Understanding Trace-Element Sources and Transport to Upper Basin Creek in the Vicinity of the Buckeye and Enterprise Mines

By M.R. Cannon, Stanley E. Church, David L. Fey, Robert R. McDougal,
Bruce D. Smith, and David A. Nimick

Chapter E1 of

Integrated Investigations of Environmental Effects of Historical Mining in the Basin and Boulder Mining Districts, Boulder River Watershed, Jefferson County, Montana

Edited by David A. Nimick, Stanley E. Church, and Susan E. Finger

In cooperation with the
United States Department of Agriculture (USDA) Forest Service

Professional Paper 1652–E1

U.S. Department of the Interior
U.S. Geological Survey

Contents

Figures

Tables

CONVERSION FACTORS AND DATUM

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
inch (in.)	2.54	centimeter (cm)
	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.589	square kilometer
	Volume	
cubic foot (ft^3)	28.3168	liter
cubic yard (yd^3)	0.7646	cubic meter
	Flow	
cubic foot per day (ft^3/d)	0.028317	cubic meter per day
cubic foot per second (ft^3/s)	0.028317	cubic meter per second
	Hydraulic Conductivity	
foot per day	0.3048	meter per day
	Transmissivity	
foot squared per day (ft^2/d)	0.0929	meter squared per day

Temperature can be converted to degrees Celsius (°C) or degrees Fahrenheit (°F) by the following equations:

°C = 5/9 (°F - 32)
°F = 9/5 (°C) + 32

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD29); horizontal coordinate information is referenced to the North American Datum of 1927 (NAD27).

Chapter E1
Understanding Trace-Element Sources and Transport to Upper Basin Creek in the Vicinity of the Buckeye and Enterprise Mines

By M.R. Cannon, Stanley E. Church, David L. Fey, Robert R. McDougal, Bruce D. Smith, and David A. Nimick

Abstract

The Buckeye mine and adjacent Enterprise mine, located about 10 miles north of Basin, Montana, were intermittently operated in the late 1800s and early 1900s. Upper Basin Creek flows next to acid-generating pyritic rocks and the tailings left from the mining and milling operations. Overland runoff from the mine area is rich in trace elements and measurably affects water quality in upper Basin Creek, primarily during spring snowmelt and high streamflow. Detailed studies of the sources of trace elements and modes of transport to upper Basin Creek were needed to aid in designing remediation.

Geochemical analyses of core samples from areas of mill tailings identified zones containing the highest concentrations of trace elements. Geophysical surveys identified areas of high conductivity that could result from ground water containing high concentrations of dissolved solids. Ground-water samples from test wells identified areas containing high concentrations of dissolved aluminum, arsenic, cadmium, copper, iron, lead, manganese, and zinc.

During spring runoff, dissolved trace-element loads measured in upper Basin Creek were largely derived from small tributary inflows draining the area of the Buckeye and Enterprise mines. Runoff from the mine area caused concentrations of copper, lead, and zinc in upper Basin Creek to exceed the State of Montana aquatic-life standards. For all trace elements except arsenic, ground water contributed only a small part of the dissolved trace-element load to upper Basin Creek.

Introduction

The Buckeye and Enterprise mines in the upper Basin Creek area of west-central Montana are two of many inactive or abandoned metal mines that were intermittently operated in the late 1800s and early 1900s. Wastes left from the mining and processing of ore include pyritic rocks and tailings from gravity and flotation mills. Most of the flotation-mill tailings were deposited in the flood plain of upper Basin Creek, on lands now administered by the Beaverhead-Deerlodge National Forest (fig. 1). Upper Basin Creek, which flows along the southern margin of the mill tailings, receives surface-water and ground-water discharge from the tailings and areas around the mines. That discharge is rich in trace elements and measurably affects water quality in Basin Creek. State of Montana water-quality standards for aquatic life are exceeded in Basin Creek, downstream from these mines, during times of high runoff.

The United States Department of Agriculture (USDA) Forest Service and U.S. Environmental Protection Agency identified the need for remediation of the Buckeye and Enterprise mine area; however, the size of the affected area and the number of potential trace-element sources made the planning of remediation complex. The site contained multiple potential sources of trace elements, which could be transported via surface- and ground-water pathways to upper Basin Creek. Potential sources of trace elements included an adit that discharged acidic water, piles of waste rock near the mines, tailings from an early mill that were located on a hillslope adjacent to the Basin Creek valley floor, and flotation-mill tailings on the flood plain of upper Basin Creek.

Purpose and Scope

The purpose of this report is to present data and results from a comprehensive investigation of trace-element sources and transport to upper Basin Creek from surface and ground water near the Buckeye and Enterprise mines. The investigation was conducted by the U.S. Geological Survey in 1998–99. Prior to the comprehensive investigation near the mines, surface water and streambed sediment were sampled to determine the extent, magnitude, and seasonal patterns of trace-element

Figure 1. Location of Buckeye and Enterprise mines near upper Basin Creek, Mont. Altitude in feet.

concentrations in a large part of the Basin Creek drainage (Nimick and Cleasby, 2000; Fey, Unruh, and Church, 1999). Results of those samples indicated that the area of the Buckeye and Enterprise mines was contributing trace elements to upper Basin Creek through the transport of acidic, trace-element-rich water and sediment. Seasonal samples from upper Basin Creek indicated that the greatest concentrations and loads of trace elements occurred during spring runoff and much smaller concentrations occurred during low streamflow. Those initial water and sediment samples from upper Basin Creek clearly showed a need for a more thorough characterization of trace-element sources and mechanisms of transport to the stream.

The scope of the investigation was limited to public lands in upper Basin Creek that are adjacent to the Buckeye and Enterprise mines. To better understand the sources of trace elements and mechanisms for transport to upper Basin Creek, a multidisciplinary approach was used that examined (1) geochemistry of mill tailings and streambed sediment, (2) geophysical properties of tailings, alluvial sediments, and pore water, (3) ground-water flow and quality, and (4) surface-water flow and quality. Results of the investigation were used to aid in the development of efficient and cost-effective remediation plans for the mine site and adjacent area of public lands. Remediation activities at the site were conducted in 2000–01 by the USDA Forest Service.

Description of Study Area

The Buckeye and Enterprise mines are located in upper Basin Creek about 10 mi north of the town of Basin in Jefferson County, Mont. (fig. 1). The Buckeye mine was intermittently operated from 1868 to 1908, although the principal period of mining activity was from 1896 to 1903 (Ruppel, 1963). The ore vein, which contained gold-bearing pyrite and minor quantities of silver-bearing galena, was worked through shafts that were sunk to a depth of 100–200 ft. The adjacent Enterprise mine was operated at about the same time, but was closed before 1900. The Enterprise mine had a 400-ft vertical shaft that accessed an ore vein similar to the one at the Buckeye mine. The 5-ft thick Buckeye ore vein and the adjacent smaller veins are nearly vertical and apparently occupy fault zones trending N. 85° W. within the Butte quartz monzonite (Ruppel, 1963). During the time of mine operation, ore from the mines was processed by a gravity mill located at the Buckeye site. In the 1940s during World War II, a flotation mill was built on the flood plain of Basin Creek (fig. 2) to reprocess the old tailings from the gravity mill (Roby and others, 1960; Metesh and others, 1994). An estimated 5,000 cubic yards of flotation tailings and sandy material accumulated in the Basin Creek flood plain (Fey, Church, and Finney, 1999) as a result of activities at the flotation mill. These flood-plain tailings occupied about 3.3 acres in an irregularly shaped area of about 200 by 750 ft.

Altitudes within the study area range from about 7,020 ft along Basin Creek at the west end of the study area to 7,100 ft at the mine workings. Basin Creek drops about 20 ft as it meanders for a distance of about 4,300 ft from east to west through the study area. Because of its relatively high altitude, the area receives nearly 30 in. of precipitation per year, much of it falling as snow from late October through May (U.S. Department of Agriculture, 1981).

Sources of Trace Elements

Several potential sources of trace elements were present at the Buckeye and Enterprise mines and adjacent area. Sources included a mine adit discharging water, piles of pyritic waste rock on private property, and dispersed deposits of mill tailings on public land along upper Basin Creek. The size of the area affected by elevated concentrations of trace elements such as arsenic, cadmium, copper, lead, and zinc that are associated with the mineral deposit was unknown. To assess the lateral and vertical extent of the affected area, detailed geochemical studies were conducted on the mill tailings and soils on the flood plain of upper Basin Creek, and geophysical surveys were used to examine properties of subsurface materials along upper Basin Creek and the surrounding area.

Figure 2. Flotation mill active during the 1940s and associated tailings on flood plain of Basin Creek at Buckeye and Enterprise mines, October 1996. Buckeye mine is behind mill near clearing in trees. Enterprise mine is in trees on right side of photograph.

Flotation-Mill Tailings

The distribution, thickness, and volume of flotation-mill tailings as well as underlying fluvial sediment with elevated trace-element concentrations were estimated by Fey, Church, and Finney (1999) from 35 shallow cores collected from the flood plain of upper Basin Creek (fig. 3) in 1997. These cores were 1 inch in diameter and typically as much as 24 inches in length. The cores were subdivided into 196 samples on the basis of visual identification of differences in mineralogy, organic content, and degree of oxidation. Each sample was analyzed by geochemical and binocular-microscopic methods. Trace-element concentrations and mineralogy determined from these analyses were used to distinguish contaminated and uncontaminated material and to estimate the volume of the contaminated material (Fey, Church, and Finney, 1999). Further investigation of the mill tailings was warranted to determine the source of trace elements in underlying ground water, whether the tailings had potential for further oxidation and associated release of acid and trace elements, and what processes cause lateral and vertical dispersion of trace elements in the tailings and across the flood plain.

Geochemistry of Tailings

The geochemistry of the flotation-mill tailings was examined by detailed analysis of a core (2 inches in diameter and 79 in. long) collected from the thickest part of the mill tailings in July 1998. This core, as well as a nearby exploratory trench (approximately 10 ft long and 7 ft deep), revealed a zone of oxidized waste that graded downward into unoxidized, pyrite-rich waste near the base of the tailings. The core was subdivided into 27 samples. Sample descriptions as well as geochemical and mineralogical data from the core are in table 1. The data indicate four distinct sections corresponding to the oxidized zone (the upper 22 in.), the partly oxidized zone (22–41 in.), the unoxidized pyritic zone (41–62 in.), and buried soil developed in flood-plain sediment (62–79 in.). At the base of the mill tailings, buried wetland grasses overlie the top organic-rich layer of the buried soil. Geochemical and mineralogical data for the 2-in. core are used to demonstrate how the tailings weathered and how trace elements were mobilized, redistributed within the core, and, in some cases, leached out of the tailings. The mechanisms by which trace elements were released by weathering and dispersed through the flood plain can be understood by examination of the differences in element concentrations (from the 1-in. cores) in total- and leach-digestions as well as the distribution of primary and secondary minerals and their relative abundance within the cores.

Figure 3. Location of mill tailings and core holes on flood plain of upper Basin Creek.

Total-Digestion Data

The samples from the 2-in. core were processed using a total-digestion procedure that used a mixture of strong acids (Fey and others, 2000). Concentrations of major elements such as calcium, sodium, iron, and aluminum clearly show the difference between mill tailings and the underlying buried soil and reflect differences in the mineralogy of these two units (table 1). These differences in element concentrations are caused by the large difference in proportions of the deposit-related minerals found in the rocks that were milled and the rock-forming minerals typically found in the premining flood-plain sediment beneath the tailings. Other differences in element concentrations were caused by oxidation of the abundant sulfide minerals (such as pyrite) in the tailings and leaching of the oxidation byproducts. Calcium and sodium were present in the tailings at very low concentrations, but in the underlying soil zone they were present at concentrations one to two orders of magnitude higher. This pattern largely reflects the original compositions of the tailings and underlying buried soil, with much smaller amounts of feldspar and other rock-forming minerals in the tailings compared to the soil. Aluminum exhibited a somewhat similar but less distinct pattern. Aluminum concentrations were lower in the tailings (1.6–4.4 percent) and higher in the underlying soil (5.2–9.0 percent), again reflecting the larger proportion of rock-forming minerals in the buried soil.

Within the tailings, variations in iron and aluminum concentrations with depth reflect processes that affected the tailings after their deposition on the flood plain. Iron is hosted primarily in pyrite, which likely was distributed fairly uniformly throughout the original tailings. However, iron concentrations in the core were lower in the oxidized zone (less than 1 percent) and higher in the unoxidized pyritic zone (2.6–5.6 percent). This pattern likely developed because pyrite and other sulfide minerals in the upper part of the tailings pile were oxidized and their constituents leached from the oxidized zone. The wide range in iron concentrations within just the unoxidized pyritic zone reflects the variable amount of quartz, the dominant silicate mineral in the tailings, which diluted the amount of pyrite present in individual layers sampled in the zone. Aluminum concentrations were higher in the oxidized zone (3.5–4.4 percent) than in the unoxidized pyritic zone (1.7–3.6 percent). The aluminum distribution is also a result of the leaching of the sulfide-oxidation byproducts. As these components were removed, aluminum, which was not leached, was concentrated in the oxidized zone, primarily in kaolinite that formed during weathering.

Similar to the major elements, the distribution of trace elements in the core (fig. 4) reflects the original mineralogy as well as subsequent processes that differentially mobilized and sequestered the trace elements. Strontium and silver concentrations, like calcium, sodium, and iron concentrations, reflect the original composition of the tailings and buried soil. In the tailings, strontium concentrations were low and silver concentrations were high, whereas this pattern was reversed in the buried soil. Strontium represents the rock-forming trace elements typical of the underlying premining flood-plain sediment, whereas silver represents the deposit-related trace elements that were concentrated in the tailings.

Arsenic, cadmium, copper, lead, and zinc are the trace elements that pose risk to aquatic life in Basin Creek (Farag and others, this volume, Chapter D10). These elements were enriched in the tailings (fig. 4*B*, *C*) but had distinctly different mobilities during oxidation and weathering in place. Silver is a relatively immobile trace element during oxidation and weathering. The uniform distribution of silver through the tailings (fig. 4*C*) indicates that the tailings had a fairly uniform composition as they were dumped from the flotation mill and that, initially, the tailings in the core likely were homogeneous. Therefore, comparing the distributions of the trace elements of concern to the distribution of silver provides useful information about the weathering processes. Lead, like silver, is relatively immobile (fig. 4*C*). Arsenic (fig. 4*C*) is more mobile during weathering than silver and lead but less mobile than cadmium, copper, and zinc (fig. 4*B*). Moderate to large increases in concentrations of trace elements occurred at the boundary between the oxidized zone and the partly oxidized zone (22 in. depth) and, for most trace elements, at the boundary between the partly oxidized zone and the unoxidized pyritic zone (41 in.). Concentrations also were high, particularly for arsenic, cadmium, copper, and zinc, near the top layer of the buried soil (64.3 in.). These increases were produced by downward leaching of the trace elements mobilized by sulfide oxidation in the oxidized zone. Some of the leached trace elements were sequestered as organic complexes at the top of the buried soil, which presumably had very low trace-element concentrations prior to deposition of the tailings. Below the organic material in the buried soil, concentrations of trace elements of concern decreased markedly over a distance of a few inches (fig. 4). Concentrations of arsenic, which behaves as an anion, and zinc, which remains mobile up to a pH of about 8, decreased gradually with depth reflecting their greater mobility and greater penetration into the buried soil horizon.

