Interim report on the scientific investigations in the Animas River watershed, Colorado to facilitate remediation decisions by the U.S. Bureau of Land Management and the U.S. Forest Service, March 29, 2000 Meeting, Denver, Colo.

by **U.S. Geological Survey**

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INTRODUCTION

The joint U.S. Department of the Interior and U.S. Department of Agriculture Abandoned Mine Lands Initiative (AMLI) was developed as a collaborative effort between the Federal land management agencies (FLMA, that is the U.S. Bureau of Land Management and the U.S. Forest Service) and the U.S. Geological Survey (USGS) in 1996. The stated goal of the AML Initiative was to develop a strategy for gathering and communicating the scientific information needed to develop effective and cost-efficient remediation of abandoned mines within the framework of a watershed. Four primary objectives of the AMLI are to:

1. Provide the scientific information needed (in the short-term) by the FLMAs to make decisions related to the design and implementation of cleanup actions,
2. Develop a multi-disciplined, multi-division approach that integrates geologic, hydrologic, geochemical and ecological information into a knowledge base for sound decision making,
3. Transfer technologies developed within the scientific programs of the USGS to the field and demonstrate their suitability to solve real, practical problems, and
4. Establish working relationships among involved members of land management and regulatory agencies within the framework of a watershed approach to the cleanup of abandoned mines.

Long-term process-based research, including development of analytical tools, is recognized as being critical to the long-term success in remediating watersheds impacted by historical mining activities (AML 5-year plan, http://amli.usgs.gov/amli).

In a meeting of Federal agencies (U.S. Bureau of Land Management [BLM], U.S. Bureau of Reclamation [BOR], U.S. National Park Service [NPS], U.S. Forest Service [USFS], the U.S. Environmental Protection Agency [EPA], the U.S. Fish and Wildlife Service [F&WS]), and State agencies (Colorado Division of Public Health and Environment, Colorado Division of Mines and Geology), several watersheds were examined within the state whose water quality was presumed to be impacted by historical mining activities. The Animas River watershed (fig. 1) was selected by the State and Federal agencies as one of two watersheds in the U.S. to be studied in detail by the USGS in the AML Initiative. Beginning in October 1997, each of the four Divisions of the USGS (Water Resources, Geologic, Biological Resources, and National Mapping) initiated a collaborative integrated science study of the watershed. Funds were provided from USGS base funding to each of the four Divisions in response to the priorities set by Congressional action and within the flexibility provided by the budgetary framework funding individual research programs. The AML Initiative provides for a five-year focused scientific effort in the two watersheds with final synthesis of the scientific results from each to be published in 2001. Publications are released on the AML web site on a regular basis (http://amli.usgs.gov/amli).

On March 29, 2000, the USGS hosted a meeting for the BLM and USFS to discuss remediation options that were under consideration for the summer of 2000. The purpose of this report is to provide an overview of the scientific rational provided by the USGS to meet objective one above, and to summarize our preliminary interpretations of our data. Additional information from sites on private lands have been collected by the State of Colorado, EPA, and the ARSG. Unfortunately, these data have not been fully supplied to the USGS so our conclusions are based only upon our data. These interpretations provide science-based constraints on possible remediation options to be considered by the FLMA, the State, and local property owners in the Animas River watershed. The report is presented in outline format to facilitate discussion of remediation options at the March 29, 2000 meeting. Not all historical mining sites within the watershed are on public lands. This should not be construed to be a final report of the USGS on the scientific constraints on remediation options being considered within the watershed.

The effects of various remediation options are considered in the upper Animas River watershed in this report. Different remediation options differ in terms of the scale of their benefits. Some options may have benefits only on a local scale, whereas others may have benefits both locally and on a watershed scale. Benefits from a watershed-scale remedial action may be evident only far downstream from the remediated site.

Geographic Setting

Within this report, the Animas River watershed (fig. 1) is subdivided into three basins: 1) the upper Animas River basin above the confluence with Cement Creek, 2), the Cement Creek basin, and 3) the Mineral Creek basin. The Animas River watershed is an area of rugged mountainous relief. In order to break the watershed down into areas that can be considered and assess the impact of remediation on individual sites, subbasins were defined on the basis of the drainage area of the major tributaries that drain directly into these streams. For example, the Middle Fork Mineral Creek drainage area is a subbasin in the Mineral Creek basin. The discussions that follow in this report focus on the geologic complexity, mine and adit locations, and metal loading of the three basins, and the potential impact on water quality and toxicological effects on biota of the remediation options within each of the three basins.

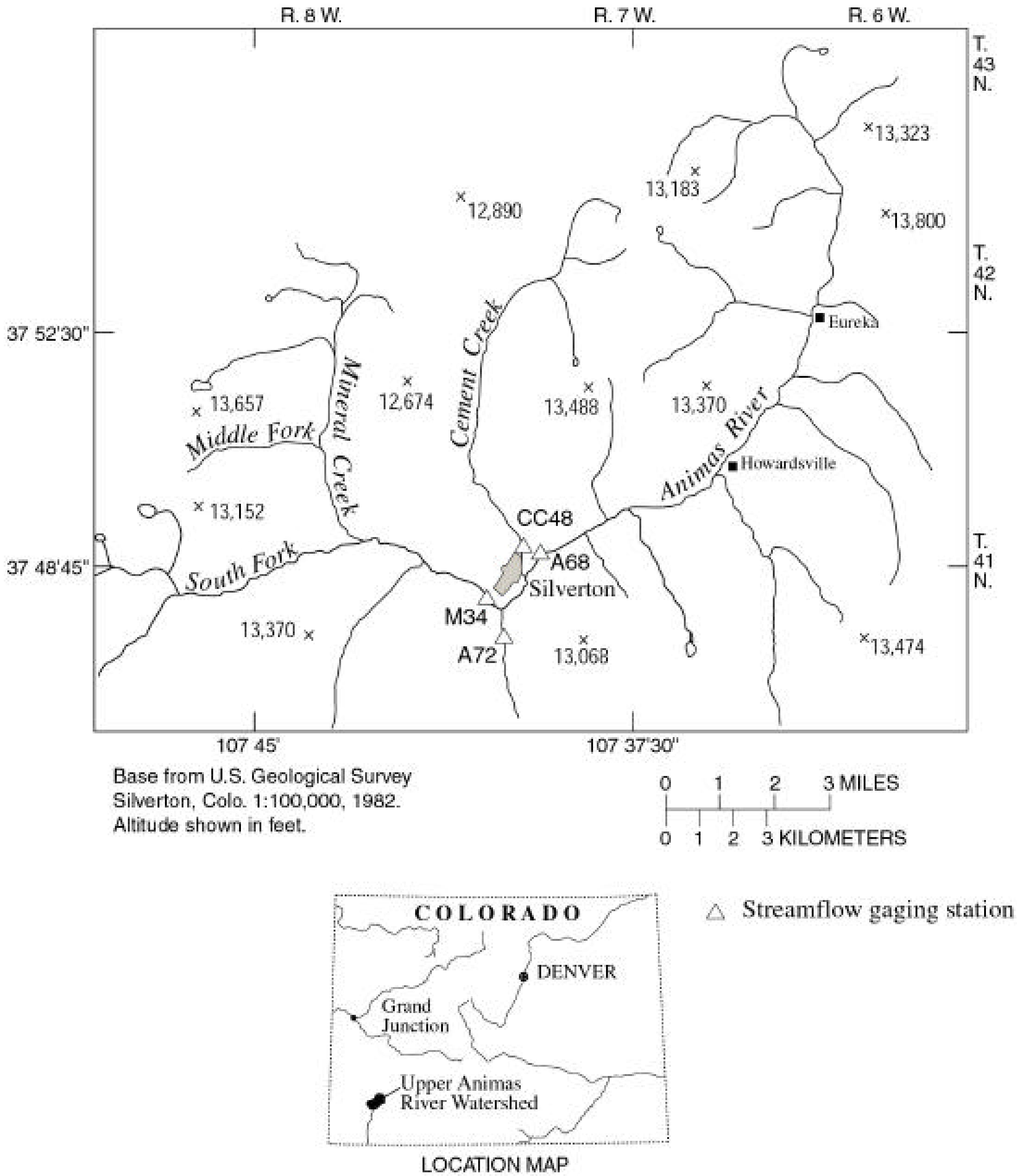

Figure 1. Map of the Animas River watershed showing the upper Animas River, Cement and Mineral Creeks, and some of their major tributaries. Gaging stations are shown near the confluences of the major streams. The gaging station below the confluence with Mineral Creek at Silverton, Colorado, site A72, has been designated by the State Water Quality Control Commission as the compliance site for water quality measurements for the Animas River watershed. The three basins discussed constitute the drainage from the upper Animas River above the confluence with Cement Creek (A68), the drainage from Cement Creek above Silverton (CC48), and the drainage from Mineral Creek above the confluence with the Animas River (M34). Major peaks are indicated by the x with the elevation of the peak.

Geologic Setting

The Animas River watershed (fig. 1) has its headwaters in the mountainous terrain above Silverton, Colo. and drains south into the San Juan River in northern New Mexico. Elevations range from more than 13,000 ft (3,900 m) at the headwaters to less than 6,000 ft (1,830 m) at the confluence with the San Juan River near Aztec, New Mexico. Rocks in the headwaters of the Animas River watershed north of Silverton are largely Tertiary volcanic rocks. Two calderas formed (fig. 2); the more recent of which is the Oligocene Silverton caldera, which created a large circular depression approximately 8 miles (13 km), in diameter (Lipman and others; 1976, Yager and Bove, in press). The central part of the caldera was partially filled by igneous intrusive and volcanic rocks that formed as a result of eruption of late Tertiary ash flows and andesitic to dacitic volcanic rocks. During the cooling of the caldera fill, water-rich hydrothermal fluids containing carbon dioxide gas altered the lavas forming an alteration assemblage of calcite-epidote-chlorite that provides acid-neutralizing potential for near-surface springs and surface waters (generally near a pH of 6.0-7.5). This area of the Animas River watershed above Silverton was extensively fractured forming a network of regionally small fractures that control ground-water flow. These structures controlled the hydrothermal alteration and mineralization by subsequent Miocene hydrothermal activity (Burbank and Luedke, 1968; Casadevall and Ohmoto, 1977). Subsequent pervasive and intense hydrothermal alteration and mineralization events postdate the formation of the Silverton caldera by one to several million years (Lipman and others, 1976; Bove and others, 1999). Geologic mapping and airborne geophysical surveys suggest that regional alteration extended from the surface to significant depths. This later hydrothermal fluid contained sulfur-rich fluids and metals that produced various vein and alteration mineral assemblages, all of which include abundant pyrite. The late alteration event also removed the acid-neutralizing mineral assemblage of calcite-epidote-chlorite.

Uplift, glaciation, and erosion of the area in the recent geologic past has resulted in the rugged relief in the headwaters of the Animas River. Mineral deposits were exposed at the surface prior to mining (Church and others, 2000). As a result, weathering reactions with these more intensely altered rocks produce acidity and release metals

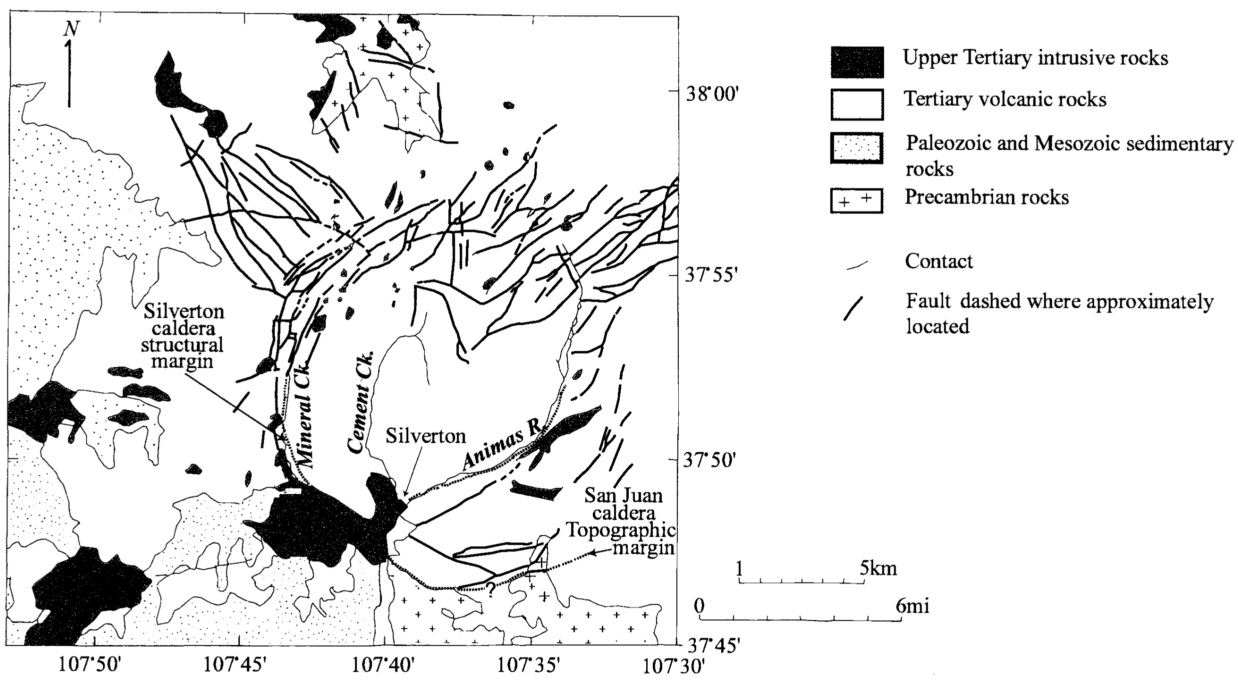

Figure 2. Generalized regional geologic map of the Animas River watershed. The Animas River and Mineral Creek follow the structural margin of the Silverton caldera. In addition to the ring-fractures that were created when the Silverton and the earlier San Juan calderas formed, radial and graben faults, which host much of the subsequent vein mineralization, are shown schematically (modified from Casadevall and Ohmoto, 1977).

to the surface and ground waters (Bove and others, 2000; Mast and others, 2000). Springs draining ground water from these intensely altered rocks have pH values in the range of 2.7-4.0. More than one hundred years of historical mining activity has created many miles of underground workings and produced large volumes of mine waste rock that have been pulverized to remove ore metals. These mine workings provide pathways for ground water that has reacted with mineralized rock producing acidic waters that flow from mine adits. The increase in the surface area and exposure of large amounts of pyrite to oxidation in the waste rock piles has resulted in large anthropogenic sources of acidic drainage that impact water quality and aquatic and riparian habitats in the watershed. Changes in the different drainage basins resulting directly from historical mining activities can be seen by the comparison of the streambed sediment geochemical baseline prior to mining and today (Church and others. 2000). As a result, there has been a loss of productive aquatic and riparian habitat and a reduction in recreational and aesthetic values. Furthermore, the increased acidity and metal loading constitutes a potential threat to downstream drinking water supplies.

