The Water-Quality Effects of a Bulkhead Installed in the Dinero Mine Tunnel, near Leadville, Colorado

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Abstract In 2009, a bulkhead was installed in Dinero tunnel to reduce drainage and improve water quality and aquatic habitat downstream in Lake Fork Creek. Monitoring during 2006 and 2010 to 2012 indicated water-quality improvement in Lake Fork Creek (zinc concentrations and loads decreased). However, water quality degraded in areas adjacent to Dinero tunnel (pH decreased and zinc concentrations increased) due to increased water-table elevation behind the bulkhead. Continued monitoring will help assess if water-quality degradation continues adjacent to Dinero tunnel, and if low pH, zinc-rich water breaks through the Dinero wetland area and negates water-quality improvement in Lake Fork Creek.

Keywords mine drainage, bulkhead, water quality, monitoring

Introduction

The Dinero tunnel is a historic mine adit in the Sugar Loaf Mining District near Leadville, Colorado (fig. 1). The mining district produced silver, some gold, lead, and zinc primarily from 1880 until 1893, and then operated sporadically until the 1920s (Singewald 1955). Mine drainage from Dinero tunnel is the primary source of manganese and zinc loading to Lake Fork Creek (Walton-Day and others 2005). Water-quality data for 2002–2009 indicate that cadmium, manganese, and zinc chronic aquatic-life water-quality criteria were periodically exceeded in portions of Lake Fork Creek downstream from Dinero tunnel (Lake Fork Watershed Working Group 2010). Benthic macro-invertebrate surveys indicated macro-invertebrate abundance and diversity decrease downstream from Dinero tunnel (Barrack 2001, Lake Fork Watershed Working Group 2010). In 2009, a bulkhead was installed in Dinero tunnel to reduce water flow from the tunnel and help improve downstream water quality and aquatic habitat (fig. 1). Hydrostatic pressure recorded behind the bulkhead has been relatively steady since late in 2010, and indicates that groundwater elevation rose to approximately 115 m above the bulkhead after installation and closure; mine pool elevation is approximately 3,097 m.

The U.S. Geological Survey, in cooperation with the Colorado Division of Reclamation, Mining, and Safety, the Bureau of Land Management, and Colorado Mountain College conducted a monitoring program to assess the water-quality effects of bulkhead emplacement. Monitoring of water quality and discharge in surface water, springs, and seeps within about a 3 km radius of the tunnel was conducted prior to and for three years following bulkhead closure. Samples were collected from between 22 to 50 of the 70 sites shown on Fig. 1 four times (June, July, August, and October) in 2006 before bulkhead installation and closure, and during high and low flow periods (generally June and September) in 2010, 2011,

