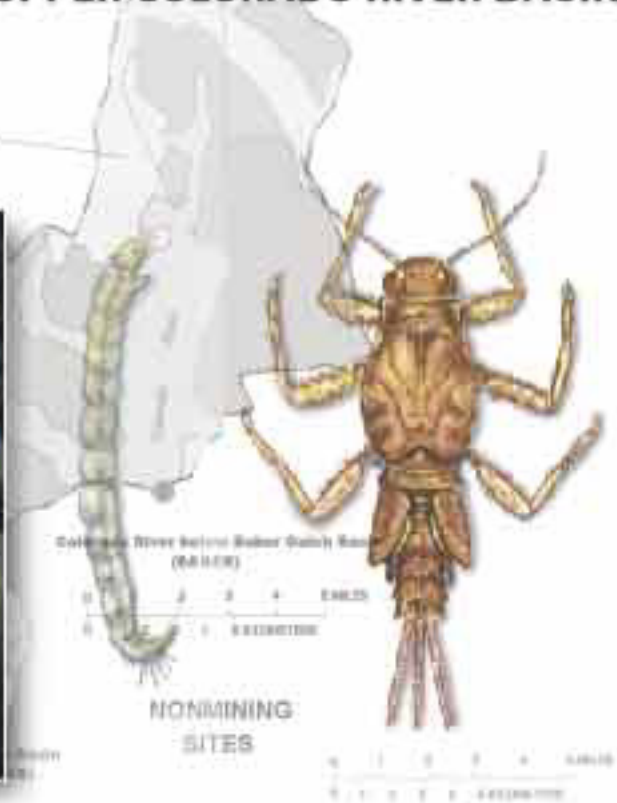
NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

RELATIONS OF BENTHIC MACROINVERTEBRATES TO CONCENTRATIONS OF TRACE ELEMENTS IN WATER, STREAMBED SEDIMENTS, AND TRANSPLANTED BRYOPHYTES AND STREAM HABITAT CONDITIONS IN NONMINING AND MINING AREAS OF THE UPPER COLORADO RIVER BASIN, COLORADO, 1995–98



Water-Resources Investigations Report 02–4139

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Lower right, photograph of Red Mountain Creek near Idarado Mine near Ironton, Colorado.
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Relations of Benthic Macroinvertebrates to Concentrations of Trace Elements in Water, Streambed Sediments, and Transplanted Bryophytes and Stream Habitat Conditions in Nonmining and Mining Areas of the Upper Colorado River Basin, Colorado, 1995–98

By Scott V. Mize and Jeffrey R. Deacon

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FOREWORD

The U.S. Geological Survey (USGS) is committed to serve the Nation with accurate and timely scientific information that helps enhance and protect the overall quality of life, and facilitates effective management of water, biological, energy, and mineral resources. Information on the quality of the Nation's water resources is of critical interest to the USGS because it is so integrally linked to the long-term availability of water that is clean and safe for drinking and recreation and that is suitable for industry, irrigation, and habitat for fish and wildlife. Escalating population growth and increasing demands for the multiple water uses make water availability, now measured in terms of quantity *and* quality, even more critical to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program to support national, regional, and local information needs and decisions related to water-quality management and policy. Shaped by and coordinated with ongoing efforts of other Federal, State, and local agencies, the NAWQA Program is designed to answer: What is the condition of our Nation's streams and ground water? How are the conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues. NAWQA results can contribute to informed decisions that result in practical and effective water-resource management and strategies that protect and restore water quality.

Since 1991, the NAWQA Program has implemented interdisciplinary assessments in more than 50 of the Nation's most important river basins and aquifers, referred to as Study Units. Collectively, these Study Units account for more than 60 percent of the overall water use and population served by public water supply, and are representative of the Nation's major hydrologic landscapes, priority ecological resources, and agricultural, urban, and natural sources of contamination.

Each assessment is guided by a nationally consistent study design and methods of sampling and analysis. The assessments thereby build local knowledge about water-quality issues and trends in a particular stream or aquifer while providing an understanding of how and why water quality varies regionally and nationally. The consistent, multiscale approach helps to determine if certain types of water-quality issues are isolated or pervasive and allows direct comparisons of how human activities and natural processes affect water quality and ecological health in the Nation's diverse geographic and environmental settings. Comprehensive assessments on pesticides, nutrients, volatile organic compounds, trace metals, and aquatic ecology are developed at the national scale through comparative analysis of the Study-Unit findings.

The USGS places high value on the communication and dissemination of credible, timely, and relevant science so that the most recent and available knowledge about water resources can be applied in management and policy decisions. We hope this NAWQA publication will provide you the needed insights and information to meet your needs, and thereby foster increased awareness and involvement in the protection and restoration of our Nation's waters.

The NAWQA Program recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for a fully integrated understanding of watersheds and for cost-effective management, regulation, and conservation of our Nation's water resources. The Program, therefore, depends extensively on the advice, cooperation, and information from other Federal, State, interstate, Tribal, and local agencies, nongovernment organizations, industry, academia, and other stakeholder groups. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch
Associate Director for Water

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot (ft)
inch	2.54	centimeter (cm)
inch	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=1.8\ (°C)+32$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Altitude, as used in this report, refers to distance above or below sea level.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Concentrations of chemical constituents in streambed sediment and bryophytes are given in micrograms per gram (µg/g).

ADDITIONAL ABBREVIATIONS

(%) percent
(Al) aluminum
(As) arsenic
(Cu) copper
(Fe) iron
(Pb) lead
(Zn) zinc

Relations of Benthic Macroinvertebrates to Concentrations of Trace Elements in Water, Streambed Sediments, and Transplanted Bryophytes and Stream Habitat Conditions in Nonmining and Mining Areas of the Upper Colorado River Basin, Colorado, 1995–98

By Scott V. Mize *and* Jeffrey R. Deacon

Abstract

Intensive mining activity and highly mineralized rock formations have had significant impacts on surface-water and streambed-sediment quality and aquatic life within the upper reaches of the Uncompahgre River in western Colorado. A synoptic study by the U.S. Geological Survey National Water-Quality Assessment Program was completed in the upper Uncompahgre River Basin in 1998 to better understand the relations of trace elements (with emphasis on aluminum, arsenic, copper, iron, lead, and zinc concentrations) in water, streambed sediment, and aquatic life. Water-chemistry, streambed-sediment, and benthic macroinvertebrate samples were collected during low-flow conditions between October 1995 and July 1998 at five sites on the upper Uncompahgre River, all downstream from historical mining, and at three sites in drainage basins of the Upper Colorado River where mining has not occurred. Aquatic bryophytes were transplanted to all sites for 15 days of exposure to the water column during which time field parameters were measured and chemical water-quality and benthic macroinvertebrate samples were collected. Stream habitat characteristics also were documented at each site.

Certain attributes of surface-water chemistry among streams were significantly different. Concentrations of total aluminum, copper, iron, lead, and zinc in the water column and concentrations of dissolved aluminum, copper, and zinc were significantly different between nonmining and mining sites. Some sites associated with mining exceeded Colorado acute aquatic-life standards for aluminum, copper, and zinc and exceeded Colorado chronic aquatic-life standards for aluminum, copper, iron, lead, and zinc. Concentrations of copper, lead, and zinc in streambed sediments were significantly different between nonmining and mining sites. Generally, concentrations of arsenic, copper, lead, and zinc in streambed sediments at mining sites exceeded the Canadian Sediment Quality Guidelines probable effect level (PEL), except at two mining sites where concentrations of copper and zinc were below the PEL. Concentrations of arsenic, copper, iron, and lead in transplanted bryophytes were significantly different between nonmining and mining sites. Bioconcentration factors calculated for 15-day exposure using one-half of the minimum reporting level were significantly different between nonmining and mining sites. In general, concentrations of trace elements in streambed sediment and transplanted bryophytes were more closely correlated than were the concentrations of trace elements in the water column with streambed sediments or concentrations in the water column with transplanted bryophytes.

Stream habitat was rated as optimal to suboptimal using the U.S. Environmental Protection Agency Rapid Bioassessment Protocols for all sites in the study area. Generally, stream habitat conditions were similar at nonmining compared to mining sites and were suitable for diverse macroinvertebrate communities. All study sites had optimal instream habitat except two mining sites with suboptimal instream habitat because of disturbances in stream habitat.

The benthic macroinvertebrate community composition at nonmining sites and mining sites differed. Mining sites had significantly lower total abundance of macroinvertebrates, fewer numbers of taxa, and lower dominance of Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies), and a larger percentage of tolerant species than did nonmining sites. The predominance of *Baetis* sp. (mayflies), Hydropsychidae (caddisflies), and large percentage of Orthocladiinae chironomids (midges) at mining sites indicated that these species may be tolerant to elevated trace-element concentrations. The absence of Heptageniidae (mayflies), Chloroperlidae (stoneflies), and *Rhyacophila* sp. (caddisflies) at mining sites indicated that these species may be sensitive to elevated trace-element concentrations.

Comparison of field parameters and chemical water-quality characteristics to biological conditions was conducted using a water quality score (WQS) and a biological condition score (BCS). In general, as the WQS increased, the BCS also increased. Nonmining sites had higher WQS's and BCS's than mining sites. The BCS categorized the nonmining sites as nonimpaired, and the mining sites were categorized as slightly to severely impaired. Other important factors in this study that influenced surface-water quality include stream pH, chemical solubility of trace elements, stream temperature, stream elevation, organic inputs into the stream, basin geology, and stream habitat at a site. Although high concentrations of some trace elements may occur naturally, trace-element concentrations at mining sites were much higher. High trace-element concentrations appear to affect the macroinvertebrate communities more than the other factors at these sites. Mayfly, stonefly, and caddisfly abundance and the percentage of midge species are good indicators of mining effects at sites in the study area.

INTRODUCTION

The National Water-Quality Assessment (NAWQA) Program is a long-term program of the U.S. Geological Survey (USGS) designed to describe the status and trends in the quality of the Nation's surface- and ground-water resources and to provide an understanding of the natural and human factors that can affect the quality of these resources (Leahy and others, 1990). The program is interdisciplinary and integrates biological, chemical, and physical data to assess the Nation's water quality at local, regional, and national levels. The NAWQA Program is designed to use multiple lines of evidence to assess water quality. Using several types of media to assess the water quality provides integrated information that is a more complete description of the water quality than is possible with just one sampling medium.

Benthic macroinvertebrate-community surveys are one of the few means of directly assessing the biological integrity of a site and represent a group of aquatic organisms that are sensitive to changes in water chemistry and physical habitat (Meador and Gurtz, 1994). The water quality of stream reaches can be characterized by evaluating the results of qualitative and quantitative measurements of the benthic macroinvertebrate community. The macroinvertebrate component of NAWQA biological community surveys is designed primarily to characterize the distribution and community structure of benthic macroinvertebrate species and their relation to water and streambed-sediment quality. The species composition and community structure of macroinvertebrates provide evidence of physical and chemical conditions present in a stream over timescales ranging from months to years (Cuffney and others, 1993).

Intensive mining activity and highly mineralized rock formations have influenced the surface-water and streambed-sediment quality and aquatic biology in the upper reaches of the Uncompahgre River in western Colorado (fig. 1). Drainage from several abandoned mines and adits, combined with drainage from the

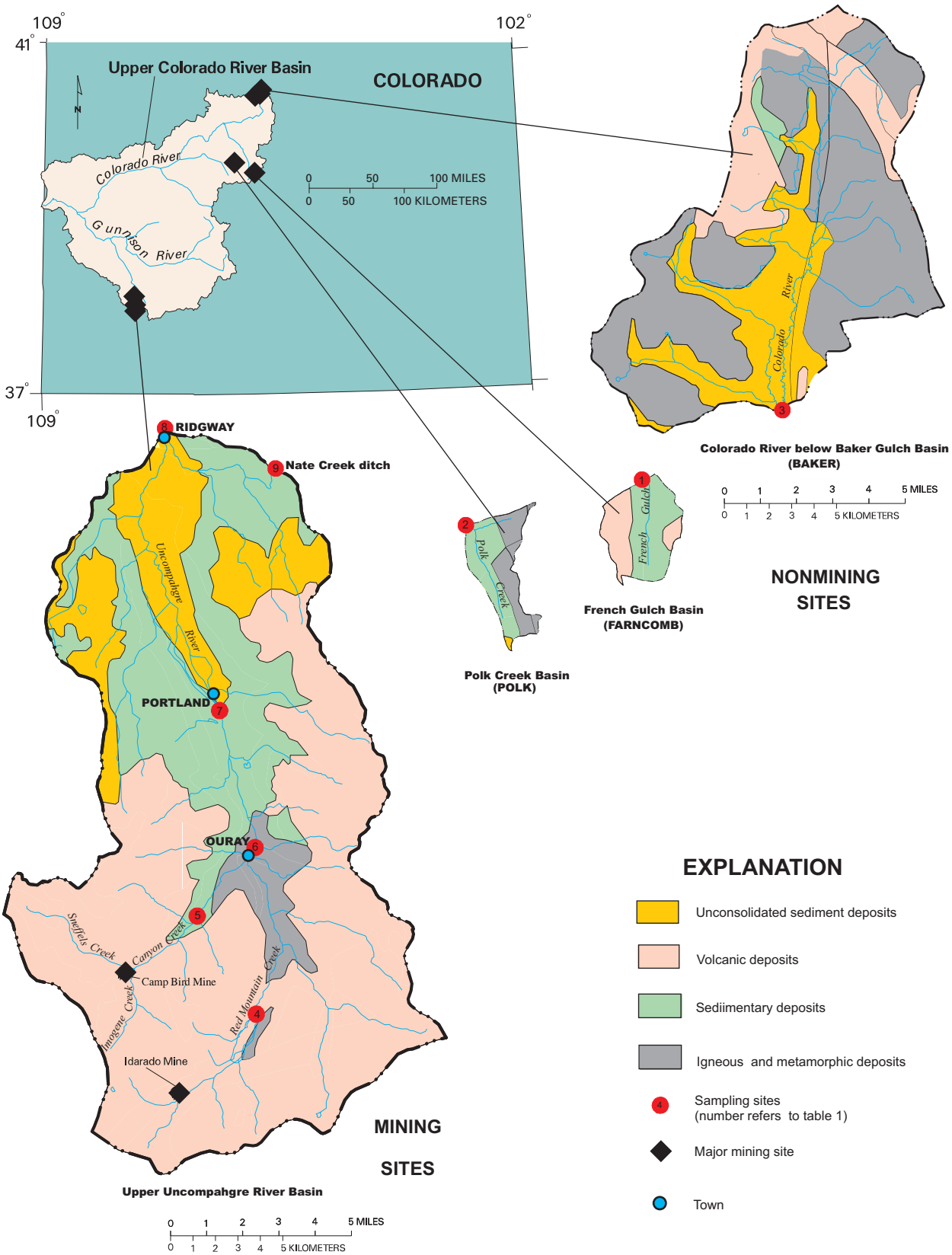

Figure 1. Location and basin surficial geology (King and Beikman, 1974a, b) of nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1995–98.

Idarado and Camp Bird Mines and tailings in the Red Mountain and Canyon Creek watersheds (fig. 1), potentially contribute to the degradation of tributaries in the upper Uncompahgre River Basin (Moran and Wentz, 1974). The Uncompahgre River, which is a trout stream upstream from Red Mountain Creek, contains little or no aquatic life from the mouth of Red Mountain Creek to the mouth of Canyon Creek near Ouray and supports only a limited fishery for several miles downstream from that point (Rouse, 1970).

The Upper Colorado River Basin (UCOL), which includes the Uncompahgre River, was selected for the NAWQA Program. A study was completed in the upper Uncompahgre River Basin in 1998 to better understand the relations of trace elements in water, streambed sediment, and aquatic life. The study area (fig. 1; table 1) is composed of five mining (mining-affected) sites in the upper Uncompahgre River Basin and three nonmining (minimally affected) sites in other drainage basins in the Upper Colorado River Basin. Water, streambed sediment, bryophyte (aquatic moss), benthic macroinvertebrate, and habitat data were collected at all sites during summer low-flow conditions. With the exception of streambed sediment, all sample media were collected in July and August 1997 and 1998. Streambed-sediment samples were collected during low-flow conditions in September and October of 1995 and 1996. Although the streambed-sediment samples were not collected during the same years as the collection of data for water, bryophytes, macroinvertebrates, and habitat, these samples can still provide important information about the water-quality conditions at the sites because no known large-scale disturbances or mining activities occurred in the basin between sampling periods.

Purpose and Scope

The purposes of this report are to (1) compare trace-element concentrations in the water column, streambed sediment, and transplanted bryophytes in the study area, with emphasis on six selected trace elements (aluminum, arsenic, copper, iron, lead, and zinc); (2) estimate bioconcentration of the six selected trace elements by using transplanted bryophytes in the study area; (3) evaluate stream habitat conditions in the study area; (4) compare benthic macroinvertebrate community composition at nonmining and mining sites in the study area; and (5) report the relation between natural and human-related factors affecting the concentration of the six selected trace elements in water, streambed sediment, and transplanted bryophytes at nonmining and mining sites in the study area. Trace-element concentrations in water, streambed sediment, and transplanted bryophytes are presented; data describing the benthic macroinvertebrate community composition and qualitative stream habitat characteristics are given for five sites in the upper Uncompahgre River Basin and three sites in the Colorado River, French Gulch, and Polk Creek Basins in western Colorado during 1995–98.

Previous Work

Bioassessments have been used to monitor water and streambed-sediment quality for many years. In many cases, samples were collected to determine whether ecological integrity was present or to assess differences among mining-affected sites and nonaffected sites (Nelson and Campbell, 1995). An investigation of the effects of metal-mine drainage on surface-water quality in mining districts throughout Colorado was done by the USGS in cooperation with the Colorado Water Pollution Control Commission (Moran and Wentz, 1974). Moran and Wentz also studied the physical and chemical processes involved in metal-mine drainage and the effects on water and sediment quality and aquatic life. Moran and Wentz concluded that fish and macroinvertebrate populations had been virtually eliminated in Red Mountain Creek, and the decline in water quality of the upper Uncompahgre River was caused by metals, acid, and large amounts of iron hydroxide particles delivered to the Uncompahgre from Red Mountain and Canyon Creeks. Nelson and Campbell (1995) and Osmundson (1992) studied the effects of trace elements on aquatic life upstream and downstream from Ridgway Reservoir near Ridgway, Colo., and found the reservoir served as a sink for trace elements in the system.

Description of Study Area

The study area (fig. 1; table 1) is composed of five mining (mining-affected) sites in the upper Uncompahgre River Basin and three nonmining (minimally affected) sites in other drainage basins in the Upper Colorado River Basin. Mining sites were

Table 1. Description of sampling sites in the Upper Colorado River Basin, Colorado, 1995–98

[--, no data available; °F, degrees Fahrenheit]

Site number (fig. 1)	Site name	Site abbreviations	Site identification	Site elevation (feet)[1]	Site mean annual precipitation[2] (inches per year)	Site mean annual temperature[3] (°F)	Drainage area (square miles)
			NONMINING SITES				
1	French Gulch above Farncomb Hill near Breckenridge, CO	Farncomb	392838105572900	10,540	23.72	35.6	4.7
2	Polk Creek at Interstate Highway 70 near Vail, CO	Polk	393527106143500	9,640	23.77	37.0	4.2
3	Colorado River below Baker Gulch near Granby, CO	Baker	09010500	8,750	23.33	38.4	53.4
			MINING SITES				
4	Red Mountain Creek above Crystal Lake near Ironton, CO	Red Mountain	375732107394000	9,610	--	--	18.1
5	Canyon Creek below Squaw Gulch near Ouray, CO	Canyon	380007107413600	8,514	--	--	23
6	Uncompahgre River at Ouray, CO	Ouray	380115107402001	7,707	26.94	43.6	73.3
7	Uncompahgre River above Cutler Creek near Ouray, CO	Cutler	380448107420800	7,250	--	--	93.1
8	Uncompahgre River near Ridgway, CO	Ridgway	09146200	6,878	16.84	43.2	149

Site abbreviations	Stream order[4]	Predominant lithology [5]	Predominant soil order[6]	Predominant vegetation type[7]	Predominant substrate[8]	Embeddedness class[9]	RBP site habitat rating[10]
			NONMINING SITES				
Farncomb	2	Sedimentary/igneous	Alfisols	Alpine-meadow-barren	Cobble	5	OPTIMAL
Polk	3	Sedimentary/metamorphic	Entisols	Spruce-fir forest	Cobble	4	OPTIMAL
Baker	3	Igneous metamorphic	Alfisols	Alpine-meadow-barren	Cobble	4	OPTIMAL
			MINING SITES				
Red Mountain	3	Igneous	Inceptisols	Alpine meadow-barren	Cobble	4	OPTIMAL
Canyon	4	Igneous	Alfisols	Alpine meadow-barren	Cobble	4	OPTIMAL
Ouray	5	Sedimentary/metamorphic	Alfisols	Spruce-fir forest	Cobble	3	SUBOPTIMAL
Cutler	5	Sedimentary	Mollisols	Spruce-fir forest	Cobble	3	SUBOPTIMAL
Ridgway	5	Sedimentary	Entisols/Mollisols	Pine-Douglas fir forest	Cobble	3	OPTIMAL

[1] Feet above sea level.
[2] Site mean annual precipitation, for years 1995 to 1998, from the nearest climatic data-collection station according to Colorado Climate Center (2001) .
[3] Site mean annual temperature, mean of monthly temperature data for years 1995 to 1998 from the nearest climatic data-collection station according to Colorado Climate Center (2001).
[4] Stream order determined according to Strahler (1952).
[5] Predominant lithology near the sampling site, modified from King and Beikman (1974a, b).
[6] Predominant soil order near the sampling site, modified from Heil and others (1977).
[7] Predominant vegetation type near the sampling site, modified from Kuchler (1964).
[8] Predominant substrate sampled for benthic macroinvertebrates.
[9] Rated on a scale from 1 (signifying over 75 percent of surface area of gravel, cobble, and boulder particles covered by fine sediment) to 5 (signifying less than 5 percent surface area of gravel, cobble, and boulder particles covered by fine sediment).
[10] Rapid Bioassessment Protocols (modified) site habitat rating; see table 9 for more information.

selected on the upper Uncompahgre River to represent water-quality conditions affected by highly mineralized geology and mining land-use practices and were Red Mountain Creek above Crystal Lake near Ironton, Colo. (Red Mountain), Canyon Creek below Squaw Gulch near Ouray, Colo. (Canyon), Uncompahgre River at Ouray, Colo. (Ouray), Uncompahgre River above Cutler Creek near Ouray, Colo. (Cutler), and Uncompahgre River near Ridgway, Colo. (Ridgway). The nonmining sites were French Gulch above Farncomb Hill near Breckenridge, Colo. (Farncomb), Polk Creek at Interstate Highway 70 (I–70) near Vail, Colo. (Polk), and Colorado River below Baker Gulch near Granby, Colo. (Baker). Although some geographic and geological features differ among nonmining and mining sites (table 1), all sites are located in the Southern Rocky Mountain ecoregion (Omernik, 1987). To minimize natural difference among site groups, the mean values of environmental variables of the three nonmining sites were used for statistical comparisons to mining sites.