Leachate Data

The samples from the 2-in. core also were processed using a passive-leach procedure (Fey and others, 2000). Deionized water was used as the leachate and was mixed at a 20:1 mass ratio with the sample. The samples were leached for 24 hours without agitation to simulate the dissolution reactions that probably would occur when sulfidic tailings are exposed to surface water. Data are in table 2 and figure 5. Leachate from all intervals in the core was acidic, indicating that sulfide oxidation was occurring and that acid and trace elements would be mobile in the tailings and at least parts of the buried soil. The pH of the leachate solutions was slightly higher in the oxidized zone (pH from 3.41 to 3.68) than in the partly oxidized zone and unoxidized pyritic zone (pH from 2.53 to 3.09). In the buried soil below the tailings, the pH increased with depth. Specific conductance and sulfate concentration

Table 1. Mineralogy and concentrations of selected major and trace elements in core intervals from a 2-in. diameter core in

[Core intervals expressed as the midpoint of the depth in the core from the surface (corrected for compaction). Major-element concentrations expressed in weight percent (parts per hundred); trace-element concentrations expressed in parts per million; minerals identified by XRD listed in order of decreasing abundance; cm, centimeter; mm, millimeter; ppm, parts per million; tr., trace; XRD, X-ray diffraction; <, less than minimum reporting level; --, not analyzed]

Sample No.	Depth (mid-point, in inches)	Sample description	High-density minerals, identified by XRD	Minerals, in addition to quartz and mica identified by XRD	Aluminum (weight percent)
Oxidized zone					
98BMF109-Aa	1.8	Light-gray/pale-yellow tailings, medium sand	anglesite, tr.sphalerite	orthoclase	4.4
98BMF109-Ab	5.3	Coarse tailings, sand sized to 1 mm	anglesite, tr.sphalerite	anglesite, kaolinite	4.3
98BMF109-Ac	8.6	Unsorted tailings with clay-size matrix	anglesite, tr.sphalerite	anglesite, kaolinite	4.2
98BMF109-Ad	11.8	Unsorted tailings with clay-size matrix	anglesite, tr.sphalerite	anglesite, kaolinite	4.2
98BMF109-Ba[1]	15.0	Light-gray tailings, poorly sorted into 0.52-cm thick beds, coarse grains to 2 mm.	anglesite, tr.sphalerite	anglesite, kaolinite	3.8
98BMF109-Bb[1]	17.9		anglesite, tr.sphalerite, gold	anglesite, orthoclase	3.5
98BMF109-Bc[1]	20.8		anglesite, tr.sphalerite	anglesite	3.6
Partly oxidized zone					
98BMF109-Ca	23.2	Pale-yellow fine-grained tailings, 90 percent "clay" size.	anglesite	anglesite	4.0
98BMF109-Da	25.4	Pale-yellow/cream tailings, coarse- and fine-grained.	anglesite	anglesite	2.8
98BMF109-Ea	28.2	Pale yellow/gray, coarse and fine grained	anglesite	anglesite	2.5
98BMF109-Fa	31.1	Bright-yellow sand, unsorted tailings	anglesite	anglesite	1.9
98BMF109-Ga	34.4	Pale-yellow cream tailings with lenses of sulfide grain, layered.	anglesite	anglesite	2.2
98BMF109-Ha	37.5	Light-gray light-yellow fine to coarse oxidized sulfide tailings.	anglesite	anglesite	1.8
98BMF109-Ia	39.7	Yellow, medium sand tailings	anglesite	anglesite, scorodite	1.6
Unoxidized pyritic zone					
98BMF109-Ja	42.4	Cream and dark-gray, sulfides, fine sand	pyrite, anglesite	anglesite, pyrite	3.3
98BMF109-Ka	45.5	Light- and dark-gray, sulfides, fine sand	pyrite, anglesite	pyrite, anglesite, sphalerite	2.6
98BMF109-La	48.8	Fine sand with gray sulfides	pyrite, anglesite	sphalerite, pyrite, anglesite	1.8
98BMF109-Ma	52.2	Pale-yellow tailings, some gray sulfides, medium to coarse sand, moderately sorted.	pyrite, anglesite	pyrite, anglesite	1.7
98BMF109-Mb	54.9	Pale-yellow tailings, some gray sulfides, medium to coarse sand, moderately sorted.	pyrite, anglesite	pyrite, anglesite	2.0
98BMF109-Na	57.1	Light-dark-gray tailings, fine sand, pyrite	pyrite, anglesite	pyrite, anglesite	3.2
98BMF109-Oa	59.9	Cream, poorly sorted fine-sand size tailings	pyrite	pyrite, anglesite	3.6
Buried soil					
98BMF109-P	62.0	Organic layer	--	--	
98BMF109-Qa	64.3	Soil, dark brown at top	tr. pyrite	halloysite, plagioclase	5.2
98BMF109-Qb	67.8	Light brown at bottom	none	montmorillonite, kaolinite, plagioclase	7.6
98BMF109-Qc	71.5	Soil	none	montmorillonite, kaolinite, plagioclase	9.0
98BMF109-Qd	75.0	Soil	zircon, tr. hornblende	montmorillonite, kaolinite, plagioclase	8.9
98BMF109-Qe	78.0	Soil	zircon, tr. hornblende	montmorillonite, kaolinite, plagioclase	8.7

[1] Sample descriptions refer to all three samples.

mill tailings along upper Basin Creek.

Calcium (weight percent)	Iron (weight percent)	Potassium (weight percent)	Sodium (weight percent)	Arsenic (ppm)	Cadmium (ppm)	Copper (ppm)	Lead (ppm)	Manganese (ppm)	Silver (ppm)	Strontium (ppm)	Zinc (ppm)
Oxidized zone											
0.02	0.86	2.1	0.05	1,600	2	54	6,100	140	52	25	280
.02	.82	2.1	.04	1,700	<2	35	7,500	140	48	24	210
.02	.80	2.0	.04	1,300	<2	47	6,900	130	48	26	260
.01	.78	2.0	.03	1,400	<2	43	7,400	140	62	21	180
.009	.63	1.8	.02	500	<2	38	5,000	120	42	15	170
.009	.57	1.6	.01	480	<2	66	8,300	120	92	9	240
.01	.62	1.7	.009	640	<2	60	7,000	120	64	7	210
Partly oxidized zone											
.01	1.8	1.9	.02	13,000	9	110	37,000	190	190	20	1,400
.008	1.6	1.3	.007	11,000	9	110	22,000	140	110	12	1,500
.009	1.6	1.2	.007	13,000	7	200	14,000	120	110	13	1,200
<.005	2.8	.89	<.005	26,000	10	270	12,000	94	64	8	1,600
.008	2.3	1.0	.009	21,000	15	360	15,000	120	98	14	2,600
.006	1.7	.86	<.005	16,000	13	250	16,000	99	70	14	2,300
<.005	4.4	.75	<.005	44,000	19	400	20,000	86	88	9	3,000
Unoxidized pyritic zone											
.009	4.0	1.6	.01	18,000	48	2,900	58,000	180	300	16	6,900
.01	5.6	1.2	.01	31,000	70	3,200	52,000	160	220	10	9,800
<.005	4.6	.88	<.005	22,000	60	2,000	26,000	110	120	6	9,000
<.005	3.1	.78	<.005	14,000	27	790	12,000	92	52	6	4,400
.006	2.6	.94	<.005	13,000	31	1,000	9,100	92	34	8	4,700
.02	4.3	1.5	.01	20,000	64	4,300	19,000	140	80	20	8,400
.01	3.6	1.7	.02	13,000	44	2,700	8,600	130	59	18	5,600
Buried soil											
--	--	--	--	--	--	--	--	--	--	--	--
.27	1.8	.60	.26	9,400	190	3,200	500	190	2	59	12,000
.56	2.1	.98	.52	2,500	17	43	110	350	<2	110	6,400
1.1	3.7	1.4	.80	2,300	2	50	160	680	<2	220	3,300
1.0	4.2	1.4	.80	2,300	7	75	160	700	<2	190	1,100
1.2	3.8	1.7	1.1	1,900	9	90	440	610	<2	230	820

Figure 4. Relation of selected trace-element concentrations in total digests to depth in the 2-in. core through mill tailings, upper Basin Creek. Concentrations of silver in samples below 64.3 in. were less than minimum reporting level of 2 parts per million and are not shown. *A*, strontium, manganese; *B*, cadmium, copper, zinc; *C*, silver, arsenic, lead.

in the leachate were well correlated (fig. 5, $R^2 = 0.88$). Both sulfate concentration and specific conductance increased in the leachate with depth in the tailings and decreased in the buried soil. Iron concentrations in the leachate were low in the oxidized zone and high in the unoxidized pyritic zone. Iron concentrations in the oxidized zone were low because the iron had been leached out of the oxidized zone as shown by the total-digestion data.

Leachate data reflect the mobility of trace elements during oxidization of the tailings, with arsenic being the most mobile (concentration increase of about three orders of magnitude through the tailings); cadmium, copper, and zinc less mobile; and antimony, lead, and silver least mobile (fig. 5). The presence of native sulfur (identified visually) and the very soluble hydrous iron arsenate, scorodite, in the partly oxidized zone (table 1) indicates that the mobility of the trace elements was limited with depth by low permeability in tailings. The immobility of lead is clearly shown by the presence of anglesite (lead sulfate, which is relatively insoluble) in the oxidized and partly oxidized zones (table 1). No jarosite (iron-rich, hydrous potassium aluminum sulfate) was observed in the core, perhaps because insufficient potassium was available to form this mineral. Muscovite, which contains potassium, was sparse in the flotation wastes, so mobile potassium was not readily available to form jarosite. Deposit-related trace elements generally were sequestered at the top of the buried soil horizon immediately below the organic layer (62 in.), with the exception of manganese, zinc, and arsenic, which had elevated concentrations throughout the buried soil (fig. 5).

Table 2. Specific conductance, pH, and concentrations of sulfate and selected trace elements in leachate from various depth intervals of core samples collected from the mill tailings along upper Basin Creek.

[Core intervals expressed as the midpoint of the depth in the 2-in. diameter core from land surface (corrected for compaction). ICP, inductively coupled plasma; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; <, less than minimum reporting level; --, not analyzed (organic layer)]

Sample No.	Depth (mid-point, in inches)	Specific conductance of leachate (µS/cm)	pH of leachate	ICP[1] Sulfate (mg/L)	ICP[2] Aluminum (µg/L)	ICP[3] Antimony (µg/L)	ICP[3] Arsenic (µg/L)	ICP[3] Cadmium (µg/L)	ICP[1] Copper (µg/L)	ICP[2] Iron (µg/L)	ICP[3] Lead (µg/L)	ICP[2] Manganese (µg/L)	ICP[2] Silver (µg/L)	ICP[1] Strontium (µg/L)	ICP[1] Zinc (µg/L)
Oxidized zone															
98BMF109-Aa	1.8	189	3.41	35	200	150	71	15	440	44	12,000	33	22	18	3,400
98BMF109-Ab	5.3	127	3.56	26	98	150	69	13	450	9.2	15,000	18	10	13	2,500
98BMF109-Ac	8.6	111	3.63	23	73	54	25	9.8	640	5.0	17,000	11	5.4	12	1,800
98BMF109-Ad	11.8	124	3.62	23	120	100	38	7.5	670	14	18,000	5.3	6	12	1,300
98BMF109-Ba	15.0	116	3.68	23	96	240	28	9.3	710	58	18,000	5.7	15	8.9	1,900
98BMF109-Bb	17.9	122	3.67	23	120	500	67	8.2	490	68	18,000	5.2	24	8.2	1,600
98BMF109-Bc	20.8	131	3.62	24	56	580	81	7.8	390	82	18,000	3.7	17	5.3	1,700
Partly oxidized zone															
98BMF109-Ca	23.2	610	3.09	97	590	1,600	250	41	2,000	2,200	9,500	14	530	4.0	8,400
98BMF109-Da	25.4	760	2.94	120	560	1,500	210	51	3,500	5,100	7,400	17	240	2.6	13,000
98BMF109-Ea	28.2	900	2.90	160	730	1,700	230	66	5,600	10,000	6,100	23	68	4.0	18,000
98BMF109-Fa	31.1	1,330	2.77	260	820	1,900	370	100	11,000	25,000	5,000	32	55	3.5	31,000
98BMF109-Ga	34.4	1,350	2.75	240	570	2,100	630	99	11,000	18,000	4,700	31	69	5.1	32,000
98BMF109-Ha	37.5	860	2.82	160	150	1,700	1,800	67	7,700	8,300	5,400	21	40	4.0	22,000
98BMF109-Ia	39.7	1,320	2.73	230	190	1,200	5,200	88	10,000	13,000	4,800	27	41	3.4	31,000
Unoxidized pyritic zone															
98BMF109-Ja	42.4	3,280	2.53	900	1,600	1,700	24,000	1,000	87,000	94,000	3,000	280	3	15	280,000
98BMF109-Ka	45.5	2,170	2.82	770	780	1,200	18,000	1,500	88,000	83,000	3,500	300	<2	3.4	310,000
98BMF109-La	48.8	1,330	3.02	440	210	720	12,000	900	46,000	45,000	4,100	190	<2	2.1	170,000
98BMF109-Ma	52.2	1,050	2.95	270	210	380	8,400	490	22,000	23,000	4,400	120	<2	6.7	83,000
98BMF109-Mb	54.9	1,350	2.90	350	480	330	7,400	640	35,000	26,000	4,000	180	<2	7.6	120,000
98BMF109-Na	57.1	2,590	2.76	900	3,400	600	14,000	1,700	140,000	100,000	3,200	540	<2	7.0	270,000
98BMF109-Oa	59.9	2,100	2.79	670	4,200	530	15,000	1,200	96,000	74,000	4,000	530	<2	5.3	180,000
Buried soil															
98BMF109-P	62.0	--	--	--	--	--	--	--	--	--	--	--	--	--	--
98BMF109-Qa	64.3	4,400	2.84	2,200	200,000	71	65,000	9,700	120,000	19,000	780	5,300	<2	120	720,000
98BMF109-Qb	67.8	1,830	3.43	840	46,000	11	6,600	580	440	1,500	130	8,600	<2	260	320,000
98BMF109-Qc	71.5	760	3.88	330	3,500	11	2,100	28	45	180	44	12,000	<2	380	86,000
98BMF109-Qd	75.0	370	4.14	140	740	3.5	3,600	51	36	65	13	7,200	<2	310	12,000
98BMF109-Qe	78.0	290	4.15	110	580	14	1,200	85	26	50	35	5,900	<2	270	7,600

[1] Inductively coupled plasma-atomic emission spectrometry (ICP-AES) data. [2] Inductively coupled plasma-mass spectrometry (ICP-MS) used at low concentrations; inductively coupled plasma-atomic emission spectrometry data used at higher concentrations. [3] Inductively coupled plasma-mass spectrometry data.

Figure 5. Relation of selected trace-element and sulfate concentrations in leachate to depth in the 2-in. core through mill tailings, upper Basin Creek. Sample numbers and analytical results are presented in table 2 and in Rich and others (this volume, Chapter G). Concentrations of silver in samples below 45.5 in. were less than minimum reporting level of 2 micrograms per liter and are not shown.