Mining History

Placer gold deposits were discovered in 1871 on Arrastra Creek above Silverton by prospectors following the occurrence of gold upstream. Following the signing of a treaty with the Ute Indians in 1873, between 1,000 and 1,500 mining claims were staked in the Animas River watershed upstream from Silverton. Mining activity spread rapidly throughout the area. The ore deposits in the headwaters of Mineral Creek (fig. 1) were discovered in 1881. The railroad was extended from Durango in 1882, providing inexpensive transportation to the smelters in Durango. Mining continued in the Animas River watershed at various levels of activity until 1991 when the Sunnyside Mine was closed. Mines in several major mining districts within the Animas River watershed have recorded production. Deposits in the Red Mountain district in the northwestern part of the Silverton caldera, the Eureka district in the Eureka graben within the Silverton caldera, and the South Silverton district along the southern margin of the Silverton caldera southeast of the town of Silverton comprised the majority of the mineral production (fig. 2). More than 11 million tons of ore were milled over this period (Burbank and Luedke, 1968).

There are also several unmined porphyry molybdenum deposits in the Mineral Creek area. Some of the porphyry molybdenum deposits are surrounded by large iron bogs at the surface. Iron bogs are found elsewhere within the basin associated with springs flowing from mineralized and altered areas within the watershed.

AML Initiative Studies

The USGS conducted several kinds of studies and data collection efforts in order to characterize the watershed and the impacts of mining. Geologic studies were undertaken to define the geologic controls that affect the extent of impact to the streams. Hydrologic studies were done to determine the levels of metals in the streams and the relative contribution of various point and natural sources within those reaches. Biological studies determined the current health of key species of fish and benthic organisms, the toxicity of the stream environment, and limitations due to alteration of physical habitat characteristics. Cartographic data were collected to provide a base for geospatial referencing of scientific data and to allow geospatial analysis of the interrelationships among the various types of watershed data that were collected. Together, these data allow the USGS to develop a picture of the current physical and ecological state of the watershed and to estimate which remediation actions may have the most potential for success.

Geologic Studies

The USGS has undertaken geologic and geochemical studies designed to establish the geologic framework of the watershed. These studies, many of which are still in progress, are designed to evaluate the geologic controls that will affect remediation actions within the Animas River watershed. They include:

- Project personnel have compiled a geologic map of the watershed (scale 1:48,000) on the basis of published and unpublished mapping done over the past century, unpublished USGS airborne geophysical data, and new mapping (Yager and Bove, 2000; B.D. Smith, unpub. data, 1999). These data provide a lithologic and structural framework for interpretation of the integrated AML studies.

- Mineralogical and alteration maps of the entire watershed, as well as selected detailed study areas determined by new field mapping, airborne geophysics, and AVIRIS remote sensing, have been compiled to produce a watershed scale interpretation of the hydrothermal alteration within the caldera. These data and interpretations characterize multiple mineralization processes throughout the watershed, the primary and weathered composition of rocks and alluvium, and the potential for generation or attenuation of acidic waters and metals (Dalton and others, 2000; Yager and others, 2000; Bove and others, 2000).

- Characterization of primary stages of ore formation and rock alteration, the structural controls on ore distribution, and the role of post-glacial and modern weathering processes on the release of acid or metals to near-surface waters were evaluated (Nash, 1999a,b; Mast and others, 2000; Bove and others, 2000; Yager and others, 2000). Studies of pre-mining baseline waters demonstrate that the degree of metal mobilization and acid production correlates well with the type of altered rock and structural features in which these waters interact (Bove and others, 2000).

- An updated mine inventory and new sampling of mine waste dumps and mill tailings, with chemical analyses and leach tests to determine the potential of these materials to generate acid and release metals were utilized to develop a numeric ranking of dump sites on public lands. These data summarize the likely impact of the mine sites for reclamation planning (Nash, 1999a,b, 2000; Fey and others, 2000).

- A revised inventory of mines on public lands indicates that less than 50 sites out of the hundreds of mines and small prospects on public lands have water flowing and transporting contaminants beyond the mined area. These sites have been described and ranked (Nash, 1999a, 1999b); 17 sites were ranked as high and medium priority for reclamation.

- Hydrogeochemical investigations of adit flow indicate that more than 30 adits on both public and private lands have adit flows in excess of 25 gal/min. that degrade water quality. Of these, half are on public lands.

- Interim interpretations of hydrologic interactions with unmined rocks, structures, mines, and mined materials that rank sources and pathways of mine-related contaminants on public lands (Nash, 1999a,b; Fey and others, 2000).

- Maps of the distribution and composition of young, pre-mining alluvium in floodplains of the major streams indicate the composition of weathered detritus and surface waters prior to mining (Church and others, 1997; Church and others, 2000).

- Maps of the distribution and composition of iron-rich deposits (for example, ferricrete, bogs, and peat deposits), their ages of formation, and implications on the release of acid rock drainage thousands of years ago.

- Geomorphological evaluation of the pre-mining nature of the channels and floodplains of the Animas River from Eureka to Howardsville, identification of the cause of changes in those landforms, identification of chemistry of pre-mining and historical sediments, documentation of historical (post 1945) trends in nature of channels and floodplains, and identification of the locations and volumes of ore-mill tailings in the reach (Vincent and others, 1999; J.G. Elliott and K.R. Vincent, unpub. data, 1998).

The USGS studies of hydrothermal alteration within the watershed form a framework for the assessment of probability of successful remediation within individual basins. A preliminary map summarizing the different alteration zones within the Animas River watershed is in figure 3. This map has been developed from an interpretation of the AVIRIS data (Dalton and others, 2000) on the basis of field examination of alteration suites within subbasins by D.J. Bove and D.B. Yager (unpub. data, 2000). The alteration intensity varies from the regional propylitic alteration associated with the late stages of caldera formation to increasingly more intense alteration associated with subsequent mineralization events. These subsequent events are the weakly sericitic alteration associate with polymetallic vein mineralization, the quartz-sercite-pyrite (QSP) mineralization associated with porphyry molybdenum and subsequent vein deposits, and the acid sulfate alteration suite associated mineralization in the Red Mountain Pass area at the headwaters of Mineral Creek and the Anvil Mountain area between Cement Creek and Mineral Creek basins.

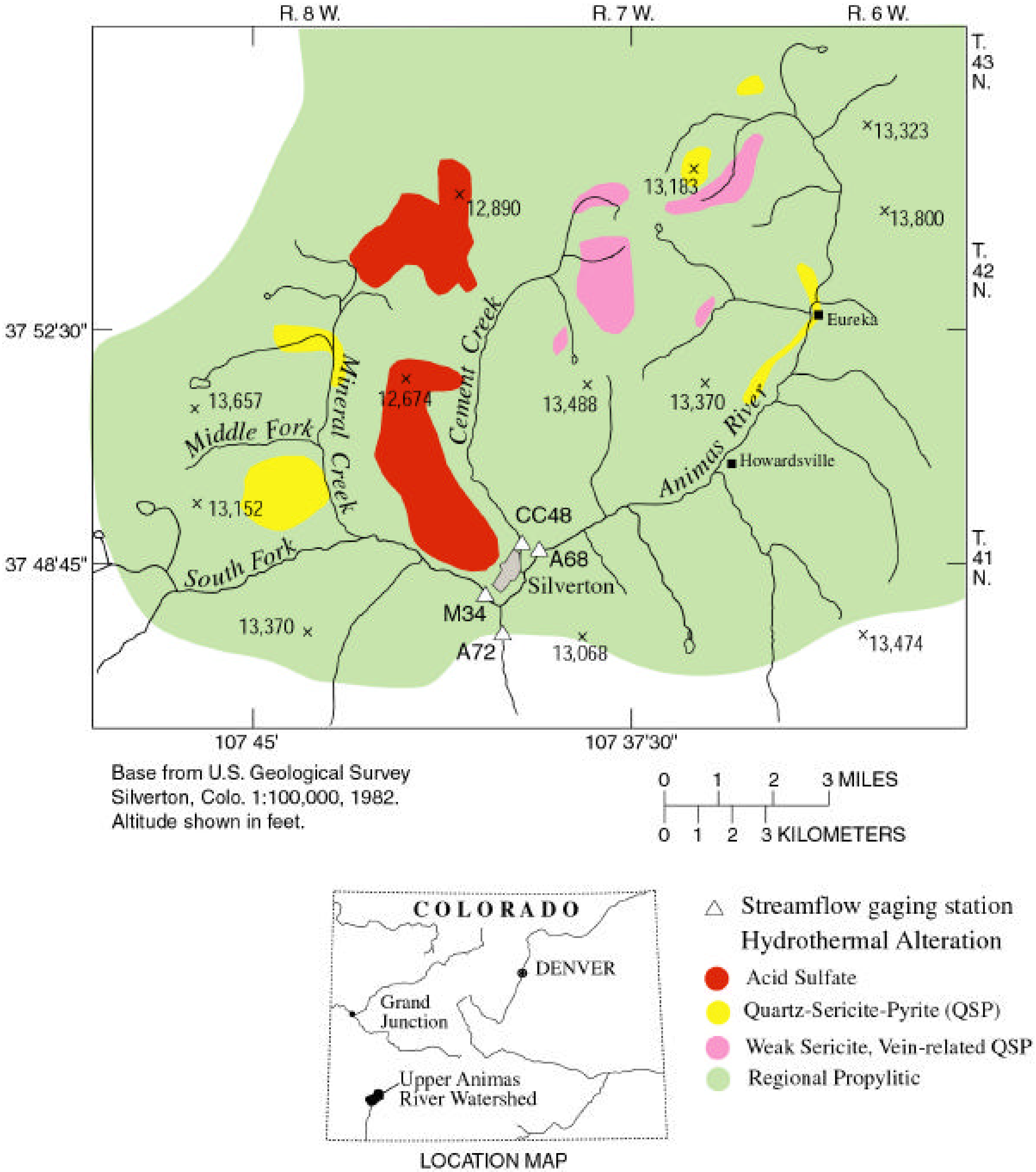

Figure 3. Preliminary analysis of areas of differing hydrothermal alteration associated with mineralization events in the Animas River watershed (D.J. Bove, D.B. Yager, and J.B. Dalton, unpub data, 2000).

The USGS has examined the waste-rock dumps within the Animas River watershed associated with mine sites on Federal lands. The data in figure 4 are from Fey and others (2000) and utilize size, acid generation potential, and releasable metals as criteria for the ranking. The data in figure 5 are from Nash (1999a,b) and incorporate size, mineralogy, chemistry, water chemistry from adits, and proximity to receiving streams as additional parameters for the mine waste dump ranking. These maps also provide the reader with specific site names referred to throughout the text.

