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Scientific Investigations Report 2015–5008

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

Cover photograph: Looking upstream from seepage from the Bullion Mine adit, Jefferson County, Montana, May 23, 2013. Photograph by Craig L. Bowers, U.S. Geological Survey.

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U.S. Geological Survey, Reston, Virginia: 2015

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Suggested citation:
Sando, S.K., Clark, M.L., Cleasby, T.E., and Barnhart, E.P., 2015, Water-quality trends for selected sites in the Boulder River and Tenmile Creek watersheds, Montana, based on data collected during water years 1997–2013: U.S. Geological Survey Scientific Investigations Report 2015–5008, 46 p., *http://dx.doi.org/10.3133/sir20155008*.

ISSN: 2328-0328 (online)

Acknowledgments

The authors would like to recognize the U.S. Geological Survey hydrologists and hydrologic technicians involved in the collection of the water-quality and streamflow data for their dedicated efforts. Also, the authors would like to recognize the valuable contributions to this report from the insightful technical reviews by Skip Vecchia and Dave Naftz of the U.S. Geological Survey.

Special thanks are given to Nancy Rusho and Robert Wintergerst of the U.S. Forest Service for their support of this study.

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
ounce, fluid (fl. oz)	0.02957	liter (L)
pint (pt)	0.4732	liter (L)
quart (qt)	0.9464	liter (L)
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton per day (ton/d)	0.9072	metric ton per day
ton per day (ton/d)	0.9072	megagram per day (Mg/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
$°F=(1.8\times°C)+32$

Datum

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1988 (NGVD 88).

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Supplemental Information

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

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

Water year is the 12-month period from October 1 through September 30 of the following calendar year. The water year is designated by the calendar year in which it ends. For example, water year 2010 is the period from October 1, 2009, through September 30, 2010.

Abbreviations

EPA	U.S. Environmental Protection Agency
FAC	flow-adjusted concentration
log	logarithm (base 10)
LRL	laboratory reporting level
NGVD 88	National Geodetic Vertical Datum of 1988
NWQL	National Water Quality Laboratory
MLR	multiple linear regression
p-value	statistical probability level
Q	daily mean streamflow, in cubic feet per second
RPD	relative percent difference
SEE	standard error of estimate
USFS	U.S. Forest Service
USGS	U.S. Geological Survey

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Abstract

In the Boulder River and Tenmile Creek watersheds in southwestern Montana, there was intensive mining during a 40-year period after the discovery of gold in the early 1860s. Potential effects from the historic mining activities include acid-mine drainage and elevated concentrations of potentially toxic trace elements from mining remnants such as waste rock and tailing piles. In support of remediation efforts, water-quality monitoring by the U.S. Geological Survey began in 1997 in the Boulder River and Tenmile Creek watersheds and has continued to present (2014). The U.S. Geological Survey, in cooperation with the U.S. Forest Service, investigated temporal trends in water quality at 13 sites, including 2 adit (or mine entrance) sites and 11 stream sites. The primary purpose of this report is to present results of trend analysis of specific conductance, selected trace-elements (cadmium, copper, lead, zinc, and arsenic), and suspended sediment for the 13 sites.

For the stream sites, multiple linear regression of constituent concentrations on time, streamflow, and season was used for flow-adjusted trend analysis. For the adit sites, relations between constituent concentrations and streamflow were much weaker than for the stream sites. Thus, streamflow was not included in multiple linear regression trend models for the adit sites, and the trend results represent temporal changes in unadjusted concentrations.

The datasets for the sites in the Boulder River and Tenmile Creek watersheds were not specifically designed for trend analysis. All of the study sites have variability in within-year sampling frequency. However, the within-year sampling frequency was similar among most sites in individual years. Although the study datasets are not ideally suited for precise definition of temporal trends, generally strong similarity in sample-collection characteristics of the datasets among most sites provides a reasonable basis for relative comparisons of trend results among sites.

Trend results for the adit sites in the Boulder River watershed (Bullion Mine adit [site 2] and Crystal Mine adit [site 6]) do not provide clear evidence of substantial trending during June 2003 through September 2013. Water quality of the adit sites probably is affected by complex processes that are not well defined in the study datasets. As such, the trend-analysis structure of the study might not be suitable for accurate description of temporal trends in water quality at the two adit sites.

Trend results for most stream sites in the Boulder River watershed for water years 2000–13 (water year is the 12-month period from October 1 through September 30 and is designated by the year in which it ends) indicate decreasing trends in flow-adjusted specific conductance, in flow-adjusted concentrations (FACs) for most filtered and unfiltered-recoverable trace elements, and in suspended sediment. Overall, magnitudes of the decreasing trends in FACs of metallic contaminants are largest for Bullion Mine tributary at mouth (site 3), Jack Creek at mouth (site 4), and Cataract Creek at Basin (site 8). For sites 3, 4, and 8, magnitudes of decreasing trends generally ranged from about -5 to -10 percent per year. Notably, the watersheds upstream from sites 3, 4, and 8 have been targeted by substantial remediation activities.

Overall, magnitudes of decreasing trends in FACs of metallic contaminants are considered intermediate for Basin Creek at Basin (site 5), High Ore Creek near Basin (site 9), and Boulder River below Little Galena Gulch (site 10). For sites 5, 9, and 10, the magnitudes of the decreasing trends generally ranged from about -2 to -5 percent per year.

Decreasing trends in FACs of metallic contaminants for Boulder River above Kleinsmith Gulch (site 1) and Cataract Creek above Uncle Sam Gulch (site 7) generally are minor to small (ranging from about -1 to -2 percent per year) and for most metallic contaminants the changes are within fairly small ranges at generally low FACs. The watershed of site 1 has smaller mining effects than most other study sites. The watersheds of site 1 and 7 have not been targeted by substantial remediation activities. Consideration of trend patterns among all stream sites in the Boulder River watershed provides strong evidence that remediation activities are the primary cause of decreasing trends in metallic contaminants.

Trend results for sites in the Tenmile Creek watershed generally are more variable and difficult to interpret than for sites in the Boulder River watershed. Trend results for Tenmile Creek above City Diversion (site 11) and Minnehaha Creek near Rimini (site 12) for water years 2000–13 indicate decreasing trends in FACs of cadmium, copper, and zinc. The magnitudes of the decreasing trends in FACs of copper

generally are moderate and statistically significant for sites 11 and 12. The magnitudes of the decreasing trends in FACs of cadmium and zinc for site 11 are minor to small and not statistically significant; however, the magnitudes for site 12 are moderate and statistically significant. In general, patterns in FACs for Tenmile Creek near Rimini (site 13) are not well represented by fitted trends within the short data collection period, which might indicate that the trend-analysis structure of the study is not appropriate for describing trends in FACs for site 13. The large decreasing trend in FACs of suspended sediment is the strongest indication of change in water quality during the short period of record for site 13; however, this trend is not statistically significant.

Introduction

In the Boulder River and Tenmile Creek watersheds in southwestern Montana, there was intensive mining during a 40-year period after the discovery of gold in the early 1860s. Although most of the mining involved small operations, the cumulative environmental effect was large because of the hundreds of sites where mine wastes and mill tailings were discarded with little regard for potential lasting effect on rivers or streams. Potential effects from the historic mining activities include acid-mine drainage and elevated concentrations of potentially toxic trace elements from mining remnants such as waste rock and tailing piles. Remediation of these mining remnants in both watersheds has been ongoing since about 1998 (Nimick and others, 2004).

Much of the study area is located on public land, including State land, U.S. Forest Service (USFS) land, and Bureau of Land Management land. As such, remediation of environmental effects of the mine wastes has involved coordinated efforts by multiple State and Federal agencies to assess the extent of contamination and to develop and implement remediation strategies. In support of the coordinated remediation efforts, water-quality monitoring by the U.S. Geological Survey (USGS) began in water year 1997 (water year is the 12-month period from October 1 through September 30 and is designated by the year in which it ends) in the Boulder River and Tenmile Creek watersheds and has continued to present (2014).

Data in the USGS monitoring program span a sufficient number of years to allow statistical testing for temporal trends in water-quality constituents and properties. Thus, the USGS, in cooperation with the USFS, investigated temporal trends in water quality at 13 sampling sites (fig. 1, table 1).

Purpose and Scope

The primary purpose of this report is to present results of trend analysis of specific conductance, selected trace-elements (cadmium, copper, lead, zinc, and arsenic), and suspended sediment for 13 selected sampling sites in the Boulder River and Tenmile Creek watersheds based on data collected during water years 1997–2013. The 13 sites include 2 adit (or mine entrance) sites and 11 stream sites. The report also presents background information on mining and remediation activities in the Boulder River and Tenmile Creek watersheds, trend-analysis methods, and factors that affect trend analysis and interpretation. The information is presented to assist in evaluating trend results.

The datasets of the 13 sites are variable with respect to data-collection periods; within-year frequency of data collection; and thus, the amount of data available for trend analysis. Variability in the datasets complicates consistent statistical analysis among the sites. A primary objective of this report is to generally describe relative variability in trend patterns as consistently as possible among site and constituent combinations, given the available data. In cases where the structure of the datasets might affect confidence in the trend-analysis results and the capability to compare results among sites, factors that contribute to greater uncertainty in results are acknowledged and discussed.

Description of Study Area

The study area consists of the Boulder River watershed upstream from Boulder River below Little Galena Gulch near Boulder, Mont (site 10, fig. 1, table 1) and the Tenmile Creek watershed upstream from Tenmile Creek near Rimini (site 13, fig. 1, table 1). Boulder River and Tenmile Creek originate in the Boulder Mountains (not shown on fig. 1) in southwestern Montana. The Boulder River flows generally southeast about 75 miles (mi) from the headwaters to the confluence with the Jefferson River near Cardwell (fig. 1). Tenmile Creek flows generally northeast about 30 mi from the headwaters to the confluence with Prickly Pear Creek (not shown on fig. 1).

Hydrographic and Hydrologic Characteristics

In this section of the report, the hydrography (stream lengths and drainage areas) and hydrology (mean annual streamflow) of the study area are described to facilitate understanding fluvial transport characteristics for trace elements within the study area. Hydrographic characteristics were determined by geographic information system analysis of the USGS National Hydrography Dataset (U.S. Geological Survey, 2014a).

For the Boulder River watershed, none of the study sampling sites have associated streamflow-gaging stations. Mean annual streamflows of the sampling sites were estimated by synthesizing daily mean streamflows for water years 1997–2013 based on analyses of at-site streamflows at times of sampling (measured by using methods described in Rantz and others, 1982) in conjunction with daily mean streamflows for USGS streamflow gaging station 06033000 (Boulder River near Boulder, Mont.; U.S. Geological Survey, 2014b), which is located outside of the study area (and not shown on fig. 1)

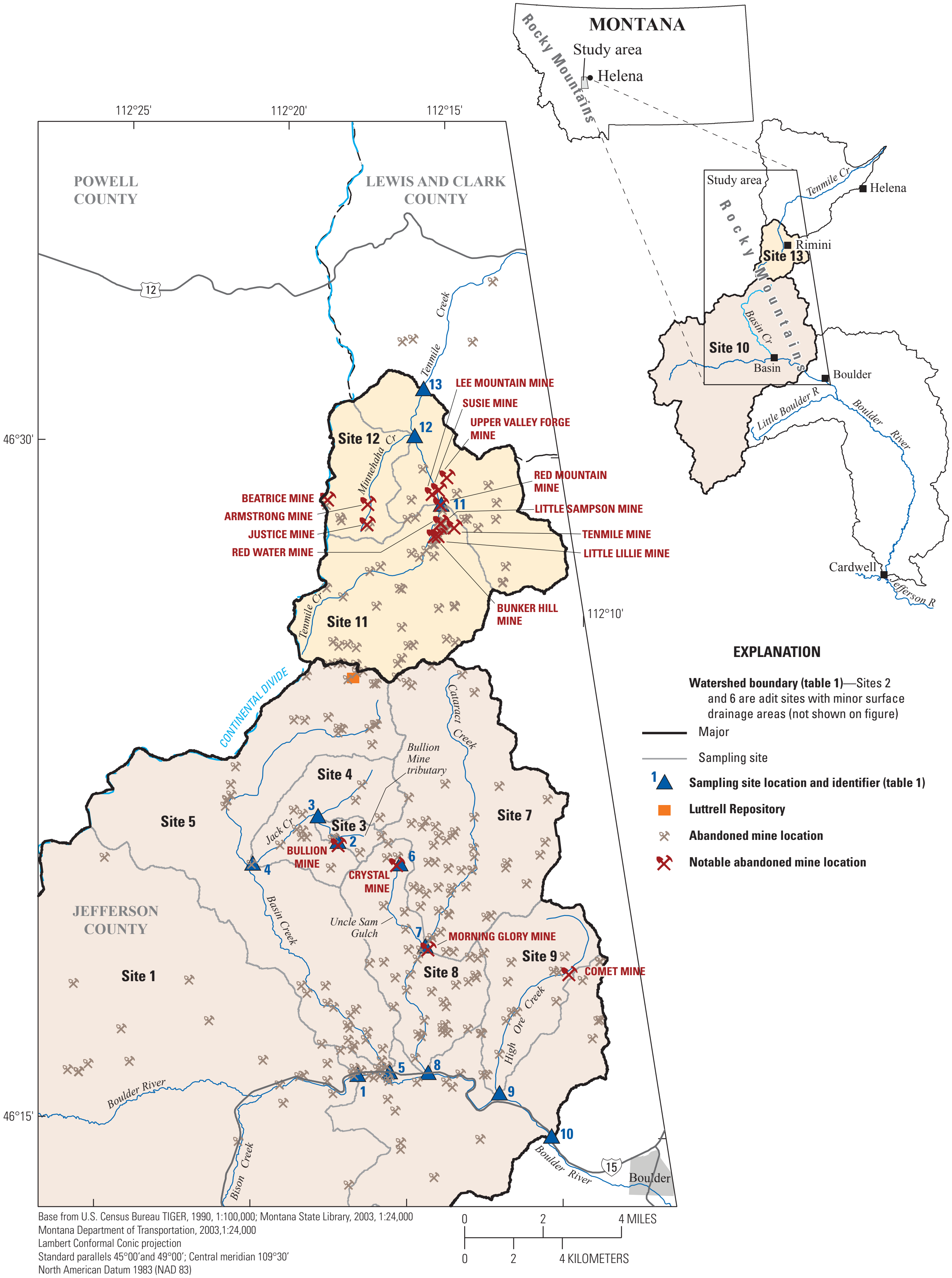

Figure 1. Location of selected sites in the Boulder River and Tenmile Creek watersheds, Montana.

Table 1. Information for selected sampling sites in the Boulder River and Tenmile Creek watersheds, Montana.

[Water year is the 12-month period from October 1 through September 30 and is designated by the year in which it ends. NA, not applicable]

Site number (fig. 1)	Site identification	Site name	Abbreviated site name	Site group	Drainage area, square miles	Abandoned mine density, mines per square mile	Period of water-quality data collection during water years 1997–2013	Trend-analysis period(s), (decimal years)
1	06031450	Boulder River above Kleinsmith Gulch, near Basin, Mont.	Boulder River above Kleinsmith Gulch	Stream (Boulder River watershed)	217.7	0.3	1997–2003, 2012–13	October 1996–September 2013 (1996.75–2013.75)
2	462120112173701	Bullion Mine Adit near Basin, Mont.	Bullion Mine adit	Adit (Boulder River watershed)	NA	NA	1999–2013	June 2003–September 2013 (2003.5–2013.75
3	462153112181701	Bullion Mine tributary at mouth, near Basin, Mont.	Bullion Mine tributary at mouth	Stream (Boulder River watershed)	3.6	2.2	1997–2013	October 1996–September 2013 (1996.75–2013.75)
4	462047112201901	Jack Creek at mouth, near Basin, Mont.	Jack Creek at mouth	Stream (Boulder River watershed)	8.5	1.9	2000–13	January 2000–September 2013 (2000.05–2013.75)
5	06031600	Basin Creek at Basin, Mont.	Basin Creek at Basin	Stream (Boulder River watershed)	41.6	1.5	1997–2013	October 1996–September 2013 (1996.75–2013.75)
6	462053112153601	Crystal Mine Adit near Basin, Mont.	Crystal Mine adit	Adit (Boulder River watershed)	NA	NA	2003–13	June 2003–September 2013 (2003.5–2013.75
7	461905112144201	Cataract Creek ab Uncle Sam Gulch near Basin, Mont.	Cataract Creek above Uncle Sam Gulch	Stream (Boulder River watershed)	23.0	2.3	1997–2003, 2005–07, 2011–13	May 1997–September 2013 (1997.38–2013.75)
8	06031960	Cataract Creek at Basin, Mont.	Cataract Creek at Basin	Stream (Boulder River watershed)	33.5	2.7	1997–2013	October 1996–September 2013 (1996.75–2013.75)
9	06032300	High Ore Creek near Basin, Mont.	High Ore Creek near Basin	Stream (Boulder River watershed)	8.8	1.5	1997–2002, 2011–13	October 1996–September 2013 (1996.75–2013.75)
10	06032400	Boulder River below Little Galena Gulch near Boulder, Mont.	Boulder River below Little Galena Gulch	Stream (Boulder River watershed)	322.8	0.8	1997–2013	October 1996–September 2013 (1996.75–2013.75)
11	462853112144101	Tenmile Creek above City Diversion, near Rimini, Mont.	Tenmile Creek above City Diversion	Stream (Tenmile Creek watershed)	15.2	3.0	1997–2013	May 1999–September 2013 (1999.38–2013.75)
12	463023112153701	Minnehaha Creek above City Diversion near Rimini, Mont.	Minnehaha Creek near Rimini	Stream (Tenmile Creek watershed)	5.4	1.3	1997–2013	May 1997–September 2013 (1997.37–2013.75)
13	06062500	Tenmile Creek near Rimini, Mont.	Tenmile Creek near Rimini	Stream (Tenmile Creek watershed)	33.0	2.1	2005–13	March 2005–September 2013 (2005.18–2013.75)

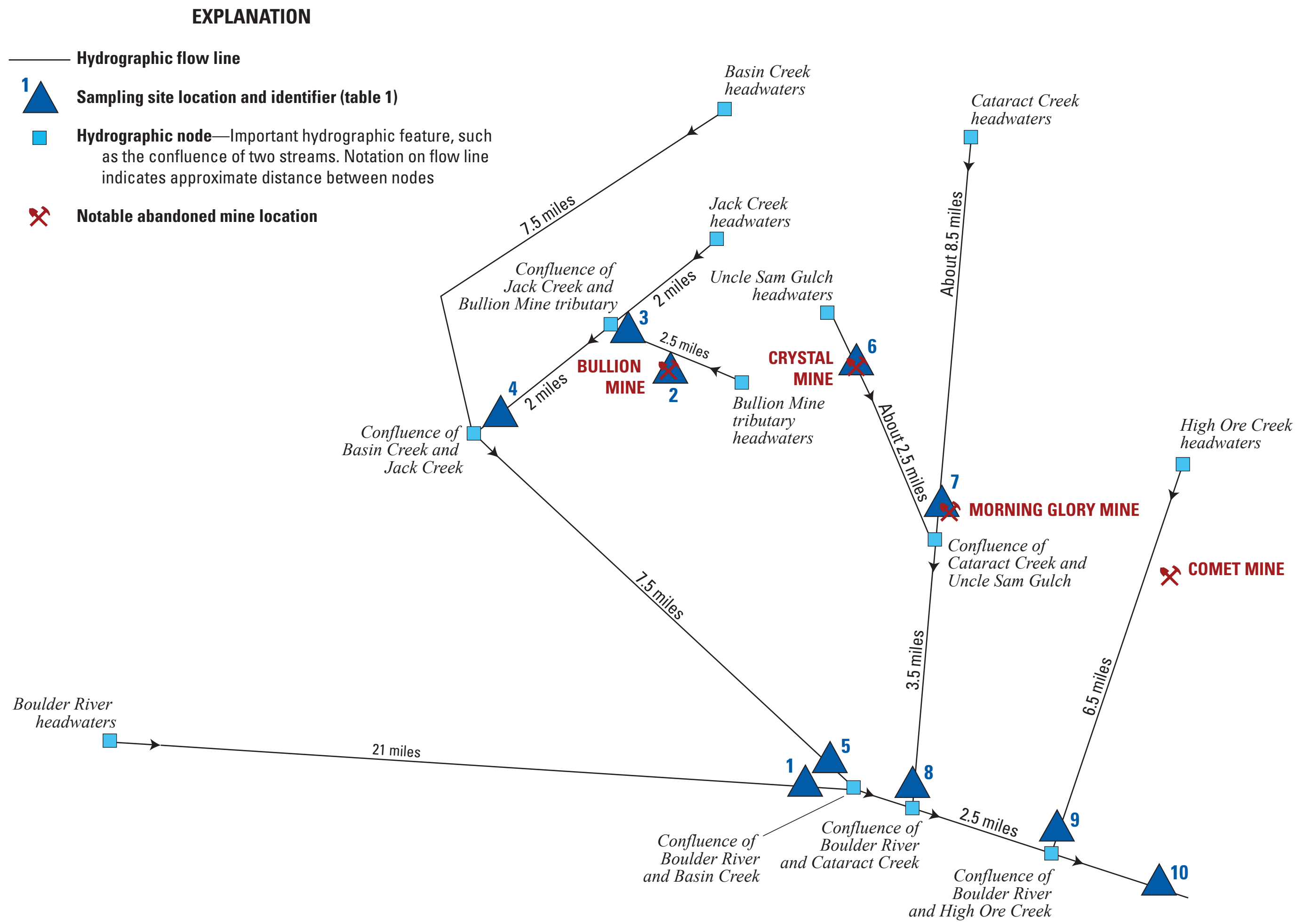

Figure 2. Simplified hydrographic flow diagram for the study area in the Boulder River watershed, Montana.

about 6.5 miles downstream from Boulder River below Little Galena Gulch (site 10). Estimated daily mean streamflows were synthesized by using the MOVE 1 procedure (Hirsch, 1982) in the USGS Streamflow Record Extension Facilitator software described by Granato (2009). For the Tenmile Creek watershed, Tenmile Creek near Rimini (site 13, fig. 1, table 1) has an associated streamflow-gaging station; thus, mean annual streamflow was determined from the recorded data. However, for the other sites in the Tenmile Creek watershed (Tenmile Creek above City Diversion [site 11, fig. 1, table 1] and Minnehaha Creek near Rimini [site 12], fig. 1, table 1), at-site streamflows at times of sampling were not sufficiently correlated with daily mean streamflows of nearby streamflow-gaging stations to allow synthesis of daily mean streamflows; thus, estimated mean annual streamflows are not reported for sites 11 and 12.

Boulder River Watershed

To facilitate discussion of the hydrography of the study area in the Boulder River watershed, a simplified hydrographic flow diagram is presented in figure 2. Upstream from Boulder River above Kleinsmith Gulch (site 1, fig. 1, table 1), the geology of the Boulder River watershed largely is unmineralized with little historic mining, as evidenced by a low density of abandoned mines for site 1 (0.3 mines per square mile (mi^2); table 1). The drainage area of site 1 is 217.7 mi^2, which accounts for about 67 percent of the drainage area of Boulder River below Little Galena Gulch (site 10, fig. 1, table 1) at the downstream end of the study area in the Boulder River watershed. The estimated mean annual streamflow for site 1 is about 23 cubic feet per second (ft^3/s), which accounts for about 61 percent of the estimated mean annual streamflow for site 10 (about 38 ft^3/s).

From site 1, the Boulder River flows about 1 mi to the confluence with Basin Creek. Basin Creek at Basin (site 5, fig. 1, table 1), which is about 1 mi upstream from the confluence with the Boulder River, has a drainage area of 41.6 mi^2 (about 13 percent of the drainage area of site 10) and an estimated mean annual streamflow of about 6.4 ft^3/s (about 17 percent of the mean annual streamflow of site 10). Jack Creek enters Basin Creek about 7.5 mi downstream from the Basin Creek headwaters. Jack Creek at mouth (site 4, fig. 1, table 1), which is about 0.1 mi upstream from the confluence with Basin Creek, has a drainage area of about 8.5 mi^2 and an estimated mean annual streamflow of about 2.1 ft^3/s. Bullion Mine tributary enters Jack Creek about 2.0 mi downstream from the Jack Creek headwaters. Bullion Mine tributary at mouth (site 3, fig. 1, table 1), which is about 20 feet (ft) upstream from the confluence with Jack Creek, has a drainage area of about 3.6 mi^2 and an estimated mean annual streamflow of about 0.26 ft^3/s. Bullion Mine adit (site 2, fig. 1, table 1) is located about 1.6 mi upstream from the mouth of Bullion Mine tributary.