Arsenopyrite

Early descriptions of ore from the Buckeye and Enterprise mines identified arsenopyrite as a significant mineral. However, no arsenopyrite was identified by X-ray diffraction of bulk samples or the high-density-mineral concentrates from the 2-in. core (table 1). Arsenopyrite generally is absent from most of the mine wastes present in the Basin mining district (Desborough and Fey, 1997). In addition, no arsenic minerals were identified in the unoxidized pyritic zone (table 1) that would account for the arsenic concentrations of 11,000–44,000 parts per million (ppm) (1.1 to 4.4 percent) in the partly oxidized zone (fig. 4; table 1). Too much arsenic is present in the pyritic zone of the core to be incorporated into pyrite and, therefore, the arsenic must be hosted in another mineral. Arsenic could possibly be present as an amorphous phase in the pyritic zone and, therefore, not detected by X-ray diffraction (XRD).

Dispersion of Tailings on the Flood Plain

Descriptions of the 1-in. core samples (Fey, Church, and Finney, 1999) indicated that the majority of these samples looked more like flood-plain sediment than like tailings, even though many of the samples had high concentrations of the deposit-related trace elements. These observations indicate that the tailings were subjected to various weathering and dispersion processes after their deposition in the 1940s. Tailings likely were mobilized and transported away from the original pile by physical processes (wind or water erosion) and then redeposited and mixed with sediment on the flood plain or transported to Basin Creek. In addition, trace elements have been mobilized and leached by water from the tailings by chemical processes. Portions of these trace elements then were precipitated or adsorbed before reaching Basin Creek, thus increasing trace-element concentrations in flood-plain sediment. The effects of this physical and chemical dispersion on the flood-plain surface can be examined using the total-digestion geochemical data from both the 1-in.-diameter cores (fig. 3; Fey, Church, and Finney, 1999) and the 2-in.-diameter core (table 1). The 1-in. cores provide spatial data over a large part of the flood-plain area affected by tailings, whereas the 2-in. core provides detailed vertical information.

The contrast in silver and strontium concentrations provides a useful tool to differentiate between tailings and underlying premining flood-plain sediment and to understand physical and chemical dispersion processes. The contrast in concentrations was clear in the 2-in. core (fig. 4), in which tailings had low strontium (6–26 ppm) and high silver concentrations (34–300 ppm) while premining flood-plain sediment (buried soil) had high strontium (59–420 ppm) and low silver (<2–2 ppm) concentrations. However, only 11 of the 196 one-inch core samples had strontium concentrations less than 30 ppm and silver concentrations greater than 2 ppm. These 11 samples likely contained essentially pure tailings because the 11 samples were from the cores collected nearest the 2-in. core, which was located in the thickest part and presumably near the center of the tailings pile. The proportion of tailings in the other 185 one-inch core samples apparently was much less. Figure 6 shows box plots of strontium and silver concentrations for each of the 1-in. cores from the main traverse line (fig. 3). The coincidence of low strontium concentrations and high silver concentrations for the two 1-in. cores next to the 2-in. core near the center of the mill-tailings pile is apparent. Cores farther away from the 2-in. core had higher strontium and lower silver concentrations, indicating that the material at these sites was mostly flood plain sediment unaffected by tailings.

Figure 7 shows the relation between concentrations of strontium and other trace elements in the top layers of each of the 1-in. cores. The data are ordered from left to right in the graph on the basis of increasing strontium concentration, which also indicates a greater proportion of flood-plain sediment relative to tailings. In figure 7*A*, silver and lead, which behave similarly and were shown to be less chemically mobile in the 2-in. core (fig. 4*C* and 5), show marked decrease in concentration as strontium concentration increases. This pattern suggests that silver and lead were dispersed primarily by physical transport of tailings away from the original pile. In contrast, concentrations of arsenic, cadmium, copper, and zinc (fig. 7*B*, *C*) do not decrease as markedly as lead and silver concentration. These elements were shown to be more easily mobilized by chemical processes from the oxidized tailings than were lead and silver (figs. 4 and 5). Therefore, these elements most likely were dispersed to a greater extent by a chemical process involving mobilization, transport, and redeposition within the tailings area. Manganese, however, shows different behavior (fig. 7*D*): its concentration increases slightly as strontium concentration increases. This trend is opposite the concentration trend exhibited by most other trace elements and suggests that manganese is not derived from the tailings but from another source, such as ground water, that could affect all portions of the flood plain.

Shallow Subsurface Sources

Surface-geophysical surveys were conducted during the summers of 1998 and 1999 to examine the location and extent of shallow subsurface materials with high electrical conductivity, which could be related to elevated trace-element concentrations in the mill tailings along upper Basin Creek and the surrounding area. Defining the extent of potentially contaminated ground water also was a primary purpose of the geophysical investigations. Shallow subsurface materials were examined with a combination of electromagnetic, magnetic, and direct-current resistivity methods.

An electromagnetic (EM) survey was used to map the distribution of conductive materials in the mill tailings and in the underlying and surrounding valley-fill sediments and bedrock. Generally, in this type of environment, areas of high conductivity are caused by the presence of wet clays in soils or by high dissolved-solids concentrations in ground water. Magnetic metallic objects such as buried pipes, cables, or milling artifacts can cause conductive anomalies. A total-field magnetic reconnaissance survey was used to locate any metallic objects in the subsurface and differentiate them from areas with wet clays or high dissolved-solids concentration. Buried metallic objects are distinguishable because they are both conductive and magnetic.

Direct-current (DC) resistivity soundings were made on the tailings and adjacent areas to examine the vertical distribution of conductive material and to estimate the depth to bedrock beneath the tailings. Resistivity data were converted to the reciprocal values with units of conductivity so that they could be correlated directly with the electromagnetic (EM) data.

Figure 6. Range and distribution of silver and strontium concentrations in total digestions of 1-in. cores along main traverse through mill tailings, upper Basin Creek. Minimum concentration shown for silver is minimum reporting level of 2 parts per million. Location of main traverse line and sample sites shown in figure 3. Each core was divided into four to seven samples. Data are in Fey, Church, and Finney (1999).

Electromagnetic Survey of Conductive Materials

An electromagnetic (EM-34) survey conducted in 1998 and electromagnetic (EM-31) surveys conducted in 1998–99 were used to map subsurface conductivity of the mill tailings and the surrounding meadows and forested areas. These surveys measured the distribution of conductive materials in the subsurface at depths from about 10 to 100 ft. Measurements of conductivity at varying depths were achieved by use of two different EM instruments, with a horizontal and vertical transmitter/receiver dipole orientation for each instrument. In the horizontal magnetic dipole (HMD) orientation, the transmitter and receiver coils are perpendicular to the ground. In the vertical magnetic dipole (VMD) orientation, the transmitter and receiver coils are positioned parallel to the ground, resulting in a greater depth of exploration. The

Figure 7. Relation of strontium and selected trace-element concentrations in total digests of 1-in. cores through mill tailings, upper Basin Creek. *A*, silver and lead; *B*, arsenic and copper; *C*, cadmium and zinc; *D*, manganese. Only data for samples from the contaminated zones of these cores are shown to reduce amount of data plotted. Contaminated zones were defined by Fey, Church, and Finney (1999) and included upper portion of each core where concentration of cadmium, copper, lead, silver, or zinc exceeded average crustal abundance values by about 10–50 times, depending on the trace element. Cadmium and silver concentrations reported as less than 2 parts per million are not plotted.

Geonics EM-34 has variable coil spacing that ranges from 33 ft (10 m) to 131 ft (40 m). For this survey, the EM-34 spacing was set at 33 ft, resulting in an approximate exploration depth of 49 ft in the VMD orientation, and an approximate depth of 25 ft (McNeill, 1980) in the HMD orientation. The Geonics EM-31 has a fixed intercoil spacing of 12 ft, which results in an exploration depth of approximately 20 ft in the VMD orientation, and approximately 10 ft in the HMD orientation. Data collected by each of these instruments will hereinafter be referred to based on their relative exploration depths, deep (EM-34) and shallow (EM-31). A survey grid (fig. 8) that covered the tailings and adjacent area was constructed with an origin point near the thickest part of the tailings.

Figure 8. Location of electromagnetic (EM) survey grid and test wells.

Contours of the deep and shallow survey data show a high positive apparent-conductivity anomaly near the survey-grid origin (figs. 9*B* and 10). The 2-in. core collected near the conductivity anomaly encountered several layers about 1 in. thick of oxidized and unoxidized sulfides (table 1). Laboratory measurements of sulfide layers from the core show that the conductivity is on the order of 1,000 millisiemens per meter (mS/m) (D.V. Smith, written commun., 1999). The anomaly near the grid origin likely is the result of these highly conductive sulfide layers.

Contours of the deep VMD data show a negative conductivity anomaly near the survey-grid origin (fig. 9*A*). Buried magnetic metallic objects or lateral heterogeneities in layered deposits typically can result in similar responses. Another possibility is that the conductivity values, indicated in the core analysis, are high enough to allow for the low-induction-number approximation to be invalid. At high conductivity values (greater than 100 mS/m), the approximation of the linear relationship between instrument response and terrain conductivity becomes invalid and the reading becomes negative. This effect typically is more pronounced in the VMD orientation (McNeill, 1980).

The shallow contour maps (fig. 10) show three areas where subsurface conductivities substantially increase. First, an anomaly interpreted as a body of conductive material extends from the area of the survey-grid origin to the southwest toward Basin Creek (fig. 10*A*). This anomaly, in terms of depth, position, and conductivity, is consistent with the potentiometric surface and direction of ground-water flow at the mill-tailings site on the flood plain (fig. 14, presented in ground-water section). Second, the shallow contour map of VMD data shows an area of high conductivity in the northeast part of the survey area, south of the Enterprise mine. The higher conductivity observed in this area may be the result of elevated concentrations of major ions and trace elements in the ground water. A seep of red-colored water in the area of this anomaly was observed in July 1999. Third, an area of relatively high conductivity (fig. 10*A*) is indicated southwest of and on the other side of Basin Creek from the mill tailings in an area of wet meadows. Lithologic and geochemical data from cores or boreholes in this area are not available, but the conductivity could be the result of mill tailings deposited in this area during high streamflow. However, the higher conductivity more likely is caused by the presence of conductive clays or organic material, or both, in the meadow soil.

Magnetic Survey of Shallow Anomalies

During the summer of 1999, a total-field magnetic survey of the north-south and east-west base lines (fig. 11) was conducted using a proton precession magnetometer (Telford and others, 1990). Three measurements were taken at 33-ft (10-m)

Figure 9. Deep subsurface apparent conductivity measured using an EM-34 along upper Basin Creek. *A*, vertical magnetic dipole; *B*, horizontal magnetic dipole.

intervals and averaged to account for temporal variations in the Earth's magnetic field. This survey was intended to detect buried magnetic metallic objects that might cause the local EM anomalies.

Of particular interest was the area near the grid origin where EM results indicated an area of high conductivity caused either by a buried conductive metallic object or by lateral heterogeneity in the layered mill tailings. The total-field magnetic survey indicated several metallic objects near the surface that caused local magnetic anomalies along the north-south magnetic survey line. However, no substantial magnetic anomalies were found along the east-west line, and no substantial magnetic anomalies were found in the area of the grid origin (fig. 12). Therefore, buried magnetic metallic objects are not a likely source of the high conductivity anomalies in the area of the grid origin. The likely source of the high conductivities is a zone of layered sulfides in the mill tailings.

Direct-Current Resistivity Soundings of Conductive Materials

Direct-current (DC) resistivity soundings were conducted in eight locations using an SAS DC resistivity system made by ABEM Instrument AB, Sweden, and a Schlumberger electrode array (Smith and Sole, 2000). Seven of these soundings were made on and near the main area of mill tailings (fig. 11) to provide detailed information about the subsurface variations and to possibly define the depth to bedrock. One additional sounding was made in an area of exposed granite bedrock about 2 mi northwest of the tailings (not shown in fig. 11) to directly measure the resistivity of bedrock. The sounding data (McDougal and Smith, 2000) were interpreted using software from Interpex (RESIX-IP version 2.14; Interpex, 1993).

Subsurface conductivity as interpreted from the DC soundings is shown in figure 13. Data from soundings DCS-1

Figure 10. Shallow subsurface apparent conductivity measured using an EM-31 along upper Basin Creek. *A*, vertical magnetic dipole; *B*, horizontal magnetic dipole.

and DCS-3 (fig. 11) were not used because lateral heterogeneities affected the interpretation. For each sounding, the estimated subsurface conductivity was assumed to be located at the midpoint of the interpreted subsurface layer. The layer thickness increases at an approximately logarithmic rate because the resolution decreases at a similar rate. Consequently, the depths to points of estimated subsurface conductivity (sounding data points, fig. 13) increase logarithmically. The estimate of the conductivity of the last layer should be taken as relatively resistive or conductive because the soundings did not approach a constant value asymptotically at large electrode spacings.

A conductive anomaly at a depth of about 25 ft exists in the center of the section (fig. 13) at DCS-2. The anomaly is interpreted to be a body of conductive material, most likely ground water with high dissolved-solids concentrations. A

Figure 11. Location of total-field magnetic survey lines and direct-current (DC) resistivity soundings.

relatively high subsurface conductivity anomaly also exists at DCS-6. This anomaly is located between the Enterprise mine and upper Basin Creek.

The sounding made on a nearby bedrock outcrop to the northwest of the tailings (DCS-8) showed that the conductivity of shallow bedrock is about 5 mS/m. None of the subsurface conductivities are this low except perhaps for DCS-2, DCS-4, and DCS-5 (fig. 13). Consequently, granite underlying the mill tailings, with similar electrical properties as the outcropping area, may lie more than 98 ft deep. However, the granite in the stream valley likely is more weathered and has a higher volume of water than the outcrop area of DCS-8. Also, the underlying granite aquifer could have fractures that contain clays or that have water with high dissolved-solids content, which would produce higher conductivities and consequently place its depth at less than 98 ft.

Figure 12. Results of total-field magnetic survey.

Figure 13. Subsurface conductivity from direct-current resistivity soundings. Trace of section shown in figure 11.

Transport of Trace Elements to Upper Basin Creek

Ground-water movement and surface-water runoff are the primary means of transport of trace elements from sources in the area of the Buckeye and Enterprise mines to upper Basin Creek. Studies were made of the local ground-water flow systems, quality of ground water, surface-water runoff, and quality of surface water to evaluate trace-element loads transported to upper Basin Creek by ground and surface water.

Ground Water

Ground-water resources along the upper Basin Creek valley and the area of the Buckeye and Enterprise mines were examined to identify aquifers and determine their characteristics, define ground-water and surface-water interaction along upper Basin Creek, and evaluate effects of acidic drainage on quality of ground water. Trace-element loads entering Basin Creek from acidic ground water in the study area were estimated to evaluate the effects of ground-water discharge on trace-element concentrations and loads in upper Basin Creek.

General Geohydrologic Setting

Two distinct aquifers, with vastly different hydraulic characteristics and flow systems, exist in the study area. One aquifer is a fractured bedrock system, composed of fractured, weathered, and mineralized granitic rocks of the Boulder batholith; the second aquifer is an unconsolidated porous system composed of till, alluvium, colluvium, organic-rich wetland deposits, and volcanic ash. The unconsolidated deposits underlie the flood plain of Basin Creek and overlie granitic rocks of the Boulder batholith.