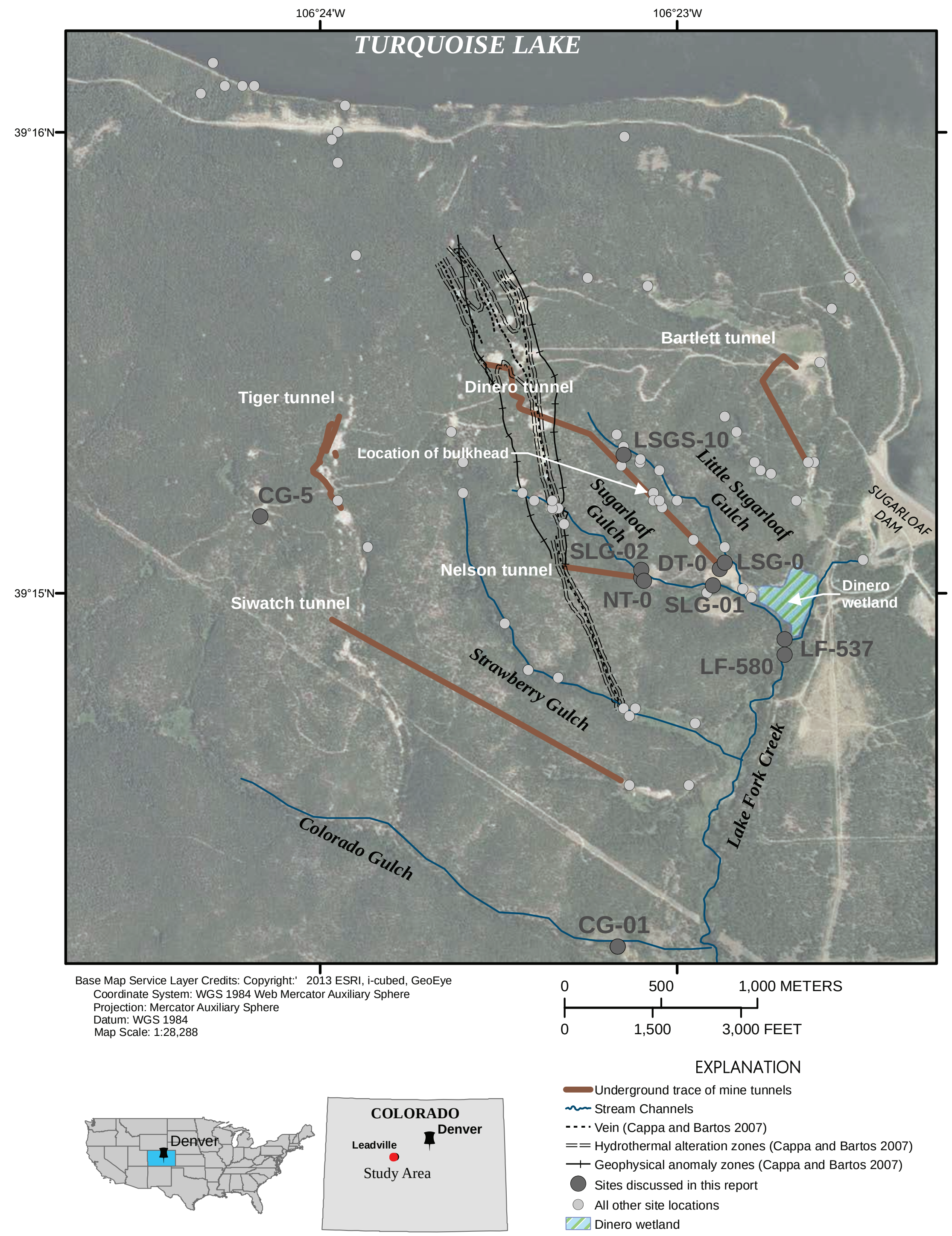

Fig. 1 *Sugar Loaf Mining District showing sample sites, mine tunnels, and a vein system with associated hydrothermal alteration.*

and 2012 after bulkhead installation and closure. The objective of this paper is to present results for sites adjacent to the Dinero tunnel and in Lake Fork Creek downstream from

[DT-0: Dinero tunnel portal; LF-537: channel draining Dinero area; LF-580: Lake Fork Creek downstream from Dinero area; Q: discharge; Total refers to concentrations and loads in unfiltered samples; Zn_{tot}: total Zn concentration; M_{Zn}: total Zn load; J: June; M: May, O: October; S: September]