From the mouth of Basin Creek, the Boulder River flows about 1.0 mi to the confluence with Cataract Creek. Cataract Creek at Basin (site 8, fig. 1, table 1), which is about 250 ft upstream from the confluence with the Boulder River, has a drainage area of 33.5 mi^2 (about 10 percent of the drainage area of site 10) and an estimated mean annual streamflow of about 5.1 ft^3/s (about 13 percent of the mean annual streamflow of site 10). Cataract Creek above Uncle Sam Gulch (site 7, fig. 1, table 1), which is located about 8.5 mi downstream from the Cataract Creek headwaters and about 50 ft upstream from Uncle Sam Gulch, has a drainage area of 23.0 mi^2 and an estimated mean annual streamflow of 4.5 ft^3/s. Uncle Sam Gulch flows about 2.5 mi from the headwaters to the confluence with Cataract Creek. Crystal Mine adit (site 6, fig. 1, table 1) is located at the headwaters of Uncle Sam Gulch. Cataract Creek at Basin (site 8, fig. 1, table 1) is about 3.5 mi downstream from Uncle Sam Gulch.

From the mouth of Cataract Creek, the Boulder River flows about 2.5 mi to the confluence with High Ore Creek. High Ore Creek near Basin (site 9, fig. 1, table 1), which is about 0.1 mi upstream from the confluence with the Boulder River, has a drainage area of 8.8 mi^2 (about 3 percent of the drainage area of site 10) and an estimated mean annual streamflow of about 0.74 ft^3/s (about 2 percent of the mean annual streamflow of site 10). From the mouth of High Ore Creek, the Boulder River flows about 2 mi to Boulder River below Little Galena Gulch (site 10, fig. 1, table 1).

Tenmile Creek Watershed

To facilitate discussion of the hydrography of the study area in the Tenmile Creek watershed, a simplified hydrographic flow diagram is presented in figure 3. Tenmile Creek flows about 7 mi from the headwaters to Tenmile Creek above City Diversion (site 11, fig. 1, table 1). Site 11 has a drainage area of 15.2 mi^2 which accounts for about 46 percent of the drainage area of Tenmile Creek near Rimini (33.0 mi^2) at the downstream end of the study area in the Tenmile Creek watershed. In the watershed of site 11, there is transbasin diversion of tributary streamflows to provide municipal water supply to the city of Helena. The principle municipal supply diversion is directly from Tenmile Creek about 200 ft downstream from site 11.

From site 11, Tenmile Creek flows about 2 mi to the confluence with Minnehaha Creek. Minnehaha Creek near Rimini (site 12, fig. 1, table 1), which is about 150 ft upstream from the confluence with Tenmile Creek, has a drainage area of 5.4 mi^2 (about 16 percent of the drainage area of site 13). From the confluence with Minnehaha Creek, Tenmile Creek flows about 1.5 mi to Tenmile Creek near Rimini (site 13, fig. 1, table 1). In the intervening watershed between sites 11 and 13, there are multiple transbasin diversions of tributary streamflows (including Minnehaha Creek) to provide municipal water supply to the city of Helena.

Physiographic, Climatic, and Geologic Characteristics

The study area lies within the Middle Rockies Ecoregion (not shown on fig. 1; Woods and others, 2002), which is characterized by forested mountains and intermontane valleys. Altitudes in the Boulder River watershed upstream from Boulder River below Little Galena Gulch (site 10, fig. 1, table 1) range from about 5,480 to 8,750 ft above the National Geodetic Vertical Datum of 1988 (NGVD 88). Altitudes in the Tenmile Creek watershed upstream from Tenmile Creek near Rimini (site 13, fig. 1, table 1) range from about 4,860 to 8,230 ft above NGVD 88. In the study area, vegetation is predominantly subalpine fir, Douglas fir, and ponderosa pine conifer forests in the high-altitude mountainous areas; mixed conifers, shrubs, and grasses in the mid-altitude foothills; and grasses in the low-altitude valley areas (Woods and others, 2002). In the mountainous areas, the predominant land uses are recreation, timber harvest, and mining; and in the valleys, the predominant land uses are livestock grazing and hay production.

Areally-weighted mean annual precipitation (1981–2010 30-year normal; PRISM Climate Group, 2014) in the study area is about 20 inches. Based on climatic data for Boulder, Mont., at an altitude of about 4,900 ft (Western Regional Climate Center, 2014), mean annual precipitation for low-altitude parts of the study area is about 11 inches, with about 50 percent of mean annual precipitation falling primarily as rain during May–July. December is the coldest month (mean monthly temperature of 4.6 degrees Celsius), and July is the warmest month (mean monthly temperature of 18.4 degrees Celsius). Based on climatic data for the Basin Creek SNOTEL station at an altitude of 7,180 ft (Natural Resources Conservation Service, 2014), mean annual precipitation for high-altitude parts of the study area is about 25 inches, with about 35 percent of mean annual precipitation falling primarily as rain during May–July. Fall and winter precipitation falling primarily as snow accounts for a larger part of annual precipitation in high-altitude areas than in low-altitude areas.

Most of the study area is underlain by the Cretaceous granitic rocks of the Boulder Batholith bedrock unit (Church and others, 2004). Other bedrock units in the study area (particularly in parts of the Tenmile Creek watershed) include Cretaceous metamorphosed sandstone and siltstone, Cretaceous andesitic volcanic rocks of the Elkhorn Mountains Volcanics, and Tertiary volcanic rocks composed of rhyolite

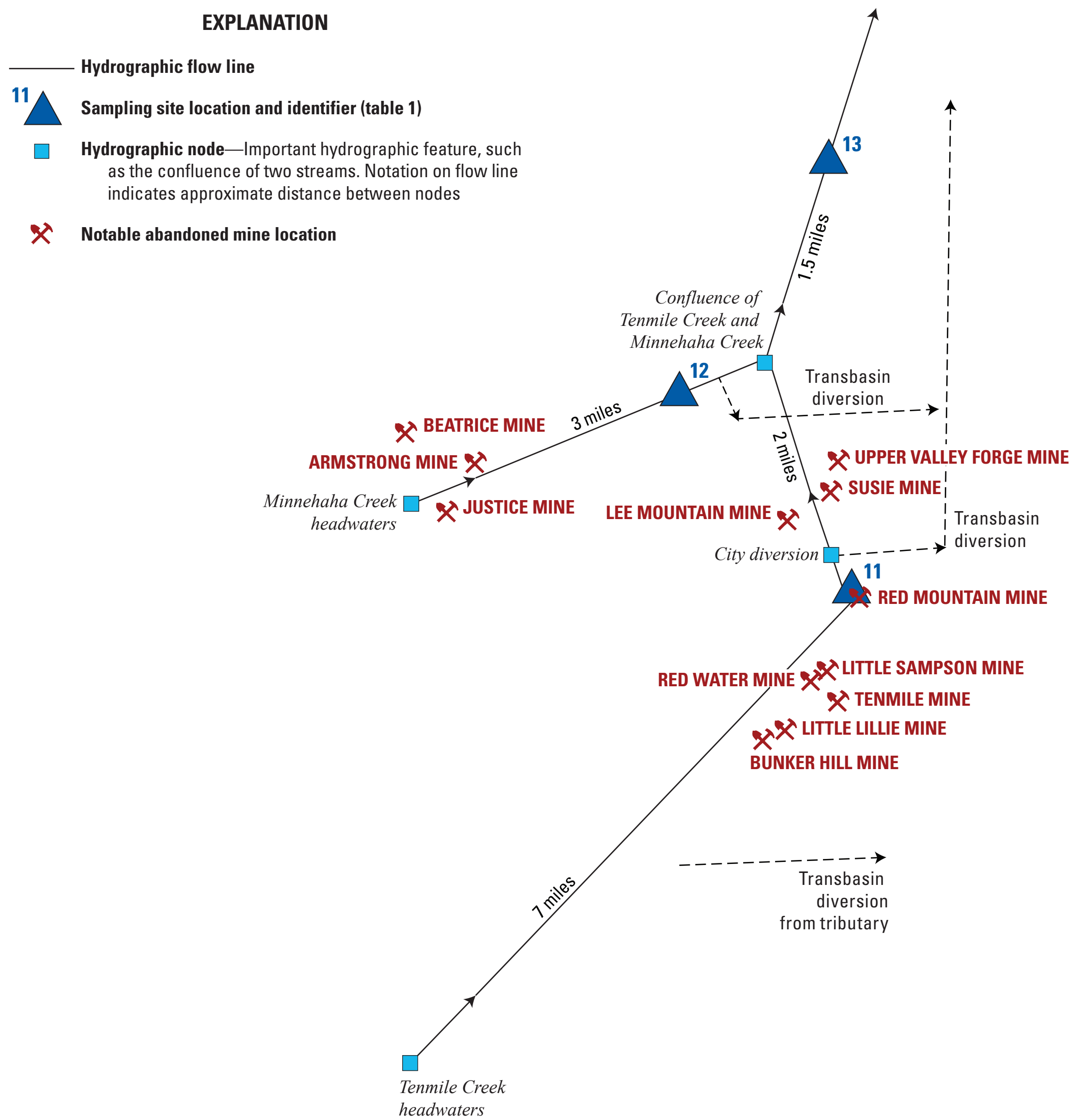

Figure 3. Simplified hydrographic flow diagram for the study area in the Tenmile Creek watershed, Montana.

and tuff (Cleasby and Nimick, 2002). The ore bodies in the study area that have been the target of extensive mining activities are variable in composition and resulted from late Cretaceous and late Tertiary periods of mineralization (Church and others, 2004; Knopf, 1913). The geology of the study area is described in detail by Nimick and others (2004), in Cleasby and Nimick (2002), and in numerous citations in those reports.

Overview of Mining and Remediation Activities

In the Boulder River and Tenmile Creek watersheds in southwestern Montana, there was intensive mining during a 40-year period after the discovery of gold in the early 1860s. Most of the mining involved small operations, which generally accessed ore deposits less than 50 ft wide (U.S. Geological Survey, 2004). Although these operations generally were small, the cumulative environmental effect was large because of the numerous sites where mine wastes and mill tailings were discarded with little regard for environmental effects. Densities of abandoned mines (table 1) in the study sampling-site watersheds provide general relative information on extent of mining activities among the watersheds. However, the abandoned mine densities do not always provide an accurate indication of mining effects on stream systems between the watersheds. For an individual mine, mining effects are related to the size of the mine operation, the amount of waste generated, and the handling of the waste; these factors are highly variable among individual mines.

In addition to the numerous small mining operations in the study area, there were several notable large mines that remained in operation longer, generated more waste than most small operations, or both. Notable abandoned mines in the

Boulder River watershed include the Bullion, Crystal, Morning Glory, and Comet Mines (fig. 1). The Bullion Mine in the Basin Creek watershed periodically operated during 1897–1984, was most productive during 1901–48 (U.S. Environmental Protection Agency, 2014a), and produced about 30,000 tons of ore during 1905–55 (CH2MHILL, 2013a). The Crystal Mine in the Cataract Creek watershed periodically operated during 1885–1983 and produced about 61,000 tons of ore during the operation period (CH2MHILL, 2013b). The Morning Glory Mine in the Cataract Creek watershed operated from the late 1890s through the 1960s and produced about 20,000 tons of ore during 1920–57 (Montana Department of Environmental Quality, 2009). The Morning Glory Mine produced less ore than the other notable mines in the Boulder River watershed, but was considered notable because of the close proximity to the Cataract Creek channel. The Comet Mine in the High Ore Creek watershed periodically operated during 1880–1941 and produced about 496,000 tons of ore after 1902 (Montana State University, 2014). In the study area, stream channels downstream from the Bullion, Crystal, and Comet Mines were among the most contaminated by mining wastes (Finger and others, 2004). Further, based on analysis of data collected during 2001–05, the Bullion and Crystal Mine adits were the primary sources of metals in the Basin Creek and Cataract Creek watersheds, respectively, and lead isotopic data indicated that the Crystal Mine was the major source of some metals in streambed sediment in the Boulder River (Unruh and others, 2009).

In the Tenmile Creek watershed, individual mines generally had shorter longevity and smaller total ore production than the Bullion, Crystal, and Comet Mines in the Boulder River watershed. Active mining in the Tenmile Creek watershed was from the 1870s through the 1930s, with sporadic mining through 1953 (U.S. Environmental Protection Agency, 2008). Notable abandoned mines in the Tenmile Creek watershed include the Armstrong, Beatrice, Bunker Hill, Justice, Lee Mountain, Little Lillie, Little Sampson, Red Mountain, Red Water Mines, Susie, Tenmile, and Upper Valley Forge Mines (fig. 1). Several mines have been noted as major contributors to trace-element loads to Tenmile Creek, including the Lee Mountain, Little Sampson, Red Water, and Susie Mines (fig. 1; U.S. Environmental Protection Agency, 2008). The Armstrong, Beatrice, and Justice Mines (fig. 1) operated within the Minnehaha Creek watershed.

Unremediated surface contamination from historic mining can potentially affect many aspects of a watershed for many centuries (Gray, 1997; Leblanc and others, 2000). In the Boulder River watershed, early remediation focused on the Comet Mine in the High Ore Creek watershed. In the 1980s, a diversion channel was constructed to route High Ore Creek around the tailings deposited in the valley bottom near the Comet Mine (Church and others, 2004), and then in 1997–99, mill tailings and tailings flood-plain deposits were removed by the Montana Department of Environmental Quality and the Bureau of Land Management (Finger and others, 2004). The Basin Creek, Cataract Creek, and Tenmile Creek watersheds were designated as Superfund sites on the National Priorities List in 1999. During 2001–02, remediation activities by the USFS and U.S. Environmental Protection Agency (EPA) began in the Basin Creek and Cataract Creek watersheds and focused primarily on wastes associated with the Bullion and Crystal Mines. U.S. Environmental Protection Agency (2014a) reported that during 2001–02, about 27,000 cubic yards of waste associated with the Bullion Mine operations in the Basin Creek watershed were removed, uncontaminated limed soils were installed, and vegetation was re-established. Unruh and others (2009) reported that 40,900 cubic yards of mine and mill wastes were removed during 2000–02. After 2002, various additional remediation activities were done in the Basin Creek watershed, including waste removal and revegetation near some smaller mines in headwaters areas of Jack Creek (Browne, 2009). During 2000-02 in the Cataract Creek watershed, some wastes associated with the Crystal Mine operations were removed and a surface mine trench was lined and backfilled (U.S. Environmental Protection Agency, 2014b). After 2002, various additional remediation activities were done in the Cataract Creek watershed, including waste removal and revegetation near some smaller mines and also at the Morning Glory Mine near the confluence of Uncle Sam Gulch and Cataract Creek (Robert Wintergerst, U.S. Forest Service, written commun., September 2014).

In the Tenmile Creek watershed, groundwater, streams, and soils have been affected by historic mining activities. Primary constituents of concern are arsenic, cadmium, copper, lead, and zinc (U.S. Environmental Protection Agency, 2014c). The USFS has the lead role in remediation activities of Federal lands in the Tenmile Creek watershed. Remediation activities where there is a mix of Federal and private land have been done cooperatively by the EPA, USFS, and the State of Montana. Remediation in the Tenmile Creek watershed began in 1999, when the EPA removed waste from the Bunker Hill, Tenmile, Red Mountain, and Susie Mines. During 2000–01, additional waste removal was done at the Bunker Hill, Tenmile, Red Mountain, Susie, Beatrice, Justice, and Upper Valley Forge Mines (U.S. Environmental Protection Agency, 2008). Other high-priority mine waste was removed in the upper watershed including at the Lee Mountain Mine. Contaminated soils have been removed from some residential properties near Rimini, Mont., and road base was applied to Rimini Road to eliminate contaminated dust (U.S. Environmental Protection Agency, 2014d). During 2012–13, about 20,000 cubic yards of mine waste was excavated from Lee Mountain and Little Lillie Mine areas. Mine wastes have been transported to the Luttrell Repository (fig. 1). Excavated areas were backfilled with uncontaminated material and vegetation was re-established. Total volume of material excavated from the upper Tenmile Creek watershed was about 354,000 cubic yards (U.S. Environmental Protection Agency, 2014d).

Data Collection and Analytical Methods

Water-quality sample collection (fig. 4) by the USGS began in water year 1997 at seven sites in the Boulder River watershed (sites 1, 3, 5, 7, 8, 9, and 10; fig. 1, table 1) and two sites in the Tenmile Creek watershed site (sites 11 and 12, fig. 1, table 1). During water years 1999–2000, the monitoring program was expanded by the addition of two sites in the Boulder River watershed (sites 2 and 4, fig. 1, table 1). The monitoring program also was expanded during 2003–05 by the addition of one site in the Boulder River watershed (site 6, fig. 1, table 1) and one site in the Tenmile Creek watershed (site 13, fig. 1, table 1). Thus, there have been 13 sites in the monitoring program with variable periods of record (fig. 4, table 1). Sites 1, 7, and 9 (fig. 1, table 1) have periods (ranging from 1 to 8 years) when data collection was suspended.

The within-year frequency of data collection was somewhat inconsistent for the monitoring program, with the number of samples collected at an individual site ranging from 1 to 12 samples per year. However, all sites have median within-year sampling frequencies of 4 samples per year during years of data collection. Interannual variability in the operation of the monitoring program resulted from variability in available funding and program objectives.

During the study period, water samples for the 11 stream sites (table 1) were collected from vertical transits throughout the entire stream depth at multiple locations across the stream by using standard USGS methods (U.S. Geological Survey, variously dated). Those methods provide a width-and-depth integrated composite that is intended to be representative of the entire flow passing through the cross section of a stream. Isokinetic samplers were used when water depth was sufficient and grab sampling was used when water depth was insufficient. For the two adit sites (table 1), grab sampling was used for all samples because of insufficient water depth.

Specific conductance was measured onsite in subsamples from the composite water samples. Subsamples of the composite water samples also were analyzed at the USGS National Water Quality Laboratory (NWQL) in Denver, Colo. for filtered (0.45-micrometer pore size filtration completed in the field) and unfiltered-recoverable concentrations of the trace elements included in the trend analysis (table 2). The methods of analysis used by NWQL for filtered and unfiltered-recoverable trace elements are described by Fishman (1993), Garbarino and Struzeski (1998), Garbarino and others (2006), and Hoffman and others (1996). Water samples also were analyzed

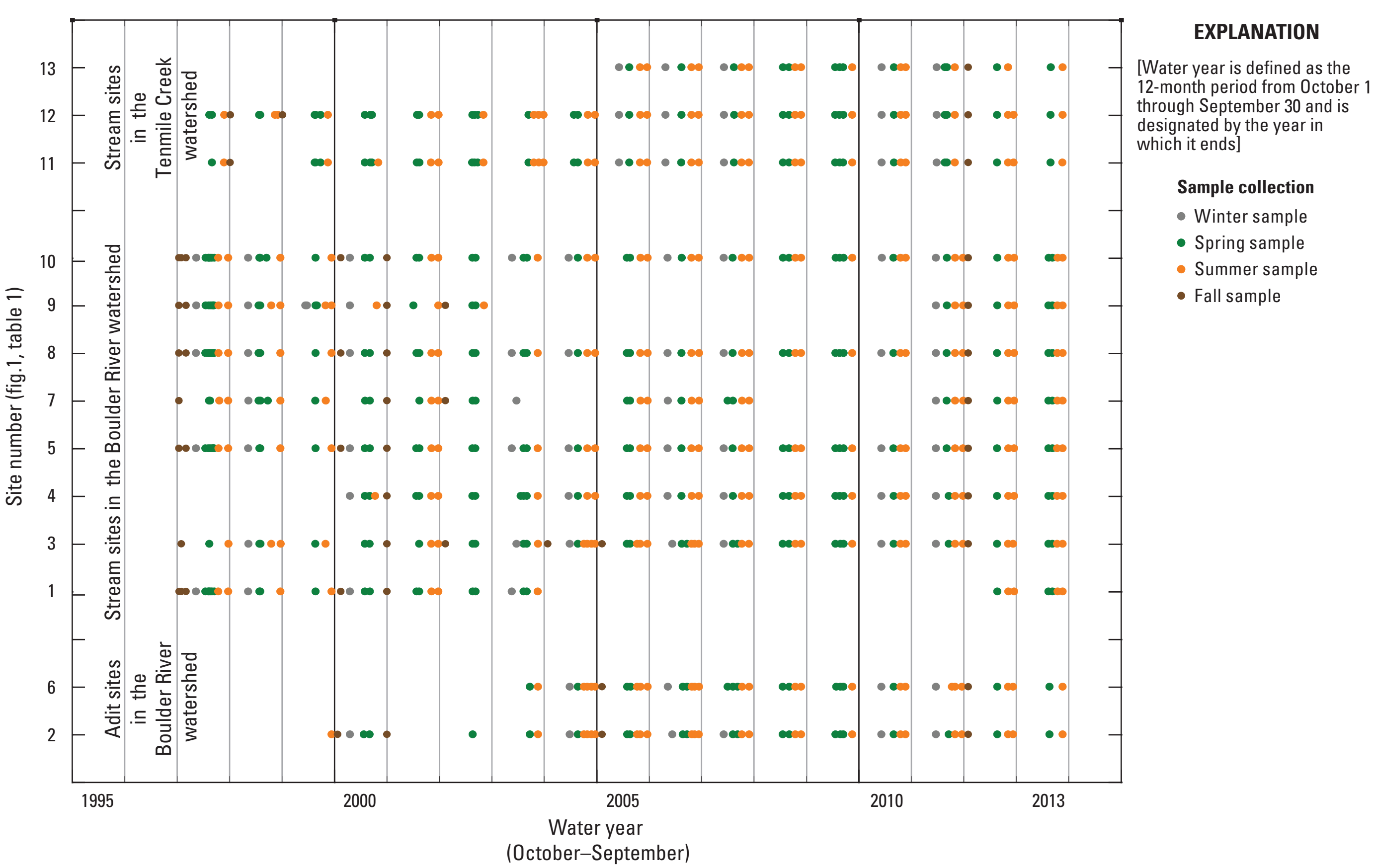

Figure 4. Temporal characteristics of water-quality sample collection for sites in the Boulder River and Tenmile Creek watersheds, Montana.

for suspended-sediment concentrations by the U.S. Geological Survey laboratory in Helena, Mont., using procedures described by Dodge and Lambing (2006).

Consistent field-collection and laboratory-analytical methods are important in trend analysis to be confident that observed trends represent real environmental changes and not methodology changes. Therefore, any changes made in field-collection and laboratory-analytical methods during the study period could be an issue of concern. Consistent field and laboratory methods were generally applied during the study period. However, a change was made in about water year 2000 by NWQL in the analytical method for most metallic trace elements from graphite furnace atomic absorption spectrophotometry (Fishman, 1993) to inductively coupled plasma-mass spectrometry (Garbarino and Struzeski, 1998; Garbarino and others, 2006). Potential effects of this issue on trend analysis were investigated by Sando and others (2014) and determined to be minor.

Table 2. Property and constituents included in the trend analysis and information relating to laboratory reporting levels.

