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The effects of acidic mine drainage from historical mines in the Animas River watershed, San Juan County, Colorado—What is being done and what can be done to improve water quality?

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ABSTRACT

Historical production of metals in the western United States has left a legacy of acidic drainage and toxic metals in many mountain watersheds that are a potential threat to human and ecosystem health. Studies of the effects of historical mining on surface water chemistry and riparian habitat in the Animas River watershed have shown that cost-effective remediation of mine sites must be carefully planned. Of the more than 5400 mine, mill, and prospect sites in the watershed, ~80 sites account for more than 90% of the metal loads to the surface drainages. Much of the low pH water and some of the metal loads are the result of weathering of hydrothermally altered rock that has not been disturbed by historical mining. Some stream reaches in areas underlain by hydrothermally altered rock contained no aquatic life prior to mining.

Scientific studies of the processes and metal-release pathways are necessary to develop effective remediation strategies, particularly in watersheds where there is little land available to build mine-waste repositories. Characterization of mine waste, development of runoff profiles, and evaluation of ground-water pathways all require rigorous study and are expensive upfront costs that land managers find difficult to justify. Tracer studies of water quality provide a detailed spatial analysis of processes

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affecting surface- and ground-water chemistry. Reactive transport models were used in conjunction with the best state-of-the-art engineering solutions to make informed and cost-effective remediation decisions.

Remediation of 23% of the high-priority sites identified in the watershed has resulted in steady improvement in water quality. More than $12 million, most contributed by private entities, has been spent on remediation in the Animas River watershed. The recovery curve for aquatic life in the Animas River system will require further documentation and long-term monitoring to evaluate the effectiveness of remediation projects implemented.

Keywords: acid mine drainage, watershed impacts, historical mining, environmental effects, remediation

INTRODUCTION

Thousands of inactive hardrock mines have left a legacy of acid drainage and toxic metals across mountain watersheds in the western United States. Many watersheds in or west of the Rocky Mountains have headwater streams in which the effects of historical hardrock mining are thought to represent a potential threat to human and ecosystem health (e.g., Fields, 2003). In many areas, weathering of unmined mineral deposits, waste rock, and mill tailings in areas of historical mining may increase metal concentrations and lower pH, thereby contaminating the surrounding watershed and ecosystem. Streams near abandoned inactive mines can be so acidic or metal laden that fish and aquatic insects cannot survive (e.g., Besser and Brumbaugh, 2007; Besser and Leib, 2007; Anderson, 2007), and birds are negatively affected by the uptake of metals through the food chain (e.g., Larison et al., 2000). Although estimates of the number of inactive mine sites in the West vary, observers agree that the scope of this problem is huge, particularly in the western United States, where public lands contain thousands of inactive mines and prospects.

Numerous inactive mines are located either on or adjacent to public lands or affect aquatic or wildlife habitat on federal land. In 1995, personnel from a U.S. Department of the Interior (DOI) and U.S. Department of Agriculture (USDA) interagency task force developed a coordinated strategy for the cleanup of environmental contamination from inactive mines associated with federal lands. Estimates of the number of inactive mines that affect surface water quality on National Forest (USDA-FS) and Bureau of Land Management (BLM) administered lands were low (6000 mine sites; Greeley, 1999) relative to those provided for the entire United States by the Minerals Policy Center (131,000 mine sites; Da Rosa and Lyon, 1997). As part of an interagency effort, the U.S. Geological Survey implemented an Abandoned Mine Lands (AML) Initiative to develop a strategy for gathering and communicating the scientific information needed to formulate effective and cost-efficient remediation of inactive, abandoned mines on federal land. Objectives of the AML Initiative included: (1) watershed-scale and site characterization, understanding of the effect and extent of sources of metals and acidity, and (2) communication of these results to stakeholders, land managers, and the general public. Additional objectives addressed included transfer of technologies developed within the AML Initiative into practical methods at the field scale and demonstration of their applicability to solve this national environmental problem in a timely manner within the framework of the watershed approach. Finally, developing working relationships with the private sector, local citizens, and state and federal land management and regulatory agencies will establish a scientific basis for consensus, providing an example for future investigations of watersheds affected by inactive historical mines (Buxton et al., 1997).

The combined AML interagency effort has been conducted in two pilot watersheds (Fig. 1), the Animas River watershed study area in Colorado (Church et al., 2007c) and the Boulder River watershed study area in Montana (Nimick et al., 2004). Land and resource-management agencies are faced with evaluating the risks associated with thousands of potentially harmful mine sites on federal lands. Comprehensive scientific investigations have been conducted in both AML watersheds. The level of scientific study conducted in the AML watersheds will not be feasible in every watershed affected by historical mining. Development of criteria for evaluating ecological and environmental effects of historical mining was a paramount objective of these studies. Clearly, remediation of federal lands affected by inactive historical mines will require substantial investments of resources.

Land management and regulatory agencies face two fundamental questions when they approach a region or watershed affected by inactive historical mines. First, with potentially hundreds of dispersed and potentially contaminated mine sites, how should limited federal resources for prioritizing, characterizing, and remediating the watershed be invested to achieve cost-effective and efficient cleanup? Second, how can realistic remediation targets be identified, considering:

- The potential for adverse effects from unmined mineralized deposits (including any effects that may have been present under premining conditions or still may persist from unmined deposits adjacent to existing abandoned mines)
- The possible impact of incomplete cleanup of specific inactive historical mine sites
- Other physical or environmental factors that may limit sustainability of desired ecosystems

Figure 1. Map of the western United States showing the Boulder and Animas River watershed study areas. The Animas River watershed study area is shown in the inset map.

To answer these questions, the AML Initiative adopted a watershed approach rather than a site-by-site approach to characterize and remediate abandoned mines (Buxton et al., 1997). This approach is based on the premise that watersheds affected by acid mine drainage in a state or region should be prioritized on the basis of its effect on the biologic resources of the watershed so that the funds spent on remediation will have the greatest benefit on affected streams. Within these watersheds, contaminated sites that have the greatest impact on water quality and ecosystem health within the watershed would then be identified, characterized, and ranked for remediation. The watershed approach establishes a framework of interdisciplinary scientific knowledge and methods that can be employed at similar inactive historical mine sites throughout the nation. The watershed approach:

- Gives high priority to actions most likely to most significantly improve water quality and ecosystem health
- Enables assessment of the cumulative effect of multiple and (or) nonpoint sources of contamination
- Encourages collaboration among federal, state, and local levels of government and stakeholders
- Provides information that will assist disposal-siting decisions
- Accelerates remediation and reduces total cost compared to remediation on a site-by-site basis
- Enables consideration of revenue generation from selected sites to supplement overall watershed remediation costs.

The report by Church et al. (2007c) provides a geologic description and summary of the field and laboratory work conducted by the U.S. Geological Survey in the Animas River watershed during 1996–2000. The objectives of this study were to:

- Estimate premining geochemical baseline (background) conditions
- Define current geochemical baseline conditions
- Characterize processes affecting contaminant dispersal and effects on ecosystem health
- Develop remediation goals on the basis of scientific study of watershed conditions
- Transfer data to users in a timely and effective manner

Investigations were coordinated with personnel from the Animas River Stakeholders Group (ARSG), Colorado Division of Wildlife, Colorado Department of Public Health and Environment, Colorado Division of Mines and Geology, Colorado Geological Survey, U.S. Environmental Protection Agency, U.S. Forest Service in the Department of Agriculture, and U.S. Bureau of Land Management in the Department of Interior, all of whom are coordinating the design and implementation of remediation activities within the watershed.

DESCRIPTION OF STUDY AREA

The Animas River watershed study area is located in southwestern Colorado near Silverton, ~40 miles (65 km) north of Durango (Fig. 1). Four candidate watersheds were nominated in Colorado on the basis of geologic factors, metal loading, the status of ongoing remediation activities, general knowledge of the candidate watersheds, and the extent of federal lands within the watershed. The Animas River watershed study area was chosen as one of two pilot watersheds for the AML Initiative in May 1996.

The Animas River watershed study area, as defined in this study, is the drainage area of three large streams and their tributaries (Mineral Creek, Cement Creek, and the Animas River upstream from Silverton). Although the compliance point for water quality established by the Colorado Water Quality Control

Commission is the gauge downstream of the confluence of the Animas River with Mineral Creek (Fig. 2), the Animas River watershed study extends downstream from the confluence of Mineral Creek to an area known as Elk Park just upstream from the confluence of the Animas River with Elk Creek. Most of the watershed is in four mining districts: (1) the Silverton district, which covers the southeastern part of the watershed from the South Fork Mineral Creek to north of Howardsville; (2) the Eureka District, which covers the northern part of the Mineral and Cement Creek basins as well as the Animas River basin from Eureka north (Davis and Stewart, 1990); (3) the Red Mountain district, which extends up the Mineral Creek basin from Ohio Peak to the north and is largely outside the study area; and (4) the Ice Lake district, which is in the headwaters of South Fork Min-

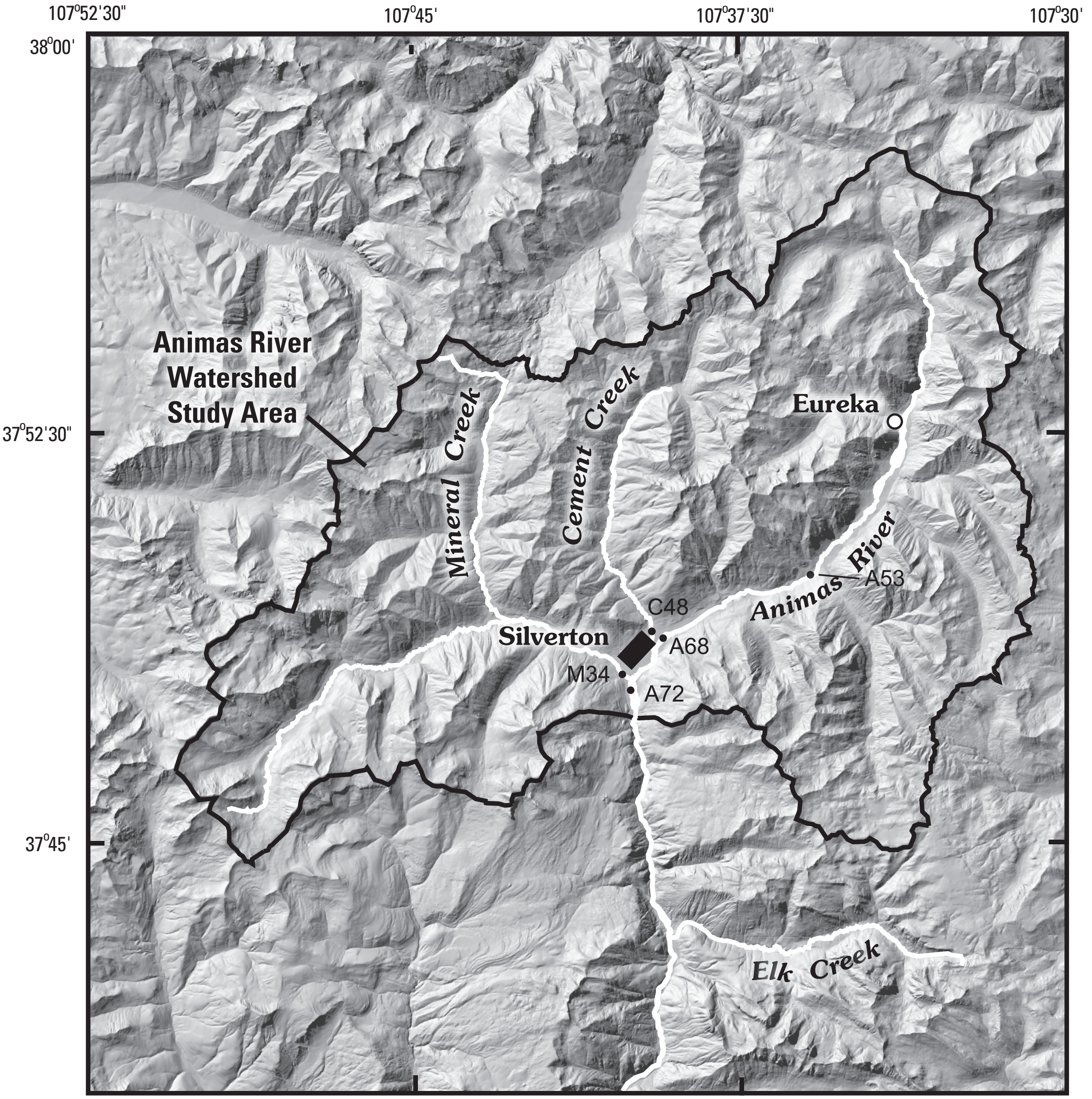

Figure 2. Shaded relief map of the Animas River watershed showing the Animas River and its main tributaries, Mineral and Cement Creeks, which are impacted by historical mining. The watershed study area boundary is outlined in black; gauging stations are shown as black dots on each of the major streams: A72, gauge 09359020; M34, gauge 09359010; A68, gauge 09358000; C48, 09358550; and A53, gauge 09357500.

eral Creek (Church et al., 2007b). During watershed studies, additional sampling and investigations were conducted downstream of the study area to document the extent of enriched trace-element concentrations downstream and to provide reference localities unaffected by historical mining (Church et al., 1997; Anderson, 2007).

The watershed is mountainous with elevations ranging from ~9300 feet (2830 m) at Silverton to more than 13,300 feet (4050 m) above sea level. The terrain is a rugged mountainous area with U-shaped and hanging valleys carved out during the last glaciation (e.g., Blair et al., 2002). Mean annual precipitation ranges from ~24–40 in/yr (600–1000 mm/yr) (NRCS, 2007). Although the population varies seasonally as temporary residents move into the area during the summer, ~400 people live in the Animas River study area throughout the year. Residents are engaged primarily in tourism, which is largely based on the historical nature of the quaint mining town of Silverton served by the historical narrow-gauge railroad from Durango (Sloan and Skowronski, 1975).

Hydrologic Setting

Stream flow in the Animas River study area is typical of high-gradient mountain streams throughout the southern Rocky Mountains. Stream flow is dominated by snowmelt runoff, which typically occurs between April and June. Snowmelt runoff often is augmented by rain during summer from July through September. Stream flow typically peaks in May or June and decreases as the shallow ground-water system drains. Spring runoff conditions extend into July. Low stream-flow conditions are typical from August to March (Fig. 3). The nearest U.S. Geological Survey stream-flow-gauging station 09359020, Animas River downstream from Silverton (period of record Oct. 1991–present, drainage area of 146 mi^2 [378 km^2]) is downstream from the confluence of Mineral Creek (Fig. 2). Stream gauges are located at the mouth of the major tributaries in the study area: the gauge on the Animas River at Silverton (09358000, period of record 1991–1993 and 1994–2004, drainage area 70.6 mi^2 [183 km^2]); the gauge on Cement Creek at Silverton (09358550, period of record 1991–1993 and 1994–2004, drainage area 20.1 mi^2 [52 km^2]); and the gauge on Mineral Creek at Silverton (09359010, period of record 1991–1993 and 1994–2004, drainage area 52.5 mi^2 [136 km^2]). These gauges measure 98% of the stream-flow drainage area upstream from Silverton. The State of Colorado operates a stream-flow-gauging station on the Animas River at Howardsville (09357500, period of record 1935–2002, drainage area 55.9 mi^2 [145 km^2]; Fig. 2). Real-time and historical stream-flow data are

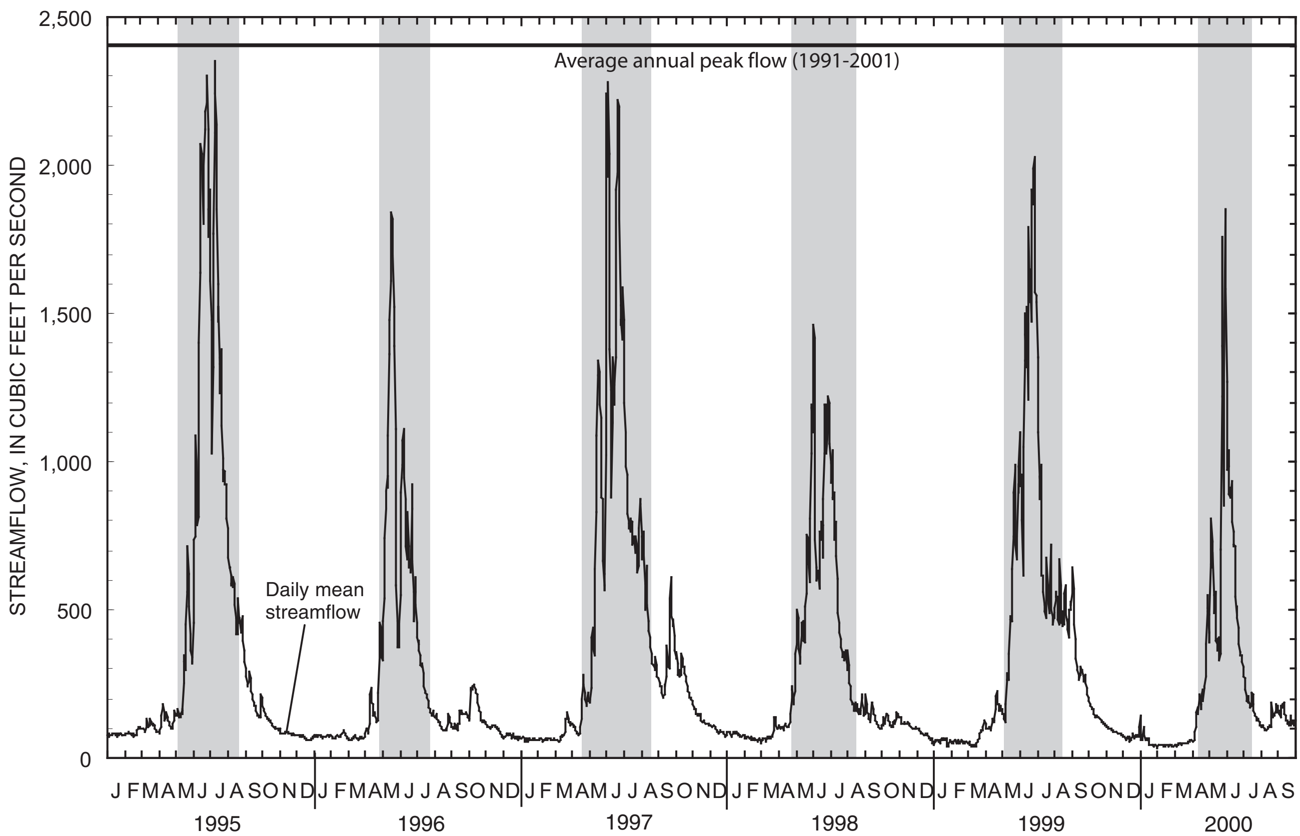

Figure 3. Daily mean stream flow during 1995–2000 in the Animas River downstream from Silverton, Colorado (USGS stream-flow-gauging station 09359020, A72, fig. 2). Average annual peak flow is 2420 ± 500 ft^3 per second for water years 1992–2001. Shaded areas indicate periods of spring runoff, which was arbitrarily defined as stream flow greater than 150 ft^3 per second.

available online (USGS, 2007b). Data are also published in the U.S. Geological Survey annual data report (Crowfoot et al., 2005).