	DT-0				LF-537				LF-580			
Month 'year	*Q* (L/s)	pH (–)	Zn_{tot} (µg/L)	M_{Zn} (kg/d)	*Q* (L/s)	pH (–)	Zn_{tot} (µg/L)	M_{Zn} (kg/d)	*Q* (L/s)	pH (–)	Zn_{tot} (µg/L)	M_{Zn} (kg/d)
J '06	7.4	5.2	19,200	12.3	1.9	3.7	9,790	1.61	408	7.0	232	8.18
J '10	0.51	6.7	3,230	0.14	4.0	4.5	1,890	0.65	235	7.0	49	0.99
J '11	1.3	6.7	4,520	0.51	17.3	4.5	4,170	6.2	487	6.5	711	29.9
M '12	0.82	6.5	5,100	0.36	0.59	4.7	4,320	0.22	484	7.2	25	1.05
O '06	4.8	6.3	10,100	4.19	2.7	4.2	6,820	1.59	549	6.9	61	2.89
S '10	0.57	6.4	4,700	0.23	0.06	4.9	2,520	0.01	84.1	6.4	70	0.51
S '11	1.1	6.2	6,050	0.57	0.85	4.5	1,720	0.13	84.7	6.6	49	0.36
S '12	0.82	6.9	5,390	0.38	0.51	4.4	1,300	0.06	490	7.5	34	1.44

Table 1 *Discharge, pH, and unfiltered zinc concentration and load, Sugar Loaf Mining District study area*

Dinero tunnel (fig. 1) to highlight changes in water quality (pH and zinc) that occurred after bulkhead emplacement.

Study Area

The study area lies on the eastern flanks of the Sawatch mountain range, west of Leadville Colorado. Elevations range from 2,926 m at site CG-01 (fig. 1) to 3,008 m at full pool elevation in Turquoise Lake, to 3,260 m at the highest sampling site (CG-5, fig. 1). Most of the Sugar Loaf Mining District is forested and contains abandoned, draining mine tunnels such as the Dinero, Bartlett, Nelson, Siwatch, and Tiger tunnels (fig. 1) and numerous mine waste and tailing piles. Precambrian granitic and metamorphic rocks underlie the study area (Singewald 1955). The area drains to Turquoise Lake, Colorado Gulch, and Lake Fork Creek, which is tributary to the Arkansas River. Average annual precipitation of 45 cm per year (1948–2006) occurs primarily as snow in the winter, with summer thunderstorms sometimes contributing substantial rainfall (Sugarloaf Reservoir climate station; Western Regional Climate Center, www.wrcc.dri.edu, accessed April 2013). Surface-water and some groundwater hydrographs are dominated by a broad peak related to snowmelt runoff and recharge of groundwater systems that generally occurs between April and July with peak flow occurring between late May and early June (Walton-Day and Poeter 2009).

Methods

Water-quality samples were collected using modifications of standard sampling protocols (U.S. Geological Survey variously dated) to facilitate sampling in remote locations where sites were accessed by hiking. Modifications included use of a portable filtering apparatus, acidification at a central location (rather than at the sampling site), and use of smaller sample bottles. Quality-control samples indicated the modified sampling methods did not adversely affect the quality of the data (K. Walton-Day unpublished data). Data and sample collection at each site included the following: (1) Measurement and documentation of the field parameters (water temperature, specific conductance, pH, and dissolved oxygen) *in situ* using individual (2006) or multiparameter (2010 to 2012) field meters that were calibrated at the beginning of each field day and received calibration checks at mid-day and at the end of the day. If calibration problems were noted, those measurements were flagged in the database, and the instrument was recalibrated before collecting more samples. (2) Measurement of flow rate in each flowing spring, draining mine feature (tunnels and seeps associated with mine waste and tailing piles), and stream site using volumetric techniques, flumes, or velocity cross-section techniques depending on the flow rate and channel configuration at each site (Rantz and others 1982; Turnipseed and Sauer 2010). (3) Collection of composited water-quality samples using equal-width increment techniques (U.S. Geological Survey variously dated), where stream channel width and depth allowed, or grab samples in smaller channels, seeps, and springs. One large composite sample (1 to 2 L) was divided into separate 125 mL unfiltered and filtered (0.45 µm) acidified aliquots (ultrapure HNO_3) for analysis of major and trace elements by high resolution- inductively coupled plasma mass spectrometry at the University of Southern Mississippi Center for Trace Analysis using procedures similar to Shiller (2003). Replicate and blank samples were collected at approximately 10 % of sample sites to assess data quality. Results indicate no adverse effects to the quality of results presented herein (K. Walton-Day unpublished data). This paper presents streamflow, pH, zinc, and iron results for a subset of all samples collected. Results from all environmental samples are publicly available through the U.S. Geological Survey National Water Information System (http://maps.waterdata.usgs.gov/mapper/index.html).

