Mine Adits, Mine-Waste Dumps, and Mill Tailings as Sources of Contamination

By J. Thomas Nash and David L. Fey

Chapter E6 of

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Abstract

The long history of exploration and mining in the upper Animas River basin has produced thousands of prospects and now-inactive mines that range in size from small exploration pits to large mines with tens of miles of workings and mine waste with a corresponding range in size. The recovery of metals required the milling of 18.6 million tons of ore that created large volumes of mill tailings, part of which were placed in streams, or placed in impoundments after 1935. The high precipitation—particularly snowfall—in this area infiltrates mine workings, mine-waste dumps, and mill tailings to create acidic drainage that in places carries high concentrations of metals. To characterize the magnitude of acidic drainage and the concentrations of contaminants, we sampled 97 mine-waste sites, 18 mill-tailings sites, and 60 mine-adit drainages—the most significant ones that we could identify on public lands. Detailed descriptions of the geochemical determinations made on mine water and mine waste enabled us to rank sites for their potential to contaminate the watershed. We utilized three scores—acid generation, metal release in leach tests, and size—to rank waste dumps and mill tailings. For mine-adit water, we utilized metal-loading scores for copper and zinc to rank the potential to contaminate water and degrade aquatic habitat.

Our geochemical characterization results and rankings of sites suggest a wide range in potential to contaminate the watershed. Out of the more than 500 identified sites on public land, only about 40 sites have sufficient size, adit discharge, or waste reactivity to be significant sources of contamination. Sites that have high rankings as sources and those identified by tracer studies of the main streams deserve attention for remediation work.

Introduction

Degraded water quality in streams of the Animas River watershed study area is well documented (Church and others, 1997; J.R. Owen, Unpublished report on water quality and sources of metal loading to the upper Animas River Basin, Colorado Department of Public Health, Water Quality Control Division, 1997; Kimball and others, this volume, Chapter E9; Wright, Simon, and others, this volume, Chapter E10), but the sources of the contaminants are numerous and difficult to quantify. Mining at large and small mines and excavating at countless prospects have disturbed millions of tons of mineralized rock in the Silverton area and resulted in chemical reactions that release acid and metals to receiving waters in the watershed. In this chapter we describe sources of contaminants from inactive mines, mine-waste dumps, and mill tailings that are on public land. The larger sources of contaminants from mining on lands administered by the U.S. Bureau of Land Management (BLM) and United States Department of Agriculture (USDA) Forest Service have been previously described by Nash (1999a, 1999b).

Although biologic criteria drive the standards for desired water quality in the Animas River watershed study area (Besser and others, this volume, Chapter D; Besser and Leib, this volume, Chapter E19), chemical methods are routinely used to measure water quality relative to biologic standards. In this study we used field and laboratory methods to obtain chemical analyses of mine-drainage water that can be evaluated in the context of water-quality standards. In addition, leach tests of mine waste (Fey, Desborough, and Church, 2000) provide a measure of *potential* for acid generation and metal release; those test results can be used to evaluate which waste materials are most reactive and possibly in need of remediation. Whereas leach tests provide reproducible and reliable chemical measurements, physical factors at the site such as the amount of rain and snowfall and the permeability of waste material can affect numerical estimates of potential acid or metals sources. The actual water quality measured from a mine adit or below a mine-waste dump is emphasized in this report because that is a real measure of conditions at a site. However, even these determinations are only an approximation of the effect on the watershed because they do not include processes that may improve or further degrade water quality after it leaves the mine adit, mill, or dump site. Whereas reactions of mine-adit water with mine-waste materials commonly add acid and metals to water, beneficial reactions with wallrocks and mixing of mine-adit drainage with shallow ground water commonly improve water quality before the mine-related water enters a stream (Nash, 2002; Plumlee and others, 1999). Water-quality investigations by Kimball and others (this volume) indicate that only a few of the sites on public land described here provide major contributions of mine drainage to the major streams of the study area.

Purpose and Scope

The purpose of this study was to describe the magnitude of contamination contributed by mines (mine-adit water), mine-waste dumps, and mill tailings on public land.

1. Field observations and sampling were designed to obtain representative information for mine sites on public land and to compare and rank them as sources of contamination. A limited number of samples were collected at private sites, with the owner's permission. Mines with no road access and located more than about 2 mi from streams were not sampled because this situation was considered not amenable to remediation.

2. Sites were visited a second time for additional observations and sampling if the initial samples suggested a substantial source of contaminants.

3. Mine and mill-tailings sites were evaluated by two class-based ranking methods, rather than by numerical methods, to address uncertainties in field measurements and sampling.

Field Methods

Mine-waste and mill-tailings samples were collected with a protocol designed to provide a statistically reliable, representative sample of the upper 30 cm of a waste pile by combining 30 or more subsamples taken at uniform intervals across the pile and sieving through a 2-mm screen (Smith, Ramsey, and Hageman, 2000). Field studies from 1996 to 2000 included one or more visits to more than 300 sites (mines or prospects). At some sites we collected replicate samples at the same time, by a second sampler, or else during the following year. A total of 173 mine-waste dump and mill-tailings samples were collected from 97 mine-waste dump sites and 18 mill-tailings sites, most of which are on public land. Sites with mine-waste dumps smaller than approximately 100 tons generally were not sampled. Twenty samples of unmined, altered rock were also collected. Representative samples of dump rocks and mill tailings from 113 sites were analyzed chemically. A total of 193 samples of mine-waste dump material, mill tailings, and altered rocks were studied using a passive leach method. Laboratory methods used in leach tests of mine waste and rock are described by Fey, Desborough, and Church (2000), and analytical results are reported in Fey, Nash, and others (2000).

Water samples were collected using a simplified method described by Ficklin and Mosier (1999); we used a disposable 60 mL syringe and 0.45 µm (micrometer) cellulose filter and the addition of ultrapure nitric acid to stabilize metals until analysis by inductively coupled plasma–mass spectroscopy (ICP-MS) and inductively coupled plasma–atomic emission spectroscopy (ICP-AES) (Nash, 1999a; Nash, 2002). The analytical results for our samples of mine-adit drainage water and mineralized surface water are reported in the database (Sole and others, this volume, Chapter G). All adits on public land known to have flowing mine drainage were sampled, along with a limited number of samples from private sites for comparison. All water samples were collected in August or September, during low-flow conditions (as defined by von Guerard and others, this volume, Chapter B).

Discharge at mine portals, an important parameter in metal load calculations, is not easily measured. Discharges were measured carefully by Mast and others (2000), but in our work were based simply on a visual estimate by Nash. Herron and others (Jim Herron, Bruce Stover, and Paul Krabacher, Unpublished Lower Animas River reclamation feasibility report, Upper Animas River Basin, Colorado Division of Mines and Geology, 2000, and similar reports for Mineral Creek, Cement Creek, and Upper Animas River reclamation, 1997, 1998, and 1998) determined mine-adit drainage discharges using a portable weir. Comparison of the estimates by Nash with discharges measured by Mast and others (2000) at the same sites for similar dates suggests that the differences are between about 20 and 50 percent. We emphasize that all measurements and estimates at mine portals are minimum values, because water commonly is lost into alluvium or into fractures in bedrock. This is evident at sites discussed later, including Grand Mogul (mine # 35, caved adit, with flow through a waste dump on alluvium), the Lark and the Joe and Johns (mines # 86 and # 87, with caved adits on alluvium), and the Bandora (mine # 332, with caved adit on mine-waste dump and talus). Because of the loss of mine water through alluvium and bedrock fractures, discharge values used in this report may err on the low side by 25–75 percent at some sites. The effect of these errors in the calculated loads, discussed later, is not easily computed but could be large for the absolute values. However, because we use ranked metal-load score classes, the relative scores are less affected by erroneous discharge values than would be numerical scores. They could change the ranking score by as much as one class (for example, "very high" would be "high").

Site names are those in Church, Mast, and others (this volume, Chapter E5) insofar as possible, but many small mines and prospects on BLM land do not have accepted names. For those sites we use the numeric code employed by Hite (Barbara Hite, Unpublished mine land inventory report for the U.S. Bureau of Land Management, U.S. Bureau of Mines, 1995) with the prefix B, such as B015.

Mineral Deposits Classification and Changes in Mining Technology

Mineral deposits of the Animas River watershed study area and vicinity can be considered to be of just a few types, or they can be split into many subtypes for special purposes such as economic geology or mining engineering (Burbank and Luedke, 1969; Casadevall and Ohmoto, 1977; Guilbert and Park, 1986; Bove and others, this volume, Chapter E3). For the purposes of this report, we used a simple three-part classification of deposits.

1. Polymetallic veins, rich in pyrite, and having variable proportions of chalcopyrite, galena, sphalerite, and gold- and silver-bearing sulf-arsenide minerals as in the Sunnyside mine and the majority of mines and prospects in the study area. These deposits tend to be along major faults inside and outside the Silverton caldera that have moderate argillic alteration halos of pyrite and clay minerals 5–10 m wide (Bove and others, this volume). Manganese minerals (pyroxmangite and rhodochrosite) are locally abundant in some veins, and tungsten (as wolframite, an iron-tungsten-oxide) and fluorine (fluorite) are abundant in some places.

2. Polymetallic breccia pipes, similar in composition to the veins but tending to be richer in sulfide and arsenide minerals, as at the Lark mine (mine # 86, Prospect Gulch) and National Belle mine (northwest of the study area, at Red Mountain Pass). These deposits are restricted to the caldera fault zone, are highly localized as intense bodies of alteration and ore minerals, and are associated with broad alteration halos of the acid-sulfate type with disseminated pyrite-alunite-clay minerals, as in the Red Mountain area (Bove and others, this volume). “Polymetallic” is an appropriate descriptor for virtually all of the deposits of the Animas River watershed study area because many base metals and metalloids (collectively called metals for simplicity) are concentrated in these deposits, even if miners emphasized silver, gold, copper, lead, or zinc for economic reasons.

3. Porphyry deposits containing shattered zones filled by copper-molybdenum quartz-sulfide veinlets, as, the peak 3,792 m and Anvil Mountain areas; these mineralized areas, having large vertical and horizontal dimensions, have been drilled, but none has been mined in this area. Weathering of pyrite in the peripheral alteration halo is a source of acidic drainage today (Yager and others, 2000; Bove and others, 2000; Bove and others, this volume).

Placer deposits of gold in alluvial gravel were mined in a few places such as Arrastra Creek; placer deposits will not be mentioned further, as they were small and made only a minor contribution to the total production in the watershed. They are, however, a reminder that mineralized rocks and veins contributed metals to streams of the area prior to mining activity. Studies by Church, Fey, and Unruh (this volume, Chapter E12) have shown elevated metal concentrations in premining sediment collected throughout the watershed.

Changes in mining and milling technology through the years have had important influences on the materials left behind in the mines or placed on mine-waste dumps and mill-tailings piles (Jones, this volume, Chapter C). In the watershed at least two stages of technology can be highlighted:

1. Early (1871–1913), small-volume mining of high-grade ore zones, with small associated milling infrastructure. The miners lacked powered equipment, created very narrow stopes, and generally brought only hand-picked high-grade ore to the surface. Mine-waste dumps were small relative to the amount of ore removed.

2. Later (after 1913), increasingly large scale mining of lower grade ores was made possible by consolidation of workings, availability of electric- and pneumatic-powered machines, and new milling technology. Selective flotation was developed to recover specific sulfide minerals. The change in milling style was first made at Sunnyside with a new flotation mill built in 1917. Zinc, one of the toxic metals of prime concern in the Animas River (Besser and Brumbaugh, this volume, Chapter E18), was not deemed economic and therefore not recovered before 1904. Significant amounts of zinc are found in all of the ores and mine-waste dumps, and zinc-rich materials were intentionally left underground in many of the older workings because smelters levied a surcharge if the concentrates contained more than 10 percent sphalerite (Ransome, 1901). In this stage, mine tunnels became many miles in length (some crossing under natural drainage divides), tramways were used to carry distant ore to centralized mills, and large mine-waste dumps and mill-tailings piles were made. Tailings handling policies changed in 1935 when regulations required that mill tailings be confined to so-called “tailings ponds” rather than be allowed to go directly into surface streams (Chase and Kentro, 1938). The very large (millions of cubic yards) tailings piles of some of the large mills in the region are physically stable today (the older ones as at Eureka were breached during storm events; Vincent and Elliott, this volume, Chapter E22). Their contents remain a matter of study and concern, however, because the piles were not built on impermeable pads (thus infiltrating water can escape through the base into alluvium). This brief review of the history and technology of mineral extraction in the study area is a reminder that individual site evaluations must consider the mode of mining and milling used at the site before remediation technologies are considered.