Bedrock underlying the study area was originally mapped as Butte quartz monzonite of Late Cretaceous or Paleocene age (Ruppel, 1963). Recent studies have classified the Butte pluton as a medium- to coarse-grained hornblende-biotite granodiorite-tonalite (O'Neill and others, this volume, Chapter D1). Fractures in the bedrock are numerous and include several steeply dipping sets of joints and one gently dipping set. Ruppel (1963) reported that one prominent joint set trends about east and dips steeply north, and one set trends about north and dips steeply west. Individual joints in the rock are rarely more than 30 ft long, but where one joint dies out, it commonly is overlapped by a parallel joint that either is entirely separate from the other, or that is connected by a linking transverse joint. Joints are open and weathered where they are exposed in outcrops. However, with increasing depth, joints typically become tighter and less weathered or contain clay.

Hydraulic conductivity of the bedrock aquifer is directly related to the number, size, clay content, and degree of connection of joints. Hydraulic conductivity is greatest near the bedrock surface and decreases substantially within 5–50 ft of the surface, based on observations of fractures in outcrops, road cuts, core holes, and wells in the Boulder batholith. Most ground-water flow within the bedrock aquifer is in the uppermost fractured and weathered zone. Deeper fractures within the batholith can be saturated, as observed in a 100-ft-deep core hole 4 mi southeast of the study area, but fracture width and hydraulic conductivity generally are very small. Recharge from precipitation and snowmelt readily infiltrates the upper zone of weathered rock; shallow ground water follows the general topographic gradient and discharges to nearby seeps, springs, and streams. Discharge from the weathered bedrock commonly is observed at abrupt changes in topographic slope and at the contact between highly weathered and jointed rock and underlying rock that is less weathered. In the Buckeye study area, ground-water flow in the bedrock aquifer follows short flow paths from areas of recharge on slopes near the mines to areas of discharge along the valley margins and into sediments of the upper Basin Creek valley. Ground-water discharge, in the form of large seeps, was observed near the base of the bedrock hillsides south and southwest of the Buckeye and Enterprise mines. The ground-water discharge observed at this site is consistent with the conceptual model of ground-water flow as presented by McDougal and others (this volume, Chapter D9).

Saturated unconsolidated deposits that include till, alluvium, colluvium, wetland deposits, and volcanic ash form a heterogeneous aquifer that is hydraulically connected to Basin Creek. The unconsolidated deposits that compose the flood plain range from less than 1 ft to more than 30 ft thick and are overlain by mill tailings near the Buckeye mine. Bouldery till makes up a large part of the unconsolidated deposits. The till is exposed near the valley margin south of Basin Creek and along the stream banks about 1,200 ft downstream from the Buckeye flotation-mill tailings. Till overlies bedrock within much of the Basin Creek valley, and a small moraine at the lower end of the study area likely formed a natural dam to postglacial Basin Creek. Sediments that accumulated upstream from the moraine included stream-laid silt, sand, and gravel; organic-rich silt and clay; and volcanic ash from the eruption of Mount Mazama, about 6,845 years before present. Geologic and hydrologic characteristics of the unconsolidated-deposits aquifer were explored with shallow test wells.

Test Wells

Nine test wells (fig. 14; table 3) were drilled in the study area by Maxim Technologies Inc., under a contract with the USDA Forest Service. The wells were drilled into the unconsolidated deposits in the flood plain of Basin Creek to characterize the aquifer, to determine directions of ground-water flow, and to measure the quality of ground water. Seven of the test wells were installed in the area mantled by or adjacent to mill tailings. The test wells were installed using hollow-stem auger methods and were constructed of 2-in. diameter PVC (polyvinyl chloride) casing and screen, with 6-in. diameter

Figure 14. Location of test wells and configuration of water table, August 3, 1999.

Table 3. Well-completion data for test wells near upper Basin Creek.

[Data from Maxim Technologies, Inc., unpub. data, 1998]

Well No. (fig. 14)	Latitude N.	Longitude W.	Altitude of land surface (feet)	Drilled depth of well (feet)	Screen interval (feet)	Height of casing above land surface (feet)	Interval of bentonite seal (feet below land surface)
1	462344	1121737	7,038.6	10.8	5.6-10.6	2.8	0-3.6
2	462343	1121741	7,039.7	24.8	16.7-21.7	2.8	0-14.0
3	462342	1121742	7,034.8	11.0	5.5-10.5	3.0	0-3.7
4	462340	1121743	7,032.5	31.0	26-31	3.1	0-23.8
5	462340	1121742	7,032.8	8.5	3.5-8.5	3.0	0-2.2
6	462342	1121746	7,032.5	10.0	4.5-9.5	3.2	0-3.7
7	462341	1121746	7,032.3	11.0	5.5-10.5	2.9	0-4.7
8	462342	1121748	7,032.0	13.0	5.5-10.5	2.8	0-4.4
9	462347	1121733	7,043.6	17.0	10-15	2.3	0-8.9
10	462339	1121743	7,034.2	5.0	4-5	2.2	none[1]

[1] Sealed with cuttings.

steel protective casing at the surface. Each well screen was packed with silica filter sand and the entire annular space above the sand was sealed with bentonite. One additional shallow well (well 10) was drilled south of Basin Creek using a hand auger. Well 10 was installed in an area where an electromagnetic survey indicated moderately high values of conductivity and the possibility of ground water affected by acidic drainage from the Buckeye mill-tailings site.

Water Levels and Flow Directions

Water levels in test wells were measured periodically between December 1998 and August 1999 (table 4). Water-level data show that the water table is near land surface under the Basin Creek flood plain and in the area containing flotation-mill tailings. During part of the year, ground water saturates much of the mill tailings along Basin Creek. Water levels generally are highest in May and June, which also is when snowmelt and rain generally increase water depth and streamflow in upper Basin Creek. At well 6, measurements made in May and June documented water levels above land surface. Ground water was observed seeping from the ground in the vicinity of well 6 during that time.

A contour map showing the configuration of the water table (fig. 14) and direction of shallow ground-water flow was prepared using water-level measurements made on August 3, 1999. Water-level data for the contour map were collected from 10 wells and from water-surface altitudes of Basin Creek, surveyed at nine locations within the study area. Water-surface altitudes in Basin Creek were similar to water-table altitudes measured in shallow wells (wells 5 and 7) near the stream, indicating hydraulic connection between the stream and flood-plain sediments.

In the upstream part of the study area in the vicinity of wells 1 and 9, ground water flows southwesterly toward Basin Creek. Ground water probably moves from the vicinity of the Enterprise mine toward wells 1 and 9, and to Basin Creek, as inferred from the topographic slope in that area.

Water-level data from wells 2 through 8 indicate that ground water follows a curved flow path as it moves south and west through the area of mill tailings on the flood plain of Basin Creek. Ground water moves southward from the general area of the Buckeye mine toward wells 2 and 3 and then moves predominantly westward along the flood plain in the area of wells 4, 7, and 8. During low streamflow conditions (July through March), little or no ground water discharges to Basin Creek adjacent to or immediately downstream from the mill tailings. In the area of wells 4, 5, 7, and 10, water-level data indicate that some water may be moving from Basin Creek into the flood-plain deposits.

During higher streamflow conditions (generally late April, May, and June), water levels in wells are at their peak for the year. Based on synoptic streamflow measurements in May 1999, the high water table during spring and early summer does not cause a measurably larger discharge of ground water directly into Basin Creek than during low flow, probably because the stream also is at a higher stage at that time. It was observed that during higher water levels, water seeps out of the ground in the western and northwestern parts of the tailings deposits and that seepage drains into small tributaries flowing into Basin Creek.

Hydraulic properties of the unconsolidated-deposits aquifer were estimated from aquifer tests conducted at the nine test wells. Aquifer tests were made using a slug-injection method; changes in head were measured with a submersible pressure transducer and programmable data logger. Aquifer test data were analyzed using the curve-matching method of Cooper and others (1967). Results of aquifer tests are presented in table 5. Hydraulic conductivity values determined from the aquifer tests ranged over 3 orders of magnitude, from 0.03 to 40 ft/d. The median hydraulic conductivity was a relatively small 0.22 ft/d, reflecting the large amount of silt and clay in the sediments underlying the Basin Creek flood plain.

During low flow, discharge of ground water from the unconsolidated-deposits aquifer to Basin Creek is minimal. The water-table configuration and flow directions drawn from water-level data collected in August 1999 (fig. 14) show that ground water discharges to Basin Creek in the stream reach upstream from the mill tailings (area 1, fig. 14), but not in the area of mill tailings (area 2, fig. 14). Ground-water discharge to Basin Creek or rate of ground-water flow through sediments underlying the Basin Creek flood plain can be estimated from the gradient of the water table, cross-sectional area of the aquifer, and hydraulic conductivity of the sediments. The rate of ground-water discharge into Basin Creek within area 1 is about 25 ft^3/d, assuming an average gradient of 0.017, an aquifer cross-sectional area of 6,900 ft^2 (15 ft × 460 ft), and an average hydraulic conductivity of 0.21 ft/d (wells 1 and 9). The calculated rate of ground-water discharge within area 1 applies to discharge from the northwest side of Basin Creek and does not include discharge from the south side of the stream.

During low flow, Basin Creek receives little or no ground-water discharge through the area of mill tailings (area 2, fig. 14). Water-table contours in figure 14 indicate that near Basin Creek, ground water flows predominantly to the west, nearly parallel with the stream. The rate of ground-water flow through the upper 15 ft of sediments in the vicinity of wells 3 through 8 during low flow is about 220 ft^3/d. The calculated flow rate is for the cross section between Basin Creek and well 6, and assumes a gradient of 0.007 (4 ft/570 ft), an aquifer cross-sectional area of 3,750 ft^2 (15 ft × 250 ft), and an average hydraulic conductivity of 8.6 ft/d (average for wells 3–8, table 3).

Water Quality and Trace-Element Loads

Quality of ground water in deposits underlying the Basin Creek flood plain was determined by analysis of samples collected at 10 test wells (fig. 14). Seven of the ten test wells (wells 2-8) were in the area of mill tailings, one well (well 10) was south of Basin Creek, and two wells (wells 1 and 9) were

Table 4. Water levels, pH, and specific conductance of ground water from test wells near upper Basin Creek.

[µS/cm, microsiemens per centimeter at 25 degrees Celsius; --, no data]

Well No. (fig. 14)	Date	Water level, below or above (+) land surface (feet)	pH (standard units)	Specific conductance (µS/cm)
1	12-01-98	2.51	4.7	758
	02-23-99	2.62	3.8	768
	04-19-99	.41	--	--
	05-20-99	.16	--	--
	05-24-99	--	4.0	529
	06-07-99	--	3.4	556
	06-14-99	.18	--	--
	08-03-99	2.65	--	--
2	12-01-98	7.66	8.4	505
	02-23-99	7.83	8.2	447
	04-19-99	6.38	--	--
	05-20-99	5.02	--	--
	05-24-99	--	7.4	416
	06-07-99	--	7.2	414
	06-14-99	5.28	--	--
	08-03-99	7.10	--	--
3	12-01-98	3.78	4.9	1,260
	02-23-99	3.86	3.6	1,690
	04-19-99	2.98	--	--
	05-20-99	2.90	--	--
	05-24-99	--	4.2	1,200
	06-07-99	--	5.9	1,110
	06-14-99	3.12	--	--
	08-03-99	3.82	--	--
4	12-01-98	1.54	7.4	516
	02-23-99	1.65	8.0	443
	04-19-99	.91	--	--
	05-20-99	.68	--	--
	05-24-99	--	7.8	445
	06-07-99	--	7.8	409
	06-14-99	.95	--	--
	08-03-99	1.60	--	--
5	12-01-98	1.90	5.8	147
	02-23-99	2.03	6.0	136
	04-19-99	1.21	--	--
	05-20-99	.90	--	--
	05-24-99	--	3.6	1,530
	06-07-99	--	3.7	1,800
	06-14-99	1.24	--	--
	08-03-99	2.03	--	--
6	12-01-98	1.46	6.6	388
	02-23-99	1.52	6.5	364
	04-19-99	.43	--	--
	05-20-99	+.21	--	--
	05-24-99	--	6.4	371
	06-07-99	--	6.9	386

Table 4. Water levels, pH, and specific conductance of ground water from test wells near upper Basin Creek.—Continued

Well No. (fig. 14)	Date	Water level, below or above (+) land surface (feet)	pH (standard units)	Specific conductance (µS/cm)
6 (cont.)	06-14-99	+.22	--	--
	08-03-99	1.54	--	--
7	12-01-98	1.74	5.9	342
	02-23-99	1.88	5.4	290
	04-19-99	1.12	--	--
	05-20-99	1.02	--	--
	05-24-99	--	5.7	256
	06-07-99	--	6.6	330
	06-14-99	1.20	--	--
	08-03-99	1.85	--	--
8	12-01-98	4.58	6.3	381
	02-23-99	4.62	6.5	273
	04-19-99	4.01	--	--
	05-20-99	3.16	--	--
	05-24-99	--	6.2	390
	06-07-99	--	7.1	427
	06-14-99	3.48	--	--
	08-03-99	4.44	--	--
9	12-01-98	2.26	7.0	920
	02-23-99	2.29	6.9	924
	04-19-99	1.03	--	--
	05-20-99	.49	--	--
	05-24-99	--	6.6	903
	06-07-99	--	6.1	911
	06-14-99	.76	--	--
	08-03-99	2.43	--	--
10	07-30-99	--	6.5	167
	08-03-99	3.45	--	--

northeast of the mill tailings between Basin Creek and the Enterprise mine (fig. 14). Before the wells were sampled for chemical analysis in June and July 1999, they were purged on three occasions with a hand bailer. The wells were purged and sampled for pH and specific conductance in December 1998, and February and May 1999 (table 4).

Water samples were collected from wells 1–9 on June 7, 1999, and from well 10 on July 30, 1999, and analyzed for common ions and dissolved (0.45-micrometer (µm) filtration) trace elements (table 6). Samples from wells 1, 3, and 5 had relatively low pH and elevated concentrations of dissolved trace elements, indicating effects from acid drainage. Well 1, which is located northeast of the mill tailings, had water with a pH of 3.4 when sampled in June 1999. Water from well 1 had relatively high concentrations of dissolved aluminum, cadmium, copper, lead, manganese, and zinc (table 6). The largest dissolved lead concentration analyzed from the 10 wells was 36 micrograms per liter (µg/L) from well 1.

Water from well 3, located near the center of the mill tailings, had a pH of 5.9 when sampled in June 1999, although a sample taken in February 1999 had a pH of 3.6 (tables 4 and 6). Water from well 3 had high dissolved concentrations of dissolved aluminum, arsenic, iron, manganese, and zinc. The

Table 5. Hydraulic properties of unconsolidated deposits along upper Basin Creek.

