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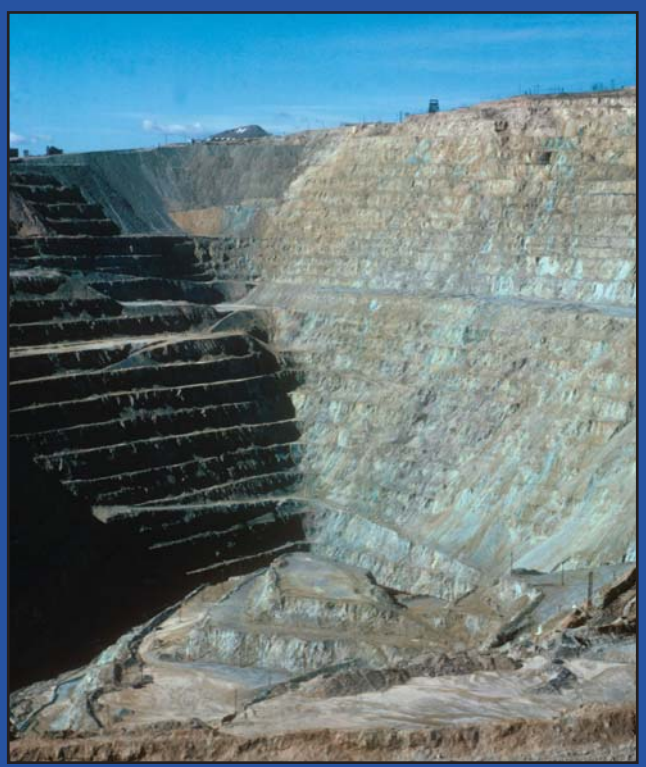

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MBMG
Montana Bureau of Mines and Geology

Cover Photos: Top, Berkeley Pit looking west towards the “Big M,” 1983. Bottom, Berkeley Pit looking southwest, “Big M” in the upper right, 2017. Photos by Ted Duaime, MBMG.

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ABSTRACT

This report provides a history of the activities related to the filling of the Berkeley Pit, lists changes in water sampling and monitoring techniques, and discusses the physical and chemical changes observed over the past 35 years.

Butte is located in southwest Montana, on the west side of the Continental Divide at the headwaters of the Clark Fork River. The city sits at an elevation of over 1 mile above sea level on a Cretaceous-age batholith that hosts a world-renowned porphyry–copper deposit. Selective underground mining was the main mining method through the 1940s, when The Anaconda Mining Company decided to explore other mining methods, such as block cave and open-pit. The Berkeley Pit began operation in 1955. The Anaconda Mining Company shut off the underground mine dewatering pumps located on the 3900 level of the Kelley Mine in April 1982, ceased operation of the Berkeley Pit 1 month later, and suspended its entire Butte mining operation in June 1983. The suspension of underground mine dewatering led to the flooding of the underground mines and filling of the Berkeley Pit. The surface water flows and ponds associated with other mine operations were diverted to the Berkeley Pit for disposal and containment. Both the underground mine waters and surface waters were acidic (low pH), with high concentrations of many metals, i.e., arsenic, iron, aluminum, cadmium, copper, and zinc. The 1983 inclusion of Silver Bow Creek and the historic Butte mining complex on the Environmental Protection Agency Superfund list drew attention to the flooding underground mines and Berkeley Pit and the potential environmental consequences related to the heavy-metal-laden water.

The Montana Bureau of Mines and Geology began sporadic sampling of water quality in the Berkeley Pit in 1984. Routine monitoring began on a semi-annual basis with the signing of the Consent Decree for the Butte Mine Flooding Operable Unit in 2002. Changes in monitoring techniques in subsequent years have improved tracking of the significant changes in the chemistry of the water. Further obstacles, such as hazards associated with potential landslides, have been overcome with the adoption of modern technology. These data demonstrate the geochemical evolution of the Berkeley Pit Lake and the importance of the ongoing, long-term monitoring program.

1.0 INTRODUCTION

A labyrinth of horizontal haulage ways, drifts, and stopes, some of which extended over 1 mi below ground surface, underlies the "Butte Hill" (fig. 1). These workings contain an elaborate network of interconnections designed to provide air for the miners and to drain groundwater to keep the workings relatively dry. As mine workings deepened, more water was encountered, and the Anaconda Mining Company (AMC) began interconnecting underground mine workings. As early as 1901, water was routed to central pump stations, where the water was collected and pumped to the surface. Unpublished AMC records identify the existence of 517 mines on the Butte Hill, 85 that were greater than 1,000 ft deep and 27 that were more than 3,000 ft deep. Metal production from the underground mines and open-pit mining in Butte was significant by any comparison. From 1880 through 2017, more than 23 billion pounds of copper was produced (table 1; Walsh, 2018).

Table 1. Butte mining district—historical metal production.

Metal	Total Produced 1880–2017
Copper*	23,826,373,953 lbs.
Zinc	4,909,202,540 lbs.
Manganese	3,702,787,341 lbs.
Lead	854,797,405 lbs.
Molybdenum	452,058,007 lbs.
Silver	734,622,679 oz.
Gold	2,922,889 oz.

*Accumulated production includes precipitated copper. Data provided by Mr. Stephen F. Walsh, Senior VP-Operations, Montana Resources (2018).

Figure 1. Underground miners in the Mountain Con Mine indicating mine workings were 1 mi deep.

AMC suspended dewatering of its underground mine operations at midnight, April 22, 1982, and announced they would suspend operations in the Berkeley Pit during May 1982. The suspension of underground mine dewatering ended almost a century of pumping groundwater from the mines that dotted the Butte Hill landscape. This announcement meant that groundwater collected in the thousands of miles of underground mine workings and diverted to the Kelley Mine pump station would begin to rise.

The decision to suspend pumping was based upon the economic cost of pumping, approximately $10 million a year, and the depressed state of the metals market (AMC, 1982). Early estimates by AMC were that it would take at least 1 year for the water level in the underground mines to reach the sump elevation of 4,263 ft (USGS datum) in the Berkeley Pit. The AMC had flooded the lower mine workings about 5 months earlier, with water rising to the 3900 level (about an 800 ft rise) in about 114 days. Based upon their estimate that the pit open area was 20 times larger than that of the underground workings, they suggested it would take at least 20 years for water levels in the pit to equilibrate with local groundwater. The AMC developed a long-term program to monitor the rate of rise in the underground mines, Berkeley Pit, and surrounding alluvial groundwater system. The program was submitted to the Montana Department of State Lands, Hardrock Bureau, for approval and oversight. [Under a governmental reorganization, the Montana Department of State Lands Hardrock Bureau became a part of the Montana Department of Environmental Quality (DEQ) in 1996.] Approved in 1982, the program included monitoring underground mines, the Berkeley Pit, and a number of existing and newly installed alluvial groundwater monitoring wells.

Monitoring activities consisted of measuring static water levels and collection of water-quality samples for chemical analysis.

The AMC continued to operate the East Berkeley Pit through June 1983, at which time they suspended all Butte mining operations. The AMC and its parent company, Atlantic Richfield Company (AR), which had bought the AMC in 1977, sold a portion of its Butte properties to Dennis Washington in 1985. Mr. Washington subsequently formed Montana Resources (MR), re-opened the East Berkeley Pit and Butte concentrator facilities, and began open-pit mining in July 1986. MR renamed the East Berkeley the Continental Pit; the names are used interchangeably in this report.

The Montana Bureau of Mines and Geology (MBMG) received funding from the 1983 Montana Legislature (House Bill 819) to implement a supplemental groundwater and seismic monitoring network in response to concerns about potential impacts to local property from groundwater rebound and its potential to trigger local seismic events (earthquakes). The MBMG installed a number of shallow alluvial groundwater monitoring wells and, in cooperation with the United States Geological Survey (USGS), installed stream gauging stations on Blacktail Creek and Silver Bow Creek.

In 1980, just prior to the suspension of mining in Butte, the United States Congress passed the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), known as Superfund, and authorized the United States Environmental Protection Agency (EPA) to implement it. The EPA added the Silver Bow Creek/Butte Area Superfund site to the CERCLA National Priorities List in September 1983; this site included contaminated groundwater in Butte's underground mine workings, the Berkeley Pit, and contaminated groundwater flowing towards the Berkeley Pit. The Butte Mine Flooding Operable Unit (BMFOU) Superfund investigation, Remedial Investigation/Feasibility Study (RI/FS), was conducted by the EPA from 1990 to 1994. Upon completion of the RI/FS in 1994, the EPA, with concurrence from DEQ, issued a Record of Decision (ROD; EPA, 1994). Major components of the ROD were: (1) long-term, continued monitoring and sampling of groundwater and surface water, (2) diversion of the Horseshoe Bend Drainage (HSB) water away from the Berkeley Pit (to slow the pit-water filling rate), (3) incorporation of the HSB water in the MR mining operations for treatment, (4) construction of a water-treatment plant if changes in mining operations prevented treatment of HSB water (e.g., mine shutdown), and (5) establishment of a maximum water level to which water in the underground mines and Berkeley Pit could rise before a pumpage/treatment plant must be built and in operation.

In 2002 the EPA and DEQ reached a settlement, referred to as a Consent Decree (CD; EPA, 2002), with a number of the potentially responsible parties for the BMFOU. Semi-annual sampling of the Berkeley Pit and vertical profiling of the pit were formally added to the long-term monitoring program. Prior to the 2002 CD, water sampling and profiling of the Berkeley Pit was performed sporadically, as access allowed or as part of the RI/FS study. Semi-annual water sampling and monitoring of the Berkeley Pit occurred from 2002 through 2012. A series of landslides in the southeast corner of the Berkeley Pit in 2012 and 2013 resulted in a suspension of monitoring activities. Monitoring resumed in 2017 with advancements in sampling and monitoring methods. The MBMG has sampled Berkeley Pit water over 65 times from 1984 through 2017, with over 260 water samples collected and analyzed for inorganic analytes.

Table 2 presents a timeline of operational changes and significant issues from 1982 through 2017 that may have affected Berkeley Pit water quality. Additionally, there were several periods during which waste rock from the Continental Pit was disposed of in the Berkeley Pit. Although exact dates of these were not recorded, the first occurrence followed the resumption of mining in 1986 and continued for a year or more. MR also disposed of waste rock in the southeast corner of the pit following the 1998 landslide in an attempt to buttress the landslide area.

1.1 Methods

The overriding purpose of this report is to document changes in sampling and monitoring procedures that may have played a role in the consistency of the data collected and changes in mine operations that could have caused variations in pit chemistry over the 35 years of data collection. Complete analytical results for samples referenced in this report are available from the MBMG online Groundwater Information Center (GWIC) at the following location: http://mbmggwic.mtech.edu/sqlserver/v11/data/dataProject.asp?project=MINEFLO-ACTIVE-ECBED&datatype=well&.

Table 2. Timeline for operational changes and natural occurrences that may have influenced Berkeley Pit water quality, 1982–2017.

Date	Event	Significance
April 1982	AMC discontinued operation of Kelley Mine pump station.	Water levels in Butte underground mines began to rise.
July 1983	AMC suspended all Butte mining activities.	Water from East Berkeley mine operations diverted to Berkeley Pit.
July 1983–April 1996	Horseshoe Bend Drainage water, water from precipitation plant and leach pad ponds diverted to Berkeley Pit.	Increased pit water-level filling rate.
July 1986	MR began mining in the Continental Pit and milling operations in the Butte concentrator.	East Berkeley (Continental Pit) water diverted away from Berkeley Pit for use in mining operations. Decreased the amount of water entering the pit, slightly reducing filling rate.
April 1996	Horseshoe Bend drainage water diverted away from the Berkeley Pit and pumped to the Yankee Doodle Tailings Dam.	Reduced the rate of rise in the Berkeley Pit, underground mine workings, and surrounding bedrock aquifer, by diverting between 3.0 and 3.5 million gallons of water per day away from the pit.
August 1998	MR began pumping water from the Berkeley Pit for copper recovery.	Water discharged back into the pit after copper recovery in the precipitation plant; high iron concentration in return water.
September 1998	Large landslide occurred in the southeast corner of the Berkeley Pit.	An estimated 1.3 million cubic yards of material entered the pit, resulting in a 2.5 ft water level rise. Wave action in pit damaged the MBMG sample platform, washing it up on a mine bench on west side of pit.
June 30, 2000	MR suspended mine operations.	Horseshoe Bend water diverted back into Berkeley Pit, resulting in an additional 3 million gallons a day or more water filling the pit. Increased monthly water-level rise in pit, underground mine system, and associated bedrock aquifer.
July 2000-February 2001	Water from Continental Pit pumped to Berkeley Pit.	Slight increase seen in filling rate (flows ranged from 200 to 285 gpm). Near neutral pH and relative low metal concentrations.

Table 2—*Continued.*

Date	Event	Significance
November 2003	MR resumed mining in Continental Pit. Horseshoe Bend water treatment plant comes online.	Horseshoe Bend water diverted away from pit and to water treatment plant; treated water used in mine operations. Sludge from plant discharged to pit. Slowed filling rate by reducing 3 million gallons per day of water from pit.
January 2004	MR resumed Berkeley Pit copper recovery project.	Water discharged back into the pit after copper recovery in the precipitation plant; high iron concentration in return water.
August 2012	Minor landslide occurred in southeast corner of Berkeley Pit.	No effect seen on pit water levels.
November 2012	Minor landslide occurred in southeast corner of Berkeley Pit.	Pontoon boat and boat dock received minor damage; boat removed for repairs. Fall Berkeley Pit sampling event canceled.
February 2013	Relatively large landslide occurred in southeast corner of Berkeley Pit.	Estimated that 0.45 million cubic yards of material entered the pit, resulting in about a 1 ft water-level rise. Wave action in pit damaged copper recovery pipeline. Copper recovery operation suspended.
February 2013–April 2017	Safety concerns related to potential pit wall failures caused cancellation of semi-annual Berkeley Pit water sampling activities.	No water quality or profiling performed in Berkeley Pit.
May 2017	MBMG/Montana Tech drone boat used for Berkeley Pit sampling/monitoring.	Semi-annual sampling/monitoring schedule resumed. Physical parameter monitoring and water-quality data reveal significant changes in water pH and iron concentrations when compared to previous pit samples.

While changes in sampling and monitoring procedures are described further later in this report, field and laboratory practices generally followed a set of standard procedures. All water-quality results presented are for the dissolved fraction and were filtered in the field using a 0.45-µm filter and preserved with 1% $HN0_3$ following USGS procedures (USGS, 1970). Sample collection methods varied by sample source. Methods for sampling from the Berkeley Pit, described in detail in subsequent chapters, included the use of point source bailers, vertical samplers, pumps, or grab methods. Other surface-water bodies were sampled with grab methods. Samples collected from subsurface mines relied on a top-fill or point-source bailer, and groundwater was sampled with a submersible pump.

The physical parameter data collected, such as pH, temperature, specific conductance, and oxidation-reduction potential (ORP), are cited as recorded. The ORP, when referenced to the Standard Hydrogen Electrode, is termed Eh, similar to pH.

After the adoption of Hydrolab sensors, the reproducibility and accuracy met the manufacturer's specifications. All probes used were temperature compensated with an error of ±0.4°C in temperature measurement. The typical errors associated with electrode measurements are ±0.2 SU for pH and ±10% for specific conductance. Dissolved oxygen has an uncertainty of ±0.6 mg/L and turbidity has an error of ±10% of the reading (Snazelle, 2017).

Water-level monitoring in underground mines during the early years of mine flooding necessitated tagging depths up to 4,000 ft below surface. A mechanical tugger (winch) was used for depths exceeding 1,000 ft. The cable was marked every 50 ft and a cloth tape was attached to the cable to determine approximate depth to water. Measurements were recorded to the hundredth of a foot; however, due to potential cable stretch and floating timbers on the water surface, measurement accuracy typically varied within 1–2 ft. Measurements in mine shafts and monitoring wells where the depth to water was less than 1,000 ft were collected with a standard water-level indicator (i.e., Solinst Model 101) and were made to the hundredth of a foot.

Open-channel flow measurements were made using a float and stopwatch during 1984 and 1985 events; subsequent measurements were from flumes or weirs.

Over the years, the sampling had to adapt to the changing conditions inside the pit and the frequency with which samples had to be taken. The volume of water in the pit was a major factor in the method of sampling employed. As of December 31, 2017, the volume of pit water had grown to 47.8 billion gallons (fig. 2).

In the 1984 and 1985 sampling events, the pit was accessed by helicopter because erosion had destroyed overland routes down to the water surface. By 1986, the water-surface elevation had increased sufficiently to allow helicopters to transport boats and personnel to exposed benches, and sampling campaigns were staged from there. In 1991, the volume of pit water had increased to 14.5 billion gallons, and boats and a stable platform were transported via roadway to the shore for sampling events. Sporadic sampling continued in this manner until 1998, when the pit volume had reached 26 billion gallons. Between 1999 and 2012, the volume increased from 27 to 43 billion gallons, and the water surface was easily accessed by road. MR installed copper recovery equipment to pump large volumes of water from the lake and maintained a large pontoon boat. That craft was also used by the MBMG for sampling and collecting depth profiles. Also during this time, a consent decree between the responsible parties and the federal government established a schedule for the MBMG to sample in the pit. Sampling was discontinued following a large landslide in 2013, due to safety concerns. Sampling resumed in 2017 using a remotely controlled drone craft, developed at Montana Tech, to collect samples and depth profiles without a human presence on the lake itself. This method of sampling was initiated when the pit had accumulated 47.2 billion gallons of water, and is likely to continue into the future.

2.0 UNDERGROUND MINING AND BERKELEY PIT DEVELOPMENT AND OPERATION

Butte has a long history of mining, dating back to 1864 with the development of gold placers in Missoula and Dublin gulches and along Silver Bow Creek (Miller, 1973). Placer mining was short-lived and quickly followed in 1866 by the development of silver mining (Miller, 1973). However, with the repeal of the Sherman Silver Purchase Act in 1893, and the presence of high-grade copper veins, Butte mining shifted to the development of copper deposits.