The Animas River watershed study area is subdivided into three large basins, the Mineral and Cement Creek basins and the upper Animas River basin. Drainage basin areas of tributary streams to the main stem drainages are also referred to here as subbasins.

Geology of the watershed is the primary factor affecting the distribution of trace-element concentrations and pH in streams in the upper Animas River watershed. Although there are more than 300 mines and an estimated 5400 mining-related features in the study area (Church et al., 2007b), not all of these features contribute to water-quality degradation. Because of the combined effects of hydrothermal alteration that is directly associated with the mineral deposits and the widespread distribution of historical mine sites throughout the watershed, it is difficult to attribute low pH values and high trace-metal concentrations exclusively to either source. The pH of water samples collected at background sites ranged from 2.58 to 8.49 compared to pH of water from mine sites that ranged from 2.35 to 7.77 (Mast et al., 2000a).

Ground-water flow is largely controlled by topography, by the distribution of unconsolidated Quaternary deposits that overlie bedrock units, and by the decrease in hydraulic conductivity of geologic units with depth. Topography strongly controls the direction of ground-water flow and the location of discharge areas. Recharge occurs on all topographic highs, with greater amounts of recharge on areas with the greatest precipitation and hydraulic conductivity (McDougal et al., 2007; Mast et al., 2007). Discharge in the form of numerous seeps and small springs occurs in topographic lows and at breaks in slope. Flow paths from recharge to discharge areas are short, commonly less than a few thousand feet. Regional ground-water flow is limited by the very low permeability of the bedrock. The overlying, thin, unconsolidated deposits have the highest hydraulic conductivity. The uppermost, fractured and weathered zone in the igneous bedrock has a lower hydraulic conductivity than the unconsolidated deposits (R.H. Johnson, written comm., 2007). Fractures are the major conduits for ground-water flow in bedrock, with more flow in the uppermost zone, where the fractures are weathered and open.

Biologic Setting

The Animas River watershed study area consists entirely of alpine and subalpine habitats. The headwaters and tributaries of the three principal basins (Animas River, Cement and Mineral Creeks) originate in treeless alpine regions with vegetation cover ranging from essentially none, especially in highly mineralized areas of the Cement and Mineral Creek basins, to relatively lush alpine meadows. Streams follow steep, narrow valleys, with the exception of a few low-gradient areas, such as the Animas River between Eureka and Howardsville, Mineral Creek near Chattanooga, and the open valley near Silverton (Bakers Park), which have relatively wide valley floors (Blair et al., 2002). Vegetation on valley walls is restricted in many areas by extensive areas of exposed rock and talus, but some areas of sparse coniferous Engelmann spruce forest occur on north-facing slopes and in valley bottoms, where deciduous trees also occur. Riparian vegetation is often limited along high-gradient streams, but low-gradient reaches typically contain extensive areas of beaver ponds and associated willow thickets except where limited by mining activity and mill tailings disposal (e.g., Vincent and Elliott, 2007).

The native fish community of the watershed before European settlement was restricted by the severe climate and hydrology and by barriers to upstream movement of fish in the Animas River canyon downstream of Silverton. The only native fish species known to occur in the watershed would be the Colorado River cutthroat trout (*Onchorhynchus clarkii pleuriticus*), although one account suggests that the mottled sculpin (*Cottus bairdi*), a species that occurs commonly in downstream reaches, may have occurred in portions of the upper watershed.

There are few accounts of the aquatic biota of the upper Animas River watershed before the most active period of mining (ca. 1890 based on district production records summarized by Jones, 2007). Ichthyologist David Starr Jordan (1891) visited the Animas River watershed in 1889 and recorded the following references, based on second-hand accounts:

> In the deep and narrow "Cañon de las Animas Perdidas" [Animas Canyon] are many deep pools, said to be full of trout.

> Above its cañon of "Lost Souls," it is clear, shallow, and swift, flowing through an open cañon with a bottom of rocks. In its upper course it is said to be without fish, one of its principal tributaries, Mineral Creek, rising in Red Mountain and Uncompahgre Pass, being highly charged with iron.

> The distribution of cutthroat trout in the upper Animas River watershed before settlement is unknown. However, the existence of water quality and habitat suitable for trout is indicated by reports of good populations of trout (undoubtedly including stocked, non-native trout) in artificial ponds near Silverton and in the Animas River upstream of Silverton near the turn of the century. (Silverton Standard, various accounts, 1903–1905)

Surveys conducted by federal and state agencies in the 1960s and 1970s indicate that the many decades of mining and milling activity had a significant adverse effect on stream biota. The reach of the Animas River upstream of Silverton (Fig. 2), which had supported trout in previous years, yielded only a single trout in an electro fishing survey in 1968 (U.S. Dept. of Interior, 1968). N.F. Smith (1976) declared this reach of the Animas River to be "essentially dead." The Colorado Division of Wildlife stocked rainbow trout, brook trout, and brown trout in the watershed between 1973 and 1993. There is no evidence that either rainbow or brown trout were able to reproduce upstream from the Animas River canyon reach; however, brook trout, which are more tolerant of pollution by acid and toxic metals than the other species, were more successful. Brook trout remains the predominant fish species in the Animas River watershed study area despite no documented stocking of this species since 1985.

Recent surveys of fish and benthic invertebrate communities (Butler et al., 2001; Anderson, 2007; Besser and Brumbaugh,

2007) indicate that the effects of poor water quality on stream communities vary widely among the three basins and suggest that stream biota have responded to some improvements in water quality. The headwaters of the Animas River upstream from Eureka (Fig. 2), the entire length of Cement and Mineral Creeks, and several smaller tributaries support little or no aquatic life due to the effects of mining and naturally acidic water draining from hydrothermally altered areas (Bove et al., 2007). The South Fork Mineral Creek and several tributaries of the upper Animas River, which drain subbasins that provide substantial acid-neutralizing capacity, support viable populations of brook trout and a few cutthroat trout. The Animas River between Maggie Gulch and the mouth of Cement Creek in Silverton supports brook trout and a substantial invertebrate community, suggesting that substantial improvements in water quality have occurred in this reach since the 1970s when the early electro fishing surveys were done (e.g., N.F. Smith, unpublished aquatic inventory: Animas-La Plata project, Colorado Division of Wildlife, Durango Colorado, 1976). Impacts of degraded water quality on stream biota persist in the Animas River for a substantial distance downstream of Silverton, although there is some evidence of recovery of fish and invertebrate communities since the Sunnyside mine closed in 1991 and remediation efforts in the watershed began immediately.

Geologic Setting

The geology of the rugged western San Juan Mountains is exceptional in that many diverse rock types representing every geologic era from the Proterozoic to the Cenozoic are preserved. It is also an area that has high topographic relief providing excellent bedrock exposures. The general stratigraphy of the San Juan Mountains near Silverton consists of a Precambrian crystalline basement overlain by Paleozoic to Tertiary sedimentary rocks and by a voluminous Tertiary volcanic cover (Fig. 4).

Precambrian rocks are exposed south of Silverton along the Animas River and in upper Cunningham Creek and are part of a broad uplifted and eroded surface (Fig. 4). The Precambrian section near the study area consists primarily of amphibolite, schist, and gneiss. South and west of Silverton, gently dipping Paleozoic to Tertiary age sedimentary strata of varying lithologies overlie Precambrian basement rocks. The sedimentary section, which crops out in subbasins in the headwaters of South Fork Mineral Creek and in other subbasins south of Silverton, is comprised mainly of marine and terrestrial limestone and mudstone in addition to terrestrial deposits of sandstone, siltstone, and conglomerate (Fig. 4). Many of these units contain calcite and are, therefore, important for their acid neutralization potential. A thick section of

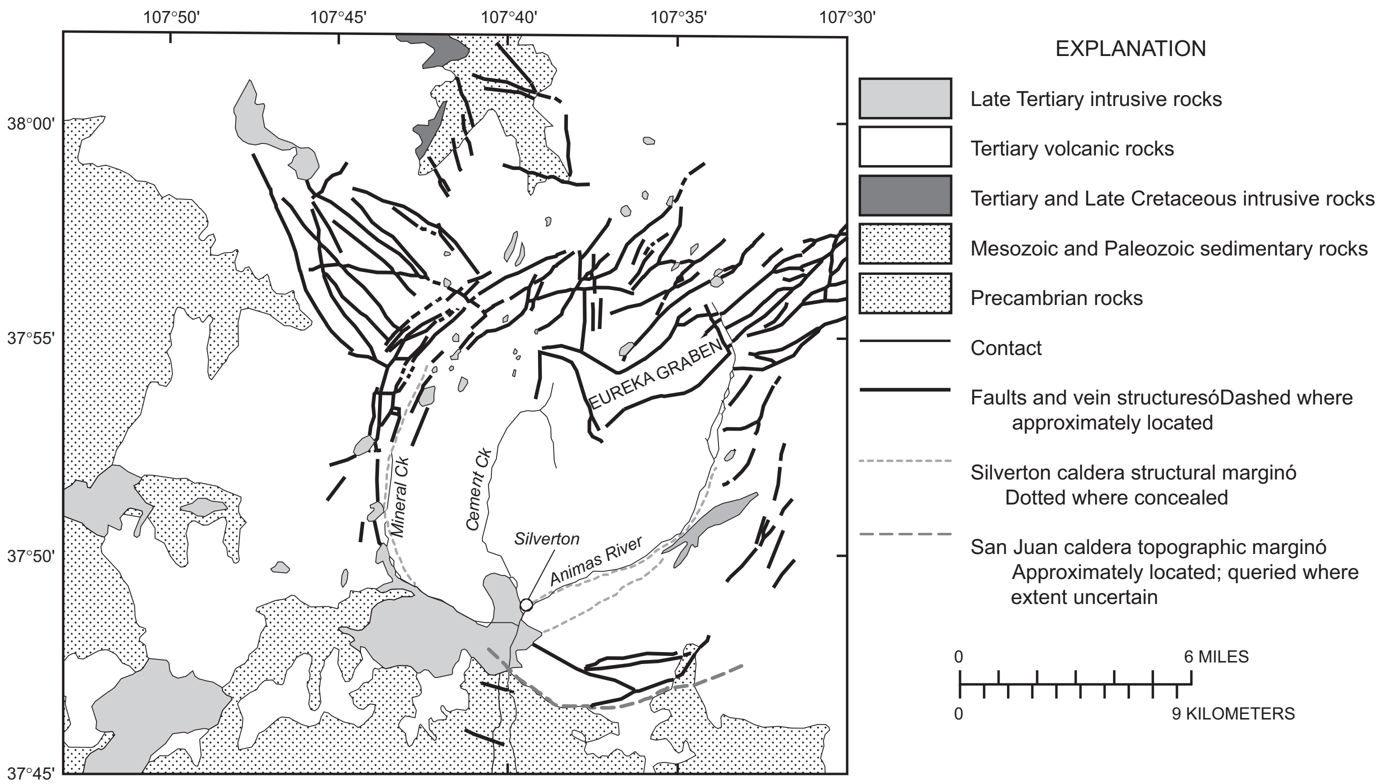

Figure 4. Generalized structural and geologic map of the Silverton caldera, upper Animas River watershed. The Animas River and Mineral Creek follow the structural margin of the Silverton caldera. In addition to the ring-fractures that were created when the Silverton and the earlier San Juan calderas formed, radial and graben faults, which host much of the subsequent vein mineralization, are shown schematically (modified from Casadevall and Ohmoto, 1977).

Tertiary volcanic rock caps the Paleozoic sedimentary rocks west and southwest of Silverton and covers most of the central part of the study area. The majority of Animas River headwater streams and tributaries originate in Tertiary volcanic and silicic (high silica content) intrusive rocks that have been deposited or emplaced in the area that is defined by Mineral Creek on the west and by the Animas River on the east, north of Silverton (Fig. 4). Subsequent hydrothermal alteration and mineralization resulted in the formation of economic mineral deposits that were exploited between 1871 and 1991. Thus, much of this study has focused on the Tertiary volcano-tectonic history and mineralization events that have contributed to present water-quality issues.

Onset of volcanism commenced between 35 and 30 Ma, with the eruption of intermediate-composition (52–63% SiO_2) lava flows and deposition of related volcaniclastic sedimentary rock forming a plateau that covered much of the San Juan Mountains area (Lipman et al., 1976). Following the early phase of intermediate-composition volcanism, silicic calderas began to form throughout the entire San Juan Mountains region. Two calderas formed in the Animas River watershed study area between ca. 28 and 27 Ma (Fig. 4). Eruption of the Oligocene (27.6 Ma) Silverton caldera created a large semicircular depression ~13 km (8 miles) in diameter, which is nested within the older (28.2 Ma) San Juan caldera (Lipman et al., 1976; Yager and Bove, 2007). The central part of the San Juan caldera is partially filled by ash-flow tuff and by later, intermediate-composition lava flows, volcaniclastic sedimentary rocks, and igneous intrusive rocks. Ash-flow tuff is a volcanic rock containing pumice, broken crystals, and wall rock fragments in a matrix of ash-size material that was ejected from the ring fracture zone of an actively forming caldera. Eruption of intermediate-composition lava flows and related volcaniclastic rocks filled the San Juan caldera volcanic depression; these rocks host the majority of the mineralization in the study area. Granitic igneous magmas intruded the southern margins of the Silverton and San Juan calderas shortly after the Silverton caldera formed. The intrusions south of Silverton formed along the caldera structural margins and are centered near the area between Sultan Mountain and peak 3792 m on the South Fork Mineral Creek (Fig. 5), in lower Cunningham Creek from Howardsville to lower Maggie Gulch, and near the mouth of Cement Creek (see Table 1).

An extensive bedrock fracture and fault network has developed in response to caldera development in the region. Structures related to caldera formation not only influence the hydrologic system today but also are largely responsible for controlling where postcaldera hydrothermal fluids altered the country rock and focused the emplacement of mineral deposits. Important faults related to caldera formation include the arcuate faults that form the caldera structural margin. In addition, the northeast-southwest trending faults and veins that comprise the Eureka graben and that cross the central core of the caldera are prominent structural features that have been extensively mineralized and mined for base and precious metals (Casadevall and Ohmoto, 1977; Yager and Bove, 2007). Northwest to southeast trending faults and veins that are radial to the caldera ring fault zone were extensively mineralized. Caldera-related faults, which in places were only partially closed by later mineralization, can extend laterally and vertically from tens of meters to a few kilometers. The structures related to the San Juan-Uncompahgre and Silverton calderas are pervasive features that were not sealed by mineralizing fluids and may be important ground-water flow paths at the basin-wide scale.

Pre- and postcaldera crustal stresses have also resulted in an extensive near surface fracture network. Fractures at the outcrop scale commonly have spacings of one centimeter to several meters. These fractures developed either as volcanic rocks cooled, forming cooling joints, or in response to regional and local tectonic stresses. Fractures that are densely spaced, unfilled by later mineralization, and interconnected focus near-surface ground-water flow at the local or subbasin scale.

Mineralization and Alteration

Multiple hydrothermal alteration and mineralization events that span a 17 m.y. history, from ca. 27 Ma to 10 Ma, were the culmination of a complex cycle of volcano-tectonic events that affected the region (Lipman et al., 1976; Bove et al., 2001). The first episode of hydrothermal alteration formed during the cooling of the San Juan caldera volcanic fill, when lava flows cooled, degassed, and released large quantities of CO_2, along with other volatile constituents such as SO_2 and H_2O. Geologic mapping and airborne geophysical surveys suggest that regional alteration extended from the surface to depths as great as 1 km (Smith et al., 2007; McDougal et al., 2007). This widespread hydrothermal alteration changed the primary minerals of the lava flows, forming an alteration assemblage that includes calcite, epidote, and chlorite (Burbank, 1960). This mineral suite is part of the preore propylitic hydrothermal assemblage, which has a high acid-neutralizing potential (Desborough and Yager, 2000). Near-surface spring and surface water that has interacted mainly with propylitic rock has a pH range of 6.0–7.5 (Mast, et al., 2000a).

Mineralization events that postdated the preore propylitic hydrothermal assemblage contained sulfur-rich hydrothermal fluids and metals that produced various vein and alteration mineral assemblages, all of which include abundant pyrite (Burbank and Luedke, 1968; Casadevall and Ohmoto, 1977). Host rock alteration in many places throughout the Animas River watershed study area effectively removed the acid-neutralizing mineral assemblage of calcite-epidote-chlorite from these subsequently altered areas. This later phase of mineralization was coincident in the timing and emplacement of multiple silicic intrusions that likely provided the heat sources for the mineralizing fluids.

