was 971 µg/L and the total-recoverable manganese concentration was 1,030 µg/L at pH of 6.4, indicating that 94 percent of total manganese was present in the dissolved phase (Mast, Evans, and others, 2000). In water from the Animas River at Silverton on January 30, 1997 (site A68 in Mast, Evans, and others, 2000), the dissolved manganese concentration was 2,830 µg/L and the total-recoverable manganese concentration was 2,950 µg/L at pH of 6.4 (95 percent in the dissolved phase). In water from Cement Creek near Silverton on January 9, 1997 (site C48 in Mast, Evans, and others, 2000),
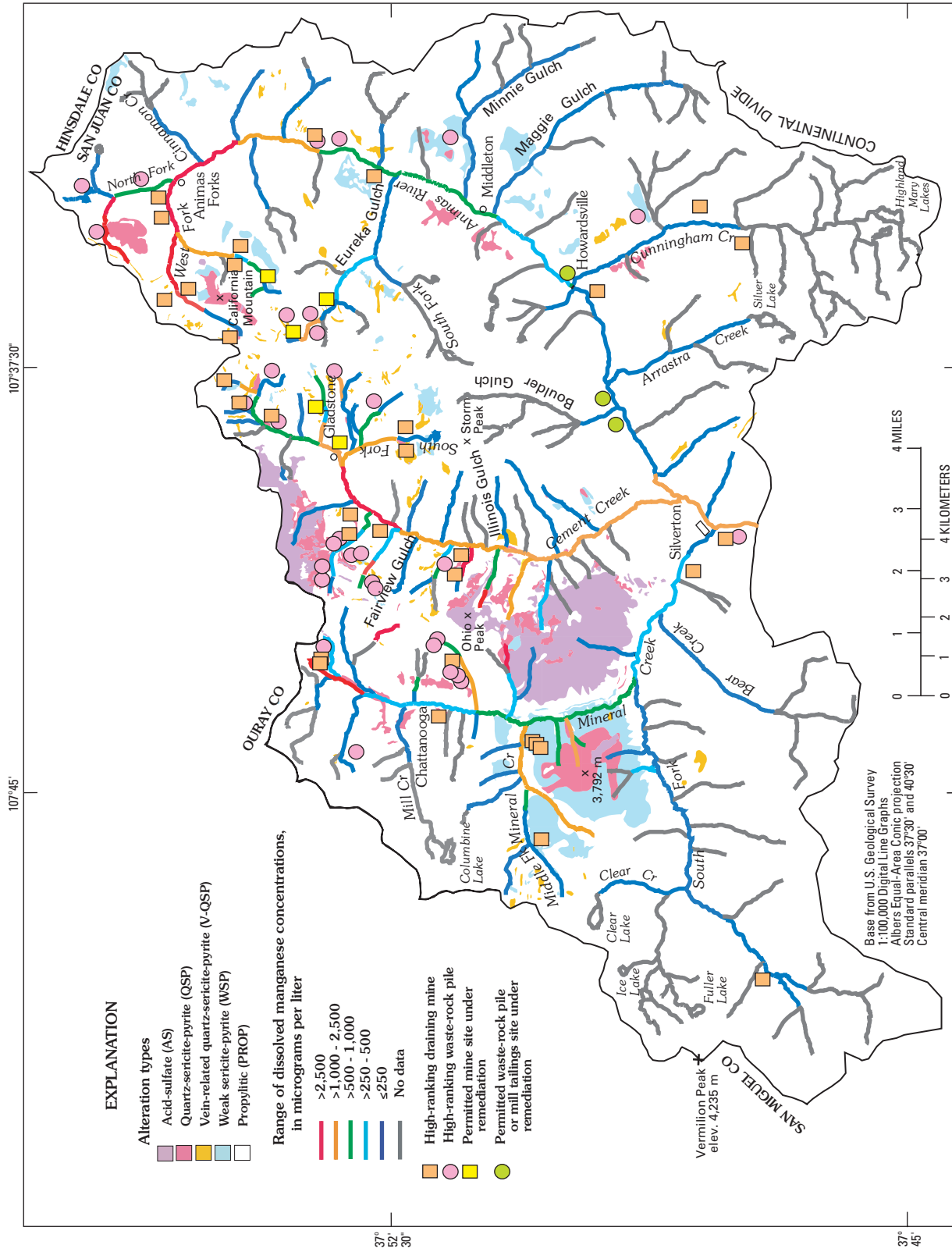
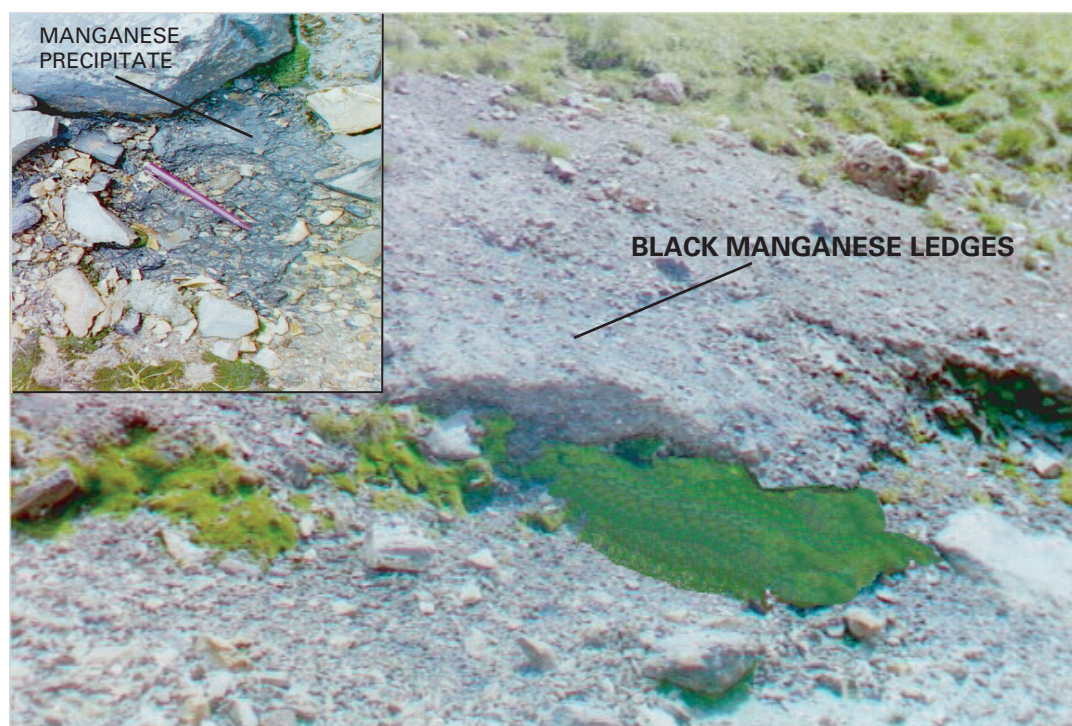**Figure 15.** Distribution of dissolved manganese concentrations in streams during low flow.