Geochemical Characterization of Mining-Related Contamination

Passive Leach Tests and Rankings

Two procedures for determining leachable metals in mine waste and other material were applied to samples in this study. One of the leaching methods was the EPA-1312 protocol, which involves mixing mine-waste material with a dilute-acid extractant and tumbling for 18 hr. This procedure is designed to approximate the effect of rainfall on mine-waste material (U.S. Environmental Protection Agency (USEPA), 1986). Because the EPA-1312 procedure is more labor intensive than the passive leach described in the next section, it was not applied to all samples from this study. Results of the EPA-1312 method are not described here but are compared with results of other methods in Fey, Nash, and others (2000). Results for the EPA-1312 leach are in Fey, Nash, and others (2000) and in the database (Sole and others, this volume). The passive leach method, developed by Desborough and Fey (1997), is a simpler approach to determining leachable metals and was applied to all samples from sites described here. A chemical ranking method utilizing the pH and soluble metals derived from the passive leach was described in Desborough and Fey (1997) and was applied in this study.

The passive leach method was applied to samples collected in the 1997, 1998, and 1999 field seasons. Selected results for some of the more significant sites on public land are presented here. In the passive leach tests, a 100-g sample was exposed to 2L of laboratory de-ionized water (pH of 5.0±0.2) in an open 4L beaker, resulting in a sample/extractant ratio of 1:20. Samples were left at rest for 1 hr, and then gently stirred for 5 s (seconds) to prevent stratification of the leachate. The pH of the leachate was measured after 24 hr and then a 60 mL sample of the leachate was filtered through a Gelman 0.45-µm (micrometer) filter using a disposable 60 mL syringe, acidified with 6 drops of ultra-pure HNO_3, and refrigerated prior to analysis by ICP-MS.

Results from the passive leach tests show that the mine-waste materials generate a wide range of metal concentrations and pH values (table 1; fig. 1). The metal concentrations in the leachate solutions are a measure of the mobile metals in the sample, and the leachate pH is one measure of the acidity generated by the sample. The acidity produced in the passive leach is predominantly from the dissolution of water-soluble acid salts. These salts are mostly hydrous iron sulfate salts such as melanterite ($FeSO_4 \bullet 7H_2O$), copiapite ($(Fe, Mg)Fe_4(SO_4)_6(OH)_2 \bullet 20H_2O$) and jarosite ($KFe_3(SO_4)_2(OH)_6$), formed as a result of the oxidation of pyrite (FeS_2) and other sulfides in the waste material. To characterize and rank the waste materials, we utilized the method of Desborough and Fey (1997), with slight modification, which assigns scores for pH and summed metal concentrations $\Sigma(As+Cd+Cu+Pb+Zn$, in µg/L). For pH values greater than 6.0, a score of 0 is given; for pH between 4.5 and 6.0, the score is 1; for pH between 3.5 and 4.5, the score is 2; and for pH less than 3.5, the score is 3. Similarly for summed metal content, scores are assigned as follows: less than 500 µg/L, 0; between 500 and 1,000 µg/L, 1; between 1,000 and 5,000 µg/L, 2; and greater than 5,000 µg/L, 3. Because both acid generation and metal release are significant characteristics of mine waste, we added the factors to represent the relative chemical potential for waste to adversely affect water quality. These chemical score values are shown in figure 1. For example, samples plotting in the upper left field of figure 1 score a six (three from the low pH, and three from the summed metals), and have the most potential for adversely affecting water quality. Sum scores of two, three, four, or five may result from the different possible combinations of pH and summed metal scores. Note that no samples plot in the upper three fields on the right hand side of the figure, where the high pH limits the concentrations of metals in the leachates. Although mine-adit drainage water or leachate solutions with high pH can have substantial zinc concentrations, none of our waste sample leachates had both high pH and high zinc concentrations.

The size of a mine-waste dump is also significant in estimation of its potential for contamination and should be included in the waste ranking. Size, in (2,000 lb) tons, was calculated from field estimates of length, width, and thickness; uncertainties in dump geometry and waste density suggest that the size value carries an error of roughly ±25 percent. We utilized five size categories to cover the large range in dump sizes in the study area, ranging from 1 (less than 300 tons)

Table 1. Summary of leachate chemistry for mine waste and mill tailings.

[pH in standard units; elements in µg/L (micrograms per liter)]

	pH	Al	As	Cd	Cu	Fe	Mn	Pb	Zn
				Dump samples (*n*=150)					
Minimum	2.28	0.60	0.04	0.02	0.40	0.20	5.2	0.020	0.50
Median	3.44	150	1.20	5.50	28	500	188	120	300
Maximum	8.13	14,000	3,570	165	6,960	144,000	37,400	30,000	30,900
				Mill tailings (*n*=25)					
Minimum	2.57	0.10	0.20	0.02	1.0	30	6.7	0.06	0.70
Median	3.90	11	0.30	14	111	35	405	8,000	1,710
Maximum	7.78	6,400	3.5	95	1,500	55,000	20,000	31,000	25,200

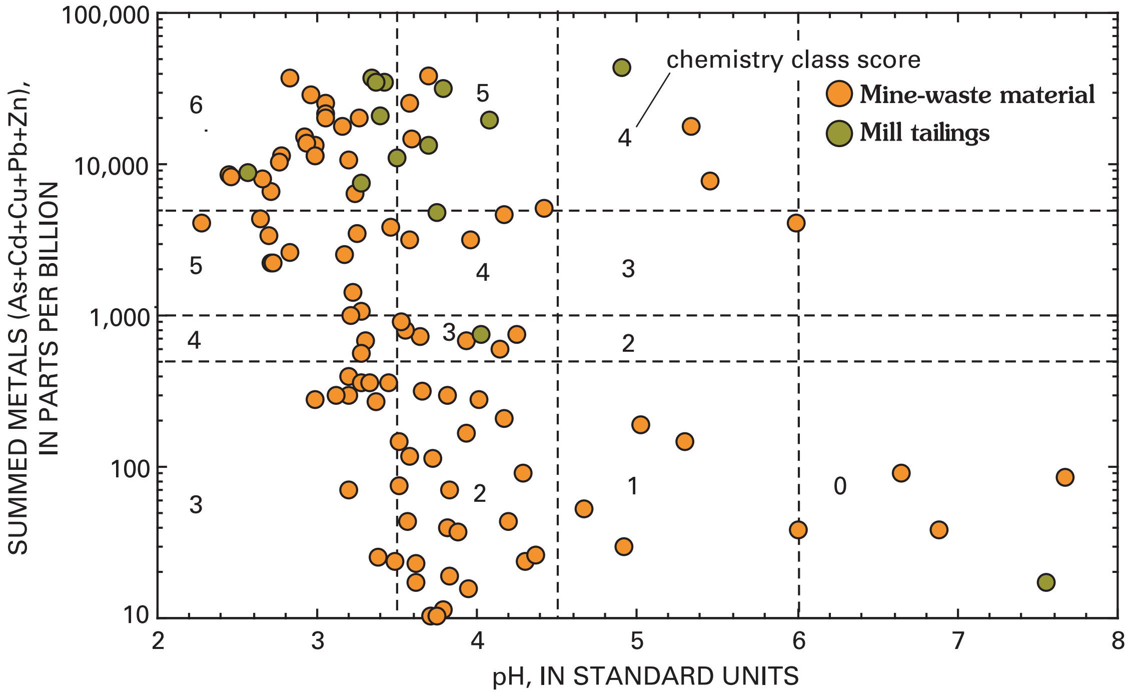


Figure 1. Composition of leachate solutions and classification of mine waste.

to 5 (greater than 50,000 tons), as shown in table 2. An overall *mine-waste score* is obtained by multiplying the dump size score by the chemistry score (sum of the pH and metal scores). Not included in the waste score are other factors such as proximity to stream, surface water flowing across waste material, draining adit water contacting waste material, proximity to ground water, substrate hydrologic conductivity, or other factors that are known to influence mine-related contamination—these attributes are considered in the verbal site descriptions later in this chapter. Finally, the mine-waste scores are converted into five classes that we define as *mine-waste rank*. The five mine-waste ranks, from “low” to “very high,” connote the approximate potential to create contamination. Each of the three parameters in the waste score carries uncertainty and error; a numerical value was not used because it might appear to be more precise than its constituent measurements could support. The locations and rankings of mine-waste dump sites on public land are in figure 2.

Geochemistry of Mill Tailings and Tailings Drainage

Mills were numerous in the Animas River watershed study area, especially along the upper Animas River where waterpower was abundant and railroad transportation available (Jones, this volume). Physical evidence remains for more than 50 mills and about 23 mill-tailings sites (Nash, 2000). Mills and associated mill-tailings impoundments fall into three stages of operation: (1) early stage (pre-1913) relatively small stamp mills and unconfined mill tailings that were mostly lost to the nearby river (either poured into the river or washed away during storms); (2) middle stage (c. 1913–1935), larger mills that used flotation to recover zinc and created larger mill-tailings impoundments, many of which failed during major storm events; and (3) late stage (post-1935), large mills that placed tailings into designed impoundments after the Executive Order in 1935 instituted regulations on mill-tailings disposal; most of these tailings are in place today. Tailings from early stage 1 mills are not candidates for remediation because they have been dispersed downstream, where they contribute to the postmining baseline geochemistry of the watershed. Some of the stage 2 tailings pose problems today, either in place or as overbank fluvial deposits transported by flood water (Vincent and Elliott, this volume; Vincent and others, 1999). Some fluvial mill tailings have been reclaimed, such as those south of Eureka. Stage 3 mill tailings, notably the large tailings impoundments of the Mayflower mill, are mostly in place (Jones, this volume).

