Science for Watershed Decisions on Abandoned Mine Lands: Review of Preliminary Results, Denver, Colorado, February 4–5, 1998

Edited By David A. Nimick and Paul von Guerard

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PREFACE

By Tim M. Bozorth[1] and Ray TeSoro[2]

There are thousands of abandoned or inactive mines on or adjacent to public lands administered by the U.S. Forest Service, Bureau of Land Management, and National Park Service. Mine wastes from many of these abandoned mines adversely affect resources on public lands. In 1995, an interdepartmental work group within the Federal government developed a strategy to address remediation of the many abandoned mines on public lands. This strategy is based on using a watershed approach to address the abandoned mine lands (AML) problem. The USGS, working closely with the Federal land-management agencies (FLMAs), is key for the success of this watershed approach.

In support of this watershed approach, the USGS developed an AML Initiative with pilot studies in the Boulder River in Montana and the Animas River in Colorado. The goal of these studies is to design and implement a reliable strategy that will supply the scientific information to the FLMAs so that land managers can develop efficient and cost-effective remediation of AML.

The symposium "Science for Watershed Decisions on Abandoned Mine Lands: Review of Preliminary Results" held in Denver, Colorado, on February 4–5, 1998, provided the FLMAs a first look at the techniques, data, and interpretations being generated by the USGS pilot studies. This multidisciplined effort already is proving very valuable to land managers in making science-based AML cleanup decisions and will continue to be of increasing value as additional and more complete information is obtained. Ongoing interaction between scientists and land managers is essential to insure the efficient continuation and success of AML cleanup efforts.

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Edited by David A. Nimick *and* Paul von Guerard

INTRODUCTION

Numerous abandoned mine lands (AML) in the United States are on, or adjacent to, federally managed land, affect aquatic or wildlife habitat on Federal land, and will require investment of Federal resources to remediate. Although estimates of the amount of AML vary, there is general agreement that the scope of this problem is huge. In 1995, a U.S. Department of the Interior (DOI) and U.S. Department of Agriculture interagency task force, including the Bureau of Land Management, National Park Service, U.S. Forest Service (Federal land-management agencies), and the U.S. Geological Survey (the DOI science agency), developed a coordinated strategy for the cleanup of environmental contamination from abandoned mine lands (AML) associated with Federal lands. This strategy is based on a watershed approach (rather than a site-by-site approach) to characterize and remediate contamination. A watershed approach would identify those watersheds within a state that are most at risk for environmental degradation from AML, and then identify, characterize, and remediate contaminated sites that have the most profound effect on water and ecosystem quality within the watershed.

As part of the interagency effort, the U.S. Geological Survey (USGS) has implemented an Abandoned Mine Lands Initiative to develop a strategy for gathering and communicating the scientific information needed to formulate effective and cost-efficient remediation of abandoned mine lands within the framework of a watershed approach. The combined interagency effort is being conducted in two pilot watersheds, the upper Animas River watershed in Colorado and the Boulder River watershed in Montana. These watersheds were selected by the interagency task force in cooperation with the States and the U.S. Environmental Protection Agency. USGS objectives include:

- estimating background (pre-mining) conditions;
- defining baseline (current) conditions;
- characterizing processes affecting contaminant dispersal and effects on ecosystem health;
- developing remediation goals; and
- transferring useful data and information to users in a timely and effective manner.

USGS expertise in water quality, hydrology, geology, geochemistry, biology, mapping, and digital-data collection and management is being applied in the pilot watersheds. Activities are being coordinated with stakeholders and Federal land-management agencies, which are coordinating design and implementation of remediation activities within these watersheds. The USGS Initiative will be conducted during 1997 through 2001, and lessons learned will be used in extension of the watershed approach to AML across the Nation.

This report provides an overview of the AML Initiative Year-One Workshop held in Denver, Colorado, on February 4–5, 1998. The objective of this workshop was to develop a dialogue among USGS scientists, Federal land-management agencies, other stakeholders, and regulatory agencies to identify the most useful scientific information and approaches for characterization of AML and to discuss use of this information within the context of a watershed approach to remediation. This report summarizes technical results of the first year of the USGS AML Initiative and includes abstracts for talks and posters presented at the workshop. Also included in this report is a paper that summarizes presentations given at the workshop by representatives of stakeholders, Federal land-management agencies, State regulatory agencies, and the U.S. Environmental Protection Agency, in a session titled "Perspectives on Implementing the Watershed Approach to Remediate Abandoned Mine Lands."

The watershed approach as presented by the interagency task force has four general components:

1. Statewide analysis and watershed prioritization—Information available at the state scale is used to prioritize watersheds for further study;

2. Watershed characterization—The extent, sources, and effects of contamination are characterized within a priority watershed; and this information is used to prioritize individual sites for remediation;

3. Site characterization in support of remediation—Detailed characterization of sites targeted for remediation is used to design and implement effective remedial measures and to define realistic remediation goals; and

4. Monitoring—Continued monitoring is implemented to measure indicators of improvement in watershed quality and effectiveness of remediation.

The watershed approach:

- gives high priority to actions likely to improve water and ecosystem quality most significantly,
- will greatly accelerate and reduce the total cost of remediation compared to remediating on a site-by-site basis,
- enables assessment of the cumulative effect of multiple and/or nonpoint sources of contamination,
- provides information that will assist watershed-scale disposal-siting decisions,
- enables consideration of revenue generation from selected sites to supplement overall watershed remediation costs, and
- fosters collaboration among Federal, State, and local levels of government and stakeholders.

During the first year of this initiative, USGS activities focused largely on component 2 of the watershed approach by conducting a watershed-scale characterization to identify sites that have a significant effect on watershed quality. However, some characterization activities were conducted at specific sites (component 3) where significant contamination already was evident. Although component 1 (statewide analysis and selection of the pilot watersheds) was accomplished previous to implementation of this initiative, USGS information used for the watershed selection process in Colorado and Montana and results of other national and statewide mapping activities were presented at the workshop and are included herein.

Additional information on the USGS Abandoned Mine Lands Initiative is available in Buxton and others (1997) and on the World Wide Web at http://amli.usgs.gov/amli. The USGS Mine Drainage Newsletter and information on the USGS Mine Drainage Interest Group is available at http://water.wr.usgs.gov/mine. Information about the activities and programs of the U.S. Geological Survey may be obtained at http://www.usgs.gov.

STATEWIDE AND NATIONAL MAPPING

The Role of Geoenvironmental Maps and Statewide Assessments in Prioritizing Watersheds for Remediation of Abandoned Mine Lands

By S.E. Church,[1] T.C. Sole,[2] D.B. Yager,[3] and A.E. McCafferty[4]

The Abandoned Mine Land (AML) Initiative is based on the premise that watersheds affected by acid-mine drainage should be prioritized so that the resources spent on remediation will have the greatest benefit on impacted streams. A U.S. Geological Survey national-scale survey is underway which will show the effect of acid mine drainage (AMD) on the surface waters of the contiguous United States. This survey shows that the existing water-quality and trace-element data are insufficient to determine the magnitude of the AMD impact on the Nation's waters. Water-quality sampling generally has not been done sufficiently close to AMD sources to accurately delineate the impact. River bed-sediment geochemical data would provide another, more integrated method to evaluate AMD at a watershed scale. Sediment data can be equally as useful as water-quality data because trace-element concentrations in sediment typically are elevated downstream of abandoned mines, because mine wastes and tailings are introduced into and transported by the stream, and because enrichment in sediment occurs as pH increases and dissolved metals sorb to iron oxy/hydroxides.

There are a variety of mineral-deposit types. The environmental responses of each to surface weathering reflect their geologic setting, size of the mining disturbance, and climatic variables. In general, when mineral deposits are produced, those mineral-deposit types that cause the greatest potential threats to the environment are: (1) those that contain abundant fine-grained pyrite in the waste rock, (2) those where large tonnages of material are disturbed, (3) those that occur in rocks that have a low capacity to neutralize the acidity released, and (4) those deposits that meet the above criteria and which are located in moist climates. Combining the knowledge of mineral deposits, ecoregions, and climatic data will lead to a better understanding of those regions in the western United States where the environmental effects of AMD from historic mines are most likely to impact the Nation's surface waters.

The GeoEnvironmental Map (GEM) was developed to integrate geologic information, environmental characteristics of different mineral-deposit types, and available water-quality data to evaluate the effect of mining on surface waters. The initial GEM (Plumlee and others, 1995) for Colorado and some information contained in its successor for Montana (McCafferty and others, 1998, this volume) were used by decision makers in these two states to evaluate watersheds proposed for study under the AML Initiative. GEMs are valuable tools for communication of multidisciplinary geologic data with land-use planners, State and local officials, and the general public. Both GEM products were prepared from existing digital data. Future GEM products created for the statewide watershed prioritization in phase one of the AML Initiative would be more useful if biologic resource data were incorporated because the aquatic data provide important indications of receptor response to AMD. In addition, water-quality data were not adequately represented in the two initial GEM products. Because of the transitory nature of the biologic and water-quality data, these data sets are more difficult to incorporate into the GEM analysis.

During a recent USGS workshop on database needs, workshop personnel evaluated the existing digital geologic databases needed to produce a GEM product for the 13 western states. Only New Mexico and Wyoming have complete geologic, geochemical, and geophysical database coverages. Current hydrologic and biologic databases were not assessed. The remaining western states have various database deficiencies which should be filled before a GEM effort for these states are undertaken. Evaluation of existing data and incorporation of mine-inventory data collected by the States and the Federal land-management agencies also are essential components of this database-building process. We must begin a new, more collaborative phase of AML planning to meet the future expectations of the general public for effective environmental remediation on Federal lands.

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OVERVIEW OF ANIMAS AND BOULDER STUDY AREAS

The Colorado and Montana Pilot Watersheds

By Paul von Guerard[1] and David A. Nimick[2]

The upper Animas River and the Boulder River watersheds have been identified as the priority watersheds in their states for remediation of contamination associated with AML. The upper Animas River watershed, located near Silverton in southwestern Colorado (fig. 1), was selected in March 1996 using a prioritization process that considered the available data, ongoing activities, and water-quality impairment from abandoned mines. The Boulder River watershed, located near the town of Basin in western Montana, about 25 miles south of Helena (fig. 2), was chosen in May 1996 from five candidate watersheds based on an analysis of geologic factors, metal loading, the status of ongoing remediation activities, general knowledge of the candidate watersheds, and extent of Federal land.

Although the geographic, socioeconomic, and geologic characteristics of each watershed have similarities, the differences are significant (table 1). Both watersheds are in mountainous terrain with abundant snowfall, but elevation and annual precipitation are less in the Boulder River watershed. The upper

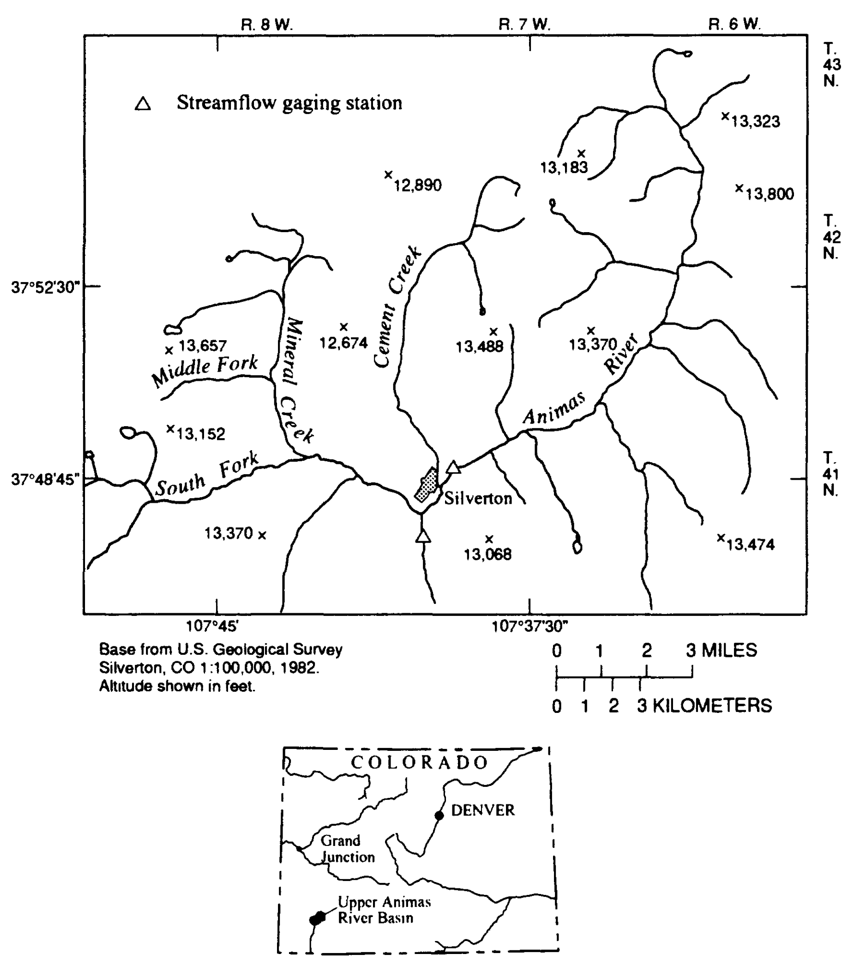

Figure 1. Location of the upper Animas River watershed, southwestern Colorado.

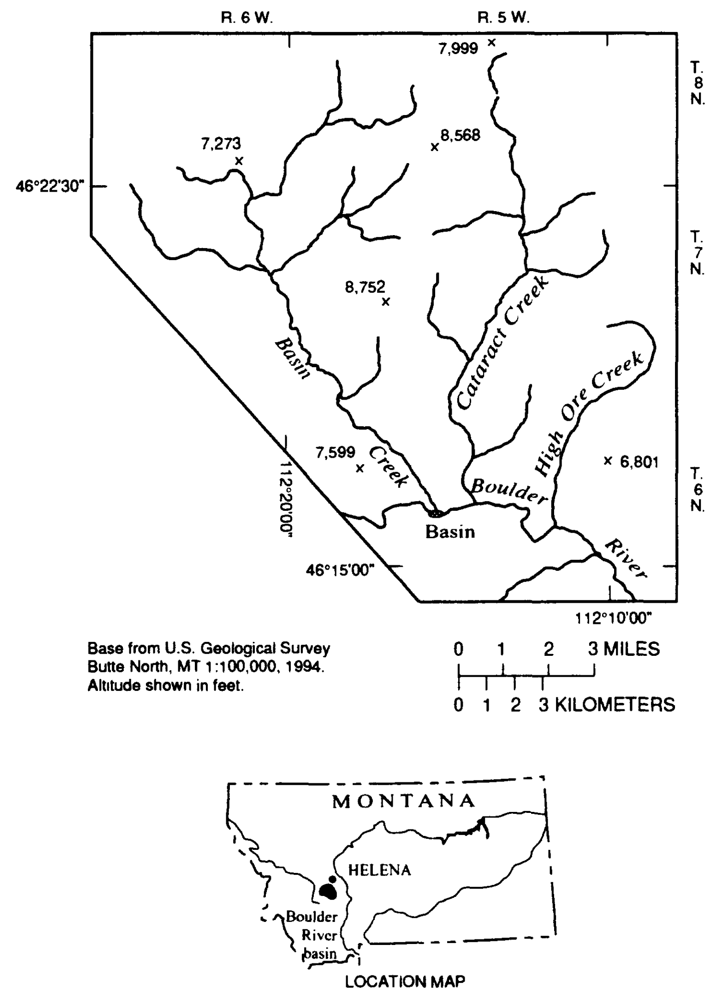

Figure 2. Location of the Boulder River watershed, southwestern Montana.

Animas River watershed is only somewhat larger than the Boulder River watershed, but their shape, relief, and drainage patterns are different. In Colorado, the study area consists of the entire Animas River watershed upstream of Silverton. In contrast, the Montana study site encompasses three adjacent Boulder River tributaries (Basin, Cataract, and High Ore Creeks) and a short reach of the Boulder River downstream of the tributary confluences. Both areas have a history of metal mining dating back to the late 1800s. Most mining activity ceased by the 1940s, although some activity occurred as recently as the 1990s. Principal metals produced from both watersheds included gold (Ag), silver (Au), lead (Pb), and zinc (Zn). Ore bodies are sulfidic, and acid mine drainage occurs in both areas. The number of abandoned mines is an order of magnitude higher in the upper Animas River watershed than in the Boulder River watershed. Much of the mining in both study areas occurred on privately-owned (patented) mining claims. However, some mine, mill, and smelter sites; and tailings deposits, along with eroded tailings distributed along various reaches of stream channels and flood plains, are located on Federal land.

Although populations in both areas vary seasonally as tourists and temporary residents move into the watersheds during the summer, the population of the upper Animas River watershed is much greater than that of the Boulder River study area. In the upper Animas River watershed, tourism, in part based on historic mining, is an important industry. Residents of the Boulder River study area are engaged primarily in mining, logging, or agricultural activities.