[Water year is the 12-month period from October 1 through September 30 and is designated by the year in which it ends. NWQL, U.S. Geological Survey National Water Quality Laboratory; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter; mg/L, milligrams per liter]

Property or constituent	Units of measurement	Number of NWQL laboratory reporting levels during water years 1997–2010	Range in NWQL laboratory reporting levels
Specific conductance	µS/cm at 25 °C	NA	NA
Cadmium, filtered	µg/L	4	0.016–0.14
Cadmium, unfiltered-recoverable	µg/L	7	0.014–0.11
Copper, filtered	µg/L	6	0.2–1
Copper, unfiltered-recoverable	µg/L	5	0.6–1.2
Lead, filtered	µg/L	4	0.015–0.12
Lead, unfiltered-recoverable	µg/L	4	0.036–1
Zinc, filtered	µg/L	4	0.6–1.8
Zinc, unfiltered-recoverable	µg/L	4	1–3
Arsenic, filtered	µg/L	8	0.022–0.26
Arsenic, unfiltered-recoverable	µg/L	8	0.09–2.6
Suspended sediment	mg/L	NA	NA

Quality Assurance

Analytical results for individual environmental samples were carefully reviewed based on (1) comparisons with associated quality-assurance sample results, (2) comparisons with results for previously collected samples at the site, (3) relations between filtered and unfiltered-recoverable concentrations, (4) relations between unfiltered-recoverable concentrations and suspended-sediment concentrations, and (5) relations between concentrations and streamflow conditions. When one or more of the review criteria indicated problematic results for a given trace-element constituent, laboratory re-analysis was performed. If the re-analysis did not resolve the problematic results, the analytical results were excluded from the trend analysis. For the study period, exclusion of analytical results based on quality-assurance reviews affected a small percentage of the study datasets (less than 1 percent of all trace-element analyses). Excluded sample results generally were sporadic and limited to short periods, and are considered to have negligible effects on trend analysis.

Analytical results for field quality-assurance samples (including field blank and replicate samples) that were collected during water years 1997–2013 were compiled and statistically summarized (*table 1–1* in appendix 1 at the back of this report). The data in appendix 1 provide information on the consistency and environmental representativeness of data collection. Analysis of analytical results for field blank samples provides information on potential effects of contamination during the sampling process on trend-analysis results. For field blank samples, the frequency of detection at concentrations greater than the laboratory reporting level at the time of analysis was less than about 10 percent for all trace elements (except copper and zinc). Filtered and unfiltered-recoverable copper had detection frequencies in blank samples of 27 and 10 percent, respectively. Filtered and unfiltered-recoverable zinc had detection frequencies in blank samples of 43 and 20 percent, respectively. The high frequency of detection in blank samples for these constituents might indicate the difficulties in representative sampling in the monitoring program, where some sites have extremely high concentrations and there is large potential for cross-contamination of sampling equipment between sites. However, for filtered and unfiltered-recoverable copper, the maximum detected concentrations in blank samples did not exceed the minimum detected concentrations in environmental samples of any of the sites except site 1. For filtered and unfiltered-recoverable zinc, the maximum detected concentrations in blank samples did not exceed the minimum detected concentrations in environmental samples of any of the sites except site 1 (fig. 1, table 1). For filtered and unfiltered-recoverable zinc, the maximum detected concentrations in blank samples exceeded the median detected concentrations in environmental samples for site 1 (fig. 1, table 1); as a result, reported results for zinc for site 1 should be used with caution and conclusions from these trend results are qualified as having larger uncertainty than other site and constituent combinations.

Relative percent differences (RPDs) for field replicate samples typically were within plus or minus 15 percent (*table 1–1*), generally indicating acceptable precision of analytical results. However, for suspended sediment, 10th percentile and 90th percentile RPDs indicated strong deviation from zero. Several factors probably contribute to lower precision for suspended-sediment analyses. The study sites generally have low suspended-sediment concentrations, with median concentrations typically less than 4 milligrams per liter (mg/L). The reporting limit for suspended-sediment analysis is 1 mg/L; and at concentrations less than 4 mg/L, the resolution of suspended-sediment analyses is poor, because concentrations are reported to the nearest whole number (Dodge and Lambing, 2006). Thus, for low concentration ranges, small absolute differences in concentrations between primary and replicate samples can result in large RPDs. Further, some of the study sites are located near areas of mine drainage and are affected by dynamic processes as the mine drainage equilibrates with surface waters. In some cases, colloidal material is produced and is incorporated in the suspended-sediment analysis. Dynamic instream processes near areas of mine drainage also might contribute to large ranges in precision for suspended-sediment analyses.

Based on analysis of quality-assurance data, the quality of the study datasets were determined to be suitable for trend analysis. However, based on field blank concentrations in excess of median concentrations for site 1, reported results for zinc for site 1 should be used with caution and conclusions from these trend results are qualified as having larger uncertainty than other site and constituent combinations.

Overview of Water-Quality Characteristics for Selected Sites in the Boulder River and Tenmile Creek Watersheds

In parts of the study area that generally are free from human disturbance, water quality of streams is governed by runoff of dilute atmospheric water deposited on generally steeply sloped watersheds with rock and soil materials derived from erosion resistant granitic rocks. Concentrations of dissolved solids typically are low and pH values typically are near to slightly above neutral. In general, mining activities in the Boulder River and Tenmile Creek watersheds can affect water-quality characteristics by lowering pH, increasing specific conductance, and contributing filtered and unfiltered-recoverable concentrations of trace elements (Nimick and others, 2004; Cleasby and Nimick, 2002).

Statistically summarizing water-quality characteristics of the sites is useful for generally describing water quality of the study sites and for providing comparative information relevant for interpretation of trend results. Statistical summaries of water-quality data for sites in the Boulder River and Tenmile Creek watersheds are presented in *table 1–2* in appendix 1 (at the back of this report). For trace elements, in addition to statistical summaries of raw concentrations, ratios of median filtered to median unfiltered-recoverable concentrations, expressed as a percentage, also are presented in *table 1–2* to provide general information on the predominant phase (that is, dissolved or particulate) of transport. Data are summarized for water years 2009–13; this period was selected as the summary period because all sites have available data, a somewhat large range in streamflow conditions is represented, and recent water-quality conditions are represented. Water-quality characteristics of the study sites are illustrated by using boxplots of the trend-analysis constituents presented in figure 5 (for the adit sites in the Boulder River watershed) and figure 6 (for the stream sites in the Boulder River and Tenmile Creek watersheds). Distributions of constituents for adit sites and stream sites are separated into two figures because of difficulties in appropriately displaying the distributions given the large differences in concentration ranges between the adit sites and stream sites.

In figure 6 (showing data for the stream sites), aquatic life standards for all metallic contaminant trace elements (cadmium, copper, lead, and zinc; hereinafter referred to as metallic contaminants) are plotted in relation to the statistical distributions of concentrations. However, in figure 5 (showing data for the adit sites), only the aquatic life standard for lead is plotted in relation to the statistical distributions of lead concentrations; for cadmium, copper and zinc, the aquatic life standards are less than the plotted scales. In figures 5 and 6, the aquatic life standards for metallic contaminants were calculated based on median hardness for water years 2009–13. In figures 5 and 6, the human health standard for arsenic is plotted in relation to the statistical distributions of arsenic concentrations.

Distributions of filtered and unfiltered-recoverable concentrations of trace elements are shown in figures 5 and 6 to provide general information on the predominant phase of transport. The predominant phase of transport varied between sites; however, cadmium, copper, and zinc generally had similar filtered and unfiltered phases compared to lead and arsenic, where the unfiltered phase was commonly the dominant phase of transport.

In this section of the report, water-quality characteristics are briefly discussed by site; first for the adit sites in the Boulder River watershed, then for the stream sites in the Boulder River watershed, and then for the stream sites in the Tenmile Creek watershed. Although information concerning relations between filtered and unfiltered-recoverable concentrations of trace elements is presented in *table 1–2* and figures 5 and 6, the relations primarily are presented for informational purposes and are not routinely discussed. Emphasis is placed on describing spatial differences in water quality among the sites and factors that affect those differences.

In the text discussion on water-quality characteristics of the stream sites, property and constituent values for a given site are compared with those for the other stream sites. To

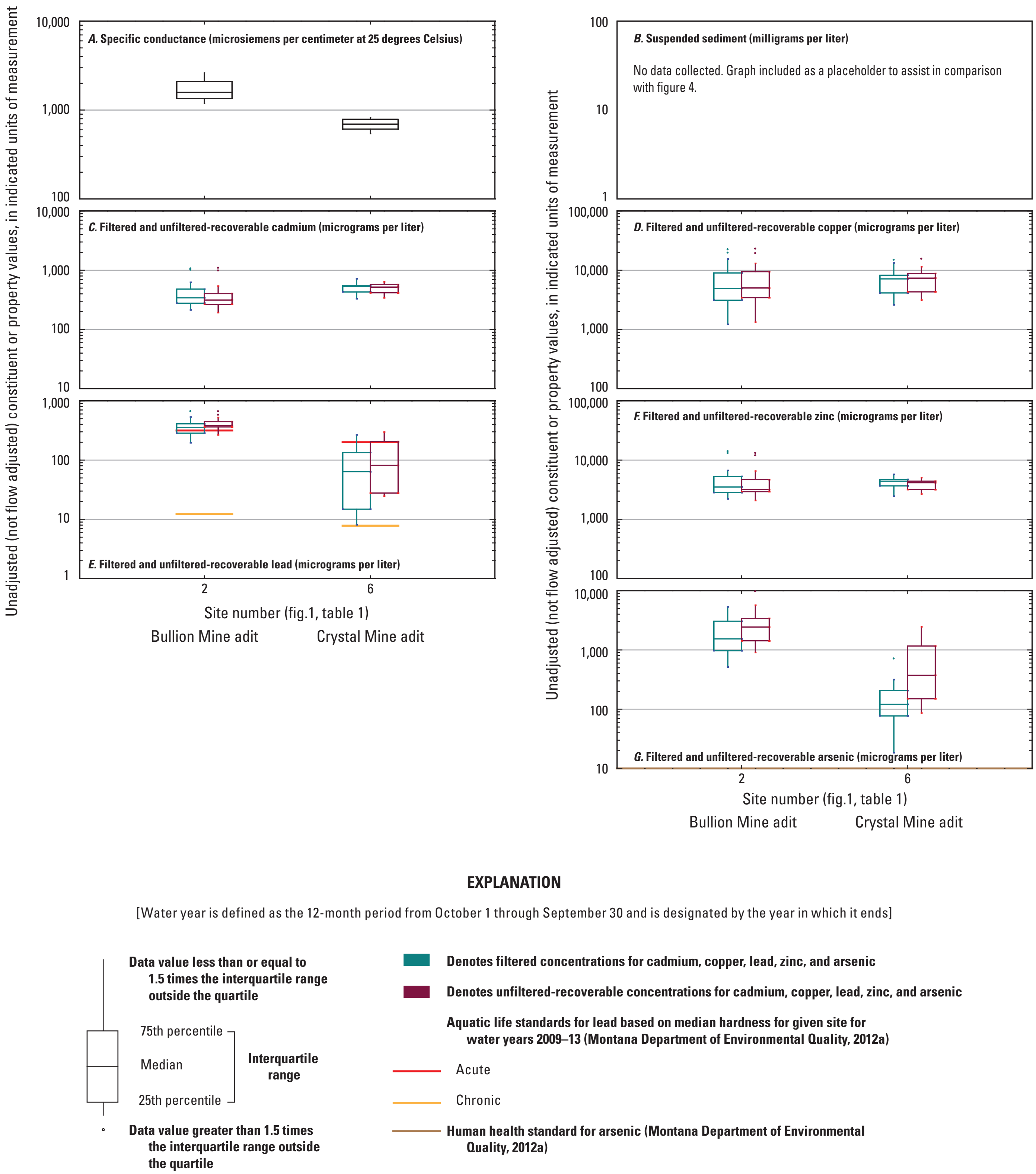

Figure 5. Statistical distributions of selected constituents for the adit sites in the Boulder River watershed, Montana, based on data collected during water years 2009–2013.

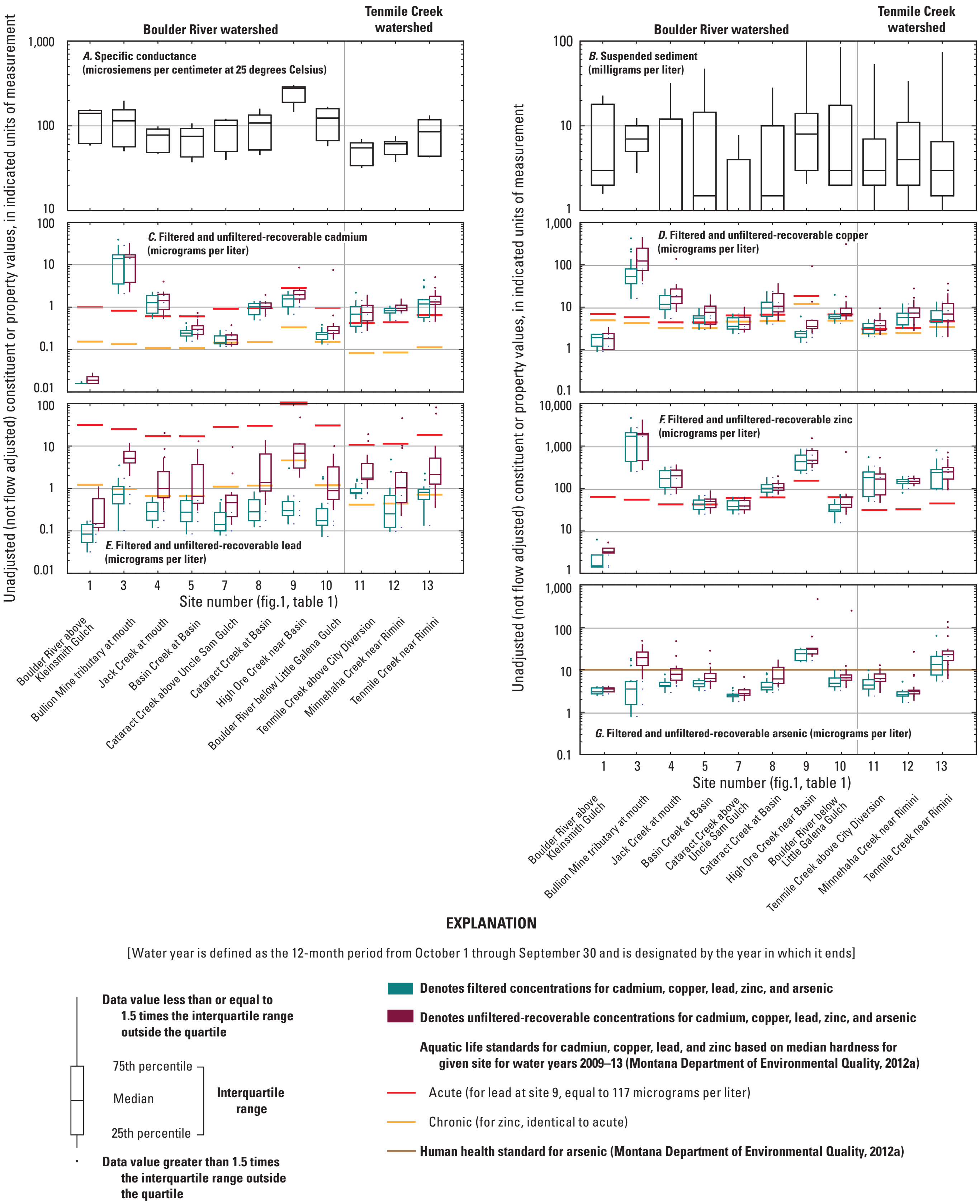

Figure 6. Statistical distributions of selected constituents for the stream sites in the Boulder River and Tenmile Creek watersheds, Montana, based on data collected during water years 2009–2013.

facilitate this discussion, the ranks of median values of properties and constituents among the stream sites are presented in table 3. The ranks of medians are ordered from largest to smallest. For example, Bullion Mine tributary at mouth (site 3, fig. 1, table 1) has the highest median concentration of filtered copper (52.8 micrograms per liter [µg/L]; *table 1–2*) of the 11 stream sites in this study; thus, the rank for the median concentration of filtered copper for site 3 is 1. Conversely, Boulder River above Kleinsmith Gulch (site 1, fig. 1, table 1) has the lowest median concentration of filtered copper (1.90 µg/L; *table 1–2*); thus, the rank for the median concentration of filtered copper for site 1 is 11. For the trace-element constituents, lower ranks of median values denote higher concentrations and represent greater effects from mining activities. However, the measurement units for pH are such that the reverse condition is true. Mining activities generally tend to acidify stream waters resulting in lower pH. Thus, higher ranks of median pH values generally represent greater effects from mining activities.

For each site, the percent of samples exceeding water-quality standards during water years 2009–13 is presented in table 4. For the hardness-based aquatic life standards for cadmium, copper, lead, and zinc, the percent exceedances presented in table 4 were based on comparison of trace-element concentrations of each individual sample with the aquatic life standards that were calculated using the hardness for each individual sample. In contrast, the statistical distributions of trace-element concentrations for water years 2009–13 shown in figures 5 and 6 are plotted in relation to aquatic life standards calculated using median hardness for water years 2009–13. Thus, in some cases, there are generally small discrepancies between the frequency of samples exceeding standards shown in figures 5 and 6 and the percent exceedances presented in table 4. The percent exceedances presented in table 4 and discussed in the text more accurately represent regulatory compliance.

Adit Sites in the Boulder River Watershed

The adit sites (sites 2 and 6) have water-quality characteristics that are substantially different from the stream sites. Bullion Mine adit (site 2, fig. 1, table 1) is a primary source of metallic contaminants in the Basin Creek watershed, and Crystal Mine adit (site 6, fig. 1, table 1) is a primary source of metallic contaminants in the Cataract Creek watershed (Nimick and others, 2004). Basin Creek and Cataract Creeks are tributary to the Boulder River (fig. 1). Medians of streamflow at time of sampling (0.01 and 0.05 ft^3/s for sites 2 and 6, respectively; *table 1–2*) are low and represent seepage of mine drainage from the adits. Medians of pH (3.0 and 4.7 units for sites 2 and 6, respectively) are lower than for any stream site and reflect the acidic nature of the mine seepage. Medians of specific conductance (1,580 and 695 microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C) for sites 2 and 6, respectively; fig. 5, *table 1–2*) are higher than for any stream site and reflect interaction of acidic mine water with rock and soil materials. Relative rankings of median concentrations of trace elements between the adit sites reflect differences in the characteristics of the ore bodies. Site 2 has median concentrations of unfiltered-recoverable lead and arsenic (384 and 1,530 µg/L, respectively) that are higher than site 6 median concentrations (81.3 and 372 µg/L, respectively). Site 6 has median concentrations of unfiltered-recoverable cadmium, copper, and zinc (521; 7,370; and 41,500 µg/L, respectively) that are higher than site 2 median concentrations (314; 5,020; and 31,800 µg/L, respectively). For both adit sites, all samples collected during water years 2009–13 exceeded all water-quality standards, except for the acute aquatic life standard for lead (exceeded in 89 and 28 percent of samples for sites 2 and 6, respectively; table 4).

Stream Sites in the Boulder River Watershed

Boulder River above Kleinsmith Gulch (site 1, fig. 1, table 1) is upstream from Basin Creek and Cataract Creek. The water quality at the site has relatively small effects from mining operations, which is evidenced by an abandoned mine density of 0.3 mines per mi^2 (substantially lower than for any other sampling site; table 1). Median streamflow at time of sampling (23 ft^3/s; *table 1–2*) and pH (7.6 units) for site 1 are higher than for most other stream sites. Median specific conductance (141 µS/cm at 25 °C; fig. 6, *table 1–2*) for site 1 also is higher than for most other sites, probably because of a larger drainage area than for most other sites, with greater opportunity for the stream water to interact with soil and rock materials. Median concentrations of unfiltered-recoverable cadmium (0.019 µg/L), copper (1.80 µg/L), lead (0.15 µg/L), and zinc (3.20 µg/L) for site 1 are lower than for any other stream site. The median concentration of unfiltered-recoverable arsenic (3.5 µg/L) for site 1 is lower than for most other stream sites. The median suspended sediment (3 mg/L) for site 1 is higher than for most other stream sites. For site 1, there were few exceedances of water-quality standards for any samples collected during water years 2009–13 (table 4). Water-quality standards exceedances include (1) the copper acute and chronic aquatic life standards (exceeded in 14 percent of samples) and (2) the lead chronic aquatic life standard (exceeded in 29 percent of samples). Water-quality characteristics of site 1 generally are representative of a background index site with small effects from mining operations.

Bullion Mine tributary at mouth (site 3, fig. 1, table 1) is about 1 mi downstream from Bullion Mine adit (site 2, fig. 1, table 1), which is a primary source of metallic contaminants to Basin Creek (Nimick and others, 2004) and strongly affects water quality at site 3. Site 3 is about 20 ft upstream from the confluence of the Bullion Mine tributary with Jack Creek. Median streamflow at time of sampling (0.61 ft^3/s; *table 1–2*) for site 3 is lower than for any other stream site, reflecting the small drainage area (3.6 mi^2). Median pH (6.8 units) for site 3 also is lower than for any other stream site. Median specific conductance (115 µS/cm at 25 °C; fig. 6, *table 1–2*) for site 3 is higher than for most other stream sites. Median concentrations

Table 3. Ranks of median values of properties and constituents among all stream sites in the Boulder River and Tenmile Creek watersheds, Montana, based on data collected during water years 2009–13.

[Water year is the 12-month period from October 1 through September 30 and is designated by the year in which it ends]

Site name and number (fig. 1, table 1)	Rank[1] of median value (largest to smallest) among all stream sites for indicated property or constituent								
	Abandoned mine density	Streamflow	pH	Specific conductance	Hardness	Calcium, filtered	Magnesium, filtered	Cadmium, filtered	Cadmium, unfiltered-recoverable
Boulder River above Kleinsmith Gulch (site 1)	11	2	4	2	2	2	2	11	11
Bullion Mine tributary at mouth (site 3)	4	11	11	4	6	6	4	1	1
Jack Creek at mouth (site 4)	6	8	7	8	8	8	8	3	3
Basin Creek at Basin (site 5)	7	3	4	9	9	9	9	8	8
Cataract Creek above Uncle Sam Gulch (site 7)	3	7	6	6	5	5	6	10	10
Cataract Creek at Basin (site 8)	2	4	3	5	4	3	5	5	5
High Ore Creek near Basin (site 9)	7	10	1	1	1	1	1	2	2
Boulder River below Little Galena Gulch (site 10)	10	1	2	3	3	4	3	9	9
Tenmile Creek above City Diversion (site 11)	1	6	10	11	11	11	11	7	7
Minnehaha Creek near Rimini (site 12)	9	9	8	10	10	10	10	6	6
Tenmile Creek near Rimini (site 13)	5	5	8	7	7	7	7	4	4

Site name and number (fig. 1, table 1)	Copper, filtered	Copper, unfiltered-recoverable	Lead, filtered	Lead, unfiltered-recoverable	Zinc, filtered	Zinc, unfiltered-recoverable	Arsenic, filtered	Arsenic, unfiltered-recoverable	Suspended sediment	Suspended sediment, percent fines
Boulder River above Kleinsmith Gulch (site 1)	11	11	11	11	11	11	9	9	4	1
Bullion Mine tributary at mouth (site 3)	1	1	3	2	1	1	8	3	2	1
Jack Creek at mouth (site 4)	2	2	5	7	5	4	6	4	10	4
Basin Creek at Basin (site 5)	6	4	7	9	8	8	4	6	8	7
Cataract Creek above Uncle Sam Gulch (site 7)	8	8	10	10	9	10	11	11	10	5
Cataract Creek at Basin (site 8)	3	3	6	5	7	7	7	8	8	10
High Ore Creek near Basin (site 9)	10	10	4	1	2	2	1	1	1	6
Boulder River below Little Galena Gulch (site 10)	4	6	9	8	10	9	3	5	4	8
Tenmile Creek above City Diversion (site 11)	9	9	2	4	4	5	5	6	4	9
Minnehaha Creek near Rimini (site 12)	5	5	8	6	6	6	10	10	3	11
Tenmile Creek near Rimini (site 13)	7	7	1	3	3	3	2	2	4	3

[1]Ranks are shaded as follows:

- Rank of 1
- Rank of 2–3
- Rank of 4–5
- Rank of 6
- Rank of 7–8
- Rank of 9–10
- Rank of 11

Table 4. Percent of samples with unadjusted unfiltered-recoverable concentrations exceeding water-quality standards for sites in the Boulder River and Tenmile Creek watersheds, Montana, water years 2009–13.

