Metal contamination and post-remediation recovery in the Boulder River watershed, Jefferson County, Montana

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ABSTRACT: The legacy of acid mine drainage and toxic trace metals left in streams by historical mining is being addressed by many important yet costly remediation efforts. Monitoring of environmental conditions frequently is not performed but is essential to evaluate remediation effectiveness, determine whether clean-up goals have been met, and assess which remediation strategies are most effective. Extensive pre- and post-remediation data for water and sediment quality for the Boulder River watershed in southwestern Montana provide an unusual opportunity to demonstrate the importance of monitoring. The most extensive restoration in the watershed occurred at the Comet mine on High Ore Creek and resulted in the most dramatic improvement in aquatic habitat. Removal of contaminated sediment and tailings, and stream-channel reconstruction reduced Cd and Zn concentrations in water such that fish are now present, and reduced metal concentrations in streambed sediment by a factor of c. 10, the largest improvement in the district. Waste removals at the Buckeye/Enterprise and Bullion mine sites produced limited or no improvement in water and sediment quality, and acidic drainage from mine adits continues to degrade stream aquatic habitat. Recontouring of hillslopes that had funnelled runoff into the workings of the Crystal mine substantially reduced metal concentrations in Uncle Sam Gulch, but did not eliminate all of the acidic adit drainage. Lead isotopic evidence suggests that the Crystal mine rather than the Comet mine is now the largest source of metals in streambed sediment of the Boulder River. The completed removal actions prevent additional contaminants from entering the stream, but it may take many years for erosional processes to diminish the effects of contaminated sediment already in streams. Although significant strides have been made, additional efforts to seal draining adits or treat the adit effluent at the Bullion and Crystal mines would need to be completed to achieve the desired restoration.

SUPPLEMENTARY MATERIAL: Analytical data for all post-remediation samples is available at: http://www.geolsoc.org.uk/SUP18344.

KEYWORDS: remediation, geochemistry, aquatic habitat, hazard quotients, Pb isotopes

In many watersheds in the western United States, historical mining has left a legacy of acid mine drainage and elevated concentrations of potentially toxic trace metals in streams. Remediation of these abandoned mines is an important yet costly endeavour. Comprehensive monitoring of pre- and post-remediation environmental conditions is essential to evaluate remediation effectiveness, to determine whether clean-up goals have been met, and to assess which remediation strategies are most effective (Finger et al. 2004a). However, adequate monitoring of remediation efforts is often not conducted. The Boulder River watershed in southwestern Montana (Fig. 1) is one area where extensive pre- and post-remediation monitoring has occurred. The existence of the large dataset for this watershed provides an unusual opportunity to evaluate the remediation undertaken and to demonstrate the importance of collecting and analysing monitoring data.

As a part of the US Geological Survey Abandoned Mine Lands Initiative (Buxton et al. 1997), Nimick et al. (2004) conducted an integrated study to evaluate the effects of historical mining on water and sediment quality and biological productivity within the Boulder River watershed near Basin, Montana. In particular, the effects of historical mining activities on the metal concentrations in sediment and water were evaluated (Church et al. 2004a; Nimick & Cleasby 2004). Concurrent studies of biofilm, macroinvertebrates, and fish were conducted to assess aquatic health in the study area (Farag...
Fig. 1. Monitoring sample localities in the Boulder River, Montana AML study area (after Finger et al. 2004b). Sites for streambed sediment samples are designated by an ‘S’, and sites for water samples are designated by a ‘W’. Biological sampling sites used by Rhea et al. (2006) are designated by a 3- or 4-letter code.
et al. 2003, 2004, 2007). The work presented here is part of this ongoing integrated study and focuses on the results of remediation in the watershed.

There are fundamental time-frame differences in the data obtained from the different media collected in watersheds affected by abandoned mines. Water quality data provide an instantaneous measure of the concentrations of constituents in the water column. The concentrations of metals in water can vary widely depending on streamflow conditions, ground- and surface-water flow, and temporal variations in loading from the various sources. In contrast, streambed sediment deposits integrate conditions over a longer time period because they are constructed of fine-grained colloidal and detrital material that accumulates for a period of several months following spring runoff. Metals in both water and sediment can affect the biodiversity and health of aquatic organisms (Farag et al. 2004, 2007; Rhea et al. 2006), and consequently, geochemical monitoring of both water and streambed sediment is necessary to evaluate the effect of historical mining on the aquatic ecosystem.

In the current study, 19 streambed sediment sites and 11 water quality sites were selected for post-remediation monitoring (Fig. 1). Biological monitoring also has been conducted at nine sites (Fig. 1; Rhea et al. 2006). Sediment samples were collected during low flow in 2001 and 2003. Water samples were collected multiple times each year from 2001 to 2005. We compare results for these post-remediation samples with data for samples collected prior to remediation (generally 1996–2000) and reported in Nimick et al. (2004). These comparisons are used to evaluate post-remediation changes in trace metal concentrations in water and sediment as well as changes in Pb isotope composition to assess improvement in aquatic habitat.

STUDY AREA
The study area includes a 24-km segment of the Boulder River near Basin, Montana, and three tributary watersheds that were affected by historical mining (Fig. 1). The Cretaceous Boulder batholith and genetically related Elkhorn Mountains Volcanics underlie the study area (Becraft et al. 1963; O’Neill et al. 2004). Mineralization within the study area consists primarily of polymetallic quartz-vein deposits related to the emplacement of the Boulder batholith (Lund et al. 2002). Sulphide minerals in the veins include pyrite, galena, sphalerite, chalcopyrite, arsenopyrite, and minor amounts of tetrachloride (Rupple 1963).

Mining in the area began in the mid-1860s with the discovery of placer gold in upper Basin Creek (Fig. 1). Mining for base (Cu, Pb, Zn) and precious metals (Ag, Au) began shortly thereafter. After an initial flurry of activity from c. 1880 to 1903, production was sporadic through 1930 with peak production of c. 30,000 short tons of ore in 1919 and 65,000 short tons of ore per year in 1924–1926. Maximum ore production of 60,000–80,000 short tons per year was reached during 1935–1940. During this period, annual production averaged just over 1,000 short tons of Pb and Zn, 100 short tons of Cu, 500,000 tro ounces of Ag, and 6,000 tro ounces of Au. By 1942, mining activity was restricted to small-scale operations and prospects, although limited Au, Ag, and base-metal production continued through the 1970s (Church et al. 2004a; Martin 2004).

Mine and prospect waste dumps and mill wastes are located throughout the study area (Metesh et al. 1994, 1995, 1996; Marvin et al. 1997). Waste material from many of the mines was dumped directly into the stream channels. Mine-waste material has been transported into and down streams, where it has mixed with and become incorporated into the streambed sediment. In some localities, for example at the Comet mine on High Ore Creek (Gelines & Tulpine 2004), mine-waste material was placed directly in stream channels and was transported downstream forming fluvial tailings deposits in riparian areas. Water quality and aquatic habitat have been affected by metal-contaminated sediment derived from mine wastes and transported downstream primarily during snowmelt and storm runoff events within the Boulder River watershed (Cannon et al. 2004; Farag et al. 2004; Nimick & Cleasby 2004).