Underground mining expanded as miners followed the rich copper veins. As the mines deepened,

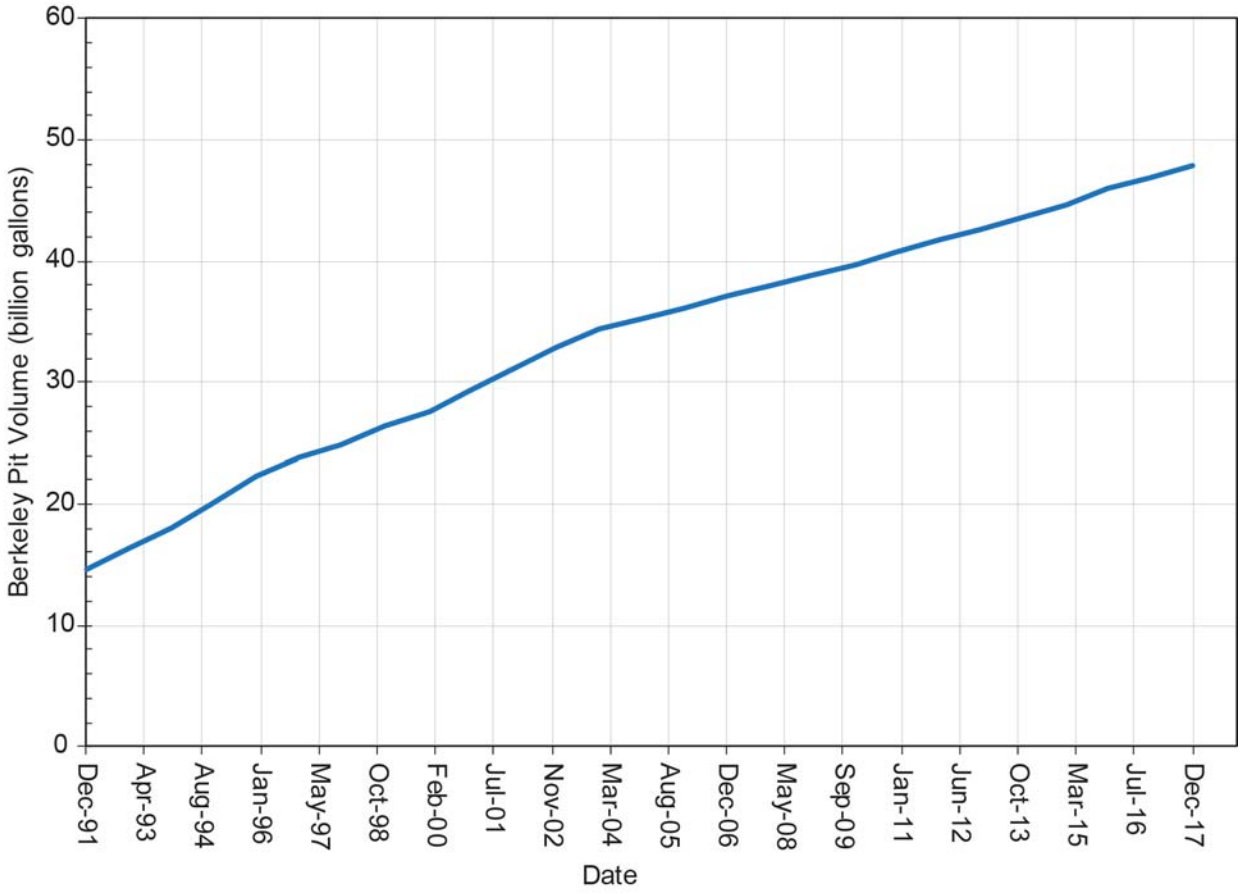


Figure 2. The growth in the volume of water captured by the Berkeley Pit from 1991 through 2017.

groundwater inflow increased, requiring the development of dewatering methods. Mining companies improved dewatering efficiency by interconnecting mines through stopes, drifts, or diamond-drill drainage holes, directing water to central pump stations where it was collected and pumped to the surface (Daly and Berrien, 1923). The first common drain level was the 2800 level, followed by the 3800 level.

The predecessor to the AMC, the Anaconda Copper Mining Company, would eventually acquire a majority of the Butte mines and began interconnecting selected mine levels for this purpose as early as 1901.

Daly and Berrien (1923) reported that up to 28 mines were dewatered through these interconnections. The High Ore Mine served as the central pump station from 1901 until 1967, when the pump station was moved to the Kelley Mine (figs. 3, 4). The acidic and highly mineralized groundwater necessitated specialized pumps and piping. The pumps in the High Ore Mine were made of a phosphor–bronze alloy, whereas the cast iron discharge pipes (water column) were lined with either lead or wood (Febles, 1914). Kelley Mine pumps and discharge lines were stainless steel.

Figure 3. High Ore Mine pump station, 2800 ft level. (Photo courtesy World Museum of Mining, Butte, MT.)

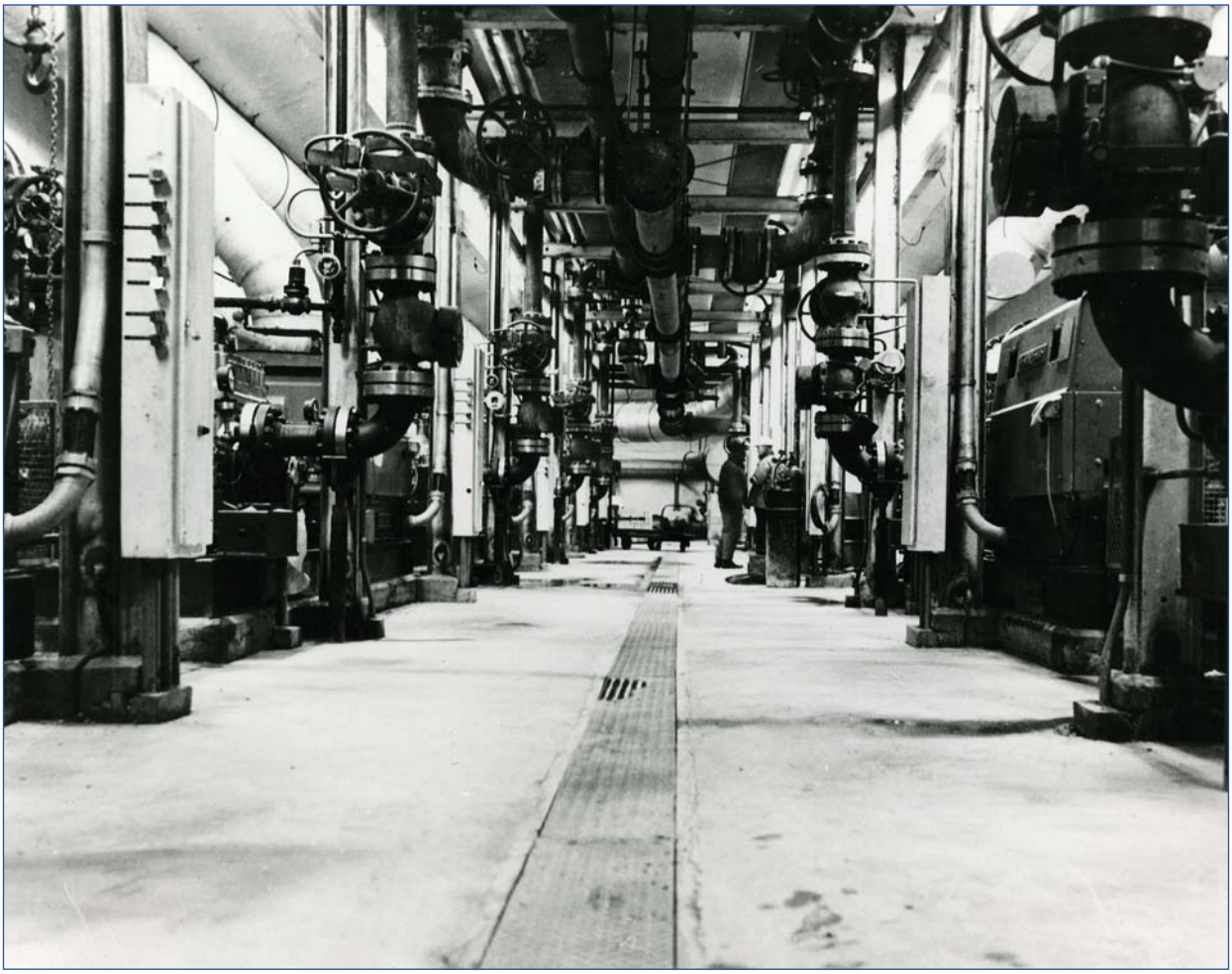


Figure 4. Kelley Mine pump station, 3900 ft level. (Photo courtesy World Museum of Mining, Butte, MT.)

Mine water pumped to the surface was transported by flume to the precipitation plant for recovery of copper (figs. 5, 6). The recovery of copper precipitate from underground mine waters had been a common practice on the Butte Hill since the 1890s (Febles, 1914). The process occurs when copper in solution is passed over scrap iron. The iron goes into solution and the copper precipitates, as shown in equation 1:

$$Fe_{(s)} + Cu^{2+}_{(aq)} \rightarrow Fe^{2+}_{(aq)} + Cu_{(s).} \quad (1)$$

Febles (1914) reported that about 1,200 gallons per minute (gpm) of underground mine water reached the High Ore plant, and from this water approximately 2,200,000 lbs of elemental copper was produced.

The AMC estimated that underground workings on the Butte Hill would extend for a distance of up to 10,000 mi and that the workings included over 42 mi of vertical shafts, and 2,716 mi of other passageways, with the remaining distance made up of stopes (Anaconda Company Trailsman, 1969). MBMG analysis and review of unpublished AMC records found that there were 512 mines (fig. 7) located on the Butte Hill, totaling over 49 mi of vertical shafts and almost 5,600 mi of horizontal workings, supporting previous AMC estimates (Duaime and others, 2004). This entire underground network was dewatered through the interconnection of workings and the central pump stations.

Butte mines produced large quantities of copper (greater than 250,000,000 lbs annually) and the AMC enjoyed high metal prices during World War II; however, following the war metal surpluses led to a reduction in output (~100,000,000 lbs annually; Miller, 1973). With the reduced output and increased operational costs as the mines deepened, the AMC decided to investigate changes to mining techniques. The first change occurred during 1944–1947, when block caving (undermining an ore body and allowing it to progressively collapse under its own weight) was tried in a portion of the Butte Hill; this was followed by larger underground developments above the 1800 level in mines such as the Leonard, Tramway, and West Colusa that demonstrated the existence of large quantities of low-grade copper reserves (Miller,

Figure 5. High Ore Mine and flume carrying underground mine water. (Photo courtesy World Museum of Mining, Butte, MT.)

1973). This block-cave development became known as the Greater Butte Project and operated from 1947 to 1952. This project ultimately led to the installation of the Kelley Mine #1 and #2 shafts, with the #1 shaft designed to haul 15,000 tons of block-cave ore per day from the 2000 level of the district. This mining method operated from April 1952 for 10 years, when it was suspended to avoid problems with slope stability within the Berkeley Pit.

Along with the block-cave mining, an extensive drilling program was undertaken that further identified and mapped out large low-grade ore reserves. Feasibility studies were conducted from 1952 through 1954 that included several test pits in the East Colusa and Skyrme mine localities. These tests determined the viability of open-pit mining, with the stripping of overburden beginning in March 1955 followed by ore production in July 1955, marking the beginning of the Berkeley Pit mine (Miller, 1973). The advent of both block-cave and open-pit mining lowered production costs and increased annual ore production. Open-pit mining allowed the use of large shovels and haul trucks to remove both waste material and ore. As the

Figure 6. Flume carrying underground mine water from High Ore Mine to precipitation plant for recovery of copper. (Photo courtesy World Museum of Mining, Butte, MT.)

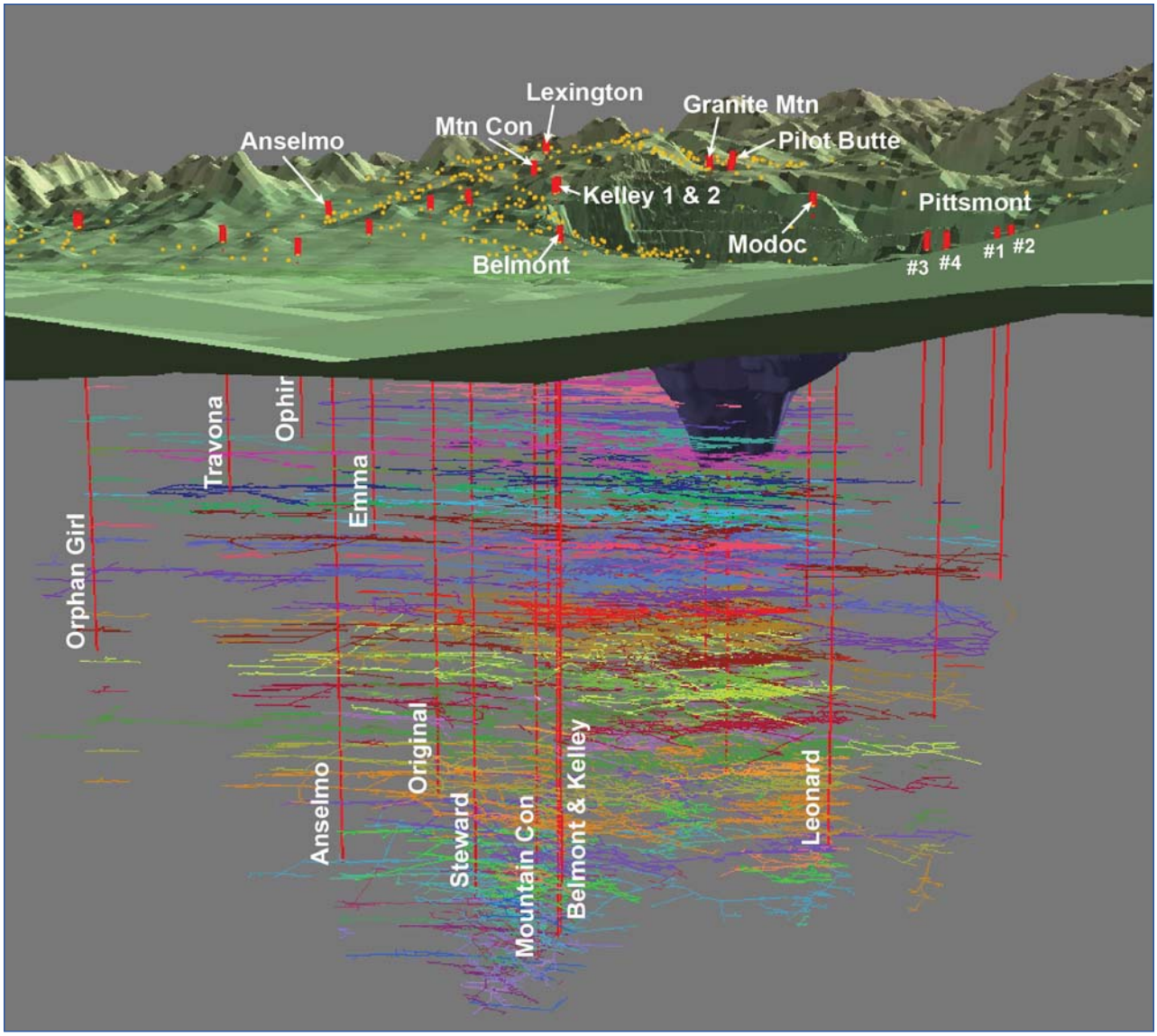


Figure 7. Map showing an oblique view of the land surface with the locations of 512 mines and east–west cross section showing the vertical extent of underground workings on the Butte Hill. The different mine levels are shown in different colors. The workings begin on the 300 level and extend to the 2000 level of the High Ore and other nearby mines. The solid red vertical lines represent selected major shafts, i.e., Orphan Boy and Anselmo shafts to the west (left) and the four Pittsmont shafts to the far east (right). The lateral distance spanned by the shafts is approximately 3.9 mi.

Berkeley Pit expanded, it engulfed many of the important underground mine yards and headframes, such as the Leonard, High Ore, Never Sweat, Anaconda, and East Colusa (fig. 8).

The Berkeley Pit continued to operate until May 1982, when the AMC suspended its operation. At that time, the total depth of the pit measured from its north high wall was 1,680 ft (AMC, 1982) and it extended 1.25 mi in an east–west direction and just over 1 mi in a north–south direction, occupying an area of almost 700 acres. Mapping performed by the MBMG using old AMC underground maps determined Berkeley Pit operations mined through approximately 13% of the total underground mine workings (fig. 9).

The Weed Concentrator was built just to the southeast of the Berkeley Pit to treat ore from the pit, and came online in May 1963. During the 1961–1963 construction period, overburden material from the Berkeley Pit was used to construct the Yankee Doodle Tailings Dam. This dam was used for disposal of mill tailings from the concentrating process (International Engineering Company, IECO, 1981).

Material from the Berkeley Pit that did not meet the required ore grade of 0.45% (Anaconda Company Trailsman, 1969), but had an average grade of 0.25% copper, was considered leach rock and was placed in leach dumps for copper recovery (Miller, 1973). These dumps buttressed the Yankee Doodle Tailings Dam

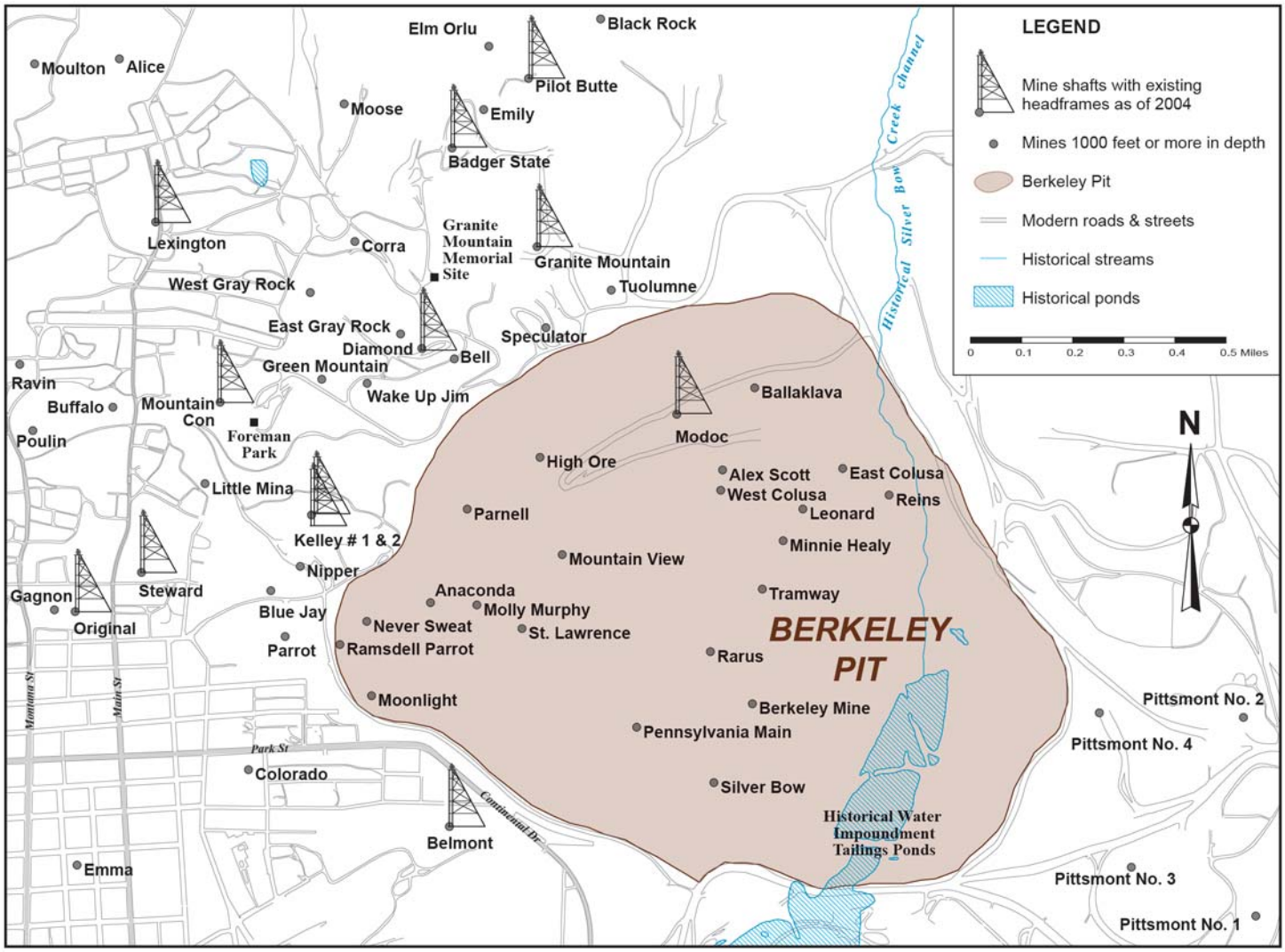


Figure 8. Location of selected underground mines engulfed by development and expansion of the Berkeley Pit.