The upper Uncompahgre River Basin in southwestern Colorado originates just west of the Continental Divide in the northern San Juan Mountains (southern part of basin) at an altitude of approximately 12,200 feet above sea level and extends north and west approximately 20 miles to the town of Ridgway. The upper part of the river drains approximately 150 square miles and travels through the towns of Ouray, Portland, and Ridgway (fig. 1, table 1). The mining sites are located in the northwestern part of the San Juan Mountains in the Red Mountain (southern part of basin in the Red Mountain Creek Basin), Mount Sneffels (western part of basin in the Sneffels Creek Basin), and Uncompahgre mining districts (central and northern parts of basin) of Ouray County in Colorado. The area is well known for historical metal-mining activities. Intensive mining activities began in the 1870's and continued to the mid-1980's; a few mines still operate. Early mine developments were concentrated in the Mount Sneffels district just west of Ouray where extensive amounts of copper, gold, lead, silver, and zinc were mined from vein deposits.

Geology

The general surficial geology of the Uncompahgre River study area consists of igneous and metamorphic bedrock of Precambrian age, sedimentary rocks of Paleozoic and Mesozoic age, volcanic deposits of Tertiary age, and unconsolidated sediment deposits of Quaternary age (fig. 1). The geology of the study area has undergone a series of five distinct episodes of deformation, some of which were accompanied by metamorphism, igneous activity, and mineralization (Westervelt and Sheriff, 1994).

The Precambrian bedrock includes diabase, granite dikes and sills, and exposed quartzite and slate. Limestones were deposited during the early Paleozoic, followed by thick beds of sandstone and shale, which were deposited through the late Mesozoic. Late Tertiary volcanism produced at least 15 variably mineralized calderas that compose the San Juan volcanic field. Mineralization occurred between 5 and 15 million years ago following igneous activity associated with resurgent doming of the San Juan and Uncompahgre calderas and the formation of the Silverton caldera (Westervelt and Sheriff, 1994). These mineralized deposits compose most of the mined deposits in the study area.

General surficial geology of the Farncomb site (fig. 1) consists of sedimentary deposits (limestone, sandstone, and shale) of Cretaceous age and volcanic deposits of Cretaceous and Tertiary age. The surficial geology of the Polk site (fig. 1) includes igneous (granite) and metamorphic rocks (biotitic gneiss, migmatite, and schist) of Precambrian age, sedimentary deposits (conglomerate, limestone, sandstone, and shale) of Pennsylvanian age, and Quaternary landslide deposits, including locally derived talus and colluvium. The surficial geology of the Baker site (fig. 1) consists mainly of metamorphic rocks (gneiss, migmatite, and schist) of Precambrian age, but some sedimentary deposits (shale) of Cretaceous age and volcanic rocks (lava flows, breccias, and tuff) and glacial drift deposits of Tertiary and Quaternary age are present in the basin (King and Beikman, 1974a, b).

Climate

Rainfall and temperature in the study area (table 1) vary in relation to elevation. Average annual precipitation in the upper Uncompahgre River Basin ranges from less than 14 inches per year in the northernmost valleys to greater than 55 inches per year in the westernmost mountainous regions (D.W. Litke, U.S. Geological Survey, written commun., 1986). Approximately 30 to 40 percent of precipitation occurs as snowfall. Mean annual temperatures in Ouray generally range from 42 to 44 degrees Fahrenheit (Colorado Climate Center, 2001).

The French Gulch area near Breckenridge receives about 19 to 30 inches of precipitation per year. Mean annual temperature for Dillon, north of Breckenridge, was 35.6 degrees Fahrenheit. The Polk Creek drainage basin near Vail normally receives about 19 to 30 inches of precipitation per year, and the mean annual temperature in the Vail area ranges from 36 to 38 degrees Fahrenheit. Precipitation in the Baker Gulch area near Granby ranges from 20 to 26 inches per year, and mean annual temperatures range from 37 to 39 degrees Fahrenheit (Colorado Climate Center, 2001).

Land Use/Land Cover

Predominant land use/land cover (fig. 2) in the study area includes forest, rangeland, and tundra. Agriculture, which includes cropland, pasture, and confined animal feeding operations, is concentrated in the open valleys in the study area. Barren lands, urban development, and surface-water features constitute the smallest percentage of land use/land cover in all basins except at the Baker site where approximately 17 percent of the basin includes other land-use types such as residential and recreational properties (Hitt, 1995).

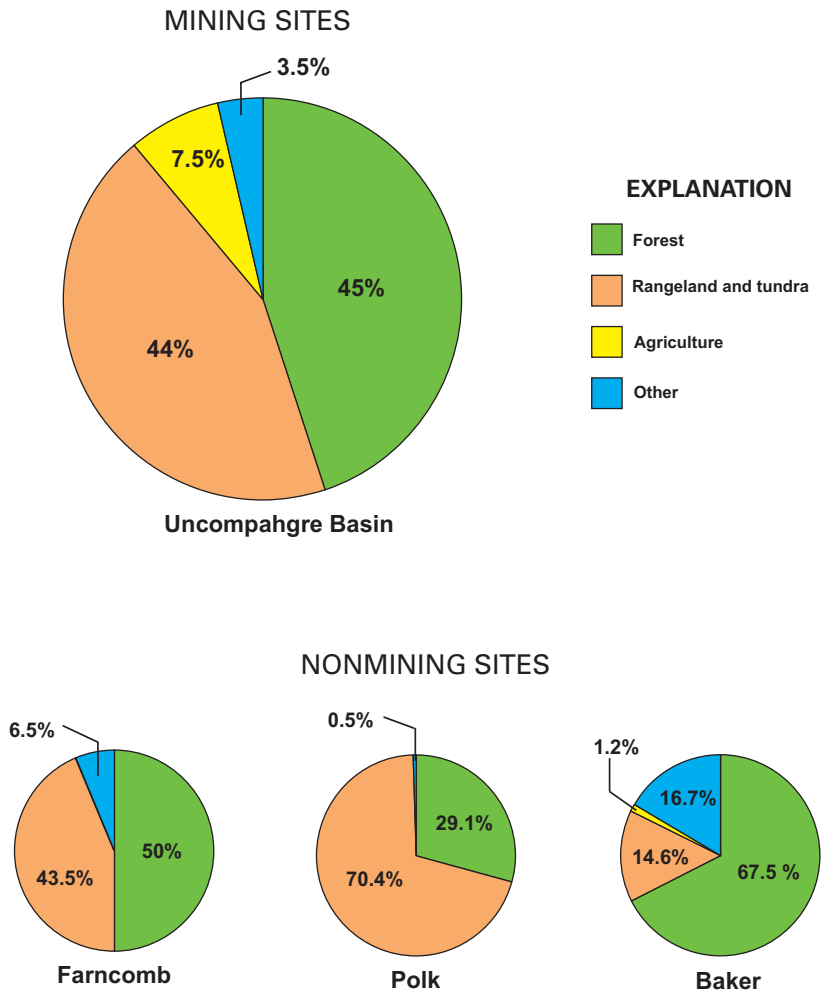

Figure 2. Percentage of land use/land cover (Hitt, 1995) at nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1995–98.

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DATA COLLECTION AND ANALYSIS

Site Selection

The study area (fig. 1; table 1) is composed of five mining (mining-affected) sites in the upper Uncompahgre River Basin and three nonmining (minimally affected) sites in other drainage basins in the Upper Colorado River Basin. Mining sites were selected on the upper Uncompahgre River to represent water-quality conditions affected by highly mineralized geology and mining land-use practices. Nonmining sites were selected in other drainage basins due to a lack of nonmining sites in the Uncompahgre River Basin, and represent water-quality conditions considered to be minimally affected by mining activities. Although some geographic and geological features vary among nonmining and mining sites (table 1), all sites are located in the Southern Rocky Mountain ecoregion (Omernik, 1987). Omernik identified that ecoregions have similar patterns and composition of biotic and abiotic phenomena (geology, physiography, vegetation, climate, soils, land use, wildlife, and hydrology) that affect or reflect differences in ecosystem quality and integrity. Comparisons of chemical and biological conditions among nonmining and mining sites were used to determine potential effects of mining land use on the benthic macroinvertebrate communities at sites in the study area. To minimize natural difference among site groups, the mean values of environmental variables of the three nonmining sites were used for statistical comparisons to mining sites.

Sample Collection

Water-chemistry, streambed-sediment, transplanted bryophyte, and benthic macroinvertebrate samples were collected and stream habitat conditions were documented once at all sampling sites in the study area during low-flow conditions between October 1995 and July 1998. Water-chemistry, transplanted bryophyte, and benthic macroinvertebrate samples were collected and stream habitat was documented at all sampling sites in July 1997 except at the Polk and Baker sites, where samples and stream habitat information were collected in July 1998. Streambed sediments were collected at all sampling sites in October 1995 except at the Farncomb and Baker sites, where samples were collected in September 1996. Bryophytes (native aquatic moss that grows in southern Rocky Mountain streams) were transplanted at all sampling sites for 15 days during which water-column and benthic macroinvertebrate samples and physical water-quality data were collected. Stream habitat characteristics also were documented at each site. Although the streambed-sediment samples were not collected during the same years as the collection of data for water, bryophytes, macroinvertebrates, and habitat, these samples can still provide important information about the water-quality conditions at the sites because no known large-scale disturbances or mining activities occurred in the basin between sampling periods.

Water-column samples and physical water-quality data were collected according to USGS NAWQA protocols (Shelton, 1994). Physical water-quality data included alkalinity, dissolved oxygen, pH, specific conductance, and temperature. Streamflow (discharge) was measured using streamflow-gaging methods described by Rantz and others (1982) except at the Ridgway and Baker sites, where discharge was recorded from USGS streamflow-gaging stations. All water-column samples were analyzed at the USGS

National Water Quality Laboratory in Arvada, Colo., using methods described in Fishman and Friedman (1989). Water-column samples for trace elements included a less than 0.45-micrometer filtered (dissolved) sample and an unfiltered (total) sample in which subsequent analysis was performed. Results of water-chemistry analyses and physical water-quality data for all sampling sites are in Appendix D and in the USGS National Water Information System (NWIS).

Streambed sediments were collected from undisturbed, continuously wetted, depositional zones in the stream channel. Each depositional zone at a sampling site was subsampled at several locations, and the subsamples were composited (Shelton and Capel, 1994). The samples were sieved in the field to less than 63 micrometers and submitted to the USGS Branch of Geochemistry Analytical Services Group Laboratory in Denver, Colo., and the USGS Research Laboratory in Atlanta, Ga., for analysis. Chemical preparation and analyses of the streambed-sediment samples followed a total digestion procedure (Horowitz and others, 1989). Streambed-sediment sample results for all sampling sites are in Appendix E and in the USGS National Water Information System (NWIS).

Samples of *Hygrohypnum ochraceum*, an aquatic bryophyte, were collected from Nate Creek ditch near Owl Creek Pass in Ouray County, Colo., during July 1997 and July 1998 to use as an indirect measure of bioconcentration of trace elements in biological communities at the sampling sites. Bryophytes were vigorously washed by hand, using tap water to remove sediment and attached macroinvertebrates. Deionized water was used as a final rinse. Ten-gram samples of spin-dried bryophytes were placed into 4-millimeter nylon mesh bags and transplanted at selected sites. Bags were attached to mason bricks using plastic O-rings and placed in the stream. To evaluate environmental variability, three bags per site were placed in riffle areas in the stream reach, including the Nate Creek ditch site, for a 15-day exposure period. According to Carter and Porter (1997), the maximum rate of uptake occurs during the first 10-day exposure for most trace elements, and significant differences in bryophyte trace-element concentrations can be found after as few as 10 days of exposure to ambient conditions. Bags were collected and bryophytes were removed and washed again, as described previously, and analyzed for trace elements (Nelson and Campbell, 1995; Nelson, 1996). Bryophyte samples were analyzed for trace elements discussed in this study using inductively coupled plasma-atomic absorption spectrophotometry for all elements except arsenic, which was analyzed using hydride generation-atomic absorption spectrophotometry at the Environmental Trace Substances Laboratory at the University of Missouri in Rolla, Mo. Results of analyses for transplanted bryophyte samples from all sampling sites are in Appendix F.

Benthic macroinvertebrate samples were collected from five representative areas of riffle habitat containing cobble substrates (richest-target habitat). Samples were collected using a slack sampler (kick net) with an area of 0.25 m^2. Five subsamples were collected and composited into one sample for each site for a total of 1.25 m^2. The samples were preserved with a 10-percent formalin solution. Macroinvertebrate samples were collected according to USGS NAWQA protocols (Cuffney and others, 1993) and were identified and enumerated at Colorado State University in Fort Collins.

Benthic macroinvertebrate samples were rinsed of formaldehyde by using tap water and a sieve. Next, macroinvertebrates were picked or sorted from debris by using a binocular dissecting microscope at low power (about 10X) and placing the organism into labeled vials with 70- to 80-percent ethanol. Finally, organisms were identified to the lowest practical taxonomic level and counted (B.C. Kondratieff, Colorado State University, written commun., 1998). Density values were based on a 1-m^2 area and were obtained by dividing the number of organisms collected by the surface area of the sampler. Results of analyses for benthic macroinvertebrate samples from all sampling sites are in Appendix G.

A qualitative assessment of habitat conditions consisted of a field form characterizing instream habitat measures including substrate types, substrate embeddedness, channel alterations, bank stability, and riparian zone features. Each habitat variable was categorized, and a total score of the variables provided a qualitative assessment of each site. Habitat-assessment data were collected according to the U.S. Environmental Protection Agency's Rapid Bioassessment Protocols (RBP) (Barbour and others, 1997).

Data Analysis

Seventeen trace elements were analyzed in the water-column samples, 24 trace elements in streambed-sediment samples, and 19 trace elements in transplanted bryophytes. Many trace-element concentrations in the water column were near or less than the minimum reporting level or indicated little variation across the study area. Six trace elements—aluminum, arsenic, copper, iron, lead, and zinc—were selected for discussion in this study because they: (1) were frequently detected in most water, streambed sediment, and transplanted bryophyte samples; (2) showed some variability in concentrations; and (3) have aquatic-life standards or water-quality guidelines associated with them. Minimum reporting levels for water-column, streambed-sediment, and transplanted bryophyte samples are listed in Appendixes A, B, and C, respectively. Complete lists of all trace elements and their concentrations in the water column, streambed sediment, and transplanted bryophytes are in Appendixes D, E, and F, respectively.

Nonparametric statistical methods were used in the data analysis because original data cannot be formed to meet parametric statistical assumptions. Nonparametric methods do not depend on the distribution of the sampled population and are applicable to small sample sizes (fewer than 10). An alpha value of 0.05 was used for the Mann-Whitney test to test for significant statistical differences between medians of two groups of data (nonmining and mining sites). Exact p-values less than or equal to 0.05 were used for the Spearman rank correlation to test significant statistical relations among trace-element concentrations in the different sampling media (water column, streambed sediment, and transplanted bryophytes); among trace-element concentrations and other water-quality parameters (pH, specific conductance, dissolved sulfate, suspended sediment, and dissolved organic carbon); and among trace-element concentrations and benthic macroinvertebrate metrics and indices.

A value of one-half of the method reporting level was substituted for concentrations in the water column that were less than the method reporting level (censored). The mean concentration of trace elements of the three bryophyte samples transplanted at each site was used for the analysis of the bryophyte data.

To compare water and streambed-sediment quality to the biological conditions at each site, a Water-Quality Score (WQS) was developed, based on information from this study, that includes five water-quality parameters that generally reflect trace-element chemistry in natural waters. The five WQS parameters, which were assumed to be independent of each other, were specific-conductance measurements and concentrations of suspended sediment, dissolved organic carbon, dissolved sulfate, and dissolved zinc in the water column. Each site was ranked in the same way with a score from one to eight that represented the quality of that constituent at that site relative to all the other sites. Except for dissolved organic carbon, all water-quality parameters were ranked high to low, corresponding to the lowest to highest concentrations of each of the five parameters at all sites. According to Rosenberg and Resh (1993), intermediate levels of organic enrichment may favor certain suspension- or deposit-feeding macroinvertebrate groups; therefore, dissolved organic carbon was ranked highest to lowest based on highest to lowest concentrations. Individual site WQS rankings for each of the five parameters were summed to arrive at a final WQS for a particular site. These scores represent the overall trace-element chemistry of the water and ultimately the effects on the macroinvertebrate community at these sites. The WQS was used to examine differences in water-quality conditions of nonmining and mining sites in the study area.

The Biological Condition Score (BCS) is a measure of the biological condition at a site, based on the benthic macroinvertebrate composition at that site, and was determined for all sites by using the U.S. Environmental Protection Agency Rapid Bioassessment Protocols III (benthic macroinvertebrates) (Plafkin and others, 1989). The BCS is an index that is determined by ranking eight biotic metrics that are commonly used in bioassessment studies. These metrics are taxa richness; the modified Hilsenhoff (1987) biotic index; the ratio of scraper to collector-filterer abundances; the ratio of Ephemeroptera, Plecoptera, and Trichoptera (EPT) to chironomid abundances; the percentage contribution of one dominant taxon; the EPT index; the community loss index; and the ratio of shredders to total abundance of all macroinvertebrates at a site. Each metric then was assigned a score according to the percentage similarity (proportion of mining-site biotic metrics compared to nonmining-site biotic metrics) between the mining sites and the nonmining sites. To use the BCS effectively, the mean values of the three nonmining sites were used to develop the percentage similarity

between nonmining and mining sites. Scores of the eight metrics at each mining site were totaled and compared to a single total metric score for the nonmining sites. The percentage comparison between the total scores provides an overall evaluation of biological condition.

According to Plafkin and others (1989), the percent comparisons to nonmining sites are used to obtain the biological condition category. The biological condition category represents the overall classification of each site based on the percentage comparisons of the BCS between nonmining and mining sites. Biological condition categories are nonimpaired (greater than 83 percent), slightly impaired (54 to 79 percent), moderately impaired (21 to 50 percent), and severely impaired (less than 17 percent). Plafkin and others (1989) suggested that assigning intermediate values (borderline values not directly assigned to one of the above category ranges) would require subjective judgment as to the correct placement of sites into biological condition categories and may need habitat and physiochemical data to aid in the decision process.

Quality-Assessment Procedures

Quality-assessment procedures were followed to ensure the consistency and accuracy of the data collection. Quality-control procedures for the water-chemistry samples included analysis of one split-replicate sample (12.5 percent of sample size) and one field-blank sample (12.5 percent of sample size) collected at the same time as the environmental sample. A split replicate is a sample that is used to determine the variability associated with sample processing, handling, shipment, and analysis (Spahr and Boulger, 1997). A split-replicate sample was processed onsite by collecting twice the usual amount of water and splitting the water into two individual samples. Each sample was individually processed using the same techniques as described in Shelton (1994) and was submitted for laboratory analysis as one environmental sample and one split-replicate sample. Laboratory analyses for environmental and split-replicate samples are described in Fishman and Friedman (1989) and included analysis of major ions and trace elements. A field-blank sample was prepared using water that is free of the analytes of interest. The field-blank sample was passed through all field-cleaned sampling equipment and then processed as a normal water-quality sample. Laboratory analyses for field-blank samples are described in Fishman and Friedman (1989) and consisted of analysis of major ions and trace elements.