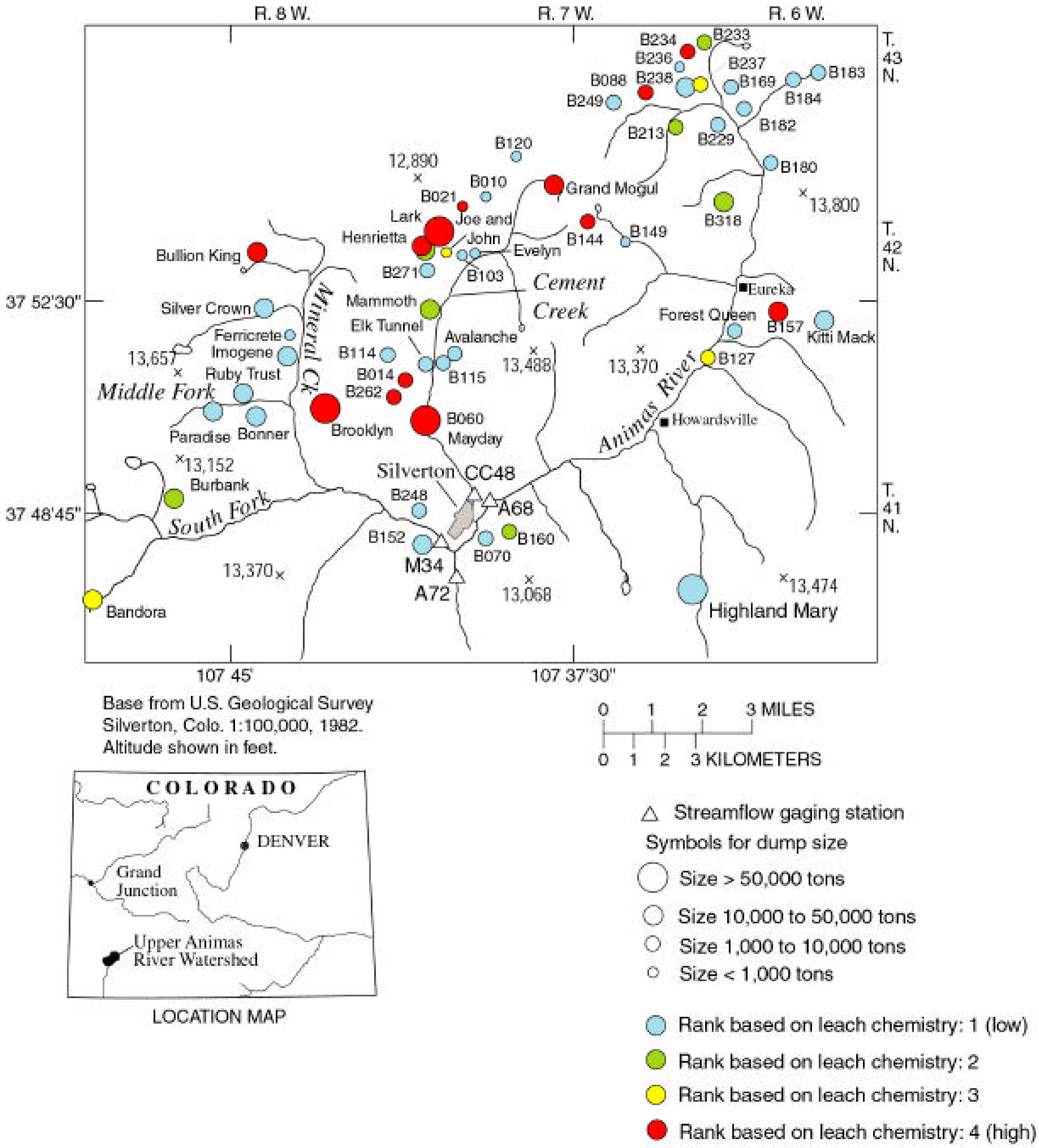

Figure 4. Ranking of mine sites on the basis of leach chemistry, acid neutralization potential, and size of the mine waste dumps (Fey and others, 2000).

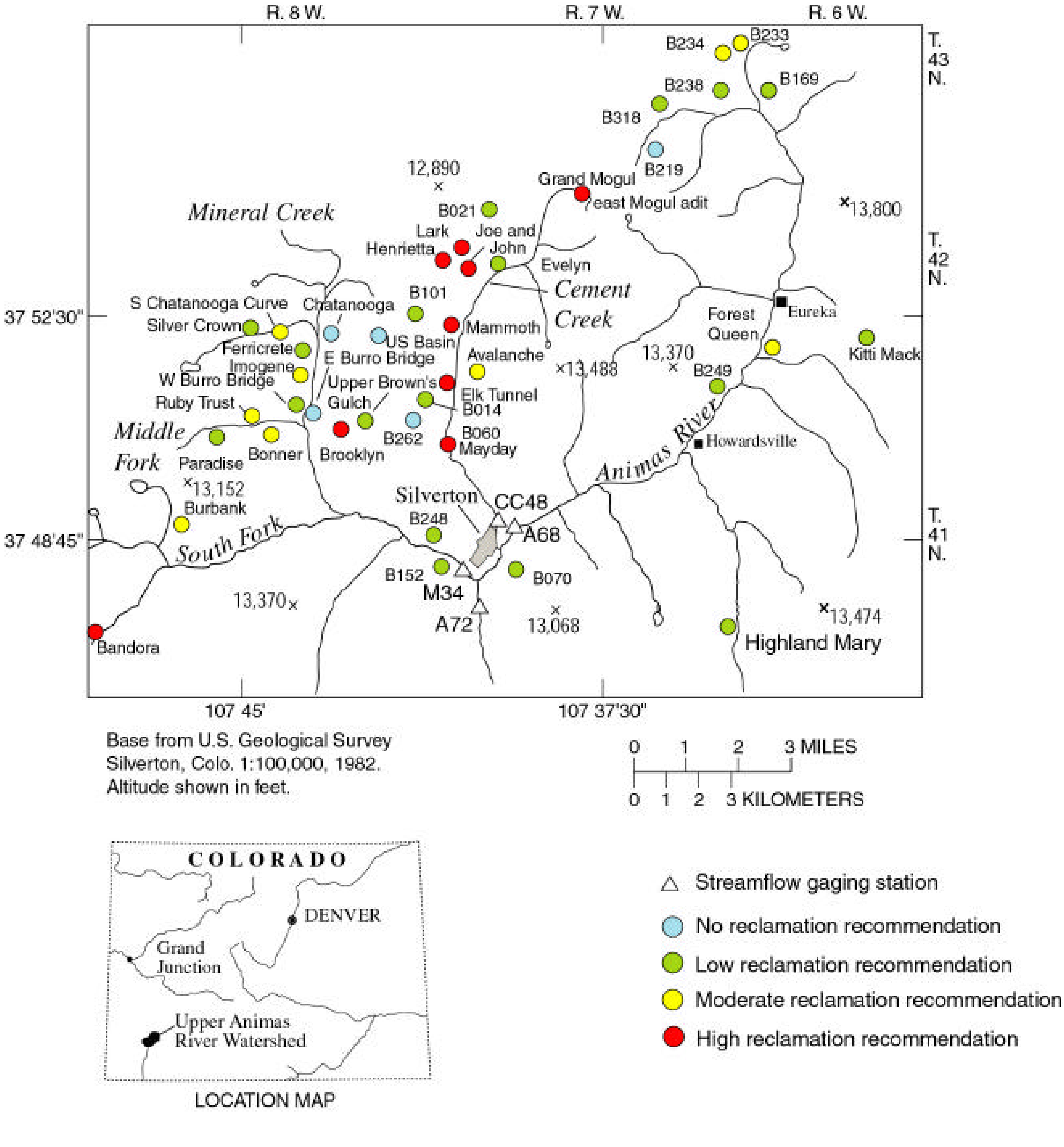

Figure 5. Ranking of mine sites on the basis of size, mineralogy, and chemistry of the mine waste dumps, water chemistry from adits, and proximity to receiving streams (Nash, 1999a,b).

Biological Studies

Several studies have been conducted to evaluate mining-related impact on the diversity and productivity of stream biological communities of the upper Animas River watershed. These studies include:

- Bioaccumulation of potentially toxic metals by stream biota and transfer of metals via stream food webs (Besser and others, in press),

- Potential limitation of stream trout populations by physical habitat of the upper Animas River watershed (Milhous, 1999),

- Characterization of the toxicity of stream water, sediment, and sediment porewater from the upper Animas River watershed to fish and aquatic invertebrates (Besser and Leib, 1999; J.M. Besser, unpub. data, 2000), and

- Determination of site-specific thresholds for toxicity of zinc and copper to fish and invertebrates in the upper Animas River (J.M. Besser, unpub. data, 2000).

Although the biological studies have identified several mechanisms that may contribute to impacts on biological communities of the upper Animas River watershed, including degradation of physical habitat and chronic toxicity of metal-contaminated sediments and diets, the available evidence indicates that the toxicity of dissolved metals in stream water is the most severe limitation on the distribution and abundance of fish and benthic invertebrates in the watershed. Toxicity tests with stream water collected from three gaging stations near Silverton, Colo. (fig. 1; A68, Animas River at Silverton; M34, Mineral Creek at Silverton; and A72, Animas River downstream of Silverton) indicate that water from all three sites is toxic to fish and/or invertebrates and that toxicity of stream water varies among seasons (J.M. Besser, unpub. data, 2000). These differences are consistent with seasonal variation in concentrations of dissolved metals, especially zinc and copper (K.J. Leib and W.G. Wright, unpub. data, 2000).

We can evaluate the potential for improvement in stream biological communities resulting from remediation in the three basins based on the assumption that the toxicity of dissolved zinc and copper in stream water is the principal factor limiting stream biological communities. We can predict the seasonal range in toxicity of stream water at the three gaging stations listed above under current conditions, on the basis of models of seasonal variations in dissolved zinc and copper concentrations (K.J.Leib; unpub. data, 2000). These models are under development, and in the future will form the basis for predicting the effectiveness of proposed remediation projects, based on projected decreases in dissolved zinc and copper concentrations. Toxicity of stream water at three Silverton gaging stations is modeled on the basis of toxicity of copper and zinc to three test organisms. Seven-day toxicity tests with freshwater amphipods, or freshwater shrimp (*Hyalella azteca*) and fathead minnows (*Pimephales promelas*) were conducted under the same conditions used to test the toxicity of stream water. Toxicity thresholds for brook trout (*Salvelinus fontinalis*), the principal fish species occurring in the upper Animas River watershed, were determined from chronic, early life-stage toxicity tests (71-day exposure period), which started with eyed-eggs and concluded 30 days after fry reached the swim-up stage. All toxicity tests were conducted in reconstituted test waters with chemical characteristics (hardness, pH, alkalinity) similar to stream water in the Animas River at Silverton. The range in toxicity for each metal was estimated from the range between toxicity thresholds for the most sensitive of the species and for a second, more tolerant species, expressed as µg/L (parts per billion) of dissolved metal (table 1). Threshold concentrations for copper toxicity to brook trout were approximated by the range of two values, representing thresholds for reductions of survival and growth. Threshold concentrations for the least sensitive species for each metal (that is, the brook trout threshold for zinc of approximately 1,000 µg/L, and the amphipod threshold for copper of 58 µg/L) rarely, if ever, occur at any of the gaging stations.

Threshold concentrations for toxicity of zinc and copper to sensitive and tolerant species in table 1 are not adjusted for seasonal variation in hardness, which modifies the toxicity of these metals. National water quality criteria for protection of aquatic life from zinc and copper toxicity (U.S. EPA, 1999), calculated on the basis of seasonal variation in hardness of stream water at the three Silverton gages, are generally similar to the toxicity thresholds for sensitive test species (amphipods for zinc, brook trout for copper; table 1). However, because hardness is greatest in summer and lowest during winter, the toxicity thresholds in table 1 may overestimate toxicity during winter and underestimate toxicity during summer.

Table 1. Toxicity thresholds for dissolved zinc and copper to 'sensitive' and 'tolerant' species, used to characterize current and projected toxicity of stream water at gaging stations.

[Thresholds are on the basis of toxicity tests in 'Animas River' reconstituted water (50 percent mortality of amphipods and minnows in 7-day test; 25 percent reduction in growth or survival of trout in early life-stage test)]

Metal	Sensitivity Level (species)		Concentration (µg/L)
Zinc	Sensitive	(amphipod)	160
	Tolerant	(minnow)	700
Copper	Sensitive	(brook trout)	8.1 (growth), 24 (survival)
	Tolerant	(minnow)	33

Hydrologic Studies

The USGS has conducted hydrologic studies of natural seeps and springs, adit drainages, and major streams within the Animas River watershed. The hydrologic studies include:

- Four years of data collection at stream gaging stations to define seasonal variability of streamflow and loads of metals for the watershed and three major basins (K.J. Leib, unpub. data, 2000),
- Two years of data collection at stream sites upstream from the stream gages, to define seasonal variability of streamflow and loads for smaller subbasins (K.J. Leib, unpub. data, 1999; Besser and Leib, 1999), and
- Discharge and chemical composition of mined and unmined sources determined throughout the basin (Nash, 2000; Wright and Nordstrom, 1999; W.G. Wright, unpub. data, 1999).
- Watershed-scale tracer-injection studies conducted at low flow to define loadings for specific stream segments along the major streams. These include:
  - Cement Creek in 1996 (Kimball and others, in press),
  - The Animas River near Silverton and from Howardsville to Silverton in 1997 (B.A. Kimball, unpub. data, 1999),
  - The Animas River from Eureka to Howardsville and from Silverton to Elk Park in 1998 (B.A. Kimball, unpub. data, 1999), and
  - Mineral Creek from Red Mountain Pass to Silverton and Cement Creek from Ross Basin to the South Fork in 1999 (B.A. Kimball, unpub. data, 1999).
- Subbasin-scale tracer-injection studies conducted at three separate dates in 1998-1999 in Prospect Gulch (Wirt and others, 1999; L.Wirt and others, unpub. data, 1999).

Streamflow gaging stations, located near the mouth of each of the three basins (fig. 1), provide data that quantify the annual hydrograph, showing the seasonal variation of streamflow. Figure 6 shows the hydrograph for the gaging station on the Animas River below Silverton, Colo. (A72, fig. 1) for water years 1995-1998. Frequent sampling and chemical analysis of the streams at the gages allow modeling of seasonal changes in loading at each of the stream gages (K.J. Leib, unpub.data, 1999). The following analysis of loads focuses on results of the tracer-injection studies during low-flow conditions of late summer, the troughs in figure 6, because ground-water inflows are more evident during that time.

New chemical and flow data from tracer-injection studies collected from the major streams provide a detailed and more accurate picture of the stream reaches that receive the greatest metal loadings. Experience with tracer studies in the western United States indicates that metal loadings calculated from tracer data are more accurate than loading calculations from conventional stream-gaging measurements. Stream discharge calculated by tracer dilution accounts for flow in the hyporheic zone (Kimball and others, 1999). However, because the tracer-injection studies in the watershed occurred in different years and at different flow conditions, it was necessary to scale the data to a common basis to make the load calculations comparable between basins. The average low-flow contribution of streamflow from each of the basins corresponds to the contributions during the time of the tracer study near Silverton in 1997 (Schemel and others, 2000; B.A. Kimball, unpub. data, 1999). This allows us to scale the loads from different basins, and provides a uniform perspective of the metal loads at the watershed scale (fig. 7). The upper Animas River basin contributed the greatest percentage of streamflow and zinc load. The copper load, however, was dominated by the contribution from Mineral Creek.