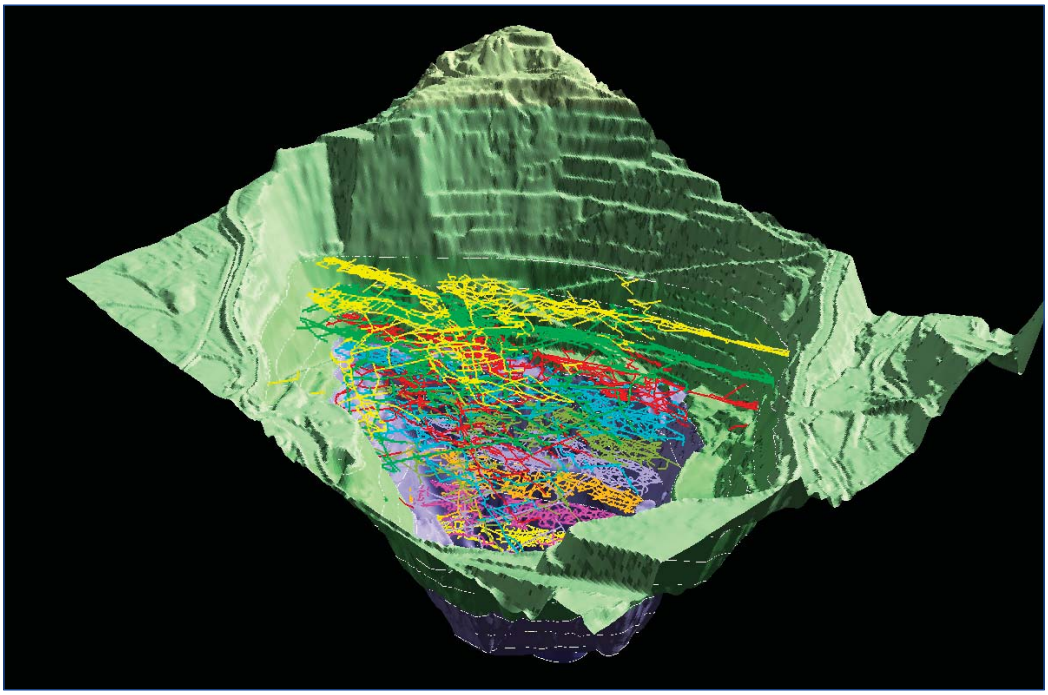


Figure 9. Three-dimensional representation of underground mine workings excavated by Berkeley Pit development and operation. The view is from the southwest corner of the pit looking northeast.

along the east side of the repository (IECO, 1981). Copper was recovered from this material by leaching it with water from the underground mine dewatering operation and recirculated precipitation plant water that had been acidified to a pH of 2.3 or lower.

3.0 SUSPENSION OF MINING AND EARLY FLOODING OF THE BERKELEY PIT AND UNDERGROUND MINES (1982–1984)

3.1 Events during 1982–1984

Underground mine dewatering at the Kelley Mine pump station averaged 5,000 gpm in April 1982, when AMC suspended dewatering. Immediately following this change in operations, water levels in the underground workings began to rise. Initial measurements of water levels made by the AMC in the Kelley Mine showed water levels rose 330 ft in May and an additional 250 ft in June of 1982. [This monitoring program established monitoring locations at a number of mines; however, the Kelley Mine has the most extensive record of water-level measurements. Obstructions in the other mine shafts prevented the measurement of water levels on many occasions (Duaime and others, 1998)]. The variation in the volume of void areas at different levels in the underground workings appeared to control the monthly rate of water-level rise.

AMC suspended operations in the Berkeley Pit in May 1982 and in the East Berkeley Pit by the end of June 1983. With the suspension of mining in the East Berkeley, the Weed Concentrator, precipitation plant, and leach pad operations were also suspended.

A summary of the important events occurring during this period is given in table 3.

3.2 Sources of Water Diverted to the Berkeley Pit and their Respective Flow Rates

With the closure of all mine operations in June 1983, the AMC breached a number of holding ponds to allow high metal–low pH water to flow to the pit. Thus, the pit became the containment site for both surface water and groundwater. An AMC handout from 1983 briefly detailed three surface-water sources routed to the pit:

1. Water pumped from the East Berkeley Pit;
2. Precipitation plant leach circuit; and
3. Great Northern (GN) leach pads, so-called because they were situated near the Great Northern Railway right-of-way.

In addition to these waters, water from the HSB area was diverted to the pit as part of 1982–1983 normal operations. Water from all the combined seepage sources was collected in a series of ponds and identified as the Horseshoe Bend drainage, or more commonly the HSB discharge. Figures 10 and 11 illustrate locations of leach pads, leach pad ponds, and HSB area waters diverted to the Berkeley Pit. Figures 12 and 13 are schematics that illustrate the various flows that entered the Berkeley Pit from 1982 to 1983. Figures 14 and 15 illustrate diverted surface water flowing down abandoned haul roads and accumulating in the bottom of the Berkeley Pit in 1983.

Table 3. Timeline for operational changes and natural occurrences that may have influenced Berkeley Pit water quality, 1982–1984.

Date	Event	Significance
April 1982	AMC discontinued operation of Kelley Mine pump station.	Water levels in Butte underground mines began to rise.
July 1983	AMC suspended all Butte mining activities.	Water from East Berkeley mine operations diverted to Berkeley Pit.
July 1983–April 1996	Horseshoe Bend Drainage water, water from precipitation plant and leach pad ponds diverted to Berkeley Pit.	Increased pit water-level filling rate.

Figure 10. Location of leach pads, leach circuit ponds, and Horseshoe Bend ponds (1998). View is from southwest looking northeast.

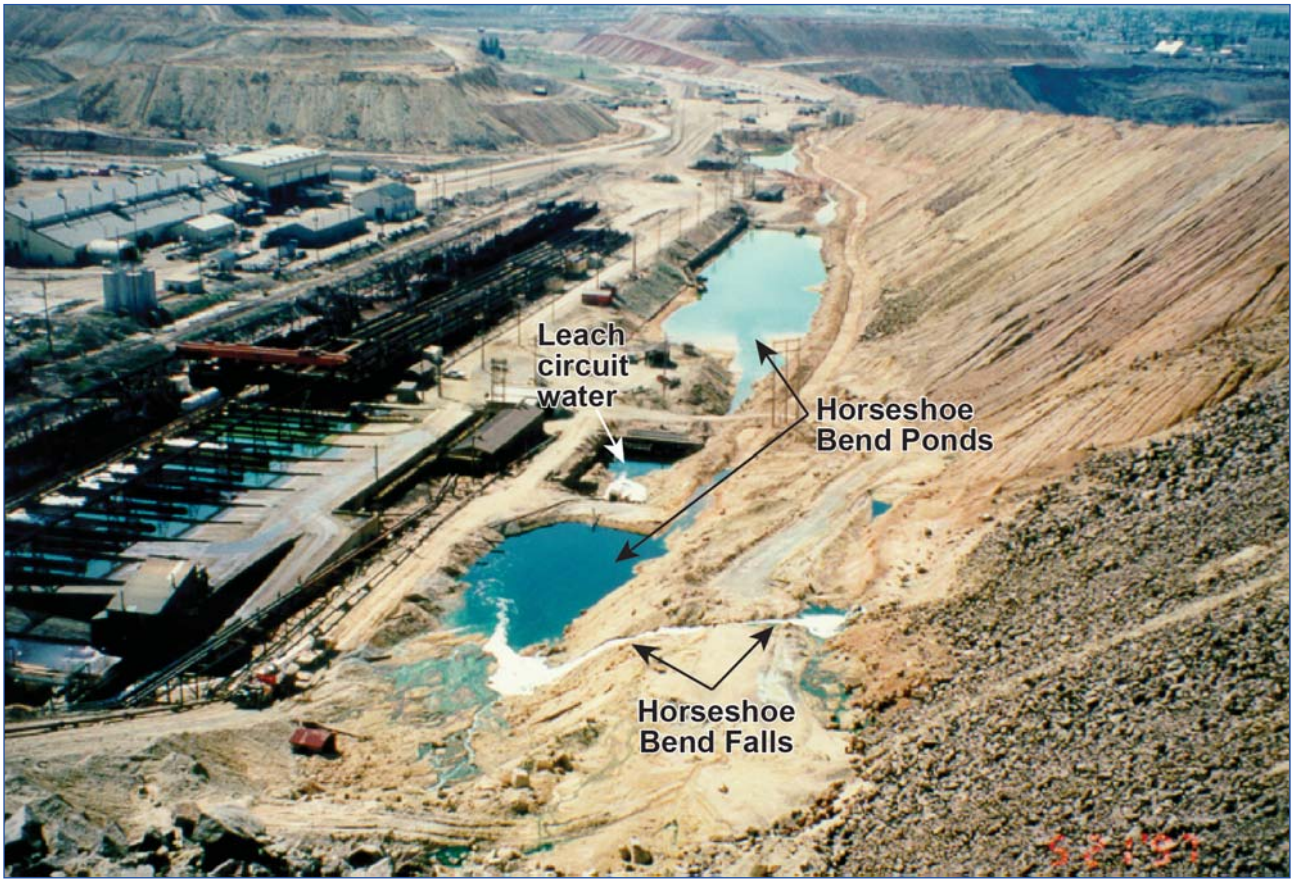
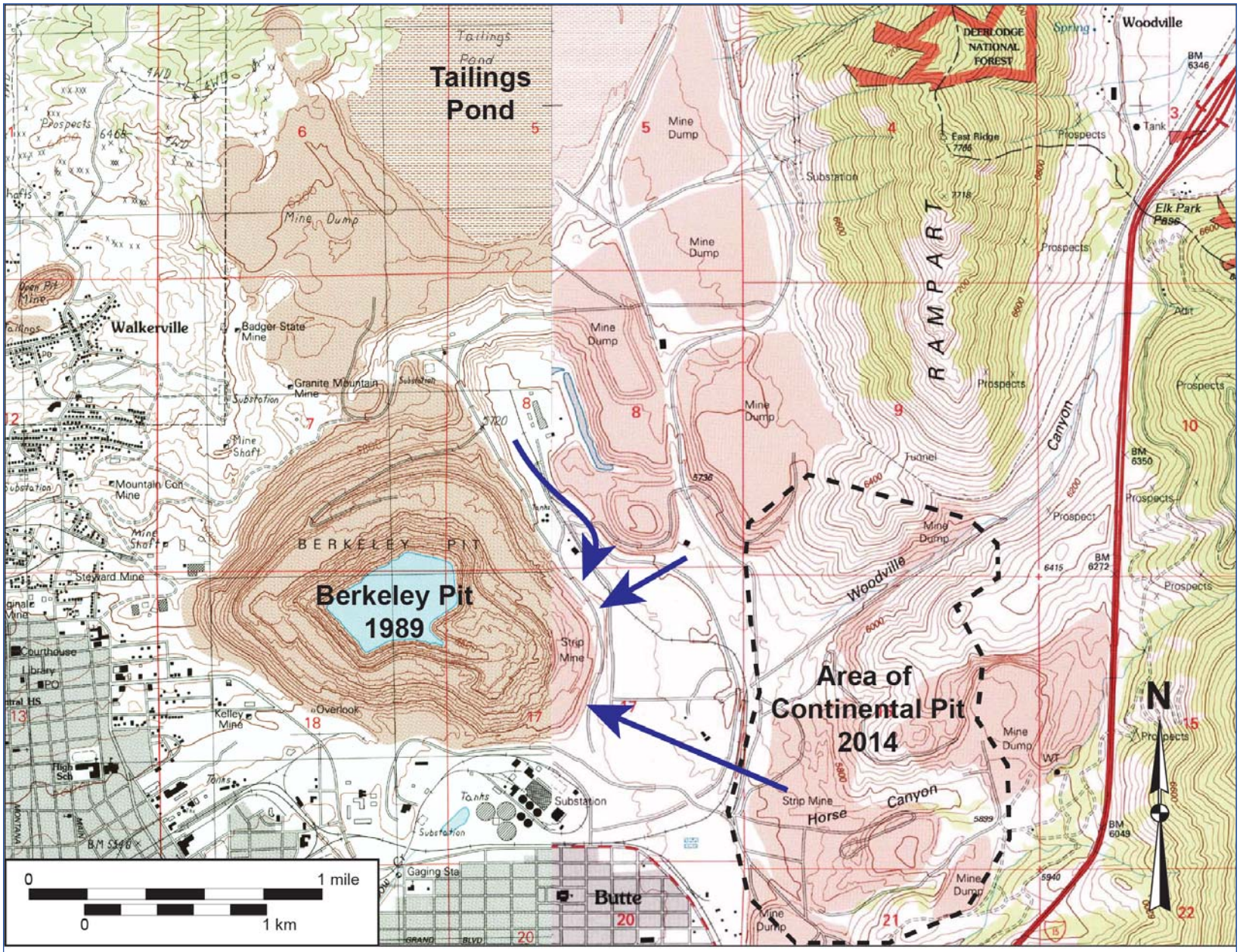


Figure 11. Horseshoe Bend area seeps, ponds, and leach circuit waters (1996). View is from north looking south.



Base from USGS Butte North 1989 24K and Elk Park 1996 24K quadrangle maps.

Figure 12. Surface-water flows diverted to the Berkeley Pit in 1982–1983.

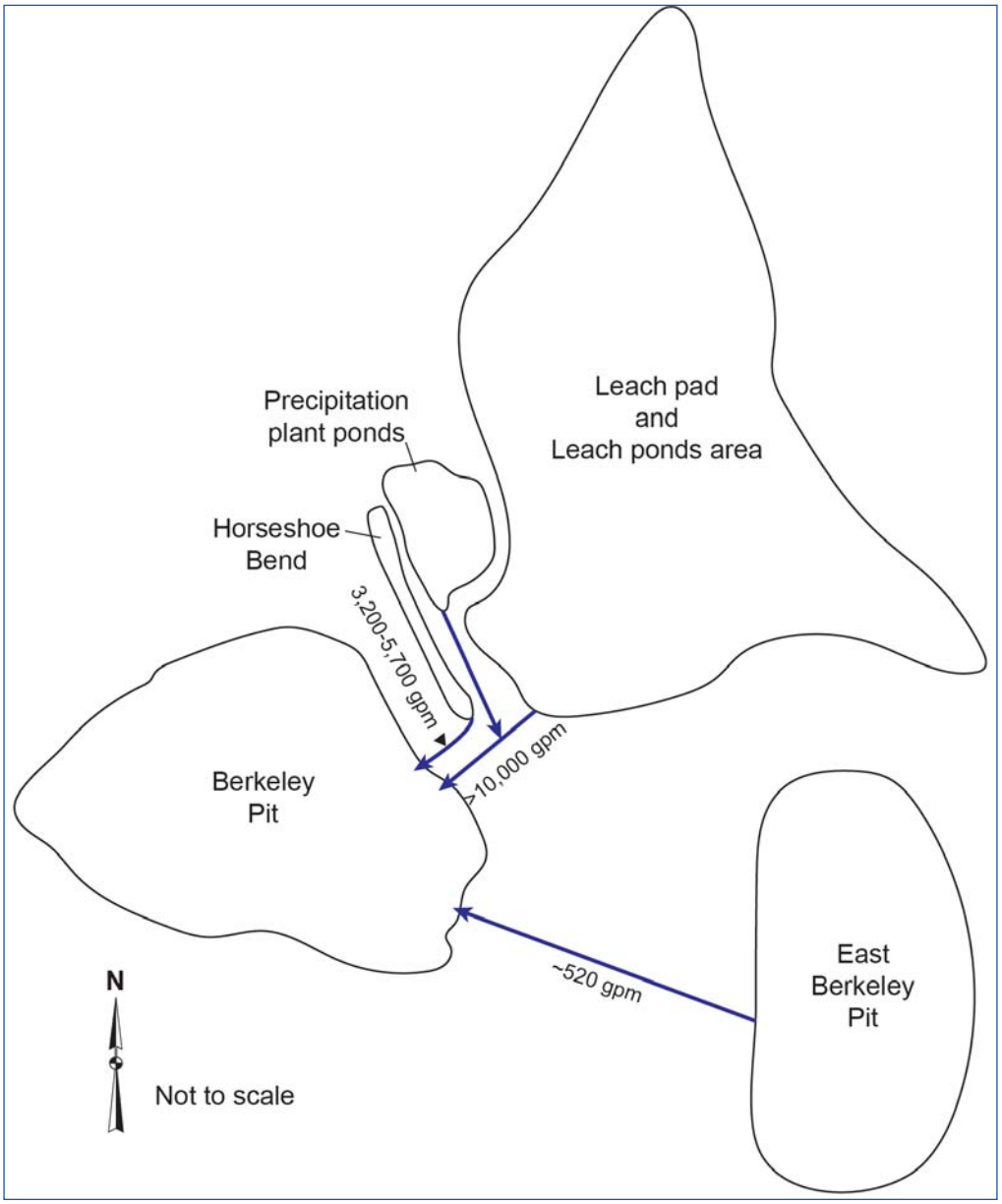


Figure 13. Surface-water flows diverted to the Berkeley Pit in 1982–1983.

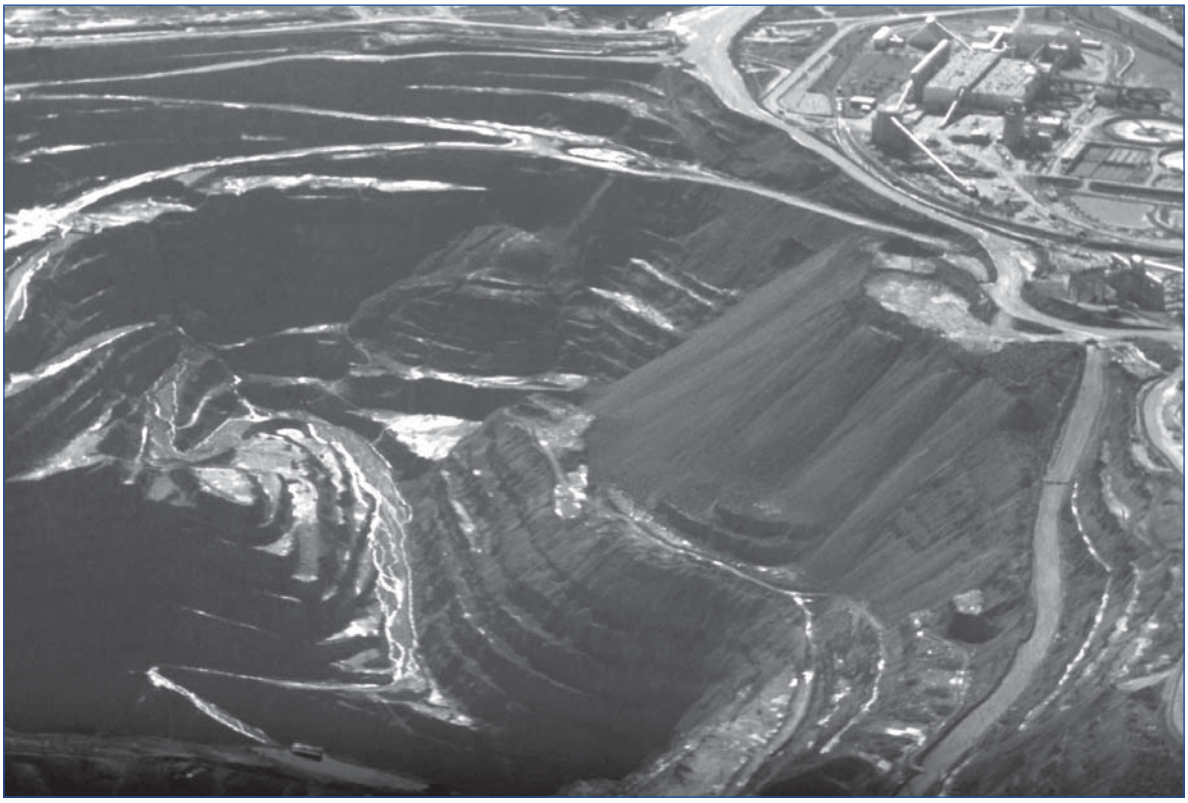


Figure 14. Diverted water flowing down abandoned haul roads and standing water in the bottom of the Berkeley Pit, looking northeast, August 1983.