Most of the mineralization events that overprint rocks affected by regional propylitization in the study area may be subdivided into three broad categories on the basis of age and style of mineralization (Bove et al., 2007). The earliest event formed between 26 and 25 Ma, was related to emplacement of granitoid intrusions near the southern margin of the San Juan and Silverton calderas in the area between Middle Fork and South Fork Mineral Creek, and consists of low-grade molybdenum-copper-porphyry mineralization (Ringrose, 1982; Bove et al., 2001). The central part of this

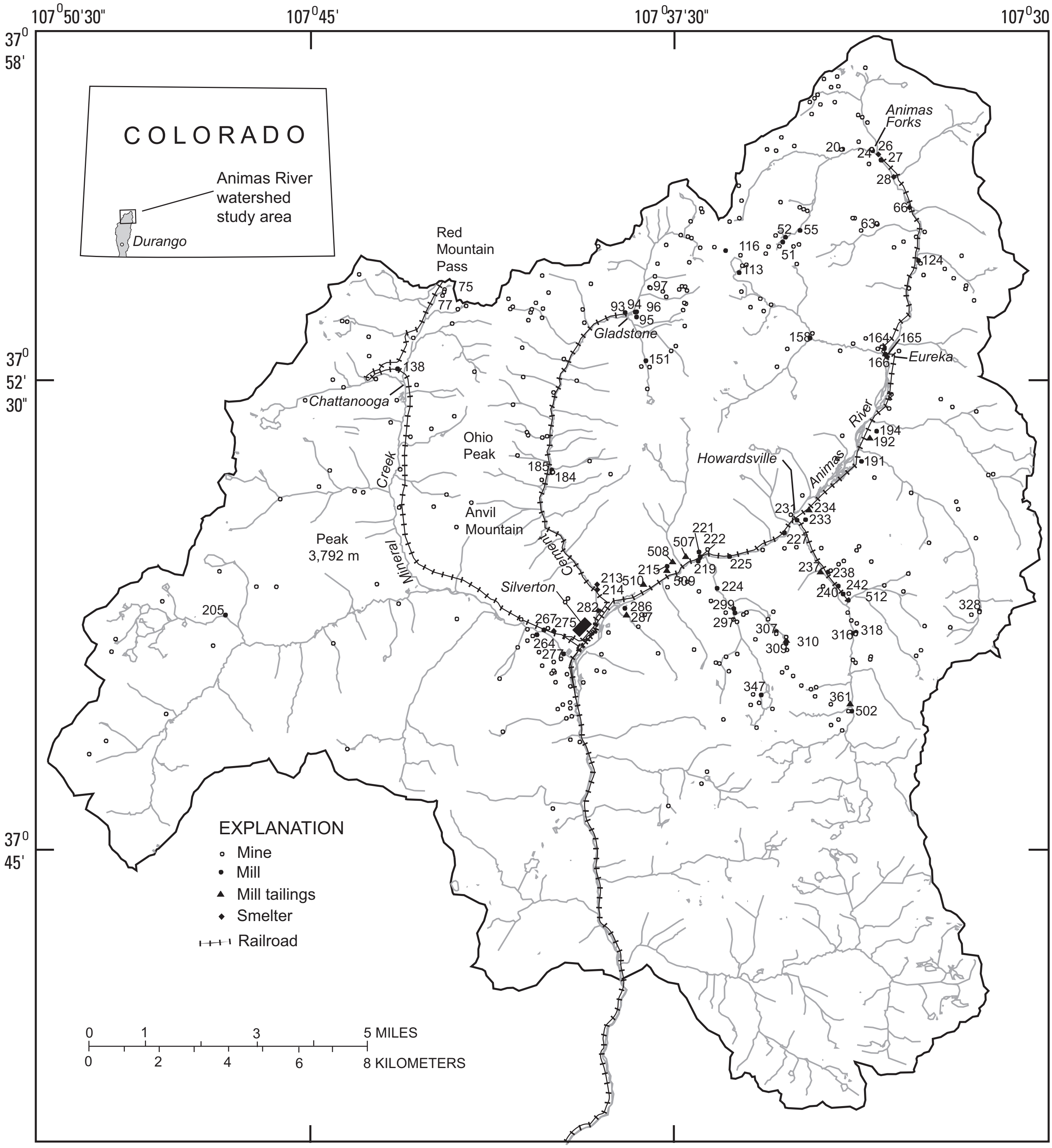

Figure 5. Localities of railroads, mills, large mill tailings, smelters, and selected mine sites referenced in text, Animas River watershed (modified from Jones, 2007). Selected mine sites referenced in text are in Table 1.

TABLE 1. MILL, LARGE MILL TAILINGS, AND SELECTED MINE SITES, ANIMAS RIVER WATERSHED

Site Name	Site No.	Site Name	Site No.
Mines		Mills (*continued*)	
Koehler tunnel	75	Ward and Shepard Mill	224
Junction mine	76	Contention Mill	225
Longfellow mine	77	Pride of the West Mill #2	227
American tunnel, Sunnyside mine	96	Little Nation Mill	231
Sunnyside mine	116	Pride of the West Mill #4	233
Mayday mine	181	Old Hundred Mill	238
Mills		Green Mountain Mill	240
Bagley Mill (Frisco)	20	Vertex Mill	242
Columbus Mill	24	North Star (Sultan) Mill	264
Gold Prince Mill	27	Victoria Mill	267
Hanson Mill (Sunnyside Extension Mill)	51	Hercules Mill (Empire)	277
Mastodon Mill	52	Lackawanna Mill	287
Sound Democrat Mill	55	Iowa Mill	297
Treasure Mountain Mill	63	Little Giant Mill	299
Mogul Mill	93	Big Giant Mill	307
Gold King Mill	94	North Star Mill #1	309
Lead Carbonate Mill	95	Pride of the West Mill #3	316
Red and Bonita Mill	97	Pride of the West Mill #1	318
Sunnyside-Thompson Mill	113	Intersection Mill	328
Silver Wing Mill	124	Silver Lake Mill #1	347
Silver Ledge Mill	138	Highland Mary Mill	502
Natalie/Occidental Mill	151	Mill Tailings	
Sunnyside Mill #1	158	Kittimack tailings	192
Sunnyside Eureka Mill	164	Pride of the West Mill tailings	234
Sunnyside Mill #2	165	Old Hundred Mill tailings	237
Yukon Mill	184	Lackawanna tailings (removed)	286
Hamlet Mill	191	North Star Mill tailings	310
Kittimack Mill	194	Highland Mary Mill tailings	361
Ice Lake Mill	205	Mayflower Mill tailings repository #1	507
William Crooke Mill	215	Mayflower Mill tailings repository #2	508
Silver Lake Mill #2	219	Mayflower Mill tailings repository #3	509
Mayflower Mill (S-D Mill)	221	Mayflower Mill tailings repository #4	510
Mears-Wilfley Mill	222		

Note: Data refer to sites in Figure 5; data from Jones (2007), Church et al. (2007a).

zoned mineralized system, centered near peak 3792 m (Fig. 5; Silverton 1:24,000-scale, USGS topographic map), is composed of bleached, quartz-stockwork-veined, quartz-sericite-pyrite altered intrusive rocks and volcanic rocks. Rock in the central part of this system is host to exposed molybdenum-copper mineralized rock (McCusker, 1982). Disseminated sulfides in this zone consist mainly of pyrite, lesser chalcopyrite, and traces of molybdenite and bornite, comprising as much as 5 volume percent of the host rock (McCusker, 1982). Progressively outward from the locus of mineralization, zones of weak-sericite-pyrite and propylitic altered igneous and volcaniclastic rocks, respectively, form the periphery of the hydrothermally altered and mineralized porphyry system.

A younger, acid-sulfate system formed at 23 Ma and developed in response to emplacement of coarsely porphyritic dacite intrusions. Dacite porphyry intrusive activity and formation of associated acid-sulfate alteration was mainly focused in two areas. One area of acid-sulfate alteration is centered in the vicinity of the Red Mountains. The Red Mountains form the headwaters of the Uncompahgre River, which flows north, and Mineral Creek, which flows south into the Animas River. The second area is located south of the Red Mountains near Ohio Peak and along Anvil Mountain, which form the drainage divide between Mineral and Cement Creeks. Acid-sulfate mineralization in the Red Mountain area is often characterized by breccia-pipe and fault-hosted vein ore with abundant copper-arsenic-antimony-rich minerals such as enargite-tetrahedrite-tennanite, in addition to copper ores of chalcocite, bornite, and covellite. This combined suite of minerals distinguishes the acid sulfate-related ores from more typical polymetallic vein deposits outside the Red Mountains area (Bove et al., 2007). Gangue minerals include barite, calcite, and fluorite. Breccia bodies and brecciated faults were commonly silicified and replaced with microcrystalline masses of quartz, alunite, pyrophyllite, natroalunite, dickite, diospore, pyrite, and traces of leucoxene. Hydrothermal sericitic assemblages that formed include quartz-sericite-pyrite and weak sericite-pyrite assemblages. The quartz-sericite-pyrite assemblage is typified by total replacement of primary host-rock minerals by quartz, abundant illite (sericite), and pyrite, whereas host-rocks affected by the weak sericite-pyrite assemblage still contain weakly altered primary plagioclase in addition to secondary chlorite derived from the earlier, regional propylitization event (Bove et al., 2007).

The third and most economically important episode of mineralization formed post 18 Ma and is closely associated with the emplacement of high-silica alkali rhyolite intrusions (Lipman, et al., 1973; Bartos, 1993). Mineral deposits formed during this episode consist of polymetallic, Cu-Pb-Zn base- and precious-metal veins deposited along caldera-related northwest-southeast trending fractures tangential to the Silverton and San Juan calderas and along primarily northeast-southwest trending graben faults and some northwesterly trending faults that originally developed during resurgence of the San Juan caldera (Varnes, 1963; Casadevall and Ohmoto, 1977). Six ore-forming stages are recognized in the Sunnyside mine, the largest producing mine developed in this youngest style of mineralization (Casadevall and Ohmoto, 1977). Ores of a massive sulfide stage formed early in the paragenetic sequence and consist of intergrown masses of spahlerite, galena, and lesser amounts of pyrite, chalcopyrite, and tetrahedrite (Casadevall and Ohmoto, 1977). Ores of gold-telluride-quartz, manganese and quartz-fluorite-carbonate-sulfate formed later. Deposition of manganese-rich ores postdate the principal gold-bearing mineralization phase and are composed of light pink bands of pyroxmangite ($MnSiO_3$) intergrown with quartz and rhodochrosite, among other manganese-bearing phases. Late-stage gangue minerals include anhydrite, fluorite, calcite, and gypsum (Casadevall and Ohmoto, 1977). Unlike the pervasive areas of alteration that are associated with both the porphyry molybdenum-copper mineralization and acid-sulfate mineralization systems that often affect entire mountain blocks, the style of post–18-Ma alteration tends to be focused adjacent to veins and vein structures. An assemblage of quartz-sericite-pyrite-zunite occurs proximal to veins. This assemblage grades laterally to assemblages of sericite-kaolinite along with increasing volume percentages of wall-rock chlorite derived from rocks affected by regional propylitization distal from the veins. Intermediate composition volcanic rocks that filled the San Juan caldera are host to 90% of this latest episode of mineralization (Bejnar, 1957).

Surface water quality that results from weathering of the highly altered areas is notable. One of many such examples is centered near peak 3792 m between South Fork Mineral Creek and Middle Fork Mineral Creek northwest of Silverton (Fig. 5). Headwater tributaries that originate in propylitic altered volcanic and volcaniclastic rocks west of peak 3792 m have near neutral pH between 6.5 and 6.8. However, as surface water and ground water interacts with hydrothermal alteration assemblages that contain abundant pyrite downstream, pH drops below 3.5 (Mast et al., 2000b; Yager et al., 2000; Mast et al., 2007).

Late Tertiary erosion exposed large areas of hydrothermally altered rock in the study area to weathering processes. Subsequent Pleistocene glaciation further sculpted the landscape, creating the classic U-shaped valleys, carving the cirque headwater subbasins, and depositing glacial moraine that is partly responsible for the spectacular scenery near Silverton. Multiple surficial deposits formed during and subsequent to glaciation and now cover over 25% of the bedrock with a veneer of porous and permeable material (Blair et al., 2002; Vincent et al., 2007; Vincent and Elliott, 2007). A several-thousand-year history of acidic drainage is recorded in many of the surficial deposits, where iron-rich ground water derived from pyrite weathering has infiltrated these deposits and cemented them with oxides of iron, forming what is referred to as ferricrete (Yager et al., 2003; Yager and Bove, 2007; Wirt et al., 2007). These recent geologic events have exposed mineral deposits to surface weathering prior to mining. Weathering reactions in areas underlain by more intensely altered rock produce greater acidity and release more metals to surface and ground water than areas underlain by propylitic altered rock (Bove et al., 2001; Mast et al., 2000b; Yager et al., 2000).

History of Mining

More than one hundred years of historical mining activity has created many miles of underground workings and produced large volumes of mine waste rock that were pulverized to remove ore metals. These mine workings provide flow paths for ground water that reacted with mineralized rock to produce acidic mine water that flows from mine adits (Mast et al., 2007; Church, et al., 2007b). The waste rock dumps have resulted in increased surface area and exposure of large amounts of pyrite to oxidation resulting in large anthropogenic sources of acidic drainage that affect water quality and aquatic and riparian habitats in the watershed. These anthropogenic conditions exacerbate the cumulative water-quality effect due to weathering the intensely hydrothermally altered rock in the watershed. Changes in the different drainage basins resulting directly from historical mining activities are apparent by comparison of data from streambed-sediment geochemical baselines prior to mining and today (Church et al., 2000; Church et al., 2007a).

Jones (2007) discusses the affects of government price supports and the demand for metals on historical mining practices in the area. These policies, as well as changes in mining practices, greatly affected mineral production in the Animas River watershed and the distribution of mill tailings in the streams. Jones (2007) identifies four major periods of production in the watershed: the smelting era (1871–1889), the gravity milling era (1890–1913), the early flotation era (1914–1935), and the modern flotation era (1936–1991). The following is summarized from his work:

- During the smelting era (1871–1889), ore was hand sorted and most was shipped directly to smelters. A few small gravity or stamp mills were in operation. Total ore production was small and the amount of mill tailings released to streams was small but unknown. There was no market for zinc, so sphalerite was left in the mines or on the mine waste dumps because the smelters charged a penalty to process ores containing more than 10% percent sphalerite (Ransome, 1901).

- During the gravity milling era (1890–1913), many small mines had a stamp mill to prepare concentrate for shipment to the smelter. Milling of ore occurred on site or trams transported ore to the mills or the railroad for shipment to smelters outside the watershed. Mill tailings were not impounded but rather were dumped in the riparian zone or directly into the streams. Sulfide recovery was ~60%. Copper was not recovered, and the demand for zinc was small, so it was generally not recovered. An estimated 4.3 million short tons of mill tailings were discharged directly into streams. The Animas River contained so much mill tailings that contaminated water downstream necessitated building a new reservoir and public water supply for the city of Durango (*Durango Democrat*, 1902).
- During the early flotation era (1914–1935), a few mills dominated ore processing in the basin. The Sunnyside Mill #2 at Eureka (site #165, Fig. 5) was a leader in applying flotation technology in the district. Ores were ground to finer grain size, and sphalerite and copper sulfide concentrates were recovered. The volume of mill tailings produced increased dramatically over the previous period. All the gravity or stamp mills in the watershed were closed down by 1921, and ore was processed at these large modern mills. In 1917, U.S. Smelting and Refining Co. built a large flotation mill at Eureka (Sunnyside Eureka Mill, site #164) to process ore from the Sunnyside mine (site #116). This mill was by far the largest in the basin; it processed ~2.5 million tons of ore from 1917 to 1930 (Bird, 1999). Sulfide recovery exceeded 80%. Mill tailings were impounded in retaining ponds on the Animas River flood plain immediately downstream from the mill to allow the fines to settle. The clear water was then allowed to decant over the tailings dams, along with the dissolved metal loads, directly into the Animas River. As evidenced by the dispersed mill tailings deposits present in the braided reach downstream from Eureka (Vincent and Elliott, 2007), floods periodically breached the tailings impoundments and released mill tailings into the Animas River. The Sunnyside Eureka Mill closed in 1930 during the Depression and reopened briefly in 1937 (Bird, 1999). An estimated 4.2 million tons of ore were processed by mills during this period (Jones, 2007). Most of the mill tailings were discharged into settling ponds in the riparian zone or directly into the streams. Frequently, floods breached these mill tailings impoundments (dams were formed using small wooden shipping barrels filled with rock) and released mill tailings into the Animas River.
- During the modern flotation era (1936–1991), the Mayflower Mill, built in 1929 (site #221, Fig. 5), was the primary mill operating in the watershed. This mill was designed not to release mill tailings to the Animas River. Although the tailings impoundment effort was not completely successful in the beginning, the majority of the mill tailings were retained after 1935 (Jones, 2007). Sulfide recovery using improved flotation technology was greater than 95% after 1940. Jones (2007) estimates that only 200,000 tons of mill tailings were released to the streams during this period. Furthermore, in support of both World War II and the Korean War, many of the old stamp mill tailings were reprocessed, and the stamp mills were burned to recover scrap iron.

Nash and Fey (2007) note that many of the old stamp mill sites contain little or no mill tailings. Given the historical mining practices just summarized above, this is not surprising. A substantial volume of mill tailings was released into the surface streams (an estimated 8.6 million short tons, or ~48% of the total district production; Jones, 2007). As a result, there has been a loss of productive aquatic and riparian habitat and a reduction in recreational and aesthetic values, values important to tourism. Furthermore, the increased acidity and metal loading constitutes a potential threat to downstream drinking water supplies.

SUMMARY OF WATER-QUALITY STUDIES

To evaluate the effects of historical mining on water quality in the Animas River watershed study area, three separate but overlapping investigations were undertaken. One study focused on sampling springs, streams, and mine water in subbasins upgradient of the major stream segments, Mineral Creek, Cement Creek, and the upper Animas River (Mast et al., 2007). Additional water-quality work was conducted by the ARSG (Butler et al., 2001). The second investigation compiled water-quality data throughout the study area (Wright et al., 2007). The third investigation encompassed a series of 13 stream tracers along the 3 major stream segments in the study area (Kimball et al., 2007). The objective of the work in the subbasins was to characterize premining baseline water quality for comparison of the results with mine adit water chemistry. The objective of the basin-wide data compilation was to evaluate spatial and temporal trends in water quality. The objective of the stream tracer studies was to quantify metal loading along the major stream segments, investigate the effects of instream processes on stream chemistry, and simulate remediation scenarios. In addition to these studies, two other process-related studies were undertaken: (1) investigation of the age, composition, and formation of ferricrete deposits (Verplanck et al., 2007; Wirt et al., 2007) and iron bogs (Stanton et al., 2007), and (2) an investigation of the seasonal variation in water quality (Leib et al., 2007).

The data set for the subbasin investigation included water samples collected from 241 spring and stream sites and 75 mine sites during summer low-flow conditions in 1997–1999. For the spring and stream sites, a ranking system primarily based on field observations was devised to evaluate the potential for mining activity effects. The ranking system consisted of four categories ranging from category I (no evidence of mining activity) to category IV (direct discharges from mine sites). Ranges and median values for pH, sulfate, and zinc concentrations for sites unaffected by mining (category I and II) are given in Table 2. The primary factor controlling the premining baseline water quality is the degree of hydrothermal alteration of the bedrock. For each site unaffected by mining, the dominant type of up-gradient hydrothermal alteration was determined.

Streams and springs draining propylitic altered rock had higher pH (5.74–8.49) and lower dissolved metal concentrations than water draining other alteration assemblages or mine adit water (Fig. 6). In addition, these sites are characterized by measurable alkalinity. Propylitically altered rock contains calcite, as well as chlorite and epidote, which dissolve and produce circumneutral water. Sulfate concentrations are slightly elevated because of the weathering of minor amounts of pyrite and gypsum (Mast et al., 2007; Nordstrom et al., 2007).

In contrast to propylitic altered rock, quartz-sericite pyrite altered rock produces water that is acidic and metal-rich (Fig. 6), reflecting an abundance of pyrite and a lack of acid-neutralizing minerals (Mast et al., 2007). The acidic water readily reacts with alumino-silicate minerals in the bedrock, producing surface and ground water with high concentrations of aluminum and silica. Quartz-sericite-pyrite altered bedrock tends to be located within or adjacent to base-metal mineralized areas, thus water draining from quartz-sericite-pyrite altered areas has relatively high concentrations of copper, manganese, and zinc (Fig. 6). Weak sericitic altered bedrock tends to produce water with intermediate compositions between that derived from propylitic or quartz-sericite-pyrite altered bedrock (Fig. 6).