The information presented from the tracer studies gives the chemical perspective from the streams; what loads actually reach the stream? For example, information on the South Fork subbasin in Cement Creek represents the combined effects of all metal sources in that subbasin and their total contribution to Cement Creek. The metal loads are in kilograms per day for zinc and copper (table 2) and the scaling makes them comparable between basins. Information for loads of total copper and zinc is emphasized because of their tie to the biological studies.

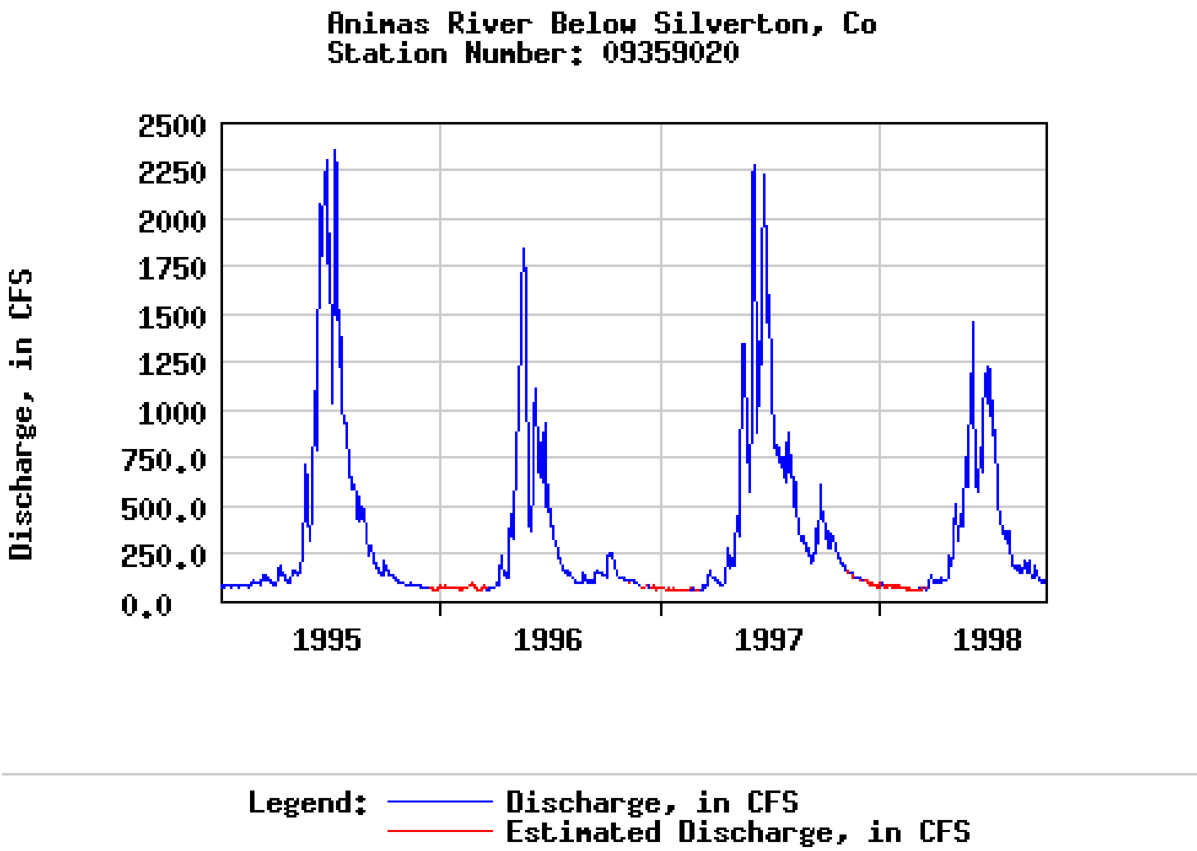

Figure 6. Hydrograph for the period Jan. 1995-Sept. 1998 measured at the USGS gaging station on the Animas River below Silverton, Colorado (A72). Discharge is expressed in cubic feet per second (cfs). Water data are available from http://waterdata.usgs.gov/nwis-w/CO/?statnum=09359020.

To summarize the loading data, results have been divided into several reaches for each basin. The locations of these reaches are indicated in figure 8. A summary of the stream reaches is listed in table 2, indicating the total loads of zinc and copper and the number of individual sampling segments from the tracer-injection studies that are included in the reach. In these streams, zinc, and especially copper are reactive and sorb to iron colloidal material (Church and others, 1997). Copper changes from the dissolved to the colloidal form as the pH of the stream water approaches 7. To account for this dynamic behavior, total copper loads, both dissolved and colloidal, are reported in table 2. We know that some of this metal load does not reach the mouth of each basin, but is stored in the colloidal material that accumulates in the biofilm and on the streambed. Studies of colloid chemistry and suspended sediment loads indicated that the easily extractable metals in the streambed sediments were dominated by the colloidal components (Church and others, 1997). Much of this stored material is transported downstream under high-flow conditions.

The ground-water hydrology of the Animas River watershed has been profoundly and permanently modified by historical mining activity. A number of mines have significant adit flow indicating that they have intersected major ground-water flow (flow rates greater than 25 gal/min). Hydrogeochemical analyses of more than 50 mine drainage sites indicates that the water quality at many sites exceeds the Colorado Water Quality Control Commission standards for aquatic life (Nash, 2000; Herron and others, 1997, 1998, 1999). This aggregate ground-water flow makes a significant contribution to the metal load of the receiving streams. Limited studies of these ground-water systems have been made during the course of the AML Initiative (W.G. Wright, M.A. Mast, J.T. Nash, and L. Wirt, unpub. data, 2000).

The hydrogeologic interpretation of loadings in the complex setting of the San Juan Mountains is enigmatic. Despite the accurate loading calculations from low-flow tracer-injection studies, **the entire load measured for a particular stream segment can not be attributed to a specific source.** Flowpaths of metal-rich water from adits, mine wastes, and mill tailings at or near the stream course may appear straight forward, but the presence of the mine waste pile on the stream bank may mask a ground-water contribution from a fault concealed by the mine waste pile for example. Flowpaths from anthropogenic sources located some distance from the stream, more than 1 km, may be even less certain. In general, our certainty about flowpaths from specific sources decreases as the distance between the assumed anthropogenic source and the stream increases. In interpreting the loading data, we imply no direct correlation with the anthropogenic source unless we have traced the inflow pathway to the source. However, in estimating the benefit of remediation, we have assumed that remediation at the mine site will totally remove the metal load once a site is remediated. Although this is unlikely, this method of analysis expresses the maximum effect that might be achieved if a specified site to be remediated were the sole source of the metal load in the segment. Detailed, site-specific engineering work must be done to establish the cause-and-effect relationships between our measurements of metal loadings and the sources of those metals and the potential for remediation.

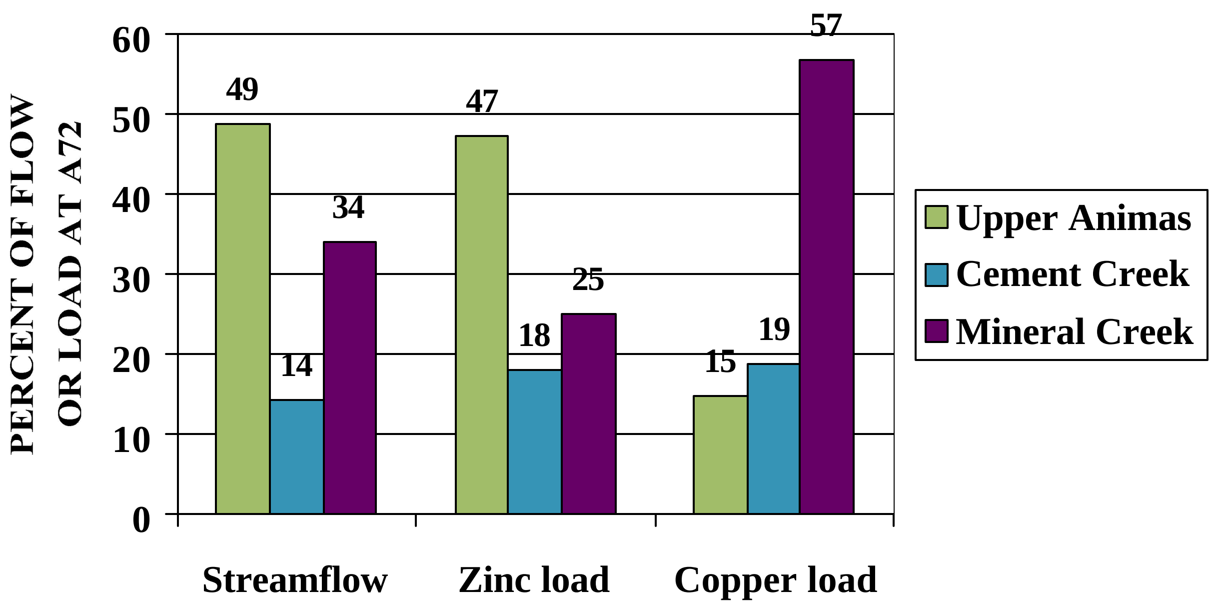

Figure 7. Contributions of discharge, zinc load, and copper load from each of the basins upstream from Silverton during low-flow conditions, 1997. Values are expressed in percent contributed to the downstream gaging station at A72 (see fig. 1).

The low-flow tracer studies, summarized here, show that the majority of mine sites on public lands contribute a small percentage to metal loads as measured in the major streams. The tracer studies suggest that these sites on public lands with smaller loading might not be high priority sites for reclamation relative to other sites that contribute greater metals loading to the major basins. Many of the specific mine sites on public lands that warrant further evaluation for removal are shown in figure 4 and figure 5 and summarized in Nash (1999a,b) and Herron and others (1997, 1998, 1999).

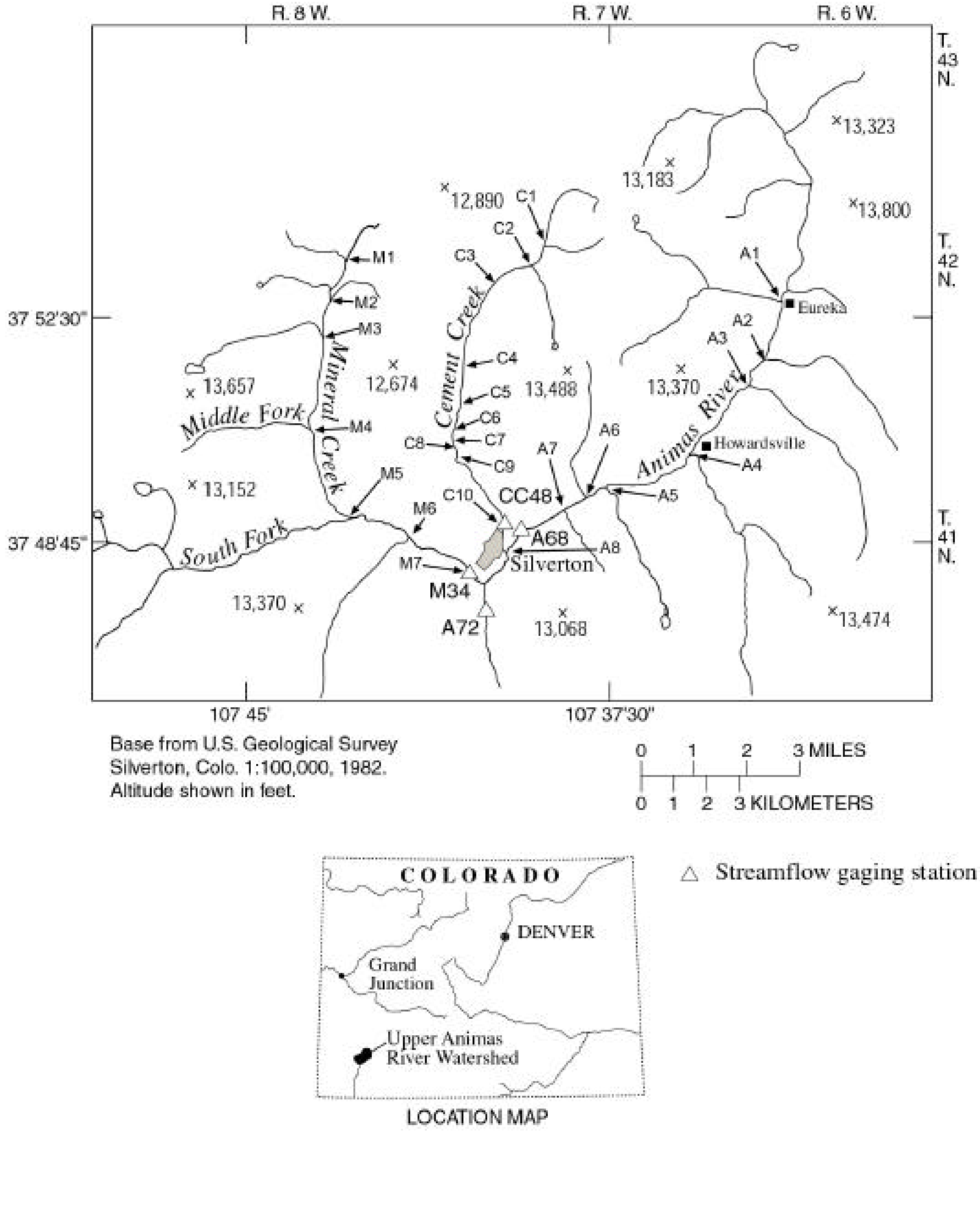

Figure 8. Map of the Animas River watershed showing the upper Animas River, Cement and Mineral Creeks, and some of their major tributaries. Gaging stations are shown near the confluences of the major streams. Stream segments referred to in text and defined on the basis of major loadings as determined from the tracer studies (see table 2) are indicated by the arrows and labels: A for upper Animas River basin, C for Cement Creek basin, and M for Mineral Creek basin. Major peaks are indicated by the x with the elevation of the peak.