The primary effect of mining in both watersheds is degraded water quality and aquatic habitat, which consequently affects aquatic and fishery resources.

Table 1. Characteristics of the upper Animas River and Boulder River watersheds

Watershed characteristics	Upper Animas River, Colorado	Boulder River, Montana
	Geography	
• Drainage area (mi^2)	150	90
• Precipitation (in/yr)	40–50	14–30
• Snowfall	high	high
• Elevation (ft)	9,200–13,800	4,900–8,800
• Primary fish species	brook trout	rainbow trout
	Socioeconomics	
• Population	500–3,500	100–200
• Major Industries	tourism	logging, mining, cattle
• Public interest in AML		
–within watershed	high	moderate
–state wide	high	high
• FLMA	USFS, BLM	USFS, BLM
• Reclamation sponsorship	Stakeholder	State
	Resources	
• General geology	Intercaldera lavas (hydrothermally altered)	Granitic batholith (veins)
• Metals mined	Ag, Au, Pb, Zn	Ag, Cu, Pb, Zn, Au
• Major mining period	1880–1990	1870–1940
• Carbonates	some	some
• Abandoned mines	1,500	150
• AML characterization	high	low
• Fisheries impacts	significant	limited

Some streams are devoid of fish, and many others may have impaired fisheries. Abandoned mines affect streams through direct discharge of acid drainage from adits, seepage from tailings piles, and erosion of tailings by storm runoff or streambank erosion. The extent of subsurface contaminant movement in both study areas is virtually unknown. The known extent of mining impact on surface waters in the Colorado area has been documented downstream to Durango and to the confluence with the San Juan River. Many of the AML sites that appear to have a serious effect on surface-water quality and local fisheries in the Boulder River watershed have been inventoried for the Federal land-management agencies by the State of Montana. These inventories included some data on water quality and chemistry of tailings and have been used to target AML sites that are likely candidates for remedial activities. In recent years, Montana has been active in remediating portions of the Comet mine on privately owned land in the upper reaches of High Ore Creek basin (fig. 2).

Commensurate with the greater impact and higher population, the upper Animas River watershed has a substantially greater amount of natural resource information and AML characterization completed to date. The Animas River Stakeholders Group (ARSG) has taken an active role in the characterization and remediation of the watershed. The ARSG represents private, local, State, and Federal entities. In contrast to the Boulder River area, where AML remediation is only beginning to be an important issue, active public involvement and interagency cooperation in addressing AML remediation has a long history in the upper Animas River watershed.

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CHARACTERIZATION OF STREAMS ON A WATERSHED SCALE

What Streams are Affected by Abandoned Mines?—Characterization of Water Quality in the Streams of the Boulder River Watershed, Montana

By David A. Nimick[1] and Tom E. Cleasby[2]

Water is the link connecting toxic metals derived from abandoned mine lands (AML) to aquatic biota and, therefore, is an integral aspect of the assessment of environmental effects associated with AML. Water quality was characterized by sampling streams throughout the Boulder River watershed, comparing trace-element concentrations to aquatic-life standards and to concentrations in reference streams, and estimating annual loading of metals from the main streams in the watershed.

Characterization of watershed water quality was based on samples collected during 1996–97 for this study and during 1989–96 by previous investigators from 113 sites during low-flow conditions and from 56 sites during high-flow conditions. pH values were near-neutral to alkaline everywhere except in isolated circumstances where acid discharge from AML affects small streams. In comparison to five reference sites, trace-element concentrations in many stream reaches were elevated, particularly in water from Jack Creek, Uncle Sam Gulch, lower Cataract Creek, High Ore Creek, and the Boulder River downstream from Cataract Creek. Longitudinal concentration profiles indicate that the primary sources of metals are three AML complexes located in the headwaters of Jack Creek, Uncle Sam Gulch, and High Ore Creek.

Cadmium, copper, lead, and zinc were the trace elements that most commonly occurred at concentrations exceeding aquatic-life standards. Montana chronic aquatic-life standards for one or more of these metals were exceeded at all sampling sites between the three main AML complexes and the confluence of the Boulder and Jefferson Rivers. Concentrations of chromium, mercury, nickel, and silver typically were less than minimum reporting levels. Concentrations of arsenic, which is pervasive in both mined and unmined areas, typically were much lower than the chronic aquatic-life standard (190 micrograms per liter). During spring runoff, cadmium and zinc concentrations decreased, whereas lead concentrations increased. Cadmium and zinc are predominantly dissolved (using 0.45-micrometer filtration) and presumably are diluted by high flow. Lead is primarily in the particulate phase, and its concentration increases as higher flows carry more sediment.

Annual loads of metals from Basin, Cataract, and High Ore Creeks and at two sites on the Boulder River upstream and downstream of these tributaries were estimated using water-quality data for 12 sample sets and flow estimates derived from the continuous streamflow record for a nearby gage on the Boulder River. Although the three tributaries combined contributed only 33 percent of the annual streamflow at the downstream Boulder River site, they contributed 41–89 percent of the cadmium, copper, lead, and zinc loads; Cataract Creek contributed the largest loads of these metals. About one quarter of the total-recoverable arsenic, copper, lead, and zinc at the downstream site came from the channel or unsampled sources. These increased loads may reflect the erosion and transport of contaminated fluvial deposits along the Boulder River.

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What Streams Are Affected by Historic, Abandoned Mines?—Preliminary Interpretation of Bed-Sediment Geochemical Data, Boulder River Watershed, Montana

By D.L. Fey[1] and S.E. Church[2]

Trace elements associated with mine wastes and drainage typically accumulate in the bed sediments of streams downstream of abandoned mines. Data on trace-element concentrations in bed sediment can be used to define stream reaches affected by historic mining, determine sources of the contaminated material, understand the transport of dissolved and particulate trace elements, and evaluate the potential metal toxicity of bed sediment to biota.

We collected bed-sediment samples from the basins of High Ore, Cataract, and Basin Creeks, all tributaries to the Boulder River. We took 47 samples in October 1996 and 36 samples in July 1997. Sample localities were selected to verify and supplement previously collected data and to further define first- and second-order stream reaches affected by historic mining activities. We also collected sediment samples from the Boulder River at sites above and immediately below the confluences of the three impacted drainages and at sites downriver to its confluence with the Jefferson River. Sediment samples downstream of the confluences with the impacted streams were taken from both sides of the river (north and south banks) to assess differences in metals distributions caused by the inflow from the tributaries.

We used three different digestions to determine trace-element concentrations in three operationally defined phases of the bed sediment: (1) a mixed strong-acid complete digestion to determine total concentrations, (2) a warm (50 degrees Celsius) 2 molar $HCl\text{-}H_2O_2$ leach to determine metals associated with iron oxy/hydroxide mineral coatings and colloidal particles (the leachable phase), and (3) a mixed strong-acid complete digestion on the resulting leach residues to determine metals bound in the silicate phases. Solutions from all digestions were analyzed by inductively coupled plasma-atomic emission spectroscopy. Preliminary interpretation of data for the 1996 samples indicates the following:

1. Concentration profiles show that leachable trace-element concentrations in bed sediment are highest just downstream of the Comet Mine in High Ore Creek and in Jack Creek and Uncle Sam Gulch downstream of the Bullion-Crystal Mine lineament. The volumes of mine waste available from these two areas are also the largest in the study area. Therefore, these areas are considered the most significant sources of metal contamination in the study area.
2. Antimony, arsenic, copper, lead, and zinc are concentrated in the leachable phase and reflect sorption of these trace elements to the particulate phase. The concentration profile for each element is determined both by the rate at which the dissolved element sorbs to particulates and the rate of downstream transport of sediment.
3. The downstream concentration profiles for antimony, arsenic, and lead are similar and indicate that these elements are removed from solution by sorption within a short distance from their sources.
4. Copper and zinc are carried further downstream from source areas than antimony, arsenic, and lead. Sorption of copper and zinc depends on water chemistry; pH is probably the dominant variable. This same phenomenon has been observed in the Animas River watershed (Church and others, 1997).
5. Historic mines in the study area have affected the Boulder River. Leachable concentrations of arsenic, copper, lead, and zinc in bed sediment are elevated above crustal abundance (background values) for more than 50 kilometers from High Ore Creek downstream to the Jefferson River. Although the data are limited by analytical sensitivity, leachable concentrations of antimony in bed sediment probably decrease to crustal-abundance values upstream of the town of Boulder.

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Fluvial Tailings Deposits in the Boulder River Watershed, Montana: Preliminary Results

By D.L. Fey,[1] S.E. Church,[2] J.S. Curry,[3] and T.C. Sole[4]

In the Boulder River watershed, tailings from mill sites have been transported into stream drainages at many locations. The tailings are either part of the active stream sediment load or in such proximity as to be transported into the stream by mass wasting, stream-bank cutting, or large runoff events. Fluvial tailings are being examined to determine volume, content of heavy metals, and potential impact to streams in the study area.

In July 1997, one-inch diameter cores were collected at six sites: (1) the tailings flat below the Buckeye-Enterprise mine and mill complex in the headwaters of Basin Creek, (2) below the mill site of the Bullion Mine, including a breached impoundment and dam, on an upper unnamed tributary of Jack Creek, (3) a smaller but similar site composed of another breached impoundment and dam several hundred meters downstream from site 2 on the same unnamed tributary, (4) two separate sites on upper High Ore Creek downstream from a breached and dissected impoundment area below the Comet Mine, and (5) a small deposit of fluvial tailings capping a bar located on the Boulder River about 200 meters (m) downstream from its confluence with Basin Creek. At each site, cores were collected along the long axis of the fluvial tailings deposit and along several perpendicular traverses. Samples were collected in plastic core tubes using a stainless-steel soil probe/sampler to a depth of up to 1 m; typical depths were 30–50 centimeters. Sample spacing was 7–15 m, depending on the size of the site.

A total of 133 core samples was collected, totaling more than 50 m in aggregate length. In the laboratory, the cores were divided into nearly 700 subsamples on the basis of visual differences in mineralogy, organic content, and leaching zones. The subsamples were ground and analyzed using total digestion and inductively coupled plasma-atomic emission spectroscopy analyses. Fine-grained pyrite and other sulfide minerals were observed in fewer than 10 of the subsamples. Many subsamples, however, contained iron oxy/hydroxide minerals and sulfate-coated quartz grains. In this talk we: (1) present the geochemical data and their relation to core depth, gross mineralogy, and visible leaching, (2) estimate the mass of fluvial tailings and metals at each site, and (3) assess the potential for impacts on streamwater quality.

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Methodologies for Characterizing Aquatic Health and Preliminary Results, Boulder River Watershed, Montana

By Aida M. Farag,[1] Dan F. Woodward,[2] Donald R. Skaar,[3] and William Brumbaugh[4]

The Boulder River and some of its tributaries receive direct effluent from abandoned mine adits and runoff from old tailings piles located in the basin. As a result, metals may accumulate in the sediment, water, and aquatic biota present in the Boulder River. The quantity and quality of aquatic biota and the overall ecological health of the Boulder River may have deteriorated as a result of these metal exposures. This biological assessment will identify the biological pathway of metals in the Boulder River watershed by measuring concentrations of metals in biofilm (abiotic and biotic material on rock surfaces), invertebrates, and fish collected from the Boulder River and a select number of its tributaries. These data along with data from fishery population surveys will be used to assess the ecological health of the Boulder River and its tributaries. Thus, we will determine if exposure to metals has resulted in a quantitative loss in fish populations in the Boulder River watershed. If impact has occurred, the recovery of fishery resources will be one of the gauges by which the success of remediation in the Boulder River watershed can be measured.

Reference sites on the Boulder River (near Red Rock Creek), the upper Boulder River, and the Little Boulder River were chosen to estimate the pre-mining conditions of the test sites in the Boulder River watershed. Nine test sites were identified to define the current conditions in the watershed: lower High Ore Creek, Cataract Creek above Uncle Sam Gulch, Cataract Creek below Uncle Sam Gulch, lower Cataract Creek, Jack Creek below the Bullion Mine, lower Basin Creek, Boulder River below Cataract Creek, Boulder River below Basin Creek, and Boulder River at Galena Gulch. Biofilm and benthic macroinvertebrates were collected from all sites. Fish gills, fish livers, and whole fish were collected from five sites. The concentrations of metals are currently being analyzed in all samples. In addition, metallothionein and lipid peroxidation will be measured in fish gill and liver samples. Fish-population surveys were performed at the five sites where fish were collected. Sample methodologies will be presented in detail, and any available results will be discussed.

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Transport and Partitioning of Zinc Among Water, Colloids, and Bed Sediments During Low-Flow Conditions, Animas River Watershed, Colorado

By B.A. Kimball[1] and S.E. Church[2]

Metals from mine drainage near Silverton, Colorado, affect water quality and aquatic life in the Animas River for more than a hundred miles downstream. Samples of water, colloids, and bed sediments were collected in October 1995 to give an overview of the sources, transport, and partitioning of toxic metals in the Animas River watershed. The transport and partitioning of zinc illustrates how metals move downstream from the upstream sources. Zinc enters the streams as a dissolved solute in water draining source rocks and also as part of the sediments that are eroded from outcrops, waste-rock piles, and tailings. Dissolved zinc is transformed to colloidal zinc as it sorbs to colloidal-iron solids during transport, especially in the mixing zones downstream from Cement and Mineral Creeks. The colloids move with the water but progressively aggregate and settle in calm areas of the stream. In this way, the originally dissolved zinc is added to the zinc in the bed sediments as zinc sorbed to aggregated, colloidal particles. This colloidal zinc occurs in the most easily digested fraction of streambed sediments and may be the most readily available zinc for aquatic organisms. The majority of zinc in the noncolloidal fraction of the bed sediments, however, is present as sphalerite, even at great distances from Silverton. Lead-isotopic data from bed-sediment samples indicate that 172 kilometers downstream at Aztec, New Mexico, 57 percent of the lead in bed sediments was derived from sources upstream from Silverton. The annual flushing of zinc during snowmelt runoff greatly increases the colloidal and sediment loads, transporting zinc to these downstream sites. Understanding these physical and chemical processes will help managers make decisions about water-quality management options for the Animas River watershed.

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Impacts of Abandoned Mine Lands on Stream Ecosystems of the Upper Animas River Watershed, Colorado

By John M. Besser,[1] Del Wayne R. Nimmo,[2] Robert Milhous,[3] and William Simon[4]

Recent surveys conducted by the State of Colorado suggested that abandoned mine lands may adversely affect the "ecological health" of streams in the upper Animas River watershed. Fish and invertebrate populations were reduced or virtually absent from stream reaches receiving heavy loadings of acidity and heavy metals from abandoned mines and natural acid drainage. The USGS, in cooperation with the Animas River Stakeholders Group (ARSG), initiated studies during 1997 to provide more detailed information on stream biological communities and to characterize the range of metal bioavailability, toxicity, and habitat quality at sites with a wide range of apparent mining impacts.

An ongoing biomonitoring study conducted by the ARSG will further characterize the abundance and taxonomic compositions of benthic invertebrate communities of the entire Animas River watershed, with an emphasis on the role of tributary inputs in the impact and recovery processes. Concentrations of heavy metals have been analyzed in tissues of stream biota (periphyton, invertebrates, and fish). Bioaccumulation and food-chain transfer of metals produce metal concentrations in invertebrates and fish which differ substantially from concentrations in water and sediment. Metal concentrations in the biota of the upper Animas River watershed are comparable to those associated with adverse effects on fish and invertebrates in other mining-impacted streams.

The toxicity of water and sediment from the Animas River and tributaries to fish and invertebrates has been evaluated in studies conducted onsite and in the laboratory. The toxicity of water differed substantially among sites, among habitats (stream water compared to interstitial water), and over time. The toxicity of water and sediment followed similar trends among sites, with greatest toxicity at sites where biotic communities are most affected.

Studies of the characteristics of stream substrata are intended to indicate whether physical impacts of mining (sedimentation or "cementation" of stream gravels) may degrade physical habitats required for fish reproduction. The results of these studies will be used to develop protocols for studying the mechanisms of impacts on stream biota and to identify target sites for monitoring the short- and long-term results of remediation.