The split-replicate results indicate that when concentrations were low (in the microgram per liter range), the differences between split-replicate concentrations were generally within 1 µg/L of each other. When concentrations were high (100–1,000 µg/L) the differences between split-replicate concentrations were generally within 2 percent of each other. The small differences in the split replicates indicate that sample processing and analysis did not introduce enough variation to affect interpretation of results. Field-blank results indicated that no detections were above the minimum reporting level; therefore, bias that could result from the contamination of environmental samples as a result of equipment cleaning, sample collection, processing, handling, shipping, and analysis (Spahr and Boulger, 1997) is minimal and did not introduce enough variation to affect interpretation of results.

Quality-control procedures for the collection of streambed sediments consisted of analysis of laboratory reference material (enriched soil) and one field-replicate sample (12.5 percent of sample size) collected at the same time as environmental samples. Field-replicate samples were collected to determine the variability in the sampling technique, in the laboratory analysis, and in the sampled depositional zones. Results of trace elements from the analysis of the laboratory reference material were within 3 standard deviations of the mean recovery of elements in the streambed-sediment reference material. The differences between environmental samples and field-replicate samples for aluminum, arsenic, copper, iron, lead, and zinc ranged from 0.10 to 19 percent and did not introduce enough variation to affect interpretation of results.

Quality-control procedures for the transplanted bryophytes consisted of using three replicate samples at each site to determine the variability of bioaccumulation processes in a single stream cross section. The coefficient of variation for bryophyte replicates ranged from 0.0 to 0.5 for the trace elements of interest, which may indicate variability in the cross section of the stream in which transplanted bryophytes were placed. For example, if transplanted bryophytes (bags) were placed in a section of the stream that had a decrease in

flow, then these bags were possibly not exposed to trace elements in the water equal to a bag that was placed in a higher velocity zone. Because of this variation, the mean concentration of three replicate samples was used for the analyses of transplanted bryophyte data to represent an estimate of a cross-sectional sample. Laboratory quality-control procedures consisted of analysis of a matrix spike, standard reference material, replicate samples, and blank samples. The U.S. Fish and Wildlife Service's Patuxent Analytical Control Facility quality-assurance program in Patuxent, Md., reviewed the results of the quality-control samples. The accuracy was measured using spike recovery reference-material analysis. Blank-sample analysis showed that trace-element concentrations in the blanks were less than minimum reporting levels for the analytes of interest and did not introduce enough variation to affect interpretation of results.

All sites were revisited and the habitat redocumented as a means of quality-control procedures for stream habitat assessment as described by the U.S. Environmental Protection Agency Rapid Bioassessment Protocols (Barbour and others, 1997). The redocumentation of habitat was conducted by the same investigator as the original habitat documentation and was used to determine the variability of the qualitative documentation procedures. Redocumented qualitative habitat data differed by less than 10 percent from the initial stream-habitat assessment and did not introduce enough variation to affect interpretation of results.

Quality-control procedures for benthic macroinvertebrate samples consisted of laboratory quality control and one field replicate (12.5 percent of sample size) to determine variability in a single stream reach. The relative percent difference (RPD) between replicate analyses was calculated using the formula:

$$RPD = \left| \frac{Sample1 - Sample2}{\frac{Sample1 + Sample2}{2}} \right| \times 100$$

Eighty percent of the biological metrics used in this report had RPD's of less than 25 percent between environmental and field-replicate samples. Benthic macroinvertebrate sampling tends to be more variable than other forms of water-quality information, probably because of natural differences in the stream microhabitats and the collection of the sample in a stream reach. Changes in the microhabitat can cause certain types of macroinvertebrate groups to become more dominant than other macroinvertebrate groups. Laboratory quality control consisted of a second taxonomist identifying and enumerating taxa in one sample (12.5 percent of sample size) previously identified and enumerated. The variability in taxa identification and enumeration procedures consisted of less than a 10-percent difference for all samples except for a 13-percent difference in total taxa for one sample and a 13-percent difference in total specimens for another sample. The results of laboratory and field-replicate quality-control measures indicate that benthic macroinvertebrate samples did not introduce enough variation to affect interpretation of results.

WATER-COLUMN SAMPLES AND PHYSICAL WATER-QUALITY PARAMETERS

Water-column samples were collected and physical water-quality parameters including discharge, alkalinity, dissolved oxygen, pH, specific conductance, and temperature were measured in the field at all sites during the biological sampling period. Alkalinity, pH, and specific conductance were analyzed using additional acid-preserved and chilled field samples obtained at the same time as field water-chemistry samples. Other water-quality parameters analyzed by the laboratory were dissolved solids, hardness, major ions and trace elements, suspended-sediment concentration, dissolved organic carbon, and suspended organic carbon. Water-column data collected for each site are listed in table 2 and Appendix D.

Specific conductance, dissolved sulfate, and concentrations of suspended sediment in the water column were generally higher at mining sites than at nonmining sites, whereas pH and dissolved organic carbon generally were lower at mining sites than at nonmining sites (fig. 3). Specific conductance, dissolved sulfate, and concentrations of suspended sediment and dissolved organic carbon were significantly different ($p \leq 0.05$) between nonmining and mining sites. Values for pH were not significantly different between nonmining and mining sites.

Table 2. Selected water-column data for samples from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98

[ft^3/s, cubic feet per second; °C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; $CaCO_3$, calcium carbonate]

Site abbreviation (see table 1 for full site names)	Discharge (ft^3/s)	Temperature (°C)	pH, field	Alkalinity, field (mg/L as $CaCO_3$)	Dissolved oxygen (mg/L)	Specific conductance, field (µS/cm)	Dissolved solids (mg/L)	Hardness, total (mg/L as $CaCO_3$)	Suspended sediment (mg/L)	Dissolved organic carbon (mg/L)
NONMINING SITES										
Farncomb	13.4	4.9	7.7	24	8.7	72	44	34	0.9	2.6
Polk	6.6	6.8	8.1	47	8.8	94	53	45	2.4	1.4
Baker	43.0	14	7.8	25	8.0	62	39	27	2.0	1.9
MINING SITES										
Red Mountain	52.4	6.4	3.8	0	8.3	415	264	120	16	0.3
Canyon	170	9.9	7.5	27	8.2	161	89	70	3.4	0.3
Ouray	260	8.5	6.9	11	8.7	194	111	80	18	0.2
Cutler	294	10	7.6	18	8.5	222	129	93	14	0.3
Ridgway	379	15	8.1	69	7.5	400	242	170	45	0.8

CONCENTRATIONS AND DISTRIBUTION OF SELECTED TRACE ELEMENTS

Water Column

Water-column chemistry may provide information on the source and transport of trace elements in a stream system. The water-column chemistry is used to assess the physical (dissolved oxygen, pH, specific conductance, and temperature) and chemical (major ions and trace elements) characteristics of stream water (Shelton and Capel, 1994). Generally, water samples contain low concentrations of trace elements, whereas streambed-sediment samples commonly contain high concentrations.

Total concentrations of aluminum, copper, iron, lead, and zinc and most dissolved concentrations (except for lead and iron) in water-column samples were significantly different ($p \leq 0.05$) among nonmining and mining sites. Dissolved concentrations of aluminum, arsenic, copper, iron, lead, and zinc in the water column were generally higher at mining sites than at nonmining sites (fig. 4). A list of all trace elements for water-column samples for the study area is in Appendix D. Trace-element concentrations at nonmining sites were below minimum reporting levels for dissolved concentrations of arsenic, copper, and lead and for total concentrations of lead and zinc. One nonmining site had a detection of dissolved zinc and a detection of total copper, whereas most sampling sites had detections of dissolved and total aluminum and iron.

The State of Colorado aquatic-life standards are based on dissolved metal concentrations except for iron, which is based on the total-recoverable metal (Colorado Department of Public Health and Environment, 1999). Calculations of aquatic-life standards for copper, lead, and zinc were based on the hardness of the water during the sampling period. Sample concentrations of trace elements in the water column were compared to the acute and chronic concentrations for aquatic life (Colorado Department of Public Health and Environment, 1999) (table 3).

Dissolved aluminum concentrations ranged from 3.8 µg/L at the Farncomb site to 9,174 µg/L at the Red Mountain site. The Red Mountain site is the only site with concentrations that exceeded the Colorado aquatic-life standards for acute and chronic concentrations of aluminum. Dissolved arsenic concentrations were not detected except at the Ridgway site, where the arsenic concentration was at the minimum reporting level of 1 µg/L. Concentrations of dissolved copper ranged from less than 1 µg/L at all nonmining sites to 338 µg/L at the Red Mountain site. Samples

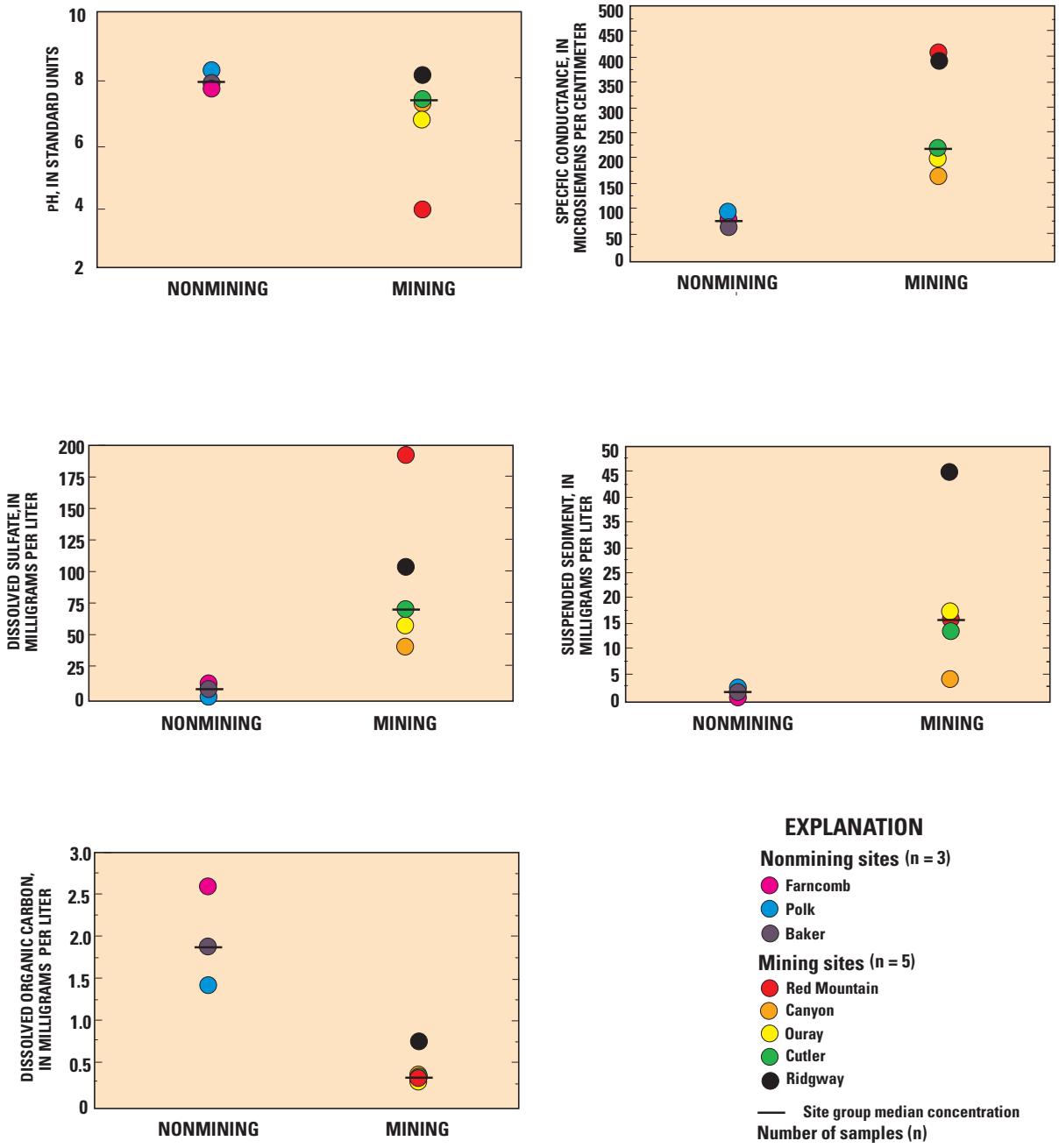

Figure 3. Selected physical and chemical water-column data for samples from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98. Data given in Appendix D.

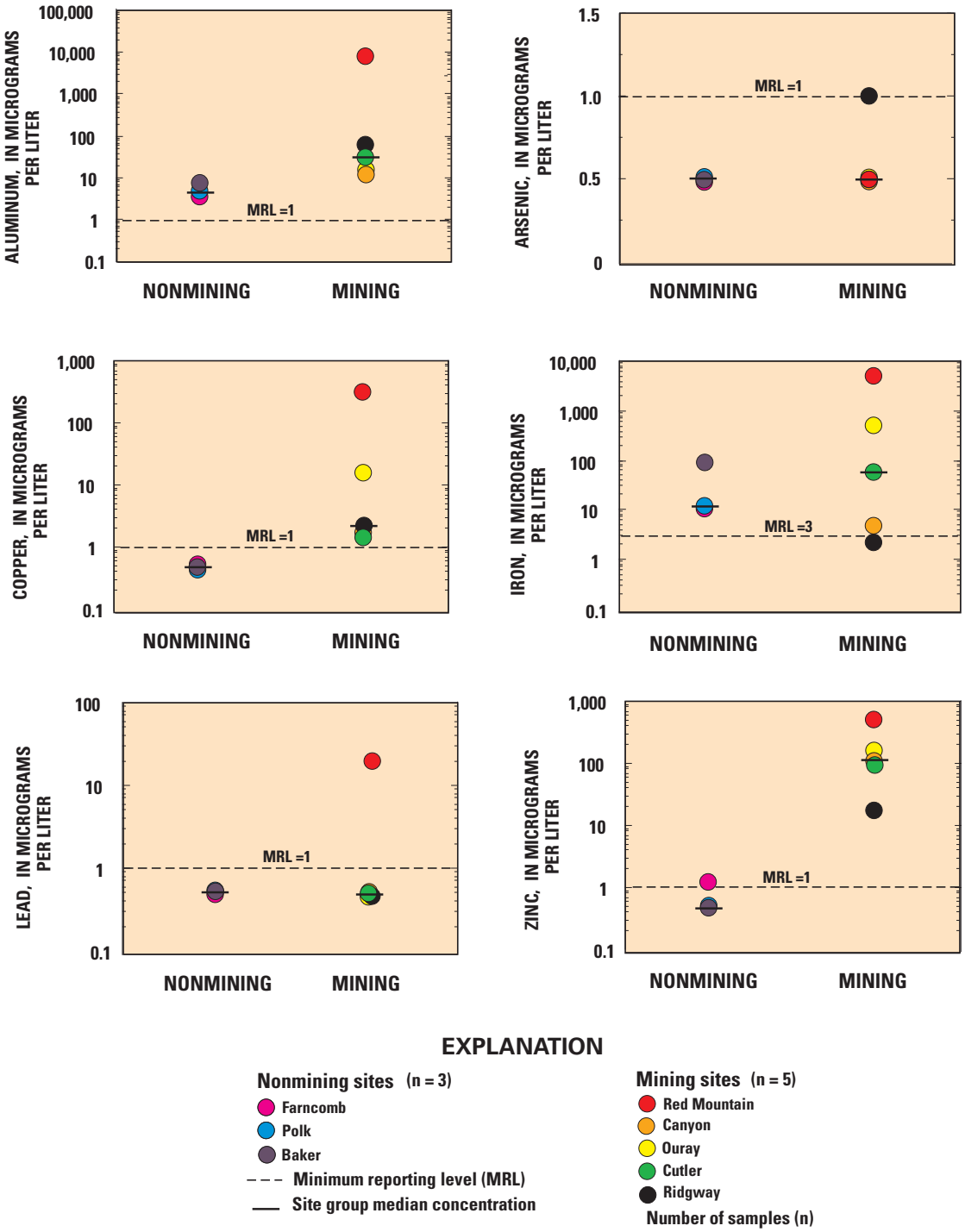

Figure 4. Concentrations of dissolved aluminum, arsenic, copper, iron, lead, and zinc in water-column samples from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98. Data given in Appendix D.

Table 3. Comparison of acute and chronic aquatic-life standards established by the Colorado Department of Public Health and Environment (1999) and selected trace-element dissolved and total concentrations in water-column samples from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98

[All values in micrograms per liter; shaded values exceed one or more Colorado aquatic-life standards, --, no data available; <, less than]

Site abbreviation (see table 1 for full site names)	Aluminum, acute standard (dissolved)	Aluminum, chronic standard (dissolved)	Aluminum from this study (dissolved)	Arsenic, acute standard[1] (dissolved)	Arsenic, chronic standard[1] (dissolved)	Arsenic from this study (dissolved)	Copper, acute standard[1] (dissolved)	Copper, chronic standard[1] (dissolved)	Copper from this study (dissolved)
NONMINING SITES									
Farncomb	750	87	3.8	360	150	<1	6.42	4.70	<1
Polk	750	87	5.6	360	150	<1	8.36	5.98	<1
Baker	750	87	9.6	360	150	<1	5.17	3.86	<1
MINING SITES									
Red Mountain	750	87	[2,3]9,174	360	150	<1	21.1	13.8	[2,3]338
Canyon	750	87	10.9	360	150	<1	12.7	8.72	1.7
Ouray	750	87	17.0	360	150	<1	14.4	9.77	[2,3]16
Cutler	750	87	35.5	360	150	<1	16.6	11.1	1.2
Ridgway	750	87	63.9	360	150	1	29.2	18.6	2.3

Site abbreviation (see table 1 for full site names)	Iron, acute standard (total)	Iron, chronic standard (total)	Iron from this study (total)	Lead, acute standard[1] (dissolved)	Lead, chronic standard[1] (dissolved)	Lead from this study (dissolved)	Zinc, acute standard[1] (dissolved)	Zinc, chronic standard[1] (dissolved)	Zinc from this study (dissolved)
NONMINING SITES									
Farncomb	--	1,000	42	16.8	0.84	<1	46.9	42.5	1.4
Polk	--	1,000	54	26.3	1.26	<1	59.5	53.9	<1
Baker	--	1,000	404	11.6	0.61	<1	38.6	35.0	<1
MINING SITES									
Red Mountain	--	1,000	[3]9,990	129	5.04	[3]20	137	124	[2,3]559
Canyon	--	1,000	123	53.9	2.35	<1	86.5	78.3	[2,3]113
Ouray	--	1,000	[3]2,150	66.9	2.84	<1	96.9	87.7	[2,3]177
Cutler	--	1,000	[3]1,795	85.3	3.51	<1	110	100	[3]102
Ridgway	--	1,000	[3]1,435	226	8.25	<1	183	166	18

[1]Colorado acute and chronic aquatic-life standards calculated from equations based on the dissolved metal concentrations and the hardness of the water at the time of sampling (Colorado Department of Public Health and Environment, 1999).

[2]Sites from this study that exceeded the Colorado acute aquatic-life standards.

[3]Sites from this study that exceeded the Colorado chronic aquatic-life standards.

from the Red Mountain site and the Ouray site had concentrations of copper that exceeded the Colorado aquatic-life standard for acute and chronic concentrations. Dissolved iron concentrations ranged from less than 3 µg/L at the Ridgway site to 5,145 µg/L at the Red Mountain site (Appendix D), and total iron concentrations ranged from 42 µg/L at the Farncomb site to 9,990 µg/L at the Red Mountain site. Iron concentrations exceeded the Colorado aquatic-life standards for chronic concentrations at all mining sites except the Canyon site. Dissolved lead concentrations were detected only at the Red Mountain site at 20 µg/L, which exceeded the Colorado aquatic-life standard for chronic concentrations. Concentrations of dissolved zinc at nonmining sites ranged from less than 1 µg/L at the Polk and the Baker sites to 1.4 µg/L at the Farncomb site, which was just above the minimum reporting level (1 µg/L). Concentrations of dissolved zinc at mining sites ranged from 18 µg/L at the Ridgway site to 559 µg/L at the Red Mountain site. All of the mining sites except the Ridgway site had zinc concentrations exceeding Colorado aquatic-life standards for acute or chronic concentrations.

Streambed Sediment

Trace elements commonly are a natural component of streambed sediment. Concentrations of trace elements in streambed sediment are strongly affected by the particle-size distribution of the sample and tend to be associated with fine-grained sediments (Brook and Moore, 1988). To determine if concentrations of trace elements in streambed sediments are elevated, concentrations were compared to mean natural background concentrations for soils in the Western United States (Jenkins, 1981; Salomons and Förstner, 1984; Shacklette and Boerngen, 1984). Concentrations of trace elements both at nonmining and mining sites were higher than suggested mean background concentrations for soils in the Western United States except for some concentrations of arsenic, copper, and lead at nonmining sites (table 4). The Farncomb nonmining site is heavily mineralized (Apodaca and others, 1995) and therefore had high naturally occurring concentrations of some trace elements. Arsenic, copper, lead, and zinc concentrations were from about two to eight times higher at the Farncomb site than at the other two nonmining sites.

Trace-element concentrations in streambed sediments at mining sites generally were higher than the ranges of concentrations at nonmining sites (fig. 5). Concentrations of copper, lead, and zinc in streambed sediment were significantly different ($p \leq 0.05$) at nonmining sites compared to concentrations at mining sites. A list of all trace elements for streambed-sediment samples for the study area is in Appendix E.