Table 2. Scaled metal loadings of dissolved zinc and copper determined from reaches in the upper Animas River watershed, San Juan County, Colo.

[Basin, tributary of the Animas River; Reach, group of stream segments from a tracer-injection study that is used in the calculation; number of segments, number of segments that are combined in the calculation.]

Basin	Reach	Number of segments in tracer study	Total Zinc Load kilograms per day / percent of watershed total	Total copper load, in kilograms per day / percent of watershed total
Load at A72 gage; Animas River below Silverton	**Watershed totals**		**125.9 / 100%**	**7.64 / 100%**
Downstream from Mineral Creek			**12.1 / 9.6%**	**0.734 / 9.6%**
Upper Animas River	**Basin totals**		**59.4 / 47.2%**	**1.14 / 14.9%**
	A1: Upstream from study area and Eureka Gulch subbasin	3	3.58 / 2.8%	0.093 / 1.2%
	A2: From Eureka Gulch to Minnie Gulch	6	6.23 / 5.0%	0.054 / 0.7%
	A3: Minnie Gulch subbasin to Maggie Gulch	5	3.81 / 3.0%	0.005 / 0.1%
	A4: Maggie Gulch subbasins to Cunningham Gulch	10	6.02 / 4.8 %	0.024 / 0.3%
	A5: Cunningham Gulch subbasin to Arrastra Gulch	15	8.78 / 7.0%	0.320 / 4.2 %
	A6: Arrastra Gulch subbasin to Boulder Creek	6	9.80 / 7.8%	0.278 / 3.6%
	A7: Boulder Creek subbasin through Blair Gulch subbasin	2	5.71 / 4.5%	0.089 / 1.2%
	A8: Below Blair Gulch to A68 gage at Silverton	10	15.5 / 12.3%	0.272 / 3.6%
Cement Creek	**Basin totals**		**22.8 / 18.1%**	**1.44 / 18.8%**
	C1: Upper Cement Creek subbasin above confluence with the North Fork Cement Creek	1	1.89 / 1.5%	0.175 / 2.3%
	C2: North Fork subbasin to South Fork	5	1.47 / 1.2%	0.390 / 5.1%
	C3: South Fork subbasin to Prospect Gulch	7	2.17 / 1.7%	0.175 / 2.3%
	C4: Prospect Gulch subbasin to Minnesota Gulch	16	3.78 / 3.0%	0.178 / 2.3%
	C5: Minnesota Gulch subbasin to Porcupine Gulch	3	2.92 / 2.3%	0.090 / 1.2%
	C6: Porcupine Gulch subbasin to Ohio Gulch	6	1.13 / 0.9%	0.066 / 0.9%
	C7: Ohio Gulch subbasin to Illinois Gulch	1	0.73 / 0.6%	0.039 / 0.5%
	C8: Illinois Gulch subbasin to Topeka Gulch	3	1.25 / 1.0%	0.051 / 0.7%
	C9: Topeka Gulch subbasin to Niagara Gulch	4	0.48 / 0.4%	0.052 / 0.7%
	C10: Niagara Gulch subbasin to Cement Creek gaging station	13	7.02 / 5.6%	0.197 / 2.6 %
Mineral Creek	**Basin totals**		**31.6 / 25.1%**	**4.33 / 56.7%**
	M1: Headwaters through Mineral Creek subbasin	14	8.38 / 6.7%	1.71 / 22.4%
	M2: From Mineral Creek through Porphyry Gulch subbasin	15	7.99 / 6.3%	1.48 / 19.4%
	M3: From Porphyry Gulch though Mill Gulch subbasin	10	1.62 / 1.3%	0.39 / 5.1%
	M4: From Mill Creek to Middle Fork, including Brown's Gulch subbasin	19	2.40 / 1.9 %	0.33 / 4.3%
	M5: Middle Fork subbasin to South Fork	14	4.14 / 3.3%	0.27 / 3.5%
	M6: South Fork subbasin to Bear Creek	4	3.95 / 2.9%	0.13 / 1.7%
	M7: Bear Creek subbasin to Mineral Creek gage	8	3.45 / 2.7%	0.02 / 0.3%

Geospatial Data Studies

A Geographic Information System (GIS) database is being created for the AML upper Animas River Basin study area. The database contains the data collected for the studies, including:

- Base cartographic data such as hydrography, hypsography, transportation, boundaries, and other cultural features for the study area,
- Field and scientific data collected during this study, registered to the base data,
- A mine and mine-related sites dataset which will incorporate information from a variety of sources, and
- Digital Orthophoto Quarter Quad (DOQQ) images for the study area, which were used to update project data to reflect current conditions.

Geospatial analysis of the data collected from the different discipline studies will be used by project scientists to interpret the data in a geologic context and to prepare the integrated synthesis for the AML Initiative.

UPPER ANIMAS RIVER BASIN ABOVE SILVERTON

Geology

- The basin is in the central to eastern part of the Silverton caldera and is comprised primarily of volcanic rocks, tuffs, and breccias. Many of the subbasins are largely underlain by volcanic rocks that are regionally weakly altered to a calcite-epidote-chlorite assemblage that would neutralize local sources of acidity (fig. 3).
- Regional structural features provided pathways for later vein mineralization have been mined for miles on strike and for thousands of feet vertically. The density of these fractures varies between the different subbasins within the upper Animas River basin (fig 2).
- Intensely altered and weathered rock likely occurs along the southern ring fracture margin zone of the Silverton caldera (fig. 2; fig. 3) as shown by airborne geophysical data. These structures may also provide pathways for ground-water migration.
- Veins range in size from 1 to more than 50 m in width. Major fractures and graben faults host wide, through-going veins that have been mined for miles on strike and for thousands of feet vertically. Bleaching and sericite-pyrite alteration along these large veins is measured in tens of feet.
- Weathering today locally creates acidic and metal-rich surface water and springs, but in most places the buffering capacity of the calcite-epidote-chlorite-altered rocks is sufficient to attenuate and localize the acidic drainage within hundreds of feet of the source.
- Fault blocks of pre-Tertiary rocks along the eastern caldera margin contain limestone which can be used as a local source of calcium carbonate to neutralize acidity in remediation projects.

Geomorphological Analysis of the Stream Channel from Eureka to Howardsville

Geomorphological analysis of the braided stream reach below Eureka was undertaken to evaluate the impact of historical mining and milling activities on the reach. Analysis of the age of deposition, chemistry, and character of the sediments deposited over time indicated that the stream reach below the historical mill site at Eureka accumulated about one meter of metal-rich sediment as a direct result of milling activities in the 1900-1930 timeframe (Vincent and others, 1999). Evaluation of remediation options for the braided reaches (fig. 9) is one of several high-priority projects being considered by the BLM and USFS in the upper Animas River watershed. The following detailed summary is an evaluation of various remediation options to be considered before a decision should be made on a course of action by the FLMA.

- History of change in the braided reach
    - The valley floor of the Eureka-to-Howardsville reach prior to mining consisted of partially-braided streams within a floodplain composed of silty-sediments covered by willow carrs (thickets), grassy areas, and localized and intermittent beaver ponds. Today, the Eureka reach is fully braided, the floodplain consists of sandy-gravel and localized tailings deposits, and is nearly devoid of vegetation.
    - The Eureka mills processed 2.5 million tons of ore between 1900 and 1930; we estimate that 80 to 90 percent of that crushed rock was released as tailings to the upper Animas River or its floodplain; these tailings contain sulfide minerals that weather in the stream providing a constant source of acidity and metals, particularly zinc and copper.
    - The rate of supply of mill tailings was as much as 5,000 times greater than the pre-mining rate of delivery of sediment to the Animas River. The consequence was that channels aggraded with alluvial gravel containing tailings. The flood plain was covered with a layer of gravel and then locally covered by beds of tailings.
    - Both the production of tailings (the cause) and floodplain aggradation (the effect) have ceased. Consequently, there is no physical reason that the valley floor environment of the Eureka-to-Howardsville reach can not revert to the character and function it had prior to ore milling.

- Metal concentrations in sediment
    - Pre-mining sedimentary deposits have naturally high metal concentrations.
    - Historical (post-1900) sedimentary deposits, however, have metal concentrations as much as ten times greater than pre-mining geochemical baseline values, because tailings became incorporated into the deposits during stream reworking or aggradation of sediments.
    - In general, the fine-fraction (sand, silt, and clay) of historical sedimentary deposits consist of two-thirds tailings and one-third natural sediments
.

- Where are the tailings now?
    - About 2 million tons of tailings were released into the fluvial system by the ore mills at Eureka. On a percent-mass basis, about 80 percent of the tailings were subsequently mobilized by the Animas River and transported downstream, out of the Eureka-to-Howardsville reach.
    - In the Eureka reach between 1960 and 1987, about 4 acres per decade of tailings beds were remobilized by stream flow, representing about 30,000 tons per decade, illustrating the efficacy of stream erosion and transport.
    - Tailings reside in the reach in two distinct deposit types: as discrete tailings beds at the surface and as disseminated deposits in the subsurface within gravel deposits.
    - Sunnyside Gold removed about 8 percent of the original tailings (120,000 cubic yards) in 1997. This was nearly all of the surficial tailings beds present in the Eureka reach.
    - We estimate that as much as 12 percent of the original tailings may still reside in the Eureka-to-Howardsville reach.
    - Thin beds of “pure” tailings rest on the floodplain surface. These tailings beds are easily remobilized by streamflow, as mentioned above, and, over time, will be remobilized and swept downstream. These tailings beds are also easy to identify in the field and would be relatively easy to excavate and haul to a repository.
    - Most of the remaining tailings are probably disseminated within thick gravel deposits in the braided reach. These tailings are not easily remobilized by streams, but remain available for interaction with ground water. It would probably take many years of streambed scour and channel migration

to remobilize these tailings, or it would require a large clean-up effort to extract the tailings from the gravel deposits.

- Changes in the floodplain since 1945
  - Natural recovery of floodplains can occur. The extent of willow carrs and wetlands increased by 14 acres between 1987 and 1997 in the Maggie-Gulch-to-above-Howardsville reach.
  - Recovery of riparian vegetation, on the basis of analysis of sequential aerial photography, indicates that there has been no effective riparian habitat recovery in the Eureka reach. Likewise, there has been no riparian vegetation recovery in the Minnie-to-Maggie reach. Willows usually require flood disturbance (or beaver activity) to become established naturally, yet disturbance by floods has occurred on a regular basis. It is not known whether tailings in the substrate diminishes the survival rate of young willows.
  - The number and size of beaver ponds has increased since 1973, and beavers have moved upstream in the reach above Howardsville. If willows can be established in the Eureka reach, beaver will take advantage of this source of food and building material and will act to promote wetlands, the establishment of more willows, and thus enhance floodplain (and channel) biodiversity, stability, and aesthetic value.

- Does a stable channel make an ecosystem healthy or does a healthy floodplain make channels stable and diverse?
  - Floods continue to rework floodplain sediments (including tailings) of the Eureka reach for two reasons. First, all natural streams rework their floodplains; this is an essential process of diversification and renewal of riparian ecosystems. Second, mobilization of the current floodplain sediments is particularly easy because the floodplain is devoid of vegetation and beds of fine sediments (other than tailings).
  - Floodplain vegetation provides roughness (thus decreasing the velocity and erosiveness of overbank flows), provides floodplain cover (that reduces floodplain erosion), and imparts root-strength and form-drag (that adds to bank stability).
  - Natural, silty floodplain sediments are cohesive and thus resist surficial erosion and make stream banks stronger, which makes for deeper pools and slows bank migration rates.
  - Floodplain vegetation traps fine sediment during flood events, and that fine sediment promotes vegetation growth.
  - Floodplain vegetation provides food and building material for beavers; the actions of beavers spread shrubbery and create diversity in floodplain ecology.
  - Stream channel restoration should not be viewed in isolation from the development of riparian habitat on their floodplains.
  - Channels engineered using concrete and steel are stable, but also restrict the natural functional interaction of channel processes and ecology with floodplain processes and ecology.