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Seasonal Fluctuations of Dissolved-Zinc Concentrations and Loads in the Mainstem Streams of the Upper Animas River Watershed, Colorado

By Kenneth J. Leib,[1] M. Alisa Mast,[2] and Winfield G. Wright[3]

Runoff and drainage from mines, mine dumps, tailings, and springs contain elevated dissolved-zinc concentrations in the upper Animas River watershed. Discharge in cubic feet per second (ft^3/s) and concentration in micrograms per liter (mg/L) from these sources vary seasonally. As a result, dissolved-zinc loads in pounds per day (lb/d) in the mainstem streams of the upper Animas River watershed vary seasonally. Better documentation of this seasonal variation is the first step in determining the correlation between source inputs and mainstem loads. The correlation is established by first observing fluctuations in mainstem loading and then relating these mainstem fluctuations to fluctuations measured in source loads. Sampling of sources can be tailored to coincide or precede periods of increased loading after the first year of data collection. This correlation can aid remediation prioritization in that remediation efforts can be focused on sources that have the highest loading impact to the system. Until recently, sampling in the basin was limited to spring runoff, summer, and early autumn. As a result, seasonal variations were not adequately defined. Although some variations in flow and loading were observed, a better characterization of low flow in winter and early spring, of spring runoff, and during periods of rainfall runoff is needed to improve the definition of dissolved-zinc concentrations and loads throughout the annual hydrograph. Sampling began at a network of four gages in November 1996 and is expected to continue through 1999. Two gages are located on the major tributaries of the Animas River (Cement Creek and Mineral Creek), and two are located on the Animas River—one upstream from the confluence of Cement Creek and one downstream from the confluence of Mineral Creek. During low flow in winter, one sample per month was taken. During spring runoff, samples were taken biweekly as the peak flow approached and then weekly during the periods of highest discharge. As the spring runoff receded, sampling decreased to biweekly and then monthly during low flow. Grab samples of several rainfall-runoff events from Cement and Mineral Creeks were obtained on the rising and falling limbs of the hydrograph. During water year 1997, dissolved-zinc loads (and corresponding concentrations) at the four gages ranged from 45.4 lb/d (679 mg/L) to 2,140 lb/d (197 mg/L), and streamflow ranged from 12.4 to 2,010 ft^3/s. During low flow in winter (November–March), loads ranged from 42.9 lb/d (938 mg/L) to 562 lb/ d (868 mg/L). During spring runoff (April–July), loads ranged from 92.1 lb/d (71 mg/L) to 2,140 lb/d (197 mg/L). And, in autumn (August–October), loads ranged from 84.4 lb/d (174 mg/L) to 626 lb/d (248 mg/L). Rainfall runoff sampled at the Mineral Creek gage in August indicated dissolved-zinc loads of 84.4 lb/d (174 mg/L) for the rising limb of the hydrograph (89.9 ft^3/s) and 90.2 lb/d (177 mg/L) for the falling limb of the hydrograph (94.4 $ft/^3s$). Maximum dissolved-zinc loads occurred between the first and second weeks of June at all four gages. Maximum concentration values occurred between February and March at all the gages except Cement Creek, where the concentration peak occurred in the second week of May. The reason for this late peak in concentration may be due to a flushing effect from spring snowmelt.

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Colloid Formation and Transport of Aluminum and Iron in the Animas River near Silverton, Colorado

By L.E. Schemel,[1] B.A. Kimball,[2] and K.E. Bencala[3]

Effects of inflow from two creeks on the transport of aluminum and iron in the Animas River near Silverton, Colorado, were studied during September 1996. Chemical compositions of both tributary creeks were influenced by remains of past mining activities and natural mineral deposits. Inflow from Cement Creek was low in pH (<4) with high (total) concentrations of aluminum and iron (5.3 and 7.5 milligrams per liter, respectively). Aluminum was dissolved in Cement Creek, but the increase in pH to about 7 upon mixing with the Animas River transformed the aluminum into colloidal particles. Iron was present both in dissolved and colloidal forms in the creek and in the river. Although discharge from Cement Creek accounted for only 21 percent of the flow of the Animas River downstream of the confluence, it contributed 95 percent of both the aluminum and iron. Inflow from Mineral Creek further increased transports of colloidal aluminum and dissolved and colloidal iron in the Animas River; however, the difference in pH between the two streams was small (<0.5 units) and no additional colloid formation was apparent. Inflow from Mineral Creek accounted for approximately 43 percent of the flow, 57 percent of the aluminum, and 55 percent of the iron in the Animas River below the confluence. Mass-balance calculations indicated that colloidal aluminum and iron were transported in this reach of the river without large losses by settling.

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Recurrence Intervals, Probability, and Annual Duration of Dissolved-Zinc Concentrations Using Flood Analysis Techniques in the Upper Animas River Watershed, Colorado

By Kenneth J. Leib,[1] M. Alisa Mast,[2] and Winfield G. Wright[3]

The recurrence interval (in days), probability (in percent), and duration (in days) of dissolved-zinc concentrations at the gage on the Animas River below Silverton, Colorado, were estimated by using flood-analysis techniques. Recurrence, probability, and duration are needed to describe exposure of fish to different zinc-concentration ranges and flow regimes in this mining-impacted river. These parameters also are useful for monitoring the progress of remediation in the basin because pre-, during-, and post-remediation models can be applied to this flood-analysis approach. First, using samples collected during 1992–93, a relation was developed between dissolved-zinc concentrations and streamflow using a hyperbolic regression model. A hyperbolic regression model is a flow-modification technique used to improve the relation between the dependent (dissolved-zinc concentration) and independent variables (mean-daily discharge). This data set was chosen to reflect pre-remediation conditions in the basin. Dissolved-zinc concentrations then were generated for the entire period of mean-daily-discharge record (water years 1992–96) using the pre-remediation model. No major flow alterations were known to have occurred in the basin upstream from the sample site; therefore, as long as the pre-remediation model was used, all mean-daily-discharge record at the gage could be used to predict pre-remediation dissolved-zinc concentrations. Next, a log-Pearson type III flood-analysis technique was applied to the computed dissolved-zinc concentrations to estimate recurrence intervals and exceedance probabilities for concentrations that range from 200 to 550 micrograms per liter (μg/L). The log-Pearson type III distribution also was used to normalize the predicted dissolved-zinc data set. Normalizing the data set reduced the tendency of the predicted dissolved-zinc values to bias extreme events.

Durations for dissolved-zinc concentrations ranging from 200 to 550 μg/L were estimated by using another flood-analysis tool known as the streamflow-duration curve (duration curve). The duration curve was constructed using the mean-daily discharge record mentioned previously. The pre-remediation model was then used in conjunction with the duration curve to determine dissolved-zinc durations for given flow regimes. A duration curve is used because each mean-daily-discharge value is used in the construction of the curve, as opposed to information obtained from a log-Pearson type III distribution, which uses the average of mean-daily discharges for each year. The duration curve and corresponding dissolved-zinc duration values represent the period of record (1992–97). Recurrence intervals for dissolved zinc ranged from 7 days for concentrations of 550 μg/L or more to 1.25 days for concentrations of 200 μg/ L or more.

Daily exceedance probabilities for dissolved zinc ranged from 90 percent for 200 μg/L and 18 percent for 550 μg/L. For dissolved-zinc durations, 200 μg/L was equaled or exceeded 328 days per year and 550 μg/L was equaled or exceeded 50 days per year.

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A Toxicological Reconnaissance of the Upper Animas River Watershed near Silverton, Colorado

By Del Wayne R. Nimmo,[1] Carla J. Castle,[2] and John M. Besser[3]

Toxicity tests were conducted during 1997 with water and sediment from the mainstem and tributaries of the Animas River near Silverton, Colorado. The toxicity of stream water to rainbow trout, *Oncorhynchus mykiss*; daphnids, *Ceriodaphnia dubia*; fathead minnows, *Pimephales promelas*; and amphipods, *Hyalella azteca*, was evaluated with 48- and 96-hour lethality tests conducted onsite. Initial tests were conducted with undiluted surface water and subsurface water (interstitial or hyporheic water) from six sites. Subsurface water was collected from shallow depressions dug in gravel bars. Two sites were selected for detailed tests which used serial dilutions of test waters with reconstituted laboratory water. The toxicity of stream sediments was tested in the laboratory using 10-day tests with *H. azteca* and the midge, *Chironomus tentans*. Fine sediment (particle diameter <0.5 millimeters) was collected from all six sites by sieving stream gravels.

Initial tests indicated that both surface and subsurface water from Cement Creek and subsurface water from the Animas River below Silverton (site A72) were toxic to daphnids, minnows, and trout. Surface water from Cement and Mineral Creeks and the Animas River above Silverton (site A68), below Silverton (site A72), and at Elk Park (8 kilometers downstream from Silverton) was toxic to daphnids but not fish. Subsurface water from South Mineral Creek (reference site), Mineral Creek, site A68, and the Animas River at Elk Park was not toxic to the test species. Subsurface water from site A72 was the most toxic sample tested and daphnids were the most sensitive species, with median lethal concentrations (LC50, expressed as percent dilution) of 31 percent, followed by minnows (35 percent), trout (40 percent), and amphipods (56 percent). Calculations of Toxic Units (measured concentration of metal divided by known toxic concentration) suggest that copper and zinc could account for the toxicity of water from site A72. Multiple samples of surface water from the Animas River at Elk Park showed intermittent toxicity, which may be attributable to variation in copper concentrations.

Survival of midges and growth of amphipods were reduced significantly by exposure to sediment from several sites (relative to the reference site, South Mineral Creek). Trends in sediment toxicity were similar to those observed in water-phase tests, with greatest adverse effects caused by sediment from Cement Creek, Mineral Creek, and site A72. In contrast, neither amphipod survival nor midge growth differed significantly among sites, and the overall magnitude of effects was less in sediment tests than in water-phase tests.

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Metal Uptake, Transfer, and Hazards in the Stream Food Web of the Upper Animas River Watershed, Colorado

By John M.Besser,[1] William Brumbaugh,[2] S.E. Church,[3] and B.A. Kimball[4]

Streams in the upper Animas River watershed of Colorado drain a highly mineralized basin which has been extensively mined for gold and other heavy metals. The water quality, aquatic habitats, and stream biota of these streams are affected by acid drainage and metal contamination from hundreds of abandoned mines and from natural weathering of rocks and soil. We conducted a survey of metal concentrations in water, suspended colloids, sediment, and stream biota from the upper Animas River watershed. The objectives of this study were to examine: (1) relationships among metal concentrations in water, suspended colloids, sediment, and biota (periphyton, benthic invertebrates, and fish); (2) transfer of metals among trophic levels; and (3) potential hazards of metal toxicity to fish.

Tributaries draining highly mineralized areas of the watershed (Cement Creek and Mineral Creek) contributed high concentrations of dissolved and colloidal iron, aluminum, zinc, and copper to the Animas River near Silverton. These metal loadings were associated with severe alterations of benthic invertebrate communities and reduction or elimination of brook trout populations.

Metal concentrations in periphyton samples (consisting of algae, other associated microorganisms, and mineral deposits) were strongly correlated with metal concentrations in fine sediment. Metal concentrations in invertebrates and fish reflected overall differences in metal loadings among sites, but also varied among taxa of invertebrates, with differences apparently related to body size and feeding mode. Livers of brook trout contained greater concentrations of copper and cadmium, and lesser concentrations of zinc and lead, than invertebrates.

Concentrations of copper in tissues of invertebrates and fish corresponded most closely to observed impacts on biota of the upper Animas River watershed. Concentrations of both copper and zinc in invertebrates from impacted sites in the watershed were similar to concentrations of these metals associated with adverse effects on invertebrates and fish in other streams draining abandoned mine lands.

These results indicate that exposure of predators such as brook trout to metals via metal-contaminated diets differs from waterborne exposure due to processing of metals through the stream food web. Chronic metal exposure of both fish and invertebrates of the upper Animas River watershed, which occurs via both water and diet, may result in impacts at sites where water is not acutely toxic.

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Rare Earth Element Geochemistry of Acid Waters: Preliminary Results Identifying Source Signatures and Instream Processes

By Philip L. Verplanck,[1] D. Kirk Nordstrom,[2] Winfield G. Wright,[3] and Howard E. Taylor[4]

The objective of this study is to determine the major processes governing the fractionation of rare earth elements (REEs) during weathering of mined and unmined mineralized rock. REE geochemistry is a powerful tool for constraining geochemical processes. This has been demonstrated in many petrologic studies but is just beginning to be applied to aqueous systems.

The Boulder River watershed, Montana, and upper Animas River watershed, Colorado, sites are ideally suited for this study because of the multidisciplinary approach that is being used at these abandoned-mine-land sites to identify processes that potentially control the occurrence and transport of contaminants. REE geochemistry is being used with other geochemical indicators to identify source signatures of acidic waters, as well as to constrain processes controlling the fate and transport of metals upon entering the fluvial system. Preliminary data from studies of subbasins within the upper Animas River watershed show subtle variations in the REE patterns of acid waters derived from various sources. These variations are currently being investigated.

A 2-kilometer long stream reach in the South Fork Cement Creek basin was sampled during low flow in October 1996 to investigate processes affecting REE geochemistry during transport. Downstream, the pH decreases, and the loads of the REEs and major and trace elements increase. Comparing the measured load at the lowermost site to the sum of the input loads, 77–93 percent of the REEs are accounted for; in contrast measured loads of calcium, cobalt, strontium, sulfate, and zinc averaged 117 ± 3 percent of the summed input loads. The percentages less than 100 percent suggest that some REE removal occurs in this acidic, alpine stream. Iron and aluminum colloids are actively precipitating, and this process may remove REEs and other metals from the water column. Field and laboratory studies are underway to investigate the role colloids play in the removal of REEs and other metals from acid waters. The results from the first year of this study show that REE variations of acid waters may help meet the AML Initiative objective of identifying processes that control the occurrence and transportation of contaminants in alpine watersheds.

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Comparison of Filtration Procedures and Analytical Procedures on Iron (II/III): Results from Upper Animas, Summitville, and Iron Mountain

By James W. Ball,[1] D. Kirk Nordstrom,[2] and Charles N. Alpers[3]

Although not particularly toxic, iron plays an important role in the mobility, bioavailability, and toxicity of other trace elements associated with watersheds affected by abandoned mine lands. The quantity of hydrous ferric oxide (HFO) moving in the water column strongly affects downstream transport and loading, and thus offsite toxicity, of many trace metals that may be adsorbed by HFO. Thus, realistic measurements of iron and HFO concentrations in streams are important for abandoned-mine-land studies.

Sample-processing time and filtration can have a substantial influence on analytical results for iron and associated elements. Rapid, microbially catalyzed oxidation of iron(II) to iron(III) and formation of HFO colloids can occur during sample processing. Because colloidal iron concentrations are often much higher than dissolved iron(III) concentrations, any colloidal material passing into the filtrate will result in overestimation of dissolved iron(III) concentrations. Iron oxidation and colloid formation during filtration may result in underestimates of iron(II) and total dissolved iron concentrations.

Effects of filtration apparatus and procedure on dissolved iron(II) and iron(III) concentrations were investigated at the Silver Ledge adit along Cement Creek near Silverton, Colorado; the Alamosa River below Terrace Reservoir near the Summitville Mine, Colorado; and the Sacramento River downstream of the Iron Mountain Mine, California. Water was filtered through 0.1-micrometer (μm) or 0.45-μm pore-size membranes and a Millipore Minitan ultrafiltration apparatus (effective pore size <0.001 μm). To determine the volume of filtered water needed to reach steady-state concentration, ten or twelve sequential 125-milliliter (mL) subsamples were collected at two locations and analyzed for ferrous and total iron using the FerroZine colorimetric technique.

Total dissolved iron concentrations in samples from Silver Ledge adit were essentially the same for 12 sequential 0.45-μm filtrates and 12 sequential 0.1-μm membrane filtrates. Iron concentrations in initial ultrafiltrate were about 91 percent of iron concentrations in 0.1- or 0.45-μm filtrates, whereas iron concentrations in ultrafiltrate collected 4.5 hours later were about 76 percent of iron concentrations in 0.1- or 0.45-μm filtrates. These results indicate that iron colloids may form and be removed during ultrafiltration.

As much as 93 percent of the total iron in water samples from the Sacramento River is removed by filtration. Only 55 percent and 16 percent of the total iron is removed from samples from the Alamosa River and Silver Ledge adit, respectively. The combination of high particulate iron and low dissolved iron concentrations in the Sacramento River increase the potential for overestimating the actual dissolved iron concentration if filtrate is contaminated with particulate iron during sample processing.

Ferric iron concentrations frequently are 1 percent or less of iron(II) concentrations. Typically, iron(III) is determined by differencing total iron and iron(II), thereby introducing uncertainties that may approach 100 percent. A method was developed for direct determination of iron(III) using complexing reagents acetohydroxamic acid for iron(III) and FerroZine for iron(II). Onsite 0.1-μm membrane filtration with direct determination of iron(II) and iron(III) may avoid the possible processing effects inherent with ultrafiltration techniques.