Figure 16.   Manganese precipitates in discharge from undisturbed springs in California Gulch.

the dissolved manganese concentration was 1,810 µg/L and the total-recoverable manganese concentration was 1,820 µg/L at pH of 3.9 (99 percent in the dissolved phase). In water from the Animas River downstream from Silverton on April 28, 1997 (A72 in Mast, Evans, and others, 2000), the dissolved manganese concentration was 1,100 µg/L and the total-recoverable manganese concentration was 1,110 µg/L at pH of 6.96 (99 percent in the dissolved phase). These examples illustrate that manganese remains in the dissolved phase in water of the study area regardless of the pH values. However, stream cobbles throughout the study area are frequently coated with a black manganese precipitate, possibly caused by biological or organic complexation of manganese (Morgan, 2000); this indicates that some manganese is lost from the dissolved phases to solid phases.

Zinc

Zinc is essential for metabolism by most living organisms, but high concentrations of zinc can be toxic to aquatic organisms (Muyssen and others, 2002). Dissolved zinc is the primary element of concern for survival of aquatic life in the Animas River watershed study area because levels of zinc exceed aquatic standards in many reaches (Besser and Brumbaugh, this volume). Zinc toxicity can be reduced by increased pH, hardness, and cadmium concentrations (Barata and others, 2002). Hence, aquatic toxicity guidelines and standards for zinc encompass complex issues. From laboratory

tests of upper Animas River water samples, zinc was more toxic to amphipods than to fathead minnows, whereas copper was more toxic to minnows than to amphipods (Besser and Leib, this volume). Zinc toxicity thresholds (EC50) for survival were 200, 704, and greater than 2,000 µg/L for amphipods, fathead minnows, and brook trout, respectively (Besser and others, this volume). Zinc is listed as a priority pollutant in surface water; it has a continuous concentration standard of 120 µg/L and a maximum concentration standard of 120 µg/L (U.S. Environmental Protection Agency, 2002). The chronic aquatic life standards for zinc established for the Animas River downstream from Silverton have numeric values that differ by month, ranging from 170 to 620 µg/L (Unpub. report to Colorado Water Quality Control Commission, ARSG, 2000). Many of the dissolved zinc concentrations in the study area exceeded the standards for aquatic life; therefore, the colors for the distribution of dissolved zinc were divided arbitrarily to show the stream segments with the highest dissolved zinc concentrations (fig. 17).

Dissolved zinc concentrations are primarily related to the presence of the deposit-related mineral sphalerite (ZnS) and trace concentrations of zinc in other sulfide minerals of the study area (Bove and others, this volume; Mast and others, this volume). During low flow, the highest dissolved zinc concentration in the study area was in water from the Koehler tunnel (MS81), the Longfellow mine (MS82), and upper Mineral Creek (COM02) (fig. 17; table 1). The dissolved zinc concentration was 10,940 µg/L in the stream affected by the Congress
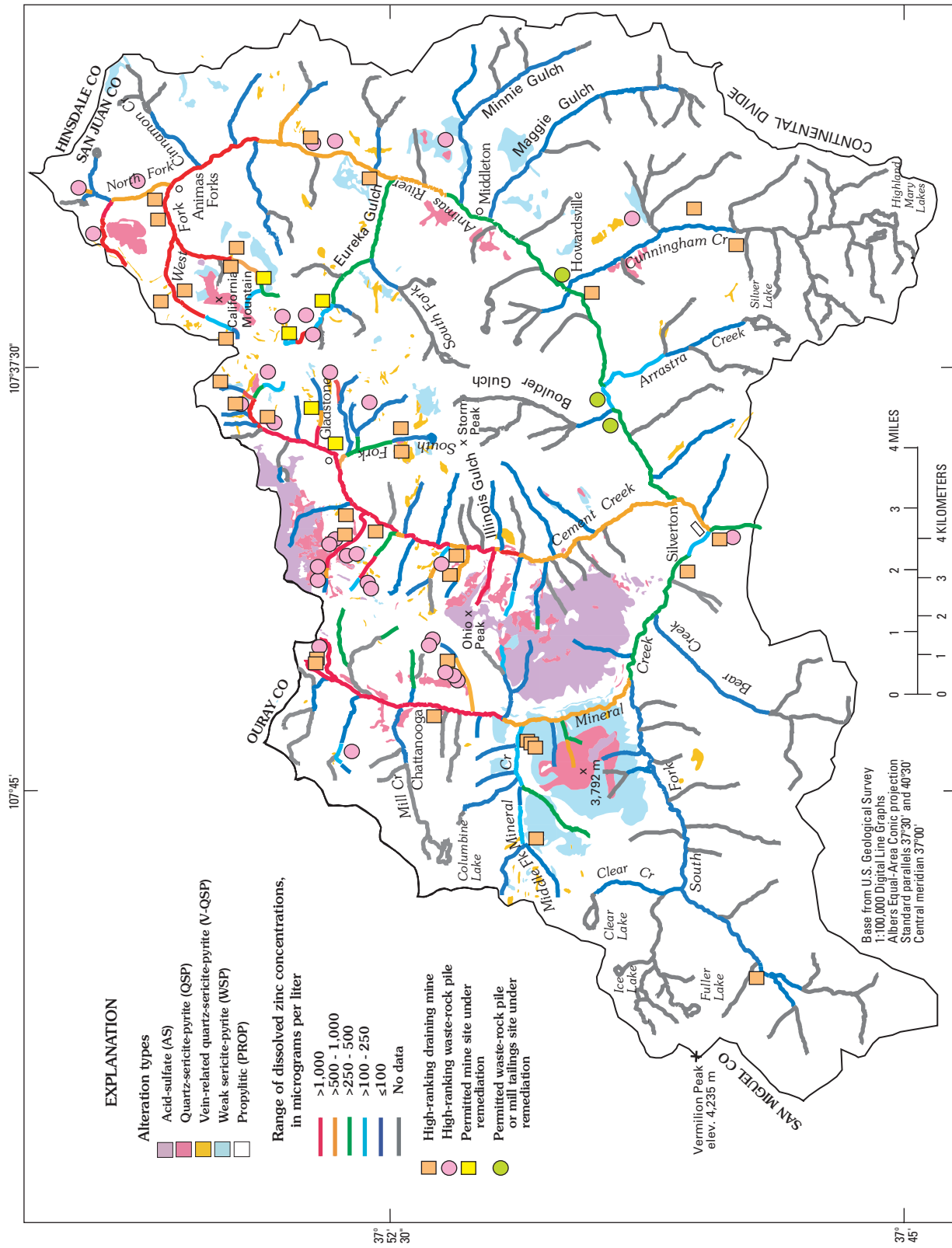
Figure 17.   Distribution of dissolved zinc concentrations in streams during low flow.