Water draining from inactive mine sites generally has the greatest range in compositions and tends to have higher dissolved sulfate and metal concentrations than most sites unaffected by mining (Fig. 6). The wide range in water quality of mine water likely results from three factors: (1) chemistry of the water entering mines varies because of weathering of different hydrothermal alteration assemblages; (2) weathering of different ore and gangue minerals depends upon the mineral deposit type (e.g., Cox and Singer, 1986); and (3) some of the sites classified as "mining-affected" may actually have been metal-poor mine prospects.

Surface Water Quality

Wright et al. (2007) compiled water-quality data collected from 1991 to 1999 from multiple sources including data collected by ARSG and the State of Colorado (Butler et al., 2001) to evaluate the spatial variation in water quality throughout the study area. The distribution of pH values in streams during low-flow conditions (Fig. 7) shows that stream segments draining more intensely altered rocks have lower pH values than streams draining propylitic altered areas. For example, streams draining Ohio Peak, which is underlain by acid-sulfate alteration, tend to have pH values < 4.5. Near Red Mountain Pass in the headwaters of Mineral Creek basin, which is underlain by acid-sulfate alteration (Fig. 7), extremely low pH values (2.4–2.5) were measured in water draining from the Longfellow mine (site #77, Fig. 5) and Koehler tunnel (site #75, Fig. 5). Much of Cement Creek has low pH (<4.5), and the Cement Creek basin is characterized by both intensely altered rock and numerous mine sites. In contrast, although a substantial percent of the mining activity occurred in the upper Animas River basin upstream of Silverton, most of the stream segments there have pH values > 6.5. This area is primarily composed of propylitic altered bedrock (Fig. 7). Similarly, relatively high pH values were measured along the South Fork Mineral Creek, which is characterized by sedimentary rock that has been partially overprinted by propylitic alteration.

The distribution of dissolved zinc concentrations in streams during low-flow conditions (Fig. 8) shows that zinc in surface water is primarily derived from sphalerite dissolution. Since zinc has been identified as a trace element in other sulfides, particularly pyrite, dissolution of pyrite also contributes to the zinc load (Bove et al., 2007). In the upper parts of Mineral Creek, Cement Creek, and the Animas River, mine adit water tends to have high zinc concentrations. The highest zinc concentration (228 mg/L) was measured in mine-adit water draining the Koehler tunnel (site #77, Fig. 5) near Red Mountain Pass. In general, zinc concentrations decrease downstream because of dilution by stream water with relatively low zinc concentrations.

Both mined and unmined areas contribute substantial loads of constituents to the streams that drain the Animas River watershed because of the widespread, extensively altered and mineralized rock in the area. Prioritizing mine-site remediation at the watershed scale requires an understanding of how multiple sources of acidic, metal-rich drainage affect the streams in the

TABLE 2. RANGES OF CHEMISTRY OF SPRINGS UNAFFECTED BY MINING AND OF MINE WATER FROM ADITS

	pH		SO_4 (mg/L)		Zn (µg/L)	
	Range	Median	Range	Median	Range	Median
Spring from sites unaffected by mining	2.58–8.49	4.89	1–1300	90	<20–14,300	28
Adit mine drainage	2.35–7.77	5.72	45–2720	310	<20–228,000	620

Note: Data summarized from Mast et al., 2000a.

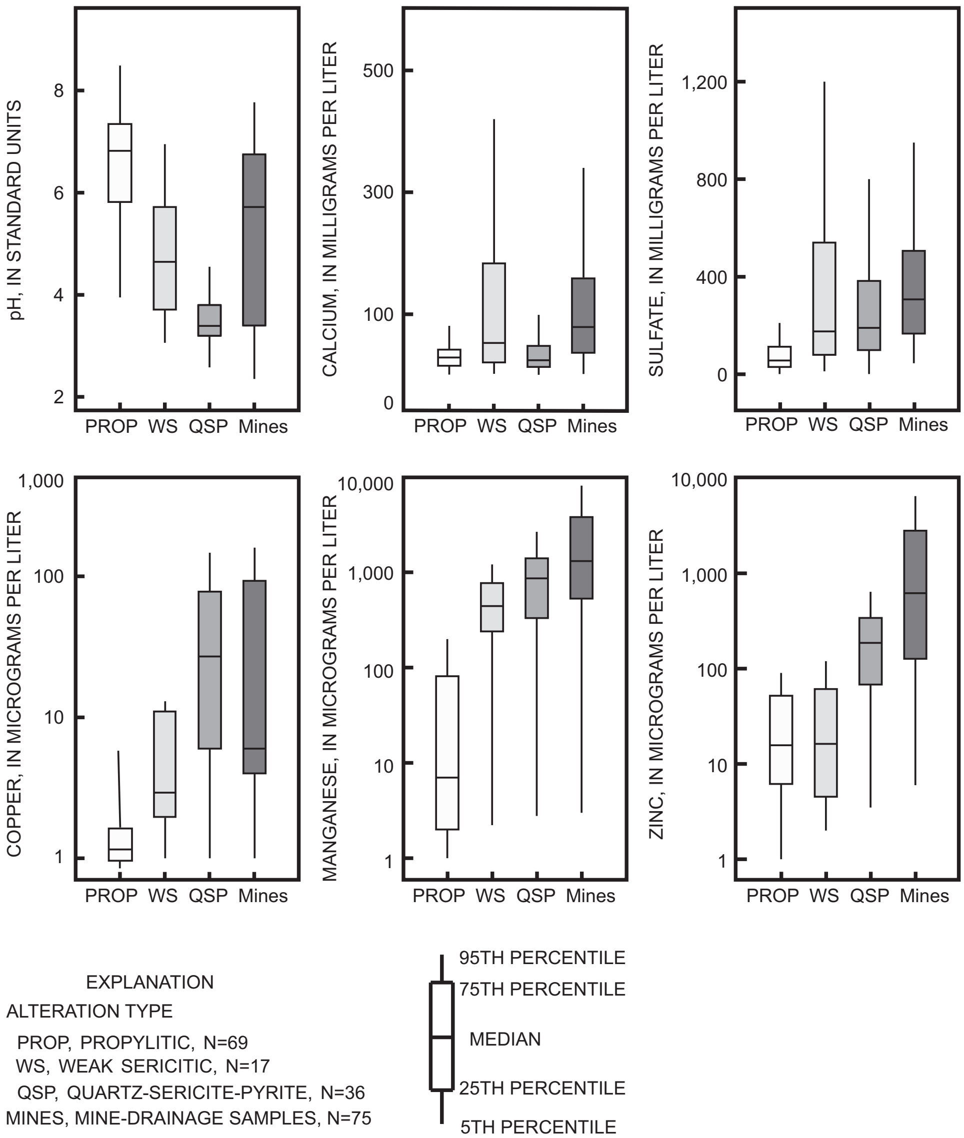

Figure 6. Comparison of dissolved-constituent concentrations in mine-adit discharge samples and in background water samples draining different alteration assemblages (from Mast et al., 2007).

watershed (Kimball et al., 2002). Contributions to the stream from all sources range from well-defined tributary contributions to dispersed, ground-water contributions. Mass-loading studies are useful to identify and compare the complex sources of loads in a watershed. A detailed mass-loading approach differs from a more traditional method of measuring load at a watershed outlet because it provides the necessary spatial detail to facilitate decisions about remediation. These studies are based on two well-established techniques: (1) the tracer-dilution method and (2) synoptic sampling. The tracer-dilution method provides estimates of stream discharge that are in turn used to quantify the amount of water entering the stream, both from tributaries and ground water, in a given stream segment (Kimball et al., 2002). Synoptic sampling of the instream flow and additional contributions from tributaries and ground-water chemistry provides a detailed longitudinal snapshot of stream water quality and chemistry (Bencala and McKnight, 1987). When used together, the tracer-dilution and synoptic sampling techniques provide discharge and concentration data that are used to determine the mass loading associated with various sources of water.

Tracer Studies

During the AML Initiative, a series of 13 tracer-injection studies established a hydrologic framework to quantify metal loading within the Animas River watershed (Kimball et al., 2007), providing a level of spatial and hydrologic detail never before collected anywhere. Within the three principal basins, 24 locations including both mined and unmined areas accounted for 73–87% of the total mass loading of aluminum, iron, copper, zinc, and manganese (Fig. 9). Weathering of extensive acid-sulfate and quartz-sericite-pyrite alteration zones in Mineral and Cement

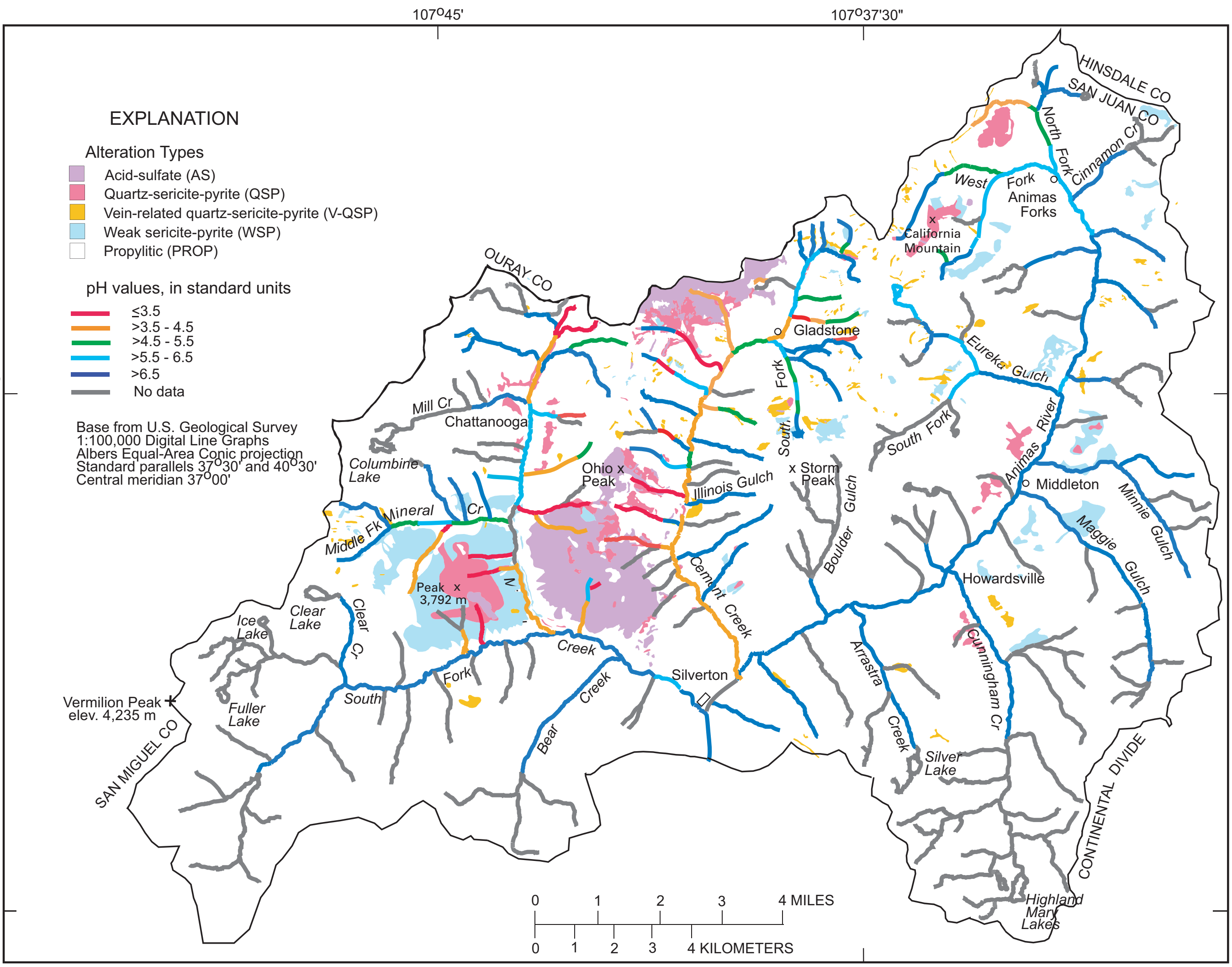

Figure 7. Distribution of pH measured in streams during low-flow conditions (1991–1999; from Wright et al., 2007). Hydrothermal alteration map from Bove et al. (2007) and Dalton et al. (2007).

Creek basins substantially contributes to loading of aluminum and iron (Figs. 9A and 9B). The location of greatest aluminum loading was the Middle Fork Mineral Creek, which drains extensive areas of quartz-sericite-pyrite alteration. Substantial aluminum and iron loads also entered Mineral Creek where it drains the acid-sulfate alteration of Ohio Peak and Anvil Mountain (Figs. 7 and 8). In Cement Creek basin, both Prospect and Minnesota Gulches drain acid-sulfate and quartz-sericite-pyrite alteration and contributed substantial aluminum and iron loads. Mineral Creek dominated the contribution of total copper load, whereas Cement Creek had the greatest contribution of total zinc load (Figs. 9C and 9D). Dispersed ground water added to the stream near Red Mountain Pass, as well as water draining the Koehler tunnel (site #75, Fig. 5), contributed substantial copper and zinc loads (Mineral Creek, site A, Fig. 9F). This is an area of acid-sulfate alteration. The Mogul mine in Cement Creek (site #97, Fig. 5), which likely drains the mine pool behind the bulkhead in the American tunnel (site #96, Fig. 5), and the North Fork Cement Creek also contributed large loads of copper and zinc (Fig. 8; Cement B and Cement C, Fig. 9F). In contrast to Cement and Mineral Creek basins, the Animas River basin drains mostly regional propylitic alteration. As a result, it does not have comparable loads of copper (Fig. 9C). Areas of vein related quartz-sericite-pyrite alteration in the headwaters of California Gulch, however, contributed substantial manganese and some zinc loading (Fig. 8; Figs. 9D and 9E). Substantial manganese and zinc loads were added to the Animas River downstream from Arrastra Creek (Fig. 8). This area drains historical mill tailings repositories (site #510, Fig. 5) that contain manganese gangue minerals from the milling of ore from the Sunnyside mine from 1961 to 1991 (Bird, 1999).

Zinc loading principally occurred in 24 areas (Fig. 9F). These areas are identified in the figure by basin, showing that

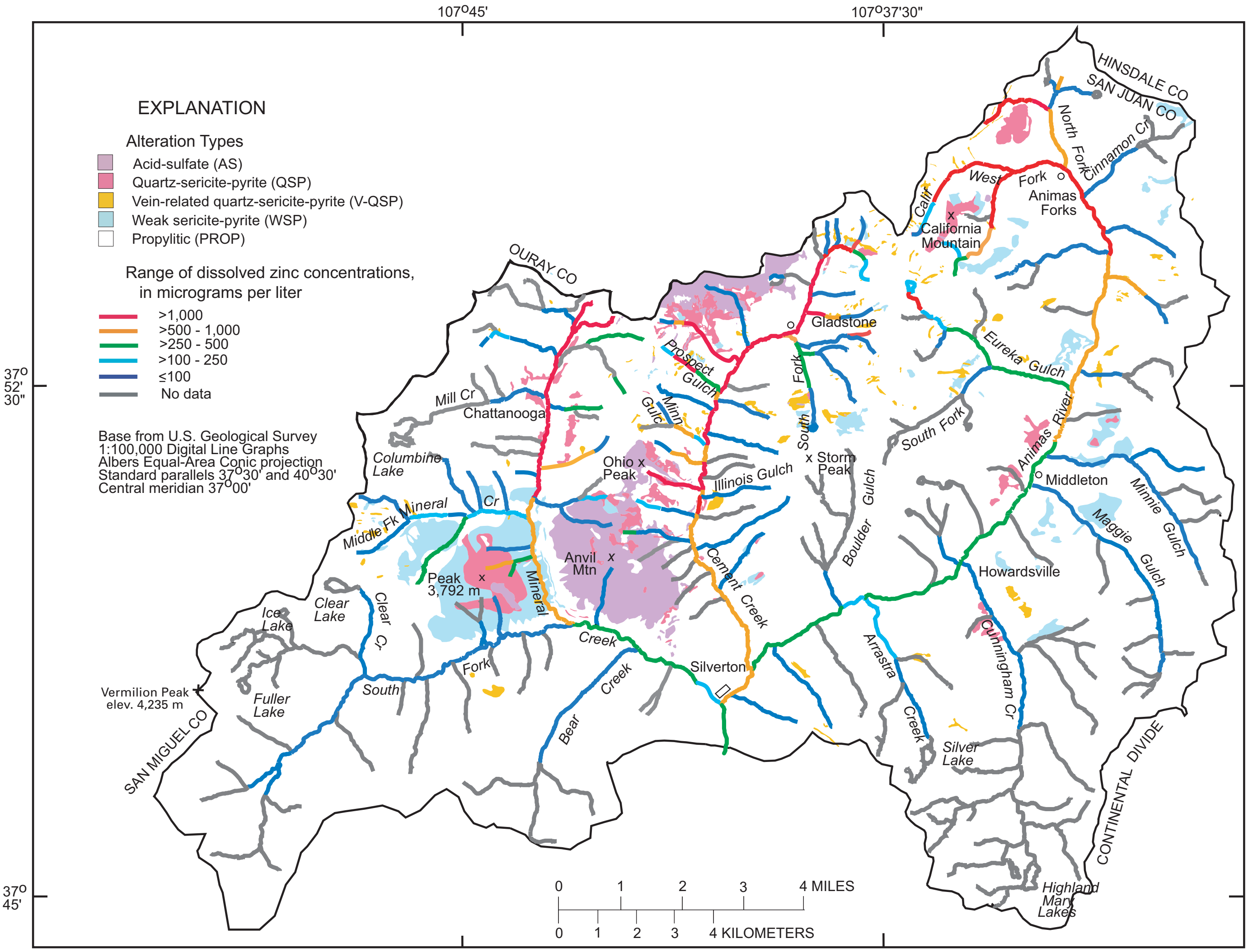

Figure 8. Distribution of dissolved zinc concentrations in streams during low flow (from Wright et al., 2007). Hydrothermal alteration map from Bove et al. (2007) and Dalton et al. (2007).

there were 4 principal areas in the Mineral Creek basin, 10 areas in the Cement Creek basin, 8 areas in the upper Animas River basin, and 1 area downstream from all three of these tributaries. These 24 areas accounted for 77% of the zinc loading in the watershed, but it is important to note that for 23% of the zinc load and for 13–29% of the load of the other metals (Fig. 9), the metal loading from other, dispersed sources could complicate remediation efforts because they would continue to release metals to the streams.