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Characterization of Aquatic Health in Mine-impacted Streams: A Case History from the Clark Fork River, Montana, and the Coeur d'Alene River, Idaho

By Dan F. Woodward,[1] Aida M. Farag,[2] and William Brumbaugh[3]

The Clark Fork River (Montana) and the Coeur d'Alene River (Idaho) were evaluated for the effects of mine wastes on the aquatic resource. (Although not part of the ongoing abandoned-mine-lands study in the Boulder River watershed, the research techniques described here would be appropriate in that watershed.) The research documented metals movement through abiotic and biotic components, determined toxicological damage to fishery resources, and quantified reductions in fish abundance. Test and reference sites were selected to remove variability caused by geology, land type, valley-bottom type, and land and water uses. Test and reference sites were compared by analysis of variance for metals concentrations in water, sediment, biofilm, invertebrates, and fish. The sites also were evaluated for abundance of wild trout and for indicators of poor fish health. Metals were most concentrated in sediment and biofilm downstream from the mining sites. Benthic invertebrates were an important pathway for dietary cycling of metals from sediment and biofilm to fish. Wild trout demonstrated a concentration of metals in gill and intestine that indicated exposure from both water and diet. Liver accumulations of metals were associated with metallothionein induction and tissue damage, which indicates systemic exposure and reduced fitness of wild trout. Abundance of wild trout were reduced both in numbers and densities at test sites having the following characteristics: significant accumulation of metals in numerous food-chain components and fish tissues, reduced short-term survival of domestic trout in live containers, and metallothionein increases in gill, liver, and/or intestine of wild trout. Other related research described food-chain and avoidance effects which occur with metals-impacted rivers. Growth and survival of young-of-the-year trout were reduced after fry were fed benthic invertebrates collected from sources with high concentrations of metals. Water concentrations of copper and zinc, below those causing death, were avoided by cutthroat trout, rainbow trout, and brown trout.

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WATERSHED CHARACTERIZATION

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Geologic Framework of Volcano-Plutonic Igneous Complexes as It Relates to the Upper Animas River and Boulder River Abandoned Mine Lands Studies

By K. Lund,[1] M.J. O'Neill,[2] D.B. Yager,[3] R.G. Luedke,[4] and D.J. Bove[5]

The upper Animas River and Boulder River study areas are in different parts of the geologically similar San Juan, Colorado, and Elkhorn Mountains, Montana, volcanic fields, which are each estimated to have covered about 10,000 square miles. Igneous activity in the mid-Tertiary San Juan volcanic field formed a well-preserved, nested caldera complex that developed as batholith-scale magmas intruded into shallow levels of the crust. The Late Cretaceous Elkhorn Mountains volcanic field is largely eroded, and the underlying plutonic parts (Boulder batholith) of a large magmatic system are revealed beneath remnants of caldera systems.

Geologic maps compiled for the upper Animas River watershed incorporate previous USGS studies focused on volcano-tectonics and formation of mineral deposits. San Juan volcanism began with eruption of intermediate-composition lava flows followed by large-volume catastrophic eruptions that formed the nested San Juan-Uncompahgre and Silverton calderas. Caldera-related structures and later regional structures provided principal pathways for post-caldera-collapse igneous intrusions and for mineral-laden fluids that followed or filled the structures. Most mineral deposits in the upper Animas River watershed consist of silver, gold, and copper-lead-zinc base-metal sulfide minerals in epithermal vein and hydrothermal breccia-pipe deposits and are closely associated with shallow-level igneous plugs and stocks. Regional-scale pervasive alteration of the volcanic rocks, preserved in various degrees of severity, is associated with late-stage igneous intrusion and hydrothermal mineralization.

Geologic maps used in the Boulder River watershed project originated during intensive study of the Boulder batholith undertaken by the USGS in the 1950's with funding from the Atomic Energy Commission. Emphasis was on characterization of the batholith but, because of interest in radioactive elements, mining history and important metals at most deposits were described. New field work and process-oriented reinterpretation of earlier maps indicate that the roof of the Boulder batholith is exposed at its interface with remnants of the associated overlying Elkhorn Mountains volcanic field. Previous mapping mainly identified textural cooling phases of a single magma. These phases are now interpreted to be chill-margin facies, several more slowly cooled textural phases, volatile-rich roof phases, and cross-cutting bodies of late-cooling magma. The volatile-rich, incompatible-element-rich magma formed the source for lode quartz-vein precious-metal deposits. Conduits and deposition sites were cooling-fracture systems located at the roof of the crystallizing magma and controlled by regional stress patterns. These deposits have only narrow alteration haloes. During mineralization, overlying volcanic units formed a barrier across which hydrothermal systems did not operate extensively. These overlying rocks may have caused local buffering during mineralization as they do at present because of their carbonate content (G.A. Desborough, personal commun., 1997).

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Digital Geologic Compilations of the Upper Animas River and Boulder River Watersheds: Geographic Information Systems Technology Used as a Scientific Interpretation Tool

By D.B. Yager,[1] K. Lund,[2] R.G. Luedke,[3] D.J. Bove,[4] M.J. O'Neill,[5] and T.C. Sole[6]

Digital geologic maps were developed from previously existing geologic maps for the upper Animas River, Colorado, and Boulder River, Montana, watersheds as geographic-information-system (GIS) base coverages for simultaneous visualization of the spatial relationships between geology and diverse abandoned-mine-lands (AML) data sets. These maps provide a multilayered base coverage capability for use in an interdisciplinary approach to a cost effective and timely evaluation of these geologically complex watersheds. Digital geologic information, such as maps of rock types, structures, and veins, is combined with rock-chemical-composition, rock-alteration, and stream-chemistry data to: (1) aid in the interpretation of alteration processes and their distribution; (2) determine how fault and mineralized-vein density and patterns may influence water quality; and (3) delineate rocks with acid-buffering capacity or acid-generating potential. Derivative maps are readily generated from the digital geology to aid in this process-oriented reinterpretation of existing geologic maps. One such derivative map of the upper Animas River watershed shows the distribution of the Burns and Henson Formations, which commonly contain calcite-bearing, altered lava flows that can significantly neutralize acid mine drainage and acidic streams and ground water that intersect these units. Use of this GIS-derivative technique provides watershed-scale data on the natural potential of AML host rocks to neutralize acidic and metal-laden waters, especially when these derivative products are combined with additional mapping of alteration and of formations with different buffering capacities, as guided in part by the application of AVIRIS remote-sensing technology. Mine-waste-pile mitigation may directly benefit from information gained from the derivative maps because waste piles that are known producers of metals and acidity can be geographically placed in context with rock units that have either natural acid-buffering potential that have mineral assemblages that contribute to water degradation. Mitigation efforts on waste piles that occur near rock units with high buffering potential may not need to be as intensive as mitigation efforts on waste piles that occur in rock units with low buffering capacity.

Observations of field relationships in the Boulder River watershed were compiled for a new process-oriented geologic interpretation of the existing descriptive geologic map. One goal of the Boulder River project is to produce, from the digitally compiled geology, a three-dimensional model that depicts the spatial relationship between igneous activity and mineralization. The newly modified, interpretive digital geologic map will be draped on the digital topographic model to provide a visualization tool that may help refine our understanding of the three-dimensional relationships between plutonism, mineralization, alteration, and fracture distribution. Such a view of the geology will test our present hypotheses about the geometry of magmatic cooling phases of the Boulder batholith, the relationship between structural and mineralization patterns, and the dimensions of acid-buffering rocks.

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Progress Report on Surficial Deposits and Geomorphology of Major Drainages of the Upper Animas River Watershed, Colorado

By Rob Blair[1]

The surficial deposits and geomorphology of the upper Animas River watershed were examined during fall 1997 with the use of color 1:19,000-scale aerial photographs. The goals of the study include: (1) mapping surficial deposits in the upper Animas River, Cement Creek, Cunningham Gulch, Mineral Creek, and the Middle Fork and South Fork of Mineral Creek drainages; (2) assessing the impact of mining activities on the above tributaries; (3) locating potential sample sites representative of pre-mining deposition; and (4) constructing a brief Holocene geomorphic history of the watershed along these drainages.

Surficial geologic strip maps that represent about one kilometer in width and approximately 125 meters above the modern flood plain have been constructed along each tributary. These maps primarily include fluvial, colluvial, and glacial units. Direct human interference of surficial deposits includes gravel mining and channel modification. Indirect human influence includes aggradation of sand and gravel resulting from increased sediment loads related to the erosion of cleared slopes, mine dumps, and tailings piles.

Mining and associated human activity have directly or indirectly modified an estimated 80 to 90 percent of the fluvial surfaces in the Animas valley from Silverton to Animas Forks. Just north of Howardsville, the flood plain has been entirely reworked. Cunningham Creek and Cement Creek occupy narrow valleys; therefore, road construction and mining activity adjacent to the stream can easily impact the whole channel. For example, the collapse of Lake Emma into the Sunnyside Mine in 1978 and its associated flush of sediment-laden waters down Cement Creek coated the entire active flood plain with muddy sediment. Approximately 50 percent of the Mineral Creek and the South Fork of Mineral Creek valley floors have been modified by human activity. Although these tributary channels have been modified, it appears that it takes only a few years or less for them to revert back to a quasi-equilibrium channel form.

The most prominent pre-mining terrace deposits are found in the wider valley floors along the upper Animas River and Mineral Creek. The most distinct terraces are located near the junction of Cunningham Creek and the upper Animas River. Glacial moraine and high-valley-floor deposits indicate that upper Mineral Creek and Middle Fork of Mineral Creek were dammed when an ice stream from South Mineral Creek blocked the upper tributary drainages approximately 16,000 years ago. Local changes in stream gradient can be found in all tributaries associated with opposing debris fans and rare landslides (Cement Creek and South Fork of Mineral Creek.)

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Watershed Characterization from the Air: Application of Geophysical Techniques to Watershed Characterization in the Boulder River Watershed, Montana

By A.E. McCafferty[1] and B.D. Smith[2]

During December 1996 and October 1997, two airborne geophysical surveys were flown over parts of the High Ore, Cataract, and Basin Creek drainages. Magnetic and five frequencies of electromagnetic data were collected from a helicopter along closely spaced flight lines [200 meters (m)] at low altitude (60 m) above the ground surface. It is important to note that the first survey was flown at the beginning stages of the project so that geophysical maps and their derivative products could be used by other project scientists to place priorities for ground investigations during the first field season.

The primary objectives of the surveys were to (1) provide subsurface information on ground-water flow and physical-property patterns to aid in prediction of possible contaminant pathways to and from proposed repository sites; (2) characterize the conductivity and magnetization of shallow geologic units to aid in identification of metal-rich rocks contributing to the metal loads in the High Ore, Cataract, and Basin Creek drainages; and (3) provide site-specific information for remediation and/or risk-assessment issues.

Geologic units rich in metal-sulfide minerals can have distinct geophysical signatures. The magnetic and conductivity data were mathematically combined to infer locations of metal-bearing plutons and zones of hydrothermal alteration, both of which may be host to metal sulfides. The various combinations of magnetization and conductivity were tentatively ranked in terms of the potential to generate acid drainage. Areas are mapped where metals and acid runoff due to mining activity and natural processes may negatively affect surface water. For example, areas with magnetization domains with extremely low values associated with relatively high conductivity levels can indicate structures and point sources likely to produce contamination. Additionally, this model identifies areas that are covered by apparently nonacid-generating rock units and may reveal areas where metal-rich rocks are at depths shallow enough to possibly allow alteration, subsequent leaching and, therefore, transport of heavy metals to streams. Follow-up studies will involve field checking of anomalous areas and the integration of these results with geologic and hydrologic information to provide a clearer understanding of the possible environmental effects within the identified areas.

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Mapping of Acid-Generating and Acid-Buffering Minerals in the Animas Watershed by AVIRIS Spectroscopy

By B. Dalton,[1] T. King,[2] D.J. Bove,[3] R. Kokaly,[4] R. Clark,[5] S. Vance,[6] and G.A. Swayze[7]

Visible-wavelength and near-infrared image cubes for the Animas River watershed from Hermosa, Colorado, to the headwaters at Animas Forks, Colorado, were acquired on June 18, 1996, by the Jet Propulsion Laboratory's AVIRIS (Airborne Visible and InfraRed Imaging Spectrometer) instrument in a 17-minute pass under cloud-free, late-morning conditions. These image cubes have been analyzed using the USGS Tricorder V3.4 implementation (R.N. Clark, U.S. Geological Survey, written commun., 1998), an expert system which utilizes a database of over 300 laboratory spectra of end-member minerals and mineral mixtures to generate maps of mineralogy, vegetation coverage, and other material distributions from image cubes using both the spectral and spatial information dimensions.

Major iron-bearing, phyllosilicate, clay, carbonate, alteration, and other minerals were identified along with several vegetation classes. Subtle spectral variations enabled discrimination between similar hydrothermal alteration products, resulting in highly detailed maps, which were generated and field-checked during the 1997 field season. The maps reveal widespread distributions of anthropogenic as well as large localized outcrops of natural acid-generating mineral assemblages such as pyrite, jarosites, alunites, and goethite. Additionally, distributions of alkaline minerals such as calcite and dolomite were determined with sufficient precision to indicate a relation between acid-buffering assemblages and stream geochemistry within the watershed. Preliminary maps of mineral distributions were used as aids to field work by several teams during the 1997 field season, and improved maps of minerals of interest will again be utilized in the 1998 field season. These maps will be on display at the poster session of this meeting.

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Digital Data for Watershed Characterization of Abandoned Mine Land

By E. Paul Martin[1]

The USGS produces a number of standard digital products that represent base cartographic, elevation, and image information in support of a wide range of applications. In some applications, these data act strictly as a reference or background cover, and in some cases, these data are integrated with scientific information to form a knowledge base for subsequent analysis and decision making. Both cases apply to the USGS abandoned-mine- land project in order to characterize the watersheds.

A digital elevation model (DEM) provides an array of elevation values that represent the terrain. When brought into a geographic information system, the software can transform the grid values into a shaded relief topographic view. While certain features are easily discernible, the DEM does not present a true picture of the ground features. A digital orthophoto quadrangle (DOQ) yields a clear view of these ground features. The DOQ is an image product derived by differential rectification from a perspective aerial photograph or other remotely sensed image data. Image displacements caused by camera tilt and terrain relief are removed. The DOQ combines the image characteristics of a photograph with the geometric qualities of a map. The DEM and DOQ in concert render a unique representation in which both the elevation and natural and cultural features are accentuated. The DOQ provides a source from which to ground truth existing vector data (for example, a digital line graph's (DLG) spatial location) or from which to compile new cultural and natural features. The combination of DEM and DOQ with DLGs (or other vector data) draped over the landscape gives a comprehensive watershed view. With the addition of more detailed scientific information and coverages (for example, water-quality data, dump-site characteristics, and geology), one now has the watershed information from which to perform more detailed analysis within the geographic information system or other modeling software.

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SOURCE OF METAL LOADING

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Integration of Mine-Drainage Effects in Watersheds Using Tracer Injections and Synoptic Sampling

By B.A. Kimball,[1] R.L. Runkel,[2] Katherine Walton-Day,[3] and K.E. Bencala[4]

Effects of acid-mine drainage occur on different scales. An individual mine might affect a single hillside, a small tributary, or an entire watershed. Streams in mineralized regions typically drain both mines and natural sources of metal-rich water that contribute to the metal load of a watershed. The spatial pattern of toxic concentrations results from the contributions of all the sources combined with the interaction of the hydrologic, biologic, and geochemical processes that influence metal transport. Injecting a tracer at a constant rate for a sufficient time provides discharge measurements for spatially intensive synoptic sampling. Three calculations help to integrate all the sources and processes of the watershed: (1) the measured instream load is calculated for each stream site as the product of concentration and discharge, (2) a minimum total loading to the stream comes from summing all positive changes of instream load between stream sites, and (3) a maximum estimate of loading from visible inflows comes from summing the product of measured inflow concentrations and the change in discharge between stream sites around the inflow. Comparison of the three calculations for a tracer-injection study in Cement Creek, Colorado, indicates that 65 percent of the zinc load was from nonpoint sources at low flow. Although 54 percent of the zinc load was transported to the Animas River as dissolved load, the other 46 percent of the zinc load was transferred to colloidal iron and transported as colloidal load or was stored in streambed coatings. Streambed coatings are flushed by snowmelt runoff and contribute to high zinc loads in the Animas River. The perspective gained from using tracer injections and synoptic sampling facilitates planning of remediation efforts.

