Monitoring Remediation—Have Mine-Waste and Mill-Tailings Removal and Flood-Plain Restoration Been Successful in the High Ore Creek Valley?

By Sharon L. Gelinas and Robert Tupling

Chapter E2 of

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CONVERSION FACTORS

Multiply	By	To obtain
acre	4,047	square meter
cubic foot per second (ft^3/s)	0.028317	cubic meter per second
cubic yard (yd^3)	0.7646	cubic meter
foot (ft)	0.8048	meter
mile (mi)	1.61	kilometers
ounce (oz)	28.35	gram
pound (lb)	453.6	gram

Chapter E2
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By Sharon L. Gelinas[1] and Robert Tupling[2]

Abstract

Mining activity in the High Ore Creek basin produced mine wastes and mill tailings that resided in waste dumps or were dispersed along the flood plain by fluvial transport. These sources of arsenic and metals degraded water quality, contaminated streambed sediment, and negatively affected the health of aquatic biota. Comet mine, the largest mine in the basin, produced the majority of the waste rock and mill tailings. Evaluation of environmental data collected by the Montana Department of State Lands, the Montana Bureau of Mines and Geology, and the U.S. Geological Survey led to large-scale remediation in the High Ore Creek valley that included both removal actions and in-place treatments. Monitoring data collected before and after remediation provide a basis for documenting the effects of cleanup actions on trace-element concentrations.

A preliminary evaluation of pre- and post-remediation data indicates that dissolved zinc concentrations have decreased in High Ore Creek. Dissolved arsenic concentrations apparently have increased, presumably owing to desorption and leaching associated with liming of waste materials. Multivariate analysis of variance (MANOVA) has shown that post-remediation dissolved zinc concentrations at the mouth of High Ore Creek and in the Boulder River below Little Galena Gulch decreased significantly from pre-remediation concentrations, although concentrations in High Ore Creek are not yet stable. Continued monitoring can determine the effects of remediation on trace-element concentrations in High Ore Creek and the Boulder River ecosystem.

Introduction

Historical mining in the High Ore Creek basin produced wastes enriched in trace elements. Consequent environmental effects were sufficiently severe to warrant some of the first abandoned mine lands (AML) remediation activities in Montana. Waste rock and mill tailings produced at the Comet mine (fig. 1), one of the largest in the Boulder River watershed, were deposited across High Ore Creek. Erosion of these materials by the stream resulted in extensive deposition of tailings on the High Ore Creek valley floor and the Boulder River flood plain (Marvin and others, 1997). Leaching of acid and trace elements, such as arsenic and metals, from these mine wastes degraded water quality sufficiently to effectively eliminate fish from High Ore Creek and impaired fisheries in the Boulder River (Farag and others, this volume, Chapter D10; Pioneer Technical Services, Inc., 1999). The Comet mine area was given a high priority for cleanup by the State of Montana (Montana Department of State Lands, 1995) because of impacts to water quality and the local fisheries. Large-scale remediation efforts were initiated by State and Federal agencies in 1997 to improve riparian and aquatic conditions in High Ore Creek.

The Comet mine, located near the headwaters, was the largest and most productive mine in the High Ore Creek basin. It produced about 3,117,770 oz of silver; 42,440 oz of gold; 2,235,680 lb of copper; 28,535,230 lb of lead; and 23,486,020 lb of zinc during its intermittent operation from 1880 to 1941 (Marvin and others, 1997). The mining operation included 18,000 ft of underground workings, a 900-ft shaft, and a large open pit (Elliott and others, 1992). Ore was processed onsite. In 1931, a new mill was built near the Comet mine to process the ore from this and other nearby mines. However, the mill closed a short time after the Comet mine ceased operations in 1941 (Becraft and others, 1963).

Large quantities of waste rock and mill tailings were left in and near High Ore Creek after the mine closed. One dump containing about 150,000 yd^3 of mine waste rock was located in an upland area east of the open pit; this dump covered 3.4 acres. Two other dumps together containing about 227,000 yd^3 and covering 5.0 acres were left in the High Ore Creek valley. In addition, two impoundments containing about 196,500 yd^3 of mill tailings covering 5.5 acres were located in the valley bottom, blocking the premining stream channel (Pioneer Technical Services, Inc., 1997).