- Options for Reclamation of Eureka-to-Howardsville Reach
  - Do nothing
    - Cost
      - No dollar cost
    - Benefit
      - No dollar cost, and no liability
    - Drawbacks
      - Slow reworking of tailings by river
      - Tailings remain source of metal to both surface runoff and ground water
      - Slow vegetation recovery
      - Aesthetic value remains low
      - Biodiversity remains low
  - Construct stable channel
    - Cost
      - High initial investment cost
      - High long-term maintenance cost
    - Benefits
      - If channel stabilization were successful, there would be minimal reworking of tailings
      - Reduced flood hazard (possibly)
      - Increased fish habitat

- Drawbacks
  - Channel maintenance required in perpetuity
  - Channel isolated from floodplain
  - Physical/biological function of the riparian zone not restored
  - In-stream biodiversity not optimized
  - Floodplain biodiversity not enhanced
  - Aesthetic value remains low
- Promote floodplain vegetation
  - Cost
    - Low
  - Benefits
    - Maximize biodiversity and function
    - Maximize aesthetic value
    - Floodplain revegetation will lead to channel stabilization and channel habitat improvement
    - Minimize reworking of tailings by river
  - Drawbacks
    - Decades required to establish willow carr
    - Floodplain remains flood-prone (although this promotes biodiversity)
  - Uncertainties (if tailings not removed)
    - Young-plant viability unknown
    - Concentration of metal in plant detritus unknown
- Remove surficial fine-tailings beds from the Eureka-to-Howardsville reach
  - Costs
    - Excavate (no sieving required)
      - 12,000 cubic yards in Eureka reach
      - 7,000 cubic yards in Minnie-to-Maggie reach
      - 2,000 cubic yards in Maggie-to-Howardsville reach
    - Dispose of tailings
      - 21,000 cubic yards
    - Benefit
      - River reworking of tailings stopped
      - River and floodplain biodiversity ultimately enhanced
    - Drawback
      - Moderate cost to remove and dispose of tailings
      - Ground water and surface runoff would react with dispersed tailings adding dissolved metal loads to the Animas River
- Remove tailings from within gravel
  - Costs
    - Excavate and sieve
      - 600,000 cubic yards in Eureka reach
      - 100,000 cubic yards in Minnie-to-Maggie reach
      - 100,000 cubic yards in Maggie-to-Howardsville reach
    - Dispose of tailings (and other sediments mixed in)
      - More than 200,000 cubic yards
  - Benefits
    - River reworking of tailings stopped
    - River and floodplain biodiversity ultimately enhanced
  - Drawbacks
    - High construction costs
    - Absence of fine material results in poor plant substrate for establishment of riparian plants
    - Absence of fine material contributes to poor channel stability

Table 3. Volume estimates of various sediments in reaches of the upper Animas River between Eureka and Howardsville, Colorado

	Eureka to Minnie Gulch	Minnie to Maggie Gulch	Maggie to above Howardsville	Totals
Area of Tailings beds, km^2 †	0.03	0.018	0.005	
Thickness of Tailings beds, m §	0.3	0.3	0.3	
Volume of Tailings beds, cubic yards	12,000	7,000	2,000	21,000
Area of Gravel Deposits, km^2 †	0.43	0.17	0.17	
Thickness of Gravel deposits, m §	1	0.5	0.5	
Volume of Gravel, cubic yards	600,000	100,000	100,000	800,000
Volume of fines in Gravel, cubic yards ††	170,000	33,000	33,000	230,000
Volume of Tailings in gravel, cubic yards ††	110,000	22,000	22,000	150,000

† The aerial extent of surficial tailings beds, and historical gravel deposits, were determined on the basis of the following: Aerial photographs were inspected and the percent of the floodplain area occupied by these deposits was estimated by eye. The percentages were converted to absolute area values using the floodplain areas determined from digitizing registered and rectified photographs.

§ Thickness of surficial tailings beds, and thickness of historical gravel deposits in the Eureka-to-Minnie reach were assumed on the basis of observations made in the trench. The thickness estimates of historical gravel deposits in the other reaches were on the basis of other limited observations.

†† It was assumed that 30 percent of gravel deposits consists of sand-and-finer sediments, and that two-thirds of the fines are tailings.

For the mass-percent statistics in the text, sediment volumes were converted to weights assuming a bulk density of 1.8 g/cc (1.35 tons/cubic yard).

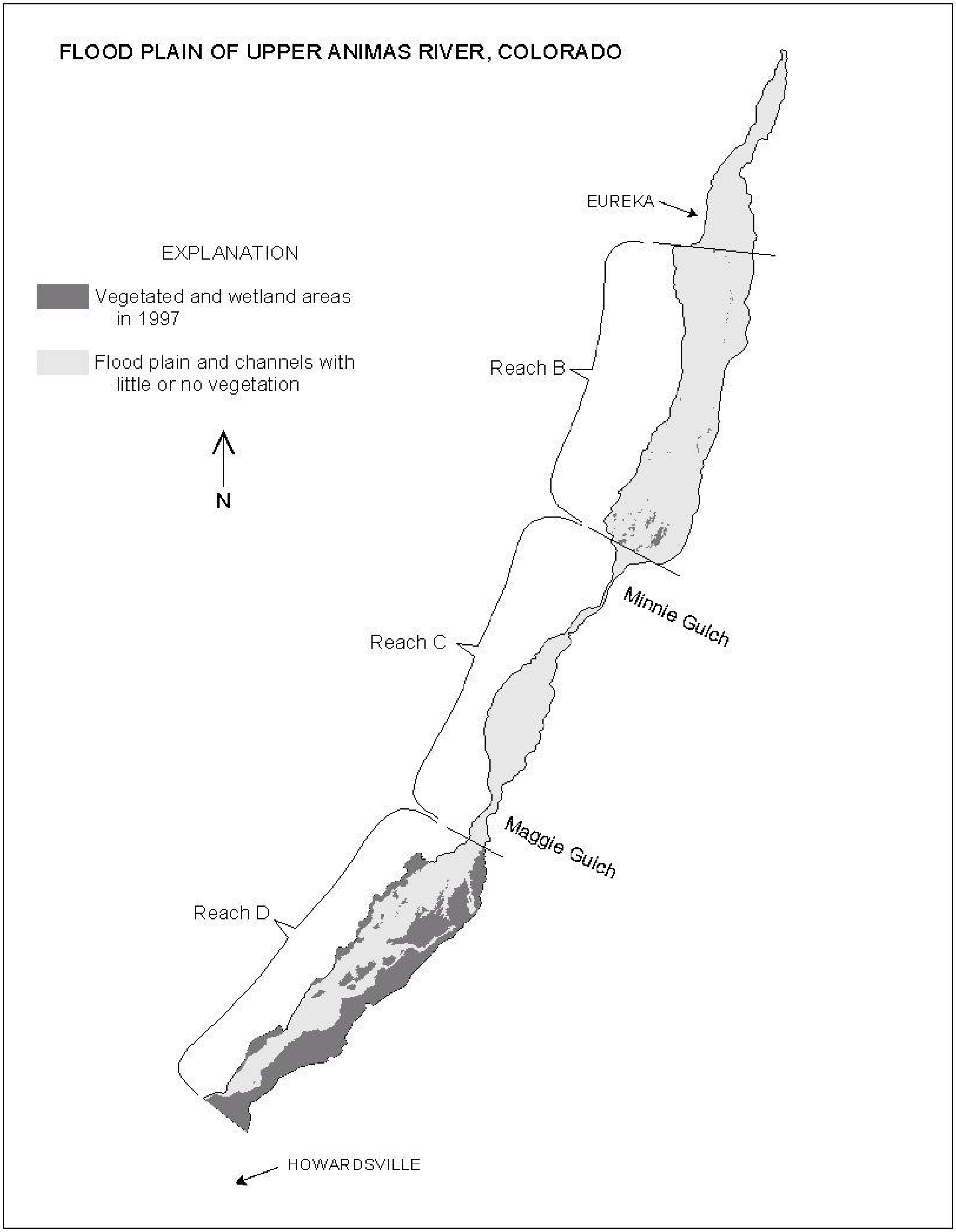

Figure 9. Diagram of different reaches of the upper Animas River discussed above. Reach A is that part of the upper Animas River basin above Eureka (reach A1, fig. 8).

Hydrology: Loading Analysis

- Two tracer-injection studies in the Eureka to Silverton reach provide data on the amounts of metals added in different stream segments. The stream reach from Howardsville to Silverton was studied in 1997 (A5-A8, fig. 8) and the stream reach from Eureka to Howardsville was studied in 1998 (A2-A4, fig 8). The loading analysis from both studies was scaled to produce a single data set for the basin.
  - Measured concentrations of zinc in the upper Animas River ranged from less than the detection limit 0.003 to 0.65 mg/L, with a median value of 0.30 mg/L. Concentrations of sampled inflows ranged from less than 0.003 to 130 mg/L. Concentrations of copper in the stream ranged from less than the detection limit at 0.01 to 0.14 mg/L, with a median of less than 0.01 mg/L, and in the inflows from less than 0.01 to 5.3 mg/L, with a median less than 0.01 mg/L.
  - Contributions of total zinc and copper loads for periods of low flow, are scaled from the individual tracer-injection studies to the watershed scale for upper Animas River, are in table 2.

- On the basis of the tracer-injection studies during periods of low flow, the upper Animas River basin accounts for 59.4 percent of the total (dissolved plus colloidal) zinc load and 14.9 percent of the total copper load at the watershed scale. This is the largest contribution of zinc among the three basins, but the smallest contribution of copper.
  - The largest total zinc loading occurred in reach labeled A8, from below Blair Gulch to the A68 Gage. There were few surface water inflows in this reach, and thus, the loads mostly are attributed to dispersed subsurface inflow to the upper Animas River basin.
  - Six of the 8 reaches contributed over 4 percent of the total watershed load of zinc. In decreasing order, these segments were A8 (12.3 percent), A6 (7.8 percent), A5 (7.0 percent), A2 (5.0 percent), A4 (4.8 percent), and A7 (4.5 percent); data from table 2 (fig. 8). The Mayflower mill tailings repositories are in reaches A6 and A7 on the north side of the upper Animas River (fig. 8).
  - Contributions of total copper load to the watershed during low flow are more difficult to distinguish because the concentrations of dissolved and colloidal copper often were below detection. Concentrations of total copper were highest upstream from the braided reach near Eureka, and were lower downstream from the braided reach (reach A2, fig. 8 or reach B, fig. 9).
  - None of the reaches listed in table 2 contributed more than 5 percent of the watershed copper load. However, reach A5 contributed 4.2 percent, reach A6 contributed 3.6 percent and reach A8 contributed 3.6 percent.

- The reaches listed in table 2 include the contribution from all sources of zinc and copper in the upper Animas River basin on both public and private lands. The loads from individual sources cannot be separated. However, likely metal sources in reaches A1, A2, A3, and A4 are partly on public lands and contribute 15.6 percent of the total zinc load to the watershed.

Biology

- Brook trout are present at varying population in the reach from above Howardsville (downstream from Minnie Gulch; A3 to the A68 gage, fig. 8) to the confluence with Cement Creek at Silverton (table 4). Trout populations in this reach may be sustained by reproduction in tributaries or off-channel beaver ponds.

- Abundance of brook trout and species richness and abundance of benthic invertebrates decrease between Howardsville and Silverton.

- During low-flow periods of late summer 1998 and late winter 1999, stream water at gage A68 (fig. 1, above Cement Creek) was toxic to amphipods, the most zinc-sensitive species, but not to fathead minnows, which are more tolerant of dissolved zinc (table 1).

- Dissolved zinc concentrations at A68 exceed toxicity thresholds for sensitive species year-round (fig. 10). Zinc toxicity probably accounts for the reduced productivity and diversity of invertebrates in the upper Animas River upstream of Cement Creek (above A68, fig. 8).

- Copper concentrations at A68 are consistently below threshold concentration affecting growth (8.1 µg/L) or survival (24 µg/L) of brook trout, the most copper-sensitive species tested (table 1).

- Brook trout populations in this reach are not directly limited by toxicity of dissolved metals. However, they may be limited by reduced invertebrate populations (due to zinc toxicity) and possibly by inadequate in-stream habitat (for spawning and over-winter survival; Milhous, 1999).

- Reduced dissolved zinc loads from sources in the upper Animas River basin should result in corresponding increases in invertebrate productivity and diversity in this reach. Such improvements may also result in increases in productivity of brook trout.

Table 4. Stream invertebrate communities and trout populations in upper Animas River watershed during AMLI biology study period

[Invertebrate sampling, fall 1996 (Anderson 2000); fish sampling, summer/fall 1998; fish collections from approximately 2 km upstream from the A68 gage; unpublished data, Mike Japhet, Colorado Division of Wildlife, Durango Colo.]

Basin	Site	Invertebrates		Trout
		No. of taxa	No. / m^2	No. fish / 300 m
Animas	Above Howardsville	11	575	327
	Cunningham Cr.	16.5	2,255	no data
	Above Cement Cr. (A68)	3.3	98	2
	Below Mineral Cr. (A72)	2.7	97	0
	Elk Park	5.3	309	23
	Above Cascade Cr.	6.3	185	80
Cement	Lower (CC48)	0	0	0
Mineral	Upper	1.3	11	0
	South Fork	15	2,769	no data
	Lower (M34)	1.8	24	0

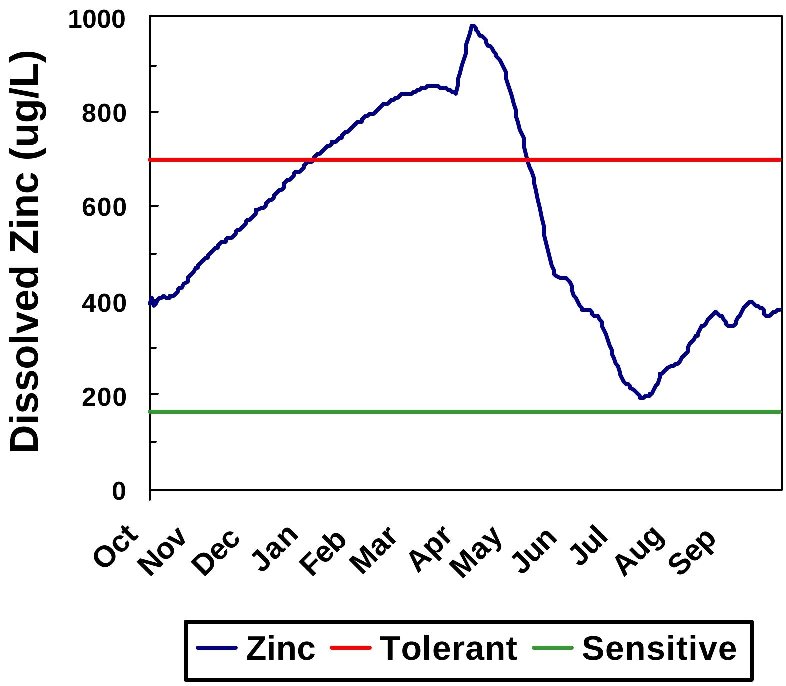

Figure 10. Modeled seasonal variation in dissolved zinc at gage A68, upper Animas River above Cement Creek, showing thresholds for toxicity of dissolved zinc to sensitive and tolerant aquatic taxa.