With the high cost of remediation, a predictive tool based upon sound science that could be used to anticipate results of various remediation options would be a desirable objective of any watershed characterization effort, particularly if it could be used in conjunction with the best state-of-the-art engineering solutions to make informed and cost-effective remediation decisions. Reactive transport models are an example of such a predictive tool developed during the AML Initiative. Solutions have been run on the study reaches in the Animas River watershed for selected stream reaches in the study area. These models integrate the tracer-dilution discharge with synoptic water chemistry from tracer studies. Runkel and Kimball (2002) provide an example by using a calibrated solute transport model to the downstream results. Two different active treatment options were evaluated to assess metal loading at Mineral Creek, site A (Fig. 9F). Option 1 removes ferric, but not ferrous, iron, whereas option 2 removes all iron from the stream at site A. Both options increase instream pH and substantially reduce total and dissolved concentrations of aluminum, arsenic, copper, and ferrous and ferric iron near the gauge on Mineral Creek. Dissolved lead concentrations are reduced by 18% with the first remediation plan. Both lead and iron are removed in an active treatment system with the second option, but this remediation option results in an increase in dissolved lead

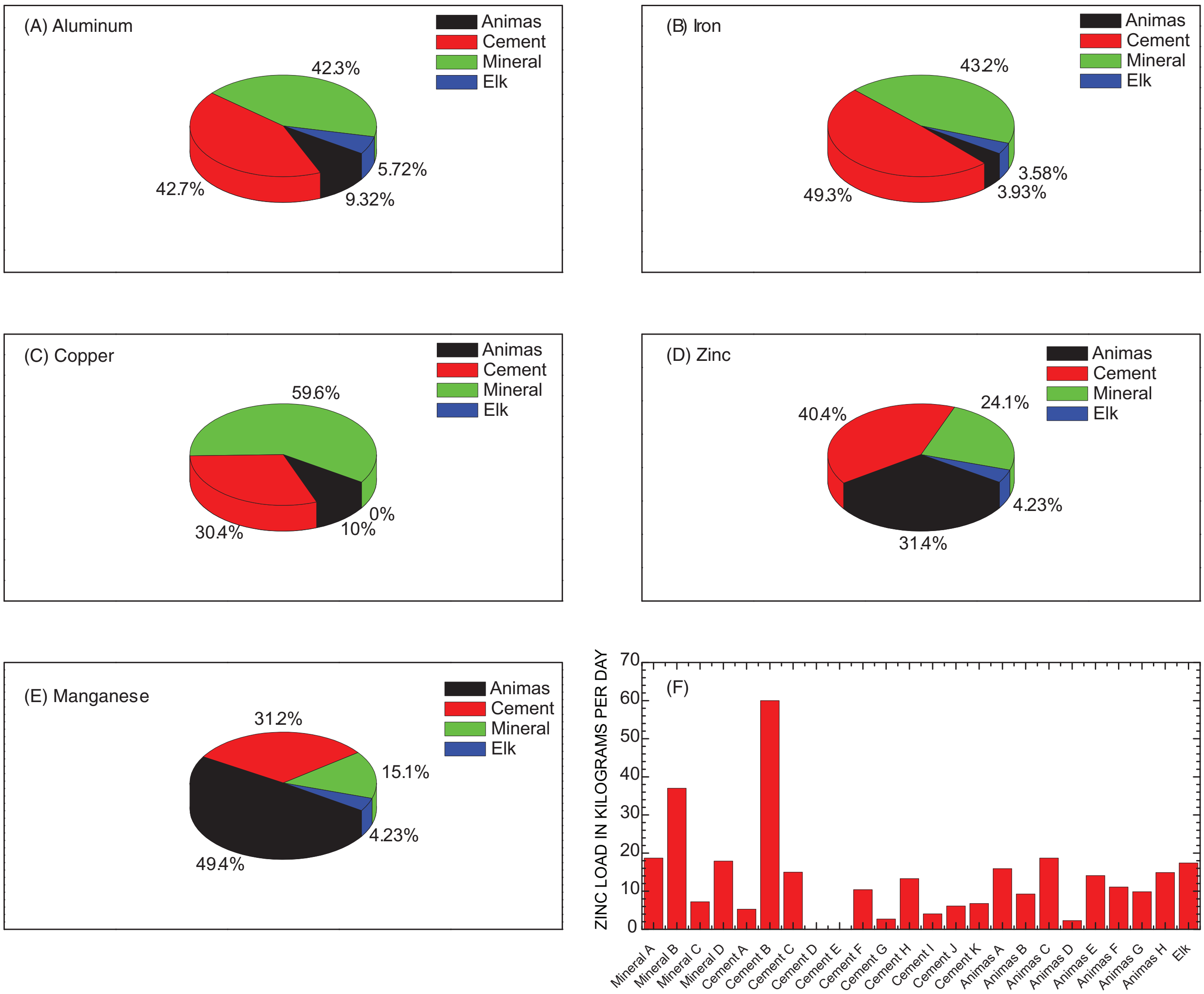

Figure 9. Pie diagrams showing loads for aluminum (A), iron (B), copper (C), zinc (D), and manganese (E). Bar chart (F) shows the loading from different mine sites for zinc.

concentrations over existing untreated conditions because additional downstream sources of lead are not attenuated by sorption to iron colloids. Neither of the proposed options, however, effectively reduces concentrations of zinc (Kimball et al., 2003).

MINES AND MILLS IDENTIFIED AS SOURCES

Large volumes of disturbed rock in the form of mine-waste dumps at historical mine sites have been implicated as the source of metals and acidity in many historical mining districts. A combination of high precipitation, extensive fracturing, and high topographic relief in many historical mining districts results in a substantial volume of ground water flowing through the rocks at the mine sites. Mining has forever changed the ground-water hydrology in historical mining districts. Historical mine adits and mine workings act as conduits for ground water, which is funneled to the surface once the mine pool is filled. The chemical reactions resulting from the interaction of ground water with these highly fractured and disturbed volumes of rock produce mine adit-water chemistries that vary only slightly throughout the year. Water chemistry from mine adits, however, is dependent upon the hydrothermal alteration type and the mineralogy of the ore (Bove et al., 2007). Flowing mine adits constitute an essentially constant source of contaminated ground water (Church et al., 2007b).

Interest in reducing the environmental effects of the many inactive mines and prospects in the Animas River watershed study area began in the early 1990s. In 1991–1992, a preliminary water-quality analysis of the Animas River watershed was coordinated by the Colorado Department of Health and Environment. The Colorado Division of Mines and Geology, U.S.D.A. Forest Service, and the U.S. Bureau of Land Management inventoried and ranked inactive mines in the study area. Unpublished reports of mine inventories in various parts of the watershed are available from the Colorado Division of Mines and Geology (CDMG Herron et al., 1997, 1998, 1999, 2000) and the Colorado Geological Survey (Lovekin et al., 1997).

Studies of the effects of mines on water quality by Nash and Fey (2007) and by the ARSG and the State of Colorado (summarized in Wright et al., 2007) were undertaken to determine which draining mine adits and mine-waste dumps most affect watershed water quality. These studies, coupled with the detailed mapping of altered areas by Bove et al. (2007) and by Dalton et al. (2007), were used to quantify the effects of historical mine wastes as sources of contaminants at a watershed scale (Walton-Day et al., 2007). Mast et al. (2007) examined acidic drainage from 75 mine sites in the watershed that contain flowing adits. Nash and Fey (2007) sampled and quantified the geochemistry of 97 mine-waste sites and 18 mill-tailings sites located on public land, each of which contained more than 100 tons of mine waste. Sampling protocols developed to obtain a representative sample are described in Smith et al. (2000), and analytical methods used are in Fey et al. (2000). The most acidic and metalliferous water (ranked 6, Fig. 10) drained mine waste from deposits containing acid-sulfate alteration, followed by quartz-sericite-pyrite alteration, and lastly by propylitic alteration (ranked 1, Fig. 10). The metal and acidity available from different mine-waste sites were quantified on the basis of the sum-of-metals concentration versus pH of the leachate water from the mine wastes. Leachate chemistry was determined using a 20:1 water/sample ratio in deionized water. The leachate equilibrated in a few minutes, and the leaching experiment could be repeated multiple times before the supply of water-soluble salts present in the mine-waste sample was sufficiently reduced such that the leachate water chemistry changed. The important conclusion here is that these mine wastes behave essentially as an infinite and constant source of potentially toxic metals and acidity. The chemistry of surface and ground water supplied by leaching of these mine wastes is constant, and the loads supplied are limited by the amount of precipitation and runoff rather than by the reaction rate of sulfides present with incident water on the mine-waste sites. Of the more than 500 mine sites on public land that were sampled, only 39 sites had a significant effect on surface water quality (Table 3, sites were classified from moderate to very high on the basis of the pH and sum of metals scores, Fig. 11; see Fey et al., 2000).

The State of Colorado, Division of Mines and Geology and the ARSG sampled private sites as well as those on public lands and using somewhat different criteria developed a different list of 31 draining mine adits and 30 mine-waste dumps that needed remediation (Wright et al., 2007). These sites are presented in Figure 12 and Table 4. Neither study included active mines sites that were undergoing remediation by Sunnyside Gold, Inc.. These 61 sites contribute ~90% of the metal loads to the three major drainages. The conclusions drawn from these studies, although they differ in scope, are very similar for the sites located on federal lands. Twenty of the 50 sites located on federal lands identified by Nash and Fey (2007) for remediation also occur on the list of 61 sites identified for remediation by the ARSG and the State of Colorado.

REMEDIATION ACTIVITIES

The Animas River Stakeholders Group and federal land-management agencies began planning for clean-up activities in the mid-1990s. Sunnyside Gold, Inc. reached an agreement with the

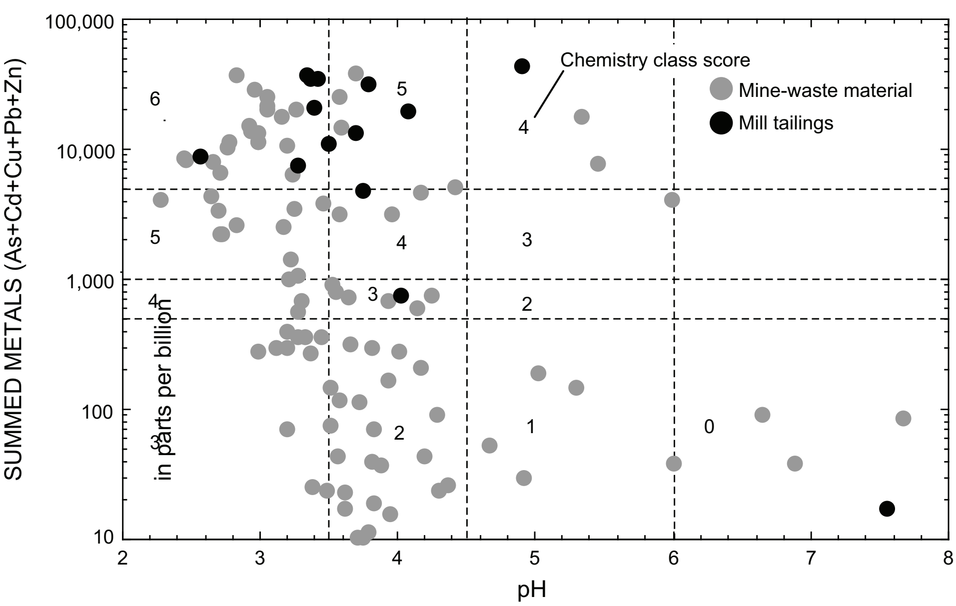

Figure 10. Composition of mine-waste leachate chemistry showing range of dissolved metal concentrations and pH from leachates from samples from 97 mine-waste sites and 18 mill-tailings sites. Dashed lines and numbers (0–6) delineate classification fields to categorize mine waters derived from mine and mill wastes (Nash and Fey, 2007).

State of Colorado to implement a number of remediation activities in the watershed as a condition for terminating its discharge permit at the American tunnel (site #96). Most of this remediation work on Sunnyside properties was completed by 1996. Remediation work completed throughout the Animas River watershed through 2004 is summarized in Table 5 and Figure 13. Funding for site remediation and watershed cleanup has come from both private and public sources. Remediation work done by Sunnyside Gold, Inc. has exceeded $10 million; most of the work has been done on permitted mine sites where they were involved directly in mining. Other remediation work has been done on mine sites identified as high priority (e.g., Koehler tunnel, site #75, Figs. 11 and 13). Funding for remediation of mine sites located on public lands has come from U.S. Bureau of Land Management and the U.S.D.A. Forest Service abandoned mine lands funds. Much of the funding for remediation work undertaken by the ARSG has come from U.S. EPA 319 grants. Funding has also been provided from various other sources: U.S. Office of Surface Mining, the San Juan Resource and Conservation District, Silver Wing Mining Company, Gold King mine, Inc., Salem Minerals, and Mining Remedial Recovery. Of the 39 priority sites identified by Nash and Fey (2007), 9 (23%) have been remediated. Of the 61 high-priority sites identified by the ARSG, 14 (23%) have been remediated. The ARSG is actively working with federal, state, and local funding sources to remediate these sites and reduce the metal loading in the Animas River watershed.

MONITORING

Data Collection and Methodology

Frequent water-quality sampling was done at the four gauges (Fig. 13). Water-quality data were collected at least monthly beginning in 1991 following the closure of the Sunnyside mine and more frequently between 1994 and 1999. Continuous stream-flow monitoring at the four stream gauges has been done since October 1, 1994. The U.S. Geological Survey, U.S. Bureau of Reclamation, Sunnyside Gold, Inc., and the Silverton Schools under the sponsorship of the Colorado River Watch Program have done most of the monthly chemical monitoring at the gauges. Monitoring was more frequent than monthly between 1994 and 1999 because all of these entities were involved in data collection. USGS and River Watch monitoring was discontinued after 1999. SGC continued monthly monitoring at A72 and monitored the other three gauges on alternate months with the U.S. Bureau of Reclamation through most of 2002. Since 2002, the River Watch program has resumed monitoring, alternating months with the U.S. Bureau of Reclamation at all four gauges.

Previous investigations in the basin have shown that stream flow and seasonality influence the concentration of most constituents (Butler et al., 2001; Leib et al., 2003). These exogenous factors, if not accounted for, may mask the effects of remediation. The effect of stream flow and seasonality on the concentration variation of solutes was removed through regression analysis. For a complete description of the methodology see Leib et al. (2003).

Moving average charts were prepared for the four gauge sites. The moving average chart smoothes irregularities owing to periodic factors not removed through the regression model. The "0," or centerline, is the expected concentration of any analyte, adjusted for stream flow and seasonal variations, observed during the baseline period. The charted variable is the difference between the observed concentration adjusted for stream flow and season and the expected concentration derived from the regression equation. If the moving average line remains between the first gridlines above and below the centerline, there is a 95% probability that there has been no shift in the 12-sample mean concentration.

The baseline period used data collected between October 12, 1994, and September 30, 1996, at A68, C48, and M34. The baseline period at Animas River downstream from Silverton, A72, uses the data collected between September 1991 and May 1996. A consent decree signed in May 1996 between the Colorado Department of Health and Environment and Sunnyside Gold, Inc. specified actions that Sunnyside Gold, Inc. was required to take before terminating their remediation permit. The valve on the American tunnel was closed in October 1996 and accelerated remediation projects were begun shortly thereafter (Table 5).

ANALYSIS OF THE MONITORING RESULTS

Mineral Creek Basin

Metals targeted for remediation in the Mineral Creek basin included cadmium, copper, and zinc. In the environmental risk assessment of surface water quality effects on aquatic life (Besser et al., 2007), dissolved copper posed the greatest risk to brook trout, the dominant species of fish in streams in the basin. Tracer loading studies (Fig. 9C) demonstrated that the Mineral Creek basin was a primary target for site remediation to reduce copper and zinc loads, particularly in the headwaters where acid-sulfate deposits containing enargite, tetrahedrite, and galena were produced from the 1880s through 1907 (Bove et al., 2007; Jones, 2007). Remediation began in Mineral Creek in November 1996 when the pond below the Koehler/Longfellow (sites #75 and #77) was drained and all sludge from the pond and mine waste from the Koehler was removed to Tailings Pond #4, site #510. In 1997 the Longfellow wastes were consolidated, neutralized with limestone, and runon/runoff controls were implemented. Mine waste was removed from the Congress mine, site # 79, and Carbon Lake mine, site #80, both near the headwaters of Mineral Creek in 2000–2003. Hydrologic controls were implemented at the Bonner mine, site #172, on the Middle Fork of Mineral Creek in 2000. A bulkhead seal was placed in the Koehler tunnel in 2003. Mine-waste consolidation, neutralization, and hydrologic controls were implemented at the San Antonio mine, site SA (north of study area boundary, Fig. 13), in 2004. Data collected during and immediately after the remediation at sites 75–77 (Fig. 13) show sharp

TABLE 3. SELECTED MINE AND MILL-TAILINGS SITES ON FEDERAL LANDS RECOMMENDED FOR REMEDIATION (NASH AND FEY, 2007), ANIMAS RIVER WATERSHED

Name	Site No.	Ranking
Mines		
Early Bird Crosscut	8	Moderate
Ben Butler mine	9	High
Hermes Group	11	High
Eagle Chief mine	14	Low
Little Ida mine	15	High
Frisco tunnel	19	High
Grand Mogul	35	Very High
Koehler tunnel	75	Very High
Henrietta mine—#7 Level	85	Very High
Lark mine	86	Very High
Joe and Johns mine	87	High
Upper Joe and Johns mine	89	Low
Eveline mine	91	Low
Clipper mine	114	Very High
Silver Crown mine	133	High
Imogene mine	136	Moderate
Ferricrete mine	137	Low
Brooklyn mine	141	High
Kansas City mine—#1 Level	145	High
Elk tunnel	147	Low
Mammoth tunnel	148	High
Avalanche mine	149	Moderate
Paradise mine	168	Moderate
Ruby Trust	169	Very High
Independence mine	171	High
Bonner mine	172	High
Monarch	180	High
Mayday mine	181	Very High
Legal Tender mine	189	Moderate
Forest Queen mine	195	Moderate
Caledonia mine	198	Very High
Kittimack mine	201	High
Burbank mine	207	High
Columbine mine	260	Moderate
Sultan tunnel	266	High
Mighty Monarch mine	285	Low
Last Chance mine	289	Moderate
Bandora mine	332	Very High
Highland Mary—#7 Level	359	Low
Henrietta mine—#8 Level	505	Very High
Henrietta mine—#9 Level	506	Very High
Unnamed prospect (Mineral Creek basin)	X	Moderate
Unnamed prospect (upper Animas River basin)	X	Low
Unnamed prospect (upper Animas River basin)	X	Low
Unnamed prospect (upper Animas River basin)	X	Low
Unnamed prospect (upper Animas River basin)	X	Moderate
Mill Tailings		
Kittimack tailings	192	Very High
Lackawanna tailings (removed)	286	Very High
North Star Mill tailings	310	Moderate
Highland Mary Mill tailings	361	Low

Note: Data refer to sites in Figure 11; data from Jones (2007); Church et al. (2007b).