Results and Discussion

Bulkhead emplacement in Dinero tunnel in 2009 greatly reduced discharge, total zinc concentration, and instantaneous zinc mass load (total load on table 1) from Dinero tunnel drainage collected at the portal (DT-0) as evidenced by lower values in 2010–2012 relative to 2006 (table 1). Similarly, zinc concentrations and instantaneous mass loads generally decreased at site LF-537 which drains most of the area that includes the Dinero tunnel, Sugarloaf Gulch, and Little Sugarloaf Gulch, and at site LF-580, located on Lake Fork Creek, downstream from LF-537 (fig. 1, table 1). In addition, pH at LF-537 generally increased by almost 1 unit during high flow. One exception to these water-quality improvements was June 2011 at LF-537 and LF-580 when snowmelt runoff was at near-record levels due to a larger than average snowpack. The large snowmelt-related runoff likely increased runoff from draining mines and abandoned mine features leading to decreased water quality at these two sites.

In contrast to these general water-quality improvements, after bulkhead emplacement, zinc concentrations increased or pH decreased (or both) at sites adjacent to Dinero tunnel (DT-0) including SLG-01 (the mouth of Sugarloaf Gulch), LSG-0 (the mouth of Little Sugarloaf Gulch), and NT-0 (the Nelson mine drainage tunnel; fig. 2). Results at CG-01 (fig. 2) indicate that decreasing pH and increasing zinc concentrations after bulkhead emplacement were not a regional phenomenon but were limited to sites near Dinero tunnel. The low pH at CG-01 during June 2011 is due to the large snowmelt-related runoff at that time, which increased runoff from mine waste in the Colorado Gulch watershed, between Tiger Tunnel and Colorado Gulch (fig. 1), causing low pH and elevated zinc concentrations. The generally decreasing water quality at SLG-01, LSG-0, and NT-0 suggests that the elevated water table and mine pool created by emplacement of the bulkhead in Dinero tunnel increases groundwater discharge into the gulches and Nelson mine tunnel and degrades water quality at these sites.

In addition to these changes in water quality, there were coincident increases in flow at some of these sites. During October 2006, low to no flow in both Sugarloaf and Little Sugarloaf Gulches prevented sampling at most sites. In contrast, in 2010 to 2012, flow in both gulches was sufficient to collect samples at almost all sites during the "low flow" sampling trips. Although 2011 was a high-flow year, flow during two years (2006, 2010) was not unusually high or low. In contrast, 2012 was a fairly low-flow year, yet most sites in these gulches had flowing water in September 2010, 2011, and 2012. The increased amount of flow observed in Sugarloaf and Little Sugarloaf Gulches during low-flow sampling after bulk-