[ft/d, foot per day; ft^2/d, foot squared per day]

Well No. (fig. 14)	Transmissivity (ft^2/d)	Hydraulic conductivity (ft/d)	Average horizontal hydraulic gradient in area of well (August 1999)	Geologic description of unconsolidated deposits in screen interval
1	1.0	0.20	0.010	Silty sand, sandy clay.
2	.19	.04	.018	Sandy, gravelly clay (till).
3	3.0	.60	.005	Sandy silt.
4	.25	.05	.003	Silty sand, sandy clay.
5	200	40	.003	Silty fine to coarse sand, sandy clay.
6	.16	.03	.018	Clayey sand, silty sand, gravel, weathered rock.
7	8.3	1.7	.015	Silty, clayey sand.
8	46	9.2	.015	Silty sand, gravel, cobbles.
9	1.1	.22	.024	Silty sand with some gravel.

largest arsenic concentration analyzed from the 10 wells was 19,000 µg/L from well 3.

Water from well 5 had a pH of 3.7 and relatively high concentrations of dissolved aluminum, arsenic, cadmium, copper, lead, manganese, and zinc. Of the 10 wells sampled, well 5 had the highest concentrations of aluminum (55,200 µg/L), cadmium (220 µg/L), copper (2,290 µg/L), and zinc (49,100 µg/L).

Wells 2, 4, 6, 7, and 8 were completed in the area of mill tailings between the Buckeye mine and Basin Creek. Water samples collected from these five wells in June 1999 had pH values that ranged from 6.6 at well 7 to 7.8 at well 4. Concentrations of dissolved aluminum, cadmium, copper, lead, and zinc were relatively low in water samples from wells 2, 4, and 6. Wells 2 and 4 are the deepest of the 10 wells and are completed in parts of the aquifer not directly affected by acid drainage. Well 6 is located at the northwestern margin of the mill tailings, upgradient from flow paths in the mill tailings, and also is not directly affected by acid drainage. Water from well 7 had relatively high concentrations of dissolved arsenic (680 µg/L) and iron (27,000 µg/L). Well 8 had a large concentration of dissolved zinc (10,300 µg/L).

Well 9, located south of the Enterprise mine, had a dissolved zinc concentration of 292 µg/L when sampled in June 1999. Well 10, located south of Basin Creek in an area not disturbed by mining, had relatively low concentrations of dissolved trace elements, except for arsenic (45 µg/L) and iron (15,000 µg/L).

Loads of trace elements reaching Basin Creek from shallow ground water can be estimated from trace-element concentrations sampled at wells and rates of ground-water flow through the upper part of the aquifer. For the stream reach upstream from the mill tailings (area 1, fig. 14), calculated ground-water discharge into Basin Creek is about 25 ft^3/d during low flow. The calculated ground-water discharge applies to the upper 15 ft of deposits, which contains most of the poor-quality water from acid drainage. Estimated trace-element loads to Basin Creek in area 1 are shown in table 7 and are based on the average trace-element concentrations at wells 1 and 9. Within area 2 of Basin Creek, ground-water flow predominantly is to the west, parallel to Basin Creek. During low flow, the dissolved trace-element load in ground water is not discharging directly to Basin Creek adjacent to the mill tailings (area 2) but likely enters Basin Creek downstream, probably within a zone from 500 to 1,200 ft west of the mill tailings. Flood-plain deposits are pinched off by a glacial moraine about 1,200 ft down valley from the mill tailings, favoring the discharge of ground water from the flood-plain deposits into Basin Creek in that area. Trace-element loads to Basin Creek from area 2 (table 7) are based on the average trace-element concentration at wells 3, 5, 6, 7, and 8 and the rate of ground-water discharge of about 220 ft^3/d during low flow.

Downstream increases in trace-element loads measured in upper Basin Creek through the Buckeye study area during low flow also can be used to evaluate the ground-water contribution to trace-element loads in Basin Creek. Water samples collected upstream (site 4B, fig. 15) and downstream (site 22B) from the mine area during low flow on October 16, 1998, showed substantial increases in some concentrations of dissolved aluminum, arsenic, manganese, and zinc (table 8). Dissolved aluminum increased from 2.3 µg/L above the mines to 12 µg/L below the mines, dissolved arsenic increased from 1 µg/L to 14 µg/L, dissolved manganese increased from 8 µg/L to 52 µg/ L, and dissolved zinc increased from 7 µg/L to 26 µg/L. Combining streamflow measurements with trace-element concentrations to compute instantaneous loads (table 9) indicated that dissolved aluminum load increased from 2.4 grams per day (g/d) above the mines to 19.4 g/d below the mines, dissolved arsenic load increased from 1.0 g/d to 22.6 g/d, dissolved copper load increased from <1 g/d to 3.2 g/d, dissolved manganese load increased from 8.4 g/d to 84.0 g/d, and dissolved zinc load increased from 7.4 g/d to 42.0 g/d.

Table 6. Concentrations of major ions and dissolved trace elements in ground water near upper Basin Creek.

[µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; <, less than minimum reporting level]

Well No. (fig. 14)	Date	Specific conductance, field (µS/cm)	pH, field (standard units)	Alkalinity, laboratory (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Potassium, dissolved (mg/L)	Sulfate, dissolved (mg/L as SO_4)
1	06-07-99	556	3.4	<1	64	11	5.3	2.4	270
2	06-07-99	414	7.2	79	43	14	17	4.5	120
3	06-07-99	1,110	5.9	<1	160	32	21	1.4	1,100
4	06-07-99	409	7.8	213	46	11	25	7.9	6.2
5	06-07-99	1,800	3.7	<1	240	36	17	1	1,100
6	06-07-99	386	6.9	125	44	9.5	14	5.3	56
7	06-07-99	330	6.6	16	31	8.1	4.9	1.5	100
8	06-07-99	427	7.1	29	45	11	9	<.1	160
9	06-07-99	911	6.1	94	140	27	16	6.5	390
10	07-30-99	167	6.5	64	14	4.6	5.9	.8	<0.1

Well No. (fig. 14)	Chloride, dissolved (mg/L)	Dissolved solids, sum of constituents (mg/L)	Aluminum, dissolved (µg/L)	Arsenic, dissolved (µg/L)	Cadmium, dissolved (µg/L)	Copper, dissolved (µg/L)	Iron, dissolved (µg/L)	Lead, dissolved (µg/L)	Manganese, dissolved (µg/L)	Zinc, dissolved (µg/L)
1	0.7	350	4,780	4	40	820	1,300	36	6,060	4,850
2	1.5	250	4	6	<1	1	55	<1	1,310	9
3	1.6	1,300	307	19,000	<1	2	130,000	3	7,080	12,200
4	4.4	230	3	26	<1	<1	310	<1	256	1
5	8.8	1,400	55,200	68	220	2,290	1,400	20	6,770	49,100
6	3.6	220	2	2	<1	<1	5,900	<1	3,770	9
7	1	190	8	680	<1	<1	27,000	<1	2,230	9
8	2.3	250	272	28	5	1	9,200	<1	2,290	10,300
9	.8	630	2	15	5	1	1,300	<1	1,140	292
10	.9	65	18	45	<1	<1	15,000	<1	135	2

Table 7. Estimated dissolved trace-element loads discharged to upper Basin Creek during low flow from shallow ground water in the vicinity of the Buckeye and Enterprise mines.

[g/d, grams per day]

Trace element	Load from area 1 (g/d)	Load from area 2[1] (g/d)
Aluminum	1.69	69.5
Arsenic	.007	24.7
Cadmium	.016	[2].28
Copper	.290	[2]2.85
Iron	.920	216
Lead	[2].025	[2].031
Manganese	2.55	27.6
Zinc	1.82	89.1

[1] Load from area 2 likely enters upper Basin Creek downstream from tailings area.

[2] For values that were reported as less than the minimum reporting level of 1 µg/L, the value of 1 µg/L was used to calculate an average trace-element concentration.

The increased load of trace elements in Basin Creek in the Buckeye study area during this base-flow period likely is primarily from ground-water discharge. These trace-element-load data collected during low flow support the calculations of ground-water discharge and verify that the volume of trace-element-rich ground water that enters Basin Creek near the mines is small. However, this ground-water discharge has a marked effect on concentrations in the stream due to the large concentrations of trace elements in the ground water and the small streamflow in Basin Creek. The loads contributed by ground water in areas 1 and 2 (table 7) can account for essentially all of the load increase during low flow in the study reach below the mines.

Dissolved trace elements entering Basin Creek from ground water generally do not cause the trace-element concentrations in Basin Creek to exceed the State of Montana acute aquatic-life standards during low flow. Dissolved and total-recoverable zinc concentrations (26 and 42 µg/L) at site 22B below the Buckeye mine (sample of October 16, 1998) were near the chronic and acute aquatic-life standard of 40 µg/L (Montana Department of Environmental Quality, 1999).

During spring snowmelt and resulting high streamflow, ground water with high dissolved trace-element concentrations (table 6) discharges from the mill tailings and increases the trace-element load in Basin Creek. The water table is at or near land surface during snowmelt. Shallow ground water and overland runoff leach the entire thickness of tailings and carry dissolved trace elements toward Basin Creek. Ground water seeps out of the upper part of the saturated tailings, combines with overland runoff, and flows into very small tributaries which discharge into Basin Creek. Shallow ground water also discharges directly to Basin Creek through diffuse bank seepage. Trace-element concentrations of these small tributaries were sampled during high runoff in May 1999 and are discussed in subsequent sections of this report.

Streambed Sediment in Basin Creek

Streambed-sediment samples were collected at six sites along Basin Creek (fig. 15) (Fey, Unruh, and Church, 1999). The minus-80-mesh (<0.18 mm) fraction was analyzed for leachable trace elements (Rich and others, this volume) to determine the location and magnitude of potential effects from the mine area. Trace-element concentrations in streambed-sediment samples are influenced by the input of material eroded upstream of the sample site as well as by the formation and subsequent deposition of colloidal material on the streambed during periods of low streamflow. Downstream increases in the concentrations of iron and trace elements are readily apparent in the streambed-sediment data summarized in table 10 and indicate that the Buckeye and Enterprise mine area is a source of iron and trace elements transported to Basin Creek and deposited on the streambed. The concentrations of antimony, arsenic, lead, and silver increase dramatically in the downstream direction, particularly between sites 21bS and 21cS, which are adjacent to the central part of the flotation-mill tailings. The location of these increases indicates the importance of the flotation-mill tailings as a source of trace elements that presumably have been transported via both surface water and ground water to Basin Creek. Ferricrete deposits (iron-hydroxide-cemented lithic deposits) on the north bank of Basin Creek at sites 21bS and 21cS provide additional evidence that iron has been transported by ground water from the mill-tailings area to Basin Creek. In contrast to antimony, arsenic, lead, and silver, the increases in concentrations of cadmium, copper, and zinc in streambed sediment are less dramatic, probably because these latter trace elements partition less strongly to the colloidal and particulate phases (Church and others, 1997; Schemel and others, 2000; Nimick and Cleasby, this volume, Chapter D5).

Surface Water

Basin Creek, a tributary of the Boulder River, drains the Buckeye study area and surrounding lands. Upper Basin Creek enters the study area from the east, is joined by a small south-flowing tributary near the Enterprise mine, and flows westerly through the study area (fig. 15). At the tributary confluence (near site 4B) above the Buckeye mine, upper Basin Creek has a drainage area of 1.51 mi^2; land-surface altitudes within this drainage area range from about 7,060 to 8,568 ft. The small south-flowing tributary (Enterprise Mine tributary) that joins upper Basin Creek in the eastern part of the study area (site 3T) has a drainage area of 0.32 mi^2 and land-surface altitudes that range from 7,060 to 7,580 ft. The combined drainage area of upper Basin Creek at the mouth of this tributary is 1.83 mi^2.

Table 8. Streamflow and water-quality data for upper Basin Creek, 1996–99.

[ft^3/s, cubic feet per second; °C, degrees Celsius; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; mm, millimeter; --, no data; <, less than minimum reporting level]

Site No. (fig. 15)	Site No.[1]	Station name	Date	Time	Streamflow, instantaneous (ft^3/s)	Specific conductance, field (µS/cm)	Temperature, water (°C)	pH, field (standard units)	Sediment, suspended (mg/L)	Sediment, suspended, diameter (percent finer than 0.062 mm)	Hardness (mg/L as $CaCO_3$)
4B	5	Basin Creek above Buckeye mine, near Basin	10-16-96	1030	--	78	--	--	--	--	--
			09-25-98	1345	0.44	79	5.0	7.6	29	99	32
			10-16-98	1045	.43	76	1.0	7.8	1	80	31
			05-28-99	1010	7.9	37	2.0	8.1	--	--	16
			09-13-99	1115	.34	79	5.0	7.8	--	--	--
3T	6	Enterprise Mine tributary near Basin	10-16-98	1055	.05	87	1.0	8.3	1	67	36
			05-28-99	1030	1.7	42	6.0	7.1	--	--	16
			09-13-99	1030	.009	104	4.0	7.9	--	--	--
6B	7	Basin Creek below Enterprise Mine tributary, near Basin	05-27-97	1130	12	42	4.0	--	--	--	--
			04-30-98	1100	5.0	55	0.0	7.0	8	66	23
			05-07-98	1315	10	45	--	7.7	48	46	18
			10-16-98	1340	.48	75	.5	7.7	1	75	31
			05-28-99	0945	9.2	39	2.5	7.2	--	--	16
			09-13-99	1130	.37	80	5.0	7.8	--	--	--
22B	8	Basin Creek below Buckeye mine, near Basin	10-16-96	1010	.51	82	0.0	7.3	1	62	34
			05-27-97	1045	15	44	5.0	7.1	10	36	16
			04-30-98	1015	6.3	57	3.0	7.3	16	32	23
			05-07-98	1445	17	49	3.0	7.0	74	77	17
			09-25-98	1215	.49	80	8.0	7.8	4	79	32
			10-16-98	1315	.66	75	.5	7.6	4	82	27
			05-28-99	0840	13	39	2.0	6.7	--	--	16
			09-13-99	1250	.35	82	11.0	7.9	--	--	--

[1] Site number previously published in Nimick and Cleasby (2000).