Throughout most of the study area, stream water pH is slightly acidic to slightly alkaline (pH = 6.5–8.2; Nimick & Cleasby 2004). Populations of brook trout (Salvelinus fontinalis), rainbow trout (Oncorhynchus mykiss), and cutthroat trout (Oncorhynchus clarki) exist in upstream reaches, that is, in stream reaches not affected by mining, within the study area (Farag et al. 2003, 2004). Drainage at some of the mine portals, however, is acidic and trout are commonly absent from stream reaches downstream from major mines (Farag et al. 2003, 2004). The granitic Boulder batholith has a high acid-neutralizing capability, primarily due to the presence of secondary calcite (Desborough & Driscoll 1998; Desborough et al. 1998a, b). Acidic mine drainage is generally quickly neutralized within a few kilometres of the source. Weakly acidic stream water (pH = 5.5–6.5) was also found in the Bullion Mine tributary to Jack Creek and in the upper reaches of Rocker Creek (tributary to Cataract Creek, Fig. 1). In the c. 1 km reach downstream from the Crystal mine on Uncle Sam Gulch, pH values as low as 3.5–3.7 were recorded during low streamflow conditions (Nimick & Cleasby 2000; Kimball et al. 2004). As a result, after mixing with higher pH water, Fe and Al precipitate quickly and may sequester some of the dissolved Cu and Pb (Kimball et al. 2004).

Three mine sites within the study area were identified as the principal sources of metal contaminants (Church et al. 2004b; Nimick & Cleasby 2004). These are the Bullion mine upstream from the Jack Creek tributary to Basin Creek, the Crystal mine on the Uncle Sam Gulch tributary to Cataract Creek, and the Comet mine on High Ore Creek (Fig. 1). Other mine sites such as the Buckeye and Enterprise mines near the headwaters of Basin Creek and the Eva May mine on upper Cataract Creek were identified as secondary sources of metals. The entire Basin Creek and Cataract Creek drainages were designated as a US EPA Superfund site in 1999.

SAMPLING AND ANALYTICAL METHODS

Water samples
Water samples were collected from 64 sites within and around the study area during 1996–2000, prior to remediation (Nimick & Cleasby 2000, 2004). Most sites were sampled during both high and low flow. Some sites were sampled monthly in order to evaluate the variations in metal concentrations throughout a hydrologic cycle. Several sites were also sampled hourly during a 48-hour period in order to evaluate diurnal variations (Nimick et al. 2003; Lambing et al. 2004). Finally, several sites were sampled during multiple years at approximately the same flow rates in order to evaluate long-term variations in metal concentrations (Nimick & Cleasby 2004). Eleven of these sites (Fig. 1) were sampled from 2001 to 2005 for the current study.

Samples were collected using USGS depth-integrating suspended-sediment samplers in order to obtain a vertical and lateral discharge-weighted sample (Knappert 1985; Edwards & Glysson 1988; Nimick & Cleasby 2000). Water samples were processed through 0.45-µm filters, and both the filtered (‘dissolved’) and unfiltered (total) samples were analysed for major and trace elements at the USGS National Water Quality...
Laboratory in Denver, Colorado using inductively coupled plasma-mass spectrometry (ICP-MS; Faires 1993; Garbarino 1999). Comparisons of data obtained from the 0.45-µm filtrates and 10 000-Dalton filtrates (ultra filtration) suggest that the 0.45-µm filtrates closely approximate the actual dissolved concentrations for the metals of concern (Nimick & Cleasby 2004). However, Fe and Al concentrations were much higher in the 0.45-µm filtrates than in the 10 000-Dalton filtrates. This illustrates that there is still a significant colloidal component in the 0.45-µm filtrates. Nevertheless, in this report we refer to the 0.45-µm filtrate as the ‘dissolved’ constituent of the sample. Results from the pre-remediation studies are in Nimick & Cleasby (2004).

Streambed sediment samples

Streambed sediment samples were collected from 63 sites during 1996–1998. Samples were collected within the study area and from the Boulder River upstream and downstream of the study area (Fey & Church 1998; Fey et al. 1999a, b, 2000). Pre-remediation results are discussed in Church et al. (2004a). Nineteen streambed sediment sites were resampled in July 2001 and September 2003 as part of the current study (Fig. 1). Sites downstream from remediated areas as well as sites presumably not affected by remediation were included to facilitate direct comparison with sites that potentially would show effects of remediation. Sample collection, preparation, and analytical methods are in Fey et al. (2000) and Unruh et al. (2000). Metal concentrations in sediment were determined from total digests of the samples by inductively coupled plasma-atomic emission spectroscopy (ICP-AES; Crock et al. 1983; Briggs 1996).

Lead isotope analyses

Lead isotopic data for samples of streambed sediment, sediment cores, and pre-mining terrace sediment were obtained from HCl-H2O2 leaches using methods described in Fey et al. (1999b) and Unruh et al. (2000). Lead was separated using anion exchange in a 2M HBr medium. Isotopic data were obtained using a VG Sector-54, seven-collector mass spectrometer. Mass fractionation during analysis was estimated from concurrent analyses of NIST standard SRM-981 (Cantazaro et al. 1968; Toft et al. 1993). Lead isotopic data for sediment samples collected in 2001 and 2003 are presented in Table A4 of the electronic supplementary material. Lead isotopic data for pre-remediation samples collected prior to 2001 are in Fey et al. (1999b), Unruh et al. (2000), and Rich et al. (2004) and are discussed in Church et al. (2004b).

PRE-REMEDINATION CONDITIONS

Water

Elevated concentrations of As, Cd, Cu, Pb, and Zn were present in stream water throughout the district prior to remediation, and the highest concentrations were present in water downstream from larger inactive mines (Kimball et al. 2004; Nimick & Cleasby 2000, 2004). In Figure 2, metal concentrations are represented as chronic hazard quotients, HQ, for dissolved Cd, Cu, and Zn in ribbon maps (Finger et al. 2004b). The HQ, for water represents the dissolved-metal concentration divided by the hardness-corrected chronic-toxicity aquatic-life standard for the metal (US EPA 1999, 2001). This normalization of the measured concentration data gives the hazard quotient (Urban & Cook 1986) that is used as a direct measure of the biological effects in risk assessment (Finger et al. 2004b). Hazard quotients were calculated for low-flow conditions when the highest dissolved-metal concentrations and lowest suspended-sediment concentrations were observed (Nimick & Cleasby 2000, 2004). Results for As and Pb are not shown. Arsenic hazard quotients were less than 1 throughout the district. Dissolved Pb concentrations during low flow were commonly near or below the minimum reporting concentrations for the analytical technique (ICP-MS), and HQ, values for Pb probably were less than 1 throughout the district. These observations reflect the insolubility of As and Pb in the near-neutral pH of most of the streams (Nimick & Cleasby 2000).