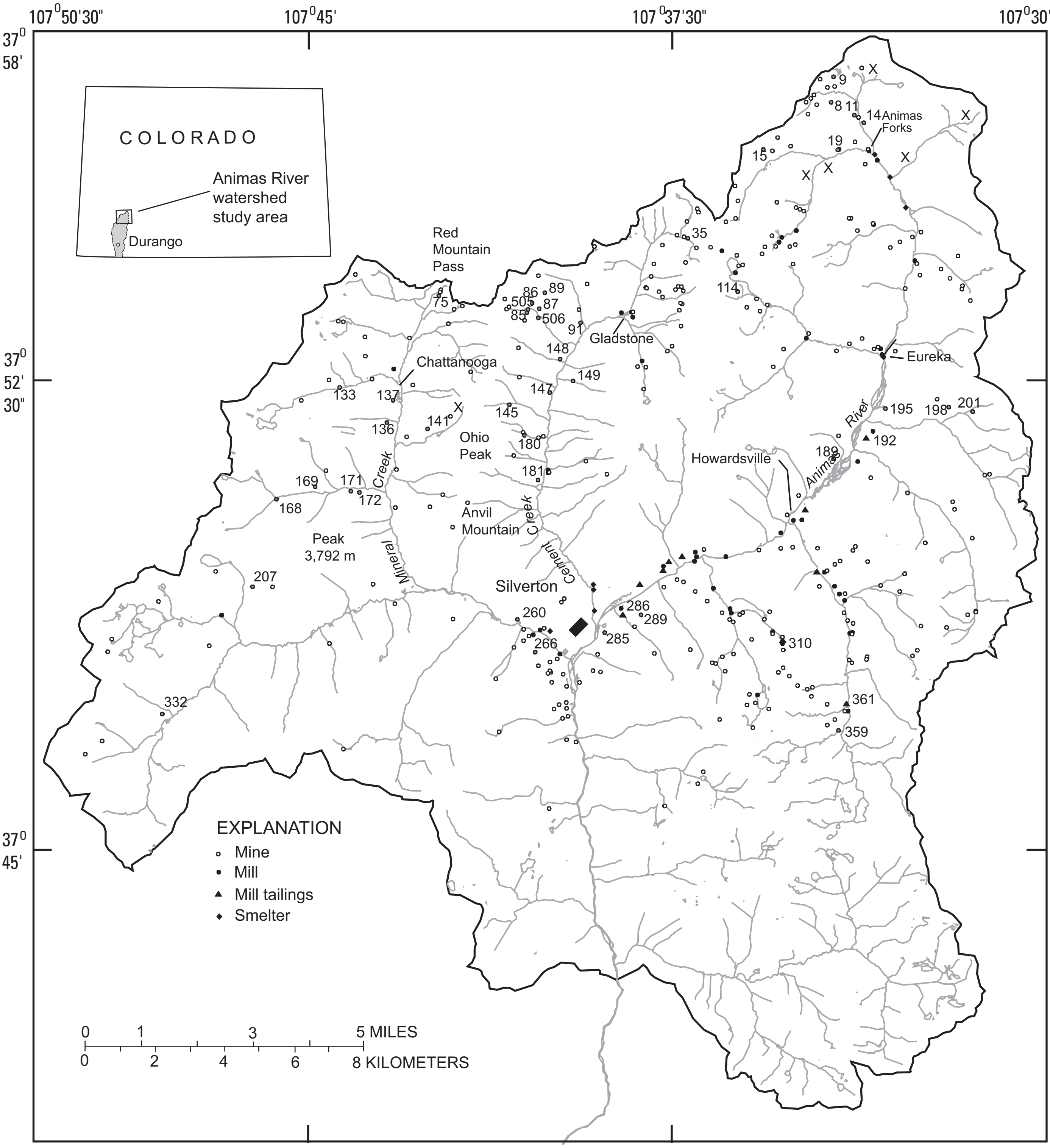

Figure 11. Location and ranking (Table 3) of mine waste, Animas River watershed. Rank is based on size, metal release, proximity to streams, and acid-generating potential (Fig. 10; modified from Nash and Fey, 2007); some sites contain multiple draining adits or mine-waste dumps. Prominent peaks discussed in text are located on map; unnamed peak between Middle and South Forks Mineral Creek is designated as peak 3792 m (USGS, 1955).

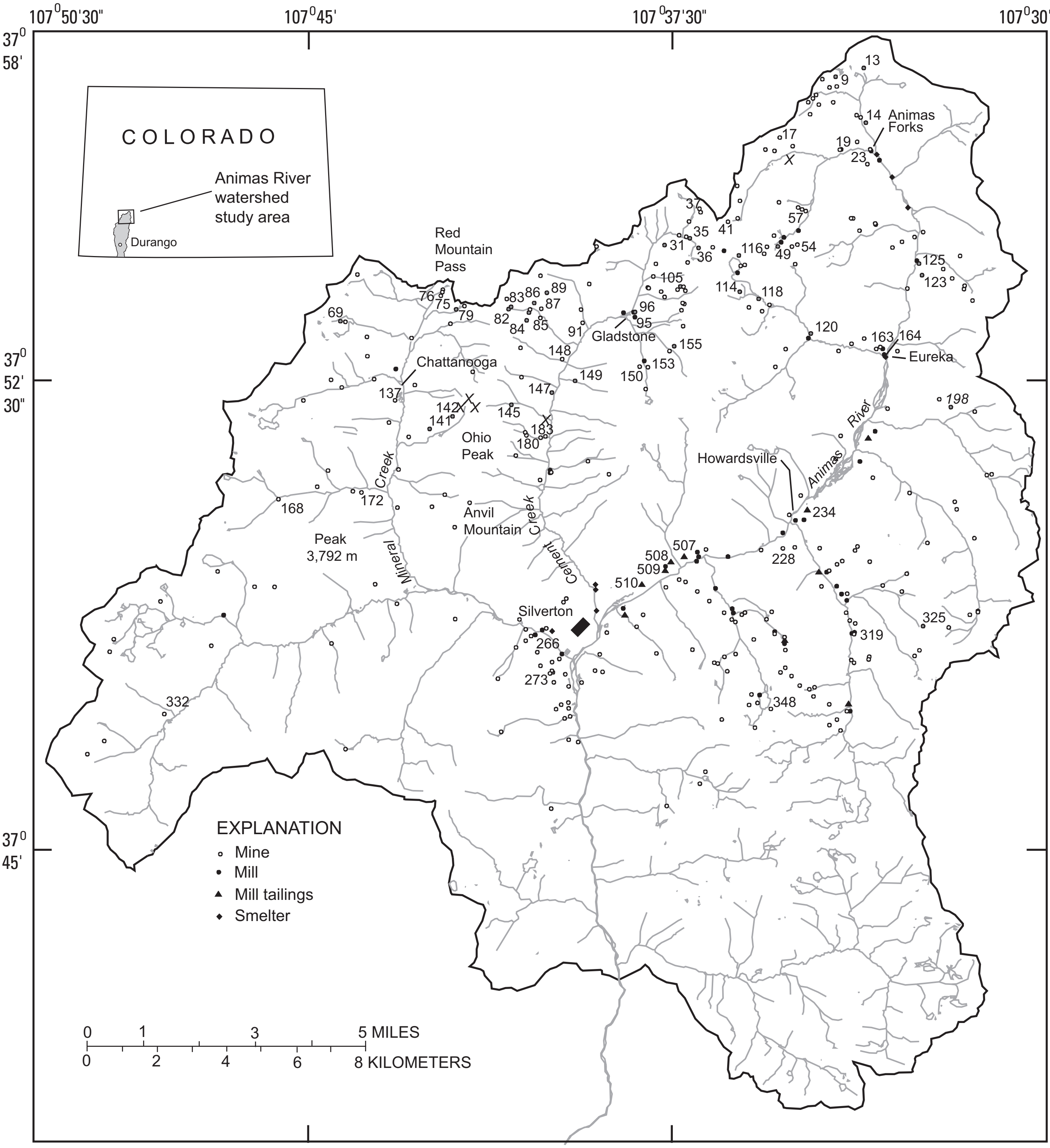

Figure 12. Location of draining mines and mine waste (Table 4) ranked by ARSG (modified from Wright et al., 2007), Animas River watershed. Rank is based on metal inventory and acid-generating potential of mine-waste dumps and metals released from draining adits; some sites contain multiple draining adits or mine-waste dumps. Prominent peaks discussed in text are located on map; unnamed peak between Middle and South Forks Mineral Creek is designated as peak 3792 m (USGS, 1955).

TABLE 4. SELECTED DRAINING MINES, WASTE ROCK PILES, AND PERMITTED MINE AND MILL SITES IN THE UPPER ANIMAS RIVER WATERSHED

Site No.	Mine or Site Name	Site No.	Mine or Site Name
	Draining Mines		**Waste Rock Pile**
31	Mogul mine	82	Galena Queen mine
2	Silver Ledge mine	145	Kansas City #2 mine
35	Grand Mogul mine	83	Hercules mine, shaft
148	Mammoth tunnel	89	Upper Joe & Johns mine
183	Anglo-Saxon mine	35	Grand Mogul mine, East
87	Joe and Johns mine	145	Kansas City #1 mine
150	Big Colorado mine	155	Black Hawk mine
180	Monarch mine	95	Lead Carbonate Mill
91	Eveline mine	84	Henrietta mine (level 3)
37	Columbia mine	36	Ross Basin mine
75	Koehler tunnel	86	Lark mine
266	North Star mine (Sultan)	??	Pride of the Rockies mine
76	Junction mine	85	Henrietta mine (Level 7)
332	Bandora mine	31	Mogul mine
172	Upper Bonner mine	141	Brooklyn mine
172	Bonner mine	69	Upper Bullion King mine
172	Lower Bonner mine	X	Unnamed shaft mine, upper Browns Gulch
137	Ferricrete mine	79	Congress mine, shaft
168	Paradise mine	142	Brooklyn mine, upper waste rock pile
141	Brooklyn mine	X	Unnamed mine, upper Browns Gulch
273	Little Dora mine	273	Little Dora mine
17	Vermillion mine	141	Brooklyn mine, lower waste rock pile
23	Columbus mine	9	Ben Butler mine
X	Lower Comet mine	125	Silver Wing mine
X	Unnamed mine	123	Tom Moore mine
54	Sound Democrat mine	8	Eagle Chief mine
42	Mountain Queen mine	13	Lucky Jack mine
125	Silver Wing mine	114	Clipper mine
19	Frisco tunnel	325	Buffalo Boy mine
163	Senator mine	118	Ben Franklin mine
348	Royal Tiger mine	198	Caledonia mine
319	Pride of the West mine	116	Sunnyside mine
228	Little Nation mine		**Permitted Mine Sites**
		105	Upper Gold King mine
		96	American tunnel mine
		49	Gold Prince mine
		116	Sunnyside mine
		120	Terry tunnel mine
			Permitted Mill Sites
		234	Pride of the West Mill tailings
		507–510	Mayflower Mill tailings

Note: Data refer to sites in Figure 12; Wright et al. (2007).

TABLE 5. SUMMARY OF RECLAMATION PROJECTS COMPLETED AS OF 2004

Project Sponsor	Project Site	Location (Fig. 12)	Type of Remediation	Date Project Completed	Improvement (Actual or Anticipated)
Private Funds					
Sunnyside Gold, Inc.	Lead Carbonate Mill	Gladstone, South Fork Cement Creek, site #95	Removal of 27,000 yd^3 of mill tailings from stream bank	1991	Reduce loading of metals to Cement Creek and erosion transport of mill tailings
Sunnyside Gold, Inc.	Mayflower Mill	Mayflower Mill tailings, sites #507–509	Recontour inactive mill tailings ponds and cap, 625,000 yd^3 of mill tailings and overburden moved	1992	Mined land reclamation—reduce loading of metals to Animas River and erosion transport of mill tailings
Sunnyside Gold, Inc.	Lake Emma Sunnyside Basin	Sunnyside mine collapse, site #116	Fill mine subsidence at Lake Emma, remove 240,000 yd^3 mine waste and recontour	1993	Mined land reclamation and reduce loading of metals to Animas River
Sunnyside Gold, Inc.	American tunnel, waste dump	Gladstone, on bank of South Fork Cement Creek, site #96	Remove 90,000 yd^3 waste dump and underlying historical mill tailings	1995	Mined land reclamation and reduce loading of metals to Cement Creek and erosion transport of mill tailings
Sunnyside Gold, Inc.	Sunnyside Eureka Mill, tailings at town site	On banks and in flood plain of Animas River, downstream of site #164	Remove 112,000 yd^3 of mill tailings	1996	Reduce loading of metals to Animas River and erosion transport of mill tailings.
Sunnyside Gold, Inc.	Sunnyside mine hydraulic seal project	Sunnyside mine, sites #116, #120, #96	Bulkheads placed in Sunnyside mine to restore hydrologic regime to approximate premining hydrology and eliminate drainage from adits	1997	Place mine workings under water to reduce oxidation, restore groundwater movement around mine workings and eliminate need for perpetual water treatment
Sunnyside Gold, Inc.	American tunnel	American tunnel at Gladstone, site #96	Divert and treat Cement Creek, fill Sunnyside mine pool to mitigate any short-term impacts of reclamation projects	8/1996 to 12/1999	Reduce loading to Animas River to offset any short term impacts of reclamation of other sites
Sunnyside Gold, Inc.	Mayflower Mill tailings, Boulder Creek	Mill tailings at site #509, flood plain of Boulder Creek	Remove 5700 yd^3 of mill tailings	1997	Reduce loading of metals to Animas River and erosion transport of mill tailings
Sunnyside Gold, Inc.	Ransom mine adit	Eureka town site, site #161	Bulkhead seal to stop deep mine drainage and reclaim portal	1997	Restore hydrologic regime and reduce rate of ore oxidation by placing mine workings under water to reduce metal loading to Animas River
Sunnyside Gold, Inc.	Gold Prince mine waste and mill tailings	Placer Gulch, site #49	Bulkhead seals to stop deep mine drainage, consolidate mine waste and mill tailings, remove 6000 yd^3 mine waste and construct upland diversions	1997	Reduce exposure to water to reduce metal loading to Animas River
Sunnyside Gold, Inc.	Longfellow-Koehler	Headwaters of Mineral Creek, Longfellow Mine, site #77; Junction Mine, site #76; Koehler tunnel, site #75	Remove Koehler Mine-waste dump (32,100 yd^3), consolidate Junction mine dump and Longfellow mine dump and cap, capture adit drainage, construct diversions, conduct feasibility study of wetland treatment of Koehler tunnel acidic drainage	1997	Reduce metal loading to Mineral Creek and erosion transport of mine waste
Sunnyside Gold, Inc.	Pride of the West Mill tailings	Howardsville, site #234	Remove 84,000 yd^3 of mill tailings	1997	Reduce metal loading to Animas River and transport of mill tailings by erosion

(*continued*)

TABLE 5 (*continued*)

Sunnyside Gold, Inc.	Sunnyside mine	Sunnyside mine, American tunnel treatment, site #96	Inject 652 tons of hydrated lime into the Sunnyside mine pool to provide increased alkalinity and reduce oxygen available in mine for pyrite oxidation	1997	Improve initial conditions as water table is restored by installing bulkhead to stop acidic mine drainage
Sunnyside Gold, Inc.	Mayflower Hydrological Control	Mayflower Mill tailings pond #1, site #507 C	apture and divert three upland drainages that provide supply to ground water up-gradient of mill tailings	1999	Minimize potential for contact of runoff with mill tailings and reduce potential for metal loading to Animas River
Sunnyside Gold, Inc.	Mayflower Mill tailings pond #4	Mayflower Mill tailings pond #4 drainage modification, site #510	Install lined diversion ditch to capture surface runoff and prevent infiltration through mill tailings	1999	Minimize potential for contact of runoff with mill tailings and reduce potential for metal loading to Animas River
Sunnyside Gold, Inc.	Mayflower Mill tailings pond #4	Divert ground water up-gradient from mill tailings pond #4, site #510	Capture ground water and divert around mill tailings impoundment, tailings pond #4	1995, 1999	Minimize potential for contact of groundwater with mill tailings and reduce potential for metal loading to Animas River
Sunnyside Gold, Inc.	Power plant flats	Animas River near old power plant, east of site #509	Remove mill tailings to tailings pond #4, site #510	2003	Reduce metal loading to Animas River
Sunnyside Gold, Inc.	Mogul mine bulkhead	Cement Creek, site #31	Install bulkhead in Mogul mine to stop acidic drainage	2003	Reduce metal loading to Cement Creek
Sunnyside Gold, Inc.	Koehler mine bulkhead	Koehler mine, (site #75)	Install bulkhead in Koehler mine to stop acidic drainage	2003	Reduce metal loading to Mineral Creek
Sunnyside Gold, Inc.	Reactive barrier	Animas River floodplain below Mayflower Mill, mill tailings pond #4 (site #510)	Passive treatment of contaminated ground water before entering Animas River	2003	Reduce metal loading to Animas River
Gold King mines, Inc.	Gold King mine	North Fork Cement Creek, site #111	Hydrologic controls for workings and mine waste	1998	Reduce metal loading to North Fork Cement Creek
Gold King mines, Inc.	Gold King mine	North Fork Cement Creek, site #111	Pipe Gold King adit discharge to Gladstone for active treatment of acidic drainage	2002	Reduce metal loading to Cement Creek
Mining Remedial Recovery	Sunbank Group	Placer Gulch, site #57	Anoxic drain, settling pond, waste consolidation, bulkhead	1995	Raise pH from draining adit, reduce metal loading to Animas River from adits and mine waste
Salem Minerals	Mammoth tunnel	Cement Creek, site #148	Settling ponds for mine drainage	1999	Reduce iron load to Cement Creek
Silver Wing Mining Co.	Silver Wing mine	Animas River, site #125	Collect acidic mine water, install hydrological controls	1995	Divert acidic drainage around mine-waste dump, reduce metals loading to Animas River
Private and Public Funds					
Silver Wing Mining Co.	Silver Wing mine	Animas River, site #125	Install anoxic drain, settling pond, and bioreactor	2000	Reduce metal loading to Animas River
San Juan R. C. & D., ARSG	Carbon Lake–Phase I	Carbon Lake mine, Mineral Creek, site #80	Removal of 1900 yd^3 of waste rock from stream channel	Phase I—1999	Reduce loading of metals, especially cadmium, copper, iron, lead, manganese, and zinc, to Mineral Creek
San Juan R. C. & D., ARSG	Carbon Lake—Phase II	Koehler tunnel, Mineral Creek, site #75	Reduce flows from Koehler tunnel by reducing infiltration into surface mine workings	Phase II—2001	Reduce metals loading to Mineral Creek by reducing infiltration of water into old mine workings

(*continued*)

TABLE 5 (*continued*)