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Ground-Water Input of Zinc to a Watershed Affected by Acidic-Mine Drainage: Simulation Results and Implications for Remediation— Cement Creek, Upper Animas River Watershed, Colorado

By Katherine Walton-Day,[1] R.L. Runkel,[2] B.A. Kimball,[3] and K.E. Bencala[4]

Solute-transport models can be used to help interpret results from tracer-injection studies in streams. The models can help provide a physically quantitative interpretation of spatial profiles of metal concentrations in streams affected by acidic-mine drainage. Separating the physical (transport) effects on instream-concentration profiles from the chemical (reactive) effects aids in interpreting dominant processes controlling these profiles and in predicting effects of different remediation approaches. The OTIS (One-dimensional Transport with Inflow and Storage) solute-transport model was used to simulate results from spatially intensive synoptic sampling with tracer injection along a 7.5-mile (12-kilometer) reach of Cement Creek upstream from Silverton, Colorado, in the upper Animas River watershed. Simulation results for zinc, in which zinc is assumed to be nonreactive at current instream pH values (pH = 6.5 decreasing to 4.2 over the first half mile of the reach, and thereafter decreasing to about 3.5 at the bottom of the reach), indicate instream concentrations of zinc are greater than can be accounted for by inputs of zinc from measurable surface inflows to the stream. The discrepancy is greatest in the stream reaches between Fairview Gulch and Minnesota Gulch, in the vicinity of Ohio Gulch, and downstream from Niagara Gulch. This result suggests that ground-water discharge probably is an important source of zinc to Cement Creek. Simulations of remediating, or "turning off," zinc-rich inflows at Prospect Gulch and the Main Fork of Cement Creek upstream from the South Fork confluence predict a zinc concentration of about 0.6 milligram per liter at the mouth of Cement Creek, a decrease of about 25 percent compared to measured concentrations. In designing future simulation studies, the following will be the working hypothesis: actual remediation probably would cause instream pH values to increase to a range in which zinc is more chemically reactive. This increased reactivity of zinc could cause zinc concentrations to decrease more than the current remediation simulations indicate. The existence of ground-water sources of zinc, however, limits the effectiveness of any engineered remediation of surface inflows of zinc to Cement Creek because the ground-water inputs may keep instream concentrations of zinc greater than clean-up standards.

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Quantification of Metal Loading by Tracer-Injection Methods in Cataract Creek, Boulder River Watershed, Montana: Study Design

By Tom E. Cleasby,[1] David A. Nimick,[2] and B.A. Kimball[3]

Tracer-injection methods can be used to determine streamflow at numerous points more accurately and quickly than is possible with traditional current-meter measurements. Consequently, tracer-injection methods combined with sampling for metals can be useful for locating and quantifying individual and diffuse sources of metal loading to streams in basins affected by abandoned mine lands and for studying instream geochemical processes that affect metal transport. The highest concentration of inactive metal mines in the Deerlodge National Forest are in the Cataract Creek watershed, and Cataract Creek is a major contributor of metals to the Boulder River. Cataract Creek was selected for this tracer-injection study because many abandoned mines in the basin are adjacent to Cataract Creek, making it possible to quantify both surface and subsurface inflows. In addition, geochemical processes affecting metal transport downstream of Uncle Sam Gulch, the largest metal contributor to Cataract Creek, could be studied.

During a 3-day field reconnaissance in July 1997, the length of the stream was measured, and tributaries and inflows from adits, tailings, and waste-rock piles were identified. The study reach is 7.7 miles long and extends from a point upstream of most mine workings, where effects of abandoned mines were thought to be minimal, downstream to the confluence with the Boulder River. Four tributaries, 21 minor inflows, and 47 instream sites were chosen for sampling during the tracer study on the basis of their location upstream or downstream from inflows or suspected metal sources. Water samples collected during the reconnaissance indicated that pH values at all sites were higher than 6.8 and that ambient chloride concentrations were <0.35 milligrams per liter.

During a 3-day period in August 1997, a tracer solution containing 219 grams per liter NaCl was injected continuously at the most upstream site at a rate calculated to increase the chloride concentration to about 3 milligrams per liter at the mouth of Cataract Creek, where streamflow was about 11 cubic feet per second. After the tracer concentration reached a constant level, samples were collected within 12 hours from the previously identified sites and analyzed for chloride and for total recoverable and dissolved (using 0.1-micrometer filtration) metals. When available, the analytical data will allow calculation of metal loads at each of the 72 sites to determine the location of important sources.

In past use of tracer-injection methods for determining metal loading in abandoned-mine-land areas, study streams typically have been acidic with high metal concentrations. In contrast, Cataract Creek has lower metal concentrations and neutral to slightly alkaline pH. Results of this study can be used to assess the utility and sensitivity of tracer-injection methods in streams with more moderate mine-drainage effects.

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Natural Contributions of Acidity and Metals to Surface Waters of the Upper Animas River Watershed, Colorado

By Dana J. Bove,[1] Winfield G. Wright,[2] M. Alisa Mast,[3] and Douglas B. Yager[4]

Copper-molybdenum (Cu-Mo) porphyry and acid-sulfate hydrothermal systems, which are noted for their association with naturally degraded waters, are areally extensive within the upper Animas River watershed. Integrated geologic and aqueous geochemical studies of three such systems in the Mount Moly, Topeka Gulch, and Prospect Gulch areas provide critical insight into pre-mining stream conditions and natural processes of metal mobilization and attenuation within the watershed.

The Mount Moly area is underlain by over 4.5 square miles (mi^2) of intensely altered and pyritized rock related to a 25.5 million year old (Ma), low-grade, Cu-Mo porphyry system. The main zone of Cu-Mo mineralization is coincident with intense quartz-sericite-pyrite (QSP) altered rock, high fracture densities, and up to 5 volume percent (vol. %) pyrite. QSP-altered rock grades outward into weak-sericitic/intense propylitic (Wk-S) (<0.5 vol. % pyrite) and finally into propylitized (chlorite ± epidote± calcite) rock. Stream waters draining the QSP alteration zone had pH values <3.4 and Ficklin metal (FM) sums (Cu+Zn+Pb+Ni+Co+Cd in micrograms per liter) averaging 360. Streams influenced chiefly by Wk-S altered rocks were slightly less degraded with pH values from 4.9 to 5.8 and FM sums of 12 to 80. Natural waters draining propylitic-altered rocks (PROP) were less affected still, with a median pH value of 6.0 and FM sum of 14. By comparison, mining impacted waters in the same area had a median pH value of 4.4 and FM sum of 1,613. Mass-balance calculations indicate up to 35 percent of FM in waters draining the Mount Moly area are derived from natural sources.

The headwaters of Topeka Gulch are underlain by intensely altered rock (>0.3 mi^2) at the margins of a 23 Ma acid-sulfate hydrothermal system centered near Ohio Peak. Downstream of Ohio Peak, rocks are dominantly QSP-altered (>3-5 vol. % pyrite) with pyrite mostly oxidized above stream level. PROP-altered rocks are present in the lower one-third of the basin. Weathering of pyrite in the QSP assemblage produces highly acidic waters with a median pH of 3.5 and FM sum of 355. An abandoned mine in Topeka Gulch is present near the PROP/QSP transition zone. Water discharging from the mine contains high concentrations of dissolved sulfate and alkalinity, which control the stream-water chemistry downstream to the subbasin outlet. The high-pH/sulfate-rich mine water (pH of 6.9, FM sum of 72) is probably buffered by propylitized rocks containing abundant calcite present in microfractures and as primary mineral replacements. Mass-balance studies indicate that over 90 percent of the FM sum at the mouth of Topeka Gulch is naturally derived.

The northern part of Prospect Gulch encompasses the margins of an extensive 23 Ma acid-sulfate hydrothermal system comprised of QSP and quartz-alunite pyrophyllite-altered rocks (0.6 mi^2) with high metal content and 8–10 vol. % pyrite. In contrast, rock in the southern part of the basin is predominantly PROP-altered, representing the margins of the acid-sulfate system. Large, mineralized fault structures (>150 feet wide) cross-cut the basin, and mineralized breccia masses are present south of the stream. A large zone of quartz-alunite-altered rock is associated with the most naturally degraded waters (pH of 3.3 and FM sum of 285). In contrast, waters draining the argillic/PROP margins of the acid-sulfate system are less degraded with pH values from 3.4 to 3.8 and FM sums <10. Waters influenced by propylitized rocks are the most pristine, with pH values >6.0 and FM sums <70. Similar to Topeka Gulch, calcite-bearing, propylitized rock buffer sulfate-rich waters that interacted with QSP-altered vein structures. Mine-impacted waters in Prospect Gulch had higher FM sums than their natural counterparts, with a median pH value of 3.2 and FM sum of 4,300.

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Comparison of Surface-Water Chemistry in Undisturbed and Mining-Impacted Areas of the Cement Creek Watershed, Colorado

By M. Alisa Mast,[1] Winfield G. Wright,[2] and Kenneth J. Leib[3]

Many tributaries in the upper Animas River watershed are acidic and have elevated concentrations of dissolved metals as a result of historical mining and natural weathering of mineralized volcanic rocks. To gain a better understanding of the relative importance of natural-background and mining-related sources of dissolved metals, more than 70 streams, springs, and draining adits were sampled during summer 1997 in the Cement Creek watershed, a 50-square-kilometer subbasin of the upper Animas River. Although prospect pits and abandoned mines are scattered throughout the study area, much of the watershed, particularly at higher elevations, is relatively undisturbed. Preliminary results indicate that natural-background and mining-impacted areas of the basin produce acidic and neutral surface water, however, concentrations of major ions and dissolved metals generally are higher at the impacted sites than at the natural-background sites. The median pH of samples collected at the mining-impacted sites was 4.28 (range 2.79 to 7.32) compared to the median value of 6.59 (range 2.97 to 7.96) at the natural-background sites. Sulfate concentrations at the sampling sites ranged from 1 to 450 milligrams per liter (mg/L) and were generally higher at the mining-impacted sites (median value 138 mg/L) than at the background sites (median value 56 mg/L). Dissolved zinc concentrations were highly variable among the sampling sites, ranging from <10 to 14,600 micrograms per liter (µg/L). Results from the natural-background springs and streams revealed a geographic pattern in surface-water chemistry that appears to be related to the degree of bedrock alteration. The eastern part of the basin is primarily underlain by propylitically altered lavas, which produce neutral surface water (pH 6.40 to 7.96) with relatively low concentrations of dissolved metals, except for zinc (as much as 230 µg/L). The western part of the basin is more intensely altered than the eastern part, and includes pervasive argillic-type alteration in the northwest quadrant and quartz-sericite-pyrite alteration localized along structures. Water draining these areas is more acidic (pH ranging from 3.25 to 4.61) and has elevated concentrations of dissolved metals. The results of this study should provide useful information for establishing water-quality standards and characterizing sources of metals loads for surface waters in the upper Animas River Basin.

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Oxygen Isotopes of Dissolved Sulfate as a Tool to Distinguish Natural and Mining-Related Dissolved Constituents in the Upper Animas River Watershed, Colorado

By Winfield G. Wright,[1] M. Alisa Mast,[2] and Kenneth J. Leib[3]

The relative contributions of dissolved constituents from natural and mining-related ground-water sources in a watershed affected by abandoned mines need to be determined to prioritize basins for remediation and to assist with the establishment of water-quality standards. The oxygen isotopes of dissolved sulfate can help distinguish between natural and mining-related sources of dissolved constituents. In hydrogeochemical systems where sulfide-mineral oxidation is the main geochemical mechanism for the production of dissolved sulfate (such as in the upper Animas River watershed), the reaction chemistry of the sulfur and oxygen molecules in dissolved sulfate can differ between natural and mining-related hydrogeochemical systems. The reaction chemistry can be affected by: (1) higher concentrations of atmospheric oxygen in mine workings compared to natural ground-water systems; (2) the presence of ferric iron (an oxidant for the oxidation of sulfide minerals); and (3) the presence of sulfide-mineral-oxidizing and sulfate-reducing bacteria. When the oxygen-isotope data are graphically related to dissolved constituents such as sulfate or zinc, water samples from natural springs, open mines, and collapsed mines plot in three separate zones, indicating that different proportions of atmospheric oxygen and water-molecule oxygen have been incorporated into the sulfate molecules or that the sulfate has been affected by sulfate reduction or gypsum dissolution. Methods to determine the relative percentage of natural and mining-related dissolved constituents using the oxygen isotopes of dissolved sulfate include: (1) the isotope dilution equation for simple mixing zones (two sources and one receiving stream); (2) the isotope mass-balance equation for streams receiving dissolved sulfate from multiple sources; and (3) graphical relations and the mathematical solution of simultaneous equations. Integrating oxygen-isotope data from natural and mining-related ground-water sites on a watershed scale can illustrate the relative contributions from the different site types.

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Determination of Pre-Mining Background Using Sediment Cores from Old Terraces in the Upper Animas River Watershed, Colorado

By S.E. Church,[1] D.L. Fey,[2] and E.M. Brouwers[3]

Determination of the pre-mining background concentrations of metals in mining districts, particularly those that were heavily mined near the turn of the century, has proven to be challenging. The approach used in the upper Animas River watershed is to search for pre-mining surfaces using established geomorphological techniques, to core the sediment preserved in these settings, to examine the sediment in these cores for metal content and for signs of pre-mining aquatic life, and to compare metal concentrations in the pre-mining sediment to those in bed sediment from active stream channels today. In this report, we discuss the results from five sites within the upper Animas River watershed where pre-mining metal concentrations have been determined: (1) from the upper Animas River near Eureka and from a terrace above Brendel Gulch about one-half mile below the Cunningham Gulch confluence, (2) from pre-mining sediment exposed in the stream bank on Cement Creek halfway between the confluences of Porcupine and Ohio Gulches, (3) from Mineral Creek about one-quarter mile south of Chattanooga, (4) from Elk Park about 5 miles south of the confluence of the Animas River with Mineral Creek, and (5) from the Animas River about one-half mile south of the confluence with Cascade Creek.

Chemical data from the total digestions of the samples show that metals concentrations are systematically enriched in bed sediment today relative to the pre-mining bed sediment collected from old terraces. The data indicate that: (1) the enrichment factor for arsenic in bed sediment today is generally 1.5 to 2, with an enrichment factor of about 6 at Chattanooga; (2) copper enrichment is generally about 6, but only about 2.5 in sediment from Cement Creek; and (3) lead and zinc enrichment factors are highly variable, ranging between 2.3 and 60. Silver, cadmium, and molybdenum also show systematic enrichments in bed sediment today relative to pre-mining sediment at various sites within the basin; however, the data for the pre-mining sediment are censored, so enrichment factors cannot be calculated for each stream reach. Historic mining has significantly changed the metal loading in bed sediment of the upper Animas River watershed above Silverton.

Terrace-sediment samples were examined for microscopic traces of terrestrial and aquatic biota, particularly for any microscopic traces of vertebrate life in the upper Animas River watershed. The terrace sediment ranges from silt to fine pebbles, with most sediment being sand-sized particles. Environments where finer-grained sediment occur tend to be better suited for preservation of microscopic biotic remains. Localities reflecting lower energy levels, such as overbank deposits, pond sediment, and abandoned meander channels have been identified in the watershed for additional examination. To date, biotic remains are dominated by terrestrial plant debris, including stems, roots, and few seeds. Much more rarely, terrace sediment includes terrestrial insect parts, as represented by the heavily chitinized and readily preservable body parts. A few isolated fish scales were recovered, which indicate the presence of aquatic life in the watershed prior to mining.

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MINE-SITE CHARACTERIZATION

Acid-Neutralizing Potential of Igneous Bedrock in Basin and Cataract Creeks, Boulder River Watershed, Montana

By G.A. Desborough[1] and P.H. Briggs[2]

This study shows that the igneous bedrock in the Basin and Cataract Creek basins has a high acid-neutralizing potential. Our studies of acid-generating properties of 19 mining-related waste piles of 500 tons or more in this area showed that leachates of samples from 15 piles had a final mean pH of 3.3, whereas samples from only three piles had a final leachate pH of between 5.9–6.8. However, the pH of stream water is routinely higher than 7.0 at all but one monitoring site in the Basin and Cataract Creek basins (Nimick and Cleasby, 1998, this volume). Results of these two studies show that if significant amounts of acid are generated from the waste piles, any drainage must be buffered by bedrock, alluvium, soil, or stream water. To test the importance of geologic materials, we designed laboratory tests that would determine the acid-neutralizing potential of representative bedrock and soils through the use of solutions that simulate water in contact with mine wastes.

In a previous study, 100-gram (g) samples of <2.0-millimeter (mm) mine waste were exposed to 2 liters (L) of deionized water at rest. In the present study, the acidic solution (pH = 2.85) generated from the previous study was mixed with crushed, <0.090-mm fractions of fresh and altered bedrock and a <2.0-mm fraction of the soils. The ratio of rock and soil exposed to the acidic solution for 24 hours at rest was 1:20. After exposure of 11 samples of granite bedrock to the acidic solution, the mean final pH of the solutions was 6.72. Interaction of four fresh samples of Elkhorn volcanic rocks with the acidic solution yielded a mean final pH of 7.00. The reaction of seven samples of silicified altered rocks from Jack Mountain with the solution yielded a mean final pH of only 3.90, and 13 soil samples provided a mean final pH of 4.20.