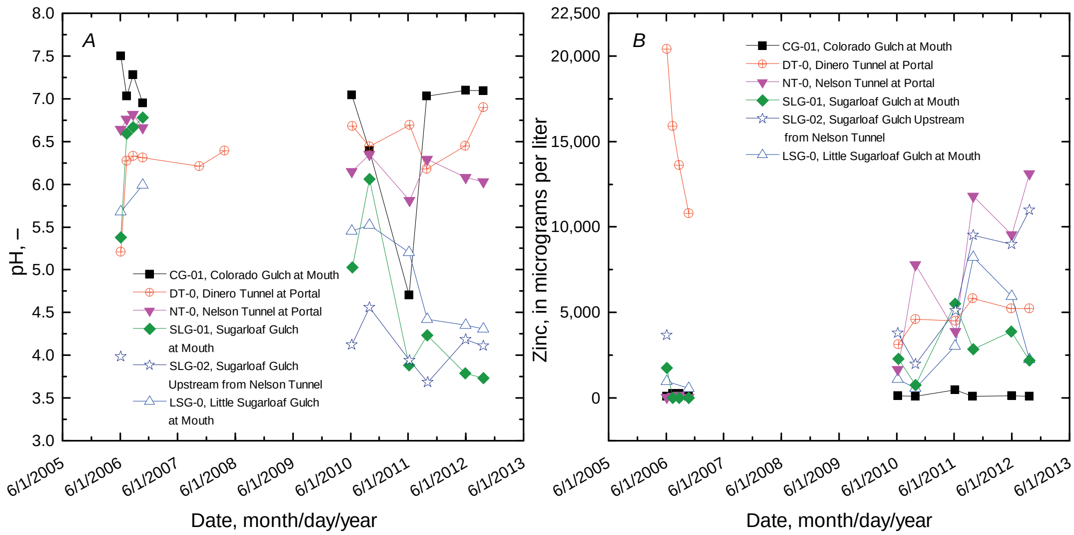

***Fig. 2** Graphs of (A) pH and (B) zinc concentrations through time at selected sample sites.*

head emplacement is additional evidence that the mine pool created by the bulkhead increased groundwater discharge to the gulches.

Water-quality changes at SLG-01 (Sugarloaf Gulch at the mouth) are related to changes at NT-0 (Nelson tunnel at the mouth) and SLG-02 (Sugarloaf gulch upstream from Nelson tunnel) because flow from the two sites combines to form most of the flow at SLG-01. At all three sites, zinc concentrations increased after bulkhead emplacement (fig. 2). Before the bulkhead (2006), NT-0 and SLG-01 had near neutral pH and SLG-02 had lower pH (fig. 2). After bulkhead emplacement, the pH at SLG-02 did not change appreciably and pH at NT-0 decreased slightly. These small pH changes do not explain the substantial reduction in pH that occurred at SLG-01. The likely cause of the low pH at the mouth of Sugarloaf Gulch (SLG-01) is the precipitation of iron oxyhydroxides associated with increasing discharge of iron from NT-0 following bulkhead emplacement. At NT-0, concentrations of filtered iron and instantaneous mass loads of filtered iron increased from median values of about 0.9 mg/L and 0.01 kg/d during 2006 to median values of 38 mg/L and 1.1 kg/d during 2010 to 2012, an increase in iron mass load of almost 2 orders of magnitude. At SLG-01, concentrations and instantaneous mass loads of filtered iron changed from median values of about 17 mg/L and 0.2 kg/d during 2006 to median values of 1.4 mg/L and 0.09 kg/d during 2010 to 2012. These comparisons indicate that there were sources of iron mass load to SLG-01 other than Nelson tunnel in 2006 (primarily SLG-02). However, more importantly, the much larger iron mass load contributed from Nelson tunnel during 2010 to 2012 was largely removed from solution by the time the water reached the mouth of Sugarloaf Gulch (SLG-01). This simplified reaction

$$Fe^{3+} + 3\,H_2O \longleftrightarrow Fe(OH)_3 + 3\,H^+ \qquad (1)$$

illustrates how precipitation of iron hydroxides (and by analogy, iron oxyhydroxides) increases acidity (lowers the pH) in solution. This reaction is likely responsible for the loss of iron load and the decrease in pH observed between NT-0 and SLG-01 during 2010 to 2012.

After bulkhead emplacement, zinc concentrations in Nelson tunnel (NT-0) have been increasing and are generally greater than those in Dinero tunnel (fig. 2). The Dinero tunnel lies within the ridge between Sugarloaf and Little

Sugarloaf Gulches (fig. 1). The Nelson tunnel is driven into the next ridge to the south, in a west/northwest direction, generally away from the Dinero tunnel (fig. 1). It is not readily apparent how water from the mine pool in the ridge between Sugarloaf and Little Sugarloaf Gulches could move into Nelson tunnel without also causing drastically increased flow in Sugarloaf Gulch. However, Fig. 1 illustrates the configuration of mineral-bearing veins relative to Nelson and Dinero tunnels. The vein at the west end of Nelson tunnel runs directly to Dinero tunnel. We hypothesize that this vein facilitates water flow between the Dinero mine pool and the Nelson tunnel. The decreased water quality at Nelson tunnel could be due to increased groundwater flow along this vein after bulkhead emplacement and subsequent raising of the water table.