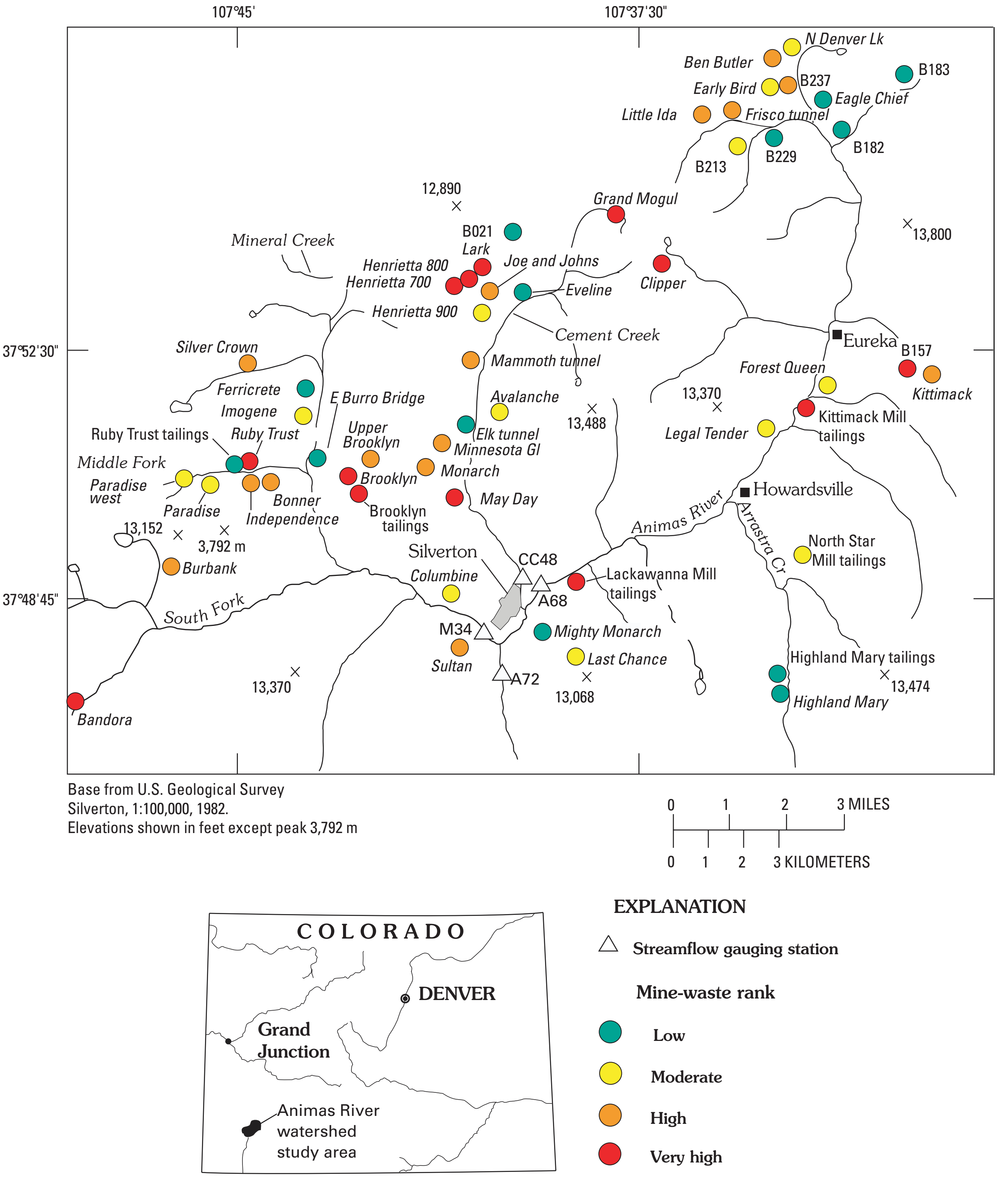
One estimate of the potential for contamination from mill tailings comes from leach tests. In our studies of 20 representative mill-tailings samples, half of the samples created leachate solutions of high acidity (pH <3.6), and these acidic solutions contained high to very high concentrations of cadmium, copper, lead, zinc, and other metals (fig. 1).

Samples of water that has reacted with mill tailings are difficult to obtain because seeps from tailings impoundments are rare in this area. In places one can collect pore water from within impounded mill tailings (from an auger hole) or water seeping from the sides of an impoundment. Pore water samples from two impoundments had pH values of 5.9 and 4.0, and high to extremely high concentrations of cadmium,

Table 2. Ranking of mine-waste sites based on size and passive leach test results.

[Site name and # from Church, Mast, and others (this volume); (3), number of samples in average. Size score, acid score, metal score, and waste score explained in text. Waste rank, VH, very high; H, high; M, medium; L, low]

Site name	Mine or site number	Size score	Acid score	Metal score	Waste score	Waste rank
Brooklyn (3)	141	5	3	3	30	VH
Kittimack tailings	192	5	2	3	25	VH
B157		4	3	3	24	VH
Grand Mogul (3)	35	4	3	3	24	VH
Lackawanna tailings	287	4	3	3	24	VH
Lark (6)	86	4	3	3	24	VH
Henrietta 700 (2)	85	4	3	2	20	VH
Henrietta 800	505	4	3	2	20	VH
May Day (2)	181	5	3	1	20	VH
Ruby Trust	169	4	3	2	20	VH
Clipper	114	3	3	3	18	VH
Bandora (3)	332	5	1.7	2	18	VH
Brooklyn tailings		3	3	3	18	VH
Monarch	180	3	3	3	18	VH
Ben Butler	9	3	2.7	3	17	H
Minnesota Gulch	144	3	3	2.5	17	H
Little Ida	15	4	3	1	16	H
Kittimack mine	201	4	3	1	16	H
Frisco tunnel	19	3	2	3	15	H
Mammoth tunnel	148	4	3	0.5	14	H
Silver Crown (2)	133	4	3	0.5	14	H
Bonner (3)	172	5	2.7	0	13	H
B237		3	2	2	12	H
Burbank	207	4	2	1	12	H
Joe and Johns	87	2	3	3	12	H
Sultan tunnel	266	4	2.5	0	10	H
Upper Brooklyn		2	3	2	10	H
B213		3	2	1	9	M
N. Denver Lake		3	2	1	9	M
Legal Tender	189	3	2.5	0.5	9	M
Forest Queen (2)	195	3	3	0	9	M
Henrietta 900	506	3	3	0	9	M
Imogene (3)	136	4	2.3	0	9	M
North Star tailings	310	3	1.5	1	9	M
Paradise West		3	3	0	9	M
Paradise (3)	168	4	2.3	0	9	M
Independence	171	3	3	0	9	M
Early Bird	8	4	2	0	8	M
Avalanche (2)	149	3	2.5	0	8	M
Last Chance	289	3	2	0.5	8	M
Columbine	260	3	2.5	0	8	M
B021 (2)		1	3	3	6	L
Mighty Monarch	285	3	2	0	6	L
East Burro bridge		3	2	0	6	L
Elk tunnel (2)	147	3	2	0	6	L
Ruby Trust tailings		1	3	3	6	L
Eveline	91	1	2	3	5	L
Ferricrete mine	137	2	2	0	4	L
Eagle Chief	14	3	1	0	3	L
B183		3	1	0	3	L
B229		3	1	0	3	L
B182		3	0	0	0	L
Highland Mary dump	357	5	0	0	0	L
Highland Mary tailings	351	5	0	0	0	L



Base from U.S. Geological Survey
Silverton, 1:100,000, 1982.
Elevations shown in feet except peak 3,792 m

Figure 2. Location and ranking of mine-waste materials at sites on public land in the Animas River watershed study area. Rank is based on size, metal release, and acid-generating potential described in table 2. Map elevations are in feet, except for the prominent peak between Middle and South Forks Mineral Creek, designated as peak 3,792 m (its elevation shown in meters).

copper, lead, and zinc. Springs and diffuse inflows on the west bank of the upper Animas River near the Powerhouse (1 mi northeast of Silverton) are acidic, highly conductive, and rich in metals (Paschke and others, 2005; Kimball and others, this volume; J.T. Nash, unpub. data, 2000); these inflows and possible relations to mill tailings warrant further investigation. Water samples of this type, collected from geologically similar mill tailings elsewhere on the Western Slope of Colorado (Nash, 2002) also tended to be acidic (pH from 2 to 4), with high to extremely high concentrations of base metals.

Mine-Adit Drainage and Ranking

Mine-adit drainage is more common in this area than in most mining areas of the United States. The combination of high precipitation, extensive fracturing (Yager and Bove, this volume, Chapter E1; McDougal and others, this volume, Chapter E13), and high relief creates numerous springs and drainage from mine tunnels. Mine tunnels are common in the study area because they afforded efficient access to deep mine workings while also draining water from the mine. Vertical mine shafts in the study area are also commonly full of water, but this water does not usually flow from the shafts and will not be considered further. Mine tunnels, on the other hand, discharge from 1 to more than 400 gpm (gallons per minute); the water quality is highly variable, and most is degraded relative to water-quality standards for drinking water or for wildlife use. All observations and sampling were conducted in late August or early September of 1997 to 2000, during lower flow stages of the hydrograph (von Guerard and others, this volume). Repeated measurement and sampling of mine-adit drainage show that some adit drainages are relatively consistent in discharge or composition, but that others vary substantially through the year. Seasonal variations in discharge and water quality were studied in detail by Mast and others (2000) and are discussed elsewhere in this report (Wright, Simon, and others, this volume, Chapter E10; Leib and others, this volume, Chapter E11; Mast and others, this volume, Chapter E7). Variations in mine-adit discharge estimates and measurements may explain some differences in ranking by various studies discussed later.

The range in geochemical data from mine-adit drainages is summarized in table 3 and figure 3. Both highly acidic and moderately acidic mine-drainage water sampled in this investigation contains dissolved metal concentrations that could be threats to aquatic life. Based on the percentage of sampled water that exceeds chronic aquatic life water-quality standards (table 3), the most common problems are with zinc, pH, and iron, followed by aluminum, manganese, copper, and cadmium; other investigations have found similar tendencies. The concentrations of lead and arsenic are much less likely to exceed water-quality standards. Because base-metal concentrations generally correlate with acidity (fig. 3; Plumlee and others, 1999), drainage water with pH values from 2 to 4 tend to have highest *concentrations* of toxic metals such as cadmium, copper, and zinc. However, metal *loadings* in the study area tend to be highest from draining adits with water having pH values from 4 to 6 with discharges greater than about 50 gpm.

Highly acidic water (pH 2.3–3.5 observed, fig. 3) is found in 27 percent of mine-adit drainages in this study; some springs have pH values in this range (Mast and others, this volume). Moderately acidic mine-adit drainage (pH 3.5–5.5) is found in 38 percent of mine-adit water in this study; springs flowing from altered red rock in the study area also commonly have pH values in this range. Near-neutral pH values (5.5–7.9) are found in 35 percent of draining mine adits, generally where tunnels have cut sedimentary rocks or propylitically altered volcanic rocks (Yager and Bove, this volume, pl. 1; Bove and others, this volume). Metal concentrations range greatly, but in general increase with acidity.

Table 3. Summary of mine-adit drainage geochemistry.

[Elements determined by ICP-MS, in parts per billion (µg/L); 108 samples; µS/cm, microsiemens per centimeter]

	Minimum	Median	Maximum	Percent exceeding ALWQ[1]
pH	2.3	5.2	7.4	84
Conductivity µS/cm	17	380	>2,000	nc
Al µg/L	1.8	380	52,850	64
As µg/L	<0.03	1.1	186	5
Cd µg/L	<0.01	2.4	1,600	45
Co µg/L	0.06	9.4	154	nc
Cu µg/L	<0.1	15	12,000	51
Fe µg/L	20	4,000	28,800	75
Mn µg/L	1.4	1,030	87,200	53
Ni µg/L	0.1	8.8	105	nc
Pb µg/L	<0.1	2.0	2,520	19
Zn µg/L	8	980	76,000	87

[1] ALWQ, Aquatic life water quality standard (chronic) of CWQCD (2001) for other parts of Colorado; nc, not computed.

Metal Concentrations

Eight metals are generally considered to be potentially harmful to aquatic health—aluminum, arsenic, cadmium, copper, iron, manganese, lead, and zinc (Manahan, 1994; U.S. Environmental Protection Agency, 1999; 2001). For aquatic biota of the Animas River watershed study area, the two metals of prime concern are copper and zinc (J.R. Owen, unpub. report, CDPH, 1997). Besser and Leib (this volume) have shown that dissolved zinc and copper have the greatest effect on aquatic biota in the study area. Other potentially toxic metals, such as silver, cobalt, mercury, molybdenum, nickel, and selenium, were detected at low concentrations