Figure 15. Standing water in the bottom of the Berkeley Pit, looking north, August 1983.

AMC personnel indicated that initial flows (mid-1983) from the precipitation plant circuit and GN leach pads exceeded 10,000 gpm (P. Doughty and T. Duaime, oral commun., 1983). Flows dropped considerably after the ponds were drained. Measurements performed by the MBMG in 1984 during water sampling determined flows from the HSB area ranged from 3,200 to 5,700 gpm with copper concentrations ranging from 70 to 85 mg/L, with a pH of 2.8. AMC developed a model, utilizing the surface mapping and modeling software Surfer, to estimate the volume of pit water based on the water-surface elevation. Using that model, the MBMG estimated that over 3 billion gallons, or enough water to fill 325 ft of the pit from its base (elevation 4,263 ft), entered the pit from May 1982 through September 1984 (fig. 16). Based on monthly water-level increases and monthly water-level elevation data contained in table 4, specifically the sudden and marked reduction of filling rates in the mines, it appears a reversal of the gradient occurred between the Belmont and Kelley mines and between the Steward and Kelley mines, at an elevation of 4,540 ft (fig. 17), or 60 ft lower than the elevation of the pit water level determined by Surfer analysis. Based on the 60 ft elevation difference and the volumes of water predicted with the model, about 850 million gallons of surface water discharged to the pit leaked into the underground mine workings from May 1982 through September 1984. This volume was approximately 25% of the surface water diverted to the pit.

3.3 Sampling of Surface Flows Entering the Berkeley Pit

The MBMG collected water samples from two surface-water sources that were diverted to the Berkeley Pit in 1984. These sources from the precipitation plant/leach pad area and the East Berkeley Pit represent the major flows directed to the pit from ancillary mine operations. Flow measurements were estimated using the float (stick) and stopwatch method.

3.4 Water Quality of Surface Flows Entering the Berkeley Pit

Analytical results of collected samples for selected species are shown in table 5. Also shown are the maximum contaminant level (MCL) values as specified by the Montana DEQ-7 (DEQ, 2017) for relevant elements. The MCL provides a contrast between the degree of contamination and the concentrations that would need to be achieved for the water to be considered safe for human health. The MBMG also sampled water from the surface of the Berkeley Pit in November 1984; results are shown in table 5 for comparison purposes. The November Berkeley Pit sample results are similar to the water-quality data from the precipitation plant/leach pad area drainage, indicating the pit water quality was strongly influenced by surface flows that were diverted into the pit. Note the decrease in flow rates measured in 1984 from the estimated 10,000 gpm in 1983. While the Southeast Ditch water,

Figure 16. Standing water in the bottom of the Berkeley Pit, looking east (1984).

Table 4. Monthly water-level increases and water-level elevations for selected underground mine locations, September 1983–September 1984.

Month-Year	Kelley Mine, Monthly Water-Level Rise/Elevation (ft)	Belmont Mine, Monthly Water-Level Rise/Elevation (ft)	Steward Mine, Monthly Water-Level Rise/Elevation (ft)
September-83	92.2/4159.6	56.0/4139.7	57.3/4146.7
October-83	44.2/4203.8	46.9/4186.6	41.5/4188.2
November-83	52.4/4256.2	43.0/4229.6	47.1/4235.3
December-83	63.4/4319.6	86.3/4315.9	89.6/4324.9
January-84	40.5/4360.1	38.8/4354.7	42.6/4367.5
February-84	29.8/4389.9	24.0/ 4378.7	23.5/4391.0
March-84	30.7/4420.6	36.0/ 4414.7	34.0/4425.0
April-84	19.6/4440.2	23.7/ 4438.4	29.5/4455.0
May-84	20.3/4460.5	20.0/ 4458.4	22.8/4477.3
June-84	20.5/4481.0	13.4/ 4471.8	22.0/4499.3
July-84	23.2/4504.2	31.0/ 4502.8	23.7/4523.0
August-84	19.4/4523.6	18.1/ 4520.9	19.7/4542.7
September-84	16.2/4539.8	20.1/ 4541.0	7.8/4550.5

with lower concentrations of trace metals, may have diluted the higher concentrations from the precipitation plant/leach pad area waters, leaching of metals from the pit wall rock may have been an additional source of metals to the pit water. The higher copper and zinc concentrations in the pit water compared to the surface-water sources suggest such leaching was taking place.

A consultant's study, the IECO hydrologic study report (IECO, 1981), discussed the presence of seepage faces on the downstream face of the tailings dam and reported flows up to 350 gpm. Water samples from this source showed a pH of 3.3 with elevated dissolved copper concentrations (9,430 µg/L). While the flow and concentrations are less than those shown for the leach-precipitation samples in table 5, they do indicate the presence of low pH, metal-laden water emanating from the seepage face.

3.5 Sources of Water Entering the Underground Mine Workings (1982–1984)

The diversion of surface flows from suspended mine operations, i.e., HSB flow, leach pad etc., to the Berkeley Pit likely provided additional water to the underground mine workings (see previous section). Based on the volumetric model of the pit, approximately 25 percent of the water that accumulated in the pit bottom leaked into the underground mine workings during the early stage of flooding, while the elevation of water in the pit exceeded the elevation of water in the workings. Monthly measurements of water levels showed that the water level in the Kelley Mine reached the elevation of the bottom of the pit (4,263 ft, as reported by USGS, NAVD29) in late November 1983, about 6 months later than predicted by AMC. The date when water levels in the mine workings exceeded the water elevation in the Berkeley Pit is not known with certainty, but was estimated to have occurred in early to mid 1984 (table 4). This estimate was based on a significant decrease in monthly water-level increases and the date that water-level gradients

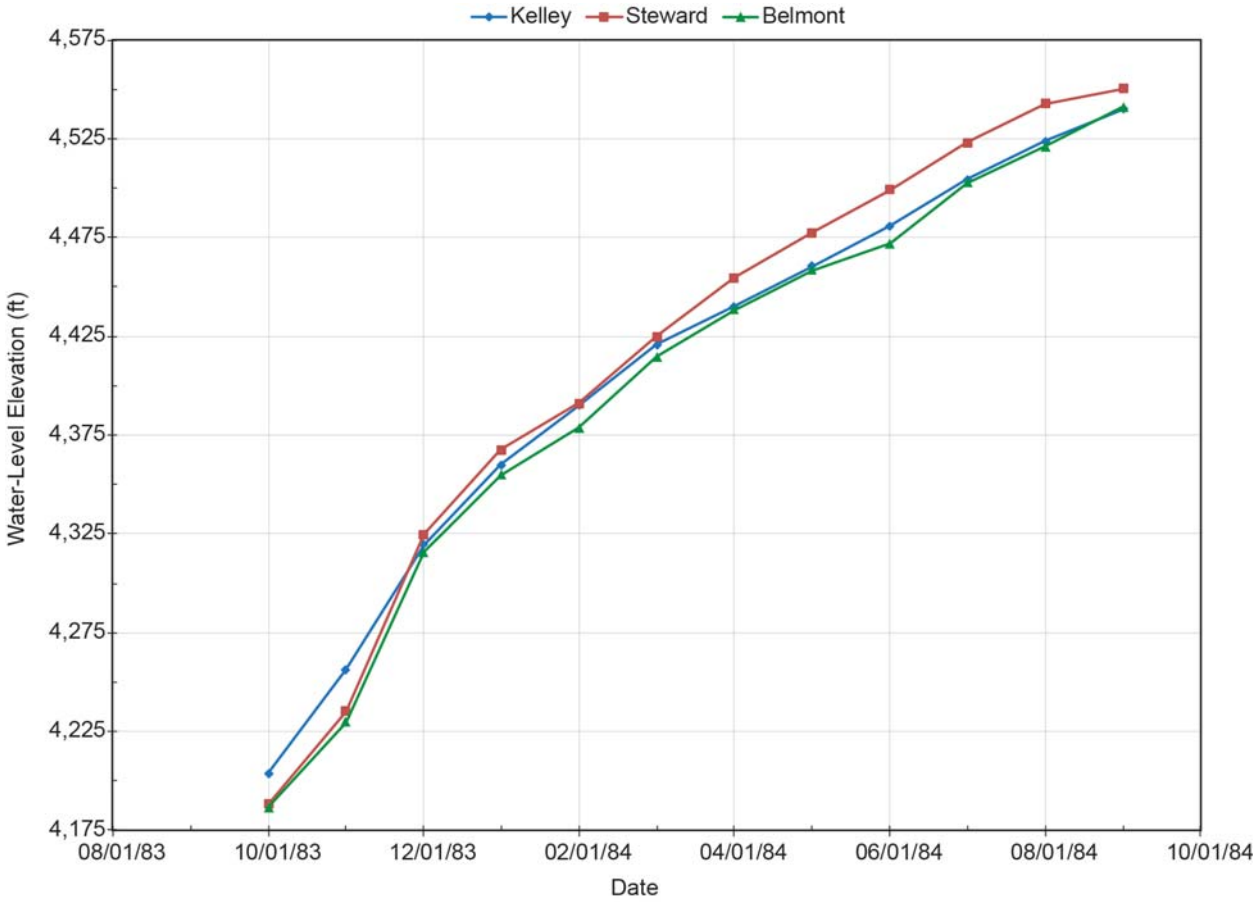


Figure 17. Underground mine water levels in the Kelley, Belmont, and Steward Mines showing gradient reversal between October 1983 and September 1984. Location of mines are shown in figure 8.

between the Kelley, Steward, and Belmont mines reversed; table 4 shows monthly water-level rise and water-level elevations for selected mines from September 1983 through September 1984, and figure 17 shows the changes graphically. Metesh (2004) discussed leakage of water from the Berkeley Pit to the underground workings in the 1982–1984 time period and estimated up to 47 percent of the water entering the underground mines was from the Berkeley Pit. Because of the multiple sources of water entering the underground mine workings and the Berkeley Pit, the first 2 years of mine flooding were complex from both flow and water-quality perspectives.

3.6 Sampling and Monitoring of the Underground Mines (1982–1984)

Water-level monitoring was performed monthly during this time period, while water-quality samples were collected three times a year for dissolved metal analysis. Water levels were measured in 1982 and 1983 using the tugger, and water samples were collected using a top-fill bailer attached to the tugger cable. A point source bailer was used for collection of 1984 multiple-depth samples (fig. 18).

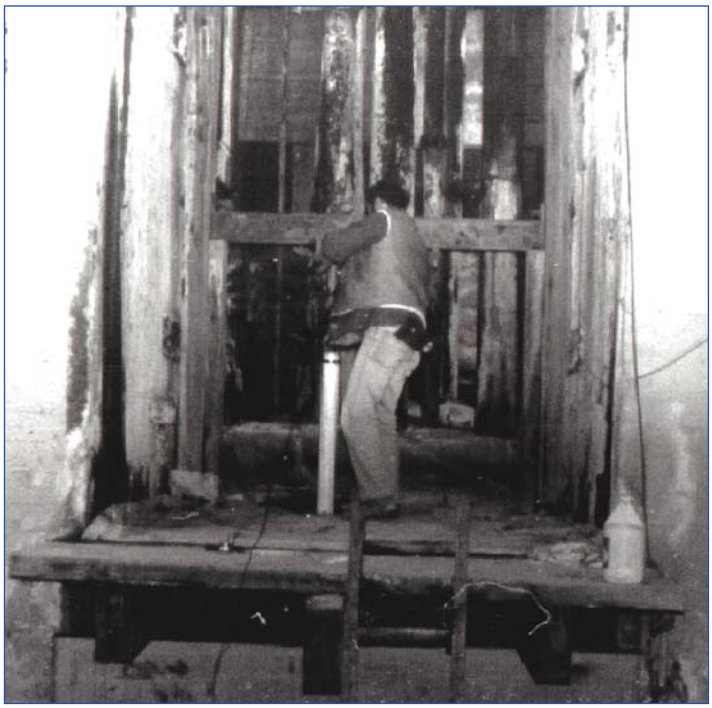


Figure 18. Point source bailer attached to tugger cable being lowered into mine shaft.

Table 5. Water quality of surface-water sources diverted to the Berkeley Pit, 1984 (results are for the dissolved fraction).

Sample ID	Sample Date	Flow (gpm)	Field pH (+/- 0.1)	Field SC (µmhos/cm)	Sulfate (mg/L)	Aluminum (µg/L)	Cadmium (µg/L)	Copper (µg/L)	Iron (mg/L)	Manganese (mg/L)	Zinc (µg/L)
							MCL 5	MCL 1,300			MCL 7,400
Precip-Leach	4/24/84	5,200	2.82	4,945	4,390	148,000	1,500	78,000	275	107	241,000
Precip-Leach	7/24/84	3,540	2.76	3,015	4,100	149,000	1,580	85,000	277	101	238,000
Precip-Leach	11/21/84	3,180	2.86	4,245	3,850	126,000	1,270	69,300	250	79.2	184,000
SE-Ditch*	11/21/84	520	2.88	1,670	988	7,300	300	35,700	8.09	12.3	31,600
Berkeley Pit	11/21/84		2.64	4,320	3,707	120,000	1,230	89,600	214	87.5	196,000

*SE-Ditch, water is combination of flow from East Berkeley Pit (Continental Pit), Altona Shaft, and waste rock dump above East Berkeley Pit (Continental Pit).

Note. MCL, maximum contaminant level for human health standards in surface water. DEQ-7 Montana Numeric Water Quality Standards, May 2017.

3.7 Water-Quality Results from the Underground Mine Workings (1982–1984)

Water flooding the underground mine workings came from a combination of bedrock and alluvial groundwater and leakage from the standing water that was accumulating in the bottom of the Berkeley Pit. AMC began collecting water-quality samples from the Kelley Mine shortly after the suspension of pumping in 1982, and the MBMG periodically sampled this site beginning in July 1983. Table 6 contains selected water-quality data from the Kelley Mine, results from an alluvial monitoring well (AMC-2) on the east side of the Berkeley Pit, and samples from various depths in the Berkeley Pit (fig. 19). These data show:

- a net water-level rise of 600 ft in the Kelley Mine between sample events;
- decreasing pH in Kelley Mine samples over time;
- significant increase in metal concentrations in Kelley Mine samples between October 1983 and October 1984 samples;

Table 6. Groundwater sample results from selected sample sites, 1983–1984 (results are for the dissolved fraction).

Sample ID	Sample Date	Sample Depth (ft)	Field pH (+/- 0.1)	Field SC (µmhos/cm)	Sulfate (mg/L)	Aluminum (µg/L)	Cadmium (µg/L)	Copper (µg/L)	Iron (mg/L)	Manganese (mg/L)	Zinc (µg/L)
							MCL	MCL			MCL
							5	1,300			7,400
Kelley Mine	10/13/83	1,700*	4.32	3,900	3,310	41,500	460	23,800	72.7	34.6	90,300
Kelley Mine	4/26/84	1,450*	3.67	6,800	NA	188,000	660	43,800	1,080	94.2	344,000
Kelley Mine	11/30/84	1,310*	3.58	7,535	8,000	124,000	950	90,000	1,633	129	678,000
Kelley Mine	11/30/84	2,200	3.60	7,940	7,830	122,000	1,250	93,400	1,629	129	666,000
Berkeley Pit	11/21/84	~5	2.64	4,320	3,707	120,000	1,230	89,600	214	87.5	196,000
Berkeley Pit	11/21/84	50–75**	2.64	4,320	4,410	142,000	1,540	164,000	256	106	255,000
AMC-2	7/26/83	92	5.56	1,340	776	170	86	210	9.18	0.73	6,000
AMC-2	10/16/84	92	5.20	3,260	2,450	660	1,180	21,600	92.6	14.7	89,700

*Sample depth is approximately 10 ft below static water level in the mine shaft.
**Composite sample of water collected at approximately 50 and 75 ft below water surface.
Note. MCL, maximum contaminant level for human health standards in surface water. DEQ-7 Montana Numeric Water Quality Standards, May 2017.

- similar aluminum, copper, and cadmium concentrations in Kelley Mine and Berkeley Pit water samples in November 1984; and
- increasing metal concentrations in alluvial well AMC-2, showing degradation in water quality from the east side alluvial system flowing into the Berkeley Pit.

The flow system and pathways of water entering the underground mine system from 1982 to mid-1984 are presented in figure 20. Figure 21 shows the flow system following the groundwater gradient reversal in mid-1984, when the Berkeley Pit became the lowest point in the underground mine drainage system. A potentiometric surface investigation confirmed that flows from surrounding aquifers were all directed toward the Berkeley Pit (Hydrometrics, 1982).

Figure 19. Map showing the location of sample sites listed in table 6.