Igneous bedrock of the area contains minor, but important, amounts of calcite. Calcite was not detected in any of these igneous rocks using three different X-ray diffractometer units. Similarly, prior petrographic studies of about 250 thin sections of the igneous intrusive rocks from the Basin 15-minute quadrangle reported no carbonate minerals. However, using a chemical stain (alizarin red) on large 10 × 10 centimeter sawed rock slabs, we found dispersed calcite in all but one fresh igneous sample. Small amounts of calcite appear to be partly responsible for the acid-neutralizing capacity of the fresh igneous rock. Minor amounts of other carbonates that we did not detect also may contribute to the acid-neutralizing potential of these rocks. The rapid neutralization of acidic solutions observed for the igneous rocks (5–30 minutes) is consistent with carbonate dissolution. Although intermediate plagioclase (andesine) in these rocks may buffer acidic solutions, it reacts much more slowly (several to many days) than calcite.

The high acid-neutralizing potential of igneous bedrock, which is widespread in the Basin and Cataract Creek basins, has favorable implications for the siting of a repository for acid-generating waste because the bedrock can be expected to neutralize some or perhaps all of the acid generated by waste in the repository.

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Effects of Selected Mine Dump Piles on Dissolved-Constituent Loads in the Cement Creek Basin, Upper Animas River Watershed, Colorado—A Preliminary Assessment

By Winfield G. Wright,[1] Kenneth J. Leib,[2] and M. Alisa Mast

In a watershed approach, the effects of dissolved-constituent discharges from mine entrances, mine-dump piles, and natural-background sources need to be integrated in order to prioritize methods of improving water quality in a watershed affected by abandoned mine lands. An important factor in the upper Animas River watershed is the effect of dissolved-constituent discharges from mine-dump piles on water quality. Two mine-dump piles were chosen for study in the Cement Creek basin upstream from Silverton, Colorado—one at the May Day Mine, which has no water discharging from the adit (a "dry dump"), and one at the Yukon Mine, which has water discharging from the adit (a "wet dump"). Wells were installed in the May Day Mine dump pile to study geochemical processes that occur as ground water infiltrates and percolates through the dump pile. Preliminary estimates of dissolved-constituent loads from the two study sites were obtained by measuring Cement Creek upstream and downstream from the sites during April 1997 and by performing a streamflow-tracer test at the May Day Mine site during October 1997. The gains in dissolved-zinc loads (which may include natural inputs) through the reaches of Cement Creek that pass each site and the percentage of the dissolved-zinc load at the mouth of Cement Creek were as follows: May Day Mine, April 1997, 7 pounds per day (lb/d), 4 percent of Cement Creek; Yukon Mine, April 1997, 6 lb/d, 3 percent of Cement Creek; May Day Mine, October 1997, 4 lb/d, 3 percent of Cement Creek. In comparison, two large natural springs in the Cement Creek basin contribute dissolved-zinc loads of 2 lb/d (1 percent of Cement Creek) and 9 lb/d (5 percent of Cement Creek) during low flow. The principal sources of water to the dry dump include hillslope runoff from the small mountain catchment uphill from the dump (which only flows during snowmelt and rainfall-runoff periods) and ground water that is discharging into the dump pile from beneath the dump. The principal sources of water to the wet dump are discharge from the adit, hillslope runoff from the mountain catchment uphill from the dump, and ground water that is discharging into the dump pile from beneath the dump. Direct rainfall that infiltrates and percolates through the dump piles is not considered to be a large contributor to dissolved-constituent loads from the dump piles; however, rainfall runoff in the form of overland flow from the dump piles might have short-term effects on water quality in streams. The effects of snowmelt on dissolved-constituent loads from the mine-dump piles are currently (1997) being assessed. The dissolved constituents in water discharging from the mine-dump piles result from hillslope runoff and adit discharge that percolate through the dump piles, interact with the dump material, and become rich in dissolved constituents. Hydrologic controls to reroute hillslope runoff and adit discharges around mine-dump piles are the first step in preventing dissolved-constituent discharges from mine-dump piles.

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Geochemical and Mineralogical Characterization of Mine Dumps on BLM Lands, Upper Animas River Watershed, Colorado: Plans and Preliminary Results

By J.T. Nash,[1] G.A. Desborough,[2] and D.L. Fey[3]

Geochemical and mineralogical studies of mine dumps in the upper Animas River watershed are underway to help the U.S. Bureau of Land Management (BLM) prioritize sites and to suggest possible methods for remediation. In the summer of 1997, approximately 200 BLM dump sites were briefly examined; 82 sites were studied further because they met the following criteria: (1) location within 3 kilometers of major streams, (2) size greater than about 100 tons, and (3) access reasonable for cleanup work. Of the more than 300 BLM sites identified by previous investigations, the majority are smaller than 100 tons, and thus, were deemed unlikely to be significant contributors to the watershed and were not considered further in this study. Onsite work included brief description of rock types, rock alteration, and ore mineralogy; an estimate of size; and collection of a representative sample of the entire dump. Composite samples were collected from 30 subsites uniformly distributed over the top and sides of each dump; at each subsite, dump rocks from a 0.5-square-meter area excavated to a depth of 10 centimeters were mixed, and a portion was passed through a 2-millimeter (mm) sieve to yield about 100 grams. The <2mm fraction is deemed most likely to be involved in short-term reactions and to contribute metals to runoff. Water draining from portals and dumps was noted at 29 sites; pH and specific conductivity were measured at all sites, and at some sites, a single reconnaissance water sample was collected for chemical analysis and comparison with results of leach tests described below.

A preliminary list of BLM problem sites was made at the end of field work in September 1997, based chiefly on visual impressions of dump mineralogy, dump size, and potential mobility of metals in acidic drainage. This working list, which closely resembled that of the U.S. Bureau of Mines and BLM, was dominated by sites at which mine or surface drainage was interacting with dump rocks. Our first impressions lead us to support the recommendations of many other workers that management of mine drainage and surface waters should be a priority in mine-dump mitigation.

Laboratory studies were initiated in November 1997 to describe the bulk mineralogy and chemistry of the <2-mm samples and their reactions in deionized water; only a few results were available to include in this abstract. At this time, we are working on a suite of 120 samples, including some dump samples from privately owned sites and some representative samples of mill tailings and unmined mineralized rocks, for comparison with the BLM dump samples. X-ray diffraction (XRD) studies have been made to determine the major minerals in the <2-mm dump samples. The XRD studies confirm the presence of many sulfate minerals that are not reliably identified in macroscopic examinations: 50 percent of the samples contain jarosite-family minerals, 10 percent contain anglesite, 3 percent contain alunite, and 3 percent contain gypsum. Sulfide minerals are common: 25 percent of samples have pyrite, 30 percent have sphalerite, and 30 percent have galena. Calcite, an important acid-buffering phase, was detected by XRD in only three samples. Quartz is present in most samples, and aluminosilicates such as feldspars, micas, and kaolinite are present in 45 to 60 percent of the samples. The aluminosilicate pyrophyllite was detected in 10 percent of the samples. The aluminosilicate minerals are normally inert, but at very low pH conditions, they can release significant dissolved aluminum that may significantly degrade water quality as a colloid. The mineral suite alunite-pyrophyllite-enargite is found only in the vicinity of the Red Mountains. Because the XRD method can not detect minerals present at less than about 1 to 3 percent (but these minor phases can be important contributors of acidity or metals), a micro-panning method was used to concentrate heavy minerals, and these were examined by microscope and analyzed by nondestructive methods. This method revealed small but important amounts of anglesite, pyrite, and other minerals that were not detected by the XRD method.

Concentrations of arsenic, cadmium, copper, iron, lead, and zinc were determined by energy dispersive X-ray analysis and are highly variable in our suite of 120 samples. Maximum concentrations of some key metals of interest are: arsenic, 11,000 parts per million (ppm); cadmium, 16 ppm; copper, 37,000 ppm; iron, 22 weight percent, lead, 96,000 ppm; and zinc, 27,000 ppm. A preliminary review of the results suggests that arsenic concentrations greater than 100 ppm only occur in the vicinity of the Red Mountains. No spatial or geologic associations are evident for copper, lead, and zinc, which have highly variable concentrations even between neighboring dumps. High concentrations (thousands of ppm) of base metals in dump samples seem to reflect methods of mining and ore processing more than ore type and geology.

Two kinds of laboratory leach tests will be made to provide information on acid generation and metal mobility. Leaching of samples under static conditions in deionized water will mimic short-term conditions similar to spring 'flush' and runoff. We also will undertake leaching tests using end-over-end agitation similar to the EPA 1312 protocol. Based on our experience with leach tests of dump samples from diverse ore types in other areas of Colorado, Montana, and Nevada, we anticipate that jarosite and alunite rather than pyrite will dominate short-term acid production. Because few of our samples from the Animas River watershed contain calcite, we anticipate that most dump samples will have low buffering capacity. Laboratory work that is underway, and additional sampling planned for the summer of 1998, should permit us to better characterize individual dump sites and allow us to estimate the contribution of these dumps to the upper Animas River watershed.

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Spectral Induced Polarization Studies of Mine Dumps near Silverton, Colorado

By David L. Campbell,[1] *David V. Fitterman,*[2] *and Robert J. Horton*[3]

To help study mechanisms that produce acid mine drainage (AMD), we made spectral induced polarization (SIP) measurements at the Mayday and Yukon mine dumps, in a Department of Interior Abandoned Mine Lands study area near Silverton, Colorado. Induced polarization is a geophysical method that has long been used to detect disseminated sulfides, and SIP is a refinement of that method that can characterize electrochemical processes taking place at mineral/pore-water interfaces. At Silverton, we made SIP measurements at intervals of 1.5 meters (m) at the Mayday dump and 3.0 m at the Yukon dump along profiles on the dump faces, investigating to depths of about 5 m below the surface.

We had expected the SIP surveys to locate sulfide-rich pockets that might be AMD sources within the dumps. We think that they did that at the Yukon dump. Field SIP measurements at the Mayday dump site, however, were relatively uniform, both laterally and with depth. None of the Mayday SIP spectra resembled those reported in the literature for typical sulfide deposits. Most Mayday SIP spectra looked alike, and even those taken on outcrops of "jarosite" (yellow-colored) and "goethite" (brownish) were only subtly different from each other. Observed variations in SIP phase are ascribed mostly to compositional variations in the dumps, while those in conductivity are ascribed to a combination of variations in composition, pore-water saturation, and amounts of dissolved solids in the pore water.

Ten samples of material from the surface of the Mayday dump were measured in the laboratory to further investigate their SIP characteristics. The resulting SIP spectra showed processes which we still must identify, but which seemed weaker than those expected for ground water interacting with sulfides. Examination of the samples using a hand lens showed they consist mostly of oxidized minerals, but their exact mineralogies still must be determined. Because field SIP spectra were similar to those measured in the laboratory, and because they were similar at all depths, we infer that material in the Mayday dump is generally homogeneous. We speculate that after 40-plus years of residence in mine dumps, the surfaces of grains of dump material at all depths have become well oxidized, thereby inhibiting the surface electrochemical reactions which give strong SIP responses. If this is so, it implies that the acid waters currently draining from the Mayday mine dump probably result mainly from process(es) involving already-oxidized minerals, rather than from primary oxidation of sulfides at grain surfaces.

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Seasonal Fluctuations of Discharge and Dissolved Constituents from Selected Abandoned Mines in the Upper Animas River Watershed, Colorado

By Winfield G. Wright,[1] Kenneth J. Leib,[2] and M. Alisa Mast[3]

Water draining from two abandoned mines—the Evelyn and Forest Queen—in the upper Animas River watershed was sampled monthly during 1996–97 to determine the ranges of discharge and dissolved-constituent concentrations for remedial-design parameters and to describe the effects of snowmelt runoff on discharge from the mines. The discharge from the Evelyn Mine ranged from 0.01 to 0.03 cubic feet per second; there were no appreciable increases in discharge from the mine during the snowmelt-runoff period in 1997. However, concentrations of dissolved aluminum, iron, manganese, sulfate, and zinc in drainage from the Evelyn Mine increased during snowmelt runoff. This trend may indicate that the collapsed mine entrance at the Evelyn Mine possibly is controlling the discharge from the mine or that there is only a small amount of snowmelt-runoff infiltration into the abandoned-mine workings through fractures in bedrock that could increase the oxidation of sulfide minerals but not significantly increase the discharge. The Forest Queen Mine had a greater relative discharge (0.02 to 0.08 cubic feet per second), and the higher discharge correlates with the snowmelt-runoff period. Dissolved-constituent concentrations decreased slightly with increased discharge; however, dissolved-constituent loads more than doubled from the mine. Notably, the pH values from the Forest Queen Mine decreased from about 4.7 to 3.7 during the snowmelt runoff. Data collected from these two mines illustrate the hydrogeochemical variability of water discharging from abandoned mines and indicate that not all mines respond the same to recharge events.

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An Overview of the U.S. Geological Survey Mine Waste Characterization Project

By Kathleen S. Smith,[1] James G. Crock,[2] G.A. Desborough,[3] David V. Fitterman,[4] Reinhard W. Leinz,[5] Maria R. Montour,[6] Mark R. Stanton,[7] Gregg A. Swayze,[8] and Robert B. Vaughn[9]

The Mine Waste Characterization Project (MWCP) of the U.S. Geological Survey Mineral Resources Program is collaborating with the Abandoned Mine Land Initiative work in the upper Animas River watershed, Colorado. We are conducting detailed studies at two abandoned mine waste dumps along Cement Creek, upstream from Silverton, Colorado. One dump, the May Day, is overseen by the Bureau of Land Management and the other dump, the Yukon, is privately owned. Our work ties into the watershed approach being used in the upper Animas River watershed by defining processes that mobilize metals from mine-waste dumps.

Release of dissolved metals, acidity, and suspended particulates from solid mine waste to receiving waters is a potentially serious and long-lasting environmental problem. Metal release and acid production depend on the mineralogical, chemical, and physical characteristics of the mine waste as well as geochemical and microbial processes. We use an integrated approach to mine-waste dumps and mill tailings. We combine bulk chemical, physical, and mineralogical characterization with geochemical leaching and weathering studies, microbiological studies, geophysical studies, toxicological studies, and geochemical modeling to determine processes controlling generation, release, and toxic effects of effluent from abandoned mine-waste material. We are integrating these data with imaging-spectroscopy data to refine remote-sensing techniques for locating and prioritizing mine-waste sites. Field and laboratory geophysical measurements are being used to determine the extent of the waste and to characterize the waste material at depth to complement the imaging-spectroscopy and geochemical analyses of surficial material. A remediation approach using zeolite granules to mitigate mine-waste runoff is being evaluated and field tested.

The MWCP is an interdisciplinary project with the goal of developing methods and tools for solid mine-waste site characterization. Researchers from a variety of disciplines, including geochemistry, geophysics, analytical chemistry, geology, and geomicrobiology, work together at selected mine-waste sites to evaluate the usefulness of diverse approaches and characterization methods. We also aim to understand processes that control the environmental impact of solid mine-waste systems. An integrated "tool kit" for the characterization and evaluation of abandoned solid mine-waste sites is an objective of this project.

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BIOLOGICAL ISSUES FOR ABANDONED-MINE-LANDS REMEDIATION

Aquatic Physical Habitat and Sediment Analysis in Evaluating Mined Land Remediation Measures: A 1998 Review

By Robert T. Milhous[1]

The broad goal of this project is to quantify the cause and effect relationship between the physical characteristics of the riverine habitat and the geochemistry of the river. This is being accomplished by investigating: (1) the nature of the physical habitat in the watershed above the Animas Canyon; (2) the sediment characteristics of the rivers; and (3) the links between sediment and metals. The project began in fiscal year 1997. The first two investigations are reviewed in this presentation. The objective of the first investigation is to answer the question: "Will improvement in the chemical quality of the water result in an improvement in the fishery or is the fishery limited by the physical characteristics of the streams?" This presentation compares the physical habitat in a relatively flat reach of the Animas River just above Howardsville to the habitat just below Howardsville. The objective of the second investigation is to determine the characteristics of the sediment in the river and tributaries above Elk Creek. Results for sites above and below Howardsville are presented. Sediment characterization will assist in answering the habitat question posed above and will contribute to understanding the dynamics of the sediment-metals link. The paper discusses the importance of temporal variability of physical habitat and the factors influencing the usability of the physical habitat, as well as its importance to aquatic ecosystems.

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Use of Ecological Indicators as Endpoints for Remediation

By Terence P. Boyle[1] *and Bob Bukantis*[2]

The diagnosis of ecological health in streams is most often determined by the status of critical physical, chemical, and biological measures. Quality and condition of the benthic macroinvertebrate and fish communities have come to be the most common biological characteristics investigated as indicators of water quality. The benthic macroinvertebrate community and an array of physical and chemical variables were sampled in September 1997 in the Boulder River watershed in High Ore Creek, Cataract Creek, Basin Creek, and the Little Boulder River. Sampling was designed to assess the current status and condition of the benthic macroinvertebrate community at impacted sites and control (or reference) sites. The data collected also will provide a baseline with which to assess future change anticipated from remediation of abandoned mine lands at a number of critical sites with different levels of impact.