Concentrations of Zn and Cd were elevated downstream from the Buckeye mine in upper Basin Creek (HQC = 1.9 and 4.6, respectively) and downstream from the Comet mine in High Ore Creek (HQC = 23 and 12.4, respectively). However, Cu remained below the aquatic chronic-toxicity standard (HQC < 1) at both sites. Strongly elevated (HQC > 10) concentrations of Cd, Cu, and Zn in water were present downstream from the Bullion mine in the Bullion Mine tributary to Jack Creek and in Uncle Sam Gulch downstream from the Crystal mine. The highest dissolved-metal concentrations in the study area were in Uncle Sam Gulch immediately downstream from the Crystal mine (HQC < 2000, 791, and 269 for Cd, Cu and Zn, respectively). Moderately to strongly elevated concentrations of these metals persisted in Jack Creek downstream from the Bullion Mine tributary to its confluence with Basin Creek (Fig. 2), and HQ, values > 1 were present in Basin Creek downstream from Jack Creek. Strongly elevated concentrations of metals, particularly Cd, were present in Cataract Creek downstream from the confluence with Uncle Sam Gulch. Moderately elevated metal concentrations also were present in the Boulder River reach in the study area (Fig. 1). Downstream from the confluence with Basin Creek, dissolved Cd and Cu concentrations were slightly elevated with HQ, = 1.2 and 1.8 for Cd and Cu, respectively. The HQ, for Cd increased to 4.0 and that for Cu to 2.1 downstream from Cataract Creek (Fig. 2). Downstream from High Ore Creek, dissolved Cd and Zn concentrations in the Boulder River increased markedly to HQ, = 5.5 and 2.3 for Cd and Zn, respectively. Dissolved Cu concentrations in the Boulder River actually decreased slightly downstream from High Ore Creek. Based on calculations of annual loads at their mouths (Nimick & Cleasby 2004, table 3), Cataract Creek was a larger source of metals to the Boulder River than either Basin Creek or High Ore Creek during the pre-remediation period.

Streambed sediment

Pre-remediation data for four metals (As, Cu, Pb, and Zn) from streambed sediment samples collected in the study area (1996–1998) are discussed in Church et al. (2004b). Although threshold values for toxic trace-metal concentrations in streambed sediment have not been adopted by regulatory agencies, consensus-based guidelines for metal concentrations in fresh-water streambed sediment have been recommended. MacDonald et al. (2000) proposed that concentrations of As (33 ppm), Cd (5 ppm), Cu (149 ppm), Pb (128 ppm), and Zn (459 ppm) would result in probable toxic effects to sensitive benthic macroinvertebrates. These values are referred to as ‘probable effects concentrations’ (PEC) and were used to calculate HQ values for sediment for four metals (As, Pb, Cu, Zn; Fig. 3). The highest concentrations of metals were present downstream from inactive mines, in particular the Crystal mine on Uncle Sam Gulch and the Comet mine on High Ore Creek.
Arsenic typically showed the highest concentrations among the four metals. Concentrations greater than 10 times the PEC values (HQ$_{As}$ >10) were present in upper Basin Creek, Jack Creek, Uncle Sam Gulch and lower Cataract Creek, and in High Ore Creek (Fig. 3a). Arsenic HQ values in sediment of High Ore Creek (HQ$_{As}$ >200) were the highest measured in the district for any element.

Arsenic concentrations in streambed sediment of Basin Creek progressively decreased downstream from the contaminant sources. The decrease may have resulted from either dilution from tributaries draining unmineralized areas or sequestering of As and other metals in slow-moving reaches of Basin Creek (Church et al. 2004b). Decreases in As concentrations with distance from the sources were also observed in Uncle Sam Gulch and High Ore Creek. However, As concentrations remained at HQ$_{As}$ >10 in lower Cataract and High Ore Creeks.

The distribution of Pb in streambed sediment was similar to that of As but at somewhat lower HQ$_{Pb}$ values (Fig. 3b). The highest Pb concentrations were present in High Ore Creek downstream from the Comet mine (HQ$_{Pb}$ = 44). However, HQ$_{Pb}$ values greater than 10 were also found in upper Basin Creek downstream from the Buckeye mine, in the Bullion Mine tributary downstream from the Bullion mine, and in Uncle Sam Gulch downstream from the Crystal mine. The distribution of Pb concentrations in Boulder River sediment were highest downstream from High Ore Creek, similar to that of As.

The distribution of Cu in streambed sediment (Fig. 3c) was similar to that of Zn (Fig. 3d), but differed from that of As and Pb. The highest concentrations of Cu were present in High Ore Creek downstream from the Comet mine (HQ$_{Cu}$ = 13) and in lower Uncle Sam Gulch (HQ$_{Cu}$ = 15). The elevated Cu concentrations in Uncle Sam Gulch also resulted in elevated Cu concentrations in lower Cataract Creek. The Buckeye mine in upper Basin Creek contributed only minor amounts of Cu with HQ = 0.2 and 0.9 in sediment upstream and downstream from the Buckeye mine, respectively. The Bullion mine appears to have contributed modest amounts of Cu that resulted in moderately elevated Cu concentrations in sediment in Jack Creek and in Basin Creek downstream from Jack Creek (HQ$_{Cu}$ = 1.3–3). Prior to remediation, the most significant source of Cu in streambed sediment of the Boulder River appears to have been the Comet mine.

Zinc and Cd (not shown) have similar geochemical properties and exhibited similar distribution patterns in streambed sediment of the Boulder River and its tributaries (Fig. 3d). The Comet mine on High Ore Creek again appears to have been the most significant source of Zn (HQ$_{Zn}$ >10). Strongly elevated Zn concentrations (HQ$_{Zn}$ >4) were also found in parts of Uncle Sam Gulch downstream from the Crystal mine and in Cataract Creek downstream from Uncle Sam Gulch. Strongly elevated Zn concentrations (HQ$_{Zn}$ = 5) were also found in sediment of lower Jack Creek. In contrast to results for Pb and As, sediment from upper Basin Creek and the Bullion Mine tributary had only modest amounts of Zn.

Prior to remediation, the Comet mine appears to have been the most significant source of Zn contamination in streambed sediment.

Fig. 2. Ribbon maps showing metal concentrations in pre-remediation (1996–1998) water samples expressed in terms of Hazard Quotients for chronic toxicity adjusted for hardness (HQC) for dissolved (a) Cd, (b) Cu, and (c) Zn in water at low flow (after Finger et al. 2004b). Reaches coloured blue had HQC less than 1. Reaches coloured yellow had HQC values of 1 to 4, orange reaches had HQC values of 4 to 7, pink reaches had HQC values of 7 to 10, and red reaches had HQC values > 10. Refer to Figure 1 for mine and site names and physiographic features.
sediment of the Boulder River (Church et al. 2004). However, significant amounts of Zn (and Cd) were also contributed by Cataract Creek (ultimately by the Crystal mine in Uncle Sam Gulch).