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Figure 1. Location of High Ore Creek, Mont., with water-quality monitoring sites and locations of inactive mines.

In addition to the Comet mine, several small mines were located in the High Ore Creek basin (fig. 1; Martin, this volume, Chapter D3, fig. 1). The Grey Eagle mine was the largest of these smaller mines, producing primarily silver (about 2,090 oz) from 1897 to 1941 from about 10,000 ft of underground workings (Elliott and others, 1992; Marvin and others, 1997). The Silver Hill mine adjoined the Comet mine and had underground workings with one shaft (Elliott and others, 1992). The Golconda/Reliance and King Cole mines, located adjacent to High Ore Creek downstream from the Comet mine, produced mainly silver, copper, and lead (Marvin and others, 1997).

At the smaller mines in the High Ore Creek basin, waste rock was the primary mining waste left after mining ceased, because the ore was processed at the Comet mill or transported out of the basin. Six dumps containing about 2,000 yd^3 of mine waste rock were located at the Silver Hill mine (Pioneer Technical Services, Inc., 1997). One dump, approximately 73,000 yd^3 in size, was located at the Grey Eagle mine (Montana Department of State Lands, 1995). One dump (about 4,300 yd^3 covering 0.26 acres) was located on the east bank of High Ore Creek at the King Cole mine. Two dumps (about 1,500 yd^3 covering 0.22 acres), one on either side of High Ore Creek, were located at the Golconda/Reliance mine (Marvin and others, 1997).

Purpose and Scope

The purpose of this chapter is to describe the pre-remediation environmental setting and cleanup activities and to present a preliminary evaluation of the remediation based on post-remediation monitoring data. The pre-remediation environmental setting was determined from data compiled from the Montana Department of State Lands, the Montana Bureau of Mines and Geology (MBMG), and this study. Water-quality data collected from 1993 through 2000 at nine MBMG sites, four U.S. Geological Survey (USGS) sites, and nine Montana Tech (Montana Tech of the University of Montana) sites were used to evaluate remediation success.

Pre-Remediation Environmental Setting

The Montana Department of State Lands (1995) and Marvin and others (1997) inventoried mine wastes at inactive mines to identify and prioritize mine sites with environmental hazards. Site inventories included sampling tailings, waste rock, adit discharge, seeps, stream water, and streambed sediment. These inventory investigations, along with Boulder River watershed characterization data collected by the USGS, describe in detail the pre-remediation environmental conditions in the High Ore Creek basin.

Trace elements such as arsenic, cadmium, copper, lead, manganese, mercury, silver, and zinc generally existed at elevated concentrations in the waste-rock dumps and tailings impoundments at the Comet mine (Church, Unruh, and others, this volume, Chapter D8, table 2), and in the waste rock at the Silver Hill, Grey Eagle, King Cole and Golconda/Reliance mines. These elevated concentrations were much higher than premining baseline data determined by Church, Unruh, and others (this volume, table 3). Water flowing through waste rock and mill tailings produced acid mine drainage. The potential to produce acid mine drainage was determined by acid-base accounting. If the sum of the potential acidity and the potential neutralizing capacity was negative, then the site was considered a potential acid producer. Two of the waste-rock dumps and one tailings impoundment at the Comet mine site and the waste rock at the Silver Hill and Golconda/Reliance mines were considered potential acid producers (Montana Department of State Lands, 1995; Pioneer Technical Services Inc., 1997, 1999).

Streamside tailings as much as several feet thick covered the banks and flood plain of High Ore Creek for several hundred feet downstream from the Comet mine. Farther downstream, the tailings became thinner and discontinuous. An estimated 32,000 yd^3 of tailings covered more than 21 acres of the High Ore Creek flood plain (Marvin and others, 1997; Pioneer Technical Services, Inc., 1999). Analysis of 42 fluvial tailings cores showed elevated concentrations of arsenic, cadmium, copper, lead, silver, and zinc along High Ore Creek between the Comet mine and the Boulder River. A substantial fraction (from 25 to 100 percent) of the trace elements were in the leachable phase (Fey and Church, 1998; Rich and others, this volume, Chapter G).

Streambed sediment had elevated concentrations of arsenic, cadmium, copper, lead, silver, and zinc. Copper concentrations were more than 50 times greater than estimated background levels, whereas arsenic, cadmium, lead, and zinc concentrations were more than 100 times greater than estimated background levels. Concentrations in streambed sediment decreased downstream in High Ore Creek, particularly below the confluence with Bishop Creek. At the mouth of High Ore Creek, the median concentrations in samples collected during 1996–98 were 4,300 ppm (parts per million) arsenic, 30 ppm cadmium, 480 ppm copper, 1,600 ppm lead, and 6,800 ppm zinc. In contrast, median concentrations in streambed-sediment samples collected in the Boulder River watershed from areas unaffected by mining were 35 ppm arsenic, <2 ppm cadmium, 32 ppm copper, 35 ppm lead, and 150 ppm zinc (Fey and others, 1999; Church, Unruh, and others, this volume; Rich and others, this volume).

Concentrations of dissolved cadmium and zinc in water from High Ore Creek during 1993–97 were elevated and consistently exceeded aquatic-life standards, while concentrations of dissolved copper and lead commonly were less than these standards. During pre-remediation low-flow conditions, average concentrations of dissolved cadmium and zinc (site 56, fig. 1) were 4.3 and 2,050 µg/L (micrograms per liter), respectively, which exceeded the State of Montana chronic aquatic-life standards of 3.5 and 177 µg/L, respectively (average hardness of stream samples collected during pre-remediation low flow used for calculating standards). During pre-remediation spring runoff, average dissolved concentrations of cadmium and zinc were 2.6 and 789 µg/L, respectively (Rich and others, this volume), which exceeded the State of Montana acute aquatic-life standards of 2.3 and 111 µg/L, respectively (average hardness during pre-remediation high flow used for calculating standards). Although trace-element concentrations were high in High Ore Creek, pH was consistently greater than 7.

Dissolved cadmium and zinc concentrations decreased downstream from the Comet mine during high- and low-flow conditions. Dilution by tributary inflow appears to have been a major factor in the decreases. Limited data for Bishop Creek and Peters Gulch showed low trace-element concentrations in these tributaries. During low flow, total-recoverable zinc concentrations in the two tributaries were 20 and 40 µg/L, respectively, whereas concentrations were 30 and <10 µg/L, respectively, during spring runoff (Rich and others, this volume).

Although zinc concentrations in Bishop Creek were low relative to the mainstem, the Grey Eagle mine is a possible source that could contribute trace elements to High Ore Creek during high flow (Pioneer Technical Services, Inc., 1999). Overland runoff and high flows can transport sediment enriched with trace elements from waste-rock dumps at the Grey Eagle mine downstream to High Ore Creek. Similarly, the waste rock at the King Cole and Golconda/Reliance mines also might have degraded water quality by contributing sediment during high flow (Marvin and others, 1997).

Upstream from the Comet mine, High Ore Creek contains a pristine fisheries environment, which includes a native population of westslope cutthroat trout and a diverse population of macroinvertebrates (Gless, 1990; Pioneer Technical Services, Inc., 1999). The waste rock and tailings in the High Ore Creek valley bottom at the Comet mine blocked fish passage and thereby isolated the westslope cutthroat trout from the rest of the Boulder River watershed where introduced species of trout occur. Presumably, westslope cutthroat trout inhabited all of High Ore Creek before mining.

Downstream from the Comet mine, High Ore Creek was considered extremely degraded by Gless (1990) based on the limited diversity of the macroinvertebrate population and elevated arsenic concentrations in water. This part of the stream did not support a fishery (Pioneer Technical Services, Inc., 1999; Farag and others, this volume). In addition, studies by Nelson (1976), Knudson (Ken Knudson, consulting biologist, Helena, Mont., written commun., 1984), and Phillips and Hill (1986) demonstrated that fish populations decreased in the Boulder River downstream from High Ore Creek owing to degraded water quality resulting primarily from high trace-element concentrations.

At the mouth of High Ore Creek, biological data indicated that trace elements were accumulating in biofilm, macroinvertebrates, and fish (Farag and others, this volume). During an experiment exposing fish to ambient stream water, survival rates of juvenile westslope cutthroat trout were very low owing to elevated concentrations of copper and zinc (Farag and others, this volume). Elevated arsenic concentrations caused dark coloration and an increased number of melanocytes on fish skin (Farag and others, this volume).

In summary, the pre-remediation environmental data showed that the large amount of waste rock and tailings near the Comet mine and acid drainage from these wastes caused elevated trace-element concentrations in water from High Ore Creek and in flood-plain and streambed-sediment deposits along High Ore Creek downstream to the Boulder River. In addition, waste rock near the Grey Eagle and Golconda/Reliance mines could have contributed to the elevated trace-element concentrations in water and in flood-plain and streambed-sediment deposits.

Remediation Along the High Ore Creek Valley

Based on chemical and biological environmental data, the Comet mine wastes and mill tailings (figs. 2, 3) were

Figure 2. Mill tailings in High Ore Creek valley at Comet mine site before large-scale remediation activities, October 1996. Photograph by D.A. Nimick.

Figure 3. Comet Mill and open-pit mine before large-scale remediation activities, October 1996. Photograph by D.A. Nimick.

considered a high priority by the State of Montana and the Bureau of Land Management (BLM) for remediation. The Montana Department of Environmental Quality (MDEQ) started preliminary remediation work at the Comet mine site in 1995. Initially, the efficiency of the existing sediment pond was improved, a new treatment pond was constructed below the sediment pond, and other erosion-control barriers were installed (Pioneer Technical Services, Inc., 1997). Large-scale remediation efforts began in September 1997. From September to December 1997, waste rock and mill tailings filling the original channel and adjacent valley bottom of High Ore Creek and 1 ft of the underlying native soil near the mine were excavated and moved to the existing open pit, which was used as an unlined repository (figs. 4, 5). From May through July 1998, other waste-rock materials were amended onsite with lime. During the second phase, planned to start in 2001, about 1,700 ft of High Ore Creek will be reconstructed to restore the channel to its approximate premining position and

Figure 4. High Ore Creek valley at Comet mine site after remediation activities, August 1998. The creek has been redirected and the area regraded. Photograph by D.A. Nimick.

Figure 5. Comet Mill and mine site after remediation activities, August 1998. Waste rock and tailings have been removed, and the open pit has been used as a repository. Photograph by D.A. Nimick.

condition through the Comet mine site. Upon completion of this project, approximately 430,500 yd^3 of waste will have been removed (Pioneer Technical Services, Inc., 1997).

Because High Ore Creek had been eroding and transporting mill tailings from the Comet mine site for many years, the area downstream from the Comet mine to the Boulder River also was targeted for remediation. In fall 1999, the BLM restored 3.73 mi of High Ore Creek on BLM and private land by removing about 5,800 yd^3 of waste rock and about 28,000 yd^3 of mill tailings from the valley bottom (Pioneer Technical Services, Inc., 1999). Upstream from Bishop Creek, flood-plain and streambed-sediment deposits were removed, the High Ore Creek channel was reconstructed, and clean material was imported to backfill the excavated areas (fig. 6). Downstream from Bishop Creek, waste rock and flood-plain deposits were either removed or amended in place with lime, but the

Figure 6. Reconstructed reach of High Ore Creek downstream from Comet mine site, December 1999. Photograph by J.H. Lambing.

stream channel was not disturbed. All excavated wastes were placed in an unlined repository (fig. 1) with a multi-layered cap, south of the Comet mine (Pioneer Technical Services, Inc., 1999).

Evaluation of Remediation

The long-term pattern of trace-element concentrations in High Ore Creek will determine whether the remediation in the basin has been successful. Decreasing concentrations over time should eventually result in improved riparian and aquatic conditions. Trace-element concentrations were assessed by graphing temporal trends for four sites, by comparing longitudinal concentration profiles for similar flow conditions before and after cleanup, and by statistical analysis.

Temporal Trends

Water-quality samples were collected at or near four USGS sites (fig. 7) on High Ore Creek from September 1993 through October 2000 (Marvin and others, 1997; Nimick and Cleasby, 2000; Tupling, 2001; Rich and others, this volume). Data for these samples show the initial effect of the MDEQ and BLM remediation projects. Dissolved and total-recoverable copper and lead concentrations commonly were less than aquatic-life standards both before and after remediation and are not discussed here in further detail. Dissolved and total-recoverable cadmium, manganese, and zinc concentrations had

Figure 7. Dissolved zinc concentrations and streamflow in four reaches of High Ore Creek, 1993–2000. Data from Marvin and others (1997), Nimick and Cleasby (2000), Tupling (2001), and Rich and others (this volume). Zinc concentrations reported as less than the minimum reporting level of 1 µg/L are plotted as 1 µg/L.

similar patterns of temporal variation. Dissolved zinc concentrations, discussed here, illustrate the effects of remediation.

Dissolved zinc concentrations upstream from the Comet mine site (site 49) did not change from 1997 through 2000 and were consistently low (less than 55 µg/L). However, dissolved zinc concentrations at two sites (sites 52 and 53) between the Comet mine and Bishop Creek generally decreased after the beginning of large-scale cleanup in 1997 (fig. 7). Dissolved zinc concentrations near the mouth of High Ore Creek (site 56) also appear to have decreased after the beginning of large-scale cleanup. Samples collected on March 25, 1999, at sites 53 and 56 reflect early spring snowmelt runoff, which had anomalously high concentrations of dissolved zinc as well as other trace elements and suspended sediment (not shown in fig. 7). Sampling was not conducted during similar snowmelt runoff conditions prior to large-scale remediation activities. Therefore, the effect of remediation activities on zinc concentrations during early snowmelt runoff cannot be evaluated.

Pre- and Post-Remediation Concentration Profiles

An objective way to look at the effects of the Comet mine remediation is to compare pre- and post-remediation trace-element concentrations along High Ore Creek during similar flow conditions. Data collected by MBMG in September 1993 (Marvin and others, 1997) and Montana Tech in April 2000 (table 1; Tupling, 2001) as part of a post-reclamation study funded by the BLM clearly show the effects of cleanup (fig. 8). Based on limited data, streamflow in April 2000 (1.7 ft^3/s at site WQ3, fig. 1) probably was similar to the flow in September 1993 (1.3 ft^3/s at site 81M, fig. 1). Again, dissolved zinc is discussed here to illustrate a pattern that was similar for dissolved cadmium and manganese. Figure 8 shows that dissolved zinc concentrations represented by two sample sets collected during similar hydrologic conditions decreased at essentially all sampling sites between 1993 and 2000. The largest decreases between 1993 and 2000 occurred at sites in the reach between the Comet and King Cole mines. However, the increase in dissolved zinc concentrations downstream from the Comet mine site in 2000 relative to site WQ15 above the mine indicates that the mine site is still a source of dissolved zinc to High Ore Creek. From Bishop Creek to the mouth of High Ore Creek, concentrations in 2000 remained essentially uniform, unlike in 1993 when concentration increases occurred downstream from Peters Gulch and the Golconda/Reliance mine sites.

Concentrations of dissolved zinc exhibit diel cycles in High Ore Creek, with concentrations fluctuating by as much as a factor of 3 between early morning and late afternoon (Lambing and others, this volume, Chapter D7). These cycles potentially could have a large effect on comparisons of concentration data, such as those in figure 8, collected on different sampling dates. Sites downstream from Peters Gulch (fig. 8) were sampled at about the same time of day during the September 1993 and April 2000 sampling episodes. Although the same sites were not sampled each year, the sampling time for each site sampled in 2000 was within 60 minutes of the sampling time for nearest site sampled in 1993. Temporal concentration variations attributable to diel cycles during a 60-minute period are only a fraction of the total diel variation and, therefore, would not be large enough to eliminate or reverse the apparent decrease in concentration shown by the post-remediation data in figure 8. Sites between Peters Gulch and the Comet mine were not sampled at similar times during the two sampling episodes. Sites were sampled in mid- to late morning in September 1993, when concentrations would be near their maximum diel values, whereas sites were sampled in mid- to late afternoon in April 2000, when concentrations would be near the diel minimum values. Therefore, the apparent decrease in concentration shown in figure 8 may be much less than shown. These data demonstrate the importance of understanding diel cycles when trends in trace-element concentrations are being assessed.

In contrast to dissolved zinc, dissolved arsenic concentrations apparently increased since large-scale remediation began in 1997. In particular, concentrations at the mouth of High Ore Creek (site 56) not only have increased from pre-remediation levels, but values that typically were less than the State of Montana human-health standard of 18 µg/L have increased to post-remediation values that typically are higher than this standard (fig. 9). One explanation for this phenomenon is that sorption onto particulates, which is an important control on arsenic mobilization, has decreased. Sorption is dependent on pH, and arsenic desorption increases as pH increases (Pierce and Moore, 1982). However, the pH of High Ore Creek does not appear to have increased after remediation began (fig. 9), so the arsenic probably is not derived from desorption of arsenic from streambed sediment. A more likely explanation of these increases in dissolved arsenic in the stream is that the lime used to amend waste rock at the mine site and flood-plain deposits downstream from Bishop Creek resulted in an increase in pH in these materials. The higher pH likely mobilized arsenic, which then leached into High Ore Creek.

Statistical Analysis

A preliminary statistical analysis of water-quality data was done by segregating available data into two sets representing pre- and post-remediation periods. Data for September 1997 were designated as the last pre-remediation sampling data. Multivariate analysis of variance (MANOVA) was used to compare the combined means of the logarithmically transformed trace-element concentrations and streamflow values. Dissolved zinc concentrations were used to represent the general differences between pre- and post-remediation metal concentrations.

Data for five monitoring sites in the Boulder River watershed (fig. 1, sites 3, 24, 47, 56, and 58) were used to evaluate the preliminary effects of the Comet mine cleanup

Table 1. Trace-element data for High Ore Creek, April 28, 2000.[1]

[ft^3/s, cubic feet per second; µg/L, micrograms per liter; <, less than minimum reporting level; —, no data]

Site No.	Station name	Stream-flow, instan-taneous (ft^3/s)	Arsenic, dis-solved (µg/L)	Arsenic, total recov-erable (µg/L)	Cad-mium, dis-solved (µg/L)	Cad-mium, total recov-erable (µg/L)	Copper, dis-solved (µg/L)	Copper, total recov-erable (µg/L)	Lead, dis-solved (µg/L)	Lead, total recov-erable (µg/L)	Zinc, dis-solved (µg/L))	Zinc, total recov-erable (µg/L)
WQ3	High Ore Creek near mouth	1.7	21.8	47.7	2.76	3.78	3.1	10.8	<2	44.3	792	1,010
WQ4	High Ore Creek at cabin residence	—	19.9	57.9	2.67	3.92	3.56	12.1	<2	52.5	768	1,070
WQ5	High Ore Creek downstream from Peters Gulch	—	19.0	61.6	2.66	4.11	4.02	12.8	<2	58.7	768	1,060
WQ7	High Ore Creek downstream from Bishop Creek.	—	13.5	40.8	2.51	3.48	2.04	9.98	<2	57.9	767	959
WQ9	High Ore Creek upstream from Bishop Creek	—	18.6	48.0	3.97	4.92	2.59	10.1	<2	44.6	1,320	1,470
WQ10	High Ore Creek downstream from reconstruc-tion.	—	14.5	18.4	5.82	5.94	<2	3.1	<2	6.42	1,940	1,910
WQ11	High Ore Creek downstream from Comet mine and above reconstruction.	—	11.4	15.8	6.44	6.22	<2	2.84	<2	5.85	2,190	2,220
WQ15	High Ore Creek upstream from Comet mine	—	1.69	2.1	<2	<2	<2	<2	<2	<2	4.22	11.9

[1]Data from Tupling (2001).

Figure 8. Dissolved zinc concentrations in High Ore Creek, September 1993 and April 2000.

Figure 9. Dissolved arsenic concentrations and pH at mouth of High Ore Creek (site 56), 1996–2000.

on the Boulder River and High Ore Creek relative to other tributaries and upstream portions of the watershed. Results of the MANOVA tests determined that the combined means of dissolved zinc concentrations and streamflow at three sites unaffected by remediation (sites 3, 24, and 47) were not significantly different between the two time periods (before and after September 1997) (table 2). In contrast, High Ore Creek (site 56) and the Boulder River below Little Galena Gulch (site 58) had significantly different means between the two periods, indicating that dissolved zinc concentrations had changed.

Figure 10 shows ordinary least squares regression relations between streamflow and dissolved zinc concentrations for both pre- and post-remediation at the five Boulder River watershed sites. Basin Creek and Cataract Creek showed very little change in the relation between the two time periods. The upper site on the Boulder River (site 3) displayed some variation, but maintained consistently low concentrations. The most downstream site on the Boulder River (site 58) displayed a clear post-remediation downward shift in zinc concentrations at low streamflows (less than 100 ft^3/s), but tended to converge with the pre-remediation relation at higher flows (greater than 100 ft^3/s). One notable feature is that High Ore Creek post-remediation data are highly scattered, indicating that dissolved zinc concentrations have not stabilized since remediation activity ended. With time, a stronger relation between streamflow and concentration might be expected to develop as remediated areas physically stabilize and hydrologic and geochemical equilibrium is established. Continued monitoring, especially at High Ore Creek and the Boulder River below Little Galena Gulch, would provide the necessary data to better demonstrate and quantify the overall change in trace-element concentrations and, ultimately, to determine the degree to which remediation was successful in improving the health of aquatic biota.

Summary

Inactive historical mines and a mill in the High Ore Creek valley produced wastes enriched in trace elements that degraded water quality and eliminated fish in High Ore Creek downstream from the Comet mine. These environmental effects were sufficiently severe to warrant remediation activities for abandoned mine lands in the basin. Pre-remediation environmental data showed that waste rock, mill tailings, fluvial tailings deposits, and streambed sediment contained elevated trace-element concentrations. MDEQ removed waste rock and tailings at the Comet mine site in 1997–98 and plans to finish reclaiming the mine site in 2001. BLM removed Comet mill tailings from the flood plain upstream from Bishop Creek, reconstructed the stream channel, and amended the waste rock and mill tailings with lime downstream from Bishop Creek.

A preliminary evaluation of pre- and post-remediation water-quality data from four sites along High Ore Creek has shown decreased dissolved zinc concentrations through time at the three sites below the Comet mine since large-scale remediation started. Downstream profiles of dissolved zinc concentrations at multiple sites along High Ore Creek in 1993 and 2000 showed consistently lower concentrations in 2000 throughout the entire reach of High Ore Creek below the Comet mine. In contrast, dissolved arsenic concentrations apparently have increased since remediation started, most likely owing to desorption and leaching associated with the pH effects of liming. Comparison of pre- and post-remediation regression relations between streamflow and dissolved zinc concentrations at five sites throughout the Boulder River watershed indicate that zinc concentrations at the mouth of High Ore Creek and the Boulder River below Little Galena Gulch have decreased since remediation started, although concentrations in High Ore Creek are not yet stable. Continued environmental monitoring would provide the necessary data to demonstrate and quantify the change in trace-element concentrations that can ultimately determine whether remediation was successful.

Table 2. Results of multivariate analysis of variance of dissolved zinc concentrations and streamflow for selected sites in Boulder River watershed for 1993–97 and 1997–2000 periods.

Site No.	Station name	Level of significance (*p*-value)[1]	Conclusion ($\alpha = 0.05$)
3	Boulder River above Kleinsmith Gulch, near Basin	0.154	Means were equal.
24	Basin Creek at Basin	.403	Means were equal.
47	Cataract Creek at Basin	.340	Means were equal.
56	High Ore Creek near Basin	.010	Means were not equal.
58	Boulder River below Little Galena Gulch, near Boulder	.003	Means were not equal.

[1]A p-value less than 0.05 indicates a significant difference between means.

Figure 10. Regression relation of dissolved zinc concentrations and streamflow for pre- and post-remediation periods at five long-term monitoring sites in Boulder River watershed, 1996–2000.

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