Opportunities to Improve Water Quality during Abandoned Mine-Tunnel Reclamation

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Abstract

In the western United States, bulkheads are constructed to limit drainage from abandoned, draining mine adits and to protect downstream resources from uncontrolled releases of degraded adit water. Although bulkheads improve safety and water-quality conditions at the mouth of the adit, elevated hydraulic pressure behind the bulkhead often causes continuing water-quality problems in new locations. Solutions to improve water-quality outcomes from bulkheads might include in situ or ex situ passive or active treatment of mine-pool water or continuing tunnel drainage, in situ treatment of groundwater plumes resulting from bulkhead emplacement, direct extraction of metals from mine water, or bactericide application.

Keywords: Mine Tunnels, Passive Remediation, Bulkheads, Reclamation, Legacy Mine Lands

Introduction

Current (2022) trends toward greater use of high technology and renewable energy sources are driving exploration and mining for rare and critical commodities that sustain these technologies. Against increased exploration and mining pressure stands the legacy of contamination on mine lands largely abandoned before the advent of modern regulations. Increased mining activity may benefit from more sustainable mining and reclamation practices applied to former mined lands.

Reclamation of abandoned mine lands presents multiple challenges including funding, liability concerns, limits of available technology, remote location of some sites, and gaps in comprehensive understanding of which waste sources contribute the most to ecosystem degradation; and therefore, most warrant cleanup. Some of these issues are beyond science (funding and liability concerns). However, progress on other issues is possible through scientific investigation and engineering solutions. Some of the most lingering and vexing challenges of reclamation are contamination to waterways and ecosystems from mine-influenced water (MIW), including drainage from abandoned mine tunnels and seepage from mine waste and tailings.

The objective of this paper is to review recent examples of the reclamation strategy of using bulkheads to improve water quality from draining mine tunnels in the western United States. In addition, we explore techniques to potentially improve the water-quality outcome of this strategy.

Bulkhead installations to improve water quality

Reclamation of draining mine tunnels using bulkheads is designed to improve water quality by limiting drainage of poor-quality water from the bulkheaded tunnel, and secondarily, by submerging remaining sulfides under water in open mine workings, which limits exposure of sulfides to oxygen and, theoretically, generation of MIW. Bulkheads generally improve safety by protecting infrastructure and downstream ecosystems from the effects of tunnel blowouts which are uncontrolled releases of water and sediment from underground mine workings, for example the 2015 Gold King mine release in Colorado, USA (U.S. Department of Interior, Bureau of Reclamation 2016). However, examples from bulkheads installed at Cement Creek, Dinero Tunnel, Captain Jack Mine, and Golinsky mine (fig. 1) indicate the water-quality effects are mixed.

Cement Creek, Silverton, Colorado

Problem

Cement Creek is tributary to the Animas River in southwestern Colorado, USA. From the early 1870s through 1991, extensive mining in over 60 km of mine tunnels recovered silver, lead, zinc, copper, and gold from polymetallic veins (Church 2007; Church *et al.* 2007). Cement Creek has low pH (as low as 3.2) and elevated metal concentrations (Cu, up to about 0.15 mg/L; Mn, up to about 3 mg/L; Zn, up to about 1.7 mg/L) (fig. 5, Walton-Day *et al.* 2021) resulting from acid mine drainage and acid rock drainage from extensive hydrothermal alteration (Church 2007).

Strategy and Results

Extensive reclamation to improve water quality in Cement Creek has targeted both solid mine waste and mine drainage and includes limited periods of active water treatment. Numerous bulkheads have been installed in draining mine tunnels to improve mine tunnel and downstream water quality. Bulkhead closure coincided with and likely caused increased drainage of poor-quality water from other, non-bulkheaded tunnels resulting in little to no substantial or long-lasting water-quality improvement in Cement Creek (Petach *et al.* 2021; Walton-Day *et al.* 2021). Additional bulkheads are planned in the area. Water quality could improve after all bulkheads are emplaced, and/or through time, as slowly rising water levels might submerge and retard oxidation of sulfide minerals.