One additional aspect of the Cu and Zn data presented in Figures 2 and 3 is the effect of pH on the distribution of metals in streambed sediment. Because Cu and Zn are more soluble than As and Pb under mildly acidic conditions, different metal distribution patterns were observed downstream from a common source. For example, water data clearly indicate that the principal source of metals in Uncle Sam Gulch was the Crystal mine (Nimick & Cleasby 2004). Concentrations of all metals in water and As and Pb in sediment were highest immediately downstream from the Crystal mine. However, because the drainage from the mine was acidic (Nimick & Cleasby 2000), Cu and Zn were

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**Fig. 3.** Ribbon maps showing metal concentrations in pre-remediation (1996–1998) sediment samples expressed in terms of Hazard Quotients (HQ) for (a) As, (b) Pb, (c) Cu, and (d) Zn (after Finger et al. 2004). Reaches are coded by colour as defined for Figure 2 and are based on the probable effect concentrations recommended by MacDonald et al. (2000). Refer to Figure 1 for mine and site names and physiographic features.

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retained in solution (Kimball et al. 2004) and were only slightly enriched in sediment immediately downstream from the mine. Further downstream from the mine, the water was eventually neutralized by inflows of alkaline water, and some of the dissolved Cu and Zn precipitated. As a result, the highest concentrations of these elements in sediment were present downstream from the source at the point where favourable conditions for precipitation occurred. A similar situation was observed for Zn data in Jack Creek.

Pre-mining baseline concentrations for four metals (As, Cu, Pb, and Zn) were estimated in two ways (Church et al. 2004b). For areas outside of the mineralized areas, pre-mining baseline concentrations were estimated from 25 streambed sediment samples collected from small (1st and 2nd order) streams. Median concentrations were As = 35 ppm, Cu = 32 ppm, Pb = 35 ppm, and Zn = 150 ppm (HQAs = 1.06, HQPb = 0.27, HQCu = 0.21, and HQZn = 0.33). For areas downstream from mine workings, pre-mining baseline concentrations were
Table 1. Remediation work completed in the Boulder River watershed, 1994–2005.

| Project Sponsor* | Project Site Affected | Type of Remediation | Date Project Started | Date Project Completed | Improvement (actual or anticipated) |
|------------------|-----------------------|---------------------|----------------------|-----------------------|-------------------------------------|
| US Forest Service and US Environmental Protection Agency | Luttrell open pit Basin Creek | Bankruptcy by Pegasus Gold, Corp. made property available to public sector. Agencies worked with bonding company to convert open pit into a mine waste repository | 1999 | ongoing | Mine-waste repository built to receive mine wastes from the Boulder and Tenmile Creek watersheds (Smith et al. 2004) |
| US Forest Service | Buckeye mine and mill site Basin Creek | Removed 10,830 yd$^2$ of mine and mill waste to Luttrell repository, graded and amended soil and seeded with native riparian vegetation | 2001 | 2001 | Removed source of metal loading to upper Basin Creek (Cannon et al. 2004) |
| US Environmental Protection Agency | Enterprise mine Basin Creek | Removed 29,008 yd$^2$ of mine waste to Luttrell repository, graded and amended soil and seeded with native vegetation. Draining adit remains at site | 2000 | 2000 | Removed source of metal loading to upper Basin Creek (Cannon et al. 2004) |
| US Forest Service and US Environmental Protection Agency | Bullion mine and mill Jack Creek | Removed 40,900 yd$^2$ of mine and mill waste to Luttrell repository, graded and amended soil and seeded with native vegetation. Two draining adits remain | 2001 | 2002 | Removed source of metal loading to Bullion Mine tributary and upper Jack Creek (Kimball et al. 2004; Nimick & Cleasby 2004; Church et al. 2004) |
| US Forest Service | Bullion smelter Jack Creek | Removed 13,800 yd$^2$ of smelter waste from a minor tributary to Jack Creek to Luttrell repository, graded and amended soil and seeded with native vegetation | 2003 | 2003 | Removed source of metal loading to tributary to Jack Creek (Church et al. 2004) |
| US Forest Service | Jack Creek | Removed 3,700 yd$^2$ of mine waste from floodplain and old tailings ponds to Luttrell repository, graded and amended soil and seeded with native vegetation | 2004 | 2005 | Removed source of metal loading to Jack Creek (Kimball et al. 2004; Nimick & Cleasby 2004; Church et al. 2004) |
| US Forest Service | Daily West mine Basin Creek | Removed 1,400 yd$^2$ of mine waste from floodplain of Basin Creek and moved to Luttrell pit | 2003 | 2003 | Removed source of metal loading to lower Basin Creek |
| US Forest Service | Lower Hector Basin Creek | Removed 300 yd$^2$ of mine waste from floodplain of minor tributary to Basin Creek to Luttrell repository, graded and amended soil and seeded with native vegetation | 2003 | 2003 | Removed source of metal loading to lower Basin Creek |
| Cataract Creek US Environmental Protection Agency and US Dept. of Energy | Crystal mine Uncle Sam Gulch and lower Cataract Creek | Installed experimental lime treatment facility to treat acidic mine drainage; project operated for two years. Target concentrations in the effluent for removal of Al, Pb, Cu, and Zn were met 54%, 57%, 52%, and 44% of the time while the plant operated | 1994 | 1996 | Removed source of metal loading to Uncle Sam Gulch and lower Cataract Creek (http://www.epa.gov/ORD/NRMRL/std/mtrb/mtrb/annual/annual2000/annual00a.htm) |
| Project Sponsor* | Project Site | Affected drainage | Type of Remediation | Date Project Started | Date Project Completed | Improvement (actual or anticipated) |
|------------------|--------------|-------------------|---------------------|----------------------|-----------------------|--------------------------------------|
| US Environmental Protection Agency | Crystal mine | Uncle Sam Gulch and lower Cataract Creek | Graded site of former open-pit mine along axis of ore deposit and installed liner to reestablish surface drainage and prevent surface runoff from entering underground mine workings; Graded surface area above mine workings, installed liner, and reestablished vegetation | 2001 | 2001 | Removed source of metal loading to Uncle Sam Gulch and lower Cataract Creek (Kimball et al. 2004; Nimick & Cleasby 2004; Church et al. 2004b) |
| High Ore Creek State of Montana | Comet mine and mill | High Ore Creek | Removed 600,000 yd$^3$ of mill tailings from retention pond in High Ore Creek valley and placed in former open-pit mine; reconstructed stream channel through mine site; contoured, graded, and reseeded with native vegetation | 1997 | 1998 | Reduced erosional transport of sediment from tailings and reduced metal loading in High Ore Creek (Gelinas & Tupling 2004) |
| US Bureau of Land Management | High Ore Creek downstream of Comet mill | High Ore Creek | Removed 35,800 yd$^3$ of fluvial mill tailings along 6 km reach of High Ore Creek and placed in an unlined repository with multi-layer top near mine site. Removed fluvial tailings and reconstructed stream channel | 1999 | 2000 | Reduced metal loading to High Ore Creek and reestablished riparian habitat downstream from Comet mill |
| Boulder River US Environmental Protection Agency | Basin townsite | Boulder River | Removed 5000 yd$^3$ of contaminated soil and tailings to mine-waste repository in Butte, Montana. Excavated areas were backfilled, graded, and revegetated. | 1998 | 1998 | Reduced metal loading to Boulder River |
| US Environmental Protection Agency | Basin townsite | Boulder River | Removed 47,000 yd$^3$ of streamside tailings, Basin Street and Jib tailings, contaminated soil from residential yards, and other source materials to Luttrell repository | 2001 | 2005 | Reduced metal loading to Boulder River |