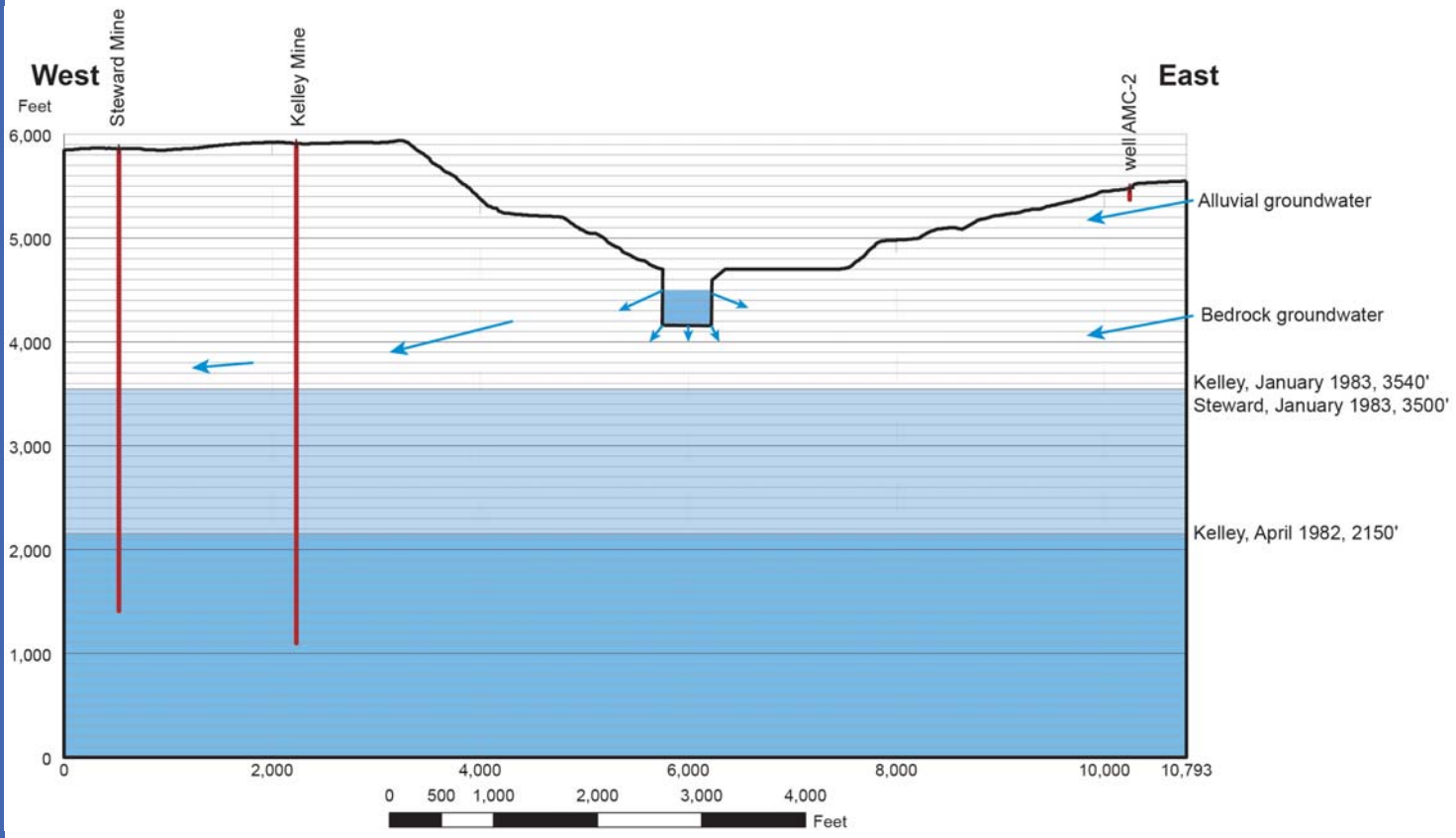


Figure 20. Schematic showing flow of Berkeley Pit water into underground mine workings. Color changes indicate water levels in mine shafts over time.

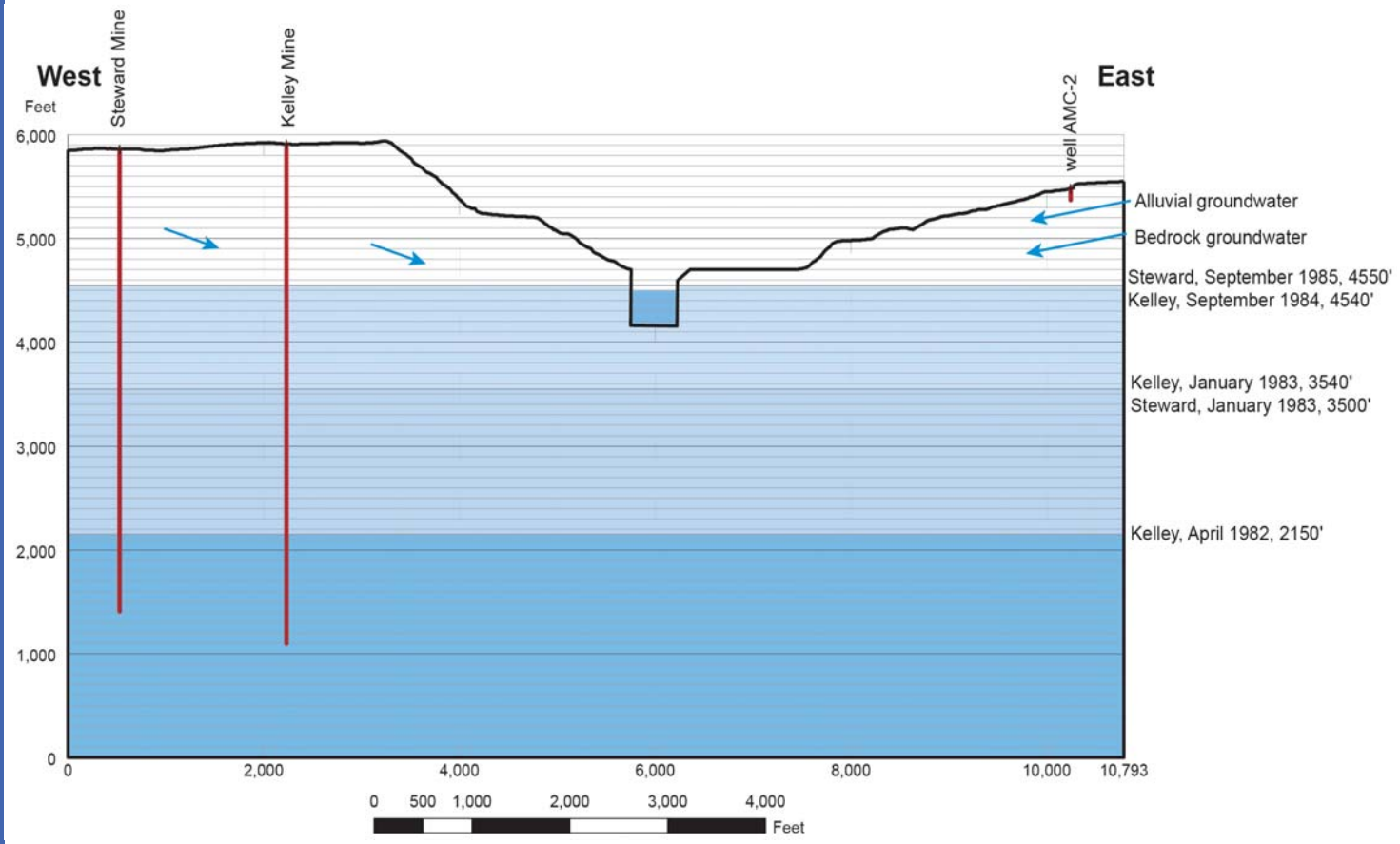


Figure 21. Schematic showing flow of underground mine water into Berkeley Pit. Color changes indicate water levels in mine shafts over time.

4.0 EARLY SAMPLING OF BERKELEY PIT AND ITS INFLOWS (1984–1998)

4.1 Events during 1984–1998

The important events for the period dealt with water handling of the Horseshoe Bend Drainage water, the resumption of open-pit mining by MR, and a major landslide. They are shown chronologically in table 7.

4.2 Grab Sampling of the Berkeley Pit with Helicopters (1984–1985)

The diversion of surface-water flows into the Berkeley Pit and the suspension of all mining activities in May 1982 led to a rapid decay of the haul roads. The runoff caused severe erosion and created gullies that made vehicle access to water in the pit bottom impossible. The Montana Department of State Lands (now known as the Montana Department of Environmental Quality) used a helicopter to collect grab samples from the pit in November 1984 and June 1985 (fig. 22). The helicopter hovered over the water surface and a point source bailer was lowered out the side door to collect samples. During the November 1984 sample event, inclement weather limited the amount of time the helicopter was able to safely operate within the pit. This resulted in the analysis of a sample composited from water collected at approximately 50 and 75 ft below the surface. In June 1985, the sample was collected from approximately 100 ft below the water surface. Sample depths were estimated from footage markings and the exact distance the helicopter was above the pit were uncertain, so the sample depths are approximations.

Table 7. Timeline for operational changes and natural occurrences that may have influenced Berkeley Pit water quality, 1983–1998.

Date	Event	Significance
July 1983–April 1996	Horseshoe Bend Drainage water, water from precipitation plant and leach pad ponds diverted to Berkeley Pit.	Increased pit water-level filling rate.
July 1986	MR began mining in the Continental Pit and milling operations in the Butte concentrator.	East Berkeley (Continental Pit) water diverted away from Berkeley Pit for use in mining operations. Decreased the amount of water entering the pit, slightly reducing filling rate.
April 1996	Horseshoe Bend drainage water diverted away from the Berkeley Pit and pumped to the Yankee Doodle Tailings Dam.	Reduced the rate of rise in the Berkeley Pit, underground mine workings, and surrounding bedrock aquifer, by diverting between 3.0 and 3.5 million gallons of water per day away from the pit.
August 1998	MR began pumping water from the Berkeley Pit for copper recovery.	Water discharged back into the pit after copper recovery in the precipitation plant; high iron concentration in return water.
September 1998	Large landslide occurred in the southeast corner of the Berkeley Pit.	An estimated 1.3 million cubic yards of material entered the pit, resulting in a 2.5 ft water-level rise. Wave action in pit damaged the MBMG sample platform, washing it up on a mine bench on west side of pit.

Figure 22. Helicopter hovering in Berkeley Pit during June 1985 water sampling event.

4.3 Water-Quality Results from Grab Samples (1984–1985)

Selected water-quality results from these sample events are presented in table 8. Observations from these results include:

- Temperature changes are noted between sample depths and time of year collected. June 1985 samples had water temperatures almost 5°C higher than the 1984 samples.
- Metal concentrations, i.e., aluminum, copper, and zinc, decreased in surface samples between 1984 and 1985.
- Metal concentrations, i.e., copper and zinc, increased with depth.
- Copper and zinc concentrations in the 1985 depth samples were considerably higher than the depth sample concentrations in 1984.

The decrease in metal concentrations in the surface samples may be related to lower concentration surface-water flows that were diverted to the pit but were not well mixed, and accumulated on the water surface, as well as to dilution from precipitation.

4.4 Sampling Using Helicopters and Boats (1986–1987)

The continued water-level increases in the Berkeley Pit provided additional opportunities for the collection of water samples. Helicopters were used to transport boats and personnel to a stable mine bench (figs. 23, 24), with the helicopter retrieving personnel and equipment at the end of the sample event. The use of manned boats allowed collection of samples at multiple depths and collection of *in situ* physical parameters during 1987. Water samples were collected using a peristaltic pump with in-line filtration. The 1986 sampling event was a cooperative investigation between the MBMG and Headwater Research Institute, with results summarized in MBMG Open-File Report 195 (Sonderegger and others, 1987); the 1987 samples were collected in conjunction with ongoing Superfund activities and results are detailed in a paper prepared by Davis and Ashenberg (1989).

Water from the Kelley Mine shaft was also collected during the 1986 and 1987 Berkeley Pit sampling events. Tables 9 and 10 present selected analytical results from both the Berkeley Pit and Kelley Mine for comparison purposes. Kelley Mine samples were collected using a point source bailer; suspended sediment and debris in the water column prevented

Table 8. Selected Berkeley Pit water-quality results for 1984–1985 sample events (results are for the dissolved fraction).

Sample Date	Sample Depth (ft)	Field pH (+/-) 0.1)	Field Temp. (°C)	Sulfate (mg/L)	Aluminum (µg/L)	Arsenic (µg/L)	Cadmium (µg/L)	Copper (µg/L)	Zinc (µg/L)
						MCL 10	MCL 5	MCL 1,300	MCL 7,400
11/21/84	Surface	2.64	5.6	3,707	120,000	54	1,230	89,600	196,000
11/21/84	50–75*	2.78	6.5	4,410	142,000	197	1,540	164,000	255,000
06/18/85	Surface	2.26	10.2	3,200	86,000	21	1,000	63,000	124,000
06/18/85	100	2.48	10.4	5,550	172,000	426	1,620	229,000	329,000

*Composite sample of water collected at 50 and 75 ft.

Note. MCL, maximum contaminant level for human health standards in surface water. DEQ-7 Montana Numeric Water Quality Standards, May 2017.

the bailer from properly closing at the bottom fitting, reducing the amount of water collected. Due to limited sample volumes, aqueous anion samples were collected at just one depth.

4.5 Water-Quality Results from Sampling Using Helicopters and Boats (1986–1987)

The 1987 Berkeley Pit sampling event provided more information than the 1986 event about changes in physical and chemical conditions throughout the pit water column due to the increased number of parameters monitored and increased number of depths sampled. However, a general comparison of data presented in table 9 indicates that the pit chemistries in 1986 and 1987 were very similar. Both datasets suggest the presence of a chemocline where concentrations of select metals, i.e., aluminum, cadmium, copper, and zinc, increase with depth. This is shown in the changes between the 1 and 110 ft 1986 samples and the 10 and 50 ft 1987 samples. It would be a fair assumption that the increase in concentrations occurred at a shallower depth in 1986, similar to those observed in the 1987 samples. One notable change between the 1986 and 1987 samples was an order of magnitude increase in arsenic concentrations at depths of 100 ft and greater. Arsenic concentrations at these depths in 1986 varied from 33 to 123 µg/L, compared to a range of 335 to 1,010 µg/L in 1987.

The 1986 and 1987 Berkeley Pit water sample results represent the earliest detailed picture of water-quality and physical parameters within the pit water body. This dataset provides a baseline for comparison to water-quality conditions over time, and the ability to identify the potential impacts of water handling or physical changes that may have affected water chemistry.

4.6 Water-Quality Results from Kelley Mine Underground Workings (1986–1987)

The 1986 and 1987 Kelley Mine samples show vertical stratification in several metal concentrations, with concentrations increasing with depth (table 10). Aluminum and zinc at the 1,100-ft-depth 1986 sample were comparable to those at depth in the Berkeley Pit. Arsenic concentrations in the Kelley Mine were much higher than those in any of the 1986 pit samples. Metal concentrations decreased from 1986 to 1987 in the Kelley Mine, which is attributed to the increasing pH in the mine water, which resulted in precipitation of metals. In general, metals concentrations in 1987 in the Kelley Mine water were considerably lower than those in pit samples, with the exception of arsenic, which was similar in the mine and the pit. The Berkeley Pit copper concentrations were orders of magnitude higher than those in the Kelley Mine water, indicating that the low-pH pit water resulted in leaching of copper from the surrounding wall rock.

Figure 23. Flat mine bench in east portion of the Berkeley Pit where helicopters were able to land and offload personnel and equipment for sampling in 1986 and 1987.

Figure 24. Helicopter ferrying boat and personnel into the Berkeley Pit for October 1986 sample event.

Table 9. Selected water-quality results from 1986 and 1987 Berkeley Pit sampling events (results are for the dissolved fraction).

Sample Date	Sample Depth (ft)	Field pH (+/- 0.1)	Field Temp. °C	Sulfate (mg/L)	Aluminum (µg/L)	Arsenic (µg/L)	Cadmium (µg/L)	Copper (µg/L)	Zinc (µg/L)
						MCL 10	MCL 5	MCL 1,300	MCL 7,400
11/17/86	1	NA	NA	NA	91,600	16	1,000	114,000	178,000
11/17/86	110	NA	NA	NA	171,000	33	1,620	196,000	375,000
11/17/86	220	NA	NA	NA	192,000	41	1,740	204,000	460,000
11/17/86	330	NA	NA	NA	201,000	50	1,800	214,000	472,000
11/17/86	390	NA	NA	NA	203,000	123	1,690	213,000	477,000
10/14/87	1	2.76	11.5	3,580	97,900	4	1,090	127,000	198,000
10/14/87	3	2.72	8.2	3,760	106,000	4	1,450	134,000	214,000
10/14/87	10	2.84	11.5	4,720	144,000	4	1,710	149,000	269,000
10/14/87	50	2.95	12.2	5,810	162,000	1	1,890	205,000	390,000
10/14/87	100	3.08	13.3	6,710	187,000	335	1,740	205,000	391,000
10/14/87	200	3.15	13.5	6,600	186,000	755	1,760	199,000	469,000
10/14/87	300	3.15	13.5	6,500	189,000	695	1,780	199,000	470,000
10/14/87	400	3.14	13.7	6,780	191,000	1,010	1,780	196,000	478,000

Note. NA, not available (not measured). MCL, maximum contaminant level for human health standards in surface water. DEQ-7 Montana Numeric Water Quality Standards, May 2017.

4.7 Dedicated Sample Platform and Pipeline Sampling (1991–1998)

Following the helicopter-supported sampling of the Berkeley Pit in 1986 and 1987, water quality was not sampled again until the spring of 1991. By this time, the water level had reached an elevation sufficient to restore vehicle access on the south side of the pit. To aid in sampling, the MBMG constructed an 8 ft by 8 ft plywood platform attached to capped, 8-in PVC pipes. The platform was towed (fig. 25) to what was believed to be the deepest part of the pit and anchored with weights to keep it from moving.

The first set of samples using the platform was collected in May 1991 as part of the Butte Mine Flooding Remedial Investigation. Between 1991 and 1998, pit monitoring was completed on an irregular schedule, with most sampled depths between 1 and 200 ft below the water surface. Table 11 presents selected water-quality data for this time period.

The MBMG collected samples from three depths, and a vertical profile of physical parameters was constructed using a Hydrolab Data Sonde to record the data in 1991, and a series of water samples from the 200 ft depth from the fall of 1993 to spring 1994. A similar series of samples from 200 ft were collected from fall 1995 into spring 1996. The March 1996 sample was collected at a depth of 100 ft while the pit was under the cover of ice (fig. 26). The 200-ft depth was sampled during 1997 and 1998.

Table 10. Selected water-quality results from 1986 and 1987 Kelley Mine sampling events (results are for the dissolved fraction).

Sample Date	Sample Depth (ft)*	Field pH (+/- 0.1)	Field Temp. 0C	Sulfate (mg/L)	Aluminum (µg/L)	Arsenic (µg/L)	Cadmium (µg/L)	Copper (µg/L)	Zinc (µg/L)
						MCL	MCL	MCL	MCL
						10	5	1,300	7,400
10/30/86	10	4.90	19.8	4,080	11,500	3,390	<2	700	23,200
10/30/86	310	4.90	19.8	4,040	10,300	3,590	<2	540	234,000
10/30/86	1,100	4.05	20.6	NA	164,000	7,000	12	1,670	510,000
10/14/87	10	4.00	17.6	NA	1,380	29	250	130	54,000
10/14/87	50	3.22	17.5	1,315	840	31	260	120	55,200
10/14/87	100	5.50	12.8	NA	2,780	888	120	140	106,000
10/14/87	200	5.48	18.6	NA	3,080	1,050	110	150	115,000
10/14/87	500	5.37	18.3	NA	3,260	1,040	110	140	114,000

*Sample depth below Static Water Level; 10/86 SWL 1,088 ft, 10/87 SWL 1,007 ft.

Note. MCL, maximum contaminant level for human health standards in surface water. DEQ-7 Montana Numeric Water Quality Standards, May 2017.

Figure 25. MBMG sample platform being towed to water sampling and monitoring location in the pit. Jim Boren, rowing in the boat; John Metesh and Fred Schmidt, riding on the platform.

Table 11. Selected Berkeley Pit water-quality results from 1991 and 1998 sampling activities (results are for the dissolved fraction).