[Water year is the 12-month period from October 1 through September 30 and is designated by the year in which it ends]

Site number (fig. 1, table 1)	Site name (fig. 1, table 1)	Percent of samples exceeding indicated standard[1]							
		Aquatic life standards							Arsenic human health standard
		Cadmium		Copper		Lead		Zinc	
		Acute	Chronic	Acute	Chronic	Acute	Chronic	Acute and chronic	
1	Boulder River above Kleinsmith Gulch	0	0	14	14	0	29	0	0
2	Bullion Mine adit	100	100	100	100	89	100	100	100
3	Bullion Mine tributary at mouth	100	100	100	100	10	100	100	85
4	Jack Creek at mouth	100	100	100	100	5	65	100	30
5	Basin Creek at Basin	30	100	63	79	15	45	75	15
6	Crystal Mine adit	100	100	100	100	28	100	100	100
7	Cataract Creek above Uncle Sam Gulch	8	75	33	42	8	33	25	0
8	Cataract Creek at Basin	75	100	65	85	5	50	100	30
9	High Ore Creek near Basin	17	100	17	17	17	67	100	100
10	Boulder River below Little Galena Gulch	10	100	45	80	5	40	25	15
11	Tenmile Creek above City Diversion	100	100	61	78	17	100	100	17
12	Minnehaha Creek near Rimini	100	100	89	100	17	72	100	6
13	Tenmile Creek near Rimini	94	100	65	76	18	82	100	82

[1]Aquatic life standards used in determining exceedances for an individual sample were calculated based on the hardness of that sample according to methods described by Montana Department of Environmental Quality (2012).

of filtered and unfiltered-recoverable cadmium (13.9 and 15.0 µg/L, respectively), copper (52.8 and 122 µg/L, respectively), and zinc (1,690 and 1,840 µg/L, respectively) for site 3 are higher than for any other stream site; and median concentrations of filtered and unfiltered-recoverable lead (0.70 and 5.16 µg/L, respectively) are higher than for most other stream sites. Although the median filtered arsenic concentration (3.5 µg/L) for site 3 is lower than for most other stream sites, the median unfiltered-recoverable arsenic concentration (19.1 µg/L) for site 3 is higher than for most other stream sites. This pattern probably relates to dynamic instream processes as the mine drainage from Bullion Mine adit equilibrates with the tributary flow, and most of the arsenic (and likewise copper and lead) drops out of solution in association with colloidal material. Production of colloidal material in the short reach between sites 2 and 3 also is evidenced by ratios of median filtered to unfiltered-recoverable concentrations of arsenic, copper, and lead that are lower for site 3 than for any other stream site (*table 1–2*). Median suspended-sediment concentration (7 mg/L) for site 3 is higher than for any other stream site except High Ore Creek near Basin (site 9, fig. 1, table 1), which probably relates to production of colloidal material. For site 3, all samples collected during water years 2009–13 exceeded all water-quality standards except for the lead acute aquatic life standard (exceeded in 10 percent of samples) and the arsenic human health standard (exceeded in 85 percent of samples; table 4).

Jack Creek at Mouth (site 4, fig. 1, table 1) is about 2 mi downstream from Bullion Mine tributary at mouth (site 3, fig. 1, table 1). Median streamflow at time of sampling (5.2 ft^3/s; *table 1–2*) for site 4 is lower than for most other stream sites and reflects about a 7.5-fold increase from the median for site 3. Changes in water quality between sites 3 and 4 primarily reflect dilution of the relatively small inflow from the Bullion Mine tributary by surface-water and groundwater inflows from areas with less mining effects. Median pH (7.4 units) for site 4 represents an increase of 0.6 unit from the median for site 3. Median specific conductance (78 µS/cm at 25 ^{o}C; fig. 6, *table 1–2*) for site 4 is about 32 percent lower than the median for site 3 and also is lower than for most other stream sites. In association with the relatively low specific conductance, hardness also is lower than for most other stream sites, which contributes to relatively higher toxicity of metallic contaminants for site 4. Median concentrations of filtered and unfiltered-recoverable cadmium (1.27 and 1.43 µg/L, respectively), copper (11.6 and 17.4 µg/L, respectively), lead (0.29 and 0.99 µg/L, respectively), and zinc (169 and 198 µg/L, respectively) for site 4 are higher than for most other stream sites. However, the median concentrations of the metallic contaminants for site 4 typically are about 80–90 percent lower than median concentrations for site 3. The median filtered arsenic concentration (4.2 µg/L) for site 4 is about 20 percent higher from the median concentration for site 3; however, the median unfiltered-recoverable arsenic concentration (7.9 µg/L) is about 60 percent lower than the median concentration for site 3. This pattern might indicate that mixing of inflow from the Bullion Mine tributary with other Jack Creek inflows results in dissolution of some colloidal arsenic from the Bullion Mine tributary but overall dilution of unfiltered-recoverable arsenic. Median suspended-sediment concentration (1 mg/L) for site 4 is lower than for any other stream site except Cataract Creek above Uncle Sam Gulch (site 7, fig. 1, table 1), which might provide evidence that colloidal material contributed from the Bullion Mine tributary is altered or deposited in the 2 mi reach between site 3 and site 4. For site 4, all samples collected during water years 2009–13 exceeded all water-quality standards except for the following: (1) the lead acute and chronic aquatic life standards (exceeded in 5 and 65 percent of samples, respectively) and (2) the arsenic human health standard (exceeded in 30 percent of samples).

Basin Creek at Basin (site 5, fig. 1, table 1) is about 7 mi downstream from Jack Creek at mouth (site 4, fig. 1, table 1). Median streamflow at time of sampling (18 ft^3/s; *table 1–2*) for site 5 is higher than for most other stream sites and reflects about a 2.5-fold increase from the median for site 4. Changes in water quality between site 4 and site 5 primarily reflect dilution of the Jack Creek inflows by surface-water and groundwater inflows from areas with less mining effects. Median pH (7.6 units) for site 5 represents an increase of 0.2 unit from the median for site 4. Median specific conductance (76 µS/cm at 25 ^{o}C; fig. 6, *table 1–2*) for site 5 is similar to the median specific conductance for site 4 and also is lower than for most other stream sites. In association with the relatively low specific conductance, hardness also is lower than for most other stream sites, which contributes to relatively higher toxicity of metallic contaminants for site 5. Median concentrations of filtered and unfiltered-recoverable cadmium (0.245 and 0.302 µg/L, respectively), copper (5.50 and 7.60 µg/L, respectively), lead (0.27 and 0.65 µg/L, respectively), and zinc (41.9 and 48.9 µg/L, respectively) for site 5 generally are about 60–80 percent lower than median concentrations for site 4. The median filtered arsenic concentration (4.7 µg/L) for site 5 is about 10 percent higher than the median concentration for site 4; however, the median unfiltered-recoverable arsenic concentration (6.3 µg/L) is about 20 percent lower than the median concentration for site 4. Median suspended-sediment concentration (2 mg/L) for site 5 is lower than for most other stream sites and only slightly higher than the median concentration for site 4 (1 mg/L). For site 5, all samples collected during water years 2009–13 exceeded at least one water-quality standard. Water-quality standards exceedances (table 4) include (1) the cadmium acute and chronic aquatic life standards (exceeded in 30 and 100 percent of samples, respectively), (2) the copper acute and chronic aquatic life standards (exceeded in 63 and 79 percent of samples, respectively), (3) the lead acute and chronic aquatic life standards (exceeded in 15 and 45 percent of samples, respectively), (4) the zinc acute and chronic aquatic life standard (exceeded in 75 percent of samples), and (5) the arsenic human health standard (exceeded in 15 percent of samples).

Cataract Creek above Uncle Sam Gulch (site 7, fig. 1, table 1) is about 50 ft upstream from Uncle Sam Gulch, which receives seepage from the Crystal Mine adit (a primary source of metallic contaminants to Cataract Creek). Although site 7 is upstream from the Crystal Mine adit, site 7 drains a watershed with a somewhat high density of abandoned mines (2.3 per mi^2; table 1) with potential for mining effects on water quality. Median streamflow at time of sampling for site 7 is 5.9 ft^3/s, median pH is 7.6 units, and median specific conductance is 101 µS/cm at 25 °C (fig. 6, *table 1–2*). Median concentrations of filtered and unfiltered-recoverable cadmium (0.147 and 0.171 µg/L, respectively), copper (3.55 and 3.90 µg/L, respectively), lead (0.14 and 0.46 µg/L, respectively), and zinc (37.2 and 38.8 µg/L, respectively) for site 7 generally are lower than for most other stream sites except Boulder River above Kleinsmith Gulch (site 1, fig. 1, table 1). Median concentrations of filtered and unfiltered-recoverable arsenic (2.5 and 2.8 µg/L, respectively) for site 7 are lower than for any other stream site. Median suspended-sediment concentration (1 mg/L) for site 7 is lower than for any other stream site except Jack Creek at mouth (site 4, fig. 1, table 1). For site 7, exceedances of water-quality standards in samples collected during water years 2009–13 were fewer than for any other stream site except site 1. Water-quality standards exceedances include (1) the cadmium acute and chronic aquatic life standards (exceeded in 8 and 75 percent of samples, respectively), (2) the copper acute and chronic aquatic life standards (exceeded in 33 and 42 percent of samples, respectively), (3) the lead acute and chronic aquatic life standards (exceeded in 8 and 33 percent of samples, respectively), and (4) the zinc acute and chronic aquatic life standard (exceeded in 25 percent of samples).

Cataract Creek at Basin (site 8, fig. 1, table 1) is about 4 mi downstream from Cataract Creek above Uncle Sam Gulch (site 7, fig. 1, table 1). Median streamflow at time of sampling (15 ft^3/s; *table 1–2*) for site 8 is higher than for most other stream sites and reflects about a 1.5-fold increase from the median for site 7. Changes in water quality between sites 7 and 8 are affected by a combination of (1) inflows from Uncle Sam Gulch, which receives seepage from the Crystal Mine adit (a primary source of metallic contaminants to Cataract Creek; Nimick and others, 2004) and (2) surface-water and groundwater inflows from areas with less mining effects than Uncle Sam Gulch. Median concentrations of unfiltered-recoverable cadmium (1.04 µg/L), copper (10.6 µg/L), lead (1.38 µg/L), and zinc (103 µg/L) for site 8 generally are higher than for most other stream sites and typically are about 1.5- to 5-fold higher than median concentrations for site 7 (fig. 6, *table 1–2*). The median unfiltered-recoverable arsenic concentration (6.1 µg/L) for site 8 is about 120 percent higher than the median for site 7. For site 8, all samples collected during water years 2009–13 exceeded at least one water-quality standard. Water-quality standards exceedances (table 4) include (1) the cadmium acute and chronic aquatic life standards (exceeded in 75 and 100 percent of samples, respectively), (2) the copper acute and chronic aquatic life standards (exceeded in 65 and 85 percent of samples, respectively), (3) the lead acute and chronic aquatic life standards (exceeded in 5 and 50 percent of samples, respectively), (4) the zinc acute and chronic aquatic life standard (exceeded in 100 percent of samples), and (5) the arsenic human health standard (exceeded in 30 percent of samples).

High Ore Creek near Basin (site 9, fig. 1, table 1) receives seepage from the Comet Mine, a major source of metallic contaminants to the Boulder River (Nimick and others, 2004). Median streamflow at time of sampling for site 9 is 1.6 ft^3/s. The median pH (8.1 units; fig. 6, *table 1–2*) and median specific conductance (277 µS/cm at 25 °C; fig. 6, *table 1–2*) for site 9 are higher than for any other stream site. The relatively high specific conductance is associated with high hardness, which also is highest compared to any other site. The increased hardness decreases the toxicity of metallic contaminants and results in values for aquatic life standards that are higher than values for any other stream site (*table 1–3*). Median concentrations of unfiltered-recoverable cadmium (1.96 µg/L) and zinc (462 µg/L) for site 9 are higher than for most other stream sites. The median unfiltered-recoverable concentration of lead (6.77 µg/L) for site 9 is higher than for any other stream site. However, the median concentration of unfiltered-recoverable copper (3.50 µg/L) for site 9 is lower than for any other stream site except Boulder River above Kleinsmith Gulch (site 1, fig. 1, table 1). The median concentrations of unfiltered-recoverable arsenic (30.0 µg/L) and suspended sediment (8 mg/L) for site 9 are higher than for any other stream site. Mine wastes, mill tailings, and fluvial deposits appear to be the source of arsenic in High Ore Creek (Nimick and others, 2004). In contrast to the high metal concentrations, aquatic life standards exceedances generally were lower at site 9 compared to most other stream sites; however, at least one water-quality standard was exceeded in all samples collected at site 9. Water-quality standards exceedances include (1) the cadmium acute and chronic aquatic life standards (exceeded in 17 and 100 percent of samples, respectively), (2) the copper acute and chronic aquatic life standards (exceeded in 17 percent of samples), (3) the lead acute and chronic aquatic life standards (exceeded in 17 and 67 percent of samples, respectively), (4) the zinc acute and chronic aquatic life standard (exceeded in 100 percent of samples), and (5) the arsenic human health standard (exceeded in 100 percent of samples). For site 9, the high hardness contributes to the low percentage of samples with aquatic life standards exceedances for cadmium and copper.

Boulder River below Little Galena Gulch (site 10, fig. 1, table 1) is about 7 mi downstream from Boulder River above Kleinsmith Gulch (site 1, fig. 1, table 1) and about 6, 5, and 2 mi downstream from the mouths of Basin Creek, Cataract Creek, and High Ore Creeks, respectively. Median streamflow at time of sampling (101 ft^3/s; *table 1–2*) for site 10 is higher than for any other stream site and reflects about a 3.4-fold increase from the median for site 1. Changes in water quality between site 1 and site 10 are affected by a combination of (1) inflows from Basin Creek, Cataract Creek, and High Ore Creek (the primary sources of metallic contaminants to the Boulder River; Nimick and others, 2004) and (2) surface-water and groundwater inflows from areas with less mining effects than Basin Creek, Cataract Creek, and High Ore Creek. Median pH (8.0 units) for site 10 represents an increase of 0.4 unit from the median for site 1. Median specific conductance (124 µS/cm at 25 °C; fig. 6, *table 1–2*) for site 10 is about 12 percent lower than the median for site 1 but is higher than for most other stream sites. Median concentrations of unfiltered-recoverable cadmium (0.281 µg/L), copper (6.95 µg/L), lead (0.89 µg/L), and zinc (41.6 µg/L) for site 10 are about 3–5-fold (copper and lead) to greater than 10-fold (cadmium and zinc) higher than median concentrations for site 1 but generally are lower than for most other stream sites. The median unfiltered-recoverable arsenic concentration (6.4 µg/L) for site 10 is about 83 percent higher than the median for site 1 and is higher than for most other stream sites. Median suspended-sediment concentration (3 mg/L) for site 10 is identical to the median concentration for site 1 and is higher than for most other stream sites. For site 10, all samples collected during water years 2009–13 exceeded at least one water-quality standard. Water-quality standards exceedances include (1) the cadmium acute and chronic aquatic life standards (exceeded in 10 and 100 percent of samples, respectively), (2) the copper acute and chronic aquatic life standards (exceeded in 45 and 80 percent of samples, respectively), (3) the lead acute and chronic aquatic life standards (exceeded in 5 and 40 percent of samples, respectively), (4) the zinc acute and chronic aquatic life standard (exceeded in 25 percent of samples), and (5) the arsenic human health standard (exceeded in 15 percent of samples).

Stream Sites in the Tenmile Creek Watershed

Tenmile Creek above City Diversion (site 11, fig. 1, table 1) drains a watershed with high density of abandoned mines (3.0 mines per mi^2; table 1) and with potential for mining effects on water quality. However, the watershed does not contain mine point sources of metallic contaminants of similar magnitude to the Bullion, Crystal, and Comet Mines in the Boulder River watershed. Median streamflow at time of sampling for site 11 is 6.6 ft^3/s. Median pH (7.2 units; *table 1–2*) for site 11 is lower than for any other stream site except Bullion Mine tributary at mouth (site 3, fig. 1, table 1). Median specific conductance (55 µS/cm at 25 °C; fig. 6, *table 1–2*) for site 11 is lower than for any other stream site. In association with the relatively low specific conductance, hardness also is lower than for any other site (*table 1–3*). Median concentrations of filtered and unfiltered-recoverable cadmium (0.682 and 0.754 µg/L, respectively) and copper (3.25 and 3.65 µg/L, respectively) for site 11 generally are lower than for most other stream sites, but median concentrations of filtered and unfiltered-recoverable lead (0.80 and 1.75 µg/L, respectively) and zinc (179 and 167 µg/L, respectively) for site 11 generally are higher than for most other stream sites. Median concentrations of filtered and unfiltered-recoverable arsenic (4.4 and 6.3 µg/L, respectively) and median suspended-sediment concentration (3 mg/L) for site 11 also generally are higher than for most other stream sites. For site 11, all samples collected during water years 2009–13 exceeded at least one water-quality standard. Water-quality standards exceedances include (1) the cadmium acute and chronic aquatic life standards (exceeded in 100 percent of samples), (2) the copper acute and chronic aquatic life standards (exceeded in 61 and 78 percent of samples, respectively), (3) the lead acute and chronic aquatic life standards (exceeded in 17 and 100 percent of samples, respectively), (4) the zinc acute and chronic aquatic life standard (exceeded in 100 percent of samples), and (5) the arsenic human health standard (exceeded in 17 percent of samples). For site 11, the low hardness contributes to the high toxicity of metallic contaminants as indicated by the high percentage of samples with aquatic life standards exceedances for cadmium, copper, and zinc.

Minnehaha Creek near Rimini (site 12, fig. 1, table 1) drains a watershed with moderate density of abandoned mines (1.3 mines per mi^2; table 1) and with potential for mining effects on water quality. However, the watershed does not contain mine point sources of metallic contaminants of similar magnitude to the Bullion, Crystal, and Comet Mines in the Boulder River watershed. Median streamflow at time of sampling for site 12 is 2.8 ft^3/s. Median pH (7.3 units; *table 1–2*) and specific conductance (62 µS/cm at 25 °C; fig. 6, *table 1–2*) for site 12 are lower than for most other stream sites. In association with the relatively low specific conductance, hardness also is lower than for most other sites, which contributes to relatively higher toxicity of metallic contaminants for site 12 (*table 1–3*). Median concentrations of filtered and unfiltered-recoverable cadmium (0.824 and 0.927 µg/L, respectively), copper (5.70 and 7.25 µg/L, respectively), lead (0.252 and 1.04 µg/L, respectively), and zinc (145 and 148 µg/L, respectively) for site 12 generally are higher than for most other stream sites. Median concentrations of filtered and unfiltered-recoverable arsenic (3.1 and 4.0 µg/L, respectively) are lower than for any other stream site except Cataract Creek above Uncle Sam Gulch (site 7, fig. 1, table 1). Median suspended-sediment concentration (4 mg/L) for site 12 is higher than for most other stream sites. For site 12, all samples collected during water years 2009–13 exceeded at least one water-quality standard. Water-quality standards exceedances include (1) the cadmium acute and chronic aquatic life standards (exceeded in 100 percent of samples), (2) the copper acute and chronic aquatic life standards (exceeded in 89 and 100 percent of samples, respectively), (3) the lead acute and chronic aquatic life standards (exceeded in 17 and 72 percent of samples, respectively), (4) the zinc acute and chronic aquatic life standard (exceeded in 100 percent of samples), and (5) the arsenic human health standard (exceeded in 6 percent of samples). For site 12, the low hardness contributes to the high toxicity of metallic contaminants as indicated by the high percentage of samples with aquatic life standards exceedances for cadmium, copper, and zinc.

Tenmile Creek near Rimini (site 13, fig. 1, table 1) is about 3.5 mi downstream from Tenmile Creek above City diversion (site 11, fig. 1, table 1) and about 1.5 mi downstream from Minnehaha Creek near Rimini (site 12, fig. 1, table 1) and the mouth of Minnehaha Creek. About 0.5 mi downstream from site 11, part of the streamflow of Tenmile Creek is diverted into a canal that feeds Chessman Reservoir (not shown on fig. 1) and supplies drinking water to the city of Helena, Mont. (Parrett and Kendy, 2001). Site 13 drains a watershed with a somewhat high density of abandoned mines (2.1 mines per mi^2; table 1) and with potential for mining effects on water quality. However, the watershed does not contain mine point sources of metallic contaminants of similar magnitude to the Bullion, Crystal, and Comet Mines in the Boulder River watershed. Further, the highest density of abandoned mines in the site 13 watershed is upstream from site 11 and part of the streamflow at site 11 is transferred outside of the watershed by the city diversion. Thus, changes in water quality between sites 11 and 13 are affected by a combination of the following: (1) undiverted inflows from site 11, (2) inflows from Minnehaha Creek, and (3) surface-water and groundwater inflows from areas that generally have less mining effects than site 11 and Minnehaha Creek. Median streamflow at time of sampling (14 ft^3/s; *table 1–2*) for site 13 is about 114 percent higher than the median for site 11. Median pH (7.3 units; *table 1–2*) for site 13 is lower than for most other stream sites. Median specific conductance (88 μS/cm at 25 °C; fig. 6, *table 1–2*) for site 13 is about 60 and 42 percent higher than the medians for sites 11 and 12, respectively. Median concentration of unfiltered-recoverable cadmium (1.32 μg/L) for site 13 is about 74 and 42 percent higher than the medians for sites 11 and 12, respectively. Median concentration of unfiltered-recoverable copper (6.05 μg/L) for site 13 is about 66 percent higher than the median for site 11 but about 17 percent lower than the median for site 12. Median concentration of unfiltered-recoverable lead (2.04 μg/L) is about 17 and 97 percent higher than the medians for sites 11 and 12, respectively. Median concentration of unfiltered-recoverable zinc (234 μg/L) for site 13 is about 40 and 58 percent higher than the medians for sites 11 and 12, respectively. Median concentration of unfiltered-recoverable arsenic (22.6 μg/L) is about 2.6- and 6.3-fold higher than the medians for sites 11 and 12, respectively. Site 13 has higher median concentrations of most metallic contaminants and arsenic than sites 11 and 12; however, the intervening drainage area between the upstream sites (11 and 12) and site 13 has a relatively low density of abandoned mines and few substantial point sources of metallic contaminants and arsenic. This circumstance might suggest that (1) contaminants are mobilized from channel and flood-plain deposits in the intervening drainage area or (2) groundwater inflows downstream from site 11 have high concentrations of metallic contaminants and arsenic. For site 13, all samples collected during water years 2009–13 exceeded at least one water-quality standard. Water-quality standards exceedances include (1) the cadmium acute and chronic aquatic life standards (exceeded in 94 and 100 percent of samples, respectively), (2) the copper acute and chronic aquatic life standards (exceeded in 65 and 76 percent of samples, respectively), (3) the lead acute and chronic aquatic life standards (exceeded in 18 and 82 percent of samples, respectively), (4) the zinc acute and chronic aquatic life standard (exceeded in 100 percent of samples), and (5) the arsenic human health standard (exceeded in 82 percent of samples). Investigation of the effects of diversions for municipal water use and small amounts of irrigation in the upper part of the Tenmile Creek watershed (Parrett and Kendy, 2001; U.S. Environmental Protection Agency, 2002) on water quality of Tenmile Creek was beyond the scope of this study.

Trend-Analysis Methods

For the stream sites, multiple linear regression (MLR) of constituent concentrations on time, streamflow, and season (Helsel and Hirsch, 2002) was used for trend analysis of selected constituents (table 2). The constituents selected for trend analysis were considered most relevant to evaluating effects of remediation of mining activities. The water-quality property pH is relevant to mining activities but was not included in the trend analysis. The log-based units of measurement for pH result in transformational complexities within the trend-analysis approach of this study and would have required an analytical approach distinctly different from all other trend-analysis constituents. Application of a special analytical approach for trend analysis for pH was beyond the scope of the study.