These data will be analyzed by multivariate methods to establish the degree of differences in the structure of the benthic macroinvertebrate community among the sites and the degree to which individual environmental variables are associated with the variability observed in the structure of the benthic macroinvertebrate communities. Subsequent analysis of the biological data will include the development and application of multimetric ecological indices.

The ultimate goal of the remediation efforts done under the auspices of the AML Initiative is the restoration of the natural resources to the best attainable condition. The best way to develop biological criteria is through knowledge of prior conditions or local reference sites. The final success of any remediation effort will be evaluated in terms of biological endpoints derived, in collaboration with the Montana Department of Environmental Quality, as specific multimetric ecological indices of the benthic macroinvertebrate community developed. These ecological endpoints for remediation will not only be the final biological test of the remediation, but can be used by State water-quality regulatory agencies as biological criteria to legally determine whether remediation has been adequate to restore beneficial-use support. A strategy for using multivariate analysis and subsequent multimetric analysis will be outlined as a procedure for integrating physical, chemical, and biological data, and placing this analysis in the context of water-quality regulations to determine biological criteria and ecological attainability.

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PRESENTING ABANDONED-MINE-LANDS INFORMATION

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The Boulder Geoenvironmental Explorer: A GIS Tool to Communicate Science to Land Managers and the Public

By A.E. McCafferty,[1] D.B. Yager,[2] and T.C. Sole[3]

The Boulder Geoenvironmental Explorer (BGE) is a prototype, PC-based viewing tool that permits visualization of the spatial relationships between diverse abandoned-mine-lands earth-science data sets for the Boulder River watershed, Montana. The prototype also includes data and interpretive products from the state geoenvironmental assessment of Montana. Information from the state-wide assessment was used in the planning process to select the Boulder River watershed for detailed study. The BGE is being utilized for a collaborative and interdisciplinary approach to problem solving, which is central to watershed studies. This tool provides a coherent, readily accessible database and greatly enhances the ability to recognize relations between diverse data layers. Data layers provided in the BGE include geologic, mine, cartographic, hydrologic, and biologic data as well as related interpretive geologic, geochemical, geophysical, and wetlands models from the U.S. Geological Survey (USGS) and U.S. Forest Service. Features found in the BGE include a customized graphical-user interface developed by the USGS in cooperation with Environmental Systems Research Institute, Inc., unified and updatable data formats, object-oriented programming, geographic-information-system (GIS) capabilities, and accessibility from either a CD-ROM or web site. The BGE was designed to be used by nontechnical users in a shared work environment. The software will be installed on a USGS web site and used by team scientists as a data-management tool for updating data and interpretations and communicating new information between team members and cooperators. Following completion of the watershed study, a CD-ROM and a web-site application will be made available to the public for land-use planning purposes, educational use, or further scientific studies.

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PERSPECTIVE ON THE WATERSHED APPROACH

Science and Regulatory Practice: The Search for Certainty

By D. Kirk Nordstrom[1]

Questions are often raised during the regulation and remediation of hazardous waste sites on how best to go about it, and scientists, engineers, and regulators are not always in agreement. The classic assertion is that regulators often think that scientists just want to do another study and that these studies are self-promoting, whereas scientists often think that regulators and remediation teams always want to rush the cleanup of a site before they have defined the problem and considered the consequences. Let's be honest—there is truth to both of these claims. Scientists do like to study problems out of pure curiosity and for prestige, and regulators do work with limited information, limited time, limited funding, and frequently with considerable political pressure to show results. Part of the problem stems from a misunderstanding of what science is, and another part stems from a misunderstanding of what is involved in regulation and remediation. Science is a way of understanding the physical world based on testing hypotheses with empirical evidence subject to open debate and peer review. Without science, there is no basis for regulation, or remediation, or testing remedial effectiveness. Remediation is the activity of correcting, curing, or ameliorating an unwanted problem. Environmental remediation is directed at specific sites with specific issues for which specific scientific knowledge is needed within a specific legal-political agenda. For complex sites, remediation is often experimental and needs focused scientific research that must be communicated to politicians and the public.

An example of a mine site where remediation failed because hydrology and wastes were inadequately characterized is contrasted with another mine site where mine plugging was avoided by applying scientific research to the possible consequences, which were found to be potentially dangerous. Technical advisory committees with broad multidisciplinary expertise can help considerably in eliminating undesirable consequences from remediation efforts.

The important questions are: Is the problem well-defined? This question addresses ultimately the known or potential risk to human and environmental health, but it also addresses what is known about contaminant sources, mobility, and fate. Has the right science been applied to the problem? The concern here is whether the appropriate scientific (medical, economic, and social as well as physical, chemical, biological, geological, hydrological, and ecological) disciplines have been used in a prioritized manner to emphasize the most relevant issues. Have we got the science right? This question refers to adequacy and reliability of the data, consideration of multiple working hypotheses, testability of hypotheses, plausibility of assumptions, and the magnitude and character of the uncertainties. Have we got the right stakeholder participation? This question addresses whether all parties who have some stake in the deliberative process have been included so that all important perspectives can be considered. Have we got the participation right? This question pertains to the adequacy and appropriateness of the response to the stakeholders and the improvement of trust. Have we developed balanced, informative syntheses? Overemphasis on analytical aspects can lead to failure without the synthesis of information communicated to the nontechnical public and decision-makers. Is there a defensible and consensual goal? Rational environmental problem solving will succeed if all parties involved share a common understanding of concepts, assumptions, remedial alternatives, potential consequences, and costs that are defensible and adequately constrained by empirical evidence. These guidelines, extracted from several publications on risk assessment, should minimize uncertainty and promote effective decision making.

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A Synopsis of Presentations and Discussions in the Thursday, February 5th Session: Perspectives on Implementing the Watershed Approach to Remediate Abandoned Mine Lands

By Margot Smit and Gary Broetzman
Colorado Center for Environmental Management

Introduction

Amidst incremental successes, the watershed approach confronts ongoing challenges. These challenges include aspects of existing institutional structures and norms, communication barriers, decisions about scientific methods, and components of the broader regulatory and legal context. In this concluding session of the workshop, representatives from State and Federal agencies and others discussed ways to approach these challenges in order to successfully implement a watershed approach. We have supplemented what emerged from these presentations with other points to consider based on our experiences and perspective as a non-profit organization. The Colorado Center for Environmental Management provides coordination, neutral facilitation, and information assistance to watershed groups in four western States working on this issue, and has produced more general policy and regulatory analysis information (Broetzman, 1998).

The Scientific Basis

The success of a watershed project is dependent on a fair and open process that enables systematic analyses for prioritizing problem sites and on a well-defined investigative process that includes comprehensive water-quality information. Successful outcomes often depend upon the identification of quantifiable goals and the selection of specific remedial actions for attaining the identified goals. In addition, a follow-up surveillance plan is essential for documenting environmental results and for determining subsequent plan adjustments.

Science provides the basis for understanding the problem, for regulation, for remediation, and for monitoring remedial effectiveness. Remediation, the activity of correcting, curing, or ameliorating an unwanted problem, is directed at specific sites with specific issues for which both specific and general scientific knowledge is needed within a specific legal-political agenda. In choosing remedial activities, questions in risk assessment need to be asked, such as: Are the problem and objectives well-defined? Has the right science been applied? Have we developed balanced and informative syntheses? Is there a defensible and consensual goal?

Generating a scientific base for decisions and striving for data consistency and compatibility are two of the challenges that are often encountered. These challenges are particularly difficult because the watershed approach calls for scientists with various scientific disciplines from different agencies as well as private entities working together towards this goal. Pilot watershed projects can provide a valuable learning experience for developing the scientific basis on this issue in a collaborative manner. They can be valuable for the information they provide and for helping to keep expectations in check. At the same time, there is a need for more collaborative research of this kind in other problem watersheds because many sites are in need of more immediate attention.

It is important to note that an optimum cleanup solution for a watershed needs to take into account all important sites (both on Federal and non-Federal lands) in order to achieve optimum cost-effective environmental improvement. In addition, implementation of remediation activities often should proceed despite lack of assurance of success, rather than having scientific studies proceed indefinitely. By monitoring and taking adaptive measures based on that monitoring, both scientific understanding and cleanup can be furthered.

Communication and Sharing of Scientific Information

Watersheds provide a framework for using scientific information to make informed decisions.

Scientific knowledge must be pooled as the issue of cleanup of abandoned mine land (AML) sites crosses jurisdictional boundaries. Time and effort are required to build the necessary relationships within which the exchange of data can occur. There is a need for the information to be synthesized and for it to be presented in an understandable format, using consistent terminology, so that everyone can communicate with each other. This kind of communication of the science will hopefully enable an easier marriage between the scientific community and land management practitioners.

The scientific process conducted under the watershed approach needs to stay out in front of policy and incorporate the realities of contemporary political and social factors as a way to facilitate buy-in to the process. For example, all stakeholders cannot be expected to understand all the scientific details, and complex scientific language can be exclusionary of group members and discourage continued involvement. Efforts need to be made to explain technical information such that it can be understood by all participants. In addition, scientific studies cannot continue indefinitely. As long as there are contaminant discharges, citizens can file lawsuits and if courts dictate the actions, cleanup may end up occurring at low priority sites. Therefore, to keep both concerned citizen groups involved and to maintain decision-making leverage in the watershed, the parties involved must together establish a timeline and a data sharing and communication process which is sensitive to each individual watershed context.

For complex sites, remediation is often experimental and requires focused scientific study. The rationale, as far as the results of this study, also must be communicated clearly to managers, politicians, and the public. Technical advisory committees, consisting of both scientists and engineers with broad multidisciplinary expertise, are essential to avoid undesirable or disastrous remediation consequences.

Support from Agency Management

There is high-level management support in the Department of Interior (DOI) and Department of Agriculture (USDA) for an interagency watershed approach and for interagency partnerships, particularly those involving teaming and cooperation among Federal and State agencies. This type of cooperation has begun under the DOI/USDA interagency Abandoned Mine Lands (AML) Initiative, where there is a desire to focus watershed efforts primarily towards efficient site cleanup measures for achieving clean streams, with a secondary focus on clean sites. DOI agencies have taken a leadership role in watershed efforts through activities by the Bureau of Land Management (BLM) and US Geological Survey (USGS), expanding on watershed activities which had been initiated by Region VIII of the U.S. Environmental Protection Agency (EPA) and the Colorado Department of Public Health and Environment. More recently, the USDA Forest Service (USFS) has been giving increased attention to watershed initiatives in coordination with the BLM.

Policy successes emerging from this focus on abandoned mine lands include the Western Mine Lands Restoration Partnership, the Western Governor's Association/National Mining Association (WGA/NMA) Joint Abandoned Mine Lands Initiative (AMLI), and the EPA National Hardrock Mining Framework.

Financial support for these Federal agency initiatives continues to grow. Last year, $1 million was available within the DOI for addressing AML problems. This year, that amount was increased to $3 million, with the funds focused on the Animas and Boulder River watersheds and on the early activities for another pilot project in Utah. Although the State of Arizona recently chose not to support a similar pilot project to be funded by DOI, additional pilot projects are being considered for watersheds in other states, including California, Idaho, Nevada, and South Dakota.

In October 1997, Vice President Gore announced a Clean Water Initiative and thereby added additional emphasis for watershed efforts. The 1999 Initiative budget will have an AML component, with about $9 million earmarked for the BLM, $0.5 million earmarked for the National Park Service, and $4.7 million for the USFS. The Initiative contains three principles: 1) cooperative and interagency approaches to achieve enhanced protection and runoff control on a watershed basis; 2) emphasis on collaboration with a role for the public; and 3) innovative approaches to watershed cleanup strategies, including liability incentives. Numerous work groups were formed to develop the Clean Water Action Plan, which was submitted to the White House in mid-February

1998, and released to the public in March as part of the Clean Water Initiative.

The USFS/BLM interagency work group currently working on the issue of abandoned mine sites on Federal lands is focusing strategically on: (1) analysis and watershed ranking; (2) site ranking and risk analysis; (3) development of a mitigation plan; and (4) follow-up monitoring. The details of the action plans consistent with funding limitations need to be worked through, and it is important for project-level managers of the different agencies to be forward thinking and plan together. This is now a focus of Gore's Clean Water Initiative.

Costs and Funding

Agencies are targeting watershed efforts as a means to strive for cost-efficient cleanup and to emphasize a voluntary approach. Through the use of combined resources, cooperative cleanup efforts can achieve effective solutions. The lack of comprehensive funding for addressing AML sites, however, continues to be a major issue. The continued limited availability of funds reinforces the ongoing need to be creative in sharing those funds and in looking for other sources.

Most of the funds to date are from Federal sources, although only about five percent of the overall metal loading from AML are believed to be coming from lands managed by the USFS and BLM (one can rationalize, however, that most of the non-Federal sites result from the Federal policies associated with the 1872 Mining Law). EPA has recently initiated cleanup of a few problem AML sites using Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) removal-action authorities and funds. However, the Federal government will not be able to cover the costs alone, hence the need for broader contributions to cleanup costs (including the potentially responsible parties (PRPs)). Montana is one of the few states that is focusing its available funds for AML cleanup, utilizing a combination of federal Surface Mining Control and Reclamation Act (SMCRA) funds and State funds.

There is an option for creative use of existing funds through the Superfund program, though misperception exists that utilizing Superfund money is equivalent to creating a Superfund site. Superfund dollars are actually going to non-National Priority List (NPL) sites in the form of removal actions and can be applied to watershed work. Of all the sites that the USFS is working on, only one is on the NPL list, despite the fact that the USFS is emphasizing CERCLA authority in its remedial activities. The funds are there, and it may be beneficial for groups to find out more about how to access them.

In considering other potential funding sources, there are currently no details on funding through NMA/WGA AMLI sponsored projects. Funds available under the EPA Brownfields program also do not pose much promise for AML cleanup because they are aimed for land use conversions, typically for urban areas. In light of this, State funding help may need further emphasis. In Montana, for example, State funds are generated from a metal and mineral tax and an oil and gas tax. Some opportunities may also exist in some States for use of revolving water quality loan funds to play an important role to encourage voluntary cleanup.

In all the watershed efforts, the remedial plans will need to incorporate a funding strategy that covers remediation and follow-up water quality monitoring. The current lack of a multi-year Federal resource commitment restricts movement towards expensive active-treatment technologies. The focus has therefore been on stabilizing and capping mine-waste piles and on passive-treatment activities for mine drainage--activities that do not involve long-term cost commitments.

A "polluter pays"/cost recovery approach is being applied by the Federal land management agencies in order to hold those parties with defined interest in a site responsible for cleanup. Through an Executive Order and the provisions of CERCLA, those agencies have both the authorities and directives to seek cost recovery for site cleanup on Federal lands. The BLM and USFS, however, differ in their emphasis towards cost recovery. The USFS has been giving greater importance in selecting those sites for cleanup actions where cost recovery can be accomplished from viable PRPs. The BLM, however, uses a more environmentally focused approach. It pursues the selection of those sites which can most efficiently achieve environmental results, while seeking cost recovery from PRPs of those sites, where viable. If PRPs are not identified, the BLM continues to pursue cleanup options at the selected sites.

Federal land management representatives described the difficulty of being perceived as the "heavy-handed government" and some have stated that this approach is not working well in this issue area. Many experience being confronted with the defensive posture of local citizens, especially when the citizens are presented with a CERCLA section "104(e) letter," an initial step for beginning to identify PRPs. Therefore many Federal agency representatives are supportive of finding means of motivating private landowners to take action without utilizing 104(e) letters. At the same time, it is recognized that no one likes to be regulated. There will most likely always be a sector of the population that considers all authority illegitimate, even with a less intensive regulatory approach.

It is unlikely that a regulator will go after an owner of property that has been in the family through generations and where the regulated action would cause a lifestyle change. Increased emphasis is being given to pursuing those PRPs that are larger companies or are readily capable of financing a solution. There are some attempts at different enforcement techniques. For example, participants from EPA described one approach where the community was asked (before utilizing a 104(e) letter) whether they wanted EPA to spend their tax dollars without the PRPs contributing their fair share of the cleanup costs. In that instance, the citizens volunteered to help identify PRPs in their community. It was noted however that it can be difficult to gain this kind of local support in identifying potentially responsible parties, and there is no guarantee that all PRPs will be identified through this approach. More pragmatically, there are examples of processes emerging where PRPs are identified, become involved in a collaborative process, and become willing (either through enhanced understanding or peer pressure) to clean up his/her site with possible help from the process participants (one example is the cleanup activities occurring in the Animas River basin).

Involvement in the Watershed Approach

Overall success in cleaning up AML sites depends upon a collaborative partnership in which all key parties work together to develop an efficient, supportable cleanup strategy while striving to overcome the common cleanup barriers of funding and coordination. Watershed initiatives are a logical and important approach for gaining this involvement and for focusing decision-making within the framework of natural hydrologic systems.

Factors that improve the chances for success include: getting a local group organized, gaining involvement of the regulatory agencies, working within timeframes and schedules, maintaining momentum through activities of the group, accessing funds, and having a good sense of when it is appropriate to call in "the law."