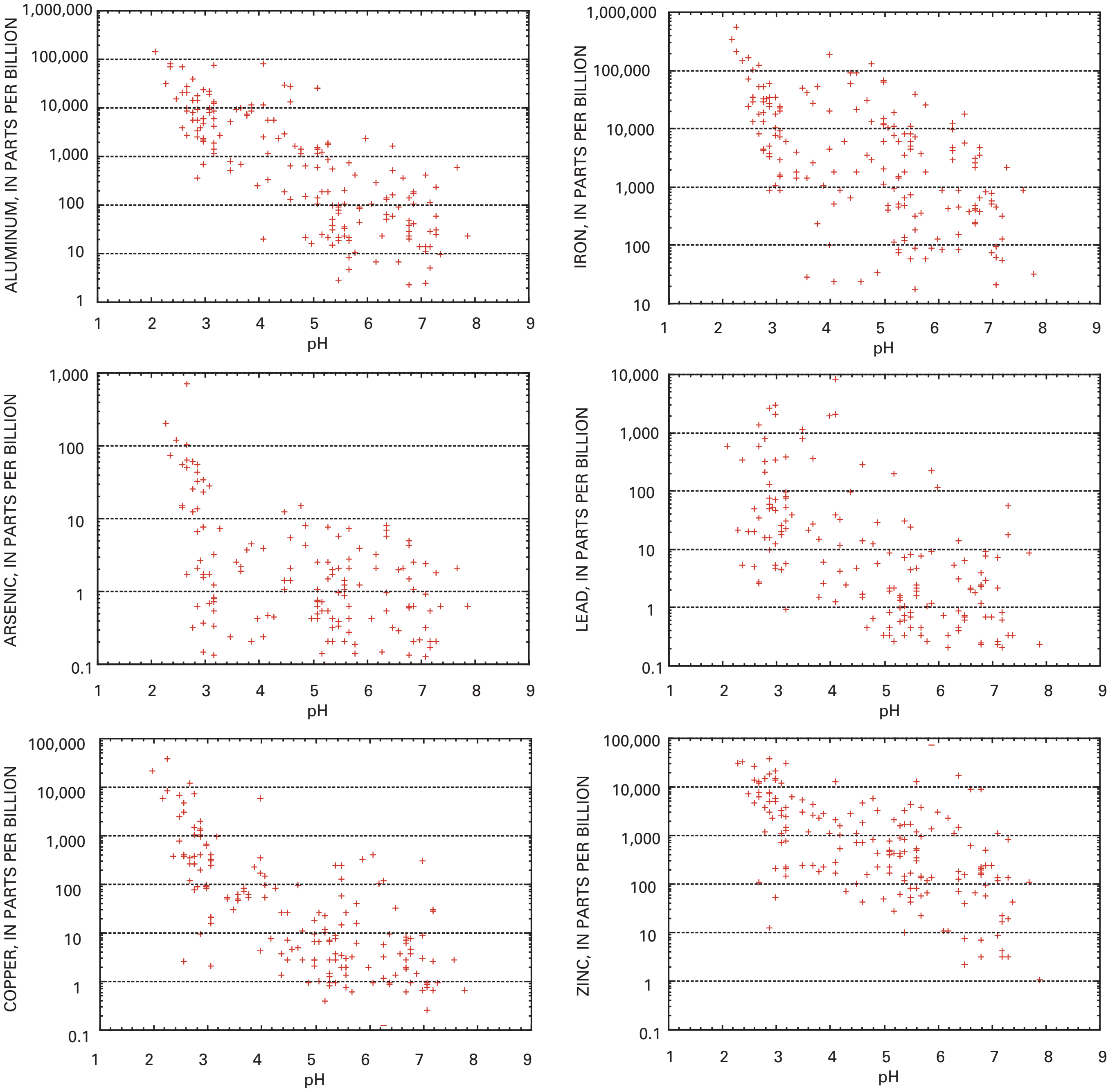


Figure 3. Composition of mine drainage water as a function of pH (standard units).

relative to standards for human and aquatic health; only in a few cases of extremely acidic mine-adit drainage water were these elements sufficiently concentrated to merit concern. Of the potentially toxic metals, some have elevated concentrations more commonly than others. Comparing our analyses of 108 water samples at mine portals and mine-waste dumps with chronic water-quality standards for aquatic life (table 3; CWQCD, 2001; Besser and others, this volume, Chapter D), we note that for more than half of the mine sites, water compositions exceeded the standards for aluminum, copper, iron, manganese, and zinc, whereas concentrations of arsenic and lead rarely exceeded the standards. In the descriptions of mine sites later in this chapter, metal concentrations in water will be described as "high" or "very high" relative to our analyses of mine-adit water (summarized in table 3): "high" denotes values greater than the median and "very high" denotes values greater than the 80th percentile of our analyzed samples. Water measurements termed "very high" are usually substantially in excess of chronic water-quality standards for aquatic life.

Metal Loads

Another measure of the degree of contamination from mine sites is the magnitude of metal loads. A metal load is the product of metal concentration and the discharge of a stream or mine adit (Mast and others, this volume; Kimball and others, this volume). Although health effects on wildlife and humans generally are related to metal concentrations, loads provide an alternative way of evaluating metal budgets in watersheds. We have calculated metal loads for representative examples of mine-adit drainage where the water composition has been determined and the discharge has been measured or estimated. Because of the time variability in discharge and metal concentrations over the year (Mast and others, 2000) and uncertainties in our discharge estimates, we have expressed the loads as ranked values (table 4). The calculated loads for sites sampled at similar times of the year over a 3-year period demonstrate substantial variations, but not enough to significantly change the relative rankings. For example, the loads calculated for the Grand Mogul mine (site # 35) for our three sample events all ranked it among the top eight sites.

Metal loads of mine-adit drainage from 49 sites have been ranked into four classes, from “very high” to “low” (fig. 4). These metal load ranks are an approximate measure of probable contamination to the watershed. The mine-adit drainage ranking (table 4) reflects the sum of scores for copper and zinc loads. The load scores for copper and zinc individually are shown in table 4. The locations and ranks of mine-adit drainages are shown in figure 4. Additional metals could be included in the ranking system, as was done by Butler, Owen, and Simon (Peter Butler, Robert Owen, and William Simon, Unpublished report to Colorado Water Quality Control Commission, Animas River Stakeholders Group, 2001). Arsenic was not included because most drainage water in the watershed has low arsenic concentrations relative to water-quality standards.

Mines on Public Land and in the Animas River Watershed Study Area: Contamination Potential from Waste Material and Adit Drainage

The following is an itemized discussion of inactive mines located on public land in the Animas River watershed study area. The discussion is broken down by basin: the upper Animas River basin, the Cement Creek basin, and the Mineral Creek basin. For each site, we present both the mine waste ranking (where waste material is present) and the mine drainage ranking (where applicable), along with field observations and other pertinent information from other reports.

Mines on Public Land in the Upper Animas River Basin

Setting

The majority of mine production in the study area was from the upper Animas River basin (Animas River upstream from Silverton), possibly as much as 80 percent of the total (estimated from production records; Nash, 2000). Much of this basin is underlain by weakly altered (propylitic) volcanic rocks in the central and eastern part of the Silverton caldera (Bove and others, this volume). Some of the large vein deposits in this subbasin are in radial faults east of the caldera, in weakly altered volcanic rocks; these weakly altered rocks provide some acid-neutralizing capacity from minerals such as calcite and chlorite. Tailings in several settings—private sites, public land, and fluvial deposits—are a significant source of contamination in this basin.

Most of the large and famous historical mines of the area, such as the Sunnyside (mine # 116), Mayflower (mine # 304), and Shenandoah-Dives (mine # 355), are on private land (Church, Mast, and others, this volume). Public land in this basin is administered by the U.S. Bureau of Land Management (BLM); more than 200 small mines and prospects are on BLM land, and 11 of these were considered to have waste piles large enough in tonnage and of sufficient reactivity to be candidates for remediation (Nash, 1999b). Fifteen mines on public land in this basin release adit drainage, and they are ranked in table 4. More than 30 historical mills were located in this basin, but most of these sites have little or no remaining mill tailings, because either (1) the tailings were not impounded and were lost to the Animas River by fluvial transport, or (2) some impounded tailings were removed and reprocessed during World War II (Jones, this volume). Fluvial mill tailings are still common in and along the upper Animas River, redeposited after floods breached mill-tailings impoundments. Fluvial mill tailings in the flood plain of the upper Animas River 1–3 mi south of Eureka are described in detail elsewhere (Vincent and Elliott, this volume).

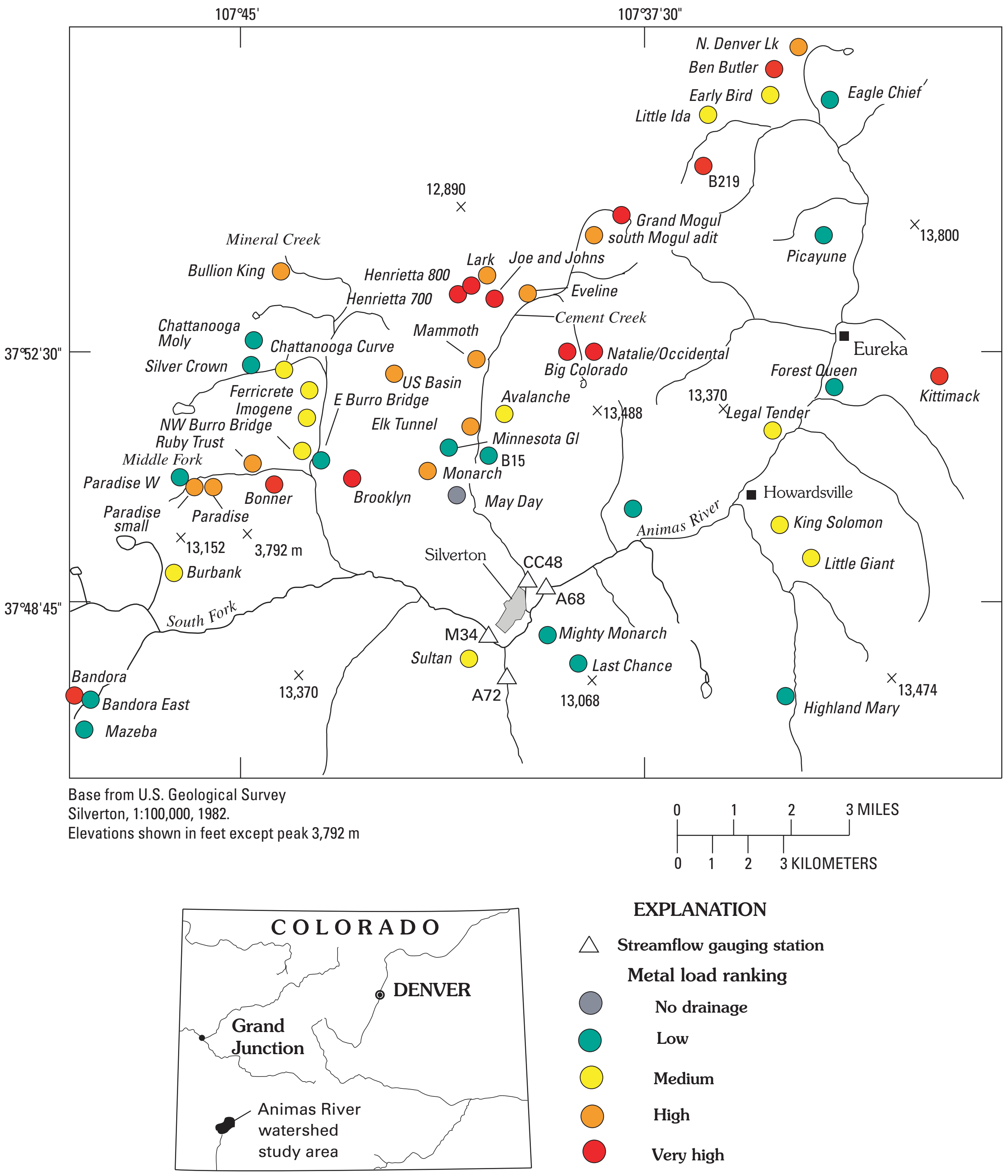
Kittimack Mill and Lackawanna Mill Tailings

Two mill-tailings sites on (or partly on) BLM land, in close proximity to the upper Animas River, are among the largest sources of contaminants from public land in this basin. These are the Kittimack Mill tailings (site # 192) and the Lackawanna Mill tailings (site # 287). The magnitude of contamination is difficult to quantify, but geochemical analysis of the tailings materials shows them to be reactive and rich in metals of concern. Because of the large volume of mill tailings at these sites, they rank as very high sources of contaminants (table 2). Leach tests on one sample from each of these mill-tailings piles show similar results: the samples generate acidic leachate solutions with extremely high dissolved

Table 4. Ranking of mine-adit discharge for sites on public land.