Sample Date	Sample Depth (ft)	Field pH (+/- 0.2)	Field Temp. (°C)	Sulfate (mg/L)	Iron (mg/L)	Aluminum (µg/L)	Arsenic (µg/L)	Cadmium (µg/L)	Copper (µg/L)	Zinc (µg/L)
							MCL	MCL	MCL	MCL
							10	5	1,300	7,400
05/21/91	3.4	2.47	13.0	7,261	666	268,700	209	1,708	178,000	506,300
05/21/91	400	2.69	6.1	8,084	1,095	284,900	880	1,573	186,000	546,600
05/22/91	3	2.73	15.2	7,217	649	274,200	209	1,807	177,800	505,400
05/22/91	225	2.84	13.5	8,010	1,088	288,000	830	1,572	191,300	552,400
08/19/92	3	NA	NA	6,930	373	79,900	103	2,300	189,000	519,000
08/19/92	200	NA	NA	8,014	966	80,500	1,303	1,960	190,000	540,000
05/18/93	3	2.91	19.6	6,080	293	252,000	108	2,032	162,000	437,000
10/07/93	200	2.55	11.9	7,508	1,083	288,000	1,190	1,927	201,000	587,000
10/21/93	200	2.57	10.0	7,622	1,088	288,000	1,200	1,900	195,000	595,000
12/01/93	200	2.64	9.6	7,994	1,035	265,000	1,210	1,773	180,000	585,000
12/09/93	200	2.54	8.6	7,882	1,141	275,000	1,220	1,840	176,000	589,000
04/19/94	150	2.44	9.0	7,650	1,160	293,000	1,300	1,928	195,000	606,000
04/19/94	200	2.45	9.0	7,643	1,107	292,000	1,210	1,895	198,000	608,000
05/23/94	200	2.74	21.0	8,318	1,172	286,000	1,296	1,855	197,000	591,000
06/19/95	200	2.72	10.8	8,500	1,212	290,000	820	2,260	198,000	634,000
10/25/95	200	2.45	9.5	8,500	1,116	278,000	730	2,163	203,000	598,000
11/08/95	200	2.31	9.8	9,000	1,138	287,000	740	2,183	204,000	619,000
11/15/95	1	2.56	11.4	7,950	447	338,000	161	2,340	189,000	555,000
03/15/96*	100	2.90	6.2	8,649	800	309,000	430	2,350	194,000	589,000
09/01/97	200	2.58	10.9	8,294	971	314,000	660	2,268	206,000	617,000
04/27/98	200	2.89	6.5	7,800	1,110	275,000	663	2,104	186,000	544,000

*Sample collected while pit surface frozen.

Note. NA, not available (not measured). MCL, maximum contaminant level for human health standards in surface water. DEQ-7 Montana Numeric Water Quality Standards, May 2017.

Figure 26. MBMG employees John Metesh and Fred Schmidt collecting samples through the ice from sample platform.

4.8 Water-Quality Results from Dedicated Sample Platform and Pipeline Sampling (1991–1998)

Sample results are shown in table 11. Water from the HSB drainage was discharging into the pit up until April 1996 when MR diverted it to the Yankee Doodle Tailings Dam as part of ongoing Superfund activities. The diversion of the HSB water may have affected pit water chemistry in regards to dissolved iron and arsenic concentrations (see fig. 27), while also slowing the filling rate of the pit and adjacent underground mines.

A plot of iron and arsenic concentrations by depth is presented in figure 27. The shallow samples were collected at a depth of about 3 ft below water surface; depths of the deep samples varied from 150 to 400 ft (see table 11 for sample depths). These two elements show the greatest contrast between concentrations near the surface and at depth. Both iron (Fe) and arsenic (As) have multiple stable oxidation states in the mine water environment, depending on the electrochemical potential of the water (Eh) and availability of dissolved oxygen. In both cases, the lower oxidation states of each (Fe^{2+} and As^{3+}) are more soluble. The higher oxidation state of iron (Fe^{3+}) is subject to hydrolysis even at low pH, resulting in a mixture of complex oxyhydroxide precipitates such as ferrihydrite or schwertmannite. These are the ochre to red precipitates that are commonly associated with acidic mine waste. The precipitates are highly surface active and have affinity for the higher valence arsenic (As^{5+} as H_2AsO_4-) at a pH lower than 6 because the surface of the iron oxyhydroxide acquires a positive charge by adsorbing protons from the water. In contrast, lower valence arsenic exists as a species that is fully protonated with no charge (As^{3+} as H_3AsO_3) and has no potential for an electrostatic interaction with protonated iron oxyhydroxide solids. Thus, adsorption and co-precipitation of iron and arsenic occur when the conditions favor the oxidation of both elements to the higher valence states.

There were two major sources of water to the pit during this period. Well-oxygenated surface water cascaded over the east wall into the pit from Horseshoe Bend, at a rate of 3.5–4.5 MGD. Oxygen-depleted water discharged into the bottom of the pit from underground mine workings at an estimated 3.2–3.3 MGD. The chemical behavior of the pit water resulted from complex mixing processes and kinetics. Between 1991 and 1994, elevated concentrations of both iron and arsenic were preserved at depth. During 1995, both iron and arsenic at depth were declining. The first samples collected following the diversion of Horseshoe Bend water to the tailings pond demonstrated a reversal in the trend, and both iron and arsenic concentrations increased in the deep samples.

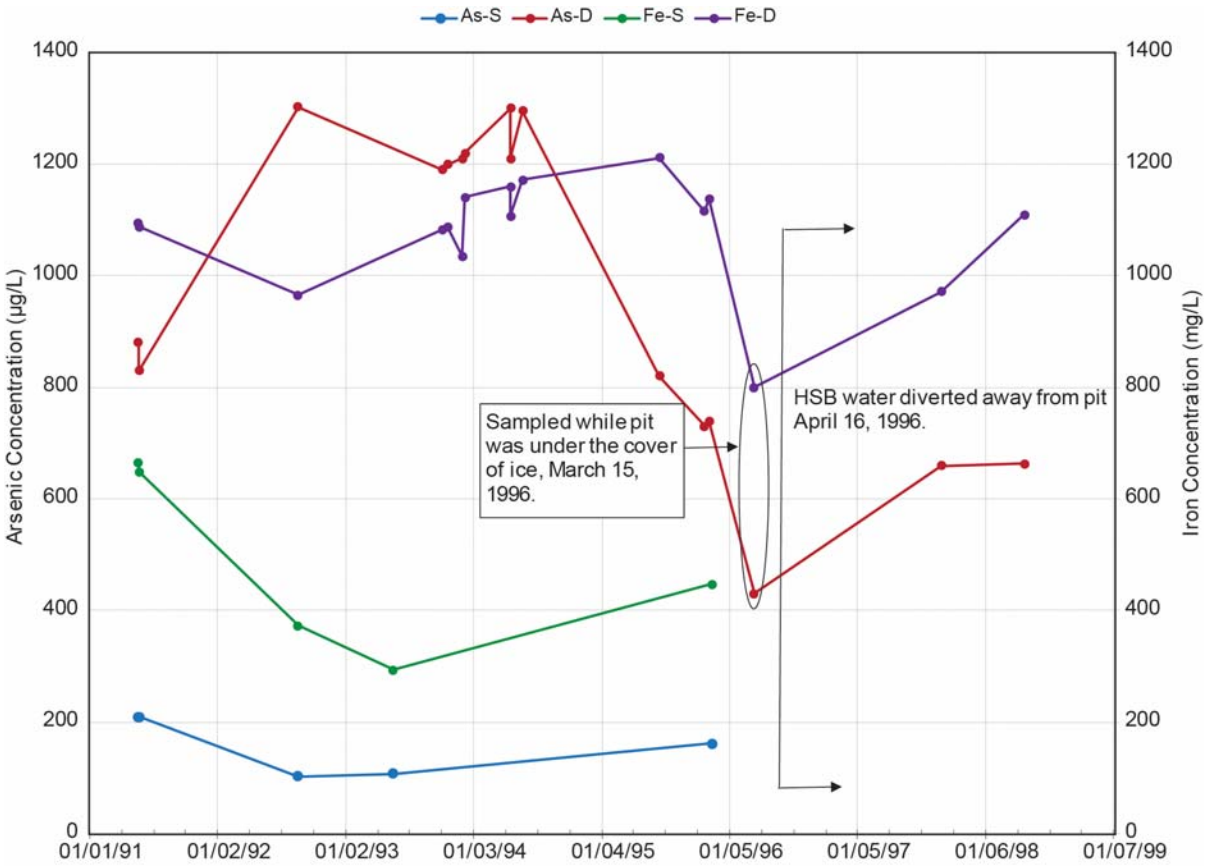


Figure 27. Dissolved iron and arsenic concentrations in Berkeley Pit water collected at shallow (-S) and deep (-D) depths. Arrows denote change following diversion of HSB water away from pit.

The influence of electrochemical potential and oxygen did not affect concentrations of other metals to the same degree as iron and arsenic. Consequently, concentrations in shallow and deep samples are similar.

Figure 28 shows aluminum and cadmium concentrations in the shallow and deep Berkeley Pit samples from 1991 through 1998. With the exception of one sample collected in August 1992, aluminum concentrations at both depths increase over time; cadmium concentrations at both depths indicate a slight upward trend also. Concentrations, while increasing, are less variable than those seen for iron and arsenic between sample events. Cadmium concentrations exceed the DEQ-7 drinking water human health standard for surface water of 5 µg/L by several orders of magnitude; aluminum does not have a regulated MCL.

Figure 29 presents copper and zinc concentrations in both the shallow and deep Berkeley Pit water samples collected from 1991 through 1998. Dissolved copper concentrations have remained fairly steady over time, while zinc concentrations rose slightly through 1997, before declining in 1998 to concentrations near those of 1991. Concentrations in all samples are orders of magnitude above drinking water standards for surface water of 1,300 µg/L for copper and 7,400 µg/L for zinc.

This method of sampling in the Berkeley Pit ended with a large landslide in the southeast corner of the pit on September 29, 1998. The wave action resulting from 3.5 million cubic yards of material falling into the pit dislodged the MBMG sample platform, depositing it on a bench on the west side of the pit about 40 ft above the pit water level. Figure 30 shows the seismic reading recorded by the MBMG Earthquake Studies Office from the landslide and resulting wave action. The recording shows that the wave action lasted several minutes after the initial slide occurred. The damage to the MBMG platform was extensive. MR had recently purchased a pontoon boat for use in their waterfowl mitigation monitoring program, and arrangements were made for use of this boat for future monitoring.

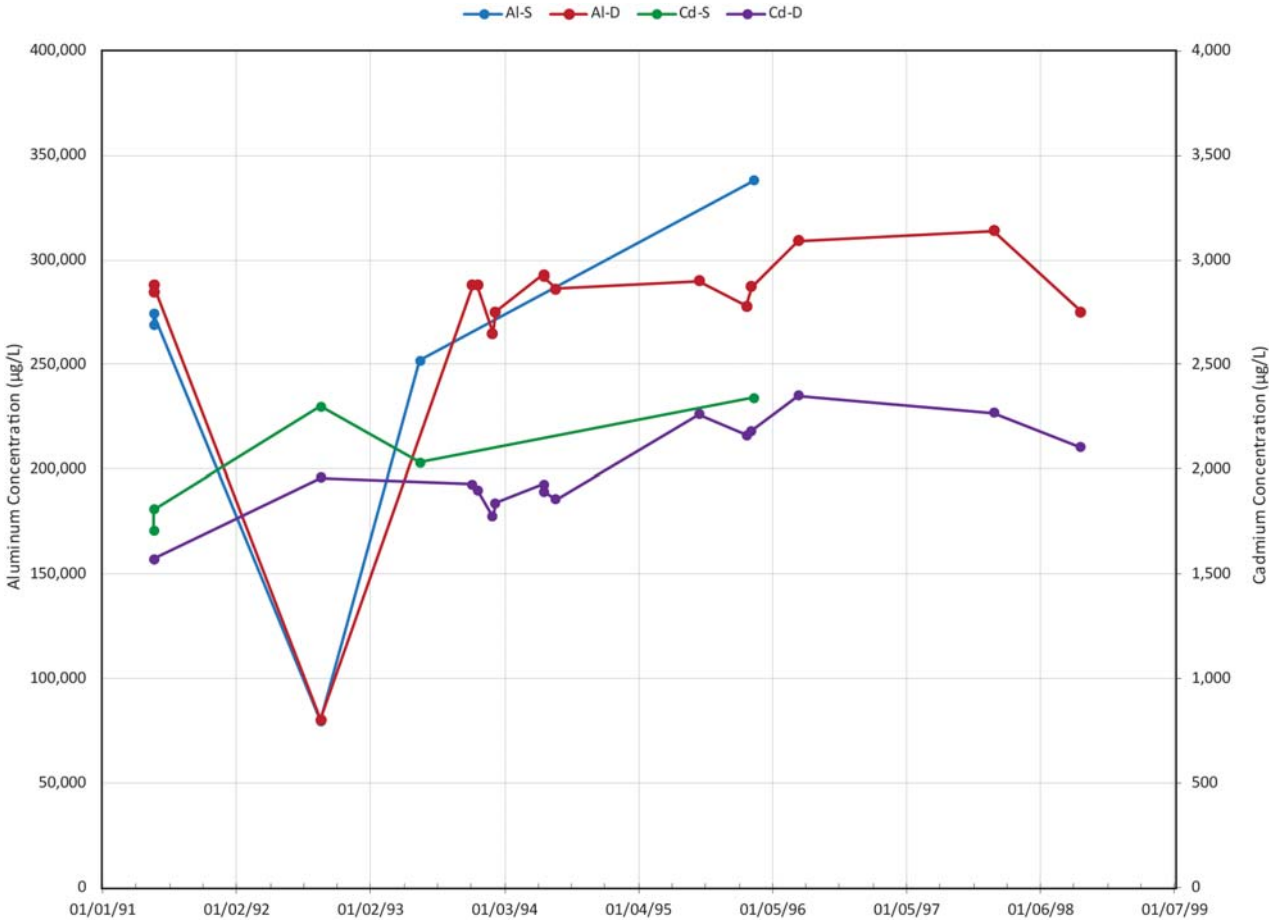


Figure 28. Dissolved aluminum and cadmium concentrations in Berkeley Pit water collected at shallow (-S) and deep (-D) depths.

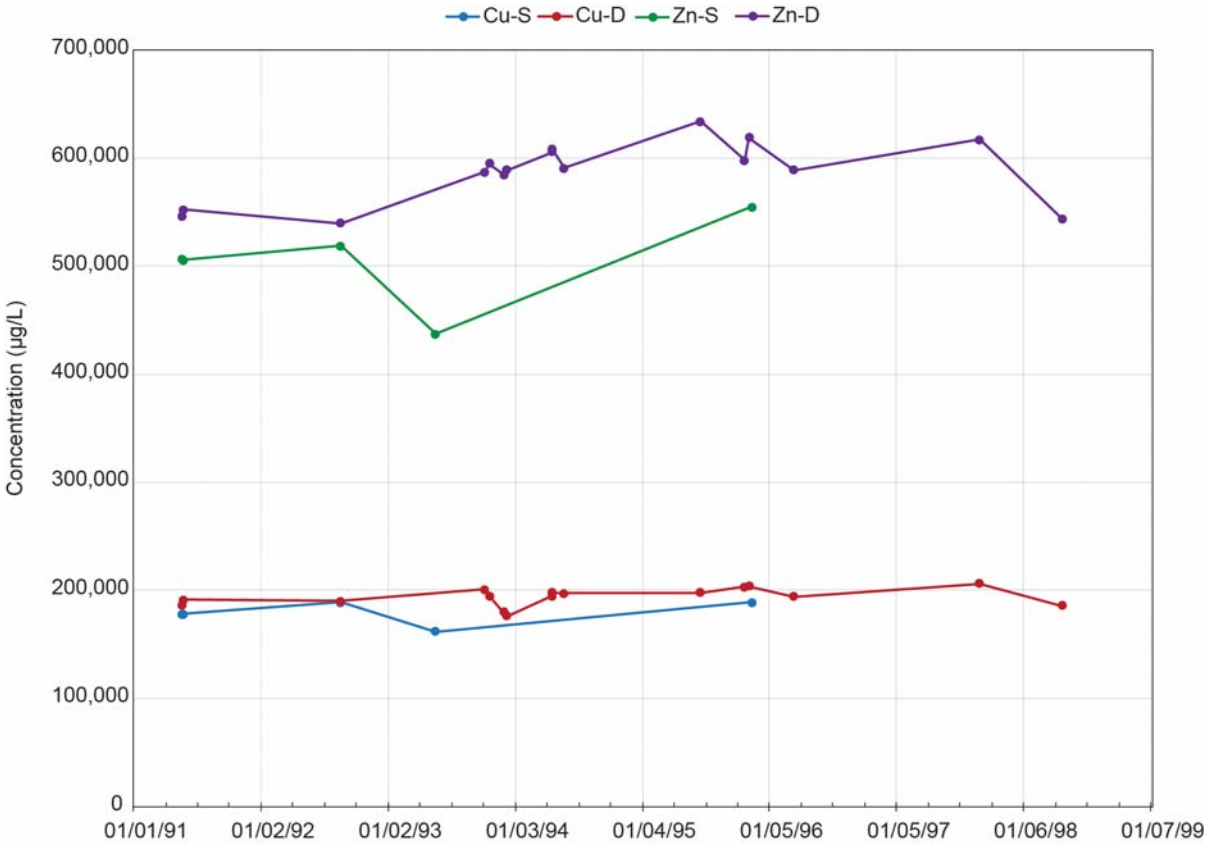


Figure 29. Dissolved copper and zinc concentrations in Berkeley Pit water collected at shallow (-S) and deep (-D) depths.

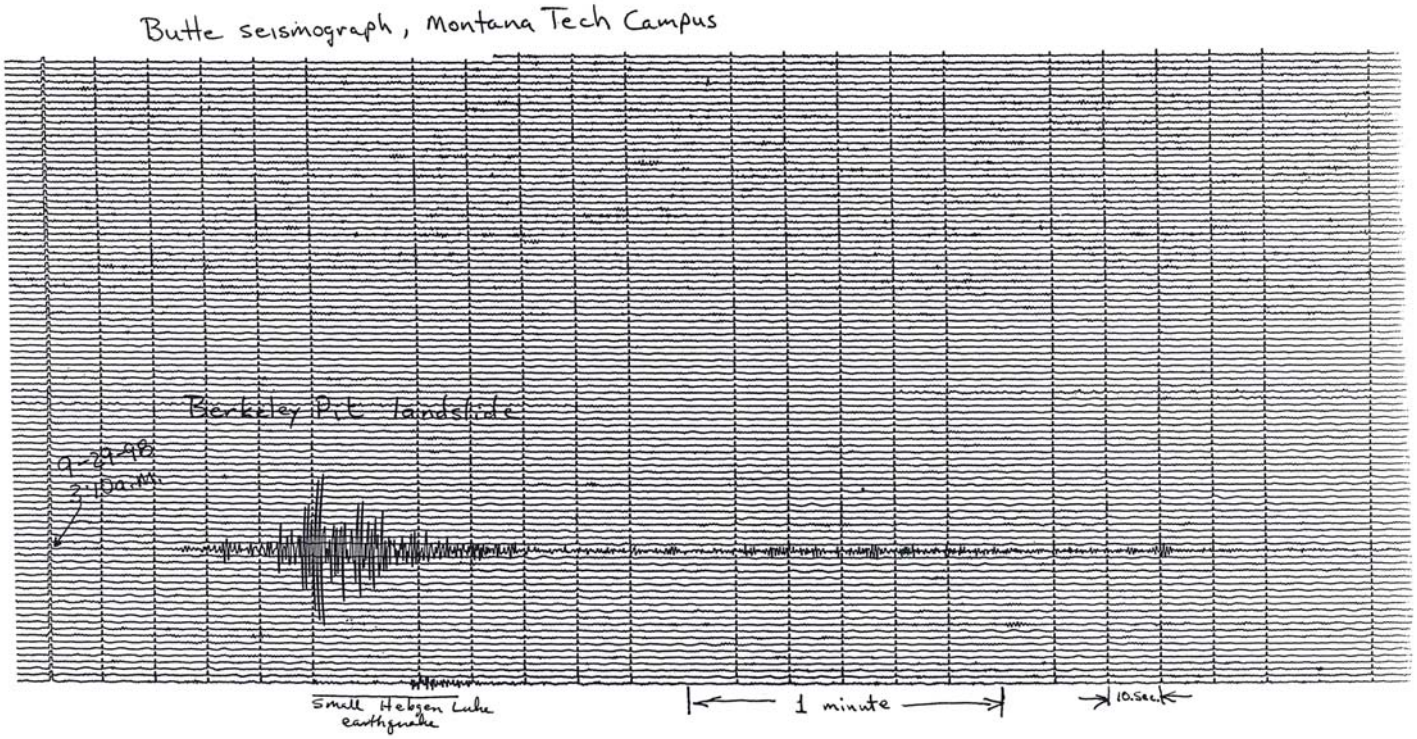


Figure 30. Graph from Montana Tech seismograph, September 29, 1998.