Dinero Tunnel, Leadville, Colorado

Problem

Mining of silver, gold, lead, and zinc occurred at the Dinero Tunnel in the Sugarloaf mining district near Leadville, Colorado, USA from the 1880s until the 1920s. The Dinero tunnel was driven to drain overlying mine workings and prior to reclamation discharged up to 7.4 × 10^{-3} m^3/s of water having near neutral pH

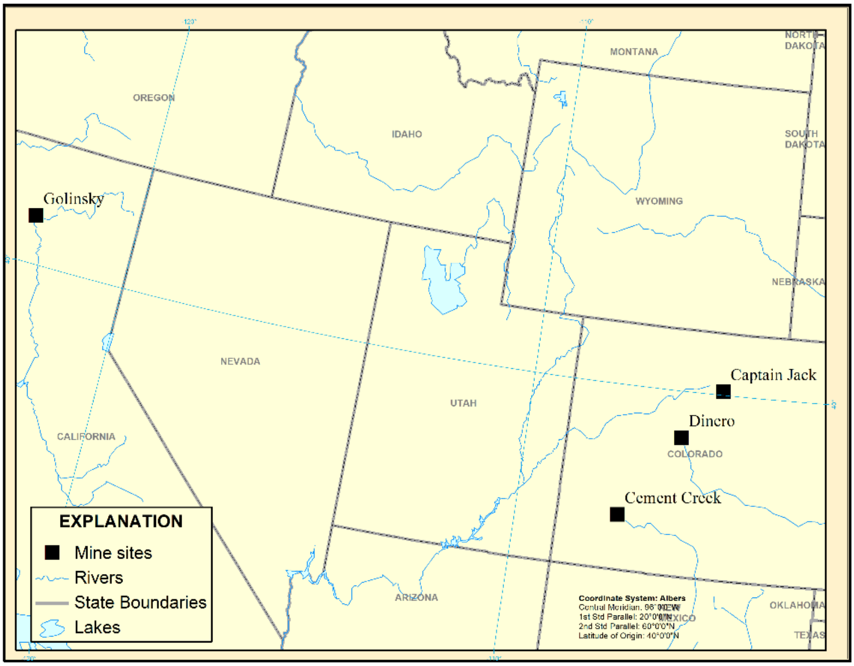

Figure 1 Map showing locations of Cement Creek, Dinero Tunnel, Captain Jack, and Golinsky mines in the western United States

and elevated dissolved concentrations of Mn (up to almost 70 mg/L) and Zn (up to almost 35 mg/L). Tunnel discharge negatively affects downstream water quality (Walton-Day and Mills 2015; Walton-Day *et al.* 2021)

Strategy and Results

A bulkhead constructed and sealed in Dinero Tunnel in 2009 resulted in mixed water-quality responses. Between 2010 and 2017, at Dinero tunnel portal significant ($p<0.05$) decreases occurred for mean discharge (85%) and dissolved Mn (73%) and Zn (96%) concentrations (Walton-Day *et al.*, 2021). However, compared to pre-bulkhead conditions, water quality degraded at a nearby draining adit and in two creeks adjacent to Dinero tunnel. Downstream, mean dissolved Mn concentrations significantly ($p<0.05$) decreased after bulkhead installation, but Zn concentrations did not significantly improve (Walton-Day *et al.* 2021).

Captain Jack Mine, Ward, Colorado

Problem

Historical mining (1860s through 1992) at the Captain Jack Superfund site near Ward, Colorado, USA drove multiple intersecting tunnels into the subsurface to exploit precious and base metal mineralization hosted in Tertiary igneous dikes. The Big Five adit draining the mine workings has low pH (as low as 2.5) and elevated metal and sulfate concentrations (Cu, up to as much as 5 mg/L; SO_4, up to as much as 750 mg/L; Zn, up to almost 3 mg/L) (Newman 2022). Adit drainage negatively affects downstream aquatic ecosystems (Colorado Department of Public Health and Environment and U.S. Environmental Protection Agency 2020).

Strategy and Results

Reclamation at the Captain Jack site included emplacement of a bulkhead and completion of multiple boreholes along and adjacent to the strike of mine workings to monitor the mine pool and adjacent groundwater. As well, an active treatment system was installed that, upon bulkhead closure, captures mine pool water, amends it with lime and organic materials, and reinjects the treated mine water back into the mine pool through a borehole upgradient from the bulkhead (Colorado Department of Public Health and Environment and U.S. Environmental Protection Agency 2019 and 2020).