For watershed projects to work, it is important to make informed decisions even in the face of political uncertainties. Montana was cited as an example where the state worked with other interests in prioritizing sites statewide and is continuing with site cleanup even with the prospects of potential citizen suits. At the same time, it is important to keep in mind the potential political repercussions of a Federal management approach for public lands being opened up to influence from State and local interests, when they may differ from national public interests.

Key participants need to be willing to work together and to educate each other and the community of the problems and possible actions. Within the groups, there can sometimes be a tendency to want to rush forward with independent activities (including activities by Federal agencies). However, the nature of the problem (and the solution) are such that no one can accomplish these goals independently, which again demonstrates the value of proceeding in a coordinated fashion involving all watershed interests. Usually the environmental problem and/or the local fear of Superfund drive the process, at least from the outset. When these concerns becomes less pervasive, there remains a challenge to maintain participation over a long time within a collaborative atmosphere and to retain a balance of power between national, State, and local entities.

The advantage for the local community to initiate a local process is that local involvement provides an opportunity to overcome a dominance of national top-down management by cultivating an overall sense of stewardship and self determination. Traditionally, locals have perceived a heavy-handedness on the part of Federal and State governments in implementing laws and environmental regulatory requirements. Ideally, a collaborative process would convert that scenario into one where those laws and regulations can be used more efficiently and appropriately to move solutions along. More recently, local interests involved in watershed processes have seen their collective abilities help shape solutions and have begun utilizing the different legal authorities and regulatory programs to achieve those solutions.

Although the term "watershed approach" may come and go, the concept of community-based efforts will continue because it make sense. Federal and State agencies can play a role in empowering locals, and can continue to find ways to adjust their way of doing business in order to work with the local conditions and collaborative structures that emerge.

Overcoming Liability/Regulatory Barriers

A watershed process is particularly suitable for addressing multiple mine sites because of their pervasiveness, unique characteristics, enormous waste volumes, perpetual flows, remote locations, and diverse ownership. Unfortunately, the regulatory framework is not well suited for an overall watershed approach. The watershed initiatives underway, in fact, face considerable challenges from the current regulatory structure. Clean Water Act liability (for example, lack of a Good Samaritan provision whereby an independent party is protected from liability associated with voluntary cleanup of a site); CERCLA liability (for example, blocks to creating a voluntary cleanup approach); land ownership/management difficulties (for example, mixed ownership of waste piles); and the technical complexity of mining sites, contribute to this difficulty. For example, the use of Section 319 funds was deferred in the remediation of sites in the Animas River basin due to fear of citizen suits under the Clean Water Act. Despite such kinds of problems, groups are encouraged to work within the scope of what is in place because of the uncertainty of changing regulations in Washington.

The "tool box" concept was put together to avoid conflicts over which regulatory tool should be used when and to focus on applying the right tool in the right situation. This concept involves conducting a comparative evaluation of all regulatory (and non-regulatory) options relevant to a watershed and accessing the views of locals in applying those options for cleanup. The tool box does not imply that one way will be used rather than another. Rather, it may offer some creative opportunities to apply one or more regulatory tools. A general watershed permit is viewed as a possible regulatory solution for providing a balance between point and nonpoint sources and for enabling pollutant trading. There are experimental approaches being initiated within the NPDES program, for example, North Carolina is attempting to use a watershed approach for permitting. All tools are available and each situation determines which tools can best achieve implementation of a desired solution. It is important to have key interests at the table in this decision-making process. CERCLA can be viewed as the fallback tool if all else fails (although in some cases use of CERCLA removal action authorities and funds may be an appropriate up-front tool to use). Pilot projects can provide a means to test this approach and to address not only the problems associated with regulatory and financial issues but also with formulating an integrated plan for cleanup of sites on both public and private lands.

Liability for cleanup by Federal land management agencies on non-Federal lands is of major concern. Although there are situations where it makes sense to take risks in that regard, legal staff within the Federal agencies often advise against it. Limitations of use of available funds also work against implementing optimum solutions. For example, BLM is allocating money for selected non-Federal lands. In contrast, USFS currently does not allow such expenditure. As a related issue, development of joint repositories for the disposal of mine wastes is a timely and important issue that needs the integrated input of legal, policy, and scientific information.

Question and Answer Session

Part of the question-and-answer session held at the conclusion of the afternoon is included in the text above since it was a continuation of the themes of the presentations. The remaining portion of the question-and-answer session is below.

Q: What is the Required or Perceived Role of the Public in AML Cleanup?

- Requirements vary. Generally, local involvement is defined as to what is best for the project or area being addressed.

- CERCLA is the same as NEPA--locally there are the opportunities to get involved, and the amount of involvement varies depending on how politically charged the site is and on the geographic location of the issue.

- In the Clear Creek, Colorado, project, county commissioners from opposite ends of the watershed had an opportunity to meet each other for the first time. Moving from the talking stage to working together on specific on-the-ground projects is important—and it is helpful when prompted by a local official.

Q: Define "Stakeholder": Are all Created Equal?

- Participating stakeholders in a collaborative watershed process are those with an interest in the area of the topic being addressed. Generally, all are viewed as equal. It's a pragmatic rather than legal definition. A consensus process for decision-making helps sidestep the issue of relative importance.

- Equal treatment becomes more of a challenge when there is the emotional charge of locals who consider their livelihoods at stake.

- Both regulatory authorities and responsible parties have more clout. On private land, it is eventually up to the owners to decide what is to be done on their land (consistent with meeting regulatory requirements), despite locals wishing to continue to have input.

Q: Given That a Functioning Ecosystem is Essential, Where do Other Species fit in as Stakeholders?

- A general answer is that compliance with the various governmental environmental programs provide an indirect means for protecting the interests of other species.

- Human health is usually the priority, but other species are also protected in the process.

- In the watersheds closer to larger populations, there tend to be groups of individuals that align with particular concerns: water quality, the sidestream issues (concerned with wetlands, riparian areas, trails), and offstream issues (concerned with the broader natural history). All of these together provide some voice for other species.

- These concerns are handled under the various programs on federal lands. In the BLM, the Natural Resource Damage Trustee's role is protection of species. Also, under FLPMA, BLM needs to take action to prevent "undue degradation."

Q: In What Areas Should Additional Research be Focused?

Some of the areas worth additional attention include:

- Practical means for conducting site assessment, defining cleanup options, and selecting the appropriate technology (or solution).

- Finding ways to meet water quality standards and determine what is attainable.

- Developing passive treatment processes with low operation and maintenance.

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APPENDIX

ABANDONED MINE LANDS INITIATIVE - YEAR-ONE WORKSHOP

Denver, Colorado

Wednesday, February 4, 1998

**Science for Watershed Decisions on Abandoned Mine Lands:
Review of Preliminary Results**

8:00 - 8:15	--	Introduction (Herb Buxton, USGS)
8:15 - 8:30	--	Federal land-management agency introductory remarks (Rob Robinson, BLM and Ray TeSoro, USFS)
8:30 - 9:00	--	The role of geoenvironmental maps and statewide assessments in prioritizing watersheds for remediation of abandoned mine lands (Stan Church, USGS)
9:00 - 9:10	--	Overview of the Colorado and Montana pilot AML watersheds (Paul von Guerard, USGS)
9:10 - 9:30	--	What streams are affected by abandoned mines?— Characterization of water quality and bed sediment in the streams of the Boulder River watershed (David Nimick, USGS)
9:30 - 09:50	--	Impacts of abandoned mine lands on stream ecosystems of the upper Animas River watershed, Colorado (John Besser, USGS)
9:50 - 10:10	--	BREAK
10:10 - 10:30	--	Seasonal fluctuations of dissolved-zinc concentrations and loads in mainstem streams of the upper Animas River watershed, Colorado (Ken Leib, USGS)
10:30 - 10:50	--	A toxicological reconnaissance of the upper Animas River watershed near Silverton, Colorado (Del Nimmo, USGS)
10:50 - 11:10	--	The importance of geologic investigations combined with GIS technology in understanding abandoned mine lands and related repository and remediation issues in the Boulder River and upper Animas River watersheds (Doug Yager, USGS)
11:10 - 11:30	--	Watershed approach to mine reclamation (Bob Wintergerst, USFS)

11:30 - 11:50	--	Watershed characterization from the air: application of geophysical techniques to watershed characterization in the Boulder River watershed (Bruce Smith, USGS)
11:50 - 1:20	--	LUNCH AND POSTERS
1:20 - 1:40	--	Mapping of acid-generating and acid-buffering minerals in the Animas River watershed by AVIRIS spectroscopy (Brad Dalton, USGS)
1:40 - 2:00	--	Digital data for watershed characterization of abandoned mine land (Paul Martin, USGS)
2:00 - 2:20	--	Gaining a watershed view of metal sources and reactive processes using tracer-injection studies (Briant Kimball, USGS)
2:20 - 2:40	--	Case studies relating geology and abandoned mines to geochemistry of springs and streams in the upper Animas River basin, Colorado (Dana Bove, USGS)
2:40 - 3:00	--	Determination of pre-mining background using sediment cores from old terraces in the upper Animas River watershed, Colorado (Stan Church, USGS)
3:00 - 3:20	--	BREAK
3:20 - 3:40	--	Potential effects of runoff from mine dumps on dissolved metal loads in streams--Preliminary results of lab and field studies for the upper Animas River and Boulder River watersheds (Win Wright and George Desborough, USGS)
3:40 - 4:00	--	Aquatic physical habitat and sediment analysis in evaluating mined land remediation measures: a 1998 review (Robert Milhous, USGS)
4:00 - 4:20	--	Use of ecological indicators as endpoints for remediation (Terry Boyle, USGS)
4:20 - 4:40	--	The Boulder Geoenvironmental Explorer: A GIS to communicate science to land managers and the public (Anne McCafferty, USGS)
4:40 - 5:30	--	POSTERS

ABANDONED MINE LANDS INITIATIVE - YEAR-ONE WORKSHOP

Denver, Colorado

Wednesday, February 4, 1998

Science for Watershed Decisions on Abandoned Mine Lands: Review of Preliminary Results

POSTERS

STATEWIDE AND NATIONAL MAPPING

The role of geoenvironmental maps and statewide assessments in prioritizing watersheds for remediation of abandoned mine lands *by S.E. Church, T.C. Sole, D.B. Yager, and A.E. McCafferty*

CHARACTERIZATION OF STREAMS ON A WATERSHED SCALE

What streams are affected by historic, abandoned mines?— Preliminary interpretation of bed-sediment geochemical data, Boulder River watershed, Montana *by D.L. Fey and S.E. Church*

Fluvial tailings deposits in the Boulder River watershed, Montana: Preliminary results *by D.L. Fey, S.E. Church, J.S. Curry, and T.C. Sole*

Methodologies for characterizing aquatic health and preliminary results, Boulder River watershed, Montana *by Aida M. Farag, Dan F. Woodward, Don Skaar, and William Brumbaugh*

Transport and partitioning of zinc among water, colloids, and bed sediments during low-flow conditions, Animas River watershed, Colorado *by B.A. Kimball and S.E. Church*

Colloid formation and transport of aluminum and iron in the Animas River near Silverton, Colorado *by L.E. Schemel, B.A. Kimball, and K.E. Bencala*

Recurrence intervals, probability, and annual duration of dissolved-zinc concentrations using flood analysis techniques in the Upper Animas River watershed, Colorado *by Kenneth J. Leib, M. Alisa Mast, and Winfield G. Wright*

Metal uptake, transfer, and hazards in the stream food web of the upper Animas River watershed, Colorado *by John M.Besser, William Brumbaugh, S.E. Church, and Briant A. Kimball*

Rare earth element geochemistry of acid waters: Preliminary results identifying source signatures and instream processes *by Philip L. Verplanck, D. Kirk Nordstrom, Winfield G. Wright, and Howard E. Taylor*

Comparison of filtration procedures and analytical procedures on iron(II/III): Results from upper Animas, Summitville, and Iron Mountain *by James W. Ball, D. Kirk Nordstrom, and Charles N. Alpers*

Characterization of aquatic health in mine-impacted streams: A case history from the Clark Fork River, Montana, and the Coeur d'Alene River, Idaho *by Dan F. Woodward, Aida M. Farag, and William Brumbaugh*

WATERSHED CHARACTERIZATION

Progress report on surficial deposits and geomorphology of major drainages of the upper Animas River watershed, Colorado *by Rob Blair*

SOURCE OF METAL LOADING

Quantification of metal loading by tracer-injection methods in Cataract Creek, Boulder River watershed, Montana: Study design *by Tom E. Cleasby, David A. Nimick, and B.A. Kimball*

Oxygen isotopes of dissolved sulfate as a tool to distinguish natural and mining-related dissolved constituents in the upper Animas River watershed, Colorado *by Winfield G. Wright, M. Alisa Mast, and Kenneth J. Leib*

Determination of pre-mining background using sediment cores from old terraces in the upper Animas River watershed, Colorado *by S.E. Church, D.L. Fey, and E.M. Brouwers* (

MINE SITE CHARACTERIZATION

Acid-neutralizing potential of igneous bedrock in Basin and Cataract Creeks, Boulder River watershed, Montana *by G.A. Desborough and P.H. Briggs*

Geochemical and mineralogical characterization of mine dumps on BLM lands, upper Animas River watershed, Colorado: Plans and preliminary results *by J.T. Nash, G.A. Desborough, and D.L. Fey*

Spectral induced polarization studies of mine dumps near Silverton, Colorado *by David L. Campbell, David V. Fitterman, and Robert J. Horton*

Seasonal fluctuations of discharge and dissolved constituents from selected abandoned mines in the upper Animas River watershed, Colorado *by Winfield G. Wright, Kenneth J. Leib, and M. Alisa Mast*

An overview of the U.S. Geological Survey mine waste characterization project *by Kathleen S. Smith, James G. Crock, G.A. Desborough, David V. Fitterman, Reinhard W. Leinz, Maria R. Montour, Mark R. Stanton, Gregg A. Swayze, and Robert B. Vaughn*

Using imaging spectroscopy to cost-effectively locate acid-generating minerals at mine sites: An example from the California Gulch Superfund Site in Leadville, Colorado *by Gregg A. Swayze, Roger N. Clark, Kathleen S. Smith, Philip L. Hageman, Stephen J. Sutley, Ronald M. Pearson, Gary S. Rust, Paul H. Briggs, Allen L. Meier, Michael J.Singleton, and Shelly Roth*

Digital geologic compilations of the upper Animas and Boulder River watersheds: Geographic information systems technology used as a scientific interpretation tool *by D.B. Yager, K. Lund, R.G. Luedke, D.J. Bove, M.J. O'Neill, and T.C. Sole*

PRESENTING ABANDONED-MINE-LANDS INFORMATION

The Boulder Geoenvironmental Explorer: A GIS tool to communicate science to land managers and the public *by A.E. McCafferty, D.B. Yager, and T.C. Sole*

ABANDONED MINE LANDS INITIATIVE - YEAR-ONE WORKSHOP

Denver, Colorado

Thursday, February 5, 1998

MORNING SESSION: Perspectives on Implementing the Watershed Approach to Remediate Abandoned Mine Lands

Moderator: Rob Robinson (Bureau of Land Management)

8:10 - 8:20	--	Introduction-Rob Robinson (Bureau of Land Management)
8:20 - 8:40	--	Kirk Nordstrom (U.S. Geological Survey)
8:40 - 9:00	--	Vic Anderson (Montana Department of Environmental Quality)
9:00 - 9:20	--	Carl Norbeck (Colorado Department of Public Health and Environment)
9:20 - 9:40	--	Bill Simon (Animas River Stakeholders Group) and Gary Broetzman (Colorado Center for Environmental Management)
9:40 - 10:00	**--**	**BREAK**

Moderator: Paul von Guerard (U.S. Geological Survey)

10:00 - 10:20	--	Cal Joyner (U.S. Forest Service and Bureau of Land Management)
10:20 - 10:40	--	Jim Dunn (U.S. Environmental Protection Agency)
10:40 - 11:00	--	Jan Gamby (U.S. Department of the Interior)
11:00 - 11:20	--	Harvey Blank (U.S. Department of the Interior)
11:20 - 11:40	--	Larry Gadt (U.S. Forest Service)
11:40 - 1:00	--	LUNCH (and continuation of the poster session)

AFTERNOON SESSION: Is the Watershed Approach Viable?

Moderator: Gary Broetzman (Colorado Center for Environmental Management)

1:00 - 3:00	--	Panel Discussion
Panel Members:		Harvey Blank (Department of the Interior) Terry Harwood (U.S. Department of Agriculture) Dan Weese (U.S. Environmental Protection Agency) Bill Simon (Animas River Stakeholders Group) Vic Anderson (Montana Department of Environmental Quality) Carl Norbeck (Colorado Department of Public Health and Environment)

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