Currently (1999), no State or Federal guidelines exist in the United States for trace elements in streambed sediment; however, the Canadian Council of Ministers of the Environment has developed interim freshwater sediment-quality guidelines for those trace elements that are considered most toxic to aquatic life (Canadian Council of Ministers of the Environment, 1999). Two guideline values have been developed: a lower value, referred to as the "interim sediment-quality guideline" (ISQG), and an upper value, referred to as the "probable effect level" (PEL). The Canadian ISQG represents the concentration below which there is little probability of adverse effects to aquatic biota. The PEL defines the concentration above which adverse effects to aquatic biota are expected to occur frequently. Both guideline values are based on the total concentration of a chemical in bulk sediment and correspond with respective responses of benthic macroinvertebrates in freshwater lake environments (Canadian Council of Ministers of the Environment, 1995). Therefore, comparison of the sediment concentrations for the less than 63-micrometer-diameter fraction analyzed in this study (table 5) may overestimate the concentrations in bulk sediment, therefore may overestimate the potential adverse affects on aquatic life (Deacon and Stephens, 1998).

Concentrations of some trace elements in streambed sediments were possibly elevated enough to adversely affect the biota at some sites (table 5). Trace-element concentrations at nonmining sites were above the ISQG for arsenic, copper, lead, and zinc at the Farncomb site, lead and zinc at the Polk site, and arsenic and zinc at the Baker site. With the exception of arsenic, lead, and zinc at the Farncomb site, nonmining-site trace-element concentrations did not exceed the Canadian Sediment Quality Guidelines PEL. Generally, all trace-element concentrations in streambed sediments at mining sites exceeded the ISQG and PEL except at the Red Mountain site, where concentrations of copper and zinc were below the PEL, and the Canyon site, where concentrations of copper were below the PEL.

Table 4. Mean concentrations and ranges of concentrations for selected trace elements in soils in the Western United States and streambed-sediment samples from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1995–96

[All values are in micrograms per gram, dry weight, unless noted as percent (%); <, less than; µm, micrometer; --, no data available]

Trace element	Western United States soils			Upper Colorado River Basin streambed sediment			
	Mean concentrations from Salomons and Förstner (1984)[1]	Mean concentrations from Shacklette and Boerngen (1984)[1]	Range of concentrations from Jenkins (1981)[1]	Mean of concentrations for nonmining sites from this study (<63-µm fraction)	Range of concentrations for nonmining sites from this study (<63-µm fraction)	Mean of concentrations for mining sites from this study (<63-µm fraction)	Range of concentrations for mining sites from this study (<63-µm fraction)
				MINING SITES		NONMINING SITES	
Aluminum (%)	--	5.8	--	7.8	7.5–8.3	8.0	7.0–8.8
Arsenic	--	5.5	1.8–6.6	23.6	4.8–59	59.2	29–160
Copper	25.8	21	20	30.7	21–46	322	92–690
Iron (%)	3.2	2.1	--	4.0	3.6–4.6	7.9	5.1–15
Lead	29.2	17	10–40	72	23–150	335	145–850
Zinc	59.8	55	--	303	130–630	812	240–1,100

[1] Background concentrations established for Western United States soils.

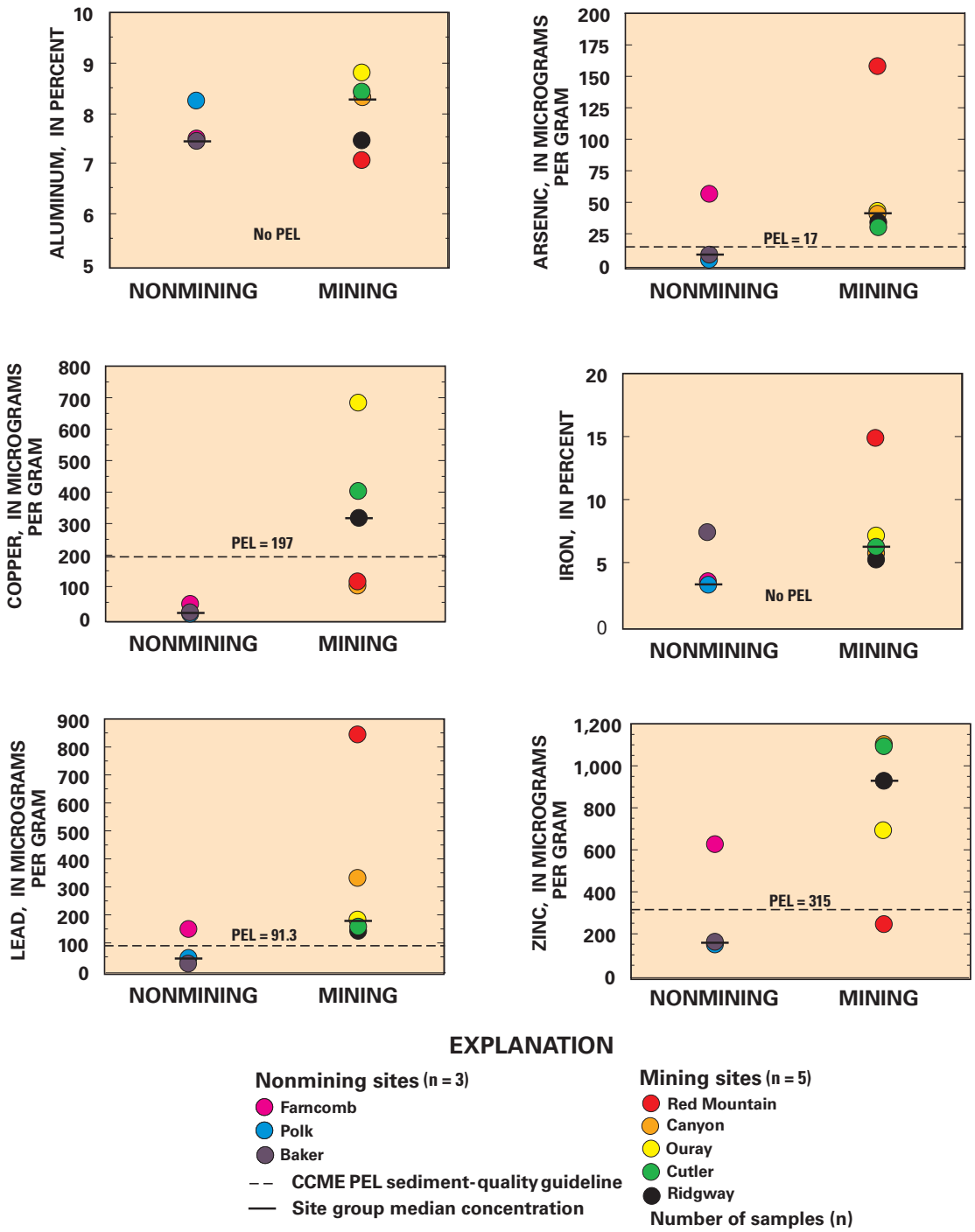

Figure 5. Concentrations of aluminum, arsenic, copper, iron, lead, and zinc in the less than 63-micrometer fraction of streambed-sediment samples from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1995–96, with comparison to Canadian Council of Ministers of the Environment (CCME) probable effect level (PEL) sediment-quality guidelines. Data given in Appendix E.

Table 5. Comparison of sediment-quality guidelines from Canadian Council of Ministers of the Environment (1999) and selected trace-element concentrations in streambed-sediment samples from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1995–96

[All values are in micrograms per gram, dry weight]

Trace element	Interim sediment-quality guideline (ISQG)[1]	Probable effect level (PEL)[2]	Sites with concentrations above PEL[3]	
			NONMINING SITES	MINING SITES
Arsenic	5.9	17	1	4, 5, 6, 7, 8
Copper	35.7	197	none	6, 7, 8
Lead	35	91.3	1	4, 5, 6, 7, 8
Zinc	123	315	1	5, 6, 7, 8

[1] The ISQG represents the concentration in bulk sediment below which there is little probability of adverse effects to aquatic biota (Canadian Council of Ministers of the Environment, 1995).

[2] The PEL defines the concentration in bulk sediment above which adverse effects to aquatic biota are predicted to occur frequently (Canadian Council of Ministers of the Environment, 1995).

[3] Sites from this study analysis of the less than 63-micrometer fraction. Site numbers correspond to figure 1 and table 1.

Transplanted Bryophytes

Transplanted aquatic bryophytes may provide information about the concentration and bioavailability of trace elements (Nelson and Campbell, 1995; Carter and Porter, 1997). When combined with other chemical and biological data, concentrations of trace elements in transplanted bryophytes may provide a useful measure of bioconcentration of trace elements. Other studies have indicated that results of bryophyte tissue analyses correspond to water-chemistry conditions (Wehr and Whitton, 1983; Jones, 1985; Jones and others, 1985; Mersch and Johansson, 1993). Studies by Carter and Porter (1997) indicated that bryophytes (*H. ochraceum*) are efficient at identifying sites contaminated by arsenic, cadmium, copper, lead, manganese, molybdenum, and zinc. Transplanted bryophytes can be used to compare the total concentration of metals in bryophyte samples to concentrations in the corresponding water column and streambed sediment (Carter and Porter, 1997).

Concentrations of trace elements in samples of transplanted bryophytes from all sites in the study area are a function of adsorption and absorption processes. A variable percentage of total metal attributed to a given bryophyte sample is attached to the external surface of the plant, and the remainder is bound in the plant cells; the proportions can vary with each metal (S.D. Porter, U.S. Geological Survey, oral commun., 2000). In this study, the concentration of trace elements in the bryophyte tissue was not differentiated between adsorption and absorption processes; therefore, reported concentrations are total concentrations of trace element on the external surface as well as within the bryophyte tissue.

Trace elements occur naturally in stream systems and may be readily bioavailable for plant uptake. To determine if concentrations of trace elements in transplanted bryophytes were elevated, concentrations were compared to initial concentrations of the source bryophyte material from the Nate Creek ditch site (table 6). Generally, concentrations of trace elements at nonmining sites were about the same or slightly higher than the initial concentrations in the transplanted bryophytes. Slightly increased trace-element concentrations in the transplanted bryophytes at the nonmining sites may be due to naturally mineralized geologic conditions upstream from these sites.

Bryophyte trace-element concentrations at the Farncomb site were the highest among nonmining sites for concentrations of aluminum, arsenic, iron, lead, and zinc. Concentrations of aluminum, arsenic, copper, iron, lead, and zinc in transplanted bryophytes at mining sites were higher than source bryophyte material (table 6) concentrations except at the Red Mountain site, where zinc concentrations were lower than the initial concentrations. Two possible factors could account for the lower zinc concentrations in the transplanted bryophytes at the Red Mountain site: (1) the low pH at this site may have stressed the bryophytes enough that the uptake process was disrupted, and zinc uptake did not readily occur; and (2) the high concentrations of iron hydroxide precipitate present at this site may have physically blanketed the bryophyte

Table 6. Comparison of selected trace-element concentrations in bryophyte (*Hygrohypnum ochraceum*) source material to trace-element concentrations in transplanted bryophytes from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98

[All concentrations are in micrograms per gram, dry weight]

Trace element	Initial concentrations of bryophyte source material[1]	Range of concentrations for sites from this study[2]	
		NONMINING SITES	MINING SITES
Aluminum	3,702	2,645–6,690	3,960–9,390
Arsenic	1.08	1.0–4.0	6.1–15
Copper	41.8	34.3–36.4	286–1,970
Iron	8,594	6,395–14,533	14,200–99,150
Lead	3.4	2.5–14.7	34.2–299
Zinc	67.2	82.5–137	45.3–2,010

[1] Represents the mean trace-element concentrations in bryophyte source material for samples from the Nate Creek ditch site, 1997 and 1998.
[2] Represents the trace-element concentrations in transplanted bryophytes for samples from nonmining and mining sites, 1997 and 1998.

tissue and altered the uptake processes that occurred on the bryophyte surfaces. Transplanted bryophytes collected at this site were heavily stained with iron hydroxides even after a thorough cleaning procedure to prepare bryophytes for analysis.

Trace-element concentrations in transplanted bryophytes at mining sites were generally higher than the ranges of concentrations at nonmining sites (fig. 6). Concentrations of arsenic, copper, iron, and lead in transplanted bryophytes were significantly different ($p \leq 0.05$) among nonmining and mining sites. A list of all trace elements for transplanted bryophyte samples for the study area are listed in Appendix F.

The relative rank (maximum trace-element concentration from all sites divided by the bryophyte source material trace-element concentration) of trace-element bioconcentration by bryophytes was determined for aluminum, arsenic, copper, iron, lead, and zinc. The relative ranking of trace-element bioconcentration by transplanted bryophytes was lead > copper > zinc > arsenic > iron > aluminum, which indicated that the transplanted bryophytes tended to favor the accumulation of lead, copper, and zinc more than arsenic, iron, and aluminum.

Bioconcentration factors (BCF's are computed as the concentration of trace element in bryophyte tissue divided by dissolved trace-element concentration in the water column) for 15-day exposure period (BCF_{15}) were calculated using the concentrations of aluminum, arsenic, copper, iron, lead, and zinc in transplanted bryophytes and instantaneous dissolved water-column concentrations (table 7). When concentrations of trace elements in the water were lower than the reporting level, BCF_{15}'s were calculated using one-half of the method reporting level. BCF_{15}'s were significantly different ($p \leq 0.05$) for arsenic, lead, and zinc at nonmining sites compared to mining sites. Differences in BCF_{15} between nonmining and mining sites are probably related to differences in geochemical sources of those constituents and resulting concentrations in the water-column samples (Carter and Porter, 1997).

Relation among Selected Trace-Element Concentrations in the Water Column, Streambed Sediment, and Transplanted Bryophytes

The relation among concentrations of trace elements in different sampling media (water column, streambed sediment, and transplanted bryophytes) at all sampling sites was examined using the Spearman rank correlation (table 8). Generally, as concentrations of aluminum, copper, iron, lead, and zinc increased in streambed sediments, these elements also increased in transplanted bryophytes. In most cases, concentrations of copper were lower in streambed sediment than in transplanted bryophytes, whereas concentrations of lead were higher in streambed sediment than in transplanted bryophytes for all sites. In general, concentra-

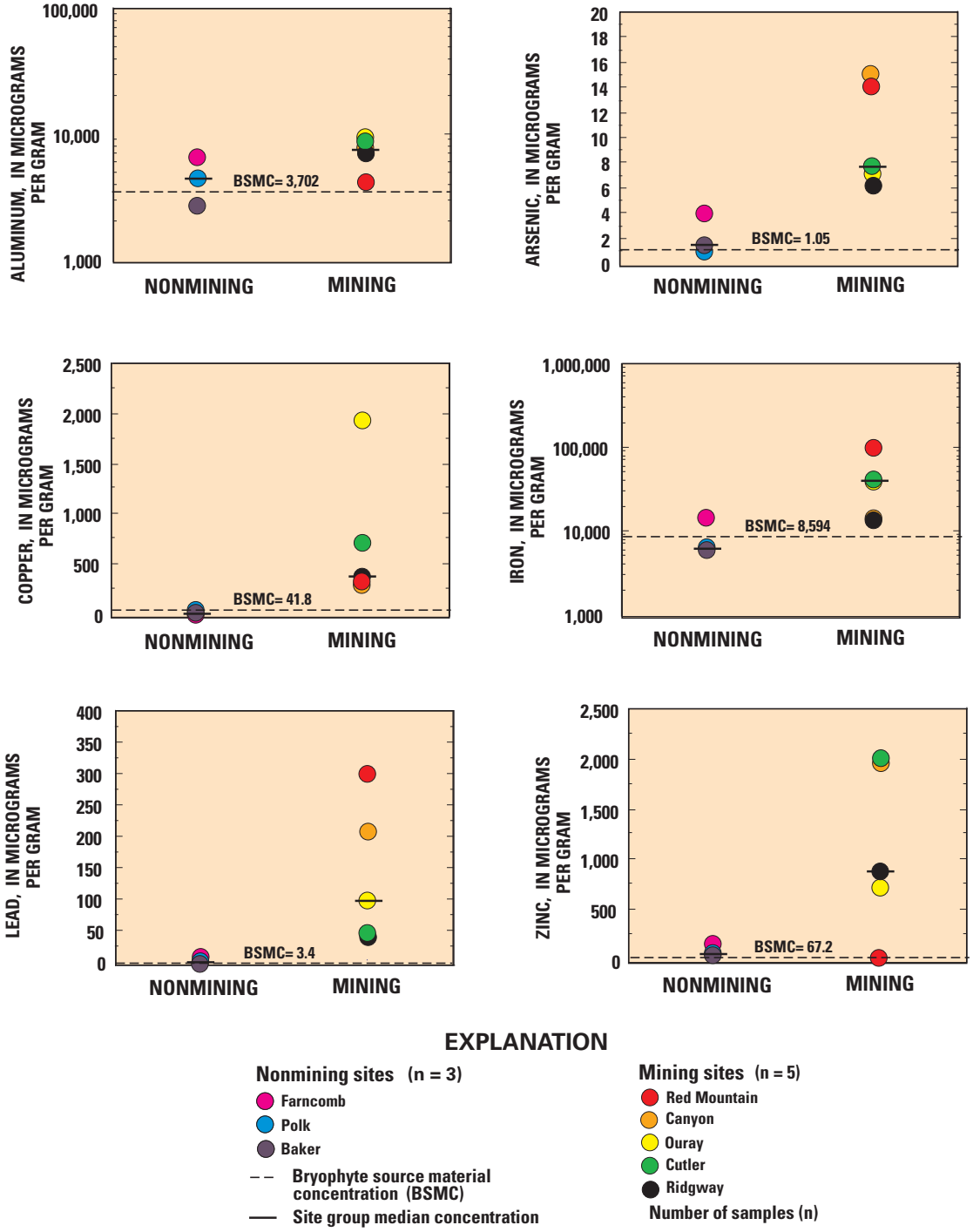

Figure 6. Concentrations of aluminum, arsenic, copper, iron, lead, and zinc in transplanted bryophyte samples from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98, with comparison to initial concentrations of bryophyte source material from Nate Creek ditch, Colorado 1997–98. Data given in Appendix F.

Table 7. Bioconcentration factors (BCF_{15}) for transplanted bryophytes (*Hygrohypnum ochraceum*) after 15-day exposure period to ambient conditions at nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98

[Concentrations are mean values of three bryophyte replicate samples; --, unable to determine because concentrations of trace elements in the water were below reporting level]

Site abbreviations	Trace element (BCF_{15})[1]					
	Aluminum	Arsenic	Copper	Iron	Lead	Zinc
NONMINING SITES						
Farncomb	1,760	--	--	1,710	--	97.9
Polk	804	--	--	512	--	--
Baker	276	--	--	59.2	--	--
MINING SITES						
Red Mountain	0.43	--	0.95	19.3	14.9	0.08
Canyon	620	--	168	3,740	--	16.3
Ouray	552	--	123	79.9	--	4.15
Cutler	247	--	611	708	--	19.7
Ridgway	103	6.1	144	--	--	49.3

[1] BCF_{15} = concentration of trace element in bryophyte tissue for 15-day exposure period divided by dissolved concentration of trace element in the water column.

Table 8. Spearman rank correlations of selected trace-element concentrations in the water-column, streambed-sediment, and transplanted bryophyte samples at nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1995–98

[All values represent rho values corrected for ties from Spearman rank correlation statistical test, p-value less than or equal to 0.05]

Trace elements	Aluminum	Arsenic	Copper	Iron	Lead	Zinc
Aluminum	0.75[b+c]		0.85[a]			
Arsenic				0.81[c]		
Copper			0.90[b+c]	0.78[b]		
Iron				0.85[b+c]		
Lead		0.76[b]		0.81[b], 0.88[c]	0.97[b+c]	
Zinc			0.90[a]			0.89[b+c]

[a] Concentration positively correlated in water-column samples.
[b] Concentration positively correlated in streambed-sediment samples.
[c] Concentration positively correlated in transplanted bryophyte samples.
[b+c] Concentrations positively correlated between streambed-sediment and transplanted bryophyte samples.

tions of aluminum and iron in streambed sediment and transplanted bryophytes decreased in a downstream direction in the upper Uncompahgre River (between the Ouray and the Ridgway sites). Samples from the Red Mountain site had (1) the highest concentrations of dissolved aluminum, copper, iron, lead, and zinc in the water column, (2) the highest concentrations of arsenic, iron, and lead in streambed-sediment samples, and (3) the highest concentrations of iron and lead in transplanted bryophyte samples than any other site. In general, concentrations of trace elements in streambed sediment and transplanted bryophytes tended to be more closely correlated with each other than either of them were with concentrations in the water column. Also, concentrations of aluminum, copper, iron, lead, and zinc in bryophytes may be useful for the estimation of concentrations of these constituents in streambed sediment.