mine (MC39, table 1), which was affected by the similar geologic setting as the Koehler tunnel and Longfellow mine (the Red Mountain district, Bove and others, this volume). By the time water in Mineral Creek reached Chattanooga (site COM07), the dissolved zinc concentrations were diluted considerably, to a concentration of 3,050 μg/L. In water from Mineral Creek near Burro Bridge (site COM13), the dissolved zinc concentrations were diluted further, to a concentration of 1,590 μg/L. These high dissolved zinc concentrations were diluted to 729 μg/L at site COM27 upstream from the confluence of Mineral Creek and South Fork Mineral Creek (fig. 1). South Fork Mineral Creek (site COM28) had a dissolved zinc concentration of 9 μg/L and pH of 7.6; the dissolved zinc concentrations at COM34 were diluted even further, to 131 μg/L (figs. 1 and 17; table 1).

One subbasin in particular with high dissolved zinc concentrations was Prospect Gulch (fig. 1), where historical mines and a number of non-mining affected springs with elevated trace-metal concentrations are located (Wirt and others, 2001). Dissolved zinc concentrations were 810 μg/L at site PG45 below the shaft mines in upper Prospect Gulch (table 1), and the concentrations remained relatively the same (at about 1,400 to 1,700 μg/L) for the remaining length of the stream. Streamflow discharges increased throughout this reach of stream; therefore, other sources—probably diffuse ground-water sources—contributed to dissolved zinc concentrations in the reach (Wirt and others, 2001). Dissolved zinc concentrations from non-mining affected springs included a spring in lower Prospect Gulch (fig. 13*A*—1,070 μg/L) and a spring downstream from the confluence of Prospect Gulch with Cement Creek (fig. 13*B*—1,280 μg/L) (Mast, Evans, and others, 2000; Mast and others, this volume; Yager and Bove, this volume). Discharge from diffuse ground-water sources affects dissolved zinc concentrations in many streams of the study area, particularly in Cement Creek (Kimball and others, 2002).

Dissolved zinc concentrations were higher in Eureka Gulch and the North Fork Animas River during high flow than during low flow; however, concentrations were diluted in several reaches of the Animas River, Cement Creek, and Mineral Creek. Even though the streamflow discharges were much greater (as much as twice the discharge as during low flow; see fig. 3 in von Guerard and others, this volume), the dissolved zinc concentrations were in the same range during snowmelt, possibly because of the flushing of zinc from soils and waste-rock piles.