* Remediation work conducted by US Forest Service, Ray TeSoro, project manager; US Bureau of Land Management, Mike Browne, project manager; Montana Department of Environmental Quality, Ben Quinones, project manager; and the US Environmental Protection Agency, Mike Bishop, project manager.
Remediation efforts in the watershed as of 2005 are summarized in Table 1. In 1999, the Luttrell open-pit mine, located just to the NW of the study area (Fig. 1), was acquired from the defunct Pegasus Gold Corporation and was converted to a mine-waste repository (Smith et al. 2004). Much of the mine-waste material removed by the USDA Forest Service and US Environmental Protection Agency was taken to the Luttrell pit mine-waste repository (Table 1).

**Basin Creek**

The Buckeye mine is located in the headwaters of Basin Creek (Fig. 1). Mill tailings from flotation processing of earlier jiggings were deposited directly onto the floodplain of Basin Creek (Fey et al. 1999a; Cannon et al. 2004). Mill tailings and contaminated floodplain sediment were removed by the USDA Forest Service in 2001 (Table 1). However, as of 2005, no remediation of the flowing acidic mine drainage from the Enterprise mine adit had been undertaken.

The Bullion mine is located on a small tributary, informally named the Bullion Mine tributary, to Jack Creek, a tributary of Basin Creek (Fig. 1). Settling ponds were constructed in the stream channel downstream from the portal to contain flotation mill tailings, but at some unknown time, probably before 1950, the dams failed and released the tailings; the Bullion Mine tributary and Jack Creek. The flood deposited metal-contaminated mill tailings on the floodplain of the Bullion Mine tributary for half a kilometre downstream of the tailings ponds and filled several sediment catchments along the main channel of Jack Creek (Church et al. 2004b). Prior to remediation, metal-contaminated sediment was still being transported down the Bullion Mine tributary into Jack Creek and ultimately into Basin Creek (Fey et al. 2000). Remediation at the site was initiated in 2001 (Table 1), although acidic mine drainage still flowed from an open adit in 2005.

**Cataract Creek**

The Eva May mine lies near Cataract Creek just upstream from Hoodoo Creek (Fig. 1). Tailings piles that extended from the mine to the creek were removed prior to the current study. However, there is still a potential pathway at the site for mine drainage to enter Cataract Creek (Kimball et al. 2004). Trace-metal loads from numerous small abandoned mines along upper Cataract Creek and its tributaries (Martin 2004) are relatively small (Kimball et al. 2004; Nimick & Cleasby 2004).

The Crystal mine is located in the headwaters of Uncle Sam Gulch, a tributary to Cataract Creek (Fig. 1). Mill tailings were deposited directly into Uncle Sam Gulch, and an open portal drains into Uncle Sam Gulch (Fey et al. 2000). Furthermore, several large trenches, which were dug into the hillside above the mine, funnelled surface water from the hillside into and through the mine. The trenches were filled, capped, and vegetation was planted over the fill in 2001 to reduce the amount of water flowing through the mine. However, acidic water was still flowing from the adit in 2005.

**High Ore Creek**

The principal source of metal contamination in High Ore Creek was the mill tailings from the Comet mine (Fey & Church 1998). The mine consisted of underground workings, an open pit, and an on-site mill (Gelinas & Tupling 2004). Mine waste and mill tailings were deposited in a retention pond in High Ore Creek. This structure subsequently failed, releasing tailings downstream. Large-scale remediation at the mine site by the State of Montana began in 1997 (Table 1). Waste rock and mill tailings were removed from the valley floor and placed in the open mine pit, which was used as an unlined repository. The High Ore Creek valley downstream from the Comet mine was restored by the Bureau of Land Management in 1999–2000. Mine waste and mill tailings were removed from the valley floor. Floodplain and streambed sediment was either removed or amended in place, and new material was imported to fill the excavated areas. Material removed from the valley floor was placed in a mine-waste repository constructed in the uplands east of the mine site (Gelinas & Tupling 2004).

**Boulder River**

The Jib Mill site is on the Boulder River, within the town of Basin and just upstream from Basin Creek. Waste from this mill was either dumped directly into the river or was washed into the river during flood events. Fluvial deposits of mill tailings were present on a 10-m by 50-m bar in the Boulder River downstream from Basin Creek (Church et al. 2004b). Whereas the source of these tailings may not be unequivocally ascribed to the Jib Mill, similar tailings were also present immediately downstream from the mill site upstream from Basin Creek. The mill waste and other mine waste in the town of Basin were removed in 2002 and placed in the Luttrell repository (Fig. 1).

**POST-REMEDIATION**

Water quality and streambed sediment samples were collected at key sites in the Boulder River watershed to assess post-remediation conditions. Remediation progressed over a period of years, and therefore the start of the post-remediation period varied among the sampling sites. Water quality samples were collected through 2005 during a range of hydrologic conditions, and streambed sediment samples were collected in 2001 and 2003 (Fig. 1). In the sections below, the discussion refers to changes observed in water quality and sediment geochemistry over the entire pre- and post-remediation monitoring period.

In evaluating metal-concentration data in water for the pre- and post-remediation periods, streamflow must be accounted for because it typically provides a strong control on concentrations (Nimick & Cleasby 2004). The seasonal variability of concentration and streamflow (discharge, Q) is shown using Uncle Sam Gulch (site 43W) as an example (Fig. 5).
seasonal pattern of streamflow typically consists of high flows during the late spring when the mountain snowpack melts and spring rains are common, and lower flows during the summer and winter. Metal concentrations typically can either decrease during high flow owing to dilution or increase owing to entrainment of sediment.

To account for the affect of streamflow in our evaluation of the water quality data, concentration data were plotted against streamflow in log-log scatter plots. The pre-remediation data were regressed linearly, and 95% confidence prediction intervals for the regression were graphed. The post-remediation data were then plotted. Comparisons of pre- and post-remediation data were made by noting the position of the post-remediation data relative to the regression line and prediction intervals for various flow conditions. Dissolved and total data were evaluated separately, as shown in Figure 6 for site 8W. Data presented for other water quality sites are limited to dissolved As and Zn and total Cu and Pb.