Inclusion of streamflow in the MLR trend analysis provides for definition of flow-adjusted trends. Flow adjustment is necessary because concentrations of many water-quality constituents are dependent on streamflow conditions that primarily are affected by climatic variability. The intent of flow adjustment is to identify and remove streamflow-related variability in concentration and thereby enhance capability to detect trends independent from effects of climatic variability.

The importance of flow adjustment is illustrated in figure 7 by using streamflow and constituent concentration data that were collected at Basin Creek (site 5, fig. 1, table1) during water years 1997–2013. Daily mean streamflow is shown in figure 7, with an associated locally weighted scatter plot smooth (LOWESS; Cleveland, 1985; Cleveland and McGill, 1984) line illustrating central tendency of the data. Unadjusted (that is, measured) concentrations of unfiltered-recoverable copper, unfiltered-recoverable arsenic, and suspended sediment also are shown in figure 7, with associated LOWESS smooth lines. LOWESS smooth lines for the constituents have similar patterns to the LOWESS smooth line for streamflow, with the relations being most pronounced for copper and suspended sediment. The similarity in LOWESS smooth lines among unadjusted concentrations and streamflow

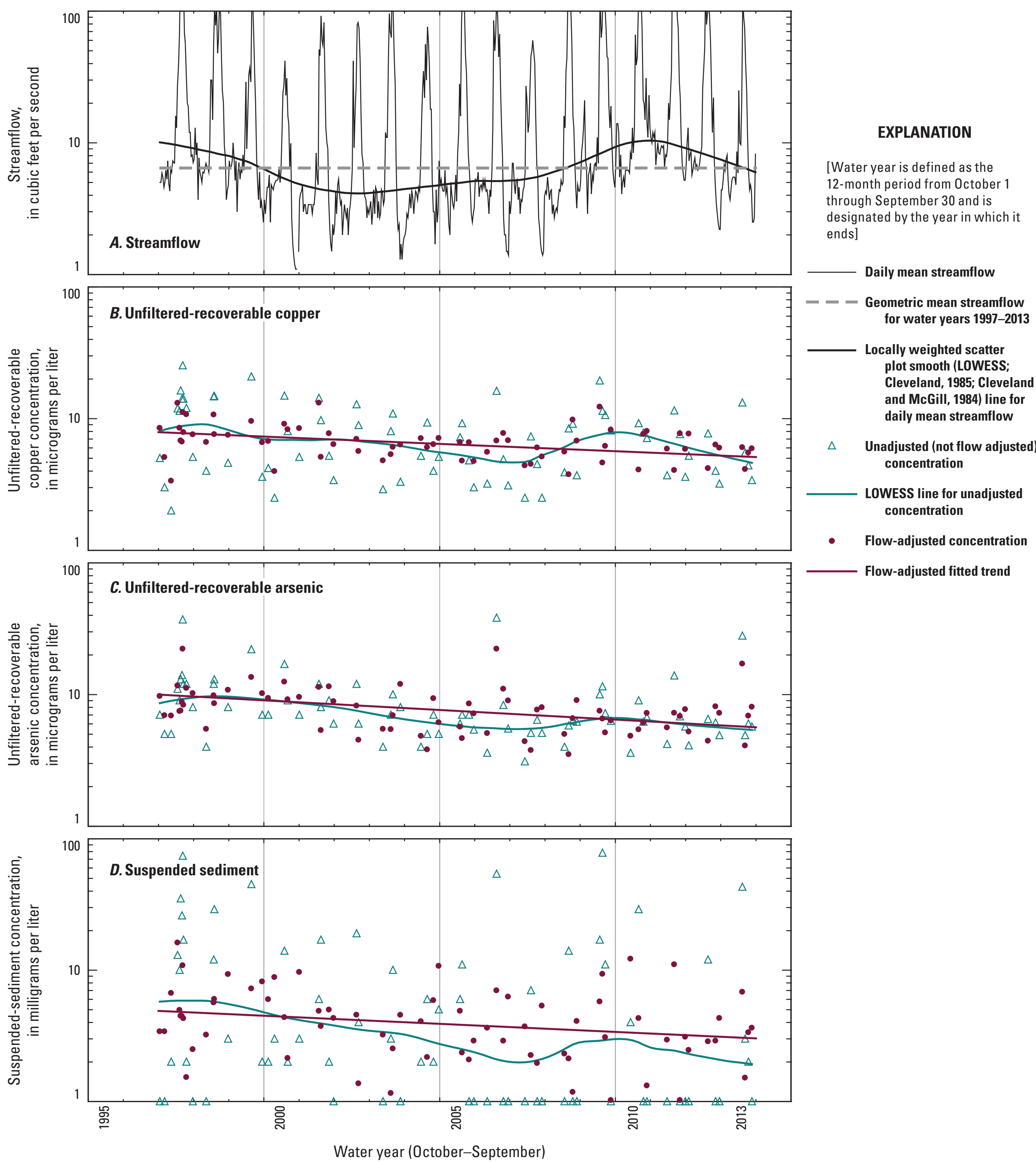

Figure 7. Selected streamflow and constituent concentration information for Basin Creek at Basin (site 5, fig. 1, table 1), based on data collected during water years 1997–2013.

indicates that temporal variability in unadjusted concentrations is strongly affected by temporal variability in streamflow. Flow-adjusted concentrations (FACs) for the constituents also are shown in figure 7, with associated MLR fitted trends. The FACs and fitted trends indicate general decreases that are independent from the temporal variability in streamflow. The dissimilar patterns among unadjusted concentrations and FACs indicate the importance of flow-adjusted trend analysis for identifying actual patterns in constituent concentrations independent from variability in streamflow conditions, which typically result from changes in land use or other human activities.

For the stream sites, a consistent MLR model was used to provide general application for the many (128) site and constituent combinations. In general, log-transformed (base-10 logarithm) constituent concentrations were regressed on log-transformed streamflow, decimal time, and periodic functions used to represent seasonal variability in concentration and streamflow relations. Regression models were developed by using least squares regression if the concentration data contained no censored observations or by using adjusted maximum-likelihood estimation (Cohn, 2005) if censored observations were present. Specific information that concerns the suitability of the MLR application to the study datasets and the procedures that determine the statistical significance and magnitude of trends are presented in appendix 2.

For the adit sites, relations between constituent concentrations and streamflow were much weaker than for the stream sites. Streamflow for the adit sites represented groundwater seepage from the adits that typically was less than 0.07 ft^3/s and had small variability among sampling dates. Thus, streamflow was not included in MLR trend models for the adit sites and the trend results represent temporal changes in unadjusted concentrations.

For MLR, fitted trends are straight-line monotonic trends determined for defined trend-analysis periods. Definition of trend-analysis periods is affected by several factors, including the timing of data collection, temporal patterns in FACs (or unadjusted concentrations for the adit sites), and the study objectives.

For the adit sites (Bullion Mine adit [site 2, fig. 1, table 1] and Crystal Mine adit [site 6, fig. 1, table 1]) trend-analysis periods were assigned consistently even though the data-collection periods somewhat differed between the sites. Data collection for site 2 during water years 1999–2002 had within-year sampling frequency that was particularly variable and two water years had only one sample each. During water years 2003–13, data-collection activities were consistent among the adit sites. Thus, for the adit sites, trends were analyzed for June 2003 through September 2013. This definition of trend-analysis periods provides for consistent comparison of trends between the adit sites.

For each stream site, the trend-analysis period was from the start of data collection to the end of water year 2013. Examination of time-series plots of FACs for the stream sites indicated that temporal patterns in FACs for most site and constituent combinations could reasonably be represented by single trend-analysis periods. Variability in the start of data collection among the stream sites generally was small. Start times ranged from water years 1997–2000 for all stream sites except Tenmile Creek near Rimini (site 13, fig. 1, table 1), which had a start time of water year 2005. Thus, for all stream sites except site 13, the definition of trend-analysis periods provides for generally consistent comparison of trends among the sites. However, for several stream sites sample-collection characteristics differ from most other stream sites and affect the comparability of trend results. This issue is discussed in the following section of this report “Factors that Affect Trend Analysis and Interpretation.”

Factors that Affect Trend Analysis and Interpretation

Ideally, water-quality trend analysis is done on data that were consistently and systematically collected within a monitoring network specifically designed for the purpose of trend analysis. The datasets for the sites in the Boulder River and Tenmile Creek watersheds do not represent ideal cases. However, the datasets were considered sufficient in longevity, data density, and quality for trend analysis to generally describe relative differences in temporal patterns in FACs. For site and constituent combinations where there are large uncertainties in trend results, conclusions concerning the results are qualified.

Data-Collection Factors

All of the study sites have variability in within-year sampling frequency among years. However, the within-year sampling frequency was similar in individual years among most sites. A notable characteristic of the study datasets is relatively poor representation of samples collected in the fall and winter. Overall, about 80 percent of all samples were collected during the spring or summer and about 20 percent were collected during the fall or winter. However, the seasonal distribution of samples generally was similar among sites.

Although the study datasets are not ideally suited for precise definition of temporal trends, generally strong similarity in sample-collection characteristics of the datasets among most sites provides a reasonable basis for relative comparisons of trend results among sites. The adit sites (Bullion Mine adit [site 2, fig. 1, table 1] and Crystal Mine adit [site 6, fig. 1, table 1]) have nearly identical sample-collection characteristics during the trend-analysis periods for the adit sites, providing a basis for comparison of results between the adit sites.

Stream sites in the Boulder River watershed that have similar sample-collection characteristics (fig. 4) are Bullion Mine tributary at mouth (site 3, fig. 1, table 1), Basin Creek at Basin (site 5, fig. 1, table 1), Cataract Creek at Basin (site 8, fig. 1, table 1), and Boulder River below Little Galena Gulch (site 10, fig. 1, table 1). Sample collection for Jack Creek at mouth (site 4, fig. 1, table 1) started later (in water year 2000) than for sites 3, 5, 8, and 10; however, during water years 2000–13, sample collection for site 4 was similar to sites 3, 5, 8, and 10. Trend results for site 4 are considered comparable to results for sites 3, 5, 8, and 10. Stream sites in the Boulder River watershed that have multi-year gaps in data collection are Boulder River above Kleinsmith Gulch (site 1, fig. 1, table 1), Cataract Creek above Uncle Sam Gulch (site 7, fig. 1, table 1), and High Ore Creek near Basin (site 9, fig. 1, table 1). The larger dissimilarity between the datasets for sites 1, 7, and 9 and the datasets for most other stream sites results in larger uncertainties in directly comparing trend results for sites 1, 7, and 9 with trend results for most other stream sites.

Stream sites in the Tenmile Creek watershed that have similar sample-collection characteristics (fig. 4) are Tenmile Creek above City Diversion (site 11, fig. 1, table 1) and Minnehaha Creek near Rimini (site 12, fig. 1, table 1). Sample-collection characteristics for sites 11 and 12 in the Tenmile Creek watershed also generally are similar to sample-collection characteristics for sites 3, 4, 5, 8, and 10 in the Boulder River watershed. Similarities in the datasets for sites 3, 4, 5, 8, 10, 11, and 12 provide a basis for comparison of trend results among the sites. Tenmile Creek near Rimini (site 13, fig. 1, table 1) has a much shorter sample collection period (water years 2005–13) than any other stream site; therefore, there might be large uncertainties in comparing trend results for site 13 than with trend results for other stream sites.

Potential Effects of Diel Cycling of Trace Elements

An important consideration in trend analysis for trace elements is potential effects of diel cycling in trace-element concentrations. Complex biogeochemical processes affected by the daily solar photocycle produce regular and dynamic changes in many physical and chemical characteristics of streams (Nimick and others, 2011). In some streams (including some of the sampling sites in this study), the biogeochemical processes can result in large diel variability in trace-element concentrations (Nimick and others, 2003).

Diel cycling in trace element concentrations has potential to affect trend results if (1) there is strong diel cycling for a given site and constituent combination and (2) there is a systematic temporal bias in the dataset with respect to time of day of sampling. For most sites, sampling times during the data-collection periods generally were within a narrow range (with the interquartile ranges of sampling times generally between 10 a.m. and 2 p.m.). During exploratory data analysis, time-series plots of sampling time were qualitatively examined for systematic temporal bias, and such bias was not clearly indicated. Also during exploratory analysis, potential effects of diel cycling on the trend results were quantitatively evaluated by including decimal day (time of sampling) as an explanatory variable in the trend models. The decimal day variable indicates the strength of diel cycling for a given site and constituent combination and also allows evaluation of the effect of temporal variability in time of sampling on the trend results. Although several site and constituent combinations had strong and statistically significant diel cycling, in no case did the inclusion of the decimal day variable in trend models provide substantially different trend results from the reported results. Thus, potential effects on trend results of diel cycling of trace elements were determined to be minor.

Statistical and Other Factors

An important consideration in interpreting trend results relates to the MLR method incorporating log transformation of constituent concentrations and streamflow. Thus, the methods evaluate changes in geometric mean concentrations (generally similar to untransformed median concentrations) in reference to log-transformed streamflow. Log transformation results in datasets that are approximately normally distributed and allow analysis using rigorous parametric procedures. However, log transformation decreases variability in the data relative to the original untransformed units representative of actual environmental variability. This factor is important in interpreting trend results with respect to regulatory issues, including compliance with human health or aquatic life standards. The trends in FACs provide general information on overall temporal changes (in terms of directions and relative magnitudes) in concentrations. However, the trends in FACs lack the specificity to indicate compliance or noncompliance with regulatory standards. In presentation of trend results, trend magnitudes and directions for trace elements are shown in conjunction with water-quality standards to provide general information on temporal changes in water quality in relation to the standards (determined based on median hardness values during water years 2009–13). Providing specific information on actual compliance with standards is not intended and relations between the reported trends and water-quality standards are not discussed in this report.

Trend-magnitude and fitted trend values are considered semiquantitative estimates determined by statistical analysis. Throughout this report, trend-magnitude and fitted trend values frequently are referred to (reported to two significant figures) in discussion of temporal and spatial changes in water quality. Reference to specific trend-magnitude and fitted trend values is intended to facilitate discussion of relative spatial and temporal differences among values; however, reference to the values is not intended to represent absolute accuracy at two significant figures. The text discussion on trend results focuses on the trend-magnitude and fitted trend values. The *p*-values (statistical probability levels) and levels of significance associated with the trend results are indicated in the tables and figures that present trend results. However, the *p*-values and levels of significance are not emphasized in the discussion of trend results. In this study, trend analysis using MLR is considered to be a useful tool for simplifying the environmental complexity in the Boulder River and

Tenmile Creek watersheds to provide a large-scale evaluation of general temporal changes in FACs. Thus, the best-fit trend lines are considered to provide important information beyond the strict statistical characteristics of the trend results (in terms of *p*-values and levels of significance) because the trend lines aid in comparing and summarizing large-scale patterns among sites.

Water-Quality Trends for Selected Sites in the Boulder River and Tenmile Creek Watersheds

Trend results for all sites are presented in summary figures (figs. 8 and 9) and tables (tables 5 and 6). Detailed results for each site are presented in appendix 3 in figures (figs. 3–1 through 3–13, *http://pubs.usgs.gov/sir/2015-5008/downloads/sir20155008_Appendix03_figures.pdf*) and tables (tables *3–1* and *3–2*). In the tables and text figures, trend results are presented for all constituents analyzed for trends (table 2). However, in the figures presented in appendix 3, presentation of results is restricted to specific conductance, copper, zinc, arsenic, and suspended sediment. Further, in the text discussion, emphasis is placed on specific conductance, copper, zinc, arsenic, and suspended sediment. Specific conductance is an index of ionic strength and provides information on extent of water contact with geologic materials and types of geologic materials present in the sampling-site watersheds. Mining activities can increase specific conductance by interaction of acidic mine water with rock and soil materials. Copper, zinc, and arsenic are constituents of concern with respect to potential toxicity issues. Copper and zinc provide examples of geochemical characteristics of metallic contaminants, and arsenic is a metalloid element with substantially different geochemical characteristics than most metallic elements. Suspended sediment is presented because it provides information on transport of particulate materials, which is a factor that can strongly affect transport of metallic contaminants.

Temporal trends are discussed by site groups (table 1; adit sites in the Boulder River watershed, stream sites in the Boulder River watershed, and stream sites in the Tenmile Creek watershed) and by site within each group. To allow various comparisons, trend magnitudes are presented as total percent change during indicated multi-year periods and also as percent change per year.

In the text discussion, qualitative observations on trend magnitudes are made. Trend magnitudes are considered to be (1) large, if the deviation from zero of the trend magnitude was larger than about 5 percent per year; (2) moderate, if the deviation from zero of the trend magnitude was about 3–5 percent per year; (3) small, if the deviation from zero of the trend magnitude was about 1.5–3 percent per year; and (4) minor, if the deviation from zero of the trend magnitude was about 0–1.5 percent per year. In some cases, where trending is in a small range at low concentrations, relatively large trend magnitudes (on a percent basis) also are considered to be minor. The qualitative descriptions were subjectively defined and are intended to facilitate relative comparison of trend patterns among site and constituent combinations. In the text discussion, the terms “significant” or “significantly” refer to statistical significance (p-value < 0.01) unless otherwise noted.

Factors affecting temporal variability in water quality in the Boulder River and Tenmile Creek watersheds are complex. Much information on observed changes in water quality is presented in this report. However, to provide detailed explanations for all of the observed changes or to link specific trends with specific remediation activities is beyond the scope of this report. The primary focus is on describing general temporal changes in water quality within the Boulder River and Tenmile Creek watersheds.

Adit Sites in the Boulder River Watershed

For the adit sites, trends were analyzed for June 2003 through September 2013. Trend results for specific conductance and filtered trace elements for the adit sites in the Boulder River watershed (Bullion Mine adit [site 2, fig. 1, table 1] and Crystal Mine adit [site 6, fig. 1, table 1]) are summarized in figure 8 and table 5. Data are incomplete for unfiltered-recoverable trace elements before water year 2009, and trend results for unfiltered-recoverable trace elements are not included in figure 8 and table 5 and are not discussed. Detailed trend results for all constituents are presented in figures *3–2* and *3–6* and in table 3–1 (*http://pubs.usgs.gov/sir/2015-5008/downloads/sir20155008_Appendix03_tables.pdf*).

Bullion Mine Adit (site 2)

Trend results for Bullion Mine adit (site 2, fig. 1, table 1) for June 2003 through September 2013 indicate minor to small decreasing trends in specific conductance and concentrations of most filtered trace elements (cadmium, lead, and zinc), a moderate decreasing trend in copper, and a moderate increasing trend in arsenic (figs. 8 and *3–2*, tables 5 and *3–1*). None of the trends for site 2 are statistically significant.

Crystal Mine Adit (site 6)

Trend results for Crystal Mine adit (site 6, fig. 1, table 1) for June 2003 through September 2013 indicate minor to small decreasing trends in specific conductance and concentrations of most filtered trace elements (cadmium, copper, zinc, and arsenic) but also indicate a large increasing trend in lead (figs. 8 and *3–6*, tables 5 and *3–1*). The small decreasing trends for specific conductance and filtered cadmium and the large increasing trend for filtered lead are statistically significant (tables 5 and *3–1*).

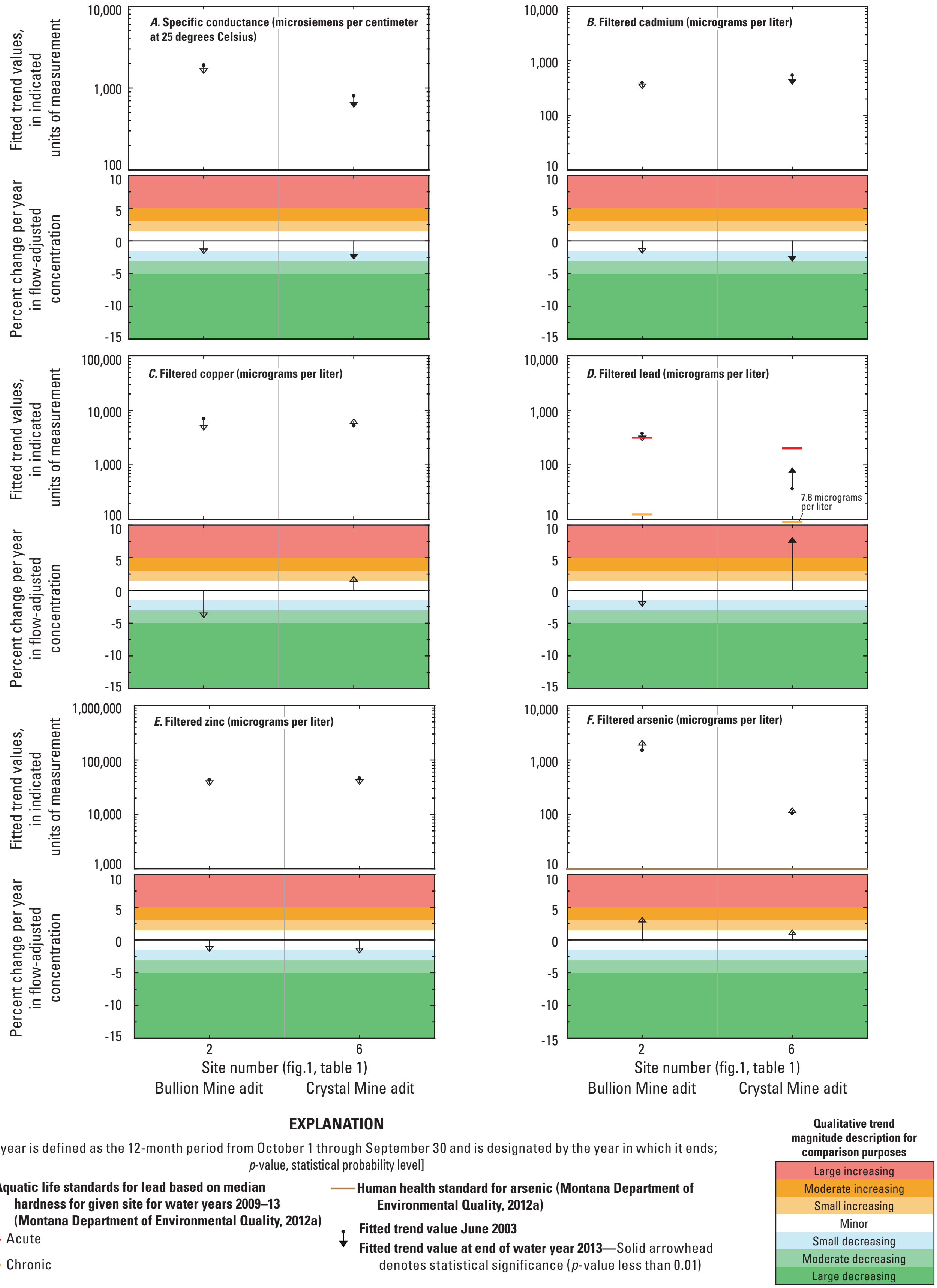

Figure 8. Water-quality trends (not flow adjusted) for June 2003 through September 2013 for the adit sites in the Boulder River watershed, Montana.

Table 5. Summary of water-quality trends (not flow adjusted) for June 2003 through September 2013 for the adit sites in the Boulder River watershed, Montana.

[Water year is the 12-month period from October 1 through September 30 and is designated by the year in which it ends. Gray shading indicates statistically significant trend (*p*-value less than 0.01). *p*-value, statistical probability level; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter]

Constituent or property, flow-adjusted units of measurement	Fitted trend values		Trend magnitudes[1]	
	Fitted trend value June 2003	Fitted trend value at end of water year 2013	Percent change per year	Total percent change from June 2003 to end of water year 2013
Bullion Mine adit (site 2, fig. 1, table 1)				
Specific conductance, µS/cm at 25 °C	1,900	1,600	-1.6	-16
Cadmium, filtered, µg/L	400	340	-1.6	-15
Copper, filtered, µg/L	7,200	4,900	-3.9	-33
Lead, filtered, µg/L	380	300	-2.1	-20
Zinc, filtered, µg/L	43,000	37,000	-1.4	-14
Arsenic, filtered, µg/L	1,500	2,000	3.1	36
Crystal Mine adit (site 6, fig. 1, table 1)				
Specific conductance, µS/cm at 25 °C	800	620	-2.5	-23
Cadmium, filtered, µg/L	540	410	-2.8	-25
Copper, filtered, µg/L	5,300	6,300	1.7	19
Lead, filtered, µg/L	37	78	7.7	114
Zinc, filtered, µg/L	46,000	39,000	-1.6	-16
Arsenic, filtered, µg/L	110	120	1.1	12

[1]Small discrepancies between trend magnitudes expressed as percent change per year and trend magnitudes expressed as total percent change are the result of rounding artifacts.