Distributions of zinc concentrations in the water column, streambed sediment, and transplanted bryophytes were generally representative of the variations of other trace-element concentrations among the different sampling media (fig. 7). Although concentrations of dissolved zinc in the water column were below the reporting level at nonmining sites, zinc was present in the streambed sediment and the transplanted bryophytes. Zinc probably occurs in streambed sediment at the Farncomb site because highly mineralized geology provides a source of trace elements at that site. At the mining sites, zinc was present in the water column as well as in streambed sediment and transplanted bryophytes. The Red Mountain site had the highest concentrations of zinc in the water column, probably due to the low pH (3.5) of the water. Zinc and other trace elements tend to occur in the dissolved phase when the stream pH is low, as seen at the Red Mountain site. Generally, in this study, concentrations of zinc and other trace elements were higher in the streambed sediment and transplanted bryophytes than in the water column. Typically, as concentrations of zinc increased in the streambed sediment, they also increased in the transplanted bryophytes.

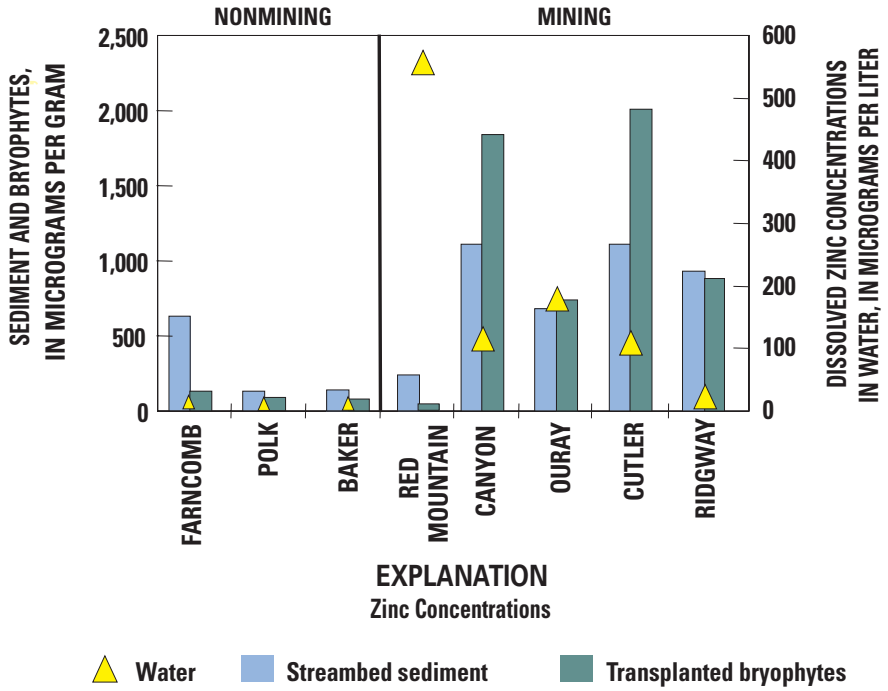

Figure 7. Distributions of zinc concentrations in water-column, streambed-sediment, and transplanted bryophyte samples from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1995–98.

STREAM HABITAT CHARACTERISTICS

Biological communities may be affected by habitat quality as well as by water and streambed-sediment quality. Stream habitat assessment is an important means of determining physical factors affecting biological communities. Stream habitat was considered on two major scales: the small-scale reach-level habitat and the large-scale basin-level habitat. Reach-level habitat includes physical features of the stream and the surrounding riparian zone such as channel substrate, vegetation, and stream geomorphology along about a 492-foot reach of stream. Basin-level habitat or environmental setting (climate, elevation, and gradient) describes general physical features of the entire basin.

The U.S. Environmental Protection Agency Rapid Bioassessment Protocols (RBP) (Barbour and others, 1997) were used to separate water-quality effects from habitat effects on biological communities. RBP's include a descriptive, visual-based habitat assessment for riffle/run-dominated streams. Habitat conditions were determined using RBP's that were modified for use in this study and include the evaluation of instream habitat, channel morphology, and riparian and bank structure at a site (table 9). Habitat characterization for each of the eight sites was documented at the time of benthic macroinvertebrate sampling at the sites.

Stream habitat was rated as optimal to suboptimal using the RBP habitat characterization for all sites in the study area (table 10). All study sites except the Ouray and Cutler sites were rated as having optimal habitat for biological communities. The Ouray and Cutler sites were rated as suboptimal because of disturbances in the stream habitat. At the Ouray site, the river has been artificially channelized with riprap and cement, and large amounts of water are forced to move through small urban drainage-control structures. A series of diversions, bridges, and construction in the riparian zone of the Cutler site has contributed to increased erosion and riparian vegetation loss at this site. Increased sediment deposition and the resulting highly embedded substrate may affect the availability of macroinverebrate habitat at the Ridgway site. Generally, stream habitat conditions were similar between nonmining and mining sites and were suitable for macroinvertebrate communities.

BENTHIC MACROINVERTEBRATE COMMUNITY STRUCTURE

The composition of benthic macroinvertebrate communities has been used to monitor effects of trace elements on streams since the early 1900's (Carpenter, 1924). Because macroinvertebrates are continuously exposed to water and sediment in streams, these organisms integrate contaminants over time and provide a measure of water and sediment quality. Typical indicators of metal-polluted streams include decreased macroinvertebrate abundance, decreased species richness, and a shift in community composition from sensitive taxa, such as some species of Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) (EPT), to tolerant taxa, such as some species of Chironomidae (midges) (Clements, 1995).

Generally, the composition of the benthic macroinvertebrate community differed among nonmining sites and mining sites (fig. 8). Mining sites tended to contain a larger percentage of the more tolerant taxa than the nonmining sites. Except for the Baker site, nonmining sites tend to have a larger percentage of the more sensitive EPT taxa than the mining sites. The taxa at the Baker site consisted of approximately 50 percent Diptera (true flies) species, but 48.5 percent of the Diptera at this site consisted of one family of Simuliidae (black flies). Clements (1994) noted that the distribution of Simuliidae (black flies) was probably more affected by factors such as seasonal fluctuations in temperature and food availability than water-quality factors.

Decreased total abundance and species richness and changes in macroinvertebrate predominant groups commonly occur in aquatic systems affected by trace elements (Rosenberg and Resh, 1993). Total abundance, taxa richness, and EPT taxa richness (table 11) were significantly different ($p \leq 0.05$) between nonmining and mining sites. Total abundance of macroinvertebrates was approximately two to eight times higher at nonmining sites than at mining sites (table 11 and Appendix G). Total taxa and EPT taxa richness (fig. 8 and table 11) also indicated differences in macroinvertebrate composition between nonmining and mining sites. Taxa and EPT taxa richness was expected to decrease with increased perturbation at a site (Barbour and others, 1997). Taxa richness almost doubled between site types, ranging from 30 to 45 species at nonmining sites and 17 to 26 species at mining sites. The number of EPT taxa ranged from 18 to 31 species at nonmining sites and 1 to 13 species at mining sites.

Table 9. Classification ranking of U.S. Environmental Protection Agency's Rapid Bioassessment Protocols (Barbour and others, 1997) habitat parameters for nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98

[%, percent; m, meters; >, greater than; <, less than]

RBP* habitat category[1]	Habitat parameters					
	Instream cover[2] (% submerged habitat)	Epifaunal substrate[3] (riffle quality)	Embeddedness[4] (% substrate surrounded by fine sediment)	Channel alteration[5] (% channelized stream reach)	Sediment deposition[6] (% recent deposition)	Frequency of riffles[7] (abundance of riffles in reach)
Optimal (16–20)	>50	wide and long	0–25	minimal	<5	frequent
Suboptimal (11–15)	30–50	wide and short	25–50	<40	5–30	infrequent
Marginal (6–10)	10–30	narrow and long	50–75	40–80	30–50	occasional
Poor (0–5)	<10	narrow and short	>75	>80	>50	flat water

RBP* habitat category[1]	Habitat parameters					
	Channel flow status[8] (% substrate exposed)	Bank vegetation protection[9] (% vegetative cover)	Bank stability[10] (erosion of streambanks)	Riparian vegetative zone width[11] (m)	RBP* site score range[12]	RBP* site habitat rating[13]
Optimal (16–20)	minimal	>90	stable	>18	200–155	OPTIMAL
Suboptimal (11–15)	<25	70–90	moderately stable	12–18	154–102	SUBOPTIMAL
Marginal (6–10)	25–75	50–70	moderately unstable	6–12	101–49	MARGINAL
Poor (0–5)	>75	<50	unstable	<6	48–0	POOR

* RBP = Rapid Bioassessment Protocols include a visual-based habitat assessment for riffle/run-dominated streams, modified for use in this study (Barbour and others, 1997).

[1] RBP habitat rank was based on a score ranging from 0 to 20 for each habitat parameter with the exception of bank vegetation protection, bank stability, and riparian vegetative zone width, which were based on scores from 0 to 10 for the right streambank and scores from 0 to 10 for the left streambank. Numbers in parentheses represent the range of scores within each category.

[2] Instream cover was based on the percentage of mix of submerged logs, undercut banks, or other stable habitat at the site.

[3] Epifaunal substrate was based on the quality of riffles (riffle width compared to stream width and riffle length compared to stream width) at the site.

[4] Embeddedness was based on the percentage of substrate surrounded by fine sediment at the site.

[5] Channel alteration was based on the percentage of disrupted stream bottom and streambanks due to dredging, channelization, or other disruptive stream activities at the site.

[6] Sediment deposition was based on the percentage of stream bottom affected by sediment deposition (enlargement of islands or point bars) at the site.

[7] Frequency of riffles was based on the relative frequency of riffles and the distance between riffles compared to the stream width at a site.

[8] Channel flow status was based on the percentage of substrate exposed at the site.

[9] Bank vegetation protection was based on the percentage of vegetative cover on the streambank at the site.

[10] Bank stability was based on the evidence of streambank erosion or bank failure and potential for future problems at the site.

[11] Riparian vegetative zone width was the width of the riparian zone not affected by human activities at the site.

[12] RBP site score ranges are the ranges that represent the sum of each habitat parameter score for a site; these ranges correspond to the RBP site habitat rating for the site.

[13] RBP site habitat rating is the overall stream habitat rating for the site, based on the total score for the site; the score corresponds to the RBP site score range.

Table 10. Habitat assessment results using U.S. Environmental Protection Agency's Rapid Bioassessment Protocols (Barbour and others, 1997) for nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98

[%, percent; m, meters; >, greater than; < less than]

Site abbreviations	Habitat parameters[1]					
	Instream cover (% submerged habitat)	Epifaunal substrate (riffle quality)	Embeddedness (% substrate surrounded by fine sediment)	Channel alteration (% channelized stream reach)	Sediment deposition (% recent deposition)	Frequency of riffles (abundance of riffles in reach)
NONMINING SITES						
Farncomb	>50	wide and long	0–25	minimal	<5	frequent
Polk	>50	wide and long	0–25	minimal	<5	frequent
Baker	>50	wide and long	0–25	minimal	<5	frequent
MINING SITES						
Red Mountain	>50	wide and short	0–25	minimal	5–30	infrequent
Canyon	>50	wide and long	0–25	<40	<5	frequent
Ouray	10–30	wide and long	25–50	>80	<5	frequent
Cutler	30–50	wide and long	25–50	<40	<5	frequent
Ridgway	>50	wide and long	25–50	minimal	5–30	frequent

Site abbreviations	Habitat parameters[1]					
	Channel flow status (% substrate exposed)	Bank vegetation protection (% vegetation cover)	Bank stability (erosion of streambanks)	Riparian vegetative zone width (m)	RBP* site score	RBP* site habitat rating
NONMINING SITES						
Farncomb	minimal	>90	stable	>18	199	OPTIMAL
Polk	minimal	>90	stable	>18	180	OPTIMAL
Baker	minimal	>90	moderately stable	>18	179	OPTIMAL
MINING SITES						
Red Mountain	minimal	>90	stable	12–18	164	OPTIMAL
Canyon	minimal	>90	stable	12–18	180	OPTIMAL
Ouray	minimal	50–70	moderately stable	6–12	128	SUBOPTIMAL
Cutler	minimal	50–70	moderately stable	6–12	146	SUBOPTIMAL
Ridgway	minimal	>90	moderately stable	12–18	157	OPTIMAL

* RBP = Rapid Bioassessment Protocols include a visual-based habitat assessment for riffle/run-dominated streams, modified for use in this study (Barbour and others, 1997).

[1] Habitat parameter descriptions are included in table 9.

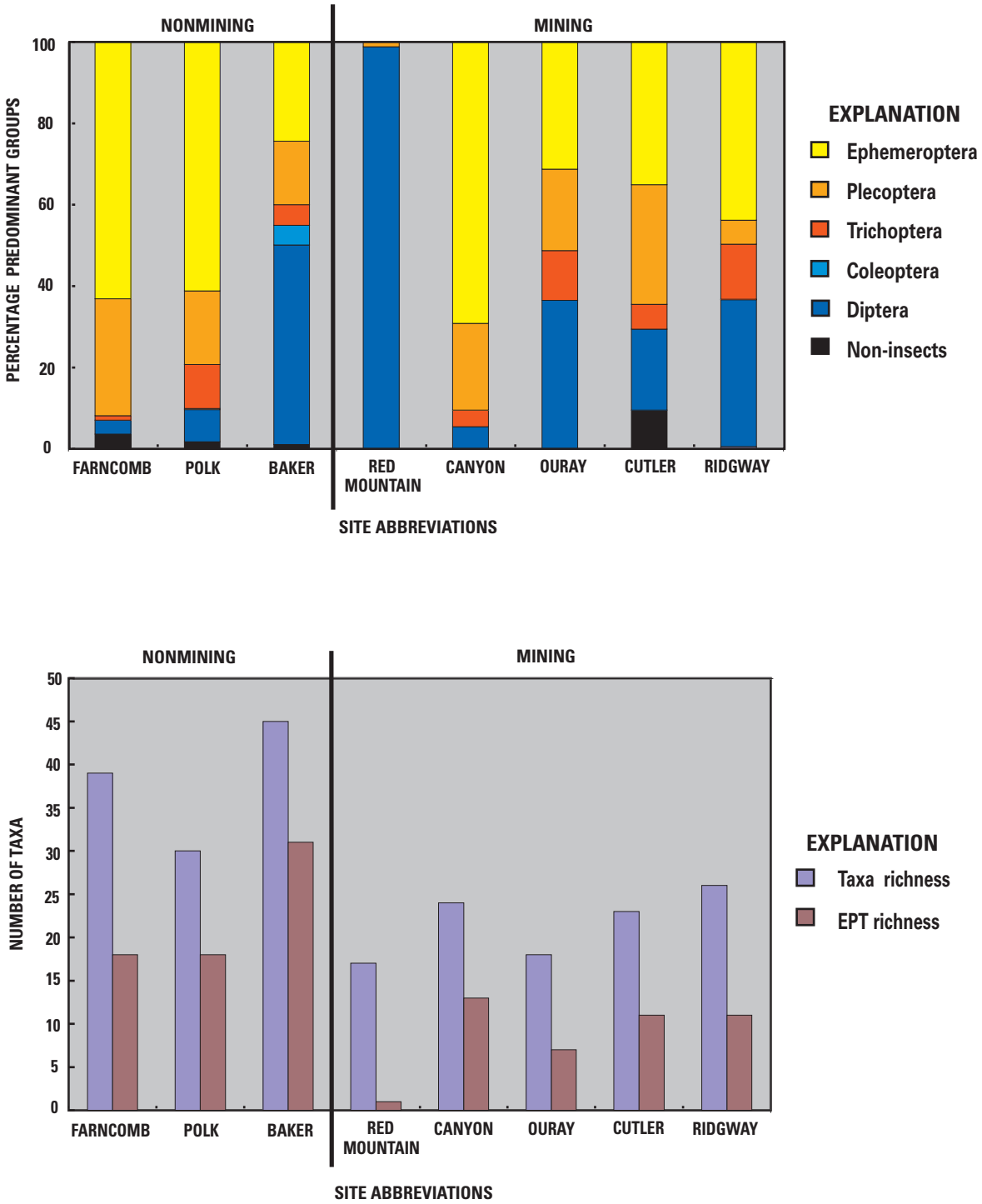

Figure 8. Composition of predominant groups, taxa, and Ephemeroptera, Plecoptera, and Trichoptera (EPT) richness of macroinvertebrates from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98.

Table 11. Selected biotic metrics from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98

Site abbreviations	Biotic metric			
	Total abundance[1]	Taxa richness	EPT[2] richness	Shannon-Weaver diversity index[3]
		NONMINING SITES		
Farncomb	3,120	39	18	3.3
Polk	1,840	30	18	3.8
Baker	6,590	45	31	3.6
		MINING SITES		
Red Mountain	68	17	1	2.7
Canyon	828	24	13	2.2
Ouray	92	18	7	3.3
Cutler	185	23	11	3.2
Ridgway	457	26	11	2.8

[1] Total abundance is based on number of organisms per square meter.
[2] EPT: Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies).
[3] Shannon-Weaver diversity index is log base 2 (Ward and Kondratieff, 1992).

The Ephemeroptera family Baetidae (mayfly), primarily *Baetis* species, dominated most sites except the Baker site, which was dominated by the Diptera family Simuliidae (black flies), and the Red Mountain site, which was dominated by the Diptera family Chironomidae (midges), primarily *Paraphaenocladius* species. Mining sites were dominated by single species (30 percent or more), whereas nonmining sites were less dominated (less than 30 percent) by a single species except at the Baker site, where species in the family Simuliidae (black flies) composed 48.5 percent of the macroinvertebrate community. The Shannon-Weaver diversity index (Ward and Kondratieff, 1992) log base 2 incorporates richness and evenness in a measure of general diversity and was significantly different ($p \leq 0.05$) between nonmining and mining sites (table 11). The Shannon-Weaver diversity ranged from 3.3 to 3.8 at nonmining sites and from 2.2 to 3.3 at mining sites. Higher Shannon-Weaver diversity scores, as found at the nonmining sites, indicate that these sites have a more highly diverse assemblage of macroinvertebrates. In general, a large diversity in the macroinvertebrate community indicates water quality that has not been degraded (Barbour and others, 1997).

Functional feeding groups are another measure of the composition of the benthic macroinvertebrate community that provides information on the balance of feeding strategies in the community. An imbalance in functional feeding groups reflects stressed conditions. Specialist feeders, such as scrapers and shredders, usually represent the more sensitive taxa and may be abundant in healthy streams. Generalist feeders, such as collectors and filterers, have a broader range of acceptable food materials than do the specialist feeders and, therefore, are more tolerant to changes in trophic interaction, production, and food-source availability (Barbour and others, 1997).

With the exception of the Baker site, specialists dominated the nonmining sites, and generalists dominated all the mining sites in the study area. Specialists ranged from 13.6 to 54.7 percent of the sample at nonmining sites and from 3.6 to 13 percent of the sample for mining sites, whereas generalists ranged from 33.4 to 68.7 percent of the sample at nonmining sites and from 51.1 to 92.9 percent of the sample at mining sites. The ratio of specialist to generalist was significantly different ($p \leq 0.05$) between nonmining and mining sites and was used to indicate the differences between the site groups (fig. 9). Generalists are more tolerant and thus become numerically dominant in response to environmental stress (Rosenberg and Resh, 1993); therefore, the specialist-to-generalist ratio generally decreases with increasing perturbation at a site. All nonmining sites except the Baker site had ratios from four to six times higher than for mining sites. Because almost one-half of the macroinverte-

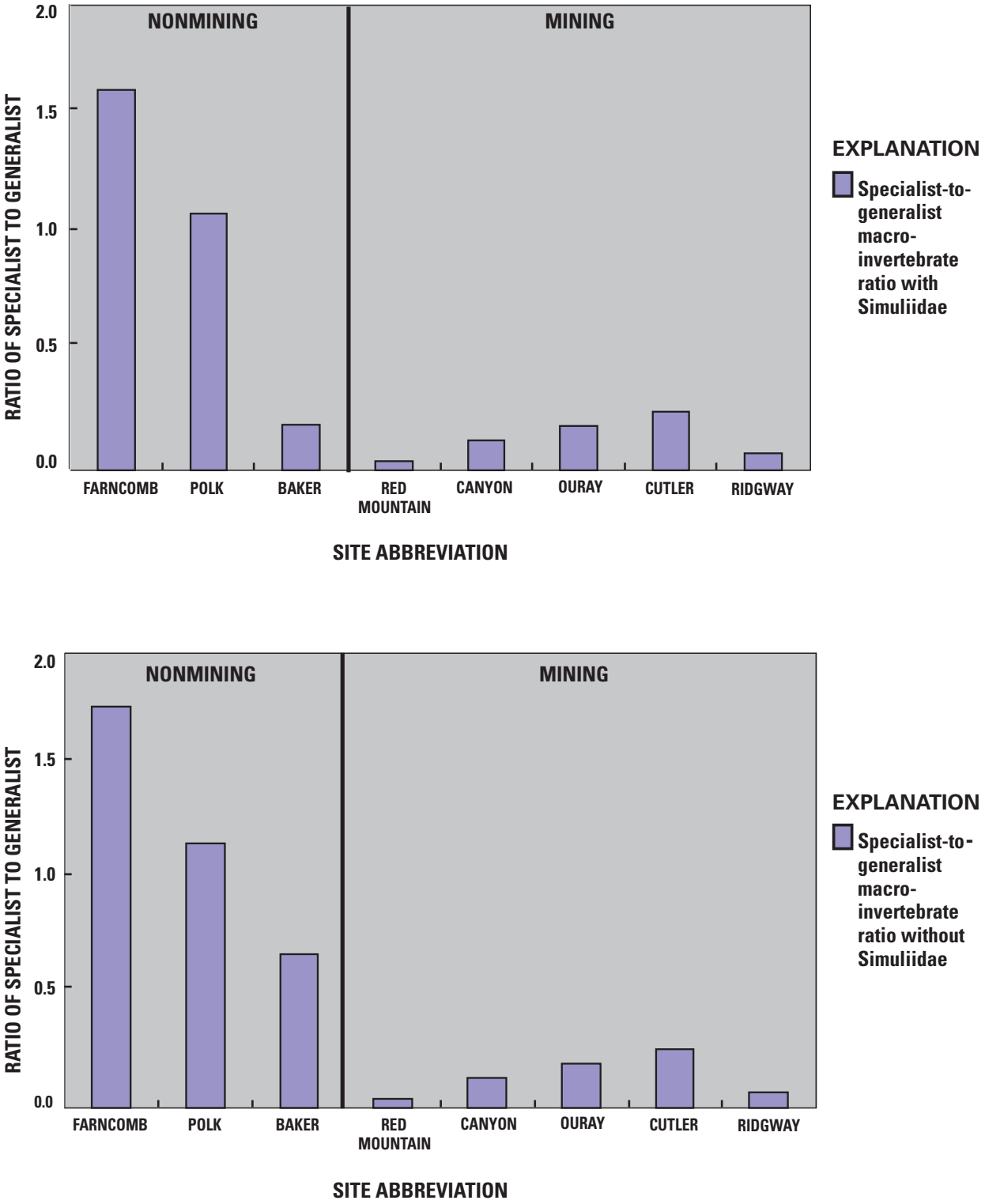

Figure 9. Ratio of specialist to generalist macroinvertebrate species with and without Simuliidae from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98.

brate community at the Baker site consisted of Simuliidae (black flies), primarily *Prosimulium onychodactylum*, which is classified as a generalist, the Baker site had a low specialist-to-generalist ratio. However, when Simuliidae (black flies) was removed from all the sites and the specialist-to-generalist ratio was recalculated, the Baker site had a ratio 2.5 times higher than for mining sites (fig. 9). Simuliids are commonly abundant at lower alpine-upper montane settings (Ward, 1986) such as the Baker site.