Basin Creek
Remediation at the Buckeye and Enterprise mines in upper Basin Creek (Fig. 1) did not change the concentrations of dissolved metals at site 8W; however, total concentrations improved somewhat, as evidenced by the presence of some post-remediation data that plot below the pre-remediation 95% prediction interval (Fig. 6). The improvement in total Pb concentration was most notable, with all post-remediation data plotting below the pre-remediation regression line. However, the Enterprise mine portal continues to release acidic water,
and dissolved metal concentrations in Basin Creek have not appreciably diminished. Streambed sediment data for site 21S also showed a large improvement, particularly for Pb concentrations, which decreased by almost an order of magnitude between 1996 and 2003 (Fig. 7a). Removal of tailings and contaminated sediment in and adjacent to the stream channel has resulted in a dramatic decrease in the metal concentrations of the sediment immediately downstream from the mine sites. Further downstream at site 24S (Fig. 7b), concentrations had not yet shown any decrease in 2001.
Remediation at the Bullion mine resulted in small decreases in concentrations of dissolved Zn and total Cu and Pb at higher flows at site 17W (Fig. 8a). Overall, however, water in this stream was still acidic and metal concentrations were very high during the post-remediation period. Post-remediation samples of streambed sediment were not collected from this stream.

Remediation in the entire Jack Creek watershed, which includes the Bullion mine, Bullion smelter, and floodplain areas along Jack Creek, resulted in no changes in metal concentrations in Jack Creek through the post-remediation monitoring period (sites 63W and 42S; Figs. 7c & 8b).

Remediation in the entire Basin Creek watershed resulted in only minor decreases in concentrations of total Pb and dissolved Zn in water (site 24W, Fig. 8c) and little or no change in metal concentrations in streambed sediment (sites 30S and 31S; Fig. 7d). Despite this lack of changes, metal concentrations in biofilm and macroinvertebrates did decrease between 1997 and 2003 (site BCB of Rhea et al. (2006), near sites 31S and 24W, Fig. 1).

Improvements in water and sediment quality in the Basin Creek watershed likely have been minimal because the remediation efforts throughout the watershed involved removal of waste material and did not address the acidic drainage at the Enterprise and Bullion mines. The removals did decrease metal concentrations in streambed sediment in the immediate area of remediation, but little or no change has occurred farther downstream because of slow downstream transport of sediment by erosion.

Cataract Creek

Upstream of Uncle Sam Gulch, the Cu and Zn concentrations in streambed sediment at site 49S decreased by a factor of 2 between 1997 and 2003. This progressive improvement probably reflects the gradual, ongoing removal of the contaminated sediment introduced from the Eva May tailings by erosion.

Remediation at the Crystal mine has resulted in readily apparent decreases in dissolved Zn and total Cu concentrations in Uncle Sam Gulch (site 43W), with most post-remediation data plotting below the pre-remediation regression line and a number of data points that plot below the 95% prediction interval, particularly during lower flows (Fig. 9a). However, no change was apparent for total Pb, and dissolved As concentrations increased. Changes in metal concentrations in streambed sediment (site 57S, Fig. 10a) generally mirrored those in water as Zn and Cu concentrations decreased by a factor of 2 whereas Pb and As concentrations in sediment remained virtually unchanged between 1996 and 2003.

Some affects of the remediation at the Crystal mine were apparent in Cataract Creek. Significant improvement was observed for dissolved Zn and total Cu at site 47W (Fig. 9b), but metal concentrations in streambed sediment were similar to pre-remediation values at sites 50S and 53S (Fig. 10d). The data for sites 50S and 53S demonstrate that metal concentrations in streambed sediment can exhibit substantial annual variation, thus increasing the difficulty of establishing temporal trends. Rhea et al. (2006) noted consistent decreases in metal concentrations in macroinvertebrates between 1997 and 2003 at their site LCC (near sites 53S and 47W, Fig. 1), but no consistent trends were observed for biofilm.

Remediation in the Uncle Sam Gulch watershed was directed primarily toward decreasing acid mine drainage as opposed to removal of contaminated materials (Table 1). As a result, concentrations of dissolved Cd, Cu, and Zn in Uncle Sam Gulch and lower Cataract Creek were generally reduced by factors of 2–3, but metal concentrations in streambed sediment have remained virtually unchanged.

High Ore Creek

Remediation of the Comet mine area resulted in decreased concentrations of dissolved Zn in High Ore Creek at site 56W (Fig. 11a). Total Cu and Pb concentrations remained relatively constant, and, as observed in Uncle Sam Gulch, dissolved As concentrations increased. Metal concentrations in streambed sediment decreased dramatically at site 59S just downstream from the Comet mine (Fig. 12a). Concentration decreases ranged from a factor of 10 for Cu to a factor of 3 for Zn. Further downstream at site 63S, improvement in sediment quality was not as dramatic (Fig. 12b). Arsenic concentrations decreased by only 30%, and concentrations of Cd, Cu, Pb, and Zn decreased by a factor of 2.

The Comet mine and mill sites received the most extensive and costly restoration in the district (Gelinas & Tupling 2004). Large quantities of metal-rich mine and mill wastes that had been deposited in the stream valley had contaminated the streambed and floodplain sediment (Fey & Church 1998). Stream restoration by the US Bureau of Land Management involved removal or amendment of the streambed and banks and re-establishment of willows in the riparian zone. As a result, High Ore Creek has shown the most improvement in aquatic habitat of the three tributary watersheds. However, metal concentrations in water and sediment of High Ore Creek were still elevated in 2002–2003 (Figs. 11a & 12a). Seepage from the waste repository is thought to degrade water quality in High Ore Creek (Sudbrink 2006) and to contribute to ongoing elevated metal concentrations in the stream (Morris et al. 2005; Gammons et al. 2007).

The results for High Ore Creek indicate that remediation of the metal sources in streambed sediment alone will not immediately produce the desired results in streambed sediment throughout the drainage because erosional transport of contaminated sediment out of the impacted stream reach can take a number of years if not decades (e.g. Vincent & Elliott 2007). In 1996 prior to stream restoration, metal concentrations in sediment at site 59S (Fig. 12a), immediately downstream from the Comet mine, were higher than those observed farther downstream at site 63S. Although metal concentrations at both sites were lower in 2003, the improvement at site 59S was much more evident. Metal concentrations in sediment at this site in 2003 were similar to (Pb, Zn) or lower (As, Cu) than those at site 63S (Fig. 12b). This large decrease in metal concentrations at site 59S likely resulted from the complete removal and restoration of the streambed and floodplain in the reach of High Ore Creek just downstream from the Comet mine. As of 2007, willows had been re-established in the riparian zone and a fish were present in the stream (Mike Browne, pers. comm., 2007), although the stream still exhibited some signs of toxicity (Nimick et al. 2007).