Summary of Trend Results for the Adit Sites in the Boulder River Watershed

Trend results for the adit sites in the Boulder River watershed (Bullion Mine adit [site 2, fig. 1, table 1] and Crystal Mine adit [site 6, fig. 1, table 1]) do not provide clear evidence of substantial trending during June 2003 through September 2013. For some trace elements, temporal variability in concentrations is somewhat inconsistent, with sporadic increases and decreases. Although apparent for several trace elements, this pattern is well evidenced by filtered arsenic for site 2 (*fig. 3–2*) and unfiltered-recoverable arsenic for site 6 (*fig. 3–6*). The statistically significant large increasing trend for filtered lead for site 6 was affected by a sharp increase in concentrations within a short time frame near the end of the trend-analysis period (from water year 2010 to water years 2011–12). Water quality of the adit sites probably is affected by complex processes that are not well defined in the study datasets. As such, the trend-analysis structure of the study might not be suitable for accurate description of temporal trends in water quality for the adit sites.

Stream Sites in the Boulder River Watershed

Stream sites in the Boulder River watershed include Boulder River above Kleinsmith Gulch (site 1, fig. 1, table 1), Bullion Mine tributary at mouth (site 3, fig. 1, table 1), Jack Creek at mouth (site 4, fig. 1, table 1), Basin Creek at Basin (site 5, fig. 1, table 1), Cataract Creek above Uncle Sam Gulch (site 7, fig. 1, table 1), Cataract Creek at Basin (site 8, fig. 1, table 1), High Ore Creek near Basin (site 9, fig. 1, table 1), and Boulder River below Little Galena Gulch (site 10, fig. 1, table 1). For each stream site in the Boulder River watershed, trends were analyzed for the period from the start of data collection through September 2013. The detailed trend results based on the entire periods of record are presented in *figure 3–1*, *figures 3–3 through 3–5*, *figures 3–7 through 3–10*, and *table 3–2*. Because of the small differences in the starts of data collection among sites, a 14-year comparison period (water years 2000–13) was defined to allow for summaries and comparisons of trend magnitudes among sites. Trend results for water years 2000–13 for the stream sites in the Boulder River watershed are summarized in figure 9 and table 6.

In figure 9, trend magnitudes and directions for trace elements are shown in conjunction with water-quality standards to provide general information on temporal changes in water quality in relation to the standards. Providing specific information on actual compliance with standards is not intended. Subjectively-based qualitative descriptions of trend magnitudes are indicated in figure 9 and are intended to facilitate relative comparison of trend patterns among site and constituent combinations.

Boulder River Above Kleinsmith Gulch (site 1)

Trend results for Boulder River above Kleinsmith Gulch (site 1, fig. 1, table 1) for water years 2000–13 generally indicate minor to small decreasing trends in flow-adjusted specific conductance, in FACs of filtered and unfiltered-recoverable trace elements, and in FACs of suspended sediment (figs. 9 and *3–1*, tables 6 and *3–2*). However, moderate decreasing trends were determined for unfiltered-recoverable copper and zinc, but the trends were within fairly small ranges at generally low FACs. No statistically significant trends are indicated. Overall, the magnitudes of the decreasing trends generally are within the range of about -1 to -2 percent per year, and for most trace elements these changes are within fairly small ranges at generally low FACs. Notably, the dataset for site 1 is largely dissimilar from datasets for most other sites, which results in larger uncertainties in directly comparing trend results for site 1 with those for most other stream sites. However, site 1 has a low density of abandoned mines and is generally representative of a background index site with small effects from mining operations; thus, small trending in FACs of trace elements is intuitively reasonable.

Bullion Mine Tributary at Mouth (site 3)

Trend results for Bullion Mine tributary at mouth (site 3, fig. 1, table 1) for water years 2000–13 indicate moderate to large decreasing trends in flow-adjusted specific conductance, in FACs of all filtered and unfiltered-recoverable trace elements (except filtered arsenic), and in FACs of suspended sediment (figs. 9 and *3–1*, tables 6 and *3–2*). The decreasing trends in FACs for all constituents (except filtered lead and arsenic) are statistically significant (tables 6 and *3–2*). Overall, the magnitudes of the decreasing trends in FACs of trace elements generally are within the range of about -8 to -10 percent per year. The magnitudes of the decreasing trends in flow-adjusted specific conductance and in FACs of all metallic contaminants and unfiltered-recoverable arsenic for site 3 are larger than for any other stream site.

Decreasing trends for Bullion Mine tributary at mouth (site 3) are consistent with remediation efforts in the watershed. The EPA, in partnership with the USFS, began remediation of mining wastes at the Bullion Mine during 2000 (CH2MHILL, 2013a). About 40,900 cubic yards of mine and mill waste was removed and disposed at the Luttrell Repository (Unruh and others, 2009). The surface was graded and soils were amended and reseeded with native vegetation. Removal of wastes was completed in 2002. Minor to small decreasing trends for some metals also were determined for the Bullion Mine adit (site 2), which might also have contributed to the decreasing trends for site 3. Factors that contribute to the trends for site 2 were not determined; however, the magnitude of the trends for site 3 was larger than the magnitude of the trends for site 2, suggesting remediation downstream from site 2 probably is the major cause of the trends for site 3. Although FACs are decreasing for site 3, measured concentrations during water years 2009–13 exceeded all aquatic life standards except the lead acute aquatic life standard (table 4). The Bullion Mine adit discharges have been identified as the primary source of trace elements in the Basin Creek watershed (Nimick and others, 2004). A feasibility study was prepared for the Bullion Mine to identify potential remediation alternatives for the mine area (CH2MHILL, 2013c).

Jack Creek at Mouth (site 4)

Trend results for Jack Creek at mouth (site 4, fig. 1, table 1) for water years 2000–13 indicate a minor decreasing trend in flow-adjusted specific conductance, moderate to large decreasing trends in FACs of all filtered and unfiltered-recoverable trace elements (except filtered lead and arsenic), and a large decreasing trend in FACs of suspended sediment (figs. 9 and *3–4*, tables 6 and *3–2*). The decreasing trends in FACs for all trace elements (except filtered lead and arsenic) and suspended sediment are statistically significant (tables 6 and *3–2*). Overall, the magnitudes of the decreasing trends in FACs of trace elements generally are within the range of about -5 to -8 percent per year. The magnitudes of the decreasing trends in FACS of all metallic trace elements and unfiltered-recoverable arsenic for site 4 generally are larger than for the other stream sites except Bullion Mine tributary at mouth (site 3, fig. 1, table 1) and (for some constituents) Cataract Creek at Basin (site 8, fig. 1, table 1). The magnitude of the decreasing trend in FACs of suspended sediment for site 4 was larger than for any other stream site in the Boulder River watershed.

The pattern of decreasing trends in FACs of all filtered and unfiltered-recoverable trace elements for Jack Creek at mouth (site 4) is similar to the pattern of trends for site 3, which indicates that remediation efforts in the Bullion Mine tributary watershed probably are a major cause of the trends for site 4. Additional removal of smelter waste and mine waste from the flood plain and tailings ponds in the Jack Creek drainage during 2003–05 (Unruh and others, 2009) also likely contributed to the decreasing trends. The magnitude of the trends for site 4 are smaller than the magnitude of the trends for site 3, which is a result of dilution of trace element concentrations by surface-water and groundwater inflows from areas with less mining effects.

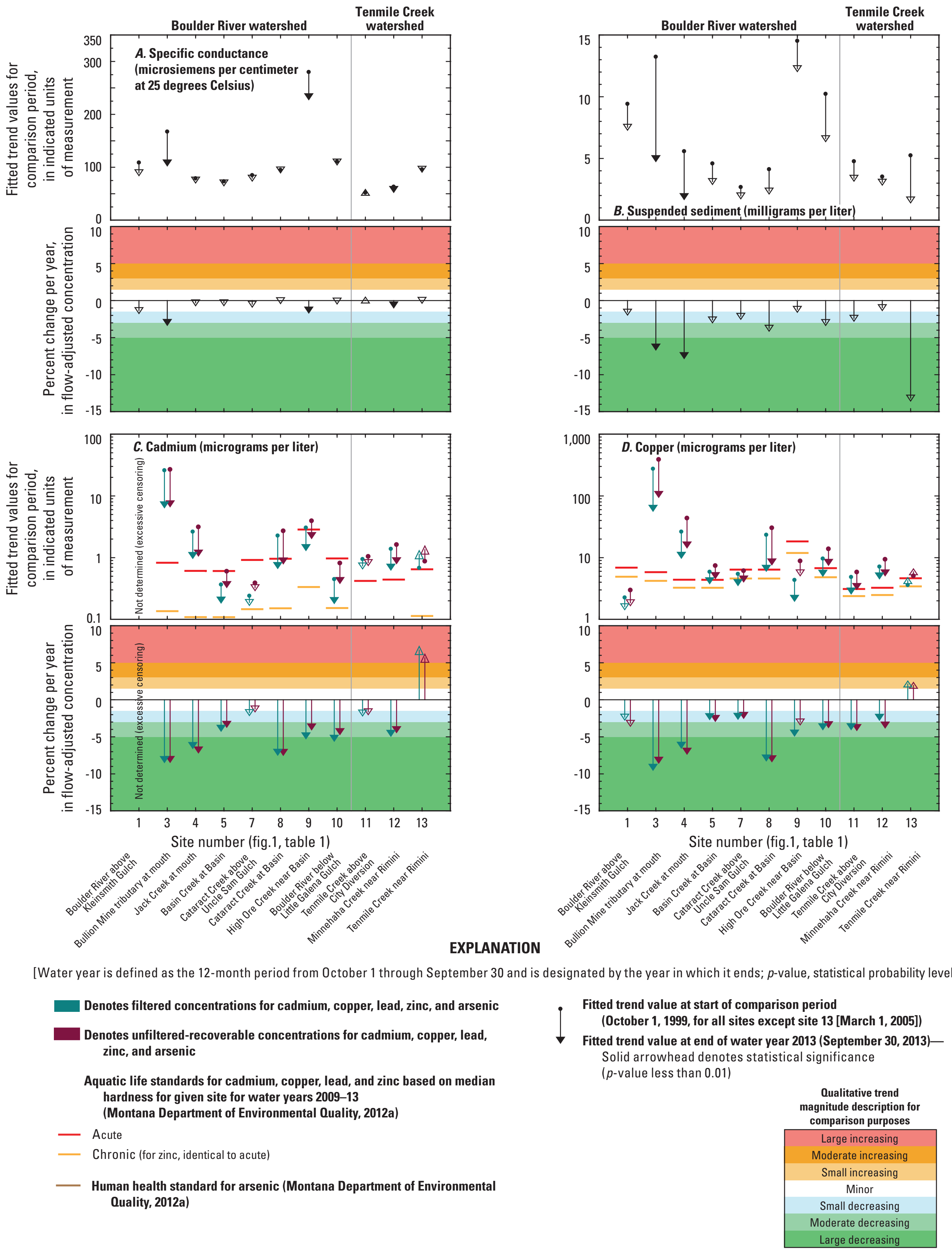

Figure 9. Flow-adjusted water-quality trends for water years 2000–13 for the stream sites in the Boulder River and Tenmile Creek watersheds, Montana.

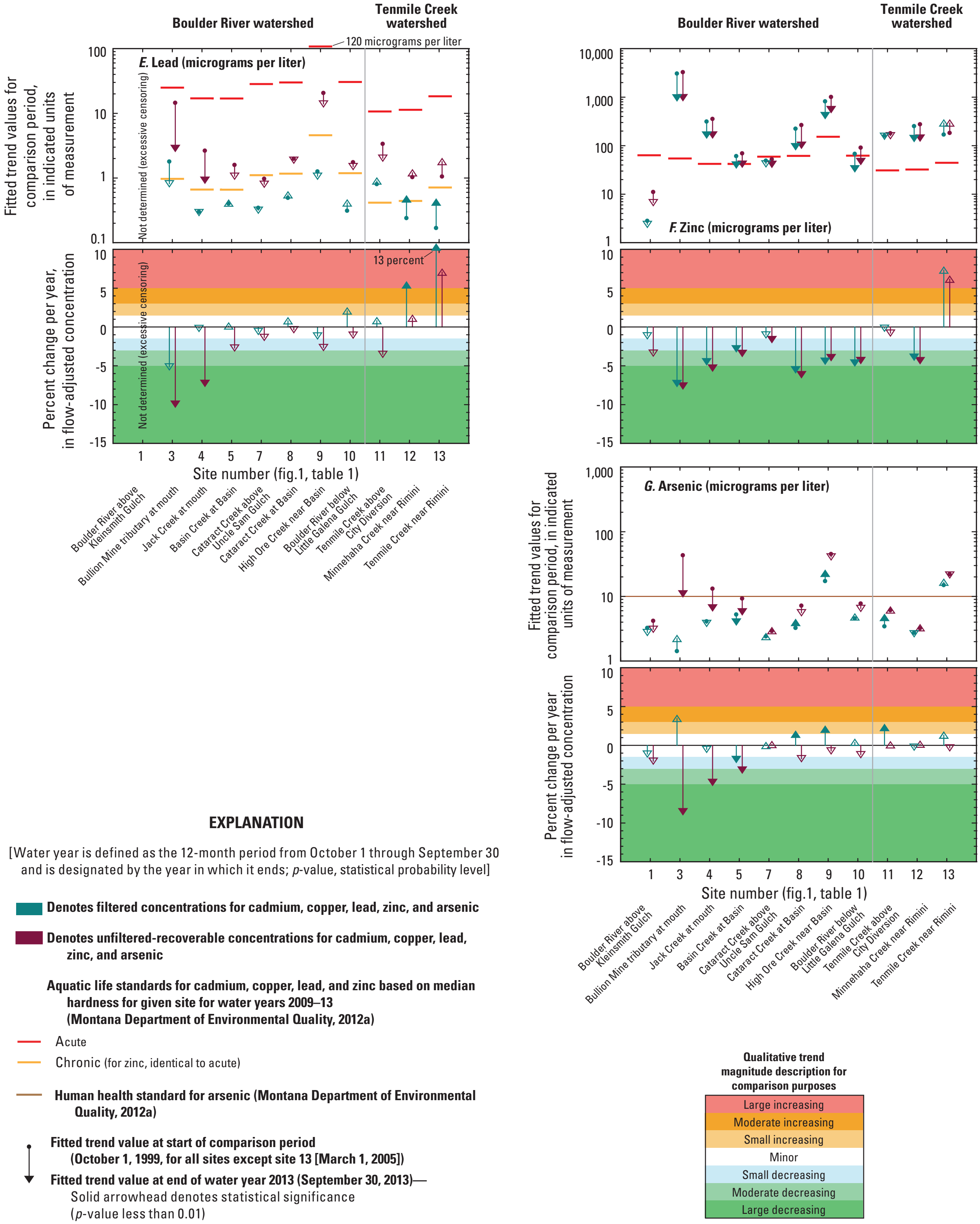

Figure 9. Flow-adjusted water-quality trends for water years 2000–13 for the stream sites in the Boulder River and Tenmile Creek watersheds, Montana.—Continued

Table 6. Summary of flow-adjusted water-quality trends for water years 2000–13 for the stream sites in the Boulder River and Tenmile Creek watersheds, Montana.

[Water year is the 12-month period from October 1 through September 30 and is designated by the year in which it ends. Gray shading indicates statistically significant (*p*-value less than 0.01) trend. *p*-value, statistical probability level; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter; mg/L, milligrams per liter; ND, not determined]

Constituent or property, flow-adjusted units of measurement	Fitted trend values		Trend magnitudes[1]	
	Fitted trend value at start of comparison period (October 1, 1999, for all sites except site 13 [March 1, 2005])	Fitted trend value at end of water year 2013	Percent change per year	Total percent change from start of comparison period to end of water year 2013
Boulder River above Kleinsmith Gulch (site 1, fig. 1, table 1)				
Specific conductance, µS/cm at 25 °C	109	90	-1.3	-17
Cadmium, filtered, µg/L	ND[2]	ND[2]	ND[2]	ND[2]
Cadmium, unfiltered-recoverable, µg/L	ND[2]	ND[2]	ND[2]	ND[2]
Copper, filtered, µg/L	2.3	1.6	-2.3	-30
Copper, unfiltered-recoverable, µg/L	3.0	1.9	-3.2	-37
Lead, filtered, µg/L	ND[2]	ND[2]	ND[2]	ND[2]
Lead, unfiltered-recoverable, µg/L	ND[2]	ND[2]	ND[2]	ND[2]
Zinc, filtered, µg/L	2.8	2.4	-1.1	-14
Zinc, unfiltered-recoverable, µg/L	11	6.7	-3.4	-39
Arsenic, filtered, µg/L	3.2	2.8	-1.1	-13
Arsenic, unfiltered-recoverable, µg/L	4.2	3.1	-2.0	-26
Suspended sediment, mg/L	9.4	7.5	-1.6	-20
Bullion Mine tributary at mouth (site 3, fig. 1, table 1)				
Specific conductance, µS/cm at 25 °C	167	108	-2.9	-35
Cadmium, filtered, µg/L	26	7.2	-8.1	-72
Cadmium, unfiltered-recoverable, µg/L	27	7.5	-8.0	-72
Copper, filtered, µg/L	270	63	-9.1	-77
Copper, unfiltered-recoverable, µg/L	390	110	-8.2	-72
Lead, filtered, µg/L	1.8	0.82	-5.1	-54
Lead, unfiltered-recoverable, µg/L	15	2.9	-9.9	-81
Zinc, filtered, µg/L	3,100	970	-7.3	-69
Zinc, unfiltered-recoverable, µg/L	3,300	980	-7.6	-70
Arsenic, filtered, µg/L	1.4	2.2	3.5	57
Arsenic, unfiltered-recoverable, µg/L	43	11	-8.5	-74
Suspended sediment, mg/L	13	5.0	-6.3	-62
Jack Creek at mouth (site 4, fig. 1, table 1)				
Specific conductance, µS/cm at 25 °C	79	76	-0.3	-3.8
Cadmium, filtered, µg/L	2.6	1.1	-6.2	-58
Cadmium, unfiltered-recoverable, µg/L	3.1	1.2	-6.8	-61
Copper, filtered, µg/L	26	11	-6.1	-58
Copper, unfiltered-recoverable, µg/L	44	16	-6.9	-64
Lead, filtered, µg/L	0.30	0.29	-0.2	-3.3
Lead, unfiltered-recoverable, µg/L	2.6	0.93	-7.3	-64
Zinc, filtered, µg/L	310	170	-4.5	-45
Zinc, unfiltered-recoverable, µg/L	350	170	-5.3	-51

Table 6. Summary of flow-adjusted water-quality trends for water years 2000–13 for the stream sites in the Boulder River and Tenmile Creek watersheds, Montana.—Continued

[Water year is the 12-month period from October 1 through September 30 and is designated by the year in which it ends. Gray shading indicates statistically significant (*p*-value less than 0.01) trend. *p*-value, statistical probability level; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter; mg/L, milligrams per liter; ND, not determined]

Constituent or property, flow-adjusted units of measurement	Fitted trend values		Trend magnitudes[1]	
	Fitted trend value at start of comparison period (October 1, 1999, for all sites except site 13 [March 1, 2005])	Fitted trend value at end of water year 2013	Percent change per year	Total percent change from start of comparison period to end of water year 2013
Jack Creek at mouth (site 4, fig. 1, table 1)—Continued				
Arsenic, filtered, µg/L	4.1	3.8	-0.5	-7.3
Arsenic, unfiltered-recoverable, µg/L	13	6.7	-4.8	-48
Suspended sediment, mg/L	5.6	1.9	-7.4	-66
Basin Creek at Basin (site 5, fig. 1, table 1)				
Specific conductance, µS/cm at 25 °C	73	70	-0.3	-4.1
Cadmium, filtered, µg/L	0.37	0.21	-3.8	-43
Cadmium, unfiltered-recoverable, µg/L	0.60	0.37	-3.3	-38
Copper, filtered, µg/L	5.9	4.2	-2.3	-29
Copper, unfiltered-recoverable, µg/L	7.4	5.1	-2.5	-31
Lead, filtered, µg/L	0.40	0.41	0.1	2.5
Lead, unfiltered-recoverable, µg/L	1.6	1.1	-2.7	-31
Zinc, filtered, µg/L	61	40	-2.8	-34
Zinc, unfiltered-recoverable, µg/L	69	42	-3.4	-39
Arsenic, filtered, µg/L	5.2	4.0	-1.8	-23
Arsenic, unfiltered-recoverable, µg/L	9.3	5.8	-3.2	-38
Suspended sediment, mg/L	4.6	3.1	-2.6	-33
Cataract Creek above Uncle Sam Gulch (site 7, fig. 1, table 1)				
Specific conductance, µS/cm at 25 °C	85	79	-0.5	-7.1
Cadmium, filtered, µg/L	0.24	0.19	-1.7	-21
Cadmium, unfiltered-recoverable, µg/L	0.39	0.33	-1.2	-15
Copper, filtered, µg/L	5.4	3.9	-2.2	-28
Copper, unfiltered-recoverable, µg/L	6.1	4.5	-2.1	-26
Lead, filtered, µg/L	0.35	0.32	-0.6	-9
Lead, unfiltered-recoverable, µg/L	0.97	0.80	-1.3	-18
Zinc, filtered, µg/L	49	42	-1.0	-14
Zinc, unfiltered-recoverable, µg/L	52	41	-1.6	-21
Arsenic, filtered, µg/L	2.4	2.4	-0.0	0.0
Arsenic, unfiltered-recoverable, µg/L	2.9	3.0	0.1	3.4
Suspended sediment, mg/L	2.7	2.0	-2.1	-26
Cataract Creek at Basin (site 8, fig. 1, table 1)				
Specific conductance, µS/cm at 25 °C	95	95	-0.0	0.0
Cadmium, filtered, µg/L	2.3	0.75	-7.1	-67
Cadmium, unfiltered-recoverable, µg/L	2.7	0.89	-7.1	-67
Copper, filtered, µg/L	23	6.7	-7.8	-71
Copper, unfiltered-recoverable, µg/L	30	8.6	-8.0	-71

Table 6. Summary of flow-adjusted water-quality trends for water years 2000–13 for the stream sites in the Boulder River and Tenmile Creek watersheds, Montana.—Continued

[Water year is the 12-month period from October 1 through September 30 and is designated by the year in which it ends. Gray shading indicates statistically significant (*p*-value less than 0.01) trend. *p*-value, statistical probability level; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter; mg/L, milligrams per liter; ND, not determined]