[Site name and mine number from Church, Mast, and others, this volume; (3), samples in average; site names with B from Hite (unpub. report, U.S. Bureau of Mines, 1995); Cu R and Zn R, copper and zinc load ranks; MD rank, mine discharge rank; MD class, mine discharge class (VH, very high; H, high; M, medium; L, low); Cond., specific conductance in µS/cm (microsiemens per centimeter); Q, adit discharge in liters per minute]

Adit site	Mine No.	Sample ID	Cu R	Zn R	MD rank	MD class	pH	Cond	Q L/m
Grand Mogul (3)	35	NAW 530	1	2	1	VH	3.1	470	100
Natalie/Occidental	153	NAW 551	3	1	2	VH	5.2	498	1,600
Joe and Johns	87	NAW 217	2	4	3	VH	2.7	740	80
Brooklyn (3)	141	NAW 508	5	7	4	VH	3.5	590	80
Big Colorado	150	NAW 552	9	6	5	VH	3.6	960	400
Henrietta 800 (2)	505	NAW 213	4	9	6	VH	2.5	1,651	22
B 219 prospect		NAW 713	12	5	7	VH	3.2	1,110	20
Ben Butler (3)	9	NAW 156	8	11	8	VH	3.0	453	11
Kittimack (3)	201	NAW 235	7	14	9	VH	5.8	236	93
Henrietta 700	85	NAW 215	11	10	10	VH	2.5	1,550	20
Bandora (3)	332	NAW 399	21	3	11	VH	6.3	484	93
Bonner (3)	172	NAW 517	13	12	12	VH	2.9	545	53
Monarch	180	NAW 321	6	16	13	H	4.1	270	40
Paradise (3)	168	NAW 520	22	8	14	H	4.7	1,010	533
Lark	86	NAW 204	10	21	15	H	3.2	380	20
Mammoth	148	NAW 227	18	13	16	H	4.7	983	160
Ruby Trust (2)	169	NAW 524	17	15	17	H	6.0	272	1,200
Eveline	91	NAW 201	15	26	18	H	3.1	370	40
N. Denver Lake (3)		NAW 161	24	17	19	H	3.6	182	17
Elk tunnel (3)	147	NAW 311	25	19	20	H	6.0	938	400
U.S. Basin	143	NAW 582	14	33	21	H	5.6	807	20
Mogul South	30	NAW 329	23	25	22	H	4.4	380	12
Paradise small		NAW 869	32	18	23	H	5.1	605	160
Ferricrete (2)	137	NAW 512	28	22	25	M	5.2	280	140
Avalanche (3)	149	NAW 309	16	36	26	M	3.8	372	40
Early Bird	8	NAW 150	19	34	27	M	3.2	339	6
Little Giant	303	NAW 721	30	23	28	M	5.2	120	20
Burbank (2)	207	NAW 603	26	28	29	M	3.8	388	500
King Solomon	306	NAW 883	20	41	30	M	3.2	40	40
Little Ida	15	NAW 380	27	32	31	M	5.2	90	20
Imogene (3)	136	NAW 511	33	29	32	M	6.6	219	147
NW Burro Bridge		NAW 598	34	30	33	M	7.3	201	40
Chattanooga Curve	135	NAW 579	37	31	34	M	7.3	282	40
Sultan tunnel	266	NAW 298	29	39	35	M	5.4	494	100
Legal Tender	189	NAW 396	42	27	36	M	5.3	337	93
Paradise west		NAW 868	35	37	37	L	4.9	183	400
Forest Queen (2)	195	NAW 232	46	24	38	L	7.2	990	80
Silver Crown	133	NAW 577	36	38	39	L	5.2	360	40
Mighty Monarch	285	NAW 735	39	40	40	L	5.5	183	200
B015		NAW 412	38	47	41	L	5.2	600	12
Bandora east		NAW 647	48	35	42	L	3.2	505	20
Minnesota Gulch	144	NAW 878	40	37	43	L	5.6	264	40
Highland Mary	359	NAW 741	41	45	44	L	2.9	239	40
Chattanooga Moly		NAW 872	40	46	45	L	5.8	581	40
Last Chance	289	NAW 064	44	42	46	L	6.7	230	240
East Burro Bridge		NAW 597	43	48	47	L	7.2	148	12
Eagle Chief	169	NAW 144	45	44	48	L	4.6	80	20
Mazeba		NAW 651	49	43	49	L	5.7	210	20
Picayune prospect		NAW 852	47	49	50	L	6.8	164	20



Base from U.S. Geological Survey
Silverton, 1:100,000, 1982.
Elevations shown in feet except peak 3,792 m

Figure 4. Location and ranking of mine drainage sites on public land, Animas River watershed study area. Ranking explained in text and in table 4. Map elevations are in feet, except for the prominent peak between Middle and South Forks Mineral Creek, designated as peak 3,792 m (elevation shown in meters).

concentrations of copper, manganese, lead, and zinc. Pore water from the Kittimack Mill tailings (site # 192, fig. 5) had a pH of 4.0, high cadmium, and very high copper, lead, and zinc concentrations. Pore water from the Lackawanna Mill tailings (site # 287, fig. 6) had a pH of 5.9, high copper and lead concentrations, and extremely high cadmium, iron, manganese, and zinc concentrations. These chemical results suggest a high potential for contamination. Results from a tracer study by Kimball and others (this volume) show that downstream from the Kittimack Mill tailings, colloidal Fe and dissolved Ca, Mg, Mn, Cu, Zn, and SO_4 increase. Their location on the flood plain made them vulnerable to erosion in extreme storms, and seepage or runoff from these impoundments can travel straight into the Animas River with little or no chance for natural attenuation. A series of shallow wells is needed to test for actual infiltration of contaminated water into alluvium beneath the mill tailings and the magnitude of ground-water flow toward the river.

Leach tests on one sample from the Lackawanna Mill tailings impoundment showed high acid generation and high metal release, for a waste rank of very high. Likewise, a leach test of one sample from the Kittimack Mill tailings impoundment showed moderate acid generation and high metal release; the Kittimack waste ranking is also very high because the volume of tailings appears to be larger than that at the Lackawanna site.

The Lackawanna Mill tailings, entirely on public land, were removed by the BLM in the fall of 2000 and transported to a new repository at the May Day mine site (# 181) on Cement Creek. Similar removal action or substantial remediation work should be considered for the Kittimack Mill tailings, which are partly on BLM land.

North Denver Lake and Ben Butler Mines

Two small mines on BLM land in the northern part of the upper Animas River basin are moderate sources of contamination (Nash, 1999b) because the dump materials are highly sulfidic and mine workings release acidic water. The adit north of Denver Lake (site B233, fig. 7) releases water with a pH of 3.0 and high to extremely high concentrations of cadmium, copper, lead, and zinc; the drainage load ranking is high. The open trench at the Ben Butler mine (mine # 9; fig. 8) contains water with a pH of 3.5 and very high cadmium, copper, lead, and zinc concentrations; the load ranking is very high. The acidic drainage from North Denver Lake mine infiltrates alluvium before it reaches wetlands at the headwaters of the upper Animas River. The water at the Ben Butler mine trench flows only slightly and cannot be traced on the surface to Burrows Creek, a tributary to the upper Animas River. Passive leach tests show that these sulfidic waste materials generate acidic leachate solutions (pH values 3.55 and 2.83) carrying high

Figure 5. Tailings from Kittimack Mill (site # 192) cover tens of acres in flood plain of upper Animas River. Because the mill tailings were piled on alluvial gravels, metals leached from the tailings would probably migrate through the permeable gravels to the river.

Figure 6. Yellow and gray tailings from Lackawanna Mill (site # 287) were placed in flood plain of the upper Animas River, east of Silverton. Because of evidence that the tailings were releasing contaminants to the river, the BLM removed the tailings in 2001 and emplaced them in a repository at the May Day mine.

Figure 7. A small mine north of Denver Lake was the source of the pile of sulfide-rich rocks in foreground. A small flow of water from the adit gains acid and metals on the dump, then flows east to wetlands at the source of the upper Animas River. Drainage in foreground is about ½ m across.

Figure 8. Large quartz-sulfide veins that were mined at the Ben Butler mine are exposed in these shallow trenches, and sulfidic mine waste covers the adjacent slope. Little water from the trenches flows onto the surface, but some may flow into the subsurface. Trench is about 2 m across.

concentrations of base metals. More specifically, the sample from Ben Butler mine released extremely high concentrations of lead and zinc and high concentrations of cadmium and copper. The waste leach ranking for North Denver Lake mine is medium and for Ben Butler mine is high (table 2).

Little Ida Mine

Major quartz-sulfide veins under Tuttle Mountain, west of the Ben Butler mine, were worked by several major mines. Other smaller mines explored parts of the vein system and produced sulfide-rich mine-waste dumps of moderate size. The Little Ida mine (site # 15) and a mine adjacent to the Frisco tunnel (site # 19) are on public land. Leach tests on mine waste from the Little Ida mine showed high acid generation and low metal release, for a waste rank of high. The leach test on waste from the mine near the Frisco tunnel showed moderate acid generation but high metal release, for a waste rank of high.

Kittimack Mine

This mine adit (mine # 201) high above Minnie Gulch (fig. 9) releases a moderate discharge of water with a pH of 5.5, but the metals are sufficiently concentrated to produce a load ranking of very high. Leach tests on mine-waste material showed high acid generation and relatively low metal release; the summary waste rank is very high. The relatively high metal loadings rank suggests that the mine-adit drainage merits its attention. However, the fact that the rocks and alluvium in this area are propylitically altered suggests that natural attenuation of metals may occur as the mine-drainage water flows toward the upper Animas River, about 2 mi to the west.

Site B157

West of the Kittimack mine several north-trending adits explored sulfide veins. One of the dumps, B157, is of moderate size and highly sulfidic. The collapsed adit at site B157 does not release mine drainage. Leach tests on waste-dump material from B157 showed high acid generation and high metal release, for a very high waste score. Because this site is relatively dry, it may pose a lower risk of contamination than chemically similar waste dumps that are wet.

Clipper Mine

In the alpine Sunnyside Basin the Clipper mine (mine # 114) workings are small in comparison with others nearby. However, the medium-sized waste dump is highly sulfidic and produces a notable kill zone (an area downslope

Figure 9. The Kittimack mine has a dump of modest size and relatively low sulfide content, but water flowing from the caved adit (left side of photo) is of concern. Although the pH of the water (5.8) is not highly acidic, the water carries substantial amounts of zinc.

of a dump where vegetation has been killed and cannot be reestablished, due to mine drainage or the presence of waste material) for several hundred feet downslope, indicating acidic runoff. The workings release no mine drainage. Leach tests show high acid production and high metal release, for a waste rank of very high (table 2).

Site B219

Drainage from a small prospect in California Gulch has a drainage load ranking of very high because the small flow of water contains especially high metal concentrations. This prospect is so small as to be virtually a natural outcropping; a small mine tunnel explored a quartz vein 3 ft wide. No mine waste was studied because the volume is so small; thus we have no waste ranking for site B219.

Forest Queen

The Forest Queen mine (site # 195) was a problem because the mine tunnel released a substantial flow of water, and it formerly ran over the mine-waste dump into nearby wetlands. This site has been studied by several scientists (Stanton, Fey, and others, this volume, Chapter E25). Remediation was undertaken by the BLM in 1999 as a technology demonstration project. The mine-adit drainage was not unusually acidic, but the water quality was degraded. This drainage was measured and sampled at least 21 times by Mast and others (2000), who recorded pH values in the range of 3.7–6.6 during a 4-year period. In August 1997, the mine-adit drainage at the collapsed portal had a pH of 5.1 and high concentrations of cadmium, iron, and zinc (concentrations of arsenic, copper, and lead were lower than in most mine water). Concentrations of dissolved zinc ranged from 355 to 709 ppb (Church, Mast, and others, this volume, table 7); the one Nash sample contained 435 ppb zinc. The load ranking is low. Passive leach studies of two samples yielded similar results, a high score for acid generation and a very low score for metal release. The mine-waste rankings are medium. A water sample collected below the mine-waste dump in 1997 (prior to remediation) contained lower metal concentrations than did the water at the portal.

Mighty Monarch and Last Chance Mines

Two mine tunnels on Kendall Mountain east of Silverton release high flows of near-neutral water that contains only slightly elevated metal concentrations. The drainage load rankings are low for the Mighty Monarch (site # 285) and low for the Last Chance mine (site # 289). Leach tests on waste from the Mighty Monarch mine showed moderate acid generation but low metal release; the waste ranking is low. Tests on two samples of waste from the Last Chance mine showed moderate acid generation and low metal release, for waste rankings of medium (table 2).