Community responses to trace elements measured in this study were similar to responses reported for other streams in Colorado (Ward, 1986; Clements, 1994, 1995; Clements and Kiffney, 1995). These studies indicated that careful examination of certain species of EPT and Chironomidae may be useful in distinguishing between sites affected by trace elements in the Rocky Mountain region. The abundance of mayflies, stoneflies, and caddisflies and the percentage of Diptera subfamily Orthocladiinae (orthoclad midges) to the family Chironomidae (midges) were compared to determine differences between nonmining and mining sites. A complete list of benthic macroinvertebrate data for this study is given in Appendix G. In this study, benthic macroinvertebrate density was based on a 1-m^2 area and was obtained by dividing the number of organisms collected by the surface area of the sampler.

Ephemeroptera (mayflies)

Mayfly abundance and richness have been used as indicators of elevated trace-element concentrations in stream water. Low mayfly abundance and richness as reported by Winner and others (1980), Clements (1994), and Clements and Kiffney (1995) may be related to increases in trace-element concentrations. Winner and others (1980) stated that mayflies were present only at the least polluted sites and that mayflies and caddisflies were very sensitive to copper and zinc pollution. Mayfly abundance was at least 2 times higher at the nonmining sites compared to the mining sites in this study (fig. 10). Mayfly abundance ranged from 1,128 to 1,973 individuals at the nonmining sites and from 0 to 573 individuals at the mining sites. Mayfly richness ranged from 7 species at the Farncomb site to 14 species at the Baker site (nonmining sites) and from 0 species at the Red Mountain site to 4 species at the Canyon site (mining sites).

One genus of mayfly, *Baetis*, is considered by some stream ecologists to be more tolerant than other mayfly taxa, such as the family Heptageniidae (Clements and Kiffney, 1995). The abundance of *Baetis* sp. was plotted against the total mayfly abundance at each site (fig. 10). The number of *Baetis* sp. ranged from 506 to 710 individuals (33.2 to 44.8 percent of the total mayfly community by site) at nonmining sites and from 144 to 530 individuals (72 to 94.4 percent of the total mayfly community by site) at mining sites that had mayflies. The predominance of *Baetis* sp. in the mayfly community at mining sites and a decrease in the total mayfly community at mining sites indicates that *Baetis* sp. may be more tolerant of elevated trace-element concentrations than other mayflies.

Clements and Kiffney (1995) determined that the total abundance and species richness of mayflies and the abundance of Heptageniidae (mayflies) were the most reliable indicators of the effects of trace elements in southern Rocky Mountain streams. The abundance of the mayfly family Heptageniidae was compared to the total mayfly abundance at each site (fig. 10). The number of Heptageniidae ranged from 330 to 1,263 individuals (20.5 to 64 percent of the total mayfly community by site) at nonmining sites and from 0 to 25.6 individuals (0 to 4.5 percent of the total mayfly community by site) at mining sites. The predominance of Heptageniidae within the mayfly community at nonmining sites and the decrease in the overall mayfly community at mining sites indicated that the Heptageniid mayflies may be more sensitive to elevated trace-element concentrations than other mayflies.

Plecoptera (stoneflies)

Stonefly populations, like mayfly abundance and richness, have been used to indicate elevated trace-element concentrations in stream water. Ward (1986) and Clements and Kiffney (1995) stated that temperature and changes in elevation may more strongly affect stonefly populations than mayflies or caddisflies. Ward (1986) stated that certain abundant stoneflies may be missing entirely during summer sampling because these species mature and emerge well before maximum stream temperatures are attained. Therefore, stonefly populations should be

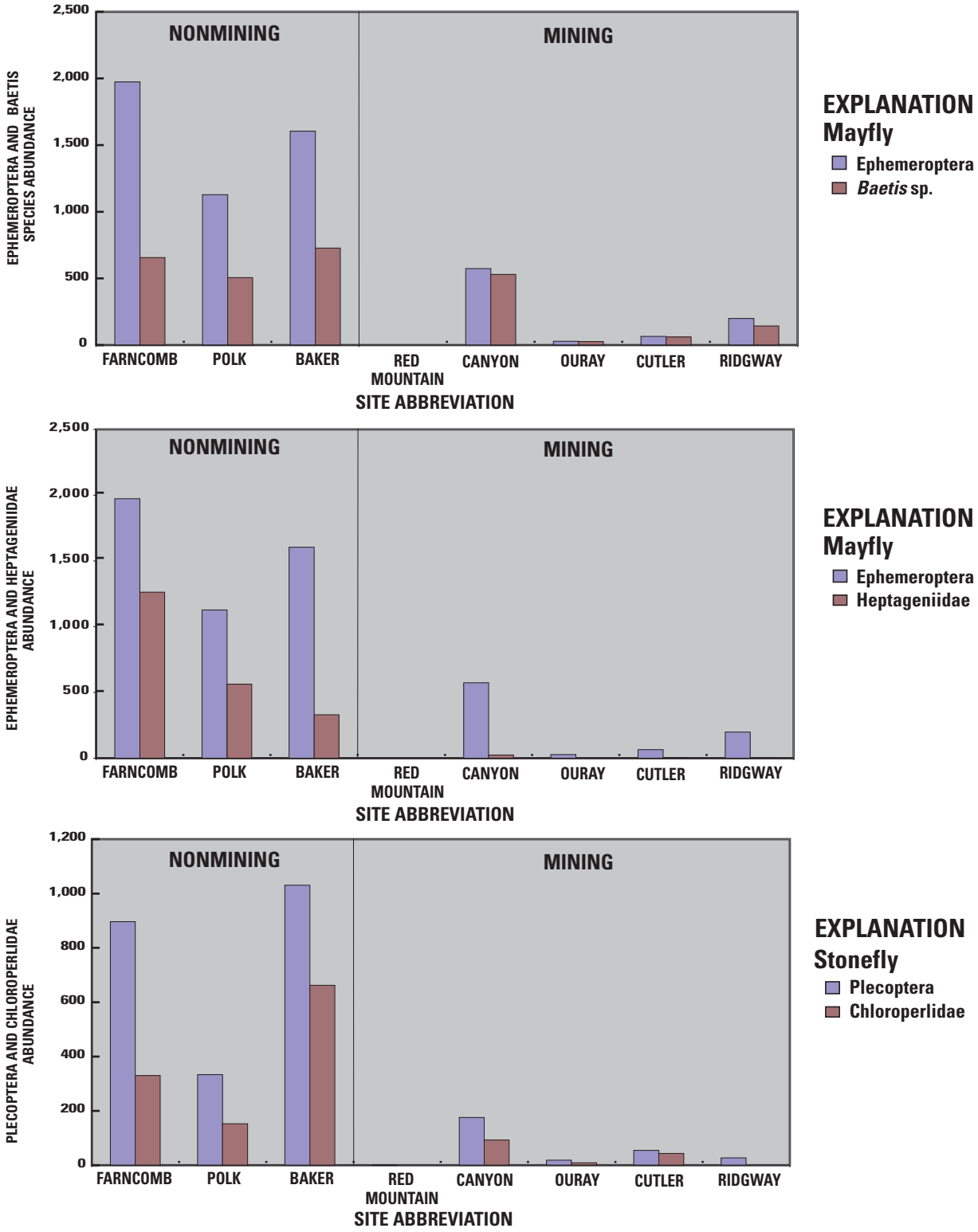

Figure 10. Abundance of selected mayfly and stonefly taxa from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98.

used with caution when large temperature or elevation, or both temperature and elevation, differences occur between sites. Clements (1995) reported that stoneflies are moderately tolerant of low levels of trace elements and are commonly one of the earlier groups to recover after influxes of trace elements.

Stonefly abundance was almost two to five times higher at the nonmining sites than at the mining sites (fig. 10). Stonefly abundance ranged from 334 to 1,030 individuals at the nonmining sites and from 0.8 to 176 individuals at the mining sites. Stonefly richness ranged from 6 species at the Polk site to 11 species at the Baker site (nonmining sites) and from 1 species at the Red Mountain site to 6 species at the Canyon site (mining sites).

Abundance patterns of the Chloroperlidae family of stoneflies indicated that this group was sensitive to moderate zinc concentrations and may be a useful indicator of elevated trace-element concentrations in southern Rocky Mountain streams (Clements and Kiffney, 1995). The abundance of Chloroperlidae was plotted against the total stonefly abundance at each site (fig. 10). Chloroperlidae abundance at nonmining sites was greater than at mining sites. The number of Chloroperlidae ranged from 125 to 539 individuals (29.1 to 52.3 percent of the total stonefly community by site) at nonmining sites and from 0 to 92.8 individuals (0 to 79.4 percent of the total stonefly community by site) at mining sites. The predominance of Chloroperlidae in the stonefly community at nonmining sites compared to mining sites indicates that these macroinvertebrates may be more sensitive to elevated trace-element concentrations than other stoneflies.

Trichoptera (caddisflies)

Caddisfly abundance and richness have been used as indicators of elevated trace-element concentrations in stream water. Generally, low caddisfly abundance and richness, as reported by Winner and others (1980), Clements (1994), and Clements and Kiffney (1995), may be related to increases in trace-element concentrations. Winner and others (1980) concluded that caddisflies were numerically important at the moderately impaired sites and that caddisflies and mayflies were very sensitive to copper and zinc.

Except for the Farncomb site, caddisfly abundance was from three to five times higher at the nonmining sites compared to the mining sites (fig. 11). Caddisfly abundance ranged from 33.6 to 334 individuals at the nonmining sites and from 0 to 61.6 individuals at the mining sites. Caddisfly richness ranged from 4 species at the Farncomb and Polk sites to 6 species at the Baker site (nonmining sites) and from 0 species at the Red Mountain site to 5 species at the Ridgway site (mining sites). The caddisfly abundance patterns indicated that this taxon may have recovered at the Ridgway site, where abundance is almost twice that of any other mining site, and that the richness is comparable to that at nonmining sites.

Rhyacophila sp. (caddisfly) abundance data for this study were comparable to the study by Clements and Kiffney (1995), where the highest *Rhyacophila* sp. abundances were at nonmining sites and the lowest were at mining sites. The abundance of *Rhyacophila* sp. was compared to the total caddisfly abundance at each site (fig. 11). The number of *Rhyacophila* sp. ranged from 26.4 to 195 individuals (17.5 to 97.6 percent of the total caddisfly community by site) at nonmining sites and from 0 to 8.8 individuals (0 to 35.7 percent of the total caddisfly community by site) at mining sites. *Rhyacophila* sp. was totally absent at three of five mining sites and was numerically limited at the Canyon and Ouray sites. The predominance of *Rhyacophila* sp. in the caddisfly community at nonmining sites and a decrease in the community at mining sites indicated that these cadddisflies may be more sensitive to elevated trace-element concentrations than other caddisflies.

In contrast, one family of net-spinning caddisflies, Hydropsychidae, was abundant at mining sites. Hydropsychidae abundance patterns for this study were similar to patterns in Clements and Kiffney's (1995) study, where Hydropsychidae relative abundance increased at mining sites and was lowest at nonmining sites. The abundance of Hydropsychidae was plotted against the total caddisfly abundance at each site (fig. 11). Numbers of Hydropsychidae ranged from 0 to 55.2 individuals (0 to 16.5 percent of the total caddisfly community by site) at nonmining sites and from 0 to 25.6 individuals (0 to 74.4 percent of the total caddisfly community by site) at mining sites. The predominance of Hydropsychidae in the caddisfly community at mining sites relative to nonmining sites indicates that Hydropsychid caddisflies may be more tolerant of elevated trace-element concentrations than other caddisflies.

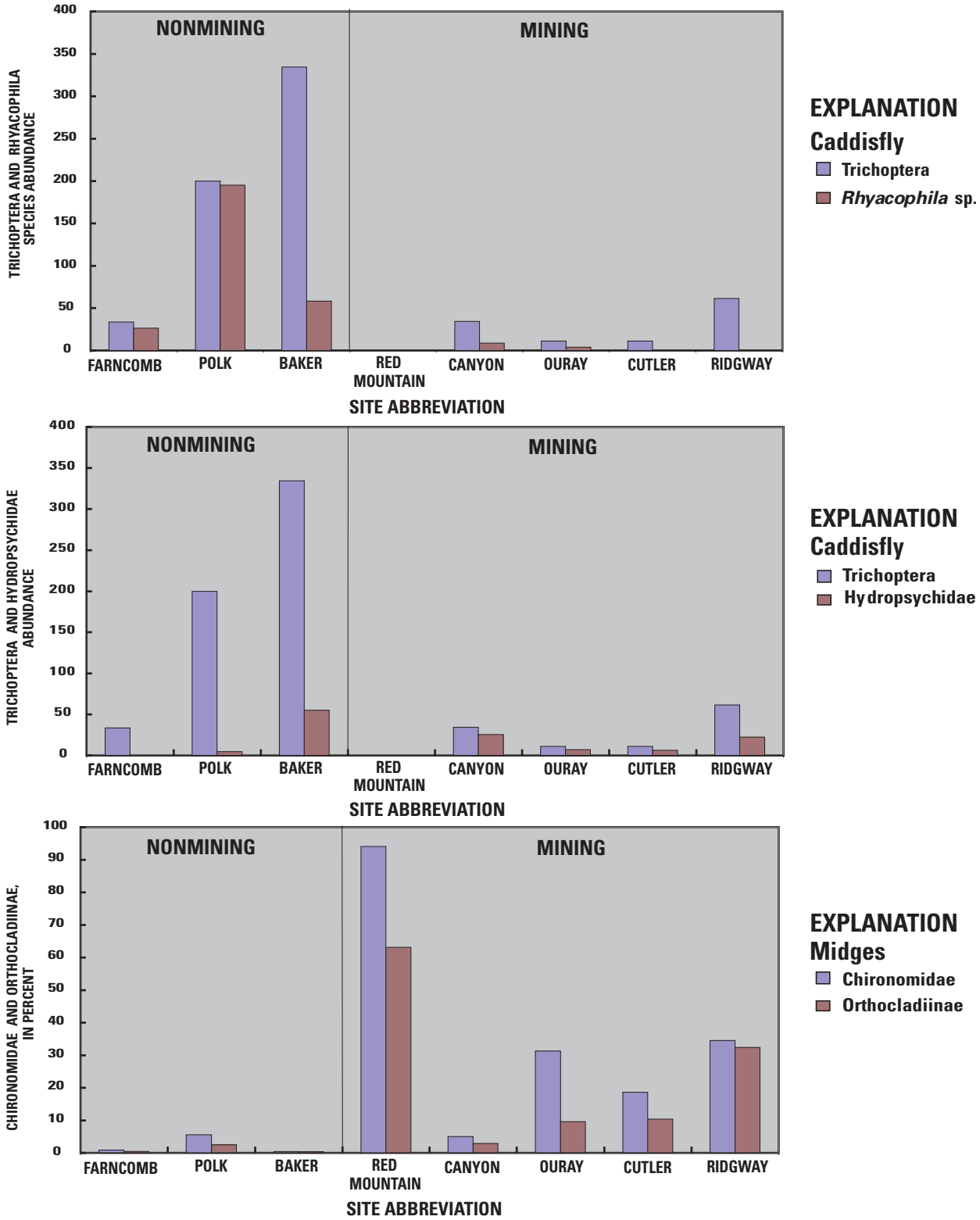

Figure 11. Abundance and percentage of selected caddisfly and midge taxa from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98.

Chironomidae (midges)

The abundance and richness of Chironomidae (midges) have also been used as indicators of elevated trace-element concentrations in stream water. Generally, increased chironomid abundance and richness, as reported by Winner and others (1980), Clements (1994), and Clements and Kiffney (1995), may be related to increased trace-element concentrations. Winner and others (1980) concluded that a large number of chironomid species may tolerate long-term exposure to increased concentrations of multiple trace elements that would otherwise eliminate most other insect species.

Chironomid species, with some exceptions, tend to be widely distributed along the elevation gradient rather than being confined to zones (Ward, 1986). Because chironomids were present at all sites in different proportions, a percentage of chironomids was used instead of abundance to compare sites in the study area. Percentage of chironomid species ranged from 0.41 to 5.6 percent of the total macroinvertebrate community at the nonmining sites and from 5.0 to 92.9 percent of the total macroinvertebrate community at the mining sites (fig. 11). Chironomid richness ranged from 5 (Baker site) to 13 species (Farncomb site) at the nonmining sites and from 7 (Ouray and Cutler sites) to 12 species (Red Mountain site) at the mining sites.

Previous work indicated that the Diptera subfamily Orthocladiinae chironomids (orthoclad midges) are highly tolerant of trace elements and are common in streams containing high concentrations of trace elements (Clements, 1995). Orthocladiinae chironomids in this study include: *Brillia*, *Cardiocladius*, *Cricotopus/Orthocladius*, *Eukiefferiella*, *Metriocnemus fuscipes group*, *Paraphaenocladius*, *Parorthocladius*, *Rheocricotopus*, *Thienemanniella*, and *Tvetenia* species (Appendix G). The percentage of orthoclads was compared to the total percentage of chironomids at each site (fig. 11). Orthoclads constituted 0.39 to 2.5 percent of the total macroinvertebrate community by site at nonmining sites and 2.9 to 61 percent of the total macroinvertebrate community by site at mining sites. Orthoclads were highly abundant, especially at the Red Mountain site, where orthoclads constituted more than 61 percent of the entire macroinvertebrate community. The predominance of orthoclads in the macroinvertebrate community at mining sites and a limited number in the community at nonmining sites indicated that othoclad midges may be more tolerant to elevated trace-element concentrations than other chironomids.

Natural and Human-Related Factors

A first step in understanding how benthic macroinvertebrate communities are related to water and sediment quality is to identify the primary factors affecting macroinvertebrate communities in a drainage basin. Five major classes of environmental factors that affect the structure and function of the stream benthic community are (1) chemical water quality, (2) hydrodynamics, (3) instream and riparian habitat, (4) energy source, and (5) biological interactions (Hambrook and others, 1997). Important chemical water-quality factors include pH, temperature, alkalinity, turbidity, hardness, chemical solubility of trace elements, nutrients, organic compounds, and dissolved oxygen. Hydrodynamic factors include precipitation, stream velocity and discharge, high-low water extremes, and other watershed characteristics. Habitat characteristics that affect communities include instream habitat, channel morphology, and riparian and bank structure. Also, energy sources such as organic matter, sunlight, nutrient availability, primary and secondary production, and seasonal patterns as well as biological interactions such as feeding, competition, predation, parasitism, reproduction, and disease can affect the community structure (Hambrook and others, 1997).

The spatial and temporal patterns of stream temperature are extremely important in structuring aquatic insect communities. The thermal regime affects distribution patterns, life-cycle phenomena, trophic relations, and behavioral responses of aquatic insects (Ward and Stanford, 1982). Thermal effects may account for some variation in the macroinvertebrates between nonmining and mining sites. Ward (1986) and Clements and Kiffney (1995) found that temperature and elevation have a greater effect on stonefly populations than on mayflies or caddisflies. In this study, organic inputs (dissolved organic carbon) tended to be much higher at nonmining sites than at mining sites, which may affect the macroinvertebrate feeding strategies and composition at mining sites.