Project Sponsor	Project Site	Location	Type of Remediation	Date Project Completed	Improvement (Actual or Anticipated)
San Juan R. C. & D., ARSG	Carbon Lake—Phase III	Congress mine, Mineral Creek, site #79	Complete removal of Congress mine-waste dump	Phase III—2003	Reduce metals loading to Mineral Creek by removal of mine wastes and beneficiation
San Juan R. C. & D., ARSG	Carbon Lake—Phase III	Carbon Lake, site #80, ditch restoration	Diversion ditch, wetlands, and stream restoration, water rights purchased and water diverted to Uncompahgre River watershed restored to Mineral Creek drainage	Phase III—2003	Reduce metals loading to Mineral Creek by removal of mine wastes and site beneficiation
San Juan R. C. & D., ARSG	Galena Queen and Hercules mines	Prospect Gulch, sites #82 and #83	Remove mine waste, install hydrological controls, add soil amendments, and revegetation	2001	Elimination of surface water leaching of toxic metals. Reduce metal loading to Cement Creek
San Juan R. C. & D., ARSG	San Antonio Project	San Antonio mine	Install hydrological controls, remove wastes from stream, consolidate wastes and neutralize, revegetation	2004	Reduce metal loading and acidity to Mineral Creek; stabilize site, remove mine wastes, restore streambed and riparian habitat
San Juan R. C. & D., ARSG	Handies Peak Project	Lucky Jack mine (site #13)	Hydrological controls, remove wastes from fen, consolidate, neutralize, and revegetation; adit and shaft closures	2004	Reduce metal loading and acidity to upper Animas River; uncover fen and restore
U.S. BLM and Duke Energy	Henrietta mine	Prospect Gulch, site #84	Hydrologic controls and mine-waste removal	2004	Reduce metal loading to Cement Creek
Public Funds					
U.S. OSM	Galena Queen mine	Prospect Gulch, sites #82	Waste consolidation and hydrological controls	1998	Reduce surface water leaching of toxic metal loading to Cement Creek
U.S. BLM	Joe & Johns mine	Prospect Gulch, site #87	Mine drainage collection and diversion	1999	Collect acidic drainage for later treatment project development, reduce metal loading to Cement Creek
U.S. BLM	Lark mine	Prospect Gulch, site #86	Install collection system for acidic water, hydrological controls	1999	Collect acidic drainage for possible treatment, remove surface water from site, reduce metal loading to Cement Creek
U.S. BLM	Forest Queen mine	Animas River near Eureka, site #195	Install collection system for acidic water and passive wetland treatment	1999	Reduce metal loading to Animas River
U.S. BLM	Mayday mine	Cement Creek, site #181	Hydrological controls, cap top of mine-waste pile	1999	Reduce surface water leaching of toxic metals
U.S. BLM	Lackawanna Mill tailings	Animas River near Silverton, site #286, site #181	Removal of mill tailings from flood plain to Mayday dump for consolidation and capping	2000	Reduce metal loading to Animas River
U.S. BLM	Elk tunnel	Cement Creek, site #147	Install limestone drain	2003	Reduce metal loading to Cement Creek
U.S. F.S.	Bonner mine	Middle Fork Mineral Creek, site #172	Install collection system for acidic water and diversion, move waste rock from avalanche path	2000	Reduce metal loading to Mineral Creek
U.S. F.S.	Brooklyn mine	Mineral Creek, site #141	Hydrologic controls and mine-waste removal	2004	Reduce metal loading to Mineral Creek

Note: San Juan R. C. & D., San Juan County Resource and Conservation District; ARSG, Animas River Stakeholders Group; U.S. OSM, U.S. Dept. of Interior, Office of Surface Mining; U.S. BLM, U.S. Dept. of Interior, Bureau of Land Management; U.S. F.S., U.S. Dept. of Agriculture, Forest Service; mine site locations from Church (2000b); mill site locations from Jones (2006); yd^3, cubic yards of material; data provided by W. Simon, written comm., Animas River Stake Holders Group, Oct. 2004, and by R. Robinson, pers. comm., U.S. BLM, Apr. 2006.

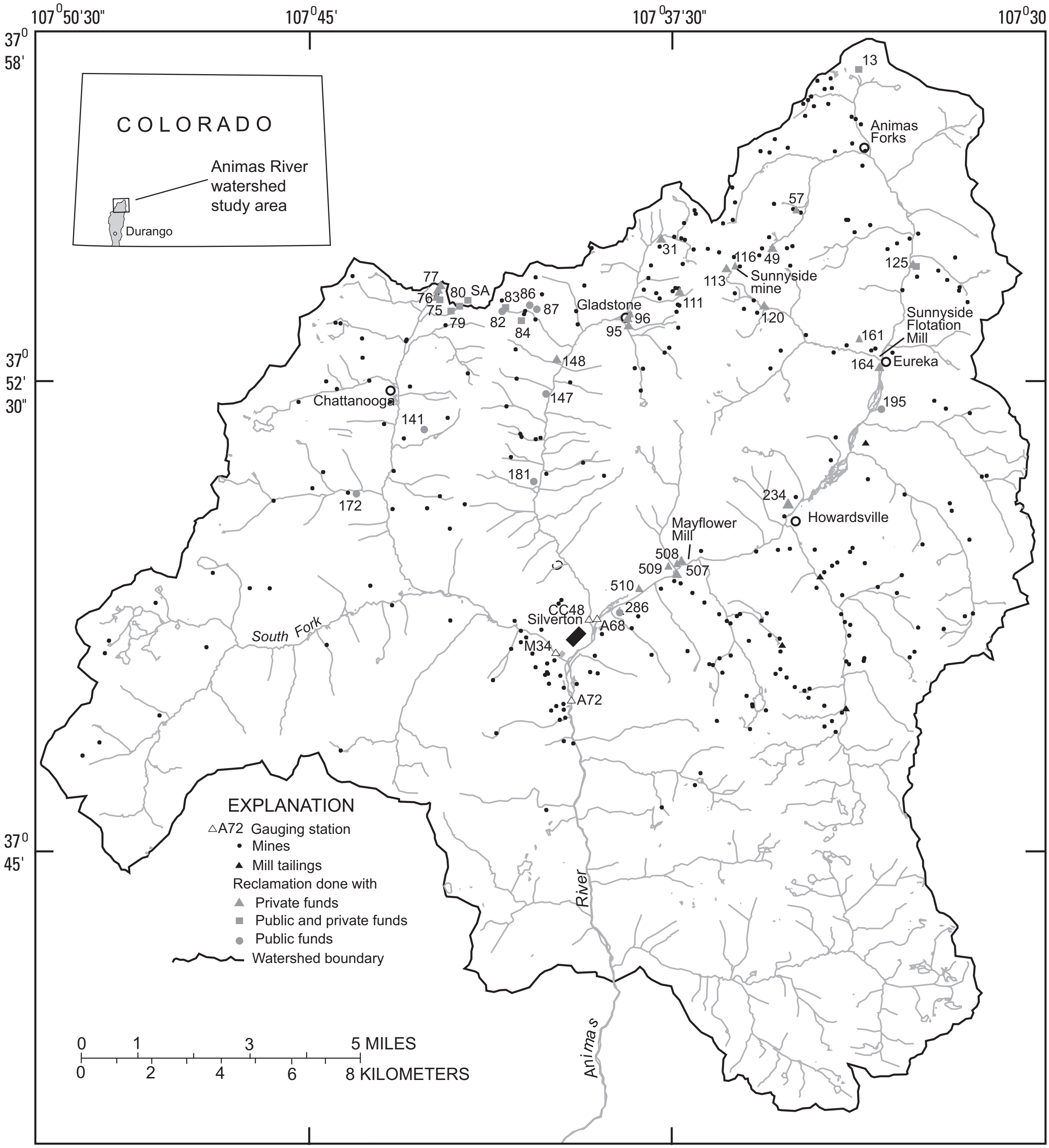

Figure 13. Map showing locations of sites remediated through October 2004 (Table 5). Sites designated by sources of funding for remediation work (private, public, or both).

increases in metal concentrations resulting from the removal of contaminated mine waste followed by continued reduction in the copper concentration in Mineral Creek. The second major remediation project at sites 79–80 (Fig. 11) resulted in long-term reduction of the copper concentration and significant improvement in copper load in Mineral Creek (Fig. 14A). A similar reduction in zinc (and cadmium) concentrations is also evident (Fig. 14B).

The total recoverable aluminum concentration (not shown) fluctuated around the baseline concentration until 2002, when it started into a steep decline. This change may be driven, in part, by the drought conditions experienced in 2002. The 12-period moving average through November 10, 2004, indicates that total recoverable aluminum concentration was 667 µg/L lower than during the 1994–1996 baseline period.

Total recoverable iron (not shown) and dissolved manganese concentrations were generally higher than the baseline condition from 1997 through most of 2002. Since 2002, concentrations of both constituents are approaching the concentrations of the baseline period. Remediation initiated at site #79 appears to have resulted in a substantial increase in the concentration of manganese (Fig. 14C).

Sulfate concentration (Fig. 14D) increased following the initial remediation work, but has been dropping since 2002. Evidence of the improved water-quality conditions downstream are indicated in the reach of Mineral Creek downstream from the confluence of South Fork Mineral Creek, which has since begun to show recovery of some invertebrates (W. Simon, pers. comm., 2004). Since 2002, the concentration of sulfate has dropped below the concentration of the baseline period.

Dissolved cadmium (not shown), copper, and zinc concentrations have all declined since late 1997 (Figs. 14A and B). The 12-period moving average indicates that through November 10, 2004, dissolved cadmium, copper, and zinc were 0.38 µg/L, 14 µg/L, and 94 µg/L, respectively, less than the concentrations during the 1994–1996 baseline period.

Cement Creek Basin

Cement Creek, which carries high concentrations of cadmium, copper, zinc, aluminum, and iron (Fig. 9), is not capable of supporting aquatic life even with remediation. However, remediation in the Cement Creek basin is vital to downstream water quality. The relationship between cadmium, copper, and zinc concentration, stream flow, and seasonality is weak in the Cement Creek basin. Remediation activities, which have been under way in Cement Creek since 1991, accompanied by treatment of the discharge from the American tunnel (site #96, Fig. 13) may explain the weak relationship among concentration, stream flow, and seasonality for the target metals—cadmium, copper, and zinc. The valve on the first American tunnel bulkhead (site #96) was closed in September 1996. The second bulkhead in the American tunnel (site #116) was sealed in August 2002. Treatment of Cement Creek upstream from the American tunnel (site #96) began in the fall of 1996 and continued through the non-runoff periods through 1999. Treatment during this period resulted in very significant reductions in mean metal concentrations (Fig. 15). The permit for the American tunnel was transferred to the Gold King mine in December 2002. Gold King continued to treat the remaining discharge from the American tunnel through May 2003. The mine pool in the Sunnyside mine reached equilibrium by November 2000; however, this was preceded by a large increase in the volume of flow from the Mogul mine (site #31) in 1999 causing a bulkhead to be placed in that portal in 2003. The Sunnyside mine pool related mitigations were completed in 2001. Remediation has occurred at 15 sites in the basin (Fig. 13; Table 5). Projects in the Cement Creek basin since October 1996 include hydrologic runon/runoff controls at Gold King mine (site #111), Joe and Johns mine (site #87), Lark mine (site #86), and Mayday mine (site #181). Settling ponds and runon/runoff controls were constructed in 1998 at the Mammoth mine (site #148). Runon/runoff controls and complete removal of mine wastes at the Hercules and Galena Queen mines (sites #82 and #83) were completed in 2001. A passive treatment system consisted of aerobic limestone drains, and settling ponds were implemented at the Elk tunnel (site #147) in 2003.

Dissolved cadmium (not shown) decreased significantly following initial treatment of Cement Creek. A series of high cadmium concentrations from July 1999 through November 1999 caused the 12-period moving average to rise above the baseline condition. This was repeated in 2000 but to a lesser degree. The near baseline condition was reached in 2002, but a steady trend upward beginning in 2003 found the average cadmium concentration to be 1.7 µg/L higher through November 10, 2004, than during the baseline period.

The dissolved copper concentration (Fig. 15A) has fluctuated around the baseline condition except for short periods in 1997 and 1999. Exceptionally high copper concentrations were measured from August 1999 through November 1999. Dissolved copper exceeded three standard deviations on four out of seven sampled dates in that time period.

The dissolved zinc concentration (Fig. 15B) decreased over 250 µg/L following closure of the American tunnel and treatment of upper Cement Creek through late 1998. The zinc concentration increased through 1999 reaching a maximum of nearly 300 µg/L higher than the baseline concentration by early 2000. The zinc concentration then declined to baseline concentration through early 2003. The zinc concentration was 341 µg/L higher than the baseline concentration in November 2004.

The concentration of dissolved manganese (Fig. 15C) was reduced over 500 µg/L, on the average, at C48 from the time treatment began until the summer of 2002. By November 10, 2004, manganese concentrations had returned to the baseline concentration.

The 12-period moving average total recoverable aluminum (not shown) concentration dropped more than 900 µg/L below the baseline condition for the first eight months following the closing of the American tunnel and initiation of treatment of Cement Creek. The average concentration remained less than

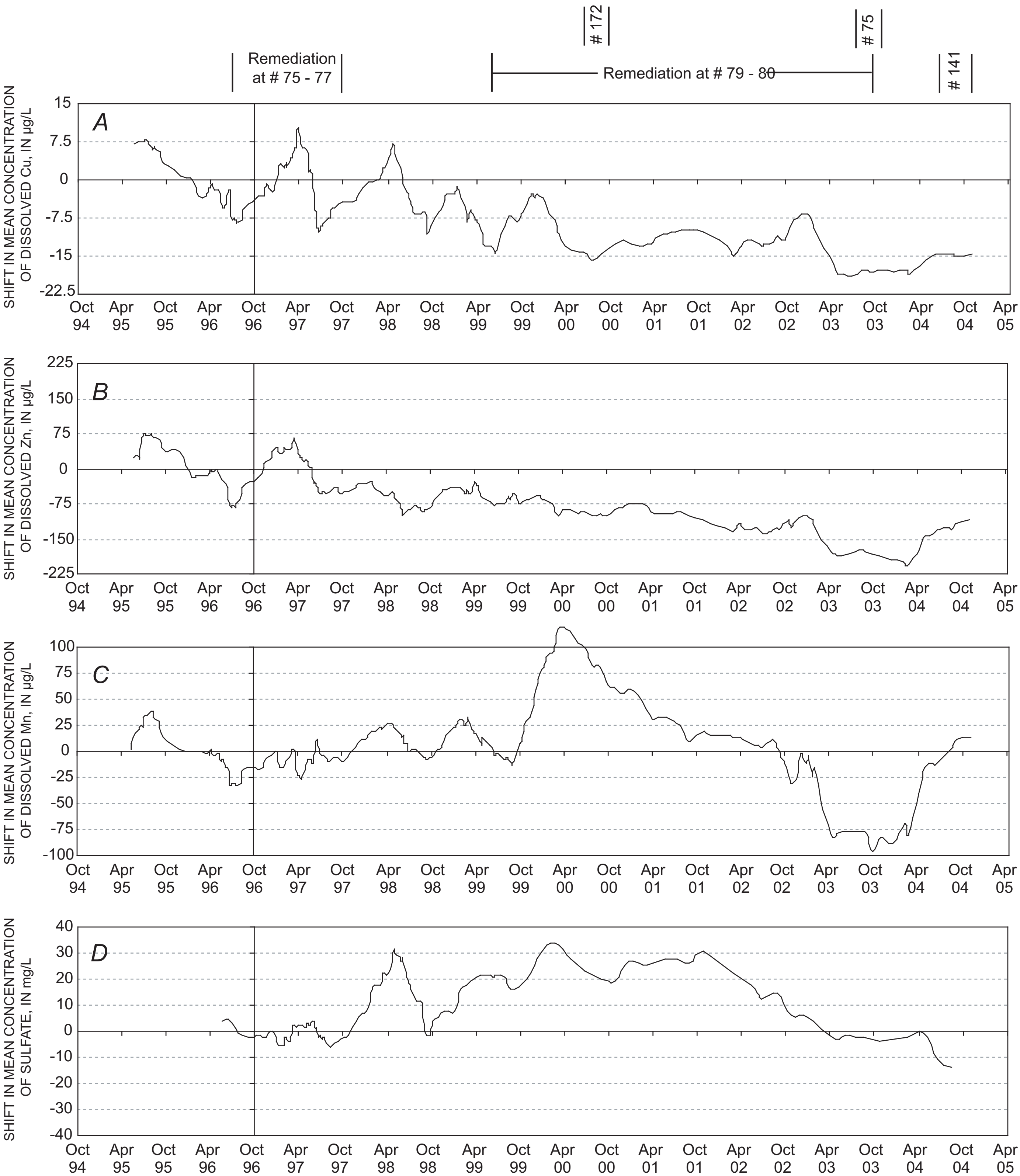

Figure 14. Twelve-sample moving average concentration determined from monitoring data: dissolved copper concentrations (A); dissolved zinc concentrations (B); dissolved manganese concentrations (C); and sulfate concentrations (D) measured at the gauge on Mineral Creek (M34, Fig. 13), 1994–2004. Baseline concentrations determined from monitoring data collected from 1994 to 1996.