Table 8. Streamflow and water-quality data for upper Basin Creek, 1996–99.—Continued

Site No. (fig. 15)	Date	Calcium (mg/L)	Magnesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Alkalinity, laboratory (mg/L as $CaCO_3$)	Sulfate (mg/L as SO_4)	Chloride (mg/L)	Fluoride (mg/L)	Silica (mg/L)	Dissolved solids, calculated (mg/L)
4B	10-16-96	--	--	--	--	--	--	--	--	--	--
	09-25-98	9.5	2.1	2.2	1.1	32	6.8	0.19	<0.10	14	55
	10-16-98	9.0	2.1	2.0	1.1	31	6.7	.24	<.10	14	53
	05-28-99	4.8	1.0	1.1	.68	15	2.7	.24	--	--	--
	09-13-99	--	--	--	--	--	--	--	--	--	--
3T	10-16-98	10	2.6	2.5	1.0	35	7.1	.26	<.10	11	55
	05-28-99	4.8	1.0	1.3	.64	11	6.6	.84	--	--	--
	09-13-99	--	--	--	--	--	--	--	--	--	--
6B	05-27-97	--	--	--	--	--	--	--	--	--	--
	04-30-98	6.7	1.5	1.3	1.0	19	6.5	.23	<.10	8.9	38
	05-07-98	5.4	1.2	1.1	.77	14	5.8	.27	<.10	7.2	31
	10-16-98	9.0	2.1	2.1	.94	31	6.8	.21	<.10	13	53
	05-28-99	4.8	1.0	1.2	.67	14	3.5	.21	--	--	--
	09-13-99	--	--	--	--	--	--	--	--	--	--
22B	10-16-96	10	2.3	2.3	1.0	32	8.7	.30	<.10	13	57
	05-27-97	4.8	1.1	1.2	.67	12	7.6	.19	<.10	9.6	33
	04-30-98	6.8	1.5	1.3	1.2	20	7.1	.28	<.10	8.9	40
	05-07-98	5.0	1.1	1.1	.91	10	8.7	.22	<.10	7.8	32
	09-25-98	9.3	2.2	2.2	.99	31	7.8	.19	<.10	14	56
	10-16-98	7.7	1.8	2.0	.83	29	7.5	.22	<.10	13	51
	05-28-99	4.7	1.0	1.2	.68	13	4.7	.22	--	--	--
	09-13-99	--	--	--	--	--	--	--	--	--	--

Table 8. Streamflow and water-quality data for upper Basin Creek, 1996–99.—Continued

Site No. (fig. 15)	Date	Aluminum, dissolved (µg/L)	Aluminum, total recoverable (µg/L)	Antimony, dissolved (µg/L)	Arsenic, dissolved (µg/L)	Arsenic, total recoverable (µg/L)	Barium, dissolved (µg/L)	Beryllium, dissolved (µg/L)	Cadmium, dissolved (µg/L)	Cadmium, total recoverable (µg/L)	Chromium, dissolved (µg/L)	Chromium, total recoverable (µg/L)
4B	10-16-96	--	--	--	--	--	--	--	--	--	--	--
	09-25-98	8.3	1,300	<1	3	4	8.1	<1	<0.3	<1	<1	--
	10-16-98	2.3	17	<1	1	2	4.7	<1	<.3	<1	<1	--
	05-28-99	52	185	--	2	4	--	--	<.3	<1	--	--
	09-13-99	--	--	--	--	--	--	--	--	--	--	--
3T	10-16-98	3.8	21	<1	<1	3	5.5	<1	<.3	<1	<1	--
	05-28-99	160	440	--	3	8	--	--	1.9	2	--	--
	09-13-99	--	--	--	--	--	--	--	--	--	--	--
6B	05-27-97	--	--	--	--	--	--	--	--	--	--	--
	04-30-98	149	350	<1	3	5	6.1	<1	<.3	<1	<1	--
	05-07-98	102	900	<1	7	10	5.5	<1	.5	<1	<1	--
	10-16-98	13	<10	<1	2	2	4.7	<1	<.3	<1	<1	--
	05-28-99	66	220	--	2	3	--	--	.4	<1	--	--
	09-13-99	--	--	--	--	--	--	--	--	--	--	--
22B	10-16-96	22	--	3	16	19	5.0	<1	.2	<1	<1	<1
	05-27-97	225	430	2	13	36	6.1	<1	1.2	1	<1	<1
	04-30-98	154	430	3	29	52	7.9	<1	.8	<1	<1	--
	05-07-98	219	1,300	7	38	500	8.3	<1	1.4	2	<1	--
	09-25-98	13	90	4	21	24	5.8	<1	<.3	<1	<1	--
	10-16-98	12	72	2	14	30	4.3	<1	<.3	<1	<1	--
	05-28-99	120	300	--	10	25	--	--	.6	<1	--	--
	09-13-99	--	--	--	--	--	--	--	--	--	--	--

Table 8. Streamflow and water-quality data for upper Basin Creek, 1996–99.—Continued

Site No. (fig. 15)	Date	Cobalt, dissolved (µg/L)	Copper, dissolved (µg/L)	Copper, total recoverable (µg/L)	Iron, dissolved (µg/L)	Iron, total recoverable (µg/L)	Lead, dissolved (µg/L)	Lead, total recoverable (µg/L)	Lithium, dissolved (µg/L)	Manganese, dissolved (µg/L)	Manganese, total recoverable (µg/L)
4B	10-16-96	--	--	--	--	--	--	--	--	--	--
	09-25-98	<1	<1	3	17	1,200	<1	7	--	13	46
	10-16-98	<1	<1	<1	48	71	<1	<1	--	8	<10
	05-28-99	--	2	2	61	240	<1	1	--	3	11
	09-13-99	--	--	--	--	--	--	--	--	--	--
3T	10-16-98	<1	<1	<1	50	190	<1	<1	--	54	73
	05-28-99	--	11	14	79	460	<1	1	--	178	220
	09-13-99	--	--	--	--	--	--	--	--	--	--
6B	05-27-97	--	--	--	--	--	--	--	--	--	--
	04-30-98	<1	9	9	190	600	<1	1	--	184	200
	05-07-98	<1	5	7	160	2,000	<1	7	--	229	330
	10-16-98	<1	<1	<1	103	130	<1	<1	--	28	26
	05-28-99	--	4	3	54	230	<1	<1	--	39	43
	09-13-99	--	--	--	--	--	--	--	--	--	--
22B	10-16-96	<1	2	4	130	170	<1	3	<4	65	70
	05-27-97	<1	18	18	180	530	10	24	<4	136	140
	04-30-98	<1	11	12	240	880	7.7	28	--	187	200
	05-07-98	<1	18	40	240	3,200	23	340	--	306	410
	09-25-98	<1	2	3	93	250	<1	2	--	48	55
	10-16-98	<1	2	3	88	380	<1	9	--	52	74
	05-28-99	--	9	11	100	350	5.4	17	--	85	91
	09-13-99	--	--	--	--	--	--	--	--	--	--

Table 8. Streamflow and water-quality data for upper Basin Creek, 1996–99.—Continued

Site No. (fig. 15)	Date	Mercury, dis-solved (µg/L)	Mercury, total recov-erable (µg/L)	Molyb-denum, dis-solved (µg/L)	Nickel, dis-solved (µg/L)	Nickel, total recov-erable (µg/L)	Silver, dis-solved (µg/L)	Silver, total recov-erable (µg/L)	Uranium, dis-solved (µg/L)	Zinc, dis-solved (µg/L)	Zinc, total recov-erable (µg/L)
4B	10-16-96	--	--	--	--	--	--	--	--	--	<10
	09-25-98	--	--	<1	<1	--	<1	--	<1	3	20
	10-16-98	--	--	<1	<1	--	<1	--	<1	7	10
	05-28-99	--	--	--	--	--	--	--	--	6	<40
	09-13-99	--	--	--	--	--	--	--	--	--	--
3T	10-16-98	--	--	<1	<1	--	<1	--	<1	15	21
	05-28-99	--	--	--	--	--	--	--	--	234	250
	09-13-99	--	--	--	--	--	--	--	--	--	--
6B	05-27-97	--	--	--	--	--	--	--	--	--	100
	04-30-98	--	--	<1	1	--	<1	--	<1	129	130
	05-07-98	--	--	<1	1	--	<1	--	<1	109	140
	10-16-98	--	--	<1	<1	--	<1	--	<1	12	15
	05-28-99	--	--	--	--	--	--	--	--	49	52
	09-13-99	--	--	--	--	--	--	--	--	--	--
22B	10-16-96	<0.1	<0.1	<1	<1	<1	<1	<1	<1	39	40
	05-27-97	--	<.1	<1	<1	<1	<1	<1	<1	173	180
	04-30-98	--	--	<1	1	--	<1	--	<1	140	150
	05-07-98	--	--	<1	<1	--	<1	--	<1	218	270
	09-25-98	--	--	<1	<1	--	<1	--	<1	24	30
	10-16-98	--	--	<1	<1	--	<1	--	<1	26	42
	05-28-99	--	--	--	--	--	--	--	--	90	95
	09-13-99	--	--	--	--	--	--	--	--	--	--

Table 9. Dissolved trace-element loads in upper Basin Creek upstream and downstream of the Buckeye and Enterprise mines, October 16, 1998.

[g/d, grams per day; <, less than]

Trace element	Instantaneous load upstream[1] (g/d)	Instantaneous load downstream[1] (g/d)
Aluminum	2.4	19.4
Arsenic	1.0	22.6
Cadmium	[2]<.4	<.5
Copper	[2]<1	3.2
Iron	50.5	142
Lead	[2]<1.2	[2]<1.6
Manganese	8.4	84.0
Zinc	7.4	42.0

[1] Site 4B used to represent load upstream of the mines, instantaneous streamflow was 0.43 ft^3/s; site 22B used to represent load downstream, instantaneous streamflow was 0.66 ft^3/s.

[2] For concentrations that were reported as less than the minimum reporting level, the value of 1 µg/L for lead and copper and 0.3 µg/L for cadmium was used to calculate a maximum value for the load.

Figure 15. Location of streambed-sediment and surface-water sampling sites, upper Basin Creek.

Table 10. Concentrations of leachable iron and selected trace elements in streambed-sediment samples, upper Basin Creek.[1]

[A 2M HCl, 1-percent H_2O_2 solution was applied to streambed-sediment samples which dissolved amorphous iron oxyhydroxide phases. Concentrations in parts per million (micrograms/gram); <, less than minimum reporting level]

Site No. (fig. 15)	Date	Antimony	Arsenic	Cadmium	Copper	Iron	Lead	Silver	Zinc
20S	July 1998	<3	34	<1	16	16,000	64	<1	160
21aS	July 1997	<3	170	2.8	61	22,000	160	1.4	500
21bS	July 1997	<3	600	1.7	50	21,000	410	3.0	390
21cS	July 1997	33	3,000	2.1	79	20,000	1,200	6.5	350
21dS	July 1997	40	3,000	3.2	99	28,000	1,600	8.6	460
21eS	October 1996	34	4,000	5.0	120	33,000	1,600	6.9	680

[1] Data from Fey, Unruh, and Church (1999, table 7).

As upper Basin Creek flows through the study area to site 22B, it receives drainage from an additional 0.71 mi^2 area, of which 0.634 mi^2 is situated south of Basin Creek and 0.076 mi^2 is situated in the vicinity of the Buckeye and Enterprise mines on the north side of Basin Creek. The total drainage area of Basin Creek below Buckeye mine (to site 22B) is 2.54 mi^2.

Flow Characteristics of Basin Creek

Streamflow in Basin Creek near the Buckeye and Enterprise mines was measured periodically at sites 4B, 6B, and 22B between October 1996 and September 1999 (table 8). The highest measured flows were in May 1997, 1998, and 1999. The maximum measured streamflow in Basin Creek was 17 ft^3/s at site 22B below the Buckeye mine on May 7, 1998. The lowest flows were measured on September 13, 1999, when streamflow in Basin Creek below the Buckeye mine was 0.35 ft^3/s. Monthly distribution of annual runoff of Basin Creek can be estimated from long-term records for the streamflow-gauging station Boulder River at Boulder, Mont. (station number 06033000). Based on 1929–98 streamflow records for the Boulder River gauge, mean monthly streamflow is greatest in May and second greatest in June (U.S. Geological Survey, issued annually). May accounts for nearly 34 percent of the mean annual streamflow and June accounts for nearly 29 percent (fig. 16). For the period August through March, each month accounts for less than 5 percent of the mean annual streamflow of the Boulder River. The monthly streamflow pattern of Basin Creek in the study area likely is similar to the monthly streamflow pattern of the Boulder River.

Water Quality and Synoptic Sampling

Analyses of water samples collected from upper Basin Creek, at various dates and streamflow conditions, documented higher concentrations of dissolved trace elements at higher streamflows (table 8). For example, dissolved zinc concentrations in Basin Creek below the Buckeye mine (site 22B) ranged from 24 µg/L during low flow on September 25, 1998, to 218 µg/L during high flow on May 7, 1998. The relationship between dissolved zinc concentration and streamflow in Basin Creek below the Buckeye mine is shown in figure 17. A similar pattern of higher concentration of dissolved trace elements with larger streamflow was observed for aluminum, cadmium, copper, lead, and manganese.

Dissolved trace-element concentrations that are higher in Basin Creek at high streamflow than at low streamflow indicate that substantial amounts of dissolved trace elements sufficient to overcome dilution effects are delivered to the stream during high flow. Observations of streamflow and overland runoff made at the study area during periods of snowmelt in April and May 1999 indicated that tailings and waste rock are probable sources of dissolved trace elements (fig. 18). On April 19, 1999, upper Basin Creek contained considerable ice, snow, and slush, restricting flow in the stream and creating ponds of water on the flood plain and mill tailings. These ponds were saturating the mill tailings, and ground-water levels were rising to near land surface, as indicated by water levels in test wells located on the flood plain (fig. 14; table 4). On May 20, 1999, snow was rapidly melting and overland runoff was considerable from areas around the Buckeye and Enterprise mines and from the mill tailings. Runoff from the mines and tailings was discharging directly

Figure 16. Monthly distribution of mean annual streamflow of Boulder River (streamflow-gauging station 06033000, fig. 1).

Figure 17. Relation of dissolved zinc concentration and streamflow for Basin Creek below Buckeye mine, 1996–99.

Figure 18. Snowmelt runoff from flotation-mill tailings entering upper Basin Creek near site 12B, May 27, 1999.

into Basin Creek; some of the runoff had a pH value as low as 3.08, as measured onsite with a portable pH meter.

Water quality was sampled and streamflow was measured in upper Basin Creek and all tributaries on May 28, 1999, to determine concentrations and loads of trace elements at numerous sites in upper Basin Creek near the Buckeye and Enterprise mines during high streamflow in order to identify the primary sources of trace elements. Water-quality samples were collected and streamflow measured at 25 sites in a short period between 0800 and 1130 hours under uniform hydrologic conditions to provide a synoptic characterization of downstream changes. Physical properties measured in the field at the time of streamflow measurement were water temperature, specific conductance, and pH. Tributaries to Basin Creek were identified as entering from the right bank (bank with mining wastes) or left bank (bank with no mining wastes). Water analyses included major ions as well as dissolved and total-recoverable trace elements. Dissolved trace elements were determined from samples filtered through 0.1-µm membrane filters. Water-quality and streamflow data for all sites are listed in table 11, and site locations appear in figure 15.

During the synoptic sampling of May 28, 1999, streamflow in Basin Creek ranged from 7.9 ft^3/s above the Buckeye mine (site 4B) to 12 ft^3/s at the most downstream site (25B). Tributary inflows ranged from 0.005 ft^3/s (site 9T) to 1.65 ft^3/s (site 3T, Enterprise Mine tributary). A plot of the measured streamflow in Basin Creek and its tributaries shows that nearly all increases in flow in Basin Creek during a runoff condition could be accounted for by tributary inflow (fig. 19). Some small changes in streamflow between measurement sites may be attributed to ground water; however, the changes are so small that they are within the measurement error of the methods used to measure streamflow. The difference between the measured streamflow in Basin Creek at site 25B and the sum of the measured streamflow at site 4B plus all tributary inflows was 0.44 ft^3/s, or 3.6 percent of the streamflow at site 25B.