Oxidized conditions and the availability of large sources of dissolved trace elements (often due to low pH, as at the Red Mountain and Ouray sites) may cause aluminum, iron, manganese, and, to a lesser

extent, arsenic and copper to precipitate from the water (Hem, 1992). Low pH may alter the benthic macroinvertebrate community by (1) increasing stress to aquatic insects and other organisms, (2) blanketing the substrate with iron hydroxide and other metal precipitates, and (3) increasing trace-element solubility and toxicity, which are normally highest under acidic conditions (Ward and Kondratieff, 1992). Precipitates blanket the substrate at the Red Mountain (iron hydroxides) and Ouray (aluminum and iron hydroxides) sites. Precipitation of iron and manganese also may clog the filtering apparatus of filter feeders (Couillard and others, 1989). Taxa and EPT richness, as well as total abundance of macroinvertebrates, is the lowest at the Red Mountain and Ouray sites. The Ouray site seems to be affected by a combination of trace-element-enriched water inflows, predominantly from the Red Mountain site and, to a lesser extent, the Canyon site.

Human-related factors as well as environmental factors can influence macroinvertebrate communities at a site. Human-related factors such as land-use and water-use practices that affect water quality and quantity and stream habitat features may ultimately limit the production of macroinvertebrate communities and should be considered when comparing macroinvertebrate communities between nonmining and mining sites. Consistent biological sampling procedures should eliminate most variability associated with certain factors, including stream velocities, high-low water extremes, and seasonal effects. Other factors that seem to be important in this study include pH, chemical solubility of trace elements, stream temperature, stream elevation, organic inputs, basin geology, and stream habitat at a site. Stream habitat conditions were suitable for macroinvertebrates at all sites. Although high concentrations of some trace elements may occur naturally, trace-element concentrations at mining sites were much higher. High trace-element concentrations appear to affect the macroinvertebrate communities more than the other factors at these sites.

COMPARISON OF WATER QUALITY TO BIOLOGICAL CONDITIONS

A comparison of physical and chemical water-quality characteristics to biological conditions was conducted using a Water Quality Score (WQS) and a Biological Condition Score (BCS) (Plafkin and others, 1989). A scattergram diagram comparison of the WQS to the BCS at the sampled sites is shown in figure 12. In general, as the WQS's increased, the BCS's also

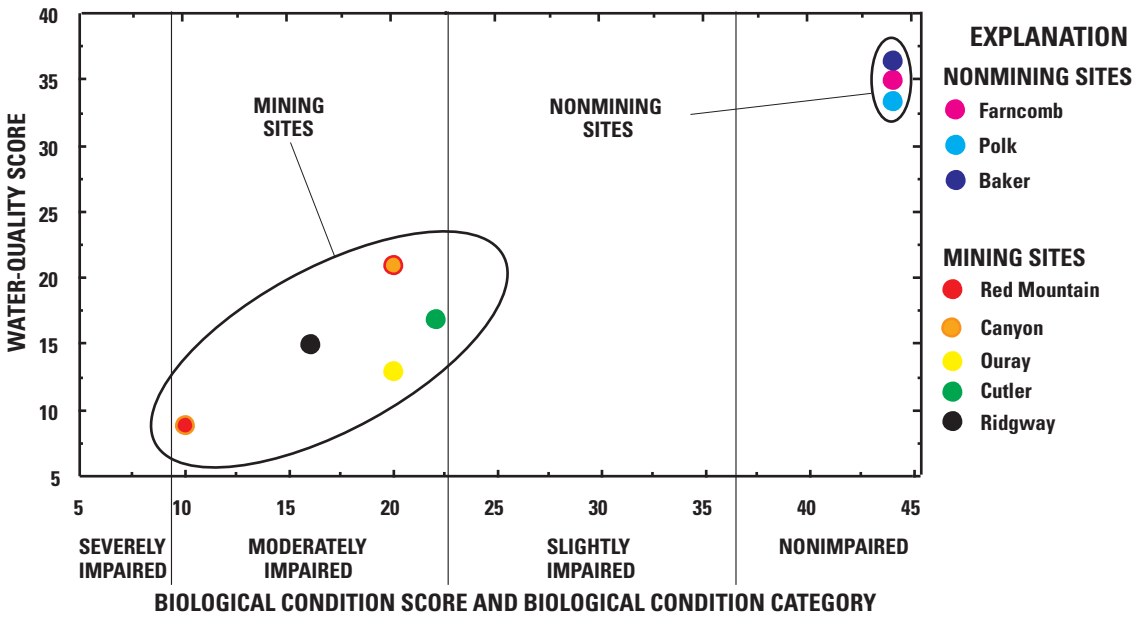

Figure 12. Relation between water-quality scores (developed in this study) and biological condition scores and biological condition categories (Plafkin and others, 1989) for nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98.

increased. Nonmining sites had higher WQS's and BCS's than mining sites. These scores were used to help identify relations between water-quality parameters (specific conductance, suspended sediment, dissolved organic carbon, dissolved sulfate, and dissolved zinc) that generally reflected trace-element chemistry in natural water and biotic metrics that describe the health of a macroinvertebrate community at a sampling site.

The comparison of nonmining and mining sites in figure 12 shows the differences between water quality and biological conditions of sites in the study. Water-quality scores ranged from 33.5 to 36.5 with a mean of 35 for nonmining sites and from 9 to 21 with a mean of 15 for mining sites. The mean BCS was 44 for the nonmining sites and 18 for the mining sites. The BCS categorized the nonmining sites as nonimpaired, and the mining sites were categorized as moderately impaired. Based on a critical review of habitat assessment and physiochemical data at these sites, the Red Mountain and Cutler sites are better represented in the severely impaired and slightly impaired categories, respectively. Although the Canyon site was categorized by the BCS as moderately impaired, this site had optimal habitat characterization and generally had better individual biotic metric results than the other mining sites. The Canyon site had a high percentage of one predominant taxon, which placed this site into a lower BCS category.

SUMMARY AND CONCLUSIONS

Intensive mining activity and highly mineralized rock formations have had significant impacts on surface-water and streambed-sediment quality and aquatic life within the upper reaches of the Uncompahgre River in western Colorado. A synoptic study by the U.S. Geological Survey National Water-Quality Assessment Program was completed in the upper Uncompahgre River Basin in 1998 to better understand the relations of trace elements (with emphasis on aluminum, arsenic, copper, iron, lead, and zinc concentrations) in water, streambed sediment, and aquatic life. Water-chemistry, streambed-sediment, and benthic macroinvertebrate samples were collected during low-flow conditions between October 1995 and July 1998 at five sites on the upper Uncompahgre River, all downstream from historical mining, and at three sites in drainage basins in the Upper Colorado River Basin where mining has not occurred. Aquatic bryophytes were transplanted to all sites for 15 days of exposure to the water column during which time field parameters were measured and chemical water-quality and benthic macroinvertebrate samples were collected. Stream habitat characteristics also were documented at each site.

Seventeen trace elements were analyzed in the water-column samples, 24 trace elements in streambed-sediment samples, and 19 trace elements in transplanted bryophytes. Many trace-element concentrations in the water column were near or less than the minimum reporting level or indicated little variation across the study area. Six trace elements—aluminum, arsenic, copper, iron, lead, and zinc—were selected for discussion in this study because they (1) were frequently detected in most water, streambed sediment, and transplanted bryophyte samples, (2) showed some variability in concentrations, and (3) have aquatic-life standards or water-quality guidelines associated with them.

Concentrations of aluminum, copper, iron, lead, and zinc in the water column were significantly different ($p \leq 0.05$) between nonmining and mining sites for all total concentrations and most dissolved concentrations. Concentrations of trace elements at mining sites exceeded Colorado acute aquatic-life standards for aluminum, copper, and zinc and chronic aquatic-life standards for aluminum, copper, iron, lead, and zinc.

Concentrations of copper, lead, and zinc in streambed sediment were significantly different ($p \leq 0.05$) between nonmining and mining sites. Streambed-sediment concentrations of arsenic, copper, lead, and zinc at some nonmining sites were above the interim freshwater sediment-quality guidelines (ISQG) developed in the Canadian Sediment Quality Guidelines. Concentrations at most mining sites and one nonmining site exceeded the Canadian sediment-quality guidelines probable effect level (PEL) for arsenic, lead, and zinc. Concentrations of copper and zinc were below the PEL at two mining sites.

Concentrations of trace elements in samples of transplanted bryophytes from all sites in the study area are a function of adsorption and absorption processes. Transplanted bryophyte concentrations of arsenic, copper, iron, and lead in transplanted bryophytes were significantly different ($p \leq 0.05$) among nonmining and mining sites. The relative ranking of trace-element bioconcentration by transplanted bryophytes was lead

> copper > zinc > arsenic > iron > aluminum, which indicates that the bryophytes tended to favor the accumulation of lead, copper, and zinc more than arsenic, iron, and aluminum. When one-half of the minimum reporting level was used for concentrations of dissolved arsenic, copper, iron, lead, and zinc in the water that were below the reporting level, bioconcentration factors (15-day exposure period) for the transplanted bryophytes were significantly different ($p \leq 0.05$) for arsenic, lead, and zinc at nonmining sites compared to mining sites.

Relations between concentrations of trace elements in different sampling media (water column, streambed sediment, and transplanted bryophytes) were examined. In general, concentrations of trace elements in streambed sediment and transplanted bryophytes tended to be more closely correlated with each other than either of them were with concentrations in the water column. Also, concentrations of aluminum, copper, iron, lead, and zinc in bryophytes may be useful to the estimation of concentrations of these constituents in streambed sediment.

Stream habitat was rated as optimal to suboptimal using the RBP habitat characterization for all sites in the study area. Generally, stream habitat conditions were similar among nonmining and mining sites and were suitable for macroinvertebrate communities. All study sites except the Ouray and Cutler sites were rated as having optimal habitat for biological communities. The Ouray and Cutler sites were rated as suboptimal because of disturbances in the stream habitat.

Generally, the benthic macroinvertebrate community composition at nonmining sites and mining sites differed. Mining sites had significantly lower total abundance, decreased taxa and EPT richness, and a larger percentage of tolerant species of benthic macroinvertebrates than did nonmining sites. The predominance of *Baetis* sp. (mayflies) and Hydropsychidae (caddisflies) and the large percentage of Orthocladiinae chironomids (midges) at mining sites indicated that these macroinvertebrates may be tolerant of elevated trace-element concentrations. The scarcity of Heptageniidae (mayflies), Chloroperlidae (stoneflies), and *Rhyacophila* sp. (caddisflies) at mining sites indicates that these macroinvertebrates may be sensitive to elevated trace-element concentrations. Also, mayfly, stonefly, and caddisfly abundance as well as the large percentage of chironomids were indicators of mining effects at sites in the study area.

Although high concentrations of some trace elements may occur naturally, trace-element concentrations at mining sites tend to be much higher because of the combination of natural and human-related inputs. The combined natural and human-related trace-element effects may degrade the biological communities at these sites. Mining land-use practices may increase the potential for biological impairment in the study area as a result of increased acidity; precipitation of iron, aluminum, and other hydroxides; and increased trace-element availability and toxicity resulting from acidic conditions. Oxidized conditions and the availability of large sources of dissolved trace elements due to low pH, as at the Red Mountain and Ouray sites, may cause iron, aluminum, manganese, and to a lesser extent, arsenic and copper to precipitate from the water. Precipitates blanket the substrate at the Red Mountain (iron hydroxides) and Ouray (aluminum and iron hydroxides) sites. Taxa richness, EPT richness, and total abundance of macroinvertebrates were the lowest at the Red Mountain and Ouray sites.

Comparison of field parameters and chemical water-quality characteristics to biological conditions was conducted using a water quality score (WQS) and a biological condition score. In general, as the WQS increased, the BCS also increased. Nonmining sites had higher WQS's and BCS's than mining sites. The BCS categorized the nonmining sites as nonimpaired, and the mining sites were categorized as slightly to severely impaired. Other important factors in this study that influenced surface-water quality include stream pH, chemical solubility of trace elements, stream temperature, stream elevation, organic inputs into the stream, basin geology, and stream habitat at a site. Although high concentrations of some trace elements may occur naturally, trace-element concentrations at mining sites were much higher. High trace-element concentrations appear to affect the macroinvertebrate communities more than the other factors at these sites. Mayfly, stonefly, and caddisfly abundance and the percentage of midge species are good indicators of mining effects at sites in the study area.

In this study, the combination of multiple sampling media (water chemistry, streambed sediment, and benthic macroinvertebrates), as well as transplanted bryophyte data and stream habitat characterization, provided evidence that trace-element factors were controlling the biological communities at study sites. Water-chemistry and streambed-sediment

data defined trace-element sources in the stream system. Trace-element concentrations in transplanted bryophytes and in the water column were used to estimate bioconcentration of trace elements that may be available for uptake by macroinvertebrates and other organisms. Benthic macroinvertebrates provided a measure of stream ecosystem health, which was compared between nonmining and mining sites. The collection of water-quality and stream-habitat data in conjunction with the biological sampling helped identify stream reaches that were influenced by natural and human-related factors.

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APPENDIX

Appendix A. Surface-water-quality field measurement constituents and minimum reporting levels for samples collected from selected sites in the study area

[mg/L, milligrams per liter; NA, not applicable; µS/cm, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter]

Constituent	Reported as	Minimum reporting level
	Laboratory and field measurements	
Acid-neutralizing capacity	mg/L $CaCO_3$	NA
Alkalinity	mg/L $CaCO_3$	NA
Dissolved oxygen	mg/L	NA
pH	standard units	NA
Specific conductance	µS/cm at 25 degrees Celsius	NA
Suspended sediment	mg/L	NA
Temperature	degrees Celsius	NA
	Calculated constituents	
Bicarbonate	mg/L as HCO_3	NA
Dissolved solids	mg/L	NA
Hardness	mg/L as $CaCO_3$	NA
	Major ions (sample filtered through 0.45-micrometer filter)	
Calcium	mg/L as Ca	0.02 mg/L
Chloride	mg/L as Cl	0.1 mg/L
Fluoride	mg/L as F	0.1 mg/L
Magnesium	mg/L as Mg	0.01mg/L
Potassium	mg/L as K	0.1 mg/L
Silica	mg/L as SiO_2	0.01 mg/L
Sodium	mg/L as Na	0.2 mg/L
Sulfate	mg/L as SO_4	0.1 mg/L
	Trace elements (sample filtered through 0.45-micrometer filter)	
Aluminum	µg/L as Al	1 µg/L
Antimony	µg/L as Sb	1 µg/L
Arsenic	µg/L as As	1 µg/L
Barium	µg/L as Ba	1 µg/L
Beryllium	µg/L as Be	1 µg/L
Cadmium	µg/L as Cd	1 µg/L
Chromium	µg/L as Cr	1 µg/L
Cobalt	µg/L as Co	1 µg/L
Copper	µg/L as Cu	1 µg/L
Iron	µg/L as Fe	3 µg/L
Lead	µg/L as Pb	1 µg/L
Manganese	µg/L as Mn	1 µg/L
Molybdenum	µg/L as Mo	1 µg/L
Nickel	µg/L as Ni	1 µg/L
Silver	µg/L as Ag	1 µg/L
Uranium	µg/L as U	1 µg/L
Zinc	µg/L as Zn	1 µg/L
	Organics (sample filtered through 0.45-micrometer filter)	
Dissolved organic carbon	mg/L as C	0.1 mg/L
Suspended organic carbon	mg/L as C	0.2 mg/L

Appendix B. Streambed-sediment constituents and minimum reporting levels for samples collected from selected sites in the study area

[µg/g, micrograms per gram, dry weight; %, percent; <, less than]

Constituent	Reported as	Minimum reporting level
	Trace elements (sample <63-micrometer fraction)	
Aluminum	percent weight as Al	0.005%
Antimony	µg/g as Sb	0.1 µg/g
Arsenic	µg/g as As	0.1 µg/g
Barium	µg/g as Ba	1 µg/g
Beryllium	µg/g as Be	1 µg/g
Cadmium	µg/g as Cd	0.1 µg/g
Chromium	µg/g as Cr	1 µg/g
Cobalt	µg/g as Co	1 µg/g
Copper	µg/g as Cu	1 µg/g
Iron	percent weight as Fe	0.005%
Lead	µg/g as Pb	4 µg/g
Lithium	µg/g as Li	2 µg/g
Manganese	µg/g as Mn	4 µg/g
Mercury	µg/g as Hg	0.02 µg/g
Molybdenum	µg/g as Mo	2 µg/g
Nickel	µg/g as Ni	2 µg/g
Selenium	µg/g as Se	0.1 µg/g
Silver	µg/g as Ag	0.1 µg/g
Strontium	µg/g as Sr	2 µg/g
Thallium	µg/g as Tl	50 µg/g
Titanium	percent weight as Ti	0.005%
Uranium	µg/g as U	0.05 µg/g
Vanadium	µg/g as V	2 µg/g
Zinc	µg/g as Zn	4 µg/g
	Organics (sample <63-micrometer fraction)	
Carbon, organic	percent weight as C	0.01%

Appendix C. Transplanted bryophyte constituents and minimum reporting levels for samples collected from selected sites in the study area

[µg/g, micrograms per gram-dry weight]

Constituent	Reported as	Minimum reporting limit
	Trace elements (sample bryophyte tissue)	
Aluminum	µg/g as Al	5.0 µg/g
Arsenic	µg/g as As	0.5 µg/g
Barium	µg/g as Ba	1.0 µg/g
Beryllium	µg/g as Be	0.1 µg/g
Boron	µg/g as B	2.0 µg/g
Cadmium	µg/g as Cd	0.1 µg/g
Chromium	µg/g as Cr	0.5 µg/g
Copper	µg/g as Cu	0.5 µg/g
Iron	µg/g as Fe	5.0 µg/g
Lead	µg/g as Pb	0.5 µg/g
Magnesium	µg/g as Mg	5 .0µg/g
Manganese	µg/g as Mn	1 .0µg/g
Mercury	µg/g as Hg	0.2 µg/g
Molybdenum	µg/g as Mo	2.0 µg/g
Nickel	µg/g as Ni	0.5 µg/g
Selenium	µg/g as Se	0.5 µg/g
Strontium	µg/g as Sr	0.5 µg/g
Vanadium	µg/g as V	0.5 µg/g
Zinc	µg/g as Zn	1.0 µg/g

Appendix D. Selected water-column data for samples collected from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98

[--, no data; ft, feet; °C, degrees Celsius; ft^3/s, cubic feet per second; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter; $CaCO_3$, calcium carbonate,; <, less than; lab, laboratory]

Site	Site abbreviation	Station number	Date	Time	Width (ft)	Discharge (ft^3/s)	Acid-neutralizing capacity (mg/L as $CaCO_3$)	Alkalinity, field (mg/L as $CaCO_3$)	Dissolved oxygen (mg/L)	pH, lab	pH, field
NONMINING SITES											
French Gulch above Farncomb Hill near	Farncomb	3928381055729	07/29/97	0810	13	13.4	27	24	8.7	7.7	7.7
Polk Creek at Interstate Highway 70 near Vail, CO	Polk	3935271061435	08/04/98	0845	4.0	6.6	50	47	8.8	7.9	8.1
Colorado River below Baker Gulch near Granby,	Baker	09010500	08/10/98	1250	34	43	27	25	8.0	7.7	7.8
MINING SITES											
Red Mountain Creek above Crystal Lake near	Red Mountain	3757321073940	07/22/97	0800	24	52.4	0	0	8.3	3.6	3.8
Canyon Creek below Squaw Gulch near Ouray, CO	Canyon	3800071074136	07/22/97	1400	37	170	29	27	8.2	7.9	7.5
Uncompahgre River at Ouray, CO	Ouray	3801151074020	07/23/97	0725	--	260	12	11	8.7	7.4	6.9
Uncompahgre River above Cutler Creek near	Cutler	3804481074208	07/23/97	0945	43	294	19	18	8.5	7.6	7.6
Uncompahgre River near Ridgway, CO	Ridgway	09146200	07/23/97	1245	43	379	70	69	7.5	8.0	8.1

Site abbreviation	Specific conductance, lab (µS/cm)	Specific conductance, field (µS/cm)	Temperature (°C)	Bicarbonate (mg/L as HCO_3)	Dissolved solids (mg/L)	Hardness (mg/L as $CaCO_3$)	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Sulfate (mg/L)	Chloride (mg/L)
NONMINING SITES												
Farncomb	79	72	4.9	29	44	34	12	0.9	1.0	0.4	10.1	0.1
Polk	99	94	6.8	57	53	45	12	3.5	1.6	0.4	1.3	0.2
Baker	65	62	14	31	39	27	7.7	1.8	1.9	0.8	4.2	0.2
MINING SITES												
Red	446	415	6.4	0	264	120	42.8	3.2	1.4	0.5	194	0.1
Canyon	162	161	9.9	33	89	70	26.1	1.2	1.6	0.3	38.6	0.2
Ouray	193	194	8.5	13	111	80	28.9	1.7	2.0	0.4	64.8	0.4
Cutler	221	222	10	22	129	93	33.9	1.9	3.0	0.5	72.0	0.8
Ridgway	398	400	15	84	242	170	58.8	6.7	9.4	1.1	114	1.5

Appendix D. Selected water-column data for samples collected from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98—Continued