Mines on Public Land in the Cement Creek Basin

Setting

Mine production from this basin was substantially smaller than from the adjacent upper Animas River basin, and only seven mills and one smelter were built. Although major production came out of the American tunnel, the ore was hauled to the Mayflower Mill on the upper Animas River and very little waste was placed nearby. Historical mill tailings impounded at Gladstone, prior to use of the American tunnel, were removed in 1996. Most of the public land in this basin is administered by the BLM. A high percentage of this basin is underlain by highly altered volcanic rocks, including parts of the three Red Mountains that contain acid-sulfate alteration and abundant disseminated pyrite (Bove and others, 2000; Bove and others, this volume). The seven mill sites were evaluated for remediation (Nash, 1999a). Fifteen sites in this basin are ranked by drainage loads in table 4.

Lark-Henrietta Mine Area

Four problematic sites are adjacent mines in upper Prospect Gulch: the Lark, Henrietta, and Joe and Johns mines, and the 1970s mine-waste dump from the 800 level of the Henrietta mine (site # 505). The Lark (site # 86) and the Joe and Johns (site # 87) mine workings are connected by a crosscut tunnel, and some evidence indicates that this crosscut carries mine drainage from the Lark workings to the Joe and Johns mine. This may explain why only a small discharge of water is released at the lowest level of the Lark mine (Lark Number 3 adit). Discharges from the Lark and the Joe and Johns adits are relatively small, but an unknown amount infiltrates into alluvium and bedrock fractures behind the collapsed portals. Remediation work in 1999 was directed at the discharge from the Joe and Johns adit. Surface water in Prospect Gulch has been studied in detail using tracer methods (Wirt and others, 1999; 2001) to quantify the sources of contamination. The work by Wirt and others demonstrates a large inflow of acidic, metal-rich water into Prospect Gulch creek in the vicinity of the Lark-Henrietta mines (fig. 10). However, these detailed studies coupled with reconnaissance studies by Nash do not provide conclusive evidence for the flow path of the acidic water. This area of about 60 acres, including both private mining claims and public land, is one of the larger sources of contamination in the Prospect Gulch subbasin and is so complex that it is difficult to reliably distinguish among many possible sources.

Mine-drainage load rankings (table 4) show how the drainages in Prospect Gulch compare with others in the study area. Drainage water from the Joe and Johns mine and the seep from the Henrietta 800-level waste pile are extremely

Figure 10. Lark mine on flank of Red Mountain # 3 created a dump of modest size but relatively high sulfide content; the dump was reclaimed by BLM in 2002. More complex are springs in the hillslope below the mine that are highly acidic and rich in metals; the springs are of uncertain origin despite several detailed studies.

high in metals and have load rankings of very high. Mine-adit drainage sampled at the portals of the Lark and Henrietta 700 (site # 85) tunnels has lower metal concentrations and load rankings of high and very high, respectively. These rankings do not consider details such as variability through the year or possible errors in flow estimates due to infiltration into bedrock fractures or alluvium that would lower the load values. The seeps in and near the Henrietta 800 waste dump are especially complex (Wirt and others, 2001).

Leach tests were made of six samples from the Lark mine upper and lower dumps (two levels of site # 86); all six samples showed high acid generation. Some variation occurred in metal release: high in three samples and medium in three samples. Considering the range in composition visible at the dump surface, the differences among samples and test results are not surprising. The average waste ranking for the Lark site is very high. Leach tests on two samples from the Joe and Johns waste dump (site # 87) showed high acid generation and high metal release, but the relatively small size of the dump makes the waste ranking high, instead of very high.

The waste dump between the Lark and Henrietta mines contains abundant sulfides and is generally less weathered than most dump piles in the area, which is consistent with reports that a lessee created this waste while exploring the 800 (deepest) level of the Henrietta mine in the 1970s. This waste pile is so close to Prospect Gulch that material slides into the creek, and runoff flows directly into the creek. A leach test on waste from the 800 mine-waste dump showed high acid generation and moderate metal release; the waste ranking is very high. Less clear is the nature of very acidic water that flows from the long narrow waste pile in several places. One possibility is that the acid and associated metals are leached from the dump when surface runoff crosses the dumps. However, there is also evidence for a series of acidic seeps between the dump and the road; these seeps have pH values near 2 and extremely high metal concentrations. Surface water, after flowing over and through the dump, has lower metal concentrations, but the higher flow volumes result in higher loadings. This surface water flows into Prospect Gulch, and related acidic, metal-rich seeps may enter the creek as diffuse inflows, which would explain at least part of the increases measured by Wirt and others (1999; 2001). A series of wells would be required to document the flow and composition of this shallow ground water and its flow path.

The Henrietta 900 tunnel (site # 506) was driven in the 1970s from a lower elevation in Prospect Gulch with the goal of intercepting ore under the Henrietta 700 level. The tunnel is dry, which is difficult to explain, and the dump contains sparse sulfide minerals, suggesting that the target was not reached (as described by Jim Herron, Bruce Stover, and Paul Krabacher, Unpublished Cement Creek reclamation feasibility report, Upper Animas River Basin, Colorado Division of Mines and Geology, 1998). The waste was tested by passive leach and found to generate acid, but it released very little metal; the waste ranking is medium. Remediation is needed to minimize the slumping of waste into Prospect Gulch, but the waste is not as problematic as most mine waste in the study.

Grand Mogul Mine

This mine (site # 35) in the northern part of the Cement Creek basin is one of the larger sources of contamination among all sites on public land. Drainage from the collapsed mine tunnel seeps through the sulfidic dump and emerges at the edge of Cement Creek (fig. 11). Because the flow is diffuse, it was difficult to determine the discharge, suspected to be on the order of 10–20 gpm but possibly higher. The dump is in the flood plain of the creek and there is no chance for natural attenuation before the mine drainage enters the stream. The mine drainage was detected as an acidic inflow enriched in aluminum, iron, copper, and zinc in the tracer studies of Cement Creek (Kimball and others, this volume). Three seep samples were collected and analyzed in 1997 and 1998 (Nash, two; Mast and others, 2000, one). The pH values ranged from 2.9 to 3.4, and concentrations of cadmium, copper, iron, manganese, lead, and zinc ranged from very high to extremely high. Computed metal loads for the Grand Mogul seepage are the highest in this study (load rank very high). Loads calculated for several repeat sampling events differ by about 20 percent, but they all rank in the very high group.

The Grand Mogul dump is highly sulfidic, and sphalerite and galena are visible. Leach tests on three samples show similar results: high acid generation and high metal release. The leach solutions were highly acidic (pH values 3.3 and 2.7) and carried extremely high concentrations of lead and zinc and very high amounts of cadmium and copper. The waste ranking is very high. The drainage water carried high concentrations of lead but not as high as suggested by the leach tests.

The flow paths of mine-adit drainage and dump seepage at the Grand Mogul are not well defined but sufficient to guide remediation planning. Ownership of the mine and waste dump is in question; the dump itself appears to be on public land.

May Day Mine

This site on lower Cement Creek (site # 181) has a relatively large dump that is rich in sulfide minerals (fig. 12; Stanton, 2000). The mine adit is dry, but water of uncertain origin flows below the dump according to piezometer data and geophysical studies (Smith and others, 2000; Wright, Kimball, and Runkel, this volume, Chapter E23). No mine-adit drainage was sampled by us, thus we have no load ranking for comparison with other sites. Leach tests on two samples of dump materials from upper and lower levels showed very different compositions, as expected from the visible differences in mineralogy. The sample from the upper level yielded an acidic solution near pH 3 that carried very high concentrations of cadmium and copper, and extremely high concentrations of lead and zinc. The second sample from the lower level,

Figure 11. Grand Mogul mine in headwaters of Cement Creek looks like hundreds of other mine sites, but tests show that the waste dump is highly reactive, capable of high acid generation and metal release. Of more direct concern is water flowing from the base of the dump, probably related to the mine workings northeast (left) of the dump; metal loadings from these seeps are among the highest found in this study.

Figure 12. May Day mine, excavated to explore veins west of Cement Creek, created these large waste piles of sulfidic rock. To minimize reactions from snowmelt and rain, the BLM reclaimed the dump in 2001 by emplacing a geosynthetic liner and covering with clean soil. Lackawanna Mill tailings were also emplaced there at that time.

with low sulfide and jarosite content, yielded much less acid and metals. The average of the two waste samples yields a mine-waste ranking of very high. In the summer of 2001, this site was made into a repository by the BLM for mill tailings from the Lackawanna Mill. A geosynthetic clay liner was installed and the site covered with clean soil for revegetation (Rob Robinson, BLM, oral commun., 2004).

Elk Tunnel

This tunnel on the west side of Cement Creek (site # 147) was driven westward to access vein deposits. The material on the dump is weakly mineralized, suggesting that the target vein was not reached. Today, the adit releases a large flow (135–260 gpm; Mast and others, 2000) of water that deposits conspicuous orange iron deposits outside the mine and down the slope to Cement Creek (fig. 13). The dump is relatively small and composed mostly of propylitically altered volcanic rocks with low sulfide content. A leach test showed moderate acid generation and very low metal release; the waste rank is low. The mine-adit drainage flows along the edge of the dump but does not appear to react with the waste materials. The mine-adit drainage has been sampled many times (10 samples, Church, Mast, and others, this volume, table 7; 3 by Nash; and several by Herron and others (Unpub. Cement Creek reclamation feasibility report, CDMG, 1998)). The pH values ranged from 6.1 to 7.2, and analyses show consistently low concentrations of most metals. Iron concentrations are high, ranging from about 2,200 to 10,000 ppb, possibly because dissolved oxygen content is very low. The metal of prime concern, zinc, ranges in concentration from about 140 to 210 ppb. The mine-drainage load rank of this site is high.

Figure 13. Elk tunnel, driven west of Cement Creek, did not intersect veins of value but does collect water from deep in the mountain. The pH of the water and the metal concentrations are not extreme, but because of the high flow, the metal loads are high.

Natalie/Occidental and Big Colorado Mines

These mines on South Fork Cement Creek release large quantities of mine-adit drainage (fig. 14) that flow directly into the creek. The weakly acidic water carries high iron concentrations and substantial concentrations of other metals. The loading ranks are among the highest in this study (very high), largely due to the high discharge. The dumps at the Big Colorado (site # 150) may be contributing metals to the drainage, but the dump at the Natalie/Occidental (site # 153) does not appear to react much with the mine water. Because of uncertainties in property status when we sampled in 1998, no waste samples were collected at these sites.

These mines clearly are significant sources of contamination in the Cement Creek basin and rank among the highest loaders in the entire study area. The Natalie/Occidental tunnel in particular should be evaluated for remediation. It is one of about eight sites in this study that release a large flow (>100 gpm) of near-neutral pH water with substantial concentrations of copper and zinc and thus are high copper and zinc loaders (table 4).

Avalanche Mine

This small site (# 149), in a canyon east of Cement Creek, is of concern chiefly because the adit releases acidic drainage. Three samples (Nash, two; Mast and others, 2000, one) show pH values ranging from 3.6 to 3.8 and very high concentrations of copper, iron, and zinc. The acidic water flows over a small mine-waste dump and into a small tributary east of Cement Creek. The drainage load rank is medium, near the median for all draining mines on public land. Leach tests on two samples produced solutions with pH values of 3.6 and 3.8, and low metal concentrations relative to other samples in this study. Concentrations of iron and cadmium in the leachates were elevated relative to biologic criteria. The average waste rank for this site is medium.

Figure 14. Collapsed adit of Natalie/Occidental mine releases one of the larger flows of mine water in the study area. Metal concentrations of the pH 6 water are not unusually high, but because of the high flow rate, loads of copper and zinc are high. Adit is about 1½ m across.