4.9 Vertical Profiling of Berkeley Pit (1991–1998)

Vertical profiling of the pit water column was conducted periodically during the 1991–1998 time period. Two events, conducted in May 1991 and May 1998, present a comparison of conditions in the pit water column during this time period. During both events, a Hydrolab DataSonde instrument was used to measure water temperature, pH, specific conductance (SC), dissolved oxygen (DO), and oxidation-reduction-potential (ORP as Eh). In 1991, the data profile was conducted by lowering the sonde through the water column, and a 300 ft direct read cable attached to the sonde sent data to a computer on the platform. In 1998, measurements were collected from just below the water surface (0.5 ft) to 100 ft, as water was pumped through a flow-through cell attached to the submerged sonde. Water samples below 100 ft were collected in a vertical sampler at 100 ft increments from 200 ft to 800 ft. These samples were pushed through the flow-through cell using nitrogen gas to keep a closed system and prevent the introduction of oxygen as physical parameters were measured.

4.10 Vertical Profile Data of Berkeley Pit (1991–1998)

Results of these profiles are presented in figures 31 through 35. A similar change in readings for all five measured parameters occurred at a depth of about 20 ft in both the 1991 and 1998 profiles. Measured values were mostly steady from that point to 300 ft with the exception of SC in the 1991 profile; 1991 SC values showed a gradual increase of about 200 µmhos/cm (2%), which is most likely instrument drift. The distinct changes at 20 ft indicate the presence of both a thermocline and chemocline in the pit water column (Gammons and Duaime, 2006). Temperature and pH values show the greatest level of variation/change in the depths below 300 ft in the 1998 profile. Both profiles show the acidic nature and high dissolved solids content of the water, similar to the water-quality data presented in the previous section.

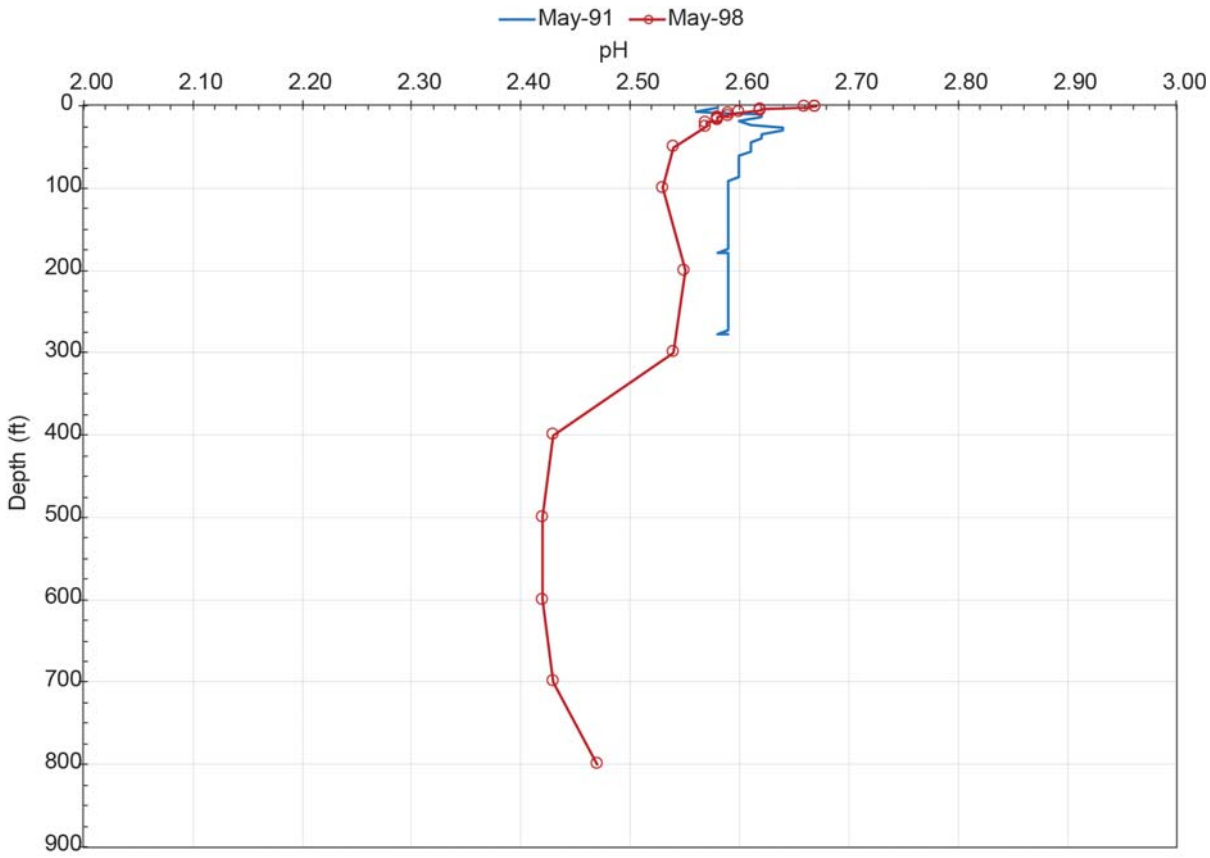


Figure 31. Berkeley Pit vertical profile showing pH changes.

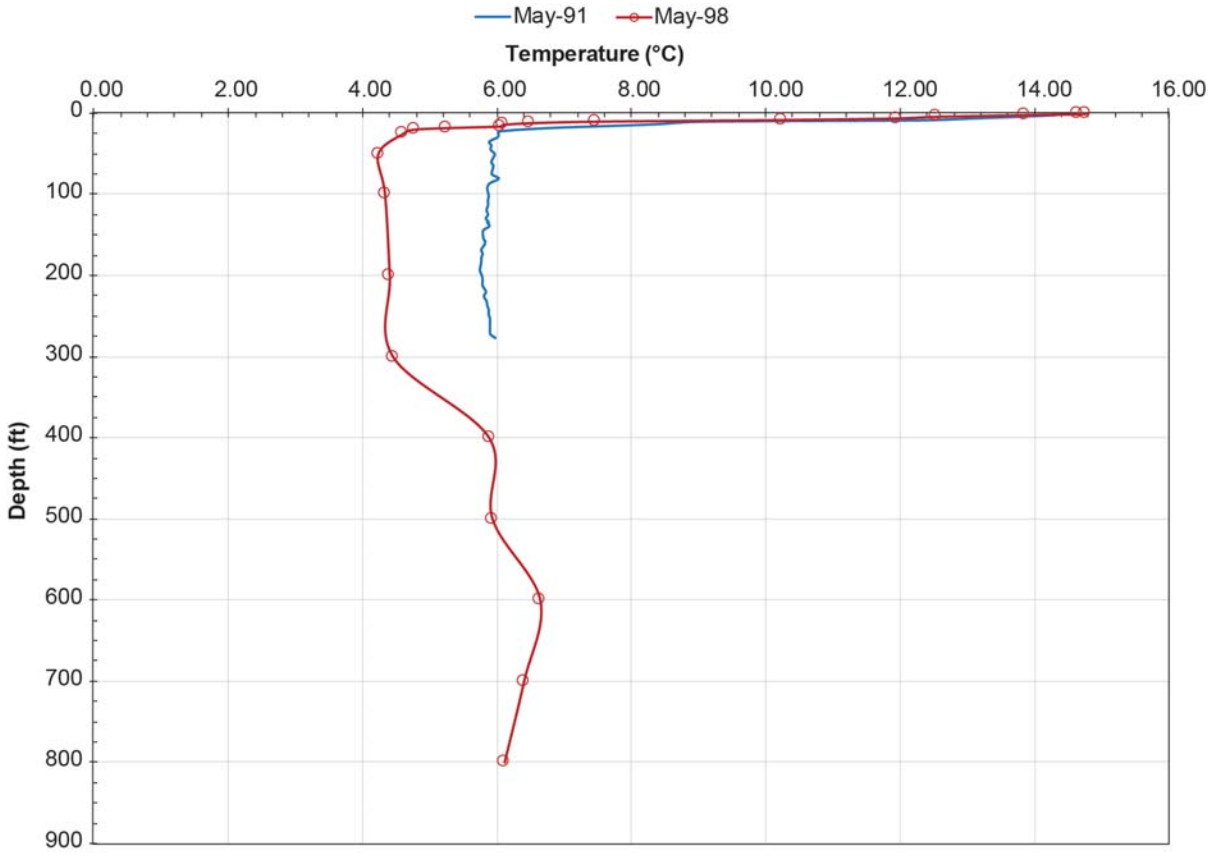


Figure 32. Berkeley Pit vertical profile showing temperature changes.

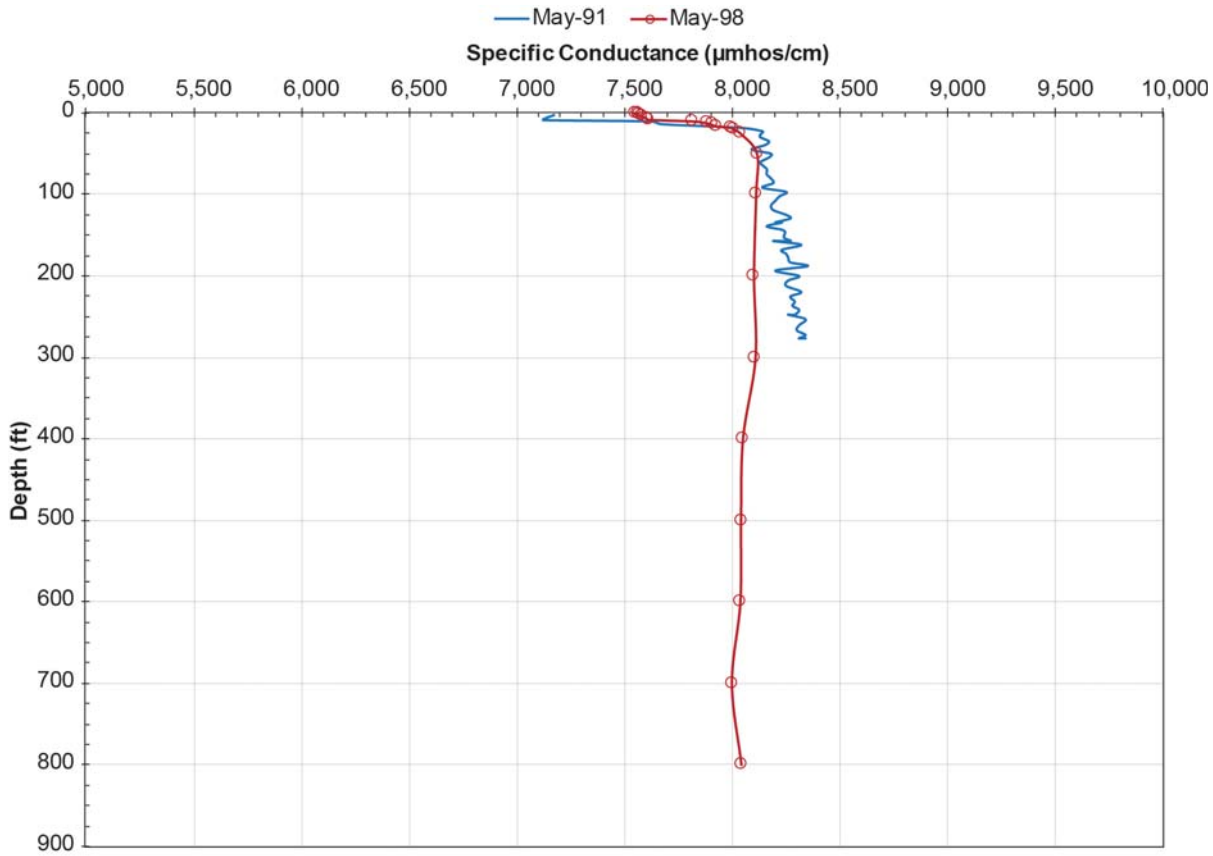


Figure 33. Berkeley Pit vertical profile showing specific conductance changes.

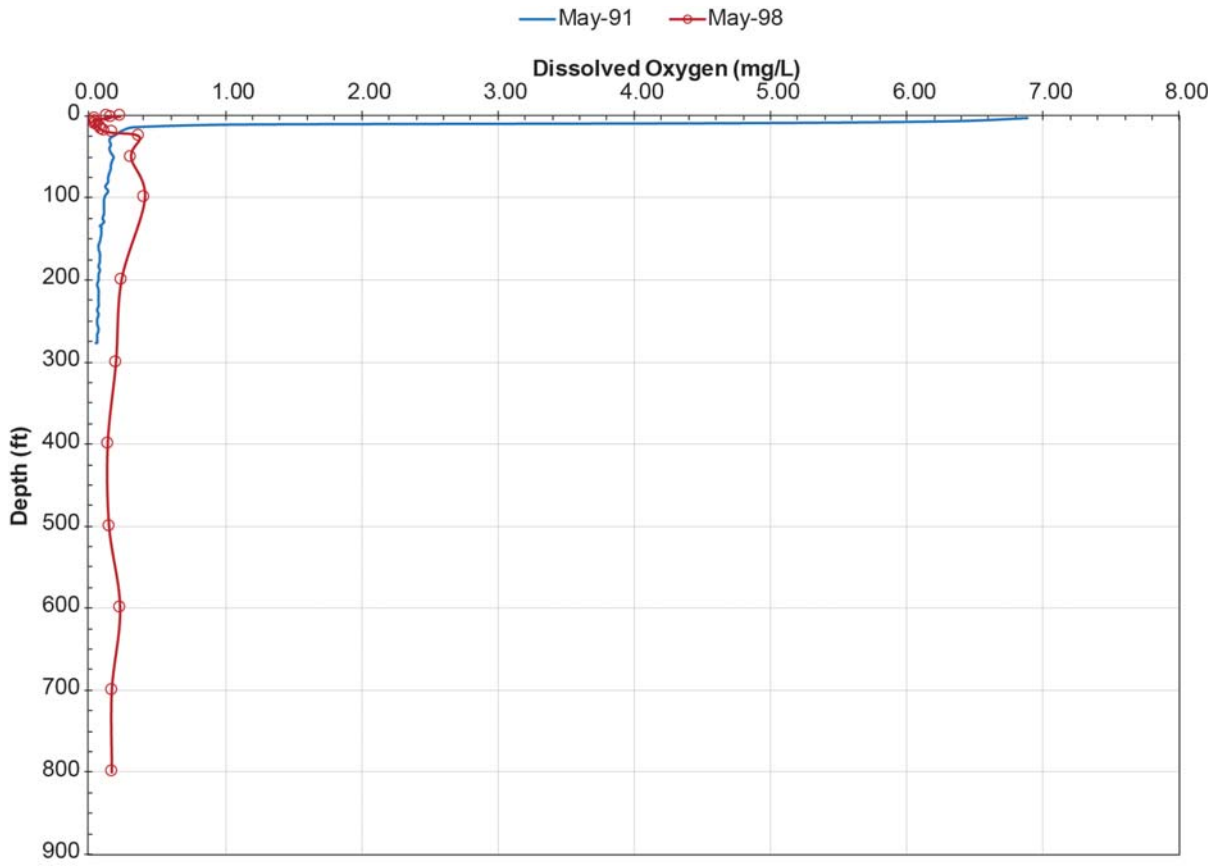


Figure 34. Berkeley Pit vertical profile showing dissolved oxygen changes.

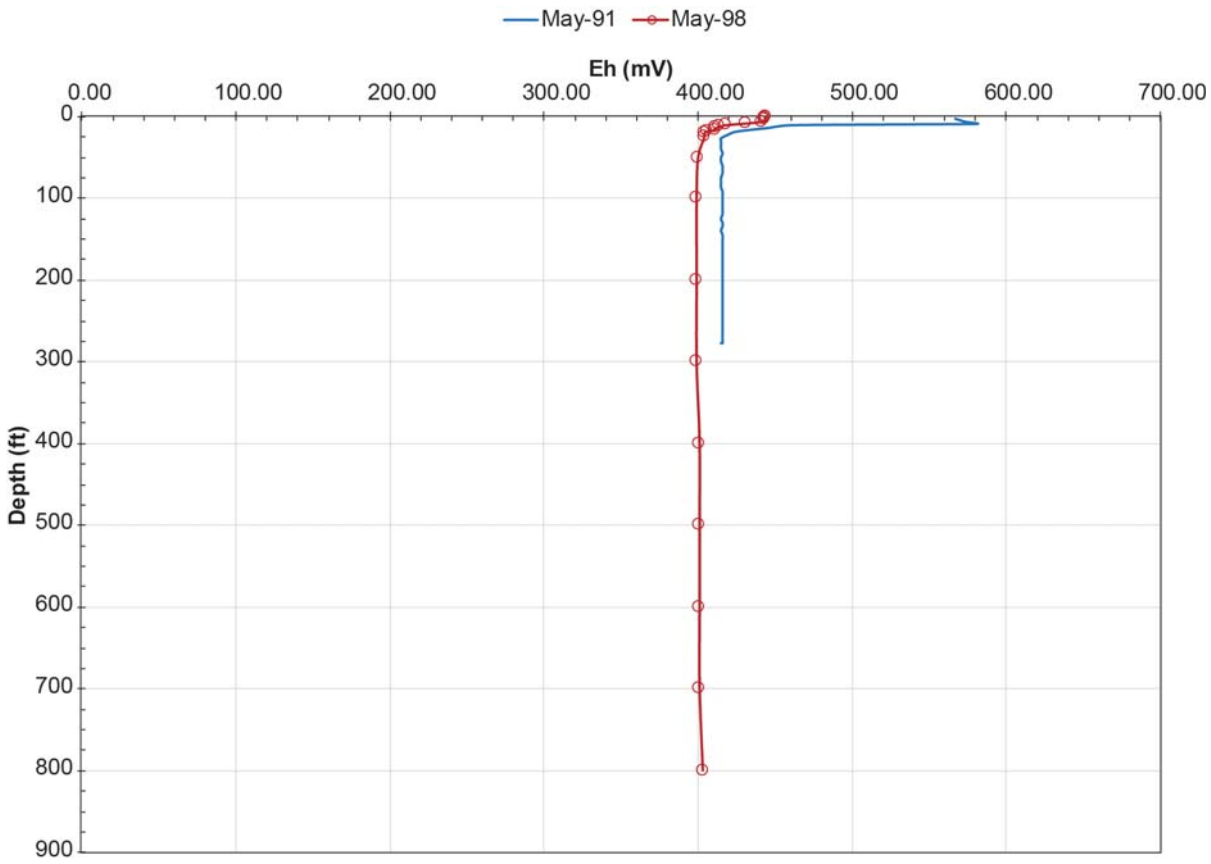


Figure 35. Berkeley Pit vertical profile showing Eh changes.