The quality of water sampled at the 25 synoptic sites (fig. 15) ranged from good-quality water typical of local, undisturbed mountain streams to acidic, trace-element-rich runoff that exceeds Montana aquatic-life standards for acute toxicity. Sites with good-quality water that could be considered as reference sites representative of undisturbed areas were Enterprise Mine tributary above the Enterprise mine (site 1T), Basin Creek above Buckeye mine (site 4B), and several tributaries to Basin Creek from the left bank (sites 14T, 18.5T, and 19T). Water from these undisturbed sites is characterized by nearly neutral pH, hardness values of 16 milligrams per liter (mg/L) or less, and low dissolved metal concentrations (dissolved cadmium <0.3 µg/L; dissolved copper from 1.8 to 2.9 µg/L; dissolved lead from <0.3 to 0.7 µg/L; and dissolved zinc from 1.4 to 3.0 µg/L).

Water from tributaries that drained waste rock or mill tailings had high concentrations of dissolved trace elements (table 11) when sampled on May 28, 1999. The highest concentrations of dissolved trace elements were: aluminum, 34,800 µg/L at site 7T; arsenic, 985 µg/L at site 17T; cadmium, 142 µg/L at site 2T; copper, 1,700 µg/L at site 7T; iron, 12,000 µg/L at site 17T; lead, 6,470 µg/L at site 11T; manganese, 23,500 µg/L at site 7T; and zinc, 17,800 µg/L at site 2T. Tributaries draining waste rock near the Enterprise and Buckeye mines (sites 2T, 7T, 9T) had the highest concentrations of dissolved aluminum, cadmium, copper, manganese, and

Table 11. Synoptic streamflow and water-quality data for upper Basin Creek and tributaries, May 28, 1999.

[Right bank, bank containing mining wastes; left bank, bank with no mining wastes. E, estimated; ft^3/s, cubic feet per second; °C, degrees Celsius; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; <, less than minimum reporting level; --, no data]

Site No. (fig. 15)	Site description	Streamflow, instantaneous (ft^3/s)	Temperature, water (°C)	Specific conductance (µS/cm)	pH, field (standard units)	Hardness, total (mg/L as CaCO$_3$)	Calcium, dissolved (mg/L)	Magnesium, dissolved (mg/L)
1T	Enterprise Mine tributary	1.52	4.0	29	7.7	12	3.7	0.8
2T	Tributary to Enterprise Mine tributary	.012	16.5	702	4.0	240	70	16
3T	Enterprise Mine tributary	1.65	6.0	42	7.1	16	4.8	1.0
4B	Basin Creek above Buckeye mine	7.87	2.0	37	8.1	16	4.8	1.0
6B	Basin Creek below Enterprise Mine tributary	9.22	2.5	38	7.2	16	4.8	1.0
7T	Basin Creek tributary, right bank	.018	10.0	849	3.4	148	38	13
8B	Basin Creek	9.89	3.0	40	7.3	17	4.9	1.1
9T	Basin Creek tributary, right bank	.005	9.0	566	3.9	153	47	8.9
10T	Basin Creek tributary, right bank	.014	6.5	383	4.1	125	41	5.8
11T	Basin Creek tributary, right bank	.018	5.5	375	3.3	30	9.5	1.6
12B	Basin Creek	10.7	2.0	41	7.3	17	4.9	1.1
13B	Basin Creek	10.2	4.0	42	7.2	17	5.0	1.1
14T	Basin Creek tributary, left bank	.58	8.0	39	6.9	16	4.8	.9
15T	Basin Creek tributary, left bank	.01	5.0	30	6.1	11	3.4	.7
16B	Basin Creek	11.1	3.0	42	7.0	16	4.8	1.1
17T	Basin Creek tributary, right bank	.021	14	504	3.1	31	9.5	1.7
18B	Basin Creek	10.8	3.0	42	7.0	17	5.0	1.1
18.5T	Basin Creek tributary, left bank	.175	--	42	6.7	15	4.5	.9
19T	Basin Creek tributary, two inflow points from left bank	1.18	5.0	25	6.2	9	2.6	.6
20T	Basin Creek tributary, left bank	.020	7.0	32	6.0	12	3.6	.8
21T	Basin Creek tributary, right bank	.066	8.5	25	5.1	5	1.6	.3
22B	Basin Creek below Buckeye mine	12.5	2.0	39	6.7	16	4.7	1.0
23T	Basin Creek tributary, right bank	.015	7.0	28	5.7	8	2.5	.5
24T	Basin Creek tributary, three inflow points from left bank	.156	.5	23	6.1	8	2.2	.6
25B	Basin Creek	12.2	1.5	39	7.0	16	4.6	1.0

Table 11. Synoptic streamflow and water-quality data for upper Basin Creek and tributaries, May 28, 1999.—Continued

Site No. (fig. 15)	Sodium, dissolved (mg/L)	Potassium, dissolved (mg/L)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L)	Alkalinity, laboratory (mg/L as $CaCO_3$)	Alumi-num, dissolved (µg/L)	Alumi-num, total recov-erable (µg/L)	Arsenic, dissolved (µg/L)	Arsenic, total recov-erable (µg/L)	Cadmium, dissolved (µg/L)
1T	1.2	0.6	1.5	0.2	12	76	231	2.3	2.3	<0.3
2T	3.7	3.6	370	.6	<1	9,980	10,300	45	50	142
3T	1.3	.6	6.6	.8	11	159	444	2.8	7.5	1.9
4B	1.1	.7	2.7	.2	15	52	185	2.2	3.8	<.3
6B	1.2	.7	3.5	.2	14	66	221	2.1	3.3	.4
7T	5.6	1.5	496	1.3	<1	34,800	32,800	123	146	107
8B	1.2	.7	4.6	.2	11	124	272	2.4	3.2	.6
9T	4.3	2.3	290	1.2	<1	14,600	14,200	271	447	57
10T	3.6	2.0	180	.5	<1	5,130	5,360	118	183	24
11T	4.4	1.7	94	.6	<1	1,350	1,800	280	5,190	23
12B	1.2	.7	4.8	.2	14	143	299	3.4	7.6	.7
13B	1.2	.7	5.2	.2	14	127	318	4.2	16	1.0
14T	1.7	.9	2.6	2.2	13	29	48	4.0	6.2	<.3
15T	1.3	.6	3.4	.3	9.2	57	136	22	32	<.3
16B	1.2	.7	--	<.1	<1	112	323	5.3	20	.7
17T	3.0	1.8	127	.5	<1	1,780	1,880	985	2,270	38
18B	1.2	.7	5.2	.2	14	126	305	7.9	23	.8
18.5T	1.7	1.0	3.0	.3	14	140	59	3.1	2.9	<.3
19T	1.1	.9	2.3	.2	9.0	64	148	1.6	3.2	<.3
20T	1.0	1.0	1.6	.4	12	78	99	33	33	<.3
21T	1.5	.7	--	--	--	94	--	182	--	1.2
22B	1.2	.7	4.7	.2	13	117	303	9.7	25	.6
23T	2.0	1.0	5.5	.6	5.5	94	205	153	220	1.3
24T	1.1	1.0	2.2	.3	8.2	69	97	15	17	<.3
25B	1.2	.7	4.6	.2	13	123	289	10	24	.6

Table 11. Synoptic streamflow and water-quality data for upper Basin Creek and tributaries, May 28, 1999.—Continued

Site No. (fig. 15)	Cadmium, total recov-erable (µg/L)	Copper, dissolved (µg/L)	Copper, total recov-erable (µg/L)	Iron, dis-solved (µg/L)	Iron, total recov-erable (µg/L)	Lead, dis-solved (µg/L)	Lead, total recov-erable (µg/L)	Manga-nese, dissolved (µg/L)	Manga-nese, total recov-erable (µg/L)	Zinc, dis-solved (µg/L)	Zinc, total recov-erable (µg/L)
1T	<1	2.8	2.8	64	208	<0.3	<1	2.1	14	1.4	<40
2T	141	740	792	402	384	17	17	11,900	11,100	17,800	17,200
3T	2.1	11	14	79	465	<.3	1.1	178	217	234	254
4B	<1	2.1	1.8	61	240	<.3	1.1	3.4	10	5.9	<40
6B	<1	3.7	3.5	54	230	<.3	<1	39	43	49	52
7T	127	1,700	1,740	5,020	4,450	26	28	23,500	20,900	15,900	14,400
8B	<1	7.5	7.7	70	256	.5	1.2	102	105	89	103
9T	67	1,090	1,060	3,190	3,050	481	470	7,520	7,060	6,930	6,470
10T	24	478	524	362	430	586	552	2,590	2,460	2,860	2,840
11T	24	434	526	1,490	7,970	6,470	10,100	1,010	995	3,020	3,020
12B	<1	8.5	9.9	77	268	2.4	5.8	102	105	94	110
13B	<1	10	12	60	278	3.9	14	113	116	108	110
14T	<1	1.8	1.7	126	300	<.3	<1	6.5	10	2.2	<40
15T	<1	5.2	6.5	98	229	3.2	9.7	21	29	18	E30
16B	<1	9.3	12	70	353	3.0	14	105	112	99	121
17T	41	757	790	12,000	12,900	3,160	3,000	907	876	5,520	5,550
18B	<1	10	12	95	323	7.3	21	103	107	106	111
18.5T	<1	2.9	2.6	--	--	.7	<1	14	5.0	2.9	<40
19T	<1	2.1	2.4	118	267	<.3	<1	11	11	3.0	<40
20T	<1	7.1	7.4	147	165	5.9	6.3	20	22	29	42
21T	--	26.1	--	166	--	46	--	63	--	157	--
22B	<1	9.4	11	101	355	5.4	17	85	90	90	95
23T	1.6	40	44	194	588	9.4	28	64	64	197	203
24T	<1	4.5	5.0	79	97	2.3	2.9	7.0	6.2	25	E28
25B	<1	9.2	11	107	360	5.0	16	84	88	88	94

Figure 19. Streamflow in upper Basin Creek, May 28, 1999.

zinc; tributaries draining mill tailings (sites 11T, 17T), had the highest concentrations of dissolved arsenic and lead. Tributary 21T, which drains from the northern margin of the mill tailings and enters Basin Creek downstream from the mill tailings, also had high concentrations of dissolved arsenic and lead.

Total-recoverable trace-element concentrations were similar to dissolved concentrations for most samples, indicating that the soluble phase was more predominant than the particulate phase, even during runoff conditions. Small differences between dissolved and total-recoverable concentrations were observed for cadmium, copper and zinc. Some of the largest differences between dissolved and total-recoverable concentrations were observed for aluminum, arsenic, iron, and lead. The large differences between dissolved and total-recoverable concentrations indicate that aluminum, arsenic, iron, and lead were being removed from solution and forming colloidal precipitates, which likely settle to the streambed. These observations are consistent with the data from the streambed sediments (table 10), which show large concentration increases for arsenic and lead from upstream of the Enterprise mine to downstream of the mill tailings.

Metals entering Basin Creek from tributaries during the runoff conditions of May 1999 caused increased concentrations that exceeded several aquatic-life standards for the State of Montana. Total-recoverable copper concentrations exceeded the acute aquatic-life standard of 3.8 µg/L for the reach of Basin Creek between sites 8B and 25B. Total-recoverable lead concentrations exceeded the chronic aquatic-life standard of 0.54 µg/L in the reach of Basin Creek between sites 12B and 25B. Total-recoverable zinc concentrations exceeded the acute aquatic-life standard of 37 µg/L for the reach between sites 6B and 25B. The extent to which these metal concentrations exceeded aquatic-life standards farther downstream in Basin Creek is unknown.

Trace-Element Loads in Basin Creek

Instantaneous loads of dissolved trace elements were calculated using streamflow and trace-element concentration data from each site sampled during the synoptic measurements on May 28, 1999. Trace-element loads (table 12) are reported in grams per day (g/d), and were calculated by multiplying streamflow (ft^3/s) times dissolved trace-element concentration (µg/L) times a units-conversion factor of 2.4466. For cadmium and lead concentrations that were less than the minimum reporting level, loads were calculated using the value for the minimum reporting level, and these loads are reported as less-than values in table 12.

Streamflow measurements and water-quality samples collected during snowmelt runoff on May 28, 1999, showed large increases in dissolved trace-element loads in Basin Creek through the area of the Buckeye and Enterprise mines. Streamflow in Basin Creek increased from 7.87 ft^3/s upstream of the Buckeye mine (site 4B) to 12.2 ft^3/s at the most downstream

Table 12. Dissolved trace-element loads for upper Basin Creek and tributaries, May 28, 1999.

[Right bank, bank containing mining wastes; left bank, bank with no mining wastes; ft^3/s, cubic feet per second; g/d, grams per day; <, less than; >, greater than]

Site No. (fig. 15)	Site description	Time	Streamflow, instantaneous (ft^3/s)	Aluminum load (g/d)	Arsenic load (g/d)	Cadmium load (g/d)	Copper load (g/d)	Iron load (g/d)	Lead load (g/d)	Manganese load (g/d)	Zinc load (g/d)
1T	Enterprise Mine tributary	1105	1.52	282	8.59	<1.12	10.6	239	<1.12	7.88	5.03
2T	Tributary to Enterprise Mine tributary	1050	.012	293	1.31	4.16	21.7	11.8	.50	350	522
3T	Enterprise Mine tributary	1130	1.65	643	11.4	7.50	43.4	318	<1.21	719	946
4B	Basin Creek above Buckeye mine	1010	7.87	1,002	41.6	<5.78	41.3	1,166	<5.78	64.5	113
6B	Basin Creek below Enterprise Mine tributary	0945	9.22	1,499	46.2	9.02	83.0	1,218	<6.77	879	1,096
7T	Basin Creek tributary, right bank	0925	.018	1,533	5.40	4.73	75.0	221	1.17	1,036	702
8B	Basin Creek	0920	9.89	2,993	58.6	14.5	181	1,685	12.1	2,457	2,157
9T	Basin Creek tributary, right bank	0915	.005	178	3.32	.70	13.3	39.0	5.89	91.9	84.8
10T	Basin Creek tributary, right bank	0900	.014	176	4.04	.82	16.4	12.4	20.1	88.6	98.1
11T	Basin Creek tributary, right bank	0840	.018	59.6	12.4	1.00	19.1	65.6	285	44.6	133
12B	Basin Creek	0815	10.7	3,743	89.7	18.3	223	2,024	61.5	2,663	2,449
13B	Basin Creek	1105	10.2	3,163	104	25.1	255	1,486	96.7	2,822	2,691
14T	Basin Creek tributary, left bank	1055	.58	41.4	5.73	<.42	2.62	179	<.42	9.23	3.18
15T	Basin Creek tributary, left bank	1045	.01	1.40	.54	<.01	.13	2.39	.08	.52	.45
16B	Basin Creek	1015	11.1	3,042	145	19.0	251	1,887	80.8	2,832	2,671
17T	Basin Creek tributary, right bank	0955	.021	91.3	50.6	1.94	38.9	617	162	46.6	283
18B	Basin Creek	0935	10.8	3,315	209	21.1	276	2,498	193	2,717	2,778
18.5T	Basin Creek tributary, left bank	0935	.175	59.8	1.34	<.13	1.25	126	.30	5.85	1.26
19T	Basin Creek tributary, two inflow points from left bank	0915	1.18	185	4.50	<.87	6.13	341	<.87	30.9	8.61
20T	Basin Creek tributary, left bank	0900	.020	3.82	1.60	<.01	.35	7.19	.29	.98	1.44
21T	Basin Creek tributary, right bank	0855	.066	15.2	29.3	.19	4.21	26.9	7.43	10.1	25.4
22B	Basin Creek below Buckeye Mine	0840	12.5	3,572	295	18.3	287	3,078	166	2,597	2,753
23T	Basin Creek tributary, right bank	0830	.015	3.46	5.60	.05	1.46	7.11	.34	2.34	7.22
24T	Basin Creek tributary, three inflow points from left bank	0820	.156	26.4	5.69	<.11	1.71	30.3	.88	2.67	9.59
25B	Basin Creek	0800	12.2	3,676	306	18.6	276	3,192	149	2,516	2,643
INCREASE BETWEEN SITES 4B AND 25B		--	4.3	2,674	264	>12.8	235	2,026	>143	2,450	2,530

NOTE: Loads were computed from unrounded streamflow values to obtain greater resolution of small differences between sites.

measurement site (site 25B), which is an increase of 4.3 ft^3/s or 55 percent. Figures 20–27 illustrate downstream changes of dissolved trace-element loads and streamflow for each of the eight trace elements analyzed in the synoptic samples from May 28, 1999. Loads are depicted for Basin Creek, individual tributaries, and the cumulative sum of the trace-element loads from site 4B plus tributaries.