Eveline Mine

This very small mine (site # 91) on Dry Gulch, about 1,000 ft north of the west-flowing reach of Cement Creek, releases a small volume of pH 3.1 water carrying high concentrations of metals. Despite the low discharge, the load ranking is high. The dump is small, but reacts with mine-adit drainage. The leach test on one waste sample shows high metal release and moderate acid generation; because the volume of waste is small, the waste rank is medium.

This site is atypical in that it creates a high loading from a small flow of water. The mine is one of several sites studied here that was excavated into a zone of ferricrete. The co-location in and along the ferricrete zone probably indicates that this mine is along a natural flow path of mineralized water. (See Wirt and others, this volume, Chapter E17.) Partial remediation of the low discharge should be feasible, but if the metal-rich flow is largely related to unmined altered rocks on Red Mountain, then remediation might not achieve the intended results.

Minnesota Gulch Mines

Several small mines in Minnesota Gulch (site # 144) created small dumps with very high concentrations of sulfide minerals, and one adit creates drainage with a pH of 2.9. Although small in size, these mines and dumps create drainage that is rich in base metals. The metal load rank of low reflects the small discharge. This drainage enters the Minnesota Gulch creek at the base of the mine-waste dumps; the creek disappears into the alluvial fan before it can reach Cement Creek, but the subsurface flow must eventually enter Cement Creek. Minnesota Gulch was determined in a tracer study to add substantial loads of aluminum, manganese, copper, and zinc to Cement Creek (Kimball and others, this volume).

Leach tests on two samples collected from two adjacent and compositionally similar waste dumps show similar results: very high acid generation and high to moderate metal release. The average waste rank for this site is very high.

Another very small prospect, site B015, just a few meters from Cement Creek, also creates a small flow of metal-rich, pH 3.2 water that flows into the creek. Due to the small discharge, the drainage load ranking for this site is low.

Monarch Mine

The Monarch mine (site # 180) in Porcupine Gulch was the site of relatively recent mining, possibly the 1970s. The collapsed lower tunnel releases a small flow of drainage, and because of high metal concentrations its drainage rank is high. Leach tests on two samples from the Monarch mine-waste dumps (upper and lower levels) showed high acid generation and high metal release; the average waste ranking for the site is very high. Mine-adit drainage and dump runoff from this site have ample opportunity to react with propylitically altered volcanic rocks before entering Cement Creek. The relatively small size of the mine and waste dumps and good road access suggest that the site would be amenable to remediation.

Mines on Public Land in the Mineral Creek Basin

Setting

Mines in this basin are much smaller than in the central part of the study area, and the amount of patented land is less than in the basins to the east. The majority of the public land in this basin is administered by the USDA Forest Service. The geology of this basin is more diverse than the other basins as it lies astride the western margin of the Silverton caldera, includes several intrusive centers and associated highly altered rocks with prominent red colors, and is the only basin with a significant amount of sedimentary rock. Seven mills were built in this basin, but all were quite small; the largest two mills were on Mineral Creek near Silverton, not far from the confluence with the upper Animas River. Mill tailings do not appear to be a significant factor in this basin. The metal load rankings of 19 sites in this basin are in table 4.

Brooklyn Mine Area

An area of about 100 acres in Browns Gulch in the vicinity of the Brooklyn mine (site # 141) is one of the most highly disturbed areas in the Mineral Creek basin and clearly is degrading the water quality of the creek. This mined area, of mixed private and public ownership, has evidently been worked by several operators over the years, with more activity in the past 20–40 years than has taken place in most of the Animas River watershed study area. The most significant problems relate to sulfidic mine-waste dumps, a small mill and tailings pond, and drainage from the major mine adit.

Water drains from the adit at about 10–20 gpm; composition of the water at the adit mouth appears to be variable over time, as analyses of pH and metals reported by Lovekin and others (Jonathan Lovekin, Michael Satre, William Sheriff, and Matthew Sares, Unpublished abandoned mine land report for San Juan Forest, Columbine Ranger District, Colorado Geological Survey, 1997), Mast and others (2000), Herron and others (Jim Herron, Bruce Stover, Paul Krabacher, and Dave Bucknam, Unpublished Mineral Creek reclamation feasibility investigations report, Upper Animas River Basin, Colorado Division of Mines and Geology, 1997) and from our work differ and show a larger range than for most mine-adit drainages. Measured pH values range from 3.2 to 4.8, and metal concentrations range from relatively low for mine water (near aquatic life standards) to highly degraded (4 to more than 20 times the aquatic life standards). The bigger problem is what happens to this water after it leaves the adit and reacts with sulfidic waste rocks on the long face of a large mine-waste dump (fig. 15).The mine-adit drainage reacts with the waste to become more acidic, dropping to a pH of 2.9, and metal concentrations rise dramatically. Iron, copper, and zinc are the most significant contaminants; zinc, at about 150 times the aquatic life standard, is possibly most problematic. The load ranking for the Brooklyn adit drainage is among the highest in this study (very high), and the loads are even higher after the water's reaction with dump materials.

Leach tests on three waste-dump samples showed consistent results: very high acid generation and moderate to high metal release. The averaged waste ranking for this site is very high. The ranking for the mill tailings also is very high; the tailings behave like the mine waste and release large amounts of metal and acid.

The Upper Brooklyn mine dump, north of the Brooklyn mine, created waste that is chemically similar to that of the Brooklyn mine, and likewise released a high amount of acid

Figure 15. Drainage from Brooklyn mine flows down over sulfidic waste rocks for more than 100 m, gaining acid and metals. Water quality degrades considerably between the adit and the base of the dumps.

in the leach test. The mine-waste ranking for the upper dump site rank is high, but the score is considerably lower than for the Brooklyn mine dump because the amount of waste is much smaller.

Browns Gulch was noted as a substantial contribution of aluminum, manganese, lead, and zinc in the Mineral Creek tracer study (Kimball and others, this volume). Multiple sources of contamination lie in this subbasin, including mines and altered rocks above and below the Brooklyn mine, but the mine and dump drainage from the Brooklyn mine area appear to be the largest source of contaminants.

Bandora, Burbank, Imogene, and Ruby Trust Mines

These four mines are problems chiefly from their release of relatively large amounts (approximate range 50–200 gpm) of near-neutral-pH but contaminated water; they will be discussed together because of their geochemical similarities. Median flow volumes include: Bandora, 45 gpm; Burbank, 39 gpm; Imogene, 75 gpm (Mast and others, 2000); Ruby Trust, 100–150 gpm (Nash estimate). Seven samples from these four sites were collected by Nash from 1997 to 1999, and 15 samples are described by Mast and others (2000). The water from these mines has near-neutral pH values (5.4–7.4), but zinc concentrations are sufficiently large to create substantial loadings. Most metal concentrations are low, but iron and manganese are high, and zinc ranges to more than 15,000 ppb. The high iron concentrations are reflected by the red iron oxyhydroxides that precipitate from the drainage water. The drainage load rankings are as follows: Bandora, very high; Ruby Trust, high; Imogene, medium; and Burbank, medium.

Bandora Mine

Leach tests were made on three samples from the Bandora mine (site # 332; fig. 16). Two samples yielded similar results—high metal release and moderate acid generation, for waste rankings of very high. One of the leachate solutions carried the highest lead concentration of this study; however, lead concentrations in mine-adit drainage water were relatively low in this study. A sample of predominantly gray sedimentary rock on one of the lower dumps released little metal and a low amount of acid, for a ranking of low. The average waste ranking for the Bandora site is very high.

Burbank Mine Tunnel

The Burbank mine tunnel (site # 207) was excavated about 20 years ago to access veins identified higher on the mountain, but our examination of the dump rocks suggests that little ore was encountered. The tunnel collects a large amount of water (fig. 17), and the pH of 6.6–7.4 suggests that much of the water had reacted with propylitically altered volcanic rocks of the type that crop out at the site. The load rankings for copper and zinc (table 4) were medium, suggesting that this is not a major source of those two metals of concern. A leach test on one dump sample showed moderate acid generation and low metal release, and a waste rank of high.

Figure 16. The Bandora mine created a series of mine-waste dumps that are relatively unreactive because they are calcareous sedimentary rocks. However, the mine tunnels collect and release water with substantial amounts of zinc, despite the near-neutral pH.

Figure 17. The Burbank mine tunnel failed to intersect veins exposed higher on the mountain, but it continues to release a large flow of water carrying enough zinc at pH 5.4–6 to be a significant loader.

Imogene and Ferricrete Mines, and Unnamed Mine Northwest of Burro Bridge

These mines are on the west side of Mineral Creek in an area of extensive ferricrete deposits. They release relatively large flows (20–100 gpm) of near-neutral-pH water that immediately deposits prominent iron oxhydroxide floc (fig. 18). Ferricrete is exposed at the mine portals, suggesting that the tunnels were made to explore fracture zones that were premining water pathways. The mine workings appear to be relatively small, judging from the small volume of waste at the portals, and the mine waste is not highly sulfidic. The concern at these sites is for the drainage waters; the drainage load rankings for all three mines are medium.

Leach tests on three samples from the Imogene mine (site # 136) showed very low metal release and moderate to high acid generation. The average waste ranking for this site is medium. A sample from the Ferricrete mine (site # 137) dump showed moderate acid generation and low metal release, for a waste ranking of low. No leach test was made of waste from the site northwest of Burro Bridge.

Although metal-enriched water flows from these tunnels, the source of metals in these mine waters may be largely from unmined altered rocks. Although remediation methods such as plugging the tunnels would be expected to reduce metal loads, analyses of flow paths and fracture systems are needed to design effective seals.

Silver Crown Mine

Near Chattanooga horseshoe curve are several prospects for molybdenum and base metals related to an intrusive complex (Bove and others, this volume). The Silver Crown mine (site # 133) is in volcanic rocks, like the majority

Figure 18. The Ferricrete mine adit was driven to explore large outcrops of ferricrete but found no ore. The mine water is typical of many in the study area with near-neutral pH but high iron content. Although zinc concentration in the water is lower than in many mine-adit waters, high flow volume creates a substantial zinc load.

of mines in the study area, but has a mineral assemblage that suggests higher temperatures of a contact or skarn-type deposit. At the surface, the volcanic rocks are not highly altered (propylitic). The predominant green colors on the dump do not suggest that acid is being generated by waste or mine discharge, but two leach tests show high acid generation; metal release was relatively low. The waste rank is high, in part because the site is relatively large. Mine-adit discharge is ranked low (table 4) and is clear; it has a pH value of 5.7, seemingly buffered by the propylitic rocks. Seepage through the dump has essentially the same pH, suggesting little or no reaction with the dump waste. The site is close to a tributary of Mineral Creek, and mine drainage and dump seepage waters flow directly into the tributary.

Ruby Trust Tunnel

The Ruby Trust tunnel (site # 169) was driven northward to intersect veins that crop out higher on the mountain. The tunnel facilitated haulage of ore to the mill and also served to drain water from the mine workings. As with numerous other deep tunnels in the area, this one continues to carry a large volume of water. Load ranking is high. The pH of 5.5–6.0 and the composition of the water suggest that the mine drainage reacted with propylitically altered rocks cut by the tunnel. Because mine-adit drainage flows over the dump and into nearby Middle Fork Mineral Creek, work to minimize reactions with the mine waste may reduce metals loading.

A leach test on one dump sample showed high acid generation and moderate metal release, for a waste ranking of very high. A leach test on a sample of mill tailings showed similar acid generation but high metal release; only a small volume of mill tailings remains at the site.

Bonner Mine

This mine (site # 172) on Middle Fork Mineral Creek had workings and dumps on several levels, and drainage is released on three levels (fig. 19). Based on 11 water samples collected from 1997 to 1999 (Nash, 4; Mast and others, 7), we know that the pH values are consistently acidic (from 2.7 to 3.4) and concentrations of cadmium, copper, iron, manganese, and zinc are high. Concentrations of zinc ranged from about 1,500 to 3,700 ppb. Concentrations of copper also were very high. Remediation work in 2000 was designed to improve water quality and water management. Information gained during excavation in September 2000 (William Simon, oral commun., 2000) suggests that the several mine levels were not interconnected, or had become sealed off, because water in the upper levels did not drain through the lowest tunnel. Mine water at three levels flowed out over mine waste prior to remediation.