After initial bulkhead closure in May 2018, and for approximately 18 months, pH decreased and metal and sulfate concentrations increased substantially (pH, down to as low as 1.5; Cu, up to as much as 56 mg/L; SO_4, up to as much as 5,300 mg/L; Zn, up to as much as 142 mg/L) (Newman 2022), possibly indicating dissolution of large amounts of efflorescent sulfate salts within the mine workings similar to that shown by Gyzl and Banks (2007) in coal mines. In addition, water-level monitoring indicated that the water was not seeping into the adjacent aquifer as had been expected, and available storage within the workings was decreasing more quickly than expected, raising concerns about uncontrolled discharges from boreholes drilled into the mine workings (Colorado Department of Public Health and Environment and U.S. Environmental Protection Agency 2019). Therefore, the bulkhead was partially opened in September 2018 which caused a fish kill downstream (Colorado Department of Public Health and Environment and U.S. Environmental Protection Agency 2019). Following additional site construction, the bulkhead was re-closed in September 2020. The second bulkheading closure was designed to submerge the acid- generating minerals and inhibit pyrite oxidation and is combined with active treatment to limit acid mine drainage (Colorado Department of Public Health and Environment and U.S. Environmental Protection Agency 2020).

Golinsky Mine, Shasta Lake, California

Problem

The Golinsky mine complex drains to a creek that is tributary to Shasta Lake in California, USA. The mine was last active in the early 1900s when copper, zinc, and minor amounts of precious metals were recovered. A lower portal discharged up to about 6.7×10^{-4} m^3/s of acidic MIW; whereas an upper portal was dry. The Golinsky MIW exhibited elevated concentrations of aluminum (31mg/L), cadmium (0.73 mg/L), copper (14 mg/L), iron (27 mg/L), manganese (0.42 mg/L), and zinc (67 mg/L) (Gusek *et al*. 2011). Another adit (Portal 3), about 100 m away which had no known direct connections to the Golinsky, discharged pH-neutral water having trace amounts of the Golinsky Mine metal suite (Gusek *et al.* 2011).

Concrete bulkheads were installed in the upper and lower portals of the Golinsky Mine in 2001 with the goals that the resulting mine pool (about 1,440 m^3) would submerge the sulfide/pyrite in the mine workings, stop sulfide weathering and acidification, and the resulting improved mine pool water would disperse into the surrounding rock mass (Gusek *et al*. 2011). Unfortunately, in the wet season, the MIW behind the lower bulkhead bled off through fractures. In the dry season, MIW leaked around the bulkhead. The mine pool elevation never rose to the upper portal bulkhead. Water quality in the nearby "clean" Portal 3 deteriorated into acidic MIW (Gusek *et al*. 2011).

Strategy and Results

Bench and pilot testing of biochemical reactor (BCR) technology revealed that the acidic MIW could be treated to acceptable standards and discharged (Gusek *et al*. 2005). A 4 L/min pilot-scale BCR was constructed about 2.4 km from the lower portal. A pipeline transported MIW from behind the bulkheads into the pilot BCR for about two years. Consequently, the mine pool behind the lower portal bulkhead was lowered. A full scale BCR was constructed in 2010.

Once the Golinsky Mine pool was drained (starting in 2004), Portal 3 MIW water quality improved. Over about five years, Portal 3 pH values rebounded to near neutral and metal concentrations decreased. Coupled discharge measurements and water-quality data were used to estimate that only 264 to 442 mL/min of MIW "leakage" (through fractures) from the Golinsky Mine pool was needed to account for the metal loading in the Portal 3 MIW (Gusek *et al*. 2011).

Techniques to further improve water quality from bulkheaded mine tunnels

The previous examples indicate that water-quality improvement after bulkhead emplacement is not guaranteed. However, due to improved safety after bulkhead emplacement, it may be advantageous to layer additional techniques onto bulkhead installation to improve water-quality outcomes. Additional strategies include passive and active treatment in situ in mine pools (e.g. Captain Jack) and ex situ in continuing tunnel drainage (e.g. Golinsky mine).

Multiple reviews and guidelines outline potential treatment techniques for MIW (e.g. Interstate Technology Regulatory Council 2013; Skousen *et al*. 2017). Techniques range from traditional active technologies that utilize acid neutralization to remove iron and other metals through mineral precipitation and sorption, to other active technologies that remove sulfide minerals (e.g. BioteQ Environmental Technologies, Inc. 2007; Interstate Technology Regulatory Council 2010a), to passive technologies that remove metals and metalloids through either oxidation/mineral precipitation/sorption or reduction/mineral precipitation (such as sulfate-reducing bioreactors, SRBs, or more generally, BCRs). Readers are referred to the references cited herein for more information.