Comparison of dissolved trace-element loads within Basin Creek with the cumulative sum of dissolved trace-element loads from tributaries indicated that dissolved trace-element loads in Basin Creek at the downstream end of the study area (site 25B) were largely derived from tributary inflows draining the Buckeye and Enterprise mines during runoff conditions. Comparison of the loads in Basin Creek and its tributaries also indicated that ground water and diffuse streambank seepage contributed only a small part of the dissolved trace-element load to Basin Creek during runoff. Arsenic was the only trace element to indicate that a substantial component of the load was from ground-water discharge or seepage from saturated stream banks directly into Basin Creek during runoff. Arsenic is widespread in surface and ground water in the area, including water draining from the south side (left bank) of Basin Creek, as indicated by water-quality samples from well 10 and tributaries 14T, 19T, and 24T (tables 6, 11, and 12). Part of the arsenic load in ground water thus likely originates on the south side of Basin Creek, in the area not disturbed by mining, because of the naturally occurring arsenic in that area.

The sum of measured loads of dissolved lead from all sampled tributaries was substantially larger than the loads in Basin Creek at downstream site 25B. The sum of measured loads of dissolved lead from the tributaries was more than three times as large as the load of dissolved lead at site 25B (fig. 25). The sum of measured loads of dissolved aluminum and cadmium from the tributaries ranged from about 10 to 30 percent, respectively, larger than the load at site 25B (figs. 20 and 22). Load inputs greater than the instream loads of Basin Creek indicate that dissolved aluminum, cadmium, and lead from tributaries were precipitating or forming colloids within Basin Creek and subsequently settling to the streambed.

Figure 20. Dissolved aluminum load in upper Basin Creek, May 28, 1999.

Figure 21. Dissolved arsenic load in upper Basin Creek, May 28, 1999.

Figure 22. Dissolved cadmium load in upper Basin Creek, May 28, 1999. For cadmium concentrations that were less than minimum reporting level of 0.3 µg/L, load values are plotted using minimum reporting level.

Figure 23. Dissolved copper load in upper Basin Creek, May 28, 1999.

Figure 24. Dissolved iron load in upper Basin Creek, May 28, 1999.

Figure 25. Dissolved lead load in upper Basin Creek, May 28, 1999. For lead concentrations that were less than minimum reporting level of 0.3 µg/L, load values are plotted using minimum reporting level.

Figure 26. Dissolved manganese load in upper Basin Creek, May 28, 1999.

Figure 27. Dissolved zinc load in upper Basin Creek, May 28, 1999.

Summary and Conclusions

The Buckeye and Enterprise mines are located in upper Basin Creek about 10 mi north of the town of Basin in Jefferson County, Mont. Pyritic ore from the mines was processed by a gravity mill located at the Buckeye mine site; gravity-mill tailings were later reprocessed through a flotation mill located on the flood plain of Basin Creek. Flotation-mill tailings on the flood plain occupy an area of about 3.3 acres and have a volume of about 5,000 cubic yards.

Basin Creek flows along the southern margin of the mill tailings and receives surface- and ground-water runoff from the mine areas and tailings, predominantly during spring snowmelt. The runoff from the mine areas and mill tailings measurably affects the quality of water in Basin Creek. The USDA Forest Service and U.S. Environmental Protection Agency have identified the need for remediation of the Buckeye and Enterprise mine area. To effectively remediate the impacts of historical mine wastes on Basin Creek and to measure the effectiveness of proposed mine-waste cleanup, it was necessary to determine sources of trace elements and their pathways of transport to the stream.

Chemical analyses of core samples from mill tailings, soils beneath the tailings, and leachate from samples prepared from a core showed four distinct geochemical zones: an oxidized and leached zone (the upper 22 in.), a partly oxidized zone (22–41 in.), an unoxidized pyritic zone (41–62 in.), and the buried soil horizon (62–79 in.). The unoxidized pyritic zone contained the highest concentrations of trace elements, whereas concentrations of most trace elements rapidly decreased with depth in the buried soil beneath the tailings.

Surface geophysical surveys, including electromagnetic, direct-current resistivity, and total-field magnetic methods, were used to examine the location and extent of high conductivity possibly related to trace-element contamination. Subsurface conductivity was mapped using EM-31 and EM-34 terrain conductivity measuring systems. The conductivity surveys measured the variation in subsurface conductivity from about 10 to 100 ft. Areas of high conductivity can result from sediments containing wet clay or high dissolved-solids concentrations in ground water. Direct-current resistivity soundings were used to quantify subsurface conductivity variations and to estimate the depth to bedrock. Total-field magnetic measurements were used to identify magnetic metals in the subsurface.

The EM surveys identified three areas of relatively high apparent conductivity and detected a conductive plume extending from the northeast part of the mill tailings to the southwest, toward the stream. This plume correlates well with the potentiometric surface and direction of ground-water flow, and with water-quality data from the monitoring wells in and around the tailings. The electromagnetic data also indicate that ground water with a high dissolved-solids concentration probably has migrated downward. Conductive zones also were identified south of the Enterprise mine and in an area of wet meadows southwest of the Buckeye tailings.

Total-field magnetic measurements indicated that buried magnetic objects were not a likely source of high conductivity near the EM survey grid origin. Therefore, the high conductivity anomaly is likely the result of the highly conductive sulfide layers that were observed in core samples from the same area.

Data from the direct-current soundings are interpreted to be a body of conductive material, most likely ground water with a high dissolved-solids content near the center of the Buckeye tailings and below the Enterprise tailings near well 9. The anomaly is slightly deeper than shown in the EM surveys, which may indicate downward movement of dissolved solids. Direct-current resistivity soundings also indicate that depth to bedrock is likely greater than 98 ft.

Two aquifers exist in the study area. One aquifer is fractured bedrock of the Boulder batholith, and the second aquifer is unconsolidated deposits consisting of till, alluvium, colluvium, organic-rich swamp deposits, and volcanic ash. The unconsolidated deposits range from less than 1 ft to more than 30 ft thick and are overlain by mill tailings in the vicinity of the Buckeye mine. The unconsolidated-deposits aquifer overlies granitic rocks and is hydraulically connected to Basin Creek. Test wells were installed in the unconsolidated-deposits aquifer to determine direction of ground-water flow, hydraulic characteristics, and water quality.

Ground water containing high concentrations of dissolved aluminum, arsenic, cadmium, copper, iron, lead, manganese, and zinc underlies the area of mill tailings and some of the area between the Enterprise mine and Basin Creek. Discharge of trace-element-laden ground water from the mine and mill-tailings areas into upper Basin Creek is small during low flow, but appears to account for essentially all of the instream load increase in upper Basin Creek during low flow. Trace-element loads from ground water elevate the concentrations of trace elements in upper Basin Creek, although the State of Montana aquatic-life standards generally are not exceeded during low flow. At times of snowmelt runoff, ground-water levels are near land surface over much of the mill-tailings area, and ground water saturates the tailings. This ground water, containing high concentrations of dissolved trace elements, seeps out of the tailings and into small tributaries that drain into Basin Creek.

Analyses of water samples collected from upper Basin Creek and tributaries, at various dates and streamflow conditions, documented higher concentrations of dissolved trace elements at higher streamflows. To determine concentrations and loads of trace elements in Basin Creek near the Buckeye and Enterprise mines during high streamflow for the purpose of identifying major sources, synoptic water-quality samples were collected for analysis and streamflow measurements were made in upper Basin Creek and all tributaries on May 28, 1999. Water quality was sampled and streamflow was measured at 25 sites, between 0800 and 1150 hours, under uniform hydrologic conditions. Water samples were analyzed for water temperature, specific conductance, pH, common ions, hardness, alkalinity, dissolved trace elements, and total-recoverable trace elements. The quality of water sampled at the 25 synoptic sites ranged from good-quality water typical of local, undisturbed mountain streams to trace-element-rich runoff that exceeded State of Montana aquatic-life standards for acute toxicity. The highest measured concentrations of dissolved trace elements were aluminum, 34,800 µg/L at site 7T; arsenic, 985 µg/L at site 17T; cadmium, 142 µg/L at site 2T; copper, 1,700 µg/L at site 7T; iron; 12,000 µg/L at site 17T; lead, 6,470 µg/L at site 11T; manganese, 23,500 µg/L at site 7T; and zinc, 17,800 µg/L at site 2T.

Tributaries draining waste rock near the Enterprise and Buckeye mines (sites 2T, 7T, 9T) had the highest concentrations of dissolved aluminum, cadmium, copper, manganese, and zinc; tributaries draining the mill tailings (sites 11T, 17T), had the highest concentrations of dissolved arsenic and lead. One tributary (21T), which drains from the northern margin of the mill tailings and enters Basin Creek downstream from the tailings, also had high concentrations of dissolved arsenic and lead.

During the May 1999 synoptic sampling, dissolved trace-element loads in Basin Creek at the downstream end of the study area (site 25B) were largely derived from tributary inflows draining the area of the Buckeye and Enterprise mines. For all trace elements except arsenic, ground water contributed only a small part of the dissolved load to Basin Creek during that period of snowmelt runoff. The sum of measured loads of dissolved aluminum, cadmium, and lead from tributaries was moderately to substantially larger than the sum of the loads in Basin Creek at downstream site 25B, indicating that these elements were precipitating or forming colloids within Basin Creek and subsequently settling to the streambed.

Metals entering Basin Creek from tributaries caused some of the State of Montana aquatic-life standards to be exceeded during runoff conditions of the synoptic sampling in May 1999. Copper exceeded the acute aquatic-life standard for the entire reach of Basin Creek between sites 8B and 25B. Lead exceeded the chronic aquatic-life standard in the reach of Basin Creek between sites 12B and 25B. Zinc exceeded the acute aquatic-life standard for the reach between sites 6B and 25B. The extent to which these metal concentrations exceeded aquatic-life standards farther downstream in Basin Creek is unknown.

References Cited

Church, S.E., Kimball, B.A., Fey, D.L., Ferderer, D.A., Yager, T.J., and Vaughn, R.B., 1997, Source, transport, and partitioning of metals between water, colloids, and bed sediments of the Animas River, Colorado: U.S. Geological Survey Open-File Report 97–151, 135 p.

Cooper, H.H., Jr., Bredehoeft, J.D., and Papadopulos, I.S., 1967, Response of a finite diameter well to an instantaneous charge of water: Water Resources Research, v. 3, no. 1, p. 263–269.

Desborough, G.A., and Fey, D.L., 1997, Preliminary characterization of acid-generating potential and toxic metal solubility of some abandoned metal-mining related wastes in the Boulder River headwaters, northern Jefferson County, Montana: U.S. Geological Survey Open-File Report 97–478, 21 p.

Fey, D.L., Church, S.E., and Finney, C.J., 1999, Analytical results for 35 mine-waste tailings cores and six bed-sediment samples, and an estimate of the volume of contaminated material at Buckeye meadow on upper Basin Creek, northern Jefferson County, Montana: U.S. Geological Survey Open-File Report 99–537, 59 p.

Fey, D.L., Desborough, G.A., and Church, S.E., 2000, Comparison of two leach procedures applied to metal-mining related wastes in Colorado and Montana and a relative ranking method for mine wastes, *in* ICARD 2000; Proceedings of the Fifth International Conference on Acid Rock Drainage, Volume 2: Society for Mining, Metallurgy, and Exploration, Inc., p. 1477–1487.

Fey, D.L., Unruh, D.M., and Church, S.E., 1999, Chemical data and lead isotopic compositions in stream-sediment samples from the Boulder River watershed, Jefferson County, Montana: U.S. Geological Survey Open-File Report 99–575, 147 p.

Interpex, 1993, RESIX-IP version 2.0 users manual: Golden, Colo., Interpex Limited, 150 p.

McDougal, R.R., and Smith, B.D., 2000, Ground geophysical study of the Buckeye mine tailings, Boulder watershed, Montana: U.S. Geological Survey Open-file Report 00–0371, 56 p.

McNeill, J.D., 1980, Electromagnetic terrain conductivity measurement at low induction numbers: Mississauga, Ontario, Canada, Geonics Limited, Technical Note TN-6.

Metesh, J.J., Lonn, J.D., Duaime, T.E., and Wintergerst, Robert, 1994, Abandoned-inactive mines program, Deerlodge National Forest—Volume I, Basin Creek drainage: Montana Bureau of Mines and Geology Open-File Report 321, 131 p.

Montana Department of Environmental Quality, 1999, Montana numeric water quality standards: Helena, Mont., Planning, Preservation, and Assistance Division, Standards and Economic Analysis Section Circular WQB-7, 41 p.

Nimick, D.A., and Cleasby, T.E., 2000, Water-quality data for streams in the Boulder River watershed, Jefferson County, Montana: U.S. Geological Survey Open-File Report 00–99, 70 p.

Roby, R.N., Ackerman, W.C., Fulkerson, F.B., and Crowley, F.A., 1960, Mines and mineral deposits (except fuels), Jefferson County, Montana: Montana Bureau of Mines and Geology Bulletin 16, 122 p.

Ruppel, E.T., 1963, Geology of the Basin quadrangle, Jefferson, Lewis and Clark, and Powell Counties, Montana: U.S. Geological Survey Bulletin 1151, 121 p.

Schemel, L.E., Kimball, B.A., and Bencala, K.E., 2000, Colloid formation and metal transport through two mixing zones affected by acid mine drainage near Silverton, Colorado: Applied Geochemistry, v. 15, p. 1003–1018.

Smith, B.D., and Sole, T.C., 2000, Schlumberger DC resistivity soundings in the Boulder watershed, Jefferson and Lewis and Clark Counties, Montana: U.S. Geological Survey Open-File Report 00–110, 31 p.

Telford, W.M., Geldart, L.P., and Sheriff, R.E., 1990, Applied geophysics, Second Edition: New York, Cambridge University Press, 770 p.

U.S. Department of Agriculture, Soil Conservation Service, 1981, Average annual precipitation Montana, based on 1941–1970 base period: Prepared in cooperation with Montana Department of Natural Resources and Conservation, Water Resources Division, Helena, Mont., 13 p.

U.S. Geological Survey, issued annually, Water resources data, Montana: Helena, Mont., U.S. Geological Survey Water-Data Report, pages vary.