Constituent or property, flow-adjusted units of measurement	Fitted trend values		Trend magnitudes[1]	
	Fitted trend value at start of comparison period (October 1, 1999, for all sites except site 13 [March 1, 2005])	Fitted trend value at end of water year 2013	Percent change per year	Total percent change from start of comparison period to end of water year 2013
Cataract Creek at Basin (site 8, fig. 1, table 1)—Continued				
Lead, filtered, µg/L	0.49	0.55	0.8	12
Lead, unfiltered-recoverable, µg/L	2.0	1.9	-0.3	-5.0
Zinc, filtered, µg/L	220	96	-5.5	-56
Zinc, unfiltered-recoverable, µg/L	270	100	-6.1	-63
Arsenic, filtered, µg/L	3.2	3.9	1.4	22
Arsenic, unfiltered-recoverable, µg/L	7.2	5.6	-1.7	-22
Suspended sediment, mg/L	4.1	2.4	-3.7	-41
High Ore Creek near Basin (site 9, fig. 1, table 1)				
Specific conductance, µS/cm at 25 °C	280	233	-1.3	-17
Cadmium, filtered, µg/L	3.1	1.5	-4.9	-52
Cadmium, unfiltered-recoverable, µg/L	3.9	2.3	-3.6	-41
Copper, filtered, µg/L	4.3	2.2	-4.5	-49
Copper, unfiltered-recoverable, µg/L	8.8	5.7	-3.0	-35
Lead, filtered, µg/L	1.3	1.1	-1.2	-15
Lead, unfiltered-recoverable, µg/L	21	14	-2.6	-33
Zinc, filtered, µg/L	820	420	-4.4	-49
Zinc, unfiltered-recoverable, µg/L	1,000	560	-3.9	-44
Arsenic, filtered, µg/L	17	23	2.1	35
Arsenic, unfiltered-recoverable, µg/L	45	41	-0.7	-9
Suspended sediment, mg/L	15	12	-1.2	-20
Boulder River below Little Galena Gulch (site 10, fig. 1, table 1)				
Specific conductance, µS/cm at 25 °C	111	110	-0.1	-0.9
Cadmium, filtered, µg/L	0.45	0.20	-5.2	-56
Cadmium, unfiltered-recoverable, µg/L	0.82	0.43	-4.3	-48
Copper, filtered, µg/L	9.6	5.6	-3.6	-42
Copper, unfiltered-recoverable, µg/L	14	8.4	-3.3	-40
Lead, filtered, µg/L	0.31	0.41	2.1	32
Lead, unfiltered-recoverable, µg/L	1.7	1.5	-1.0	-12
Zinc, filtered, µg/L	68	34	-4.6	-50
Zinc, unfiltered-recoverable, µg/L	91	47	-4.3	-48
Arsenic, filtered, µg/L	4.6	4.8	0.4	4.3
Arsenic, unfiltered-recoverable, µg/L	7.7	6.5	-1.2	-16
Suspended sediment, mg/L	10	6.6	-3.0	-34

Table 6. Summary of flow-adjusted water-quality trends for water years 2000–13 for the stream sites in the Boulder River and Tenmile Creek watersheds, Montana.—Continued

[Water year is the 12-month period from October 1 through September 30 and is designated by the year in which it ends. Gray shading indicates statistically significant (*p*-value less than 0.01) trend. *p*-value, statistical probability level; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter; mg/L, milligrams per liter; ND, not determined]

Constituent or property, flow-adjusted units of measurement	Fitted trend values: Fitted trend value at start of comparison period (October 1, 1999, for all sites except site 13 [March 1, 2005])	Fitted trend values: Fitted trend value at end of water year 2013	Trend magnitudes[1]: Percent change per year	Trend magnitudes[1]: Total percent change from start of comparison period to end of water year 2013
Tenmile Creek above City Diversion (site 11, fig. 1, table 1)				
Specific conductance, µS/cm at 25 °C	52	53	0.1	1.9
Cadmium, filtered, µg/L	0.94	0.73	-1.8	-22
Cadmium, unfiltered-recoverable, µg/L	1.0	0.83	-1.6	-17
Copper, filtered, µg/L	4.8	2.9	-3.6	-40
Copper, unfiltered-recoverable, µg/L	5.8	3.4	-3.7	-41
Lead, filtered, µg/L	0.80	0.90	0.8	13
Lead, unfiltered-recoverable, µg/L	3.4	2.0	-3.5	-41
Zinc, filtered, µg/L	160	160	-0.2	0.0
Zinc, unfiltered-recoverable, µg/L	180	160	-0.8	-11
Arsenic, filtered, µg/L	3.4	4.7	2.3	38
Arsenic, unfiltered-recoverable, µg/L	6.1	6.2	0.1	1.6
Suspended sediment, mg/L	4.8	3.4	-2.4	-29
Minnehaha Creek near Rimini (site 12, fig. 1, table 1)				
Specific conductance, µS/cm at 25 °C	63	58	-0.6	-8
Cadmium, filtered, µg/L	1.4	0.70	-4.5	-50
Cadmium, unfiltered-recoverable, µg/L	1.6	0.89	-4.0	-44
Copper, filtered, µg/L	7.2	5.1	-2.4	-28
Copper, unfiltered-recoverable, µg/L	9.4	5.7	-3.4	-39
Lead, filtered, µg/L	0.24	0.47	5.4	96
Lead, unfiltered-recoverable, µg/L	1.0	1.2	1.1	20
Zinc, filtered, µg/L	250	140	-3.9	-44
Zinc, unfiltered-recoverable, µg/L	270	140	-4.3	-48
Arsenic, filtered, µg/L	2.7	2.6	-0.2	-3.7
Arsenic, unfiltered-recoverable, µg/L	3.2	3.3	0.1	3.1
Suspended sediment, mg/L	3.5	3.1	-0.9	-11
Tenmile Creek near Rimini (site 13, fig. 1, table 1)				
Specific conductance, µS/cm at 25 °C	96	96	0.0	0.0
Cadmium, filtered, µg/L	0.68	1.1	6.7	62
Cadmium, unfiltered-recoverable, µg/L	0.87	1.3	5.7	49
Copper, filtered, µg/L	3.6	4.2	2.1	19
Copper, unfiltered-recoverable, µg/L	5.1	5.9	1.9	16
Lead, filtered, µg/L	0.17	0.42	13	147
Lead, unfiltered-recoverable, µg/L	1.1	1.8	7.1	64
Zinc, filtered, µg/L	170	290	7.3	71
Zinc, unfiltered-recoverable, µg/L	180	290	6.1	61

Table 6. Summary of flow-adjusted water-quality trends for water years 2000–13 for the stream sites in the Boulder River and Tenmile Creek watersheds, Montana.—Continued

[Water year is the 12-month period from October 1 through September 30 and is designated by the year in which it ends. Gray shading indicates statistically significant (*p*-value less than 0.01) trend. *p*-value, statistical probability level; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter; mg/L, milligrams per liter; ND, not determined]

Constituent or property, flow-adjusted units of measurement	Fitted trend values		Trend magnitudes[1]	
	Fitted trend value at start of comparison period (October 1, 1999, for all sites except site 13 [March 1, 2005])	Fitted trend value at end of water year 2013	Percent change per year	Total percent change from start of comparison period to end of water year 2013
Tenmile Creek near Rimini (site 13, fig. 1, table 1)—Continued				
Arsenic, filtered, µg/L	15	17	1.3	13
Arsenic, unfiltered-recoverable, µg/L	22	21	-0.3	-4.5
Suspended sediment, mg/L	5.2	1.6	-13	-69

[1]Small discrepancies between trend magnitudes expressed as percent change per year and trend magnitudes expressed as total percent change are the result of rounding artifacts.

[2]Not determined because of an excessive number of censored values (that is, greater than 50 percent of values were reported as less than the laboratory reporting level).

Basin Creek at Basin (site 5)

Trend results for Basin Creek at Basin (site 5, fig. 1, table 1) for water years 2000–13 indicate a minor decreasing trend in flow-adjusted specific conductance, small to moderate decreasing trends in FACs of all filtered and unfiltered-recoverable trace elements (except filtered lead), and a small decreasing trend in FACs of suspended sediment (figs. 9 and *3–5*, tables 6 and *3–2*). The decreasing trends in FACs of all trace elements (except lead) are statistically significant (tables 6 and *3–2*). Overall, the magnitudes of the decreasing trends in FACs of trace elements generally are within the range of about -2 to -4 percent per year.

The pattern of decreasing trends in FACs of filtered and unfiltered-recoverable trace elements (except for unfiltered lead and filtered arsenic) for Basin Creek at Basin (site 5) is similar to the pattern of trends for Jack Creek at mouth (site 4) and Bullion Mine tributary at mouth (site 3), suggesting that remediation activities in the upper Basin Creek watershed have an effect in the lower Basin Creek watershed. The magnitudes of the trends for Basin Creek at Basin (site 5) again are smaller than trends observed for Jack Creek at mouth (site 4) and Bullion Mine tributary at mouth (site 3) as a result of further dilution with increased drainage area.

Cataract Creek Above Uncle Sam Gulch (site 7)

Trend results for Cataract Creek above Uncle Sam Gulch (site 7, fig. 1, table 1) for water years 2000–13 indicate minor to small decreasing trends in flow-adjusted specific conductance, in FACs of all filtered and unfiltered-recoverable trace elements (except arsenic), and in FACs of suspended sediment (figs. 9 and *3–7*, tables 6 and *3–2*). The small decreasing trends for filtered and unfiltered-recoverable copper and unfiltered-recoverable zinc are statistically significant (tables 6 and *3–2*). Overall, the magnitudes of the decreasing trends generally are within the range of about -0.5 to -2 percent per year, and for most trace elements these changes are within fairly small ranges at generally low FACs. The dataset for site 7 is somewhat dissimilar (with 2 data gaps of one or more years) from datasets for most other sites, which results in larger uncertainties in directly comparing trend results for site 7 with those for most other stream sites. However, trend results suggest that trending in trace elements and suspended sediment for site 7 is smaller than for most other sites.

Cataract Creek at Basin (site 8)

Trend results for Cataract Creek at Basin (site 8, fig. 1, table 1) for water years 2000–13 indicate a minor decreasing trend in flow-adjusted specific conductance, moderate to large decreasing trends in FACs of all filtered and unfiltered-recoverable trace elements (except lead and arsenic), and a moderate decreasing trend in FACs of suspended sediment (figs. 9 and *3–8*, tables 6 and *3–2*). The decreasing trends in FACs of all trace elements (except lead and arsenic) are statistically significant. Overall, the magnitudes of the decreasing trends in FACs of most trace elements generally are within the range of about -6 to -8 percent per year. The magnitudes of the decreasing trends in FACS of all metallic trace elements and suspended sediment for site 8 generally are larger than for most other stream sites except Bullion Mine tributary at mouth (site 3, fig. 1, table 1) and (for some constituents) Jack Creek at mouth (site 4, fig. 1, table 1).

High Ore Creek Near Basin (site 9)

Trend results for High Ore Creek near Basin (site 9, fig. 1, table 1) for water years 2000–13 indicate a minor decreasing trend in flow-adjusted specific conductance, moderate decreasing trends in FACs of all filtered and unfiltered-recoverable trace elements (except lead and arsenic), and a small decreasing trend in FACs of suspended sediment (figs. 9 and *3–9*, tables 6 and *3–2*). The decreasing trends in flow-adjusted specific conductance and in FACs of filtered and unfiltered-recoverable cadmium, filtered copper, and filtered and unfiltered-recoverable zinc are statistically significant. Overall, the magnitudes of the decreasing trends in FACs of most metallic trace elements generally are within the range of about -3 to -5 percent per year. The dataset for site 9 is somewhat dissimilar (with a multi-year data gap) from datasets for most other sites, which results in larger uncertainties in directly comparing trend results for site 9 with those for most other stream sites. However, trend results suggest that trending in some trace elements and suspended sediment for site 9 generally is intermediate with respect to most other sites.

Boulder River Below Little Galena Gulch (site 10)

Trend results for Boulder River below Little Galena Gulch (site 10, fig. 1, table 1) for water years 2000–13 indicate a minor decreasing trend in flow-adjusted specific conductance, generally moderate decreasing trends in FACs of all filtered and unfiltered-recoverable trace elements (except lead and arsenic), and a small decreasing trend in FACs of suspended sediment (figs. 9 and *3–10*, tables 6 and *3–2*). The trends in FACs for filtered and unfiltered-recoverable cadmium, copper, and zinc are statistically significant. Overall, the magnitudes of the decreasing trends in FACs of most metallic trace elements generally are within the range of about -4 to -5 percent per year.

Summary of Trend Results for the Stream Sites in the Boulder River Watershed

Trend results for most stream sites in the Boulder River watershed for water years 2000–13 indicate decreasing trends in flow-adjusted specific conductance, in FACs of most filtered and unfiltered-recoverable trace elements, and in FACs of suspended sediment (fig. 9, table 6). Overall, magnitudes of the decreasing trends in FACs of metallic contaminants are largest for Bullion Mine tributary at mouth (site 3, fig.1, table 1), Jack Creek at mouth (site 4, fig. 1, table 1), and Cataract Creek at Basin (site 8, fig. 1, table 1). For sites 3, 4, and 8, magnitudes of decreasing trends generally ranged from about -5 to -10 percent per year. Notably, the watersheds upstream from sites 3, 4, and 8 have been targeted by substantial remediation activities (U.S. Environmental Protection Agency, 2014a and 2014b).

Overall, magnitudes of decreasing trends in FACs of metallic contaminants are considered intermediate for Basin Creek at Basin (site 5, fig. 1, table 1), High Ore Creek near Basin (site 9, fig. 1, table 1), and Boulder River below Little Galena Gulch (site 10, fig. 1, table 1). For sites 5, 9, and 10, the magnitudes of the decreasing trends generally ranged from about -2 to -5 percent per year.

Decreasing trends in FACs of metallic contaminants for Boulder River above Kleinsmith Gulch (site 1, fig. 1, table 1) and Cataract Creek above Uncle Sam Gulch (site 7, fig. 1, table 1) generally are minor to small (ranging from about -1 to -2 percent per year) and for most metallic contaminants the changes are within fairly small ranges at generally low FACs. The watershed of site 1 has smaller mining effects than most other study sites. The watersheds of site 1 and 7 have not been targeted by substantial remediation activities.

In the Basin Creek watershed, the magnitudes of the decreasing trends in FACs of unfiltered-recoverable zinc for sites 3, 4, and 5 are -7.6, -5.3, and -3.4 percent per year, respectively (*table 3–2*). The pattern in decreasing trends in FACs of unfiltered-recoverable zinc among sites 3, 4, and 5 suggests that a major cause of the trending is remediation activities in the watershed upstream from site 3, with dilutional reduction (that is, effects of contributions from areas with smaller mining effects) in trend magnitudes between the sites. In the Cataract Creek watershed, the magnitudes of the decreasing trends in FACs of unfiltered-recoverable zinc for sites 7 and 8 are -1.6 and -6.1 percent per year, respectively; the large difference between the trend magnitudes for these sites probably represent effects of remediation activities in or near Uncle Sam Gulch. Consideration of trend patterns among all stream sites in the Boulder River watershed provides strong evidence that remediation activities are the major cause of decreasing trends in metallic contaminants.

For most individual sites in the Boulder River watershed, decreasing trend magnitudes generally are similar among the FACs of cadmium, copper, and zinc. For most sites, trending in FACs of lead and arsenic is somewhat different from trending in FACs of cadmium, copper, and zinc. For most sites (except site 3) trending in filtered lead is minor and within fairly small ranges at generally low FACs (tables 6 and *3–2*). This pattern suggests that for most stream sites in the Boulder River watershed, lead is so strongly adsorbed to colloidal and particulate materials that there is relatively small variability in filtered lead FACs, even in association with relatively large variability in FACs of other trace elements. For most sites (except sites 3 and 4), the magnitudes of the decreasing trends in FACs of unfiltered-recoverable lead are minor to small and less than trend magnitudes for cadmium, copper and zinc. For sites 3 and 4, the magnitudes of the decreasing trends in FACs of unfiltered-recoverable lead are large and might represent effects of remediation activities in the upstream watersheds.

Trend results for most sites (sites 1, 7, 8, 9, and 10; fig. 1, table 1) indicate minor to small increasing or decreasing trends in FACs of unfiltered-recoverable arsenic. Trend results for three sites in the Basin Creek watershed (Bullion Mine tributary at mouth [site 3, fig. 1, table 1], Jack Creek at mouth [site 4, fig. 1, table 1], and Basin Creek at Basin [site 5, fig. 1, table 1]) indicate moderate to large decreasing trends in FACs of unfiltered-recoverable arsenic. Site 3 has higher unfiltered-recoverable arsenic concentrations than any other stream site (except High Ore Creek near Basin [site 9, fig. 1, table 1]; fig. 6), probably affected by ore body characteristics of the Bullion Mine. The magnitudes of the decreasing trends in FACs of unfiltered-recoverable arsenic for sites 3, 4, and 5 are -8.5, -4.8, and -3.2 percent per year, respectively. The pattern in decreasing trends in unfiltered-recoverable arsenic among sites 3, 4, and 5 suggests that the major cause of the trending is remediation activities in the watershed upstream from site 3, with dilutional reduction in trend magnitudes between the sites. Site 5 is the only site for which a statistically significant decreasing trend (small magnitude; -1.8 percent per year) in FACs of filtered arsenic is indicated. For most other sites in the Boulder River watershed, trends in FACs of filtered arsenic are either minor increasing or decreasing trends (sites 1, 4, 7, 8, and 10) or small to moderate increasing trends (sites 3 and 9). For site 3, the moderate increasing trend in FACs of filtered arsenic was within a fairly small range at generally low FACs. In the Boulder River watershed, site 9 has the highest arsenic concentrations (probably affected by the ore body characteristics of the Comet Mine and other mines in the High Ore Creek watershed) and also the highest pH values. For site 9, the small (2.1 percent per year) statistically significant increasing trend in FACs of filtered arsenic might be related to pH effects on arsenic solubility and temporal changes in pH.

Trend results for all sites in the Boulder River watershed indicate decreasing trends in FACs of suspended sediment. Trend results for two sites in the Boulder River watershed (Bullion Mine tributary at mouth [site 3, fig. 1, table 1] and Jack Creek at mouth [site 4, fig. 1, table 1])] indicate statistically significant large decreasing trends in FACs of suspended sediment. The decreasing trends in FACs of suspended sediment for sites 3 and 4 (large magnitudes of -6.3 and -7.4 percent per year, respectively) might represent effects of remediation activities in the watershed upstream from site 3.

Stream Sites in the Tenmile Creek Watershed

Stream sites in the Tenmile Creek watershed include Tenmile Creek above City Diversion (site 11, fig. 1, table 1), Minnehaha Creek near Rimini (site 12, fig. 1, table 1), and Tenmile Creek near Rimini (site 13, fig. 1, table 1). For each stream site in the Tenmile Creek watershed, trends were analyzed for the period from the start of data collection through September 2013. The detailed trend results based on the entire periods of record are presented in figures *3–11 through 3–13*. Temporal characteristics of water-quality sample collection for sites 11 and 12 generally are similar to characteristics for most sites in the Boulder River watershed; thus, the 14-year comparison period (water years 2000–13; fig. 9, table 6) used for sites in the Boulder River watershed also applies to sites 11 and 12 for summaries and comparisons of trend magnitudes among sites. Site 13 has a much shorter data collection period (water years 2005–13) than any other stream site in the Boulder River and Tenmile Creek watersheds. Trend results for site 13 are presented for informational purposes in figure 9 and table 6. However, in figure 9 and table 6 the difference in the comparison period for site 13 and all other stream sites is specifically noted; there are large uncertainties in directly comparing results for site 13 with results for other sites.

Tenmile Creek Above City Diversion (site 11)

Trend results for Tenmile Creek above City Diversion (site 11, fig. 1, table 1) for water years 2000–13 indicate a minor increasing trend in flow-adjusted specific conductance, generally small to moderate decreasing trends in FACs of filtered and unfiltered-recoverable trace elements (except filtered lead and filtered and unfiltered-recoverable zinc and arsenic), and a small decreasing trend in FACs of suspended sediment (figs. 9 and *3–11*, tables 6 and *3–2*). Trend results for filtered lead and for filtered and unfiltered-recoverable zinc and arsenic indicate minor to small increasing or decreasing trends in FACs. The moderate decreasing trends in FACs for filtered and unfiltered-recoverable copper and the small increasing trend for filtered arsenic are statistically significant. Overall, the magnitudes of the decreasing trends in FACs of filtered and unfiltered-recoverable cadmium and copper and in unfiltered-recoverable lead generally are in the range of about -2 to -4 percent per year.

Minnehaha Creek Near Rimini (site 12)

Trend results for Minnehaha Creek near Rimini (site 12, fig. 1, table 1) for water years 2000–13 indicate a minor decreasing trend in flow-adjusted specific conductance, small to moderate decreasing trends in FACs of most filtered and unfiltered-recoverable trace elements (except lead and arsenic), and a minor decreasing trend in FACs of suspended sediment (figs. 9 and *3–12*, tables 6 and *3–2*). The decreasing trends in flow-adjusted specific conductance and in FACs of filtered and unfiltered-recoverable cadmium, copper, and zinc are statistically significant. Overall, the magnitudes of the decreasing trends in FACs of most metallic trace elements (except lead) are in the range of about -3 to -4 percent per year.

Tenmile Creek Near Rimini (site 13)

Trend results for Tenmile Creek near Rimini (site 13, fig. 1, table 1) for water years 2005–13 indicate no trend in flow-adjusted specific conductance, minor to large increasing trends in FACs of most filtered and unfiltered-recoverable trace elements (except unfiltered-recoverable arsenic), and a large decreasing trend in FACs of suspended sediment (figs. 9

and *3–12*, tables 6 and *3–2*). The increasing trend in FACs of filtered lead is statistically significant; however, the indicated change is within a fairly small range at low FACs. In general, patterns in FACs for site 13 are not well represented by fitted trends within the short data collection period (*fig. 3–13*), which might indicate that the trend-analysis structure of the study is not appropriate for describing trends in FACs for site 13. The large decreasing trend in FACs of suspended sediment is the strongest indication of change in water quality during the short period of record for site 13 (figs. 9 and *3–13*); however, this trend is not statistically significant.

Summary of Trend Results for the Stream Sites in the Tenmile Creek Watershed

Trend results for sites in the Tenmile Creek watershed generally are more variable and difficult to interpret than for sites in the Boulder River watershed. Trend results for Tenmile Creek above City Diversion (site 11, fig. 1, table 1) and Minnehaha Creek near Rimini (site 12, fig. 1, table 1) for water years 2000–13 indicate decreasing trends in FACs of cadmium, copper, and zinc. The magnitudes of the decreasing trends in FACs of copper generally are moderate and statistically significant for sites 11 and 12. The magnitudes of the decreasing trends in FACs of cadmium and zinc for site 11 are minor to small and not statistically significant; however, the magnitudes for site 12 are moderate and statistically significant.

For site 11, trend results indicate a minor nonsignificant increasing trend in FACs of filtered lead and a moderate significant decreasing trend in FACs of unfiltered-recoverable lead. For site 12, trend results indicate a large significant increasing trend in filtered lead (but within a small range at low FACs) and a minor nonsignificant increasing trend in unfiltered-recoverable lead.

For site 11, trend results indicate a small significant increasing trend in FACs of filtered arsenic and a minor nonsignificant decreasing trend in FACs of unfiltered-recoverable arsenic. For site 12, trend results indicate minor nonsignificant increasing or decreasing trends in filtered and unfiltered-recoverable arsenic.

For site 11, trend results indicate a small nonsignificant decreasing trend in FACs of suspended sediment. For site 12, trend results indicate a minor nonsignificant decreasing trend in FACs of suspended sediment.

In general, patterns in FACs for site 13 are not well represented by fitted trends within the short data collection period (*fig. 3–13*), which might indicate that the trend-analysis structure of the study is not appropriate for describing trends in FACs for site 13. The large decreasing trend in FACs of suspended sediment is the strongest indication of change in water quality during the short period of record for site 13 (figs. 9 and *3–13*); however, this trend is not statistically significant.

Water-Quality Monitoring Considerations with Respect to Trend Analysis

Water-quality trend analysis for sites in the Boulder River and Tenmile Creek watersheds is limited by the available data. The datasets of the sites in the Boulder River and Tenmile Creek watersheds are not specifically structured for precise detection and quantification of water-quality trends. Several factors that contribute to the non-ideal and inconsistent data collection include the variability in funding, the priority of trend analysis with respect to other monitoring objectives, and the difficulties in site access during the fall and winter.

To improve the capability of trend analysis in the future, consideration might be given to more consistent and systematic design of the program for the purpose of trend analysis. Specific considerations might be (1) prioritizing the program objectives to clarify the importance of trend analysis relative to other monitoring objectives, (2) prioritizing each sampling site with respect to overall trend analysis for the monitoring program, and (3) making concerted effort to provide representation of fall and winter periods in the sampling design.