Remediation options that may produce basin improvements

- The upper Animas River basin accounts for about 47 percent of the low-flow total zinc load, and 15 percent of the total copper load in the Animas River watershed (as measured at gage A72, downstream of Silverton).
- If anthropogenic sources of zinc loading in this basin were effectively remediated, we would expect proportional reductions in zinc toxicity, leading to improvements in the biological communities of the reach of the Animas River upstream of Silverton that currently have low trout populations and low invertebrate production.
- Reductions in loadings of dissolved zinc from the upper Animas River basin may contribute to reductions in severity and extent of toxicity at gage A72 and downstream in the Animas Canyon below A72 (see section entitled Animas River Downstream of Silverton).
- Removal of surficial tailings beds in the upper Animas River reach (fig. 9) would remove concentrated sources of unweathered sulfide minerals in the stream bed, would keep that material from being mobilized and dispersed downstream during floods, and would enhance the ecology at the sites of the tailings beds.
- Promotion of the growth of willow carrs and development of beaver ponds on flood plains in the reaches between Eureka and Maggie Gulch (reaches B and C, fig. 9) would dramatically enhance ecological diversity and function of the riparian habitat and should increase the quality and quantity of aquatic habitat needed for brook trout in this reach.

CEMENT CREEK BASIN

Geology

- The basin is in the western interior of the Silverton caldera and is largely composed of weakly altered volcanic rocks that provide acid-neutralizing potential for surface waters on the east side of Cement Creek, for example in Boulder Gulch, which provides half of the drinking water supply for Silverton.

- This alteration style contrasts with subbasins to the north and west of Cement Creek which include post-volcanic intrusions that create large areas (5-25 km^2) of intensely altered and mineralized, pyrite-rich rocks that are densely fractured and have minimal to no acid-neutralizing potential, for example in Prospect Gulch and the Red Mountains area, which contains acid sulfate alteration and produces acidic drainage that lowers surface and spring water pH to the range of 3-4.5.

- Mined ore deposits are chiefly vein-type polymetallic ores rich in pyrite-galena-sphalerite-chalcopyrite, but also include a few breccia pipe deposits that are polymetallic and strongly enriched in arsenic and copper in the Red Mountain area. The vein structures commonly have northerly strikes and are continuous over several miles, but diverse fracture orientations are present in these highly fractured rocks.

- Large areas of the upper Cement Creek basin are underlain by highly altered rocks that geologic and airborne geophysical data indicate extend to a depth of hundreds to thousands of meters. These highly fractured, intensely altered rocks provide pathways for ground water where natural weathering processes produce large, fracture–controlled acidic seeps. This network of highly fractured rock results in seeps along the banks of the streams in Cement Creek and its subbasins, producing large iron bogs. Such processes form a dispersed natural source of acidity and dissolved metals that has been ongoing for the last 9,000 years on the basis of carbon-14 dating of logs in the ferricretes.

- The deep valleys were favorable for mine access through long, deep tunnels such as the American in Sunnyside Mine, Mammoth, Elk, and Yukon tunnels that also carried water from the mines. Today, more than a dozen of these tunnels continue to collect and discharge large volumes of ground water. Water in these drainage tunnels has been in contact with altered rock and ore in the mines, as well as alteration minerals in fractured, unmined rocks creating acidic adit flows.

- Probability for successful restoration efforts in the upper part of the Cement Creek basin is moderate to low if point sources are removed or contained by capping and water diversion efforts because of the acidity released by natural weathering of the extensive pyrite-rich alteration zones present on the west side of the Cement Creek basin (fig. 3).

Hydrology: Loading analysis

- Two tracer-injection studies have provided loading information for the mainstem of Cement Creek. The first tracer study, in 1996, began just upstream from the North Fork of Cement Creek and continued to the gage near the mouth of Cement Creek (C2 to gage CC48, fig. 8). The second study, in 1999, was conducted in the upper Cement Creek basin, extending from Ross Basin, to just downstream from the South Fork of Cement Creek (C1-C2, fig. 8). This report only includes information from the first tracer study. In addition to the two mainstem studies, three tracer studies have been completed in the Prospect Gulch subbasin, one during high-flow and two during low-flow (Prospect Gulch enters Cement Creek at C3, fig. 8). One of the low-flow studies captured runoff from a storm.
    - Measured concentrations of zinc in Cement Creek ranged from less than 0.71 to 3.9 mg/L, with a median value of 0.97 mg/L. Concentrations of sampled inflows ranged from less than 0.003 to 18.2 mg/L. Concentrations of copper in the stream ranged from less than 0.02 to 0.73 mg/L, with a

median of 0.05 mg/L, and among the inflows ranged from less than 0.01 to 6.0 mg/L, with a median less than 0.01 mg/L.
    - The 59 stream segments from the 1996 tracer study have been grouped into 10 reaches for this report and the loads for each reach were scaled to obtain a watershed perspective (table 2).

- On the basis of the tracer-injection studies, the Cement Creek basin accounts for 18 percent of the dissolved zinc load and 19 percent of the total copper load during low-flow conditions at the A72 gage below Silverton. Some of the total zinc and copper loads are lost to the streambed as colloids during low-flow conditions.
    - The greatest zinc loading occurred from reach C10 (5.6 percent). The greatest loading in that reach was from an unmined area where fractures cross the stream (Kimball and others, 1999). A small exploration adit intersects this structure at creek level. The adit flows into the iron-bog which accounts for the inflow in this reach (Kimball and others, in press).
    - The Prospect Gulch reach (C4) contributed 3.0 percent and the Minnesota Gulch reach (C5) contributed 2.3 percent of the zinc load.
    - Substantial, and nearly equal loadings of zinc occurred from the North Fork subbasin (C2; 1.2 percent), the South Fork subbasin (C3; 1.7 percent), and the area upstream from the North Fork (C1, 1.5 percent).
    - The North Fork subbasin (C2) contributed the largest load of total copper to Cement Creek (5.1 percent).
    - Reach C4, the Prospect Gulch subbasin, and reach C10, which includes the unmined fracture zone, contributed 2.3 and 2.6 percent respectively of the total copper load.
    - The South Fork subbasin (C3) and the area upstream from the North Fork (C1) both contributed 2.3 percent of the total copper load.

- As for zinc, the portion of these loadings from sources on public lands cannot be directly determined from the tracer-injection studies. There are public lands in each subbasin. Although there are definite mine-related sources in the Cement Creek basin, a substantial amount of the loading for both zinc and copper come from dispersed sources caused by natural weathering of altered zones (fig. 3). Remediation options for sites located on public lands have been discussed by Walton-Day and others (1999).

Prospect Gulch subbasin

Three tracer-dilution studies were conducted in Prospect Gulch: 1) during storm runoff under low-flow conditions in September 1998 (Wirt and others, 1999), 2) during high-flow conditions in June, 1999, and in low-flow conditions in September, 1999 (L. Wirt and others, unpub. data, 1999). Not all of the results from the last two tracer studies are available.

- Loading from the Prospect Gulch subbasin includes inferred inflows from the Joe & John, the Henrietta, and the Lark sites that contribute substantial loads of zinc, copper, iron, aluminum, and manganese.

- The greatest increase in metal loading and largest decrease in pH occurs in the 300-meter reach that flows between the Henrietta No. 7 and Lark No. 3 sites; ground water contributions along bedrock fractures to the stream may also make a substantial but unquantified contribution to dissolved metal loads.

- Water from the Henrietta No. 7 adit has a relatively stable hydrogen-oxygen isotope signature indicating a larger and more constant ground-water supply, whereas ground water from the Lark No. 3 and the Joe & John adits show seasonal variability indicating a shallow ground-water source with a short residence time.

- Tributaries and seeps near the abandoned mines have short ground-water residence times, on the order of less than a year to a few years, as evidenced by tritium dating of waters under low-flow conditions.

- Remediation of adits and waste dumps would be expected to substantially reduce dissolved loads of trace metals such as cadmium (as much as 40 percent), and much of the lead and copper contributed by Prospect Gulch to Cement Creek.

- Substantial increases in iron, zinc, and aluminum loads downstream from the study reach are from natural acidic drainage, as evidenced by ferricrete deposits and an iron bog in this lower reach have sources that are fracture controlled.

- Remediation of adits and waste dumps in Prospect Gulch may have little effect on dissolved iron, zinc, and aluminum loads contributed to Cement Creek because more than 80 percent of the low-flow loading for these constituents occurs downstream from the sites in Prospect Gulch.

- Trace-metal loading analysis does not fully consider the effect of possible increases in pH that might occur following remediation. For example, pH decreased by approximately one full pH unit (from 4.1 to ~3.2) in the 300-meter reach between the Lark and Henrietta waste-dumps and adits. If pH downstream from the mines could be increased to that in Prospect Gulch above this reach (pH 4.1) by piping water through the reach, then the concentrations of iron, aluminum, zinc, copper, and other trace metals in the lower reach might be substantially reduced.

Biology

Cement Creek (above CC48, fig. 8) supports almost no aquatic organisms except a few types of acid- and metal-metal tolerant algae (table 4). Stream water and sediment interstitial water from CC48 collected during summer of 1997 was found to be highly toxic to fish and aquatic invertebrates (D. Nimmo and J. Castle, unpub. data, 1997).

Remediation options that may produce basin improvements

- Because of the high natural loadings of acidity and low buffering capacity of the Cement Creek basin, remediation of mines and mine-related sites in the basin will not reduce acidity and dissolved metals enough to allow recovery of aquatic life in Cement Creek itself.

- Dissolved zinc and total copper loads from Cement Creek constitute substantial proportions of the cumulative loads of these metals from the three basins (18 percent of watershed zinc load and 19 percent of watershed total copper load). Reduction in copper and zinc due to remediation of sites in the Cement Creek basin would therefore contribute to recovery of biological communities in downstream reaches of the Animas River (see Animas River Downstream of Silverton).

- Preliminary results from the tracer study in the upper Cement Creek basin indicate that the contribution from the North Fork Cement Creek subbasin (C2, fig. 8) may have decreased since 1996.

MINERAL CREEK BASIN

Geology

- The basin is on the western side of the Silverton caldera (fig. 1). Intensity of the alteration is variable at the subbasin scale from very intense to nil; widespread weakly altered rocks occur throughout the Mineral Creek basin (fig. 3). Part of the basin that lies outside the caldera margin and is underlain by granitic and sedimentary rocks that contain minor amounts of mineralization (fig. 2). The acid-neutralizing capacity of the rocks within this basin varies substantially at the subbasin scale.

- Mined ore deposits in this basin are polymetallic in character, but more diverse in mineralogy, chemistry, and size than in the other two basins. The breccia pipe ores, as at Longfellow-Koehler in the Red Mountain Pass area (M1, fig. 8), are richer in arsenic and copper than most in the study area. Concentrations of molybdenum are locally elevated. Wallrock alteration, in part, reflects the host rocks and style of mineralization. Alteration types range from silicification of sedimentary rocks, to sericite-pyrite in granitic rocks of Mount Sultan, to acid-sulfate in volcanics at Red Mountain Pass (fig. 3).

- The mines in this basin are smaller than in the eastern basins. Mine waste dumps tend to be much smaller and the volume of mill tailings produced here is a small fraction of that in the eastern basins.

- The basin includes several large mineralized systems (5-25 km^2) overlying sub-economic porphyry deposits with abundant pyrite in the surrounding alteration zones. Highly altered rocks are abundant in the Anvil Mountain and the Mount Moly areas. Laterally extensive non-mining related ferricrete deposits crop out in these areas indicating that acidic drainage resulting from weathering of altered rocks has likely occurred here over thousands of years.

- Some subbasins in the northern part of the basin near Red Mountain Pass are largely underlain by highly altered (acid-sulfate) rocks that produce naturally acidic surface waters (fig. 3). Airborne geophysical data define areas of high subsurface conductivity commonly along pronounced structural trends and areas of intense alteration. These anomalously conductive zones may be associated with waters containing high dissolved solids; spring and surface waters have a pH in the range of 3-4.

- Probability for successful restoration efforts is moderate if point sources are removed or contained by capping and water diversion efforts, except in the Red Mountain Pass and Mount Moly areas where the probability for remediation success is probably lower than in other parts of the Mineral Creek basin because of the acidity released by natural weathering of the extensive pyrite-rich alteration zones present in the Mineral Creek basin (fig. 3).

Hydrology: Preliminary Loading analysis

- Three tracer-injection studies were completed in the Mineral Creek basin in the summer of 1999. The results are preliminary, but present an adequate picture of the total zinc and copper loads to guide remediation decisions.
  - Measured concentrations of zinc in Mineral Creek ranged from 0.01 to 36 mg/L, with a median value of 0.84 mg/L. Concentrations of sampled inflows ranged from less than 0.003 to 63 mg/L. Concentrations of copper in the stream ranged from less than 0.01 to 0.15 mg/L, with a median of 0.23 mg/L, and from less than 0.01 to 27 mg/L among the inflows, with a median of 0.01 mg/L.
  - There were 84 individual stream segments in the three tracer studies, and these have been combined into 7 reaches for this summary. The loads for each reach were scaled to obtain a watershed perspective (table 2).