Figure 19. Lower adit of Bonner mine, and drainage discharge that flows to Middle Fork Mineral Creek.

Leach tests on three Bonner mine-waste samples showed high acid generation and very low metal release; the average waste rank is high. The concentrations of copper and zinc in leachates were above the median for the study. Because these dumps are close to the creek, runoff can enter the creek with little or no attenuation. The dump may also be adding acid and metals to the percolating mine-adit drainage water.

Independence Mine

Independence mine (mine # 171), west of the Bonner mine complex, has a mine-waste dump that is much smaller than those at the Bonner, but the mineralogy and host rocks are similar. Leach tests show high acid generation, but low metal release, similar to waste samples from the Bonner. The waste rank is medium.

Paradise Mine Area

Several small adits near the headwaters of Middle Fork Mineral Creek release large flows of water (pH 4.7–5.2) that create prominent white and red deposits close to the portals. The largest of these, the Paradise mine (site # 168), is famous for the extremely high aluminum concentration in mine-adit drainage and the snow-white precipitate that forms on the dump (fig. 20). Mineralogical studies show that the white material is the hydrous aluminum-sulfate mineral basaluminite [$Al_4(SO_4)(OH)_{10}$•$5H_2O$]. This mine-adit drainage has a metal-load ranking of high. Load ranking for aluminum is the highest of mine-adit waters in this study, but zinc and copper loads are not as high. Load ranking for the Paradise adit is high. Nearby adit drainages (informally here named Paradise small and Paradise west) have similar compositions but lower flow. Paradise west had lower metal load rankings.

Figure 20. The white color and high flow from the Paradise mine make it famous. Several research investigations have documented the very high aluminum concentration in this water; the bright white material is an aluminum oxyhydroxide phase (basaluminite) that precipitates from the mine water.

Leach tests were made on three samples from the Paradise waste dump and one sample from the smaller dump to the west. The tests of dump waste showed moderate acid generation and low metal release; the average mine-waste rank for this site is medium. One sample of red iron floc on the Paradise mine-waste dump showed high acid generation but low metal release. A sample of the white aluminum-rich precipitate showed moderate acid generation and low metal release.

The Paradise mine workings are relatively small, judging from the size of the dumps, and the pH of the water (5.1) is relatively high. Arguments were made (Nash, 1999a; Mast, Verplanck, and others, 2000) that most of the water has reacted with unmined, altered rocks of peak 3,792 m. Steep topography and the large volume of altered rocks that make up that peak (Bove and others, this volume) produce metal-enriched shallow ground water that can flow into the mine workings or fractures. One remediation option, sealing the tunnel, would minimize water contact with mineralized rocks in the workings, but we suspect that water of similar character would be released along other fractures and that the net improvement in water quality in Middle Fork Mineral Creek would be small.

Sultan Tunnel

This site (# 266) is unusual for the study area in that the tunnel and mine workings are in a stock of granitic rock (Yager and Bove, this volume). The waste dump contains abundant pyrite, but few base-metal sulfide minerals were visible. A leach test showed high acid generation, but low release of copper and zinc; the waste rank is high because of the large dump size and high acidity. Mine drainage from the adit has substantial flow, a pH value of 6.2 (quite high), and moderate copper and zinc concentrations. The mine drainage is diverted into a simple ditch, which to some extent minimizes the interaction of mine drainage with the dump waste.

Discussion and Conclusions

Comparison with Other Studies of Mine Waste

The study of mines and their waste dumps in the Animas River watershed study area by Herron and others (Jim Herron, Bruce Stover, and Paul Krabacher, Unpublished Lower Animas River reclamation feasibility report, Upper Animas River Basin, Colorado Division of Mines and Geology, 2000) included leach analyses of waste materials from more than 130 sites in which leachate solution pH, metal concentrations, and total acidity were determined. The waste characterization studies by Herron and others are similar to our studies, and the rankings are generally similar. Comparison of rankings for 32 sites that both groups studied showed most to be similar, but rankings were substantially different for some sites. The discrepancies may reflect differences in sampling or leach protocols. If the discrepancies influence remediation planning, further studies should be made to resolve the rankings in question. Herron and others (Unpub. Mineral Creek feasibility investigation report, 1997; Unpub. Cement Creek reclamation feasibility report, 1998; Unpub. Upper Animas River reclamation feasibility report, 1999; Unpub. Lower Animas River reclamation feasibility report, 2000) are the sole source of information for mine-waste sites that are on private land.

Mine waste from representative mines and mill tailings in 22 adjoining mining districts on the Colorado Western Slope were studied by the same techniques as used here (Nash, 2002). Passive leach results for 116 samples from those mining areas span a larger range than reported here, including more values that would rank as low in the scale used here. That study supplements the results described here, and suggests that release of acid and high concentrations of heavy metals is characteristic of polymetallic mine-waste dumps in the region.

Comparison with Other Studies of Mine-Adit Drainage

Previous studies of mines on BLM land (Barbara Hite, unpublished mine land inventory report for the U.S. Bureau of Land Management, U.S. Bureau of Mines, 1995) and on USDA Forest Service land (Unpub. abandoned mine land inventory report, San Juan Forest, Columbine district, CGS, 1997) provide additional descriptions, hydrogeochemical data, and interpretations that are generally similar to those of this study. Differences of data or opinion for some specific sites have been discussed elsewhere (Nash, 1999a, 1999b). Some of those differences are matters of emphasis placed on metal concentrations rather than metal loads; the previous studies tended to emphasize problems of some mine-adit drainages having high concentrations but discharges of less than 10 L/m, whereas we emphasized the importance of sites with higher discharges and higher loads.

The metal-load rankings determined (table 4) are in fair accord with the results from Herron and others (Unpub. Mineral Creek feasibility investigation report, CDMG, 1997; Unpub. Cement Creek reclamation feasibility report, CDMG, 1998; Unpub Upper Animas River reclamation feasibility report, CDMG, 1999; Unpub. Lower Animas River reclamation feasibility report, CDMG, 2000), but the rankings for some drainage sites differ substantially. Explanations of the differences could involve numerous factors, such as time of sampling, sampling protocol, or analytical methods. Hydrogeochemical results, discharges, and computed metal loads vary in time; thus, no single sampling event should be used to determine remediation strategy.

Mine-drainage water in the headwaters of the Uncompahgre River and San Miguel River (Nash, 2002), just a few miles north and west of the Animas River watershed study area, spans a compositional range that is similar to the mine-adit drainages described here and includes some extremely acidic water that is even more metal-rich than any sampled in our study area. The Western Slope study (Nash, 2002) included sampling and chemical analysis of 180 surface-water samples; no loads were calculated. The compositional similarities are especially strong for the mine-adit drainages in Red Mountain Creek basin, north of Red Mountain Pass. This area is geologically continuous in the Red Mountain acid-sulfate alteration system (Dalton and others, this volume, Chapter E2; Bove and others, this volume) and is characterized by acidic springs and very acidic mine-adit drainage that mimic the springs and mine-adit drainages of the Prospect Gulch area (Wirt and others, 2001) and the Koehler tunnel–Carbon Lakes area (Kimball and others, this volume). Iron-rich mine-adit drainages, natural springs, and ferricrete deposits continue west from Middle Fork Mineral Creek into the Howard Fork of San Miguel River in the Iron Springs mining area near Ophir. A regional pattern of acid, iron-, copper-, and zinc-rich spring and surface waters radiates from the Red Mountain complex.

Mine Sources in Relation to In-Stream Loads

Quantification of the amount of contamination from mine-adit drainages and mine-waste dumps that moves into streams is difficult. Although great effort was made to sample inflows to streams, especially in the vicinity of the area’s inactive mines, the tracer studies of Kimball and others (this volume) were not able to directly quantify the contributions from most mines in the watershed. Even for draining mine adits within a few hundred feet of the streams, the contributions of loads are ambiguous because the hydrology and chemical reactions that add or attenuate metals in surface and shallow subsurface flows are very complex in the setting of these mines (Kimball and others, this volume). Most of the mines described here are more than a mile from the major streams that were characterized by tracer studies, and for them the contributions are especially ambiguous.

Out of the 40 or so mine sources that we identify as potentially significant, only a few are close enough to streams studied by tracer methods to possibly allow quantification of their contributions. The substantial discharges of contaminated water from mines such as Bandora, Paradise, and Bonner flow into the South and Middle Forks of Mineral Creek, streams that were not subjected to a tracer study. Two of the sites highlighted here (Grand Mogul and Kittimack Mill tailings) were among the 24 major sources of loadings detected in the tracer studies (Kimball and others, this volume), and eight of the mine sites that we ranked high or very high for mine drainage presumably contributed to high loadings on five tributaries highlighted by the tracer studies (Prospect Gulch, Minnesota Gulch, Browns Gulch, South Fork Cement Creek, and Middle Fork Mineral Creek). Three mines close to Cement Creek that are highlighted in our rankings (Mammoth tunnel, Elk tunnel, and May Day mine) were detected in the 1996 Cement Creek tracer study (Kimball and others, 2002). The contributions from the Lark, Joe and Johns, Henrietta, Minnesota Gulch, Natalie/Occidental, Brooklyn, Bonner, and Paradise mines cannot be ascertained at the point of mixing with the major streams. More detailed studies, possibly utilizing tracers injected into underground mine workings, would have to be made to quantify the influence of these and similar mines.

Significant Sources for Remediation

The Animas River watershed study area contains hundreds of potential sources of mining-related contamination (Church, Mast, and others, this volume, fig. 1), but the majority of the excavated sites shown on topographic maps are exploration prospects that disturbed less than about 50 tons of rock. The majority of mines with substantial underground workings and waste dumps are patented claims, on private property. Fewer than 100 mines and prospects on public land were of substantial size, with hundreds of meters of workings and hundreds of tons of mine waste. Out of these sites on public land, fewer than 40 create mine-adit drainage or are situated close enough to major streams to introduce contamination to the watershed that we consider to be significant.

Problematic mining sites on public land were discussed by Nash (1999a, 1999b). Two new sites have been added here, mill tailings placed on public land from the Lackawanna Mill and the Kittimack Mill. Remediation activities at these or other sites will be decided when restoration goals are defined. Dozens of mine sites in the study area release water that at times exceeds water-quality standards set by CWQCD or the Clean Water Act—at the point of discharge. However, these sources of contamination may not be measurable in major streams or at gauging station A72 south of Silverton.

The magnitude of contamination from “dry” sites—those with no obvious surface discharge—is difficult to determine. The monitor wells and detailed studies of the May Day mine (Wright, Kimball, and Runkel, this volume) demonstrate what technologies are needed to evaluate subsurface discharge from either dry or draining sites. Because reactions take place in surface and ground water between the sources and the streams, the contamination predicted by mine site water samples, or from laboratory leach tests, may not accurately reflect what enters the streams. If the abundant geochemical information available for sites on public land is insufficient to guide remediation decisions, then detailed engineering studies will have to be conducted. If required, those studies should include the drilling of wells to document shallow ground water in the vicinity of mine adits, waste dumps, and mill-tailings impoundments. Also, further study is needed on methods to identify the flow paths from mine sources to streams and the water:rock reactions along those paths that change water quality.

This study has addressed issues of mine waste and mine-adit drainage on public land administered by the BLM or the USDA Forest Service, but the same issues obviously exist for mines on private property. Studies of representative private sites by Herron and others (Unpub. Mineral Creek feasibility investigation report, CDMG, 1997; Unpub. Cement Creek reclamation feasibility report, CDMG, 1998; Unpub. Upper Animas River reclamation feasibility report, CDMG, 1999; Unpub. Lower Animas River reclamation feasibility report, CDMG, 2000), using methods similar to those described here, provide data for evaluating the private sites. Such an evaluation was done by Peter Butler, Robert Owen, and William Simon (Unpublished report to Colorado Water Quality Control Commission, Animas River Stakeholders Group, 2001). Although questions of detail may remain about the magnitude or ranking of some individual private or public sites, a general trend seems clear: most of the waste or mine-adit drainage sites with highest potential for watershed contamination (highest loads or leachate concentrations) are on private or mixed private-public sites.

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