In situ treatment of mine pool backed up behind the bulkhead

One example of in situ mine pool passive treatment is the Lilly mine in Montana, USA, where platforms of organic material were placed into the mine pool to initiate sulfate-reducing conditions. The system exhibited water-quality improvement for at least 10 years. However, a secondary oxidizing treatment system was recommended for the tunnel portal to further improve water quality (Foote *et al*. 2007). Biochemical reactor technologies are being used in situ in the mine pool to improve water quality at a flooded underground uranium mine in Colorado. Active treatment follows the in situ treatment to achieve water-quality goals. However, pilot-scale passive and semi-passive bioreactors and constructed wetland treatment systems are being investigated as lower cost, long-term alternatives to active treatment (Gault *et al*. 2022).

At Dinero tunnel, ongoing work includes drilling into the mine pool behind the bulkhead to collect water-quality samples for bench-scale testing of passive treatment technologies to investigate feasibility of in situ passive mine-pool treatment. Similar to the other passive treatment examples reported herein, passive treatment at Dinero tunnel would likely utilize sulfate reduction to take advantage of low oxygen conditions in the flooded mine workings.

The active in situ treatment system previously described for the Captain Jack site is the only example that could be identified. Such systems are generally more expensive and maintenance intensive than passive treatment, though they might be advantageous when passive treatment is not an option and water-quality improvement is desired or legally required to protect important downstream ecosystems or infrastructure, such as drinking water intakes.

Ex situ treatment of tunnel drainage

The BCR at the Golinsky mine is an example of a functioning ex situ mine drainage treatment system. Multiple examples of ex situ passive treatment systems for coal mine drainage exist in the eastern United States where Skousen and Ziemkiewicz (2005) report on design and performance of 116 individual treatment systems. Examples of ex situ treatment of drainage from metal mines in the western United States are limited. Some sites of note include a 4.5 m^3/min system at the Empire Mine State Historic Park in California that is treating iron, arsenic, and manganese, and two smaller systems that include BCR components in the Basin Creek Superfund Site in Montana. There is potential for more applications of this technique, where site, mine drainage, and climate characteristics favor successful implementation. High altitude, steep terrain, low pH of mine drainage, and harsh winter conditions at many sites likely limit widespread implementation of ex situ passive techniques.

Active treatment of tunnel drainage is fairly common in metal mines in the western United States. These active treatment plants primarily utilize acid neutralization that promotes formation of iron flocculent material with sorption of other metals onto the iron substrate. A few examples are the Argo tunnel and North Fork Clear Creek in Colorado (Interstate Technology Regulatory Council 2010b; Colorado Department of Public Health and Environment and U.S. Environmental Protection Agency 2015), continuing operations for the Gold King mine drainage in Colorado (U.S. Environmental Protection Agency 2018), and ongoing treatment at the Iron Mountain mine site in California (Jacobs *et al.* 2016). The Wellington-Oro plant near Breckenridge Colorado treats mine drainage and produces a sludge containing zinc and cadmium sulfides that can be extracted at smelters, when the market permits, or disposed as non-hazardous waste (Interstate Technology Regulatory Council, 2010a)

Other possible reclamation strategies

Additional techniques that might enhance water quality where bulkheads have been emplaced include groundwater treatment, extraction of metals from acid mine drainage, and bactericides. For the first technique, if localized groundwater plumes exist that resulted from bulkhead emplacement, for example in steep valleys, it might be possible to install permeable reactive barriers (Benner *et al.* 1999) to improve downstream water quality. Emerging research continues to investigate techniques to recover metals, particularly Rare Earth Elements from acid mine drainage (e.g. Mwema *et al.* 2022). The use of bactericides to suppress pyrite oxidation, is being reconsidered in the light of 21st century technological advancements (Gusek 2018).

Summary

Case studies presented herein demonstrate limited water-quality improvement after reclamation of draining mine tunnels using bulkheads. There is potential to augment bulkhead installation with additional passive and active techniques, both in situ and ex situ, to further improve water quality and take advantage of the safety improvements afforded by bulkheads. Ideally, design of new bulkheads might consider the potential for additional water treatment, though addition of such techniques to existing bulkhead locations is also possible, given favorable site conditions.

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