Boulder River

Ultimately, the success of the remediation efforts in the tributary stream reaches will be judged by the improvement to water and sediment quality in the Boulder River. Streambed sediment was sampled at multiple sites along the Boulder River (Fig. 1), thus allowing assessment of metal concentrations through time downstream from each of the main tributaries within the district. Streambed sediment downstream from Basin Creek (site 68, Fig. 13b) showed decreased concentrations of As, Cu, and Pb in 2003, but all metals had slightly elevated
Fig. 8. Relation between streamflow and dissolved As, total Cu, total Pb, and dissolved Zn (top to bottom) in water from the Basin Creek watershed. (a) Bullion Mine tributary (site 17W), (b) Jack Creek (site 63W), and (c) lower Basin Creek (site 24W), 1996–2005. Solid line is regression line through pre-remediation data; equation is shown in figure for each constituent. Dashed lines are the pre-remediation 95% prediction interval. Shaded area (single line for As) indicates approximate range of chronic aquatic-life standard for range of hardness typical for the site.
concentrations relative to sites 1S and 2S upstream of the district (Fig. 1). Downstream from Cataract Creek (site 9S, Fig. 13c), concentrations of all metals had decreased since 1996 but were higher than at site 6S.

Downstream from High Ore Creek, metal concentrations at the three sampling sites (12S, 13S, and 15S) decreased between 1996 and 2003, with the largest decreases at site 13S (Fig. 13e, f). Concentrations of all metals (except As) in water also decreased somewhat at moderate to high streamflow at site 58W (Fig. 11b).

The metal concentrations in water and sediment in the Boulder River downstream from High Ore Creek (sites 58W and 12S–15S) reflect the combined effects of all remediation within the district. Nimick & Cleasby (2004) concluded that, prior to remediation, the principal source of metals in water of the Boulder River was the Crystal mine on Uncle Sam Gulch. Church et al. (2004b) showed that the principal source of metals in streambed sediment was the Comet mine on High Ore Creek. Remediation efforts (Table 1) have addressed both issues. Remediation at the Crystal mine reduced acid mine drainage whereas those at the Comet mine removed mill tailings.
from the stream drainage. Both efforts have been at least partially successful as evidenced by the data in Figures 11 and 13. However, goals for complete aquatic habitat restoration (HQ and HQC) have not been reached. Rhea et al. (2006) noted decreases in metal concentrations in biofilm between 1997 and 2003 at their site BRLG (near site 58W, Fig. 1) but no consistent trends were observed for these metals in macroinvertebrates.

Lead isotope data

Lead isotopic data were measured in HCl-H2O2 leaches from a selected subset of the sediment samples to identify and quantify the contributions of deposit-related metals to the streambed sediment (Church et al. 2004b). Lead isotopic data show an inverse relationship with Pb concentrations (Church et al. 2004b). The highest 206Pb/204Pb values (18.1–18.2) and lowest Pb concentrations (<60 ppm) were present among some of the pre-mining baseline samples, streambed sediment collected from tributaries upstream from major mines, and streambed sediment collected from unmined tributary basins. A mean pre-mining baseline 206Pb/204Pb = 18.13 has been calculated for most of the study area (see table 4 of Church et al. 2004b). The highest Pb concentrations and lowest 206Pb/204Pb values were present immediately downstream from mine sites. The Pb data clearly indicated two principal sources of deposit-related Pb (>1000 ppm; Church et al. 2004b). Sediment samples from High Ore Creek downstream from the Comet mine had a relatively constant 206Pb/204Pb = 18.065, which we interpret to represent the 206Pb/204Pb of deposit-related contaminant Pb in this drainage. The highest Pb concentrations in sediment samples from the Basin and Cataract Creek drainages (Pb = 920 ppm–12 000 ppm) had 206Pb/204Pb values of 17.90–17.93 with a mean value of 206Pb/204Pb = 17.916 for the contaminant Pb isotopic composition.

Fig. 11. Relation between streamflow and dissolved As, total Cu, total Pb, and dissolved Zn concentrations (top to bottom) in water from (a) lower High Ore Creek (site 56W) and (b) the Boulder River (site 58W), 1996–2005. Solid line is regression line through pre-remediation data; equation is shown in figure for each constituent. Dashed lines are the pre-remediation 95% prediction interval. Shaded area (single line for As) indicates approximate range of chronic aquatic-life standard for range of hardness typical for the site. The circular array of dissolved Zn data for High Ore Creek (site 56W) represent samples collected hourly for 34 hours in July 2000 (Nimick et al. 2003).

Fig. 12. Metal concentrations expressed as hazard quotients as a function of year sampled for metals in streambed sediment from High Ore Creek. (a) High Ore Creek downstream from Comet mine (site 59S) and (b) lower High Ore Creek (site 63S), 1996–2003.
sites, Pb isotopic compositions showed little variation with time, which indicates that the proportions of contaminant Pb at these two sites remained fairly constant throughout the study.

Data collected in 1996 from sediment downstream from the confluence with High Ore Creek (sites 12S, 13S, and 15S; Figs. 14d–f) indicate that the vast majority of the Pb in Boulder River sediment at those sites was derived from the Comet mine on High Ore Creek (Church et al. 2004b). Sediment collected in 2001 from these three sites had slightly, but not distinctly lower $^{206}$Pb/$^{204}$Pb values within analytical uncertainties. However, sediment samples collected in 2003 had $^{206}$Pb/$^{204}$Pb values distinctly lower than the 1996 values, particularly at site 13S (Fig. 1). The lower $^{206}$Pb/$^{204}$Pb values observed in sediment collected in 2003 at all three sites downstream from High Ore Creek indicate that the source of the contaminant Pb in the Boulder River was shifting from the Comet mine to the mines of Basin and Cataract Creeks.

The isotopic composition of Pb in contaminated streambed sediment will be intermediate between that of the contaminant (ore) and the unmineralized baseline value. Once the isotopic signature of both the pre-mining baseline Pb and contaminant Pb are known, the proportion of contaminant Pb in a sediment sample can be calculated from Equation 1:

$$X_c = 100 \cdot \left( \frac{R_b - R_s}{R_b - R_c} \right)$$

where:

- $X_c$ is the percentage of Pb in the sediment derived from the contaminant source ($0 \leq X_c \leq 100$) and
R_b, R_c, and R_s represent the isotopic ratio (e.g. 206Pb/204Pb) in the baseline, contaminant, and sample, respectively (Church et al. 1993). The Pb isotopic compositions therefore provide a direct measure of the degree of contamination independent of the transport mechanism. In contrast, conventional bulk mixing calculations that use concentration data carry the implicit assumption that the metal content in a sample represents a bulk mixture of the source and baseline material. In other words, the bulk mixing calculation gives the apparent sediment contribution in cases where there is differential transport of the metals used in the calculation rather than the true metal contribution from the contaminant.