Other Metals

Other metals and constituents in the study area may be detrimental to the survival of aquatic life. Cadmium is highly toxic and tends to bioaccumulate in tissues of aquatic and terrestrial biota. Tissues of fish and aquatic invertebrates of the Animas River watershed study area were found to contain elevated concentrations of cadmium, although bioaccumulation of cadmium was not closely associated with observed impacts on stream ecosystems (Besser and others, 2001; Besser and others, this volume). Cadmium (possibly airborne) has been shown to affect ptarmigans in the southern Rocky Mountains (Larison and others, 2000). Cadmium concentrations were generally below the detection limits for most of the samples in the study area for water-quality samples analyzed by inductively coupled plasma–atomic emission spectroscopy (ICP-AES) (Mast, Evans, and others, 2000). Therefore, water-quality samples from selected sites (COA33, COA53, COA58, COA68, and COA72) were reanalyzed for cadmium using graphite furnace atomic absorption spectroscopy (GFAA), and the concentrations ranged from 0.6 to 5.1 μg/L (Mast, Evans, and others, 2000). Cadmium is listed as a priority pollutant in surface waters; it has a continuous concentration standard of 0.25 μg/L and a maximum concentration standard of 2.0 μg/L (U.S. Environmental Protection Agency, 2002). Lead also can be toxic in the environment (Prosi, 1989). Lead is listed as a priority pollutant; it has a continuous concentration standard of 2.5 μg/L and a maximum concentration standard of 65 μg/L (U.S. Environmental Protection Agency, 2002). Several streams in the study area had high dissolved lead concentrations (for example, COA33, 150 μg/L; COA58, 95 