5.0 ROUTINE SAMPLING AND PROFILING WITH A PONTOON BOAT (1998–2013)

5.1 Events during 1998–2013

Many events that took place during this period would prove to have profound effects on the evolution of the Berkeley Pit Lake. They are summarized in table 12.

In August 1998, MR began pumping pit water to the precipitation plant for the recovery of copper, at rates up to 11,000 gpm. The plant effluent water was discharged to the pit, providing a source of water depleted in copper and slightly enriched in iron. The copper recovery operation continued until July 2000, when MR temporarily suspended mining operations due to high electrical costs and depressed copper prices. With the suspension of mining, the HSB diversion to the tailings pond was discontinued and HSB water was discharged into the pit. Water pumped from the Continental Pit from July 2000 through February 2001 was also diverted to the Berkeley Pit, but the flow rate of 200–285 gpm was small in comparison to the contribution from HSB, which ranged from 2,500 to 3,500 gpm during that time period. MR resumed mining operations in November 2003 and resumed copper recovery in January 2004. During the 2000–2003 mine suspension, MR and AR constructed a water treatment plant for HSB water as part of Superfund requirements; this plant came online in November 2003, concurrent with the restart of mining. HSB water was diverted away from the pit for treatment; treated water was incorporated into the mining operations. The water treatment plant was designed as a two-stage, high-density lime precipitation plant, with aeration. Sludge from the plant was discharged to the Berkeley Pit for disposal; the sludge was alkaline, with a pH of 10–11.

A report analyzing the short- and long-term effects of sludge disposal from the plant into the Berkeley Pit was prepared for AR and MR prior to the plant's construction (MSE, 2001). A very detailed discussion of the mechanism of dissolution of the sludge as it entered the water was presented. The report predicted that after 14 years of plant operation, the sludge alkalinity would have raised the pH in the pit to 4.27 and the aluminum concentration would have increased to 366 mg/L from 295 mg/L. The report did not take into account that copper recovery would be operating simultaneously, contributing ferrous iron to the pit water.

Table 12. Timeline for operational changes and natural occurrences that may have influenced Berkeley Pit water quality, 1998–2013.

Date	Event	Significance
August 1998	MR began pumping water from the Berkeley Pit for copper recovery.	Water discharged back into the pit after copper recovery in the precipitation plant; high iron concentration in return water.
September 1998	Large landslide occurred in the southeast corner of the Berkeley Pit.	An estimated 1.3 million cubic yards of material entered the pit, resulting in a 2.5 ft water-level rise. Wave action in pit damaged the MBMG sample platform, washing it up on a mine bench on west side of pit.
June 30, 2000	MR suspended mine operations.	Horseshoe Bend water diverted back into Berkeley Pit, resulting in an additional 3 million gallons a day or more of water filling the pit. Increased monthly water-level rise in pit, underground mine system, and associated bedrock aquifer.
July 2000–February 2001	Water from Continental Pit pumped to Berkeley Pit.	Slight increase seen in filling rate (flows ranged from 200 to 285 gpm). Near neutral pH and relatively low metal concentrations.
November 2003	MR resumed mining in Continental Pit. Horseshoe Bend water treatment plant comes online.	Horseshoe Bend water diverted away from pit and to water treatment plant; treated water used in mine operations. Sludge from plant discharged to pit. Slowed filling rate by reducing 3 million gallons per day of water from pit.
January 2004	MR resumed Berkeley Pit copper recovery project.	Water discharged back into the pit after copper recovery in the precipitation plant; high iron concentration in return water.
August 2012	Minor landslide occurred in southeast corner of Berkeley Pit.	No effect seen on pit water levels.
November 2012	Minor landslide occurred in southeast corner of Berkeley Pit.	Pontoon boat and boat dock received minor damage; boat removed for repairs. Fall Berkeley Pit sampling event canceled.
February 2013	Relatively large landslide occurred in southeast corner of Berkeley Pit.	Estimated that 0.45 million cubic yards of material entered the pit, resulting in about a 1 ft water-level rise. Wave action in pit damaged copper recovery pipeline. Copper recovery operation suspended.

5.2 Sampling and Vertical Profiling with Pontoon Boat (1998–2013)

During this same time period EPA, DEQ, AR, MR, and Washington Corp. reached a Consent Decree that finalized the long-term monitoring program for the Berkeley Pit and other sites within the Butte Mine Flooding Operable Unit of the Silver Bow Creek Superfund Site. The monitoring program specified semi-annual sampling of the pit from three depths, along with vertical profiles of the pit water column. As a result, consistent monitoring and sampling began in 2002; sampling typically occurred in late spring and fall.

Many changes occurred in the Berkeley Pit and the pit monitoring program between 1999 and 2012. Moving from the small sampling platform to a pontoon boat (fig. 36) provided both a stable work platform and greater pit access. The September 29, 1998 landslide and the resulting wave action probably caused considerable mixing throughout the pit water column.

More than 35 separate water sampling/monitoring events occurred between 1999 and 2013, when multiple depth samples were collected. Samples collected in 1999, 2001, 2003, 2004, and 2012 provide a snapshot of water-quality conditions and changes in quality that may have occurred due to operational changes and various water sources entering and being removed from the pit.

Vertical profiles of the Berkeley Pit water column were conducted typically in the spring and fall each year. Between 1999 and 2005, profiles were to a depth of 300 ft; beginning in 2006, profiles were made to a depth of 600 ft as equipment was upgraded. Hydrolab DataSondes (series 3, 4, and 5) were used for all profiling. Occasionally, point source samples were taken using various types of vertical samplers to depths between 600 and 700 ft. Physical parameters were measured in the field upon sample retrieval. Physical parameters measured were consistent with prior years. Turbidity was occasionally measured in later years. Figure 37 shows a typical Data Sonde used in 2010 and later for profiling.

5.3 Water-Quality Results from Pontoon Boat Sampling (1998–2013)

Chemical stratification occurred in the 1999 dissolved water-quality data for iron, arsenic, and copper in samples collected 60 ft and deeper, shown in table 13. By 2001 the surface (1 ft) samples had considerably lower concentrations for almost all of the analytes shown in table 13, while concentrations below 50 ft were consistent with the 1999 sample results. By 2004 concentrations for iron, aluminum, arsenic, copper, and zinc had all decreased in the 50 ft sample; by 2012 concentrations had decreased throughout the entire water column. Previous reports by Duaime and others (2014) and Tucci and Gammons (2015) had determined that the reductions in metal concentrations were due to a combination of the MR copper recovery operation depleting the copper concentration throughout the entire pit, diversion of HSB water away from pit, and the co-precipitation of arsenic with iron oxides, reducing the aqueous arsenic and iron concentrations. The addition of the highly alkaline sludge from the HSB water treatment plant may have also played a role in the reduction of metal concentrations by providing alkalinity to offset the pH change that accompanied the hydrolysis of iron oxides. For instance, the precipitation of schwertmannite, one of the principal iron oxyhydroxides identified in the pit, is accompanied by the generation of protons, as shown in equation 2 (Tucci and Gammons, 2015):

$$8\,Fe^{3+}_{(aq)} + x\,SO^{2-}_{4\,(aq)} + (16-2x)H_2O \rightarrow Fe_8O_8(OH)_{8-2x}(SO_4)_{x\,(s)} + (24-2x)H^{+}_{(aq)} \quad (2)$$

For the reaction to proceed to the right, a sink for the generated acidity must have been available. As soon as the water treatment plant came online in 2003, iron and arsenic concentrations started to decline, most likely because the sludge neutralized the acidity generated in reactions similar to the one shown in equation 2 by dissolution of metal hydroxides in the sludge, as shown in equation 3. Major components of the sludge were calcium hydroxide (Stage 2) and aluminum hydroxide (Stage 1) type compounds, which would have redissolved in the acidic water:

$$Ca(OH)_{2\,(s)} + 2H^{+}_{(aq)} \rightarrow Ca^{2+}_{(aq)} + 2H_2O$$
$$Al(OH)_{3\,(s)} + 3H^{+}_{(aq)} \rightarrow Al^{3+}_{(aq)} + 3H_2O \quad (3)$$

Calcium solubility in the pit is limited by gypsum formation as $CaSO_4 \cdot 2H_2O$. Aluminum solubility would allow for concentration in the pit to increase until the pH reached 4.5. Other Stage 2 metal hydroxides such as zinc and manganese should also be soluble in low pH waters unless other equilibria were controlling their solubilites.

Figure 36. MR pontoon boat: (A) new 2011 boat dock; (B) sampling equipment during 2003 Berkeley Pit sampling event.

Figure 37. Photo of Hydrolab DataSonde Model DS5x used for Berkeley Pit profiling.

Mixing of the sludge into the pit volume probably occurred by several mechanisms. The copper recovery process pumped 11,000 gpm from the southwest side of the pit between 2004 and 2007, and from the north side of the pit from 2008 until the cessation of the recovery operation in February 2013. The same volume was returned over the eastern wall of the pit, effectively circulating greater than one volume of pit water between 2004 and 2012. The turbulence and circulation induced by this process could have had a considerable effect on mixing (Tucci and Gammons, 2015). Also, wind-driven wave action may have contributed turbulence. If sludge that initially had a pH of 10 dissolved in the low pH water while settling, the wave action could have distributed the effect throughout the pit over time. Another possibility is sediment disruption following landslides. Three landslides occurred in the southeast corner of the pit in 2012 and 2013. The slumps generated large tsunami-like waves and destroyed infrastructure of the copper recovery system. These events likely contained enough energy to distribute the settled sludge throughout the pit. In addition to mixing, the landslide material may have contributed alkalinity in the form of carbonate minerals. However, the decline in iron and arsenic concentrations began in 2006, long before the 2012 and 2013 landslide occurrences, suggesting that the copper recovery operation played the major role in distributing sludge alkalinity. Thermal and seasonal turnover are operative in the pit and those processes certainly contributed to mixing. Table 13 presents selected water-quality data from spring sampling events for these 5 years; 1999 data are from the fall period but are included to provide early data closest to the start of the 1998 copper recovery operation.

Between 1999 and 2012, concentrations of iron, arsenic, and copper decreased considerably in the 200 and 250 ft samples, ranging from 71% to 90% (table 14).

Following the concentrations of dissolved total iron, ferrous iron (Fe^{2+}), and arsenic between 1999 and 2012 also argues for the role of the HSB water treatment plant sludge in affecting the chemistry of the pit, as shown in figure 38. The treatment plant came online shortly before the copper recovery process resumed.

Table 13. Dissolved water-quality concentrations for selected analytes from spring sample events conducted in 1999, 2001, 2003, 2004, and 2012.

Sample Date	Sample Depth (ft)	Field pH (+/- 0.2)	Field Temp. 0C	Sulfate (mg/L)	Iron (mg/L)	Aluminum (µg/L)	Arsenic (µg/L)	Cadmium (µg/L)	Copper (µg/L)	Zinc (µg/L)
							MCL	MCL	MCL	MCL
							10	5	1,300	7,400
11/19/99	1	2.14	6. 6	8,646	830	233,000	242	2,190	136,000	618,000
11/19/99	20	2.13	6. 5	8,549	826	235,000	232	2,180	137,000	624,000
11/19/99	40	2.13	6.5	8,564	844	233,000	<500	2,200	134,000	630,000
11/19/99	60	2.15	4.8	8,679	938	231,000	622	2,210	188,000	604,000
11/19/99	100	2.15	4.8	8,680	940	227,000	735	2,200	185,000	600,000
11/19/99	200	2.14	4.8	8,777	942	226,000	749	2,220	184,000	609,000
05/07/01	1	2.97	11.6	5,075	208	159,000	<100	1,380	74,000	312,000
05/07/01	50	2.75	5.5	8,758	895	279,000	271	2,000	134,000	640,000
05/07/01	100	2.80	5.5	8,985	979	279,000	692	2,090	178,000	633,000
05/07/01	200	2.80	5.6	9,031	977	278,000	729	2,130	177,000	652,000
05/07/01	300	2.64	5.6	8,970	970	279,000	715	2,120	176,000	652,000
05/14/03	1	2.71	14.0	4,580	245	119,000	387	1,160	59,900	249,000
05/14/03	50	2.38	6.1	9,150	728	265,000	304	2,170	122,000	573,000
05/14/03	200	2.42	6.6	9,680	1,020	271,000	902	2,220	178,000	608,000
05/14/03	710	2.40	8.3	9,730	1,020	272,000	905	2,220	178,000	599,000
05/27/04	1	3.48	12.9	7,560	481	189,998	218	1,642	65,796	435,575
05/27/04	50	3.14	5.8	7,850	536	202,407	205	1,756	68,766	464,515
05/27/04	200	3.01	7.0	10,070	1,035	289,477	761	2,331	178,450	648,770
06/04/12	1	2.55	10.6	7,740	211	295,295	74	2,004	49,198	631,176
06/04/12	50	2.56	2. 7	8,005	246	276,769	67	2,190	51,894	601,515
06/04/12	250	2.58	2. 7	7,964	260	292,858	73	2,033	54,134	632,926
06/04/12	500	2.59	2.7	7,922	264	282,489	78	1,913	56,005	653,455
06/04/12	725	2.60	6.0	7,849	260	296,092	70	2,044	53,977	632,561

Note. MCL, maximum contaminant level for human health standards in surface water. DEQ-7 Montana Numeric Water Quality Standards, May 2017.

Table 14. Percent decrease in dissolved concentrations in Berkeley Pit 200 ft depth samples between 1999 and 2012.

Sample Date	Sample Depth (ft)	Iron (mg/L)	Arsenic (µg/L)	Copper (µg/L)
11/19/99	200	942	749	184,000
05/07/01	200	977	729	177,000
05/14/03	200	1,020	902	178,000
05/27/04	200	1,035	761	178,450
06/04/12	250	260	73	54,134
Percent Decrease		72	90	71

Pumping water from the pit brought oxygenated surface water to lower depths while the precipitation plant return was contributing ferrous iron. Within 3 years of operating under these conditions, iron and arsenic started to decline. This suggests that iron oxidation equilibria were shifted due to removal of ferric iron (Fe^{3+}) as solid oxyhydroxide precipitates (equation 4), possibly assisted by consumption of acidity by the sludge. Therefore, ferric iron was removed, allowing more ferrous iron to be oxidized to ferric iron:

$$2\,Fe^{2+}_{(aq)} + \frac{1}{2}\,O_2 + 2H^{+}_{(aq)} \rightarrow 2Fe^{3+}_{(aq)} + H_2O \quad (4)$$

Arsenic removal occurred through adsorption onto the surface of the ferric oxyhydroxide precipitates.

Based on the pumping rate of 11,000 gpm (15.84 MGD) for the copper recovery process and the year-end pit volumes from 2004 through 2012, more than 1.2 volumes of pit water would have been pumped and circulated during this 9-year period. The pumping of high concentration copper water and the recirculation of dilute copper water from the precipitation plant effluent had the net effect of lowering the overall copper concentration throughout the entire pit water column. Figures 39, 40, and 41 show the concentrations for dissolved arsenic, iron, and copper throughout the water column from the surface to over 700 ft deep between October 2002 and November 2009.

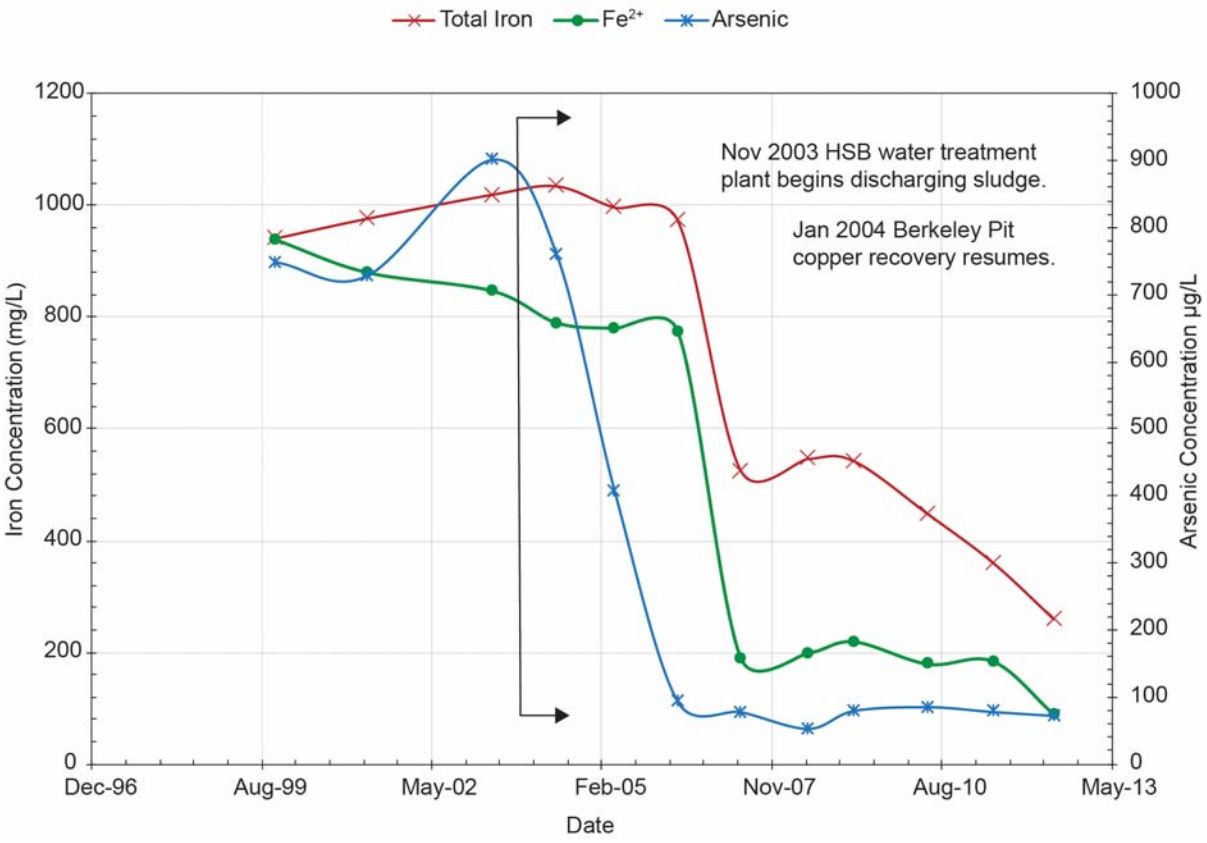


Figure 38. The change in total dissolved iron, arsenic, and ferrous iron at approximately 200 ft depth in the Berkeley Pit between 1999 and 2012. Ferrous iron determined by MR in laboratory titration. Arrows highlight changes following addition of sludge.