Site abbreviation	Fluoride (mg/L)	Silica (mg/L)	Aluminum, dissolved (µg/L)	Aluminum, total (µg/L)	Antimony, dissolved (µg/L)	Arsenic, dissolved (µg/L)	Barium, dissolved (µg/L)	Beryllium, dissolved (µg/L)	Cadmium, dissolved (µg/L)	Cadmium, total (µg/L)	Chromium, dissolved (µg/L)	Cobalt, dissolved (µg/L)	Copper, dissolved (µg/L)	Copper, total (µg/L)	Iron, dissolved (µg/L)
NONMINING SITES															
Farncomb	0.1	5.6	3.8	39	<1	<1	6.5	<1	<1	<1	<1	<1	<1	<1	8.5
Polk	0.1	5.9	5.6	44	<1	<1	107	<1	<1	<1	<1	<1	<1	<1	13
Baker	0.3	7.3	9.6	71	<1	<1	5.6	<1	<1	<1	<1	<1	<1	1	108
MINING SITES															
Red	0.1	10	9,174	8,624	<1	<1	22.5	<1	2.2	2	1.2	16	338	338	5,145
Canyon	0.2	3.9	10.9	77	<1	<1	29.3	<1	<1	<1	<1	<1	1.7	7	3.9
Ouray	0.2	5.1	17	1,660	<1	<1	29.2	<1	<1	<1	<1	2.8	16	65	532
Cutler	0.3	5.2	35.5	1,481	<1	<1	28.8	<1	<1	<1	<1	2.6	1.2	51	61
Ridgway	0.3	7.6	63.9	1,091	<1	1	32.9	<1	<1	<1	1.3	<1	2.3	25	<3

Site abbreviation	Iron, total (µg/L)	Lead, dissolved (µg/L)	Lead, total (µg/L)	Manganese, dissolved (µg/L)	Manganese, total (µg/L)	Molybdenum, dissolved (µg/L)	Nickel, dissolved (µg/L)	Silver, dissolved (µg/L)	Uranium, dissolved (µg/L)	Zinc, dissolved (µg/L)	Zinc, total (µg/L)	Suspended sediments (mg/L)	Dissolved organic carbon (mg/L)	Suspended organic carbon (mg/L)
NONMINING SITES														
Farncomb	42	<1	<1	1.9	<10	<1	<1	<1	<1	1.4	<10	0.9	2.6	<0.2
Polk	54	<1	<1	1.6	<10	<1	<1	<1	<1	<1	<10	2.4	1.4	--
Baker	404	<1	<1	12	12	<1	<1	<1	<1	<1	<10	2	1.9	<0.2
MINING SITES														
Red Mountain	9,990	20	22	696	638	<1	12	<1	<1	559	540	16	0.3	0.2
Canyon	123	<1	5.2	119	119	1.1	<1	<1	<1	113	124	3.4	0.3	<0.2
Ouray	2,150	<1	13	213	215	<1	2.2	<1	<1	177	198	18	0.2	0.3
Cutler	1,795	<1	15	194	197	<1	2.2	<1	<1	102	176	14	0.3	0.2
Ridgway	1,435	<1	10	81	137	1.5	1.1	<1	<1	18	85	45	0.8	0.5

Appendix E. Streambed-sediment data for samples collected from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1995–96

[--, no data; %, percent; µg/g, micrograms per gram-dry weight; data represent the less than 63-micrometer fraction]

Site	Site abbreviation	Station number	Date	Time	Aluminum (%)	Antimony (µg/g)	Arsenic (µg/g)	Barium (µg/g)	Beryllium (µg/g)	Cadmium (µg/g)	Chromium (µg/g)	Cobalt (µg/g)	Copper (µg/g)
NONMINING SITES													
French Gulch above Farncomb Hill near	Farncomb	392838105572900	09/04/96	0730	7.5	2.3	59	770	2.0	5.8	54	15	46
Polk Creek at Interstate Highway 70 near Vail, CO	Polk	393527106143500	09/04/96	1400	8.3	1.0	4.8	840	3.2	<1	76	12	21
Colorado River below Baker Gulch near Granby,	Baker	09010500	10/10/95	0830	7.5	0.7	7.1	620	4.0	<1	58	17	25
MINING SITES													
Red Mountain Creek above Crystal Lake near	Red	375732107394000	10/18/95	0845	7.0	16	160	690	1.1	0.6	19	8	110
Canyon Creek below Squaw Gulch near Ouray, CO	Canyon	380007107413600	10/17/95	0915	8.3	3.6	34	860	1.5	2.8	15	19	92
Uncompahgre River at Ouray, CO	Ouray	380115107402001	10/18/95	1300	8.8	3.7	41	1,000	2.0	1.2	17	20	690
Uncompahgre River above Cutler Creek near	Cutler	380448107420800	10/19/95	1010	8.4	4.4	29	1,100	1.7	2.6	15	26	400
Uncompahgre River near Ridgway, CO	Ridgway	09146200	10/19/95	1400	7.4	3.7	32	780	1.6	3.0	24	21	320

Site abbreviation	Iron (%)	Lead (µg/g)	Lithium (µg/g)	Manganese (µg/g)	Mercury (µg/g)	Molybdenum (µg/g)	Nickel (µg/g)	Selenium (µg/g)	Silver (µg/g)	Strontium (µg/g)	Thallium (µg/g)	Titanium (µg/g)	Uranium (µg/g)	Vanadium (µg/g)	Zinc (µg/g)	Organic carbon (µg/g)
NONMINING SITES																
Farncomb	3.9	150	36	1,300	0.05	6	30	2.0	1.1	260	<50	0.43	<50	160	630	3.8
Polk	3.6	43	47	670	0.05	12	29	1.0	1.3	130	<50	0.44	<50	80	130	3.4
Baker	4.6	23	40	1,100	0.04	<2	20	0.8	0.4	220	--	--	14	82	150	--
MINING SITES																
Red	15	850	16	470	0.54	10	3	1.7	22.4	260	<50	0.36	<500	125	240	1.0
Canyon	5.7	330	32	2,000	0.06	7	7	0.3	3.2	490	<50	0.53	<500	135	1,100	0.9
Ouray	7.3	190	41	1,100	0.04	6	10	0.3	2.2	380	<50	0.61	<500	145	690	0.4
Cutler	6.3	160	46	1,300	0.11	7	16	0.3	2.4	400	<50	0.57	<500	130	1,100	0.5
Ridgway	5.1	145	38	1,500	0.10	6	17	0.7	2.2	380	<50	0.44	<500	120	930	1.1

Appendix F. Transplanted bryophyte data for samples collected from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98

[Concentrations are mean values of three replicate samples; %, percent, µg/g, micrograms per gram-dry weight]

Site name	Site abbreviation	Site identification	Date	Time	Moisture (%)	Aluminum (µg/g)	Arsenic (µg/g)	Barium (µg/g)	Beryllium (µg/g)	Boron (µg/g)	Cadmium (µg/g)
NONMINING SITES											
French Gulch above Farncomb Hill near	Farncomb	392838105572900	07/29/97	0800	82.0	6,690	4.0	194	0.70	18	2.7
Polk Creek at Interstate Highway 70 near Vail, CO	Polk	393527106143500	08/12/98	1400	86.9	4,500	1.0	810	0.85	22	1.0
Colorado River below Baker Gulch near Granby, CO	Baker	09010500	08/14/98	1200	86.0	2,645	1.5	255	0.87	12	0.64
MINING SITES											
Red Mountain Creek above Crystal Lake near	Red	375732107394000	07/22/97	0900	82.7	3,960	14	56.5	0.24	0.8	0.30
Canyon Creek below Squaw Gulch near Ouray, CO	Canyon	380007107413600	07/22/97	0800	82.6	6,763	15	322	1.37	8.8	8.3
Uncompahgre River at Ouray, CO	Ouray	380115107402001	07/22/97	0730	84.9	9,390	7.1	197	1.50	4.1	4.0
Uncompahgre River above Cutler Creek near Ouray,	Cutler	380448107420800	07/22/97	0700	82.4	8,760	7.8	208	1.45	7.7	10.7
Uncompahgre River near Ridgway, CO	Ridgway	09146200	07/22/97	0630	82.1	6,567	6.1	211	0.91	16.7	5.3
Nate Creek ditch near Owl Creek Pass, CO (1997)[1]	Nate (1997)	380929107334600	07/21/97	1700	85.5	3,600	1.0	449	0.69	10.2	0.61
Nate Creek ditch near Owl Creek Pass, CO (1998)[1]	Nate (1998)	380929107334600	07/20/98	1300	87.4	3,803	1.1	442	0.55	15.7	0.51

Site abbreviation	Chromium (µg/g)	Copper (µg/g)	Iron (µg/g)	Lead (µg/g)	Magnesium (µg/g)	Manganese (µg/g)	Mercury (µg/g)	Molybdenum (µg/g)	Nickel (µg/g)	Selenium (µg/g)	Strontium (µg/g)	Vanadium (µg/g)	Zinc (µg/g)
NONMINING SITES													
Farncomb	6.7	34.3	14,533	14.7	3,613	1,663	0.06	0.47	10.3	1.37	93.7	40.8	137
Polk	4.3	36.4	6,653	4.0	3,556	6,533	0.06	1.0	5.2	3.73	71.6	20.7	88.7
Baker	3.5	35.7	6,395	2.5	2,915	5,755	0.06	0.95	6.3	2.45	75.2	18	82.5
MINING SITES													
Red Mountain	27	320	99,150	299	1,170	331	0.06	1.5	2.3	1.20	15.9	21	45.3
Canyon	11	286	14,577	202	3,223	3,783	0.09	1.3	12.3	1.21	180	34	1,843
Ouray	5.8	1,970	42,500	95.8	1,810	3,360	0.06	2.7	15.0	1.40	143	23	735
Cutler	8.1	733	43,200	47.6	1,830	2,435	0.06	0.70	41.2	1.02	172	24	2,010
Ridgway	7.1	332	14,200	34.2	3,106	3,470	0.06	1.1	26	1.47	175	39	887
Nate (1997)	4.7	45.7	9,040	4.1	3,033	4,266	0.06	0.60	7.3	1.90	69.4	37.7	72.6
Nate (1998)	4.0	37.9	8,147	2.7	3,486	5,470	0.06	0.97	3.9	2.57	72.1	26.7	61.7

[1] Bryophyte source material used for transplanting to the study sites.

Appendix G. Taxa, densities, total number of macroinvertebrates, and sampling date for samples collected from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98

[Densities and total number of macroinvetebrates are rounded to three significant figures and reported as organisms per square meter; Site abbreviations are used in this Appendix; see table 1 for full site names; --, species not collected; *, Phylum; **, Suborder]

Taxa	NONMINING SITES			MINING SITES				
	Farncomb	Polk	Baker	Red Mountain	Canyon	Ouray	Cutler	Ridgway
	07/29/97	07/30/98	07/31/98	07/22/97	07/22/97	07/22/97	07/22/97	07/22/97
CLASS								
ORDER								
Family								
Genus species								
ARTHROPODA (arthropods)*								
INSECTA (insects)								
EPHEMEROPTERA (mayflies)	--	--	--	--	--	--	--	--
Baetidae	--	--	243	--	--	--	--	--
Baetis bicaudatus	655	--	--	--	530	27.2	60.0	--
Baetis flavistriga	--	--	46.4	--	--	--	--	--
Baetis tricaudatus	--	492	154	--	--	--	--	144
Baetis sp.	--	13.6	510	--	--	--	--	--
Ephemerellidae	--	--	--	--	--	--	--	--
Drunella coloradensis	7.20	28.0	11.2	--	17.6	1.60	2.40	--
Drunella doddsi	47.2	32.8	130	--	--	--	--	--
Drunella sp.	--	--	33.6	--	--	--	--	--
Ephemerella infrequens	--	--	--	--	--	--	--	55.2
Ephemerella sp.	--	--	110	--	--	--	--	--
Serratella tibialis	--	--	18.4	--	--	--	--	--
Heptageniidae	--	--	--	--	--	--	--	--
Cinygmula sp.	372	130	96.0	--	--	--	1.60	--
Epeorus deceptivus	415	237	--	--	--	--	--	--
Epeorus longimanus	--	--	114	--	--	--	--	--
Eperous sp.	258	28.0	73.6	--	3.20	--	0.80	--
Rhithrogena robusta	218	--	--	--	22.4	--	--	--
Rhithrogena sp.	--	167	45.6	--	--	--	--	0.80
Leptophlebiidae	--	--	--	--	--	--	--	--
Paraleptophlebia sp.	--	--	17.6	--	--	--	--	--
PLECOPTERA (stoneflies)	--	--	--	--	--	--	--	--
Capniidae	6.40	--	7.20	--	--	--	--	--
Chloroperlidae	226	102	459	--	8.00	--	2.40	--
Suwallia sp.	--	9.60	18.4	--	84.8	8.80	40.8	--
Sweltsa sp.	34.4	13.6	61.6	--	--	--	--	--
Leuctridae	--	--	--	--	--	--	--	--
Paraleuctra sp.	3.20	18.4	--	--	--	--	--	--
Nemouridae	--	--	--	--	--	--	--	--
Amphinemura banksi	--	--	--	0.80	--	--	--	--
Zapada sp.	594	130	50.4	--	50.4	9.60	7.20	--
Perlidae	--	--	--	--	--	--	--	--
Claassenia sabulosa	--	--	0.80	--	--	--	--	--
Hesperoperla pacifica	--	--	4.80	--	--	--	--	--
Perlodidae	--	--	290	--	2.40	--	4.00	--
Isoperla mormona	--	--	--	--	--	--	--	0.80
Isoperla quinquepunctata	--	--	--	--	--	--	--	2.40
Megarcys signata	31.2	60.0	86.4	--	7.20	--	--	--
Skwala americana	--	--	16.0	--	--	--	--	--
Pteronarcyidae	--	--	--	--	--	--	--	--
Pteronarcella badia	--	--	36.0	--	23.2	--	--	24.0
Taeniopterygidae	0.80	--	--	--	--	--	--	--
TRICHOPTERA (caddisflies)	--	--	--	--	--	--	--	--
Brachycentridae	--	--	--	--	--	--	--	--
Brachycentrus americanus	--	--	--	--	--	--	--	36.0
Micrasema bactro	--	--	4.80	--	--	--	--	--
Glossosomatidae	--	--	--	--	--	--	--	--
Glossosoma sp.	--	--	216	--	--	--	--	--
Hydropsychidae	--	--	--	--	--	--	--	--
Arctopsyche grandis	--	4.80	55.2	--	25.6	7.20	4.80	4.00
Hydropsyche sp.	--	--	--	--	--	--	1.60	18.4
Limnephilidae	--	--	--	--	--	--	--	--
Hesperophylax sp.	--	--	--	--	--	--	--	0.80

Appendix G. Taxa, densities, total number of macroinvertebrates, and sampling date for samples collected from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98——Continued

Taxa	NONMINING SITES			MINING SITES				
	Farncomb	Polk	Baker	Red Mountain	Canyon	Ouray	Cutler	Ridgway
	07/29/97	07/30/98	07/31/98	07/22/97	07/22/97	07/22/97	07/22/97	07/22/97
CLASS								
ORDER								
Family								
Genus species								
TRICHOPTERA, continued								
Onocosmoecus unicolor	--	--	--	--	--	--	--	2.40
Rhyacophilidae	--	--	--	--	--	--	--	--
Rhyacophila alberta group	--	--	--	--	--	1.60	--	--
Rhyacophila angelita	--	--	1.60	--	--	--	--	--
Rhyacophila brunnea	--	--	40.0	--	--	--	--	--
Rhyacophila coloradensis	0.80	69.6	--	--	--	--	--	--
Rhyacophila hyalinata	16.8	51.2	--	--	7.20	2.4	--	--
Rhyacophila sp.	8.80	74.4	16.8	--	1.60	--	--	--
Uenoidae	--	--	--	--	--	--	--	--
Oligophlebodes minutus	7.20	--	--	--	--	--	4.80	--
COLEOPTERA (beetles)	--	--	--	--	--	--	--	--
Dytiscidae	--	--	--	--	--	--	--	--
Oreodytes crassulus	--	--	--	--	--	--	--	0.80
Elmidae	--	--	--	--	--	--	--	--
Heterlimnius corpulentus	--	4.80	189	--	--	--	--	--
Optioservus sp.	--	--	130	--	--	--	--	--
DIPTERA (true flies)	--	--	--	--	--	--	--	--
Blephariceridae	--	--	--	--	--	--	--	--
Bibiocephala grandis	--	--	--	--	0.80	--	--	--
Ceratopogonidae	1.60	4.80	4.80	--	--	--	--	--
Chironomidae	2.40	9.60	--	2.40	3.20	3.20	3.20	0.80
Boreochlus sp.	--	--	--	0.80	--	--	--	--
Brillia sp.	1.60	--	--	1.60	2.40	2.40	8.80	--
Cardiocladius sp.	--	--	8.80	--	--	--	--	--
Corynoneura sp.	0.80	--	--	0.80	--	--	--	0.80
Cricotopus / Orthocladius sp.	0.80	--	4.80	3.20	16.0	4.80	5.60	137
Diamesa sp.	4.80	--	--	14.4	13.6	15.2	9.60	6.40
Eukiefferiella sp.	2.40	--	2.40	3.20	--	--	--	6.40
Metriocnemus fuscipes group	0.80	--	--	--	--	--	--	--
Micropsectra sp.	1.60	--	--	0.80	0.80	--	1.60	0.80
Microtendipes sp.	--	9.60	--	--	--	--	--	--
Pagastia sp.	--	4.80	1.60	0.80	--	--	--	--
Paraphaenocladius sp.	--	--	--	31.2	2.40	0.80	4.80	--
Parorthocladius sp.	0.80	--	--	--	--	--	--	--
Polypedilum sp.	--	--	--	--	--	--	0.80	1.60
Pseudodiamesa sp.	--	--	--	1.60	--	1.60	--	--
Rheocricotopus sp.	2.40	13.6	--	--	0.80	--	--	--
Stempellinella sp.	2.40	32.8	--	--	--	--	--	--
Thienemanniella sp.	0.80	--	--	--	--	--	--	--
Thienemannimyia group	--	--	--	--	--	--	--	1.60
Tvetenia sp.	5.60	32.8	9.60	2.40	2.40	0.80	--	2.40
Dixidae	--	--	--	--	--	--	--	--
Dixa sp.	0.80	--	--	--	--	--	0.80	--
Simuliidae	--	--	--	--	--	--	--	--
Prosimulium onychodactylum	77.6	32.8	3,200	0.80	1.60	1.60	0.80	--
Simulium sp.	--	4.80	--	--	--	--	--	2.40
Tipulidae	--	--	--	--	--	--	--	--
Dicranota sp.	--	--	--	--	--	1.60	--	--
Hesperoconopa sp.	--	--	--	--	--	0.80	--	--
Hexatoma sp.	--	--	4.00	--	--	--	--	2.40
Limonia sp.	--	--	--	--	0.80	--	--	--
Rhabdomastix sp.	--	--	--	--	--	0.80	--	--
Tipula sp.	0.80	--	--	--	--	--	--	--
Brachycera**	--	--	--	--	--	--	--	--
Athericidae	--	--	--	--	--	--	--	--
Atherix pachypus	--	--	--	--	--	--	--	2.40
Empididae	--	--	--	--	--	--	--	--
Clinocera sp.	--	--	--	0.80	--	--	--	--

Appendix G. Taxa, densities, total number of macroinvertebrates, and sampling date for samples collected from nonmining and mining sites in the Upper Colorado River Basin, Colorado, 1997–98—Continued

Taxa	NONMINING SITES			MINING SITES				
	Farncomb	Polk	Baker	Red Mountain	Canyon	Ouray	Cutler	Ridgway
	07/29/97	07/30/98	07/31/98	07/22/97	07/22/97	07/22/97	07/22/97	07/22/97
CLASS								
ORDER								
Family								
Genus species								
CHELICERATA, continued								
ACARI (water mites)	--	--	33.6	--	--	--	--	--
Lebertiidae	--	--	--	--	--	--	--	--
Lebertia sp.	0.80	--	--	--	--	--	--	1.60
MALACOSTRACA	--	--	--	--	--	--	--	--
AMPHIPODA (scuds, shrimp)	--	--	--	--	--	--	--	--
Hyalellidae	--	--	--	--	--	--	--	--
Hyalella azteca	--	--	--	--	--	--	0.80	0.80
ANNELIDA (worms)*	--	--	--	--	--	--	--	--
OLIGOCHAETA (aquatic worms)	--	18.4	11.2	--	--	--	--	--
ENCHYTRAEIDA	--	--	--	--	--	--	--	--
Enchytraeidae	68.0	--	--	--	--	--	--	--
TUBIFICIDA	--	--	--	--	--	--	--	--
Naididae	--	--	--	--	--	--	--	--
Nais communis	--	--	2.40	--	--	--	--	--
NEMATODA (roundworms)*	17.6	--	23.2	--	--	--	16.8	--
PLATYHELMINTHES*	--	--	--	--	--	--	--	--
TURBELLARIA (flatworms)	--	--	--	--	--	--	--	--
TRICLADIDA	--	--	--	--	--	--	--	--
Planariidae	--	--	--	--	--	--	--	--
Polycelis coronata	26.4	13.6	--	--	--	--	--	--
TOTAL ABUNDANCE	3,120	1,840	6,590	68.0	828	92.0	185	457