μg/L; COC43, 70 μg/L; CC58, 170 μg/L; CC59, 320 μg/L; CC134, 34 μg/L; COM07, 197 μg/L; COM13, 110 μg/L; COM34, 62 μg/L; MC29, 140 μg/L, in Mast, Evans, and others, 2000). Mine drainage sites had dissolved lead concentrations ranging from less than 30 to 1,380 μg/L (Mast, Evans, and others, 2000). Lead sorbs strongly to colloids and may be transported as bed sediment; however, stream sediment was not found to be toxic to aquatic organisms in the study area (Besser and Leib, this volume). Chromium is known to be toxic to aquatic organisms, but toxicity depends on the chromium valence state (Spehar and Fiandt, 1986). Hexavalent chromium (chromium VI) is listed as a priority pollutant; it has a continuous concentration standard of 11 μg/L and a maximum concentration standard of 16 μg/L (U.S. Environmental Protection Agency, 2002). Trivalent chromium (chromium III) is listed as a priority pollutant; it has a continuous concentration standard of 74 μg/L and a maximum concentration standard of 570 μg/L (U.S. Environmental Protection Agency, 2002). Dissolved chromium concentrations (valence not determined as part of this study) ranged from less than 2 to 1,980 μg/L in streams, springs, and inactive mines of the study area (Mast, Evans, and others, 2000). Because of the high detection limits and lack of data, distribution maps are not shown for these metals; however, the presence of high concentrations of these metals in selected samples indicates that they are present in the hydrogeochemical system and are being transported in the dissolved, colloidal, or sediment phases.
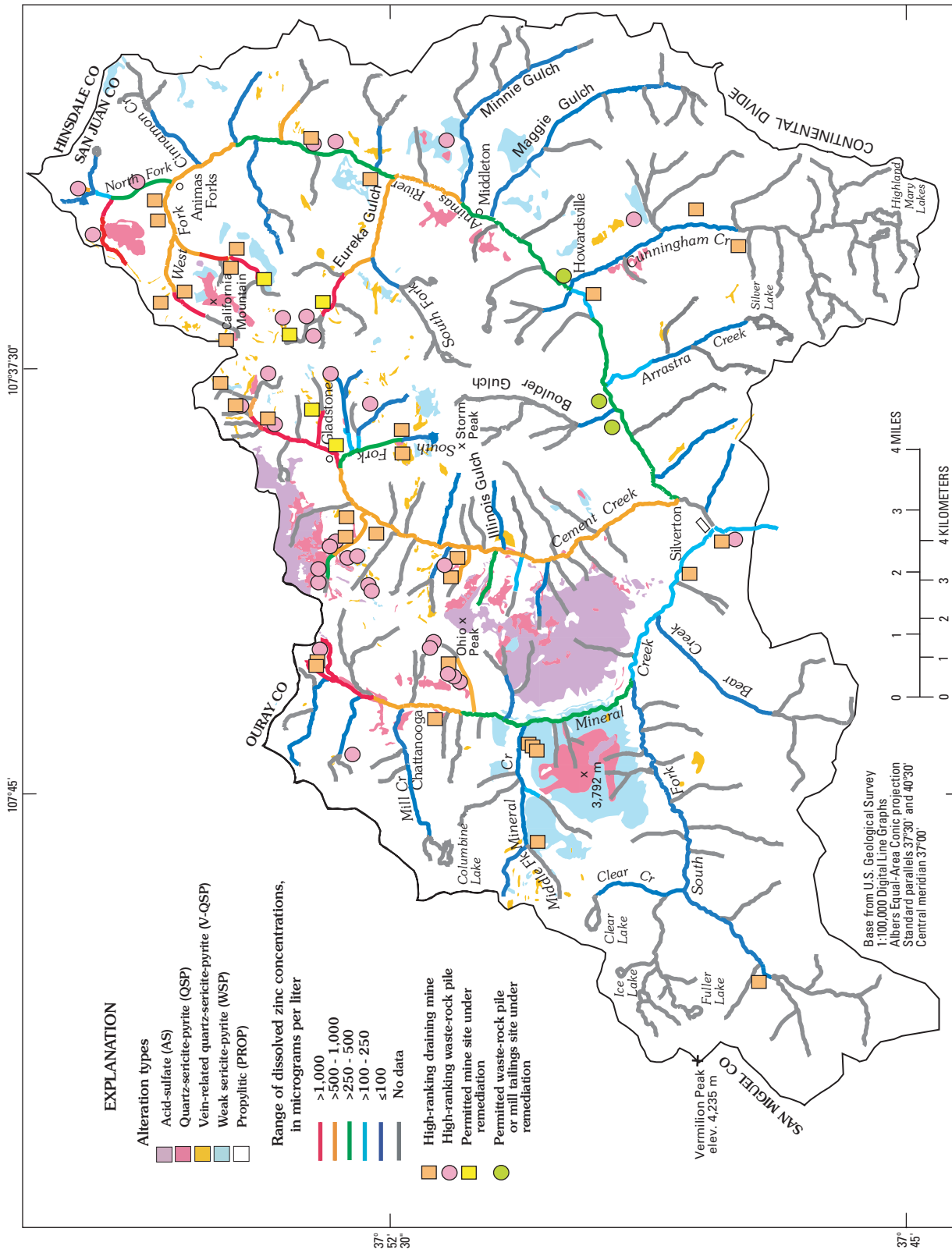
Figure 18.   Distribution of dissolved zinc concentrations in streams during high flow.