If Dinero tunnel water is causing the increased zinc concentrations at Nelson tunnel, we might expect the concentrations to be similar to, or less than, those in Dinero. For example, a new seep that emerged in Little Sugarloaf Gulch starting in September 2011 (LSGS-10, fig. 1) is fairly close to Dinero tunnel and has water quality almost identical to Dinero water collected at the same time. It is likely that water flowing to Nelson tunnel encounters soluble, metal-rich salts within the mineralized vein, or that the introduction of water to parts of the vein that previously were dry is fueling acid-mine drainage reactions, dissolving more minerals, and increasing zinc concentrations relative to those at Dinero tunnel. Similarly, at other sites showing greater zinc concentrations than Dinero (LSG-0, SLG-02, fig. 2) it is likely that the elevated water table dissolves soluble, acidic salts or fuels acid-mine drainage reactions in newly wetted, previously dry portions of the aquifer.

Implications

These findings suggest that although the Dinero bulkhead has improved downstream water quality in Lake Fork Creek, water quality has degraded in the gulches adjacent to the ridge containing Dinero tunnel, and in Nelson tunnel. The low pH, zinc-rich water that now occurs at the mouth of Sugarloaf Gulch is flowing into a wetland that exists between Dinero tunnel and Lake Fork Creek (fig. 1). This wetland is mitigating the effects of the poor-quality water, but it is not known if this poor-quality water will eventually break through to Lake Fork Creek. The elevated zinc loads at LF-580 in June 2011 (table 1) may indicate that breakthrough occurs during unusual high-flow periods. Continued monitoring may indicate if the increasing zinc concentrations observed at several locations (fig. 2) eventually level off, or even decrease. Continued monitoring would also indicate whether water-quality improvement in Lake Fork Creek continues, or if the low-pH, zinc-rich water eventually breaks through to the creek causing renewed water-quality degradation.

Summary and Conclusions

Bulkhead emplacement in Dinero tunnel in 2009 generally resulted in improved water-quality from 2010 to 2012 at the portal of Dinero tunnel (DT-0), in the main source of water draining the area near Dinero tunnel into Lake Fork Creek (site LF-537), and in Lake Fork Creek downstream from the Dinero tunnel area (site LF-580). Although water quality improved at these sites, water quality has degraded (increasing zinc concentrations or decreasing pH, or both) at the mouths of Sugarloaf Gulch (SLG-01) and Little Sugarloaf Gulch (LSG-0), which are adjacent to Dinero tunnel, and in Nelson tunnel (NT-0). In addition, after bulkhead emplacement, increased flow was noted during low-flow periods in Sugarloaf Gulch and Little Sugarloaf Gulch, indicating increased groundwater discharge to the gulches. These post-bulkhead changes suggest that the mine pool formed by emplacement of the Dinero tunnel is discharging into the two gulches and degrading water quality. Decreased pH at the mouth of Sugarloaf Gulch is likely caused by precipitation of iron oxyhydroxides associated with increasing discharge of iron from Nelson tunnel following bulkhead emplacement. Water-quality degradation in Nelson tunnel is likely due to transport of mine-pool water along mineralized veins that directly link Dinero and Nelson tunnels. Additional monitoring will help assess if water quality continues to degrade in the areas adjacent to Dinero tunnel, and if the water-quality improvements in Lake Fork Creek downstream from the Dinero area continue or are negated by the breakthrough of low pH, zinc-rich water through the Dinero wetland area.

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