Overall objectives of the monitoring program might include (1) evaluating compliance with water-quality standards, (2) evaluating short-term effects of specific remediation activities, (3) evaluating annual transport (loads) of contaminants, and (4) analyzing for long-term water-quality trends. Each of these objectives has different optimal sampling designs. For example, evaluating annual transport of contaminants would focus sampling during high-streamflow periods when there might be large variability in concentrations, but most of the annual load is transported. However, for long-term trend analysis, it might be appropriate to focus more sampling (than has been done in the past) on moderate- and low-flow periods when there is less variability in concentrations. During moderate- and low-flow periods, concentration and streamflow relations are representative of a substantial part of the annual period. Thus, the priority of long-term water-quality trend analysis with respect to other program objectives needs to be clarified to allow appropriate sampling design.

If determined that trend analysis is an important objective, consideration might be given to prioritizing each sampling site within the framework of long-term water-quality trend analysis for the overall monitoring program. In the Boulder River watershed, sites 3, 5, 8, and 10 (fig. 1, table 1) represent key locations for evaluation of remediation efforts and have the densest and most consistent datasets. For sites 3, 5, 8, and 10, consideration might be given to establishing a minimum within-year sampling frequency (for example, quarterly sampling) that has priority on an annual basis over sampling at other monitoring sites. Consideration also might be given to placing higher priority on data collection for site 1 (fig. 1, table 1) than was done in the past. Site 1 is an important background site that might serve as a benchmark for evaluating trend magnitudes of other sites. Currently (2014), dissimilarity between the dataset for site 1 and the datasets for most other sites somewhat compromises the capability of using site 1 as a benchmark. Further, if evaluating characteristics of annual transport (loads) of contaminants is an important monitoring objective, site 1 is a critical site. Annual load characteristics for site 1 are necessary as a comparison to background conditions to evaluate changes in annual load characteristics for the primary source areas of contaminants.

Consideration might also be given to placing higher priority on sampling during the fall and winter than was done in the past. Constituent transport during the fall and winter generally accounts for relatively small parts of annual loads. However, for flow-adjusted trend analysis, adequate representation of the fall and winter is important to better define concentration and flow relations throughout the annual period. Site access during the fall and winter might present challenges. Therefore, consideration might be given to deployment of MiniSipper samplers (Chapin and Todd, 2012) specifically designed for unattended collection of water samples in remote high-elevation streams affected by mining activities.

Summary and Conclusions

In the Boulder River and Tenmile Creek watersheds in southwestern Montana, there was intensive mining during a 40-year period after the discovery of gold in the early 1860s. Potential effects from the historic mining activities include acid-mine drainage and elevated concentrations of potentially toxic trace elements from mining remnants such as waste rock and tailing piles. Remediation of environmental effects of the mine wastes has involved coordinated efforts by multiple State and Federal agencies to assess the extent of contamination and to develop and implement remediation strategies. In support of the coordinated remediation efforts, water-quality monitoring by the U.S. Geological Survey (USGS) began in 1997 in the Boulder River and Tenmile Creek watersheds and has continued to present (2014). The USGS, in cooperation with the U.S. Forest Service, investigated temporal trends in water quality at 13 sites, including 2 adit (or mine entrance) sites and 11 stream sites. The primary purpose of this report is to present results of trend analysis of specific conductance, selected trace-elements (cadmium, copper, lead, zinc, and arsenic), and suspended sediment for the 13 sites. The report also presents background information on mining and remediation activities in the Boulder River and Tenmile Creek watersheds, trend-analysis methods, and factors that affect trend analysis and interpretation.

For the stream sites, multiple linear regression (MLR) of constituent concentrations on time, streamflow, and season was used for trend analysis. Inclusion of streamflow in the MLR trend analysis provides for definition of flow-adjusted trends for the stream sites. For the adit sites, relations between constituent concentrations and streamflow were much weaker than for the stream sites. Thus, streamflow was not included in MLR trend models for the adit sites and the trend results represent temporal changes in unadjusted concentrations.

For MLR, fitted trends are straight-line monotonic trends determined for defined trend-analysis periods. Definition of trend-analysis periods is affected by several factors, including the timing of data collection, temporal patterns in FACs (or unadjusted concentrations for the adit sites), and the study objectives. For the adit sites (Bullion Mine adit and Crystal Mine adit) trends were analyzed for June 2003 through September 2013. For each stream site, the trend-analysis period was from the start of data collection to the end of water year 2013. Variability in the start of data collection among the stream sites generally was small. Start times ranged from water years 1997–2000 for all stream sites except Tenmile Creek near Rimini (site 13), which had a start time of water year 2005. Thus, for all stream sites except site 13, the definition of trend-analysis periods provides for generally consistent comparison of trends among the sites.

Ideally, water-quality analysis is done on data that was consistently and systematically collected within a monitoring network specifically designed for the purpose of trend analysis. However, the datasets for the sites in the Boulder River and Tenmile Creek watersheds do not represent ideal cases. All of the study sites have variability in within-year sampling frequency. However, among most sites the within-year sampling frequency was similar in individual years. Although the study datasets are not ideally suited for precise definition of temporal trends, generally strong similarity in sample-collection characteristics of the datasets among most sites provides a reasonable basis for relative comparisons of trend results among sites. Stream sites in the Boulder River watershed that have multi-year gaps in data collection are Boulder River above Kleinsmith Gulch (site 1), Cataract Creek above Uncle Sam Gulch (site 7), and High Ore Creek near Basin (site 9). The larger dissimilarity between the datasets for sites 1, 7, and 9 and the datasets for most other stream sites results in larger uncertainties in directly comparing trend results for sites 1, 7, and 9 with trend results for most other stream sites. Also, Tenmile Creek near Rimini (site 13) has a much shorter sample collection period (water years 2005–13) than any other stream site; therefore; there might be large uncertainties in comparing trend results for site 13 with trend results for other stream sites.

Trend results for the adit sites in the Boulder River watershed (Bullion Mine adit [site 2]) and Crystal Mine adit [site 6])) do not provide clear evidence of substantial trending during June 2003 through September 2013. Water quality of the adit sites probably is affected by complex processes that are not well defined in the study datasets. As such, the trend-analysis structure of the study might not be suitable for accurate description of temporal trends in water quality.

Trend results for most stream sites in the Boulder River watershed for water years 2000–13 indicate decreasing trends in flow-adjusted specific conductance, in flow-adjusted concentrations (FACs) for most filtered and unfiltered-recoverable trace elements, and in suspended sediment. Overall, magnitudes of the decreasing trends in FACs of metallic contaminants are largest for Bullion Mine tributary at mouth (site 3), Jack Creek at mouth (site 4), and Cataract Creek at Basin (site 8). For sites 3, 4, and 8, magnitudes of decreasing trends generally ranged from about -5 to -10 percent per year. Notably, the watersheds upstream from sites 3, 4, and 8 have been targeted by substantial remediation activities.

Overall, magnitudes of decreasing trends in FACs of metallic contaminants are considered intermediate for Basin Creek at Basin (site 5), High Ore Creek near Basin (site 9), and Boulder River below Little Galena Gulch (site 10). For sites 5, 9, and 10, the magnitudes of the decreasing trends generally ranged from about -2 to -5 percent per year.

Decreasing trends in FACs of metallic contaminants for Boulder River above Kleinsmith Gulch (site 1) and Cataract Creek above Uncle Sam Gulch (site 7) generally are minor to small (ranging from about -1 to -2 percent per year) and for most metallic contaminants the changes are within fairly small ranges at generally low FACs. The watershed of site 1 has smaller mining effects than most other study sites. The watersheds of site 1 and 7 have not been targeted by substantial remediation activities.

In the Basin Creek watershed, the magnitudes of the decreasing trends in FACs of unfiltered-recoverable zinc for sites 3, 4, and 5 are -7.6, -5.3, and -3.4 percent per year, respectively. The pattern in decreasing trends in FACs of unfiltered-recoverable zinc among sites 3, 4, and 5 might suggest that the major cause of the trending is remediation activities in the watershed upstream from site 3, with dilutional reduction (that is, effects of contributions from areas with smaller mining effects) in trend magnitudes between the sites. In the Cataract Creek watershed, the magnitudes of the decreasing trends in FACs of unfiltered-recoverable zinc for sites 7 and 8 are -1.6 and -6.1 percent per year, respectively. The large difference between the trend magnitudes for sites 7 and 8 might represent effects of remediation activities in and near Uncle Sam Gulch. Consideration of trend patterns among all stream sites in the Boulder River watershed provides strong evidence that remediation activities are the major cause of decreasing trends in metallic contaminants.

For most individual sites in the Boulder River watershed, decreasing trend magnitudes generally are similar among the FACs of cadmium, copper, and zinc. For most sites, trending in FACs of lead and arsenic is somewhat different from trending in FACs of cadmium, copper, and zinc. For most sites (except site 3) trending in filtered lead is minor and within fairly small ranges at generally low FACs. This pattern suggests that for most stream sites in the Boulder River watershed, lead is so strongly adsorbed to colloidal and particulate materials that there is relatively small variability in filtered lead FACs, even in association with relatively large variability in FACs of other trace elements. For most sites (except sites 3 and 4), the magnitudes of the decreasing trends in FACs of unfiltered-recoverable lead are minor to small and less than trend magnitudes for cadmium, copper, and zinc. For sites 3 and 4, the magnitudes of the decreasing trends in FACs of unfiltered-recoverable lead are large and might represent effects of remediation activities in the watershed upstream from site 3. Trend results for most sites (sites 1, 7, 8, 9, and 10) indicate minor to small increasing or decreasing trends in FACs of unfiltered-recoverable arsenic. Trend results for three sites in the Basin Creek watershed (Bullion Mine tributary at mouth [site 3]), Jack Creek at mouth [site 4]), and Basin Creek at Basin [site 5])) indicate moderate to large decreasing trends in FACs of unfiltered-recoverable arsenic. Trend results for all sites in the Boulder River watershed indicate decreasing trends in FACs of suspended sediment.

Trend results for sites in the Tenmile Creek watershed generally are more variable and difficult to interpret than for sites in the Boulder River watershed. Trend results for Tenmile Creek above City Diversion (site 11) and Minnehaha Creek near Rimini (site 12) for water years 2000–13 indicate decreasing trends in FACs of cadmium, copper, and zinc. The magnitudes of the decreasing trends in FACs of copper generally are moderate and statistically significant for sites 11 and 12. The magnitudes of the decreasing trends in FACs of cadmium and zinc for site 11 are minor to small and not statistically significant; however, the magnitudes for site 12 are moderate and statistically significant.

In general, patterns in FACs for site 13 are not well represented by fitted trends within the short data collection period, which might indicate that the trend-analysis structure of the study is not appropriate for describing trends in FACs for site 13. The large decreasing trend in FACs of suspended sediment is the strongest indication of change in water quality during the short period of record for site 13; however, this trend is not statistically significant.

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Appendixes 1–3

Appendix 1. Summary Information Relating to Quality-Control And Water-Quality Data

Summary information is presented relating to quality-control and water-quality data. Results for quality-control equipment blank and replicate samples collected during water years 1997–2013 are summarized in table 1–1. Statistical summaries of water-quality data collected during water years 2009–13 are presented in table 1–2. Aquatic life standards (based on median hardness for water years 2009–13) are presented in table 1–3.

Appendix 1 tables can be located here: *http://pubs.usgs.gov/sir/2015/5008/downloads/sir20155008_Appendix01_tables.pdf*

Table 1–1. Summary information relating to quality-control samples (equipment blank and replicate samples) collected at sites in the Boulder River and Tenmile Creek watersheds, Montana, based on data collected during water years 1997–2013.

Table 1–2. Summary information relating to water-quality constituents and properties in samples collected at sites in the Boulder River and Tenmile Creek watersheds, Montana, based on data collected during water years 2009–13.

Table 1–3. Aquatic life standards (based on median hardness for water years 2009–13) for selected sites in the Boulder River and Tenmile Creek watersheds, based on data collected during water years 2009–13.

Appendix 2. Summary of Multiple Linear Regression as Applied in this Study

For the stream sites, multiple linear regression (MLR) of water-quality constituents on time, streamflow, and season was applied in this study following guidelines presented in Helsel and Hirsch (2002). The regression model used is represented by the equation:

$$\log(C_t) = b_0 + b_1 T_t + b_2 \log(Q_t) + b_3 \sin(2\pi T_t) + b_3 \cos(2\pi T_t) + E_t \quad (1)$$

where

log denotes the base-10 logarithm;

C_t is the value of the water-quality constituent or property, in indicated units of measurement, at time t;

b_0 is the intercept;

b_1–b_4 are the estimated slope coefficients associated with the various explanatory variables;

T_t is decimal time at time t;

Q_t is instantaneous streamflow at the time of sampling, in cubic feet per second;

$\sin(2\pi T_t)$ and $\cos(2\pi T_t)$ are periodic functions that describe seasonal variability; and

E_t is an approximately normally distributed random error.

Use of MLR for trend analysis involves regression of constituent concentration ($\log(C_t)$, eq. (1)) on streamflow ($\log(Q_t)$, eq. (1)), which inherently provides for flow adjustment and quantifies concentration and streamflow relations. The residuals from the regression of concentration on streamflow represent flow-adjusted concentrations (FACs; Helsel and Hirsch, 2002). Inclusion of periodic functions that describe seasonal variability $\sin(2\pi T_t)$ and $\cos(2\pi T_t)$ (eq. [1]) account for the effect of repetitive and persistent seasonal variability on concentration and streamflow relations. The residuals from the regression of concentration on streamflow and the periodic functions represent changes in concentration and streamflow relations through the trend-analysis period. The inclusion of decimal time (T_t, eq. [1]) in the model provides quantification of the change in concentration and streamflow relations through time and describes the temporal trend in FACs for the specified trend-analysis period. The slope coefficient for decimal time (b_1, eq. [1]) is used to determine the significance and magnitude of the trend, in percent change in the geometric mean FAC per year. The null hypothesis in the test for trend significance is that there is no trend (that is, $b_1 = 0$). If the two-tailed p-value for b_1 is less than the selected alpha level (0.01 in this report), the null hypothesis is rejected and the trend is determined to be significant. Determination of a nonsignificant trend (that is, a p-value > 0.01) does not imply that the null hypothesis is accepted (that is, that there is no trend). However, the determination of a nonsignificant trend does indicate that within the statistical framework of the analysis, a significant trend was not detected. The trend magnitude is calculated by

$$\%\Delta FAC = 100(10^{b_2} - 1), \quad (2)$$

where

$\%\Delta FAC$ is the percent change per year in the geometric mean of the flow adjusted concentration.

Application of linear regression for flow-adjusted trend analysis assumes that the residuals of the trend models are approximately normally distributed and that relations between the response variable (a given water-quality constituent) and the combined explanatory variables (time, streamflow, and periodic functions that describe seasonal variability) can be appropriately represented by a linear fit. Data for many water-quality constituents typically do not conform to a normal distribution because of positive skew (Helsel and Hirsch, 2002). To approximate normality, constituent concentrations and streamflow were transformed to logarithm (base 10) units.

For the stream sites, streamflow was included as an explanatory variable in the MLR models for all site and constituent combinations. Ordinary least squares regressions of constituent concentrations on streamflow were statistically significant (*p*-value less than 0.05) for all site and constituent combinations except one. However, in the MLR trend models the streamflow coefficient was not statistically significant (*p*-value less than 0.05) for about 20 percent of site and constituent combinations. Concerns in including nonsignificant explanatory variables in regression analysis are over fitting the regression model, unrepresentatively decreasing the error of the analysis, and possibly incorrectly defining a given trend as significant (type I error). In all cases where the streamflow coefficient was nonsignificant, trend models that did not include streamflow were examined and found to have minor effects on the errors; in no case was a type I error indicated. Thus, including streamflow in models when the streamflow coefficient was nonsignificant had minor effect on the trend results.

For the adit sites, relations between constituent concentrations and streamflow were much weaker than for the stream sites. Streamflow for the adit sites represented groundwater seepage from the adits that typically was less than 0.07 cubic foot per second (ft^3/s) and had small variability among sampling dates. Few site and constituent combinations (less than about 20 percent) had concentrations that were significantly correlated with streamflow. The streamflow coefficient generally was not significant when streamflow was included in the MLR trend models during exploratory analysis. Thus, streamflow was not included in MLR trend models for the adit sites. The regression models for the adit sites are represented by eq. 1 with the exclusion of the b_2Q_t term.

In accounting for seasonal variability, 2π sine and cosine terms were included in the regression models for all site and constituent combinations. At least one of the periodic-function coefficients was statistically significant in regression models for most (about 70 percent) of the site and constituent combinations. During exploratory analysis, representation of seasonality was investigated by considering models that included no periodic functions and also models that used different multiples of π. The various models were evaluated for effects on the trend results. Use of the 2π terms was determined to provide the best representation of most of the datasets. Inclusion of periodic functions when they were not significant in the regression model for some site and constituent combinations probably had small effect on the trend-analysis results.

The effect of serial correlation on MLR results was evaluated for each site and constituent combination. Significant serial correlation was determined if Spearman's correlation coefficient on the lag-one residuals produced a *p*-value less than 0.05 (Helsel and Hirsch, 2002). Significant serial correlation was infrequent (about 15 percent of all trend models), with the exception of filtered lead. For site and constituent combinations with significant serial correlation, trend results were evaluated for potential type I errors and determined to be unaffected by serial correlation.

The regression model results for each site and constituent combination were evaluated by examining distributions of standardized residuals, standard error of estimates (SEEs), influence and leverage statistics, and homoscedasticity of residuals. For the adit sites in the Boulder River watershed, SEEs for trend models for filtered and unfiltered-recoverable metallic trace elements ranged from 13–88 percent (mean of 40 percent), and the SEEs for trend models for filtered and unfiltered-recoverable arsenic ranged from 56–114 percent (mean of 85 percent). The SEEs for trend models for filtered and unfiltered-recoverable arsenic for the adit sites were larger than for most other site and constituent combinations, and conclusions based on the trend results are qualified as having large uncertainty.

Statistical summaries of SEEs for the regression models for the stream sites in the Boulder River and Tenmile Creek watersheds are presented in table 2–1 (*http://pubs.usgs.gov/sir/2015/5008/downloads/sir20155008_Appendix02.table.pdf*). The SEEs for trend models for most trace elements (cadmium, copper, zinc, and arsenic) ranged from 14–81 percent (mean of 33 percent). The SEEs for trend models for filtered and unfiltered lead ranged from 29–250 percent (mean of 66 percent). The SEEs for trend models for filtered and unfiltered-recoverable lead were highly variable among the stream sites; conclusions based on the trend results for site and constituent combinations with unusually large SEEs are qualified on a case-by-case basis. The SEEs for trend models for suspended sediment ranged from 51–120 percent (mean of 84 percent). The SEEs for trend models for suspended sediment were larger than for most other site and constituent combinations, and conclusions based on the trend results are qualified as having large uncertainty.

Because of the application of a consistent regression model to the large number of site and constituent combinations and of practical considerations to keep the trend periods comparable among sites and constituents, some small deviations of the residuals from model assumptions were tolerated. However, the reported regression model results were judged to provide acceptable fits representative of linearity through nearly all of the ranges in FACs. For each site and constituent combination, the fit of the regression model can be assessed by examination of the fitted trends in relation to the FACs that are shown in figures 3–1 through 3–13. For plotting purposes, the FACs were determined by adding the residuals from the regression of concentration on streamflow to the geometric mean concentration for the trend-analysis period. The distribution of the FACs about the fitted trend lines indicates the extent to which the regression model results were affected by factors such as residual heteroscedasticity and curvature.

In some cases, the fitted trends within a defined trend-analysis time period do not precisely follow the patterns in FACs and there are short-term (typically about 2–3 years) trend patterns in the FACs that are unresolved in the fitted trends. In those cases, better temporal resolution might have been attained by defining two or more trend-analysis periods within the single defined trend-analysis period for each site.

This approach was avoided because it would have required detailed case-by-case trend analysis for the large number of site and constituent combinations. An important consideration in the design of the trend-analysis structure of this study was the capability to make general comparisons among the sites and constituents with respect to evaluating potential effects of mining and remediation activities on a large-scale basis throughout consistent time periods. In some cases, when unresolved trending was apparent, more complicated trend models (with additional trend-analysis periods) were tested and the more complicated models did not change the general findings and conclusions of this report; that is, the overall fitted trends during the affected trend-analysis periods were consistent with overall patterns in FACs during the periods. However, examination of time-series plots of concentrations for both adit sites indicated somewhat inconsistent temporal patterns, with sporadic increases and decreases. Water quality of the adit sites probably is affected by complex processes that are not well defined in the study datasets. As such, the trend-analysis structure of the study might not be suitable for accurate description of temporal trends in water quality.

Appendix 3. Trend-Analysis Results

Appendix 3 tables can be located here: *http://pubs.usgs.gov/sir/2015/5008/downloads/sir20155008_Appendix03_tables.pdf*

Appendix 3 figures can be located here: *http://pubs.usgs.gov/sir/2015/5008/downloads/sir20155008_Appendix03_figures.pdf*

Table 3–1. Detailed water-quality trend results (not flow adjusted) for the adit sites in the Boulder River watershed, Montana, based on analysis of data collected during water years 1999–2013.

Table 3–2. Detailed flow-adjusted water-quality trend results for the stream sites in the Boulder River and Tenmile Creek watersheds, Montana, based on analysis of data collected during water years 1997–2013.

Figure 3–1. Flow-adjusted fitted trends for selected water-quality constituents and properties for Boulder River above Kleinsmith Gulch (site 1, fig. 1, table 1), based on analysis of data collected during water years 1997–2013.

Figure 3–2. Fitted trends (not flow adjusted) for selected water-quality constituents and properties for Bullion Mine adit (site 2, fig. 1, table 1), based on analysis of data collected during water years 1999–2013.

Figure 3–3. Flow-adjusted fitted trends for selected water-quality constituents and properties for Bullion Mine tributary at mouth (site 3, fig. 1, table 1), based on analysis of data collected during water years 1997–2013.

Figure 3–4. Flow-adjusted fitted trends for selected water-quality constituents and properties for Jack Creek at mouth (site 4, fig. 1, table 1), based on analysis of data collected during water years 2000–13.

Figure 3–5. Flow-adjusted fitted trends for selected water-quality constituents and properties for Basin Creek at Basin (site 5, fig. 1, table 1), based on analysis of data collected during water years 1997–2013.

Figure 3–6. Fitted trends (not flow adjusted) for selected water-quality constituents and properties for Crystal Mine adit (site 6, fig. 1, table 1), based on analysis of data collected during water years 2003–13.

Figure 3–7. Flow-adjusted fitted trends for selected water-quality constituents and properties for Cataract Creek above Uncle Sam Gulch (site 7, fig. 1, table 1), based on analysis of data collected during water years 1997–2013.

Figure 3–8. Flow-adjusted fitted trends for selected water-quality constituents and properties for Cataract Creek at Basin (site 8, fig. 1, table 1), based on analysis of data collected during water years 1997–2013.

Figure 3–9. Flow-adjusted fitted trends for selected water-quality constituents and properties for High Ore Creek near Basin (site 9, fig. 1, table 1), based on analysis of data collected during water years 1997–2013.

Figure 3–10. Flow-adjusted fitted trends for selected water-quality constituents and properties for Boulder River below Little Galena Gulch (site 10, fig. 1, table 1), based on analysis of data collected during water years 1997–2013.

Figure 3–11. Flow-adjusted fitted trends for selected water-quality constituents and properties for Tenmile Creek above City Diversion (site 11, fig. 1, table 1), based on analysis of data collected during water years 1999–2013.

Figure 3–12. Flow-adjusted fitted trends for selected water-quality constituents and properties for Minnehaha Creek near Rimini (site 12, fig. 1, table 1), based on analysis of data collected during water years 1997–2013.

Figure 3–13. Flow-adjusted fitted trends for selected water-quality constituents and properties for Tenmile Creek near Rimini (site 13, fig. 1, table 1), based on analysis of data collected during water years 2005–13.

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Sando and others—**Water-Quality Trends for Selected Sites in the Boulder River and Tenmile Creek Watersheds, Montana**—Scientific Investigations Report 2015–5008

ISSN: 2328-0328 (online)
http://dx.doi.org/10.3133/sir20155008