Summary

In the Animas River watershed study area, low pH and elevated concentrations of trace elements have degraded stream and surface water. Water quality is dependent upon weathering processes that take place in hydrothermally altered rocks and affect water that flows through to the streams. These weathering processes accelerate when water passes through rock disturbed by historical mining. Ground water draining from historical mine sites, and rainfall and snowmelt washing across and through mine-waste piles and mill tailings, can cause the release of considerable amounts of acidity and trace elements into nearby streams. All of these situations can produce high trace-metal concentrations and low pH values that degrade the environment and may make stream reaches toxic to aquatic life.

The pH of study area streams showed a wide range of low and high values, a variation mostly influenced by the presence or absence of nearby altered rocks. Where pH values were low (below ≈3.5), the dissolved and total-recoverable trace-metal concentration values were nearly equal to one another. Where pH values were high (above ≈6.5), in some instances dissolved trace elements were precipitating or were partitioning to solids, processes influenced by mixing of different-pH waters.

The distribution of trace-element concentrations varied greatly: the highest concentrations were evident in headwater streams near mine sites that have been suggested for remediation and in areas of highly altered rocks. The lowest trace-element concentrations were generally in headwater streams in areas of propylitic alteration, regardless of the presence of historical mines.

Because of the combined effects of hydrothermal alteration and historical mines on streams, we cannot distinguish their effects and cannot attribute low pH values and high trace-metal concentrations to either. That several historical mines have an effect on study area streams, however, has been made clear. Finally, some non-mining affected springs in the study area themselves contain low pH values and high trace-metal concentrations, which may further complicate the determination of the extent to which anthropogenic sources affect the dissolved trace-element concentrations and pH of streams.

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