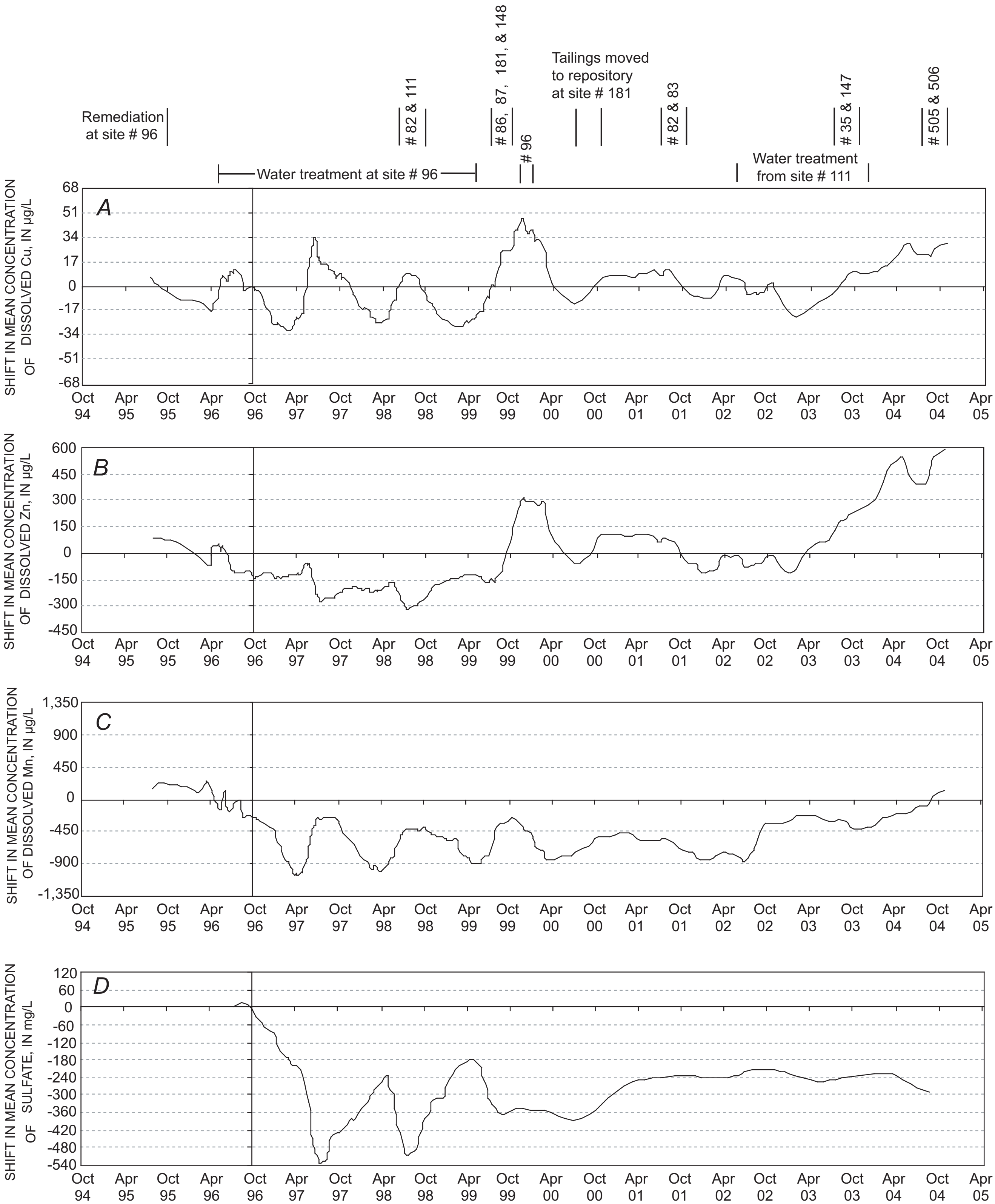

Figure 15. Twelve-sample moving average concentration determined from monitoring data for dissolved copper concentrations (A); dissolved zinc concentrations (B); dissolved manganese concentrations (C); and sulfate concentrations (D) measured at the gauge on Cement Creek (C48, Fig. 13), 1994–2004. Baseline concentrations determined from monitoring data collected from 1994 to 1996.

the baseline period through the spring of 1999. By the fall of 1999 the average concentration peaked at over 1000 μg/L higher than the baseline period. Total recoverable aluminum has fluctuated around the baseline concentration since it reached a peak in 1999 following cessation of treatment at Gladstone (site #96).

Total recoverable iron (not shown) has exceeded the baseline condition since the spring of 1999. Peak iron concentrations were reached in the spring of 2001. Although the 12-period moving average iron concentration through November 10, 2004, was nearly 1900 μg/L higher than the baseline period, total recoverable iron concentration has been decreasing toward the baseline condition since the peak was reached in 1999.

The concentration of sulfate (Fig. 15D) dropped substantially with the closing of the valve on the bulkhead in the American tunnel and remained at –240 mg/L as of November 10, 2004.

Upper Animas River Basin

The upper Animas River supports several species of trout; however, tracer studies have shown that the upper Animas River basin is the major loader for manganese and zinc (Figs. 8 and 9), both of which are soluble at the pH of water (Fig. 7). Remedial activities initiated by Sunnyside Gold Corp. began in 1991 (Table 5). These include closure of mill-tailings sites at their Mayflower Mill (sites 507–509; Fig. 13), removal of mill wastes from the Gladstone area (site #95, Fig. 13), and repair of the collapse of Lake Emma into the Sunnyside mine, which occurred in 1978 (site #116, Fig. 13; Jones, 2007). Major long-term remediation work has continued at the Mayflower Mill tailings sites 507–510 (Table 5; Fig. 13) to reduce the amount of metal added to the ground-water table by leaching from the mill tailings repositories. In addition, remediation work has been conducted at 11 additional sites (Fig. 13; Table 5) since October 1996. They include the removal of 112,000 cubic yards of tailings from the floodplain around Eureka (site #164), which was completed in 1997, and removal of 84,000 cubic yards of tailings from the floodplain at Howardsville (site #234), also completed in 1997. Mine waste or mill tailings were removed from Boulder Creek (released from site #509), Gold Prince mine (site #49), and Lakawanna Mill (sites #181 and #286). Passive treatment of adit discharge from the Forest Queen (site #195) was completed in 1999 (Table 5). Bulkhead seals were placed in the Ransom mine (site #161), the Terry tunnel (site #120), and the Gold Prince mine (site #49). Hydrologic runon/runoff controls were implemented at the Silver Wing mine (site #125).

Dissolved copper (Fig. 16A) has generally fluctuated around the baseline condition except for summer periods in 1997 and 1998 when the concentration was lower than expected.

The peaks and valleys of dissolved zinc at A68 (Fig. 16B) follow the same general pattern as those of cadmium and manganese; however, for the most part it has stayed relatively close to the baseline condition. The largest shift in the 12-period mean was nearly +300 μg/L following implementation of the consent decree (1997). The second year following the consent decree, a high of around +200 μg/L was reached. The concentration fluctuated around the mean through 2001 and then declined dramatically during the 2002 drought. This was followed by an increase to over +150 μg/L in late 2002 and early 2003. Since then the concentration has decreased to the baseline condition.

Dissolved manganese (Fig. 16C) has consistently been higher than the baseline condition since the start of remediation activities in 1996. Brief declines were noted in the summers of 1997, 1998, and 2002; however, for most of the post-consent-decree period concentrations have been more than 800 μg/L higher than baseline. The concentration appears to be in a steady decline since the spring of 2003, but through November 10, 2004, it remained over 600 μg/L above the baseline.

The declines in dissolved cadmium, copper, and zinc following the 2002 low runoff followed by steep increases in 2003 suggest that several years of weathered material accumulated and was washed off during the more normal runoff in 2003. It does not appear that either cadmium or manganese have reached an equilibrium condition following the remediation activities that have been accomplished upstream from the gauge at A68.

Total recoverable aluminum and iron are well within water-quality standards and were not analyzed at A68. Dissolved cadmium (not shown) has consistently been higher than the baseline condition except during the summers of 1998 and 2002. The highest concentrations were reached in 1997 following implementation of the consent decree, when significant remediation related disturbance occurred, and in the spring of 2003 following the 2002 drought. Since the spring of 2003, the cadmium concentration appears to be declining toward the baseline; however, cadmium was still ~0.7 μg/L higher than baseline through November 10, 2004.

Animas River Watershed

The gauge at A72 (Fig. 13) is the compliance point established by the State of Colorado for the Sunnyside Gold, Inc. consent decree. Four segments in the watershed were identified in Colorado's water-quality impaired 1998 303(d) list. The Colorado Water Quality Control Commission established water-quality goals for six parameters (Al, Cd, Cu, Fe, Mn, and Zn) and adopted total maximum daily loads in 2002 aimed at attaining aquatic life use classifications for the segments where they adopted those classifications. Water quality at A72 integrates the effects of remediation upstream from A68, C48, and M34. Total recoverable aluminum and iron were not monitored at A72 during 2000, 2001, and most of 2002; however, the data collected in 2003 and 2004 suggest that the concentration of these constituents has not changed from the baseline condition.

The dissolved cadmium concentration (not shown) generally fluctuated around the baseline period except immediately following the start of the remediation period and during the 2002 drought. By November 2004, the cadmium concentration was at the approximate baseline concentration (1.9 ± 0.64 μg/L).

The dissolved copper concentration (Fig. 17A) was generally lower than the baseline concentration in the late 1990s and

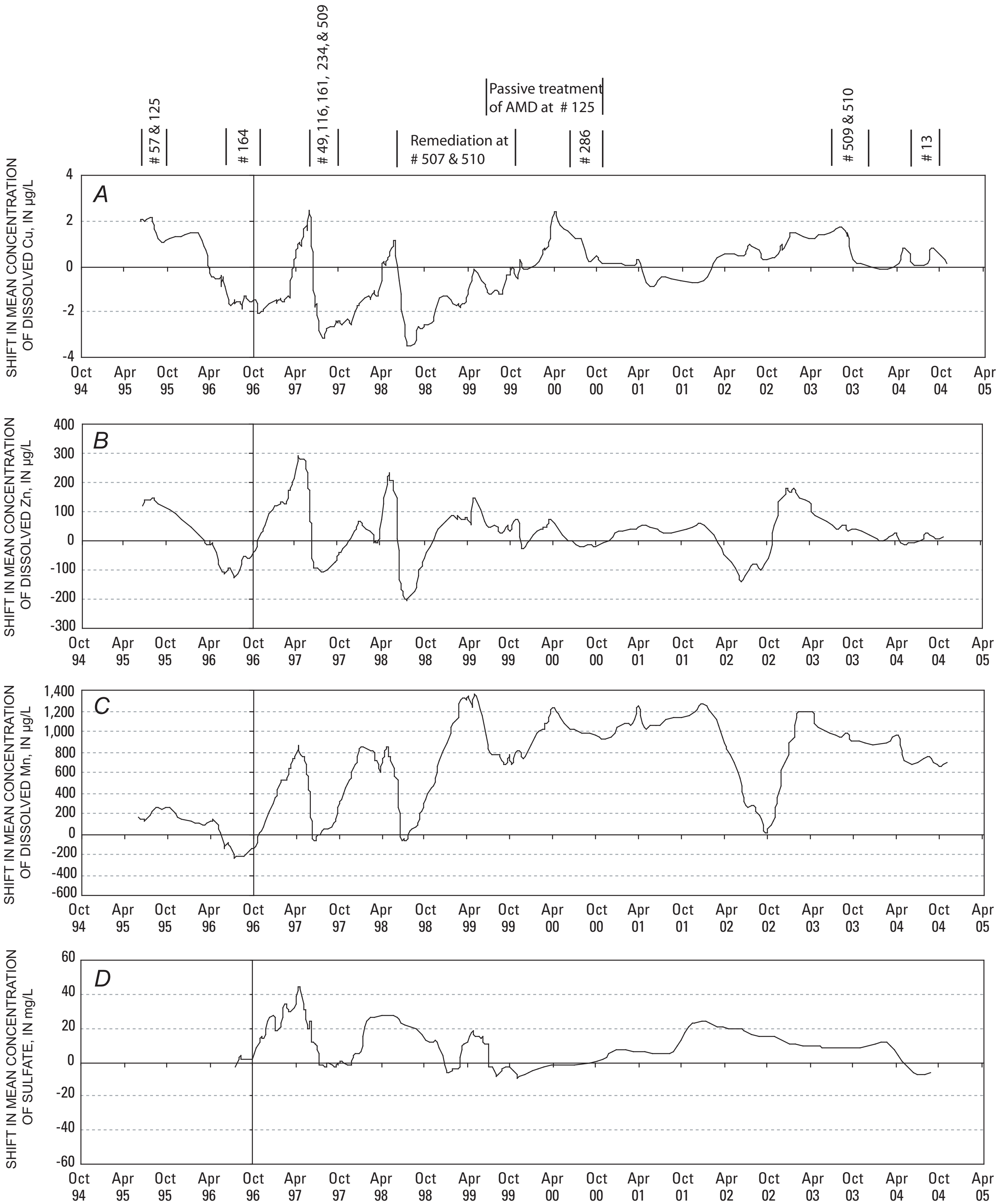

Figure 16. Twelve-sample moving average concentration determined from monitoring data for dissolved copper concentrations (A); dissolved zinc concentrations (B); dissolved manganese concentrations (C); and sulfate concentrations (D), measured at the gauge on the upper Animas River upstream from the confluence with Cement Creek (A68, Fig. 13), 1994–2004. Baseline concentrations determined from monitoring data collected from 1994 to 1996.

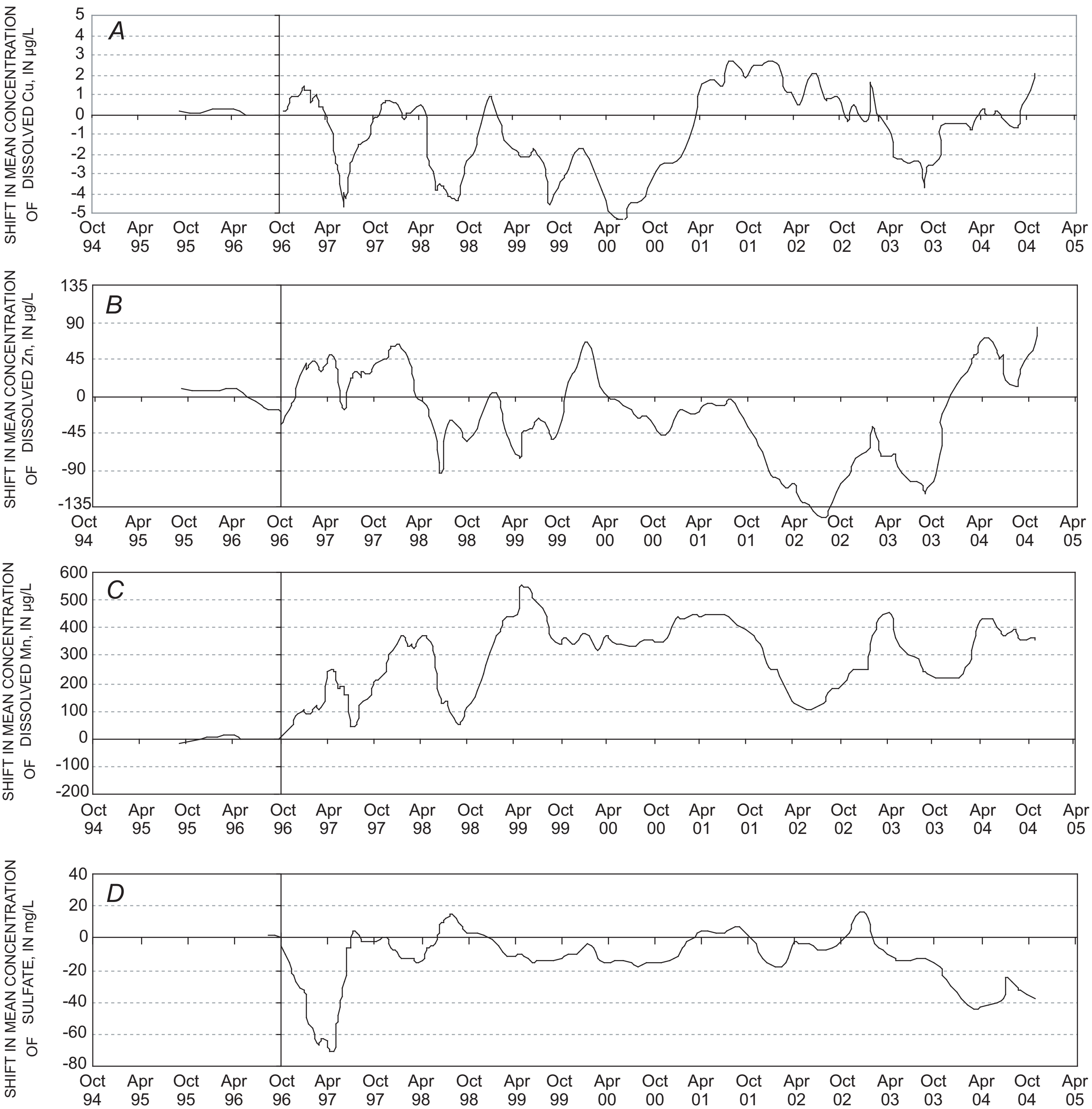

Figure 17. Twelve-sample moving average concentration determined from monitoring data for dissolved copper concentrations (A); dissolved zinc concentrations (B); dissolved manganese concentrations (C); and sulfate concentrations (D) measured at the gauge on the Animas River upstream from the confluence with Mineral Creek (A72, Fig. 13), 1994–2004. A72 is the compliance point for water-quality standards established by the Colorado Water Quality Control Commission. Baseline concentrations determined from monitoring data collected from 1991 to 1996.

during the 2002 drought, but it has increased slightly with time to +2 µg/L in November 2004.

There has been a large upward shift in the zinc concentration at A72 (Fig. 17B). The zinc concentration spiked in the late summer of 1999 and has gone from showing improvement of –90 µg/L in 2002/2003 to nearly +90 µg/L during 2004. The most likely source of the increase in zinc concentration is the increased zinc load from Cement Creek. Timing of the increase in zinc concentration corresponds well with the increase in zinc concentration in Cement Creek (Fig. 15B). Moreover, there has been no measurable change in zinc concentration at A68 (Fig. 16B), and the zinc concentration has been significantly reduced in Mineral Creek (M34; Fig. 14B).

Manganese concentration continues to be higher than those observed before remediation activities began (Fig. 17C), but recently the manganese concentration has declined in the direction of previous baseline concentration. The increase in manganese concentration at A72 is most likely the result of remediation and removal of the high-manganese tailings at site #164 and at the Mayflower Mill tailings impoundments (sites #507–510, Fig. 13) upstream from A68. Changes in the manganese concentration at C48 (Fig. 15C) and M34 (Fig. 14C) have been small.

Sulfate concentration (Fig. 17D) at A72 showed only minor changes relative to the 1991–1996 baseline concentration through early 2003. However, the sulfate concentration has decreased by about 30 mg/L in 2004.

CONCLUSIONS

The monitoring results indicate that remediation using the watershed approach, that is, focusing remediation on mine sites where it will have the largest effect on water quality, is the most cost-effective approach to improvement of water quality in a watershed affected by historical mining. Although half of the very-high priority sites on federal lands identified by Nash and Fey (2007) and by Kimball et al. (2007) have been addressed, and 23% of sites identified by both the ARSG and the USGS have been remediated through various engineering options, only small long-term gains in water quality have been demonstrated to date by the water-quality data analysis. Individual sites have responded to the remediation work done, as evidenced by the improved water chemistry at individual sites (W. Simon, pers. comm., 2003). Remediation work conducted by the federal agencies, the ARSG, and Sunnyside Gold, Inc. has addressed water-quality issues caused by some of the largest sites in the watershed. Steady improvement in water quality should continue as the effect of disturbances caused by the remediation activities' decline. Some recovery of the aquatic life in designated stream reaches has begun to occur. Recovery of the watershed to premining conditions is not an attainable goal because not all anthropogenic sources can be treated in a cost-effective manner. A substantial amount of the metal load in the surface drainages is derived simply from weathering of hydrothermally altered rock that has not been disturbed by mining (i.e., simply from weathering). As shown in the discussion of the tracer results (Fig. 9), 13–29% of the copper and zinc loads comes from these dispersed sources. Given that so many point sources have not been remediated, documenting the recovery curve for aquatic life in surface streams remains elusive while public funding for remediation activities has become more difficult to obtain due to increased demand. Continued remediation efforts should result in progressively smaller gains in water quality. Continued remediation work by the ARSG is necessary to achieve the water-quality standards set by the Colorado Water Quality Control Commission at site A72.

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