- On the basis of the tracer-injection studies, the Mineral Creek basin accounts for 25 percent of the total zinc load and 57 percent of the total copper load at the watershed scale during low flow.
  - The greatest loads of zinc occurred in the first two reaches, M1 and M2 (fig. 8) which account for 13.1 percent of the watershed total zinc load.
  - The reach from Porphyry Gulch through the Mill Gulch subbasin (M3) contributed 1.3 percent to the total zinc load. All three of these reaches, M1 through M3 (fig. 8), correspond to the large acid sulfate alteration zone (fig. 3), in addition to mining sources.
  - The same pattern of zinc loading occurred for total copper loading. The first two reaches (M1 and M2, fig. 8) contributed 34.8 percent and the third reach (M3) contributed an additional 5.1 percent.

- It is not possible to assign a percentage of this loading to sources that might occur on public land, but the impact of the natural alteration zones in Mineral Creek dominated the loading.

Biology

- Upper Mineral Creek (above the confluence of the South Fork Mineral Creek; M1-M5, fig. 8) is an acidic stream that supports little or no aquatic biota (table 4).

- The South Fork Mineral Creek supports a relatively diverse and productive aquatic community, including a self-sustaining population of brook trout (table 4). However, this subbasin is not completely free of metals impacts on stream biota, as indicated by relatively high metal concentrations in tissues of stream biota (Besser and others, 2000) and by episodic toxicity during on-site toxicity tests in summer 1998 (Besser and others, unpublished data).

- Lower Mineral Creek, downstream from the confluence of the South Fork, has circumneutral pH, but supports no fish and few aquatic invertebrates (Table 4).

- Stream water from gage M34, lower Mineral Creek at Silverton (M34, fig. 8), was toxic to fathead minnows during late winter 1999 and toxic amphipods during both late summer 1998 and late winter 1999 (Besser and others, unpublished data).

- Zinc concentrations at M34 are less than those described forA68, but dissolved zinc concentrations exceed toxicity thresholds for sensitive species from November to May (fig. 11).

- Copper toxicity is a greater problem at M34 than at either A68 or A72 (fig. 8). Total copper exceeds toxicity thresholds for growth of brook trout year-round and exceeds thresholds for survival of brook trout and more tolerant species from January to April (fig. 12).

Remediation options that may produce basin improvements

- The Mineral Creek basin contributes a substantial proportion of the dissolved copper load for the entire Animas River watershed (57 percent of total), but a lesser proportion of the total zinc load (25 percent).

- A very large percentage of the loads comes from natural drainage of the acid sulfate alteration zone near Red Mountain pass.

- Remediation of mines and mining-related sites in the Mineral Creek basin will not reduce acidity or dissolved metal concentrations enough to allow recovery of aquatic life in upper Mineral Creek, upstream from South Fork.

- Remediation efforts, especially those that reduce copper loadings, could result in improvements in biological communities of Mineral Creek downstream from the South Fork, and of the Animas River downstream from the confluence with Mineral Creek (see Animas River Downstream of Silverton).

- Because the Mineral Creek basin contributes disproportionately high loadings of total copper, remediation of sites with high copper loadings should be the highest priority.

- The amount of copper load transported by iron colloids is substantial in the Mineral Creek basin. The decrease of sources of copper load, upstream from the mixing zone below the confluence with the South Fork Mineral Creek, could reduce the amount of copper sorbed to colloids and transported to the Animas River from the Mineral Creek basin.

- Remediation of the Bandora mine site would result in improvement in water quality in the South Fork Mineral Creek watershed and could reduce the impact of historical mining on the existing trout fishery in the South Fork Mineral Creek subbasin.

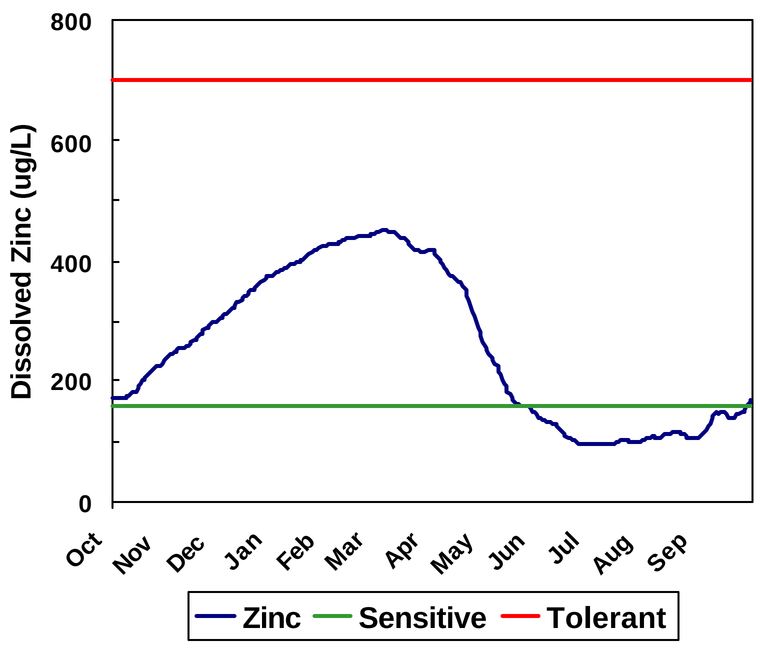

Figure 11. Modeled seasonal variation in dissolved zinc at gage M34, Mineral Creek at Silverton, showing thresholds for toxicity of dissolved zinc to sensitive and tolerant aquatic taxa.

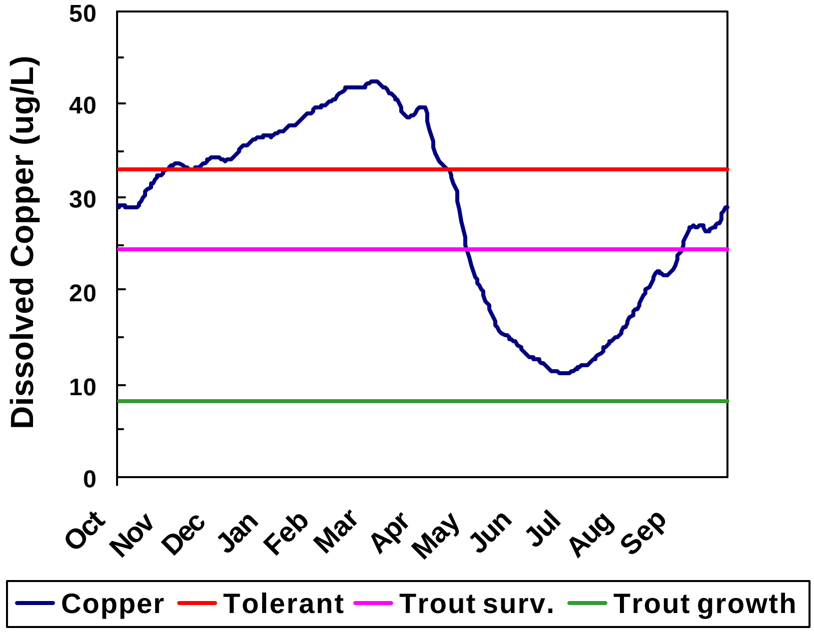

Figure 12. Modeled seasonal variation in dissolved copper at gage M34, Mineral Creek at Silverton, showing thresholds for toxicity of dissolved copper to brook trout (survival and growth) and to tolerant aquatic taxa.

ANIMAS RIVER DOWNSTREAM OF SILVERTON

Biology

- Trout are absent and the invertebrate community is reduced to low densities and low numbers of species in the Animas River downstream from the confluences of Cement and Mineral Creeks. Recovery of brook trout populations and invertebrate communities begins in the vicinity of Elk Park (about 5 km downstream from the gage at A72, fig. 8) and this recovery continues further downstream in the Animas Canyon (table 4).

- Stream water from both A72 and Elk Park was toxic to amphipods during late-summer 1998 and toxic to both amphipods and fathead minnows during late winter 1998. Fine streambed sediments at A72, which consisted primarily of iron-rich precipitates, were also toxic to amphipods during summer 1998 (Besser and others, unpublished data).

- Zinc concentrations in stream water at A72 are lower than those at A68, but remain above the threshold for toxicity to sensitive species year-round and greater than the threshold for tolerant species during late winter (fig. 13).

- Copper concentrations at A72 are less than those at M34, but exceed the threshold for reduced growth of brook trout during winter, when brook trout pass through sensitive early life-stages. Peak concentrations of total copper during late winter approach the threshold for reduced survival of early life-stages for brook trout (fig. 14).

- Effects on trout and invertebrates in the Animas River at A72 in the downstream reach reflect the cumulative contributions of dissolved zinc and copper from all three sub-basins. Effects on brook trout at A72 are primarily due to toxic effects of dissolved copper, whereas effects on benthic invertebrate communities probably result from combined effects of zinc and copper toxicity

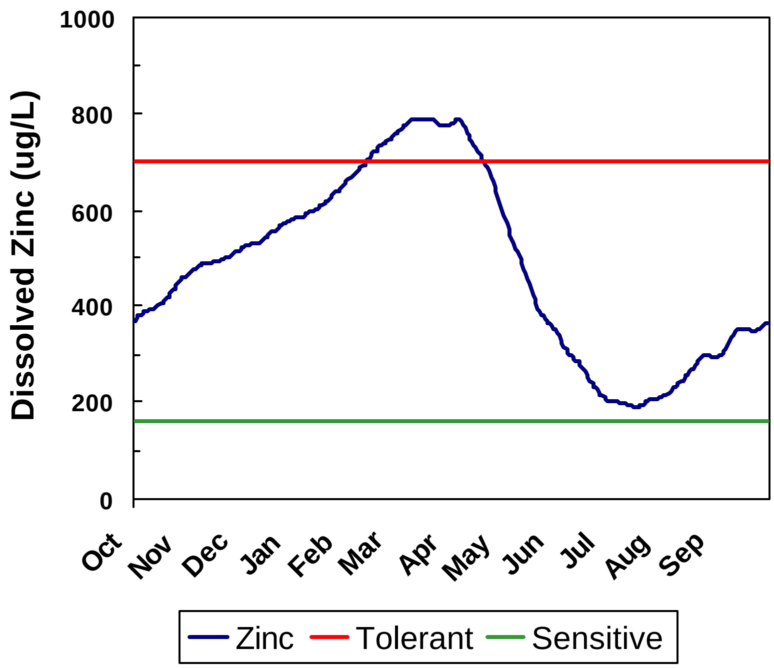

Figure 13. Modeled seasonal variation in dissolved zinc at gage A72, Animas River downstream of Silverton, showing thresholds for toxicity of dissolved zinc to sensitive and tolerant aquatic taxa.

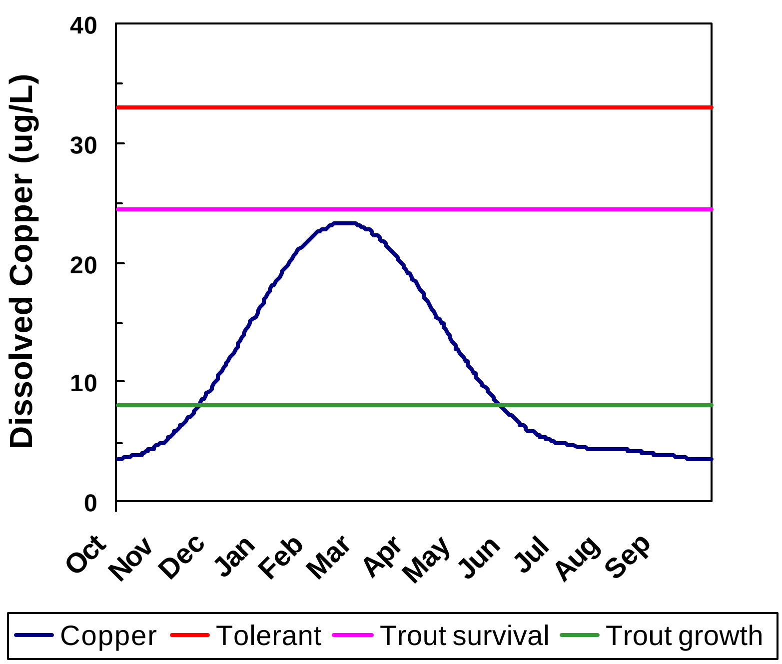

Figure 14. Modeled seasonal variation in dissolved copper at gage A72, Animas River downstream of Silverton, showing thresholds for toxicity of dissolved copper to brook trout (survival and growth) and to tolerant aquatic taxa.

Remediation options that may produce watershed improvements

- Remediation of mines and mine-related sites in the three basins will contribute to recovery of stream biota in the Animas River downstream of Silverton by reducing the toxicity of dissolved copper and zinc and by reducing the formation and deposition of iron-rich precipitates, which degrade physical habitats and contribute to toxicity of contaminated sediments.

- Reduced loading of copper, which originates primarily from the Mineral Creek basin (57 percent of watershed total loadings) will be expand the downstream reach of the Animas River which conditions can be tolerated by brook trout, perhaps facilitating re-colonization of reaches with depleted trout populations, but reduced copper loading alone will be insufficient to allow a substantial recovery of stream communities.

- Together with reduced copper loading, reduced loading of zinc, which originates primarily from the upper Animas River, Cement Creek, and Mineral Creek basins (47, 18, and 25 percent of watershed totals, respectively) will be necessary to allow substantial recovery of benthic invertebrate communities, which in turn can support a productive brook trout population.

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