The primary disadvantage of the Pb isotopic method is illustrated by the heavily contaminated sediment samples (X_c > 90%). In this case, the Pb isotopic composition of the sediment may be indistinguishable from that of the contaminant within analytical uncertainty. Addition of more contaminant Pb may significantly change the Pb concentration in the sediment but will be undetected by the Pb isotopic data because of the analytical uncertainty in the Pb isotopic analysis. A second disadvantage evident from this study is that prior to remediation 50–90% of the contaminants in the Boulder River were derived from the Comet mine.

The calculated proportions of Pb derived from the Basin-Cataract Creek source in sediment of the Boulder River are summarized in Table 2. Using Equation 1, R_c is the 206Pb/204Pb value of the Basin-Cataract Creek contaminant source (17.913), and R_s is the ratio in the sample. The term R_b represents the isotopic ratio of the non Basin-Cataract Creek Pb. Upstream from the confluence with High Ore Creek, R_b represents ‘ambient’ or pre-mining baseline Pb (206Pb/204Pb = 18.13). Downstream from the confluence with High Ore Creek, R_b represents a mixture of pre-mining baseline Pb and Pb derived from the Comet mine (206Pb/204Pb = 18.605). Thus, a range of X_c values for each sample is obtained by assuming that the ‘baseline’ Pb (R_b) is either all Comet mine Pb (lower number) or all pre-mining baseline Pb. Church et al. (2004b) showed that the lower values are more nearly correct.
Table 2. Proportion of Basin-Cataract Creek contaminant in sediment of the Boulder River.

| Site | Year | 206Pb/204Pb Xc | Xc* |
|------|------|----------------|-----|
| 6S   | 1996 | 18.078         | 24  |
| 6S   | 2001 | 18.099         | 15  |
| 6S   | 2003 | 18.075         | 26  |
| 9S   | 1996 | 18.006         | 58  |
| 9S   | 2001 | 18.031         | 46  |
| 9S   | 2003 | 18.028         | 48  |
| 12S  | 1996 | 18.048         | 11–38† |
| 12S  | 2001 | 18.046         | 12–39† |
| 12S  | 2003 | 18.030         | 23–47† |
| 13S  | 1996 | 18.063         | 1–31† |
| 13S  | 2001 | 18.051         | 10–37† |
| 13S  | 2003 | 17.970         | 64–75† |
| 15S  | 1996 | 18.056         | 6–35† |
| 15S  | 2001 | 18.043         | 15–41† |
| 15S  | 2003 | 18.023         | 20–58† |

* Percentage of Basin-Cataract Creek Pb contaminant in the Boulder River sediment from equation 1; Rr = 17.916 and Rb = 18.13.
† Downstream from High Ore Creek, two different values of Rb were used: High Ore Creek contaminant Pb, 206Pb/204Pb = 18.065; averaged baseline, 206Pb/204Pb = 18.13.

for the 1996 samples because the vast majority of the Pb in sediment of the Boulder River at these sites originated from the Comet mine on High Ore Creek.

At sites 6S downstream from Basin Creek and 9S downstream from Cataract Creek, the proportions of contaminant Pb in streambed sediment have remained fairly constant at 15–26% and 46–58%, respectively (Table 2), during the study. However, downstream from High Ore Creek, the proportion of Basin–Cataract Creek contaminant in streambed sediment increased significantly regardless of the assumptions regarding the ‘baseline’ Pb. At site 13S, the calculated proportion of Basin–Cataract Creek contaminant was less than 30% in 1996 (and probably 10% or less; Church et al. 2004b) but comprised 64–75% of the Pb in the streambed sediment at site 13S in 2003. The calculated increases in the proportions of the Basin–Cataract Creek contaminant at sites 12S and 15S are less dramatic than those calculated for site 13S but are still significant (Table 2). The absolute contaminant concentrations at sites 12S–13S decreased from 1996 to 2003 (Figs. 14d–f). Therefore, the increases in the relative contributions from the Basin–Cataract Creek contaminant reflect a decrease in the contributions from the Comet mine rather than absolute increases in the contributions from mines in the Basin and Cataract Creek drainages.

CONCLUSIONS

Monitoring of water and sediment quality and biological sampling following remedial actions undertaken by the USDA Forest Service, US Bureau of Land Management, the State of Montana, and the US Environmental Protection Agency for a period of approximately five years has demonstrated some improvement in the aquatic habitat in the Boulder River and the three tributaries impacted by historical mining. The most extensive restoration in the district occurred at the Comet mine site on High Ore Creek and has resulted in the most dramatic improvement in the aquatic environment. Large amounts of contaminated sediment and tailings were removed from the drainage and the stream channel was reconstructed. Willows were planted and the riparian habitat restored. As a result, both dissolved and total Cd and Zn concentrations in water have been reduced, particularly at low flow, and dissolved and total Cu and As concentrations remain low. Metal concentrations in streambed sediment at the Comet mine were reduced by a factor of c. 10, the largest improvement observed anywhere in the district.

Dissolved and total Cd, Cu, and Zn concentrations in High Ore Creek generally showed some improvement downstream from the remediated site to the Boulder River and within the Boulder River downstream of the mining district, although chronic aquatic-life standards for Cd, Cu, and Zn were still exceeded. In contrast, the improvement observed in sediment just downstream from remediated areas was not observed in samples collected further downstream. Although removal of the sources of these metals will prevent additional contaminants from entering the stream, it may take many years for erosional processes to diminish the effects of contaminated sediment already in place. Some improvement was observed in sediment in the Boulder River downstream from the district, but metal concentrations remained higher than desired.

Remediation at the Buckeye mine site in the headwaters of Basin Creek and at the Bullion mine site on Jack Creek, a tributary to Basin Creek, has addressed some of the sediment quality issues identified, but both sites continue to have acidic water flowing from mine adits that must be addressed before additional significant improvement in aquatic habitat can be expected.

Likewise, remediation efforts to cut off the source of water flowing into the Crystal mine have been only partially successful, and no remediation of the mill tailings present in Uncle Sam Gulch have been taken to date. Dissolved and total concentrations of Cd, Cu, and Zn in water were lowered substantially. The Cu and Zn concentrations in streambed sediment, which were apparently derived from precipitation from water prior to remediation, were also lowered. Lead and As concentrations in streambed were unaffected.

Although significant strides have been made, much can still be done to achieve the desired restoration of aquatic habitat. Adits draining at the Bullion and Crystal mines remain the primary sources of metals in the Basin and Cataract Creek drainages, respectively. The Crystal mine was previously shown to be the largest source of dissolved metals in the district (Nimick & Cleasby 2004), and Pb isotopic evidence suggests that it may now be the largest source of dissolved metals in streambed sediment of the Boulder River. Remediation efforts designed to seal these draining adits or treat the mine effluent would address the large impacts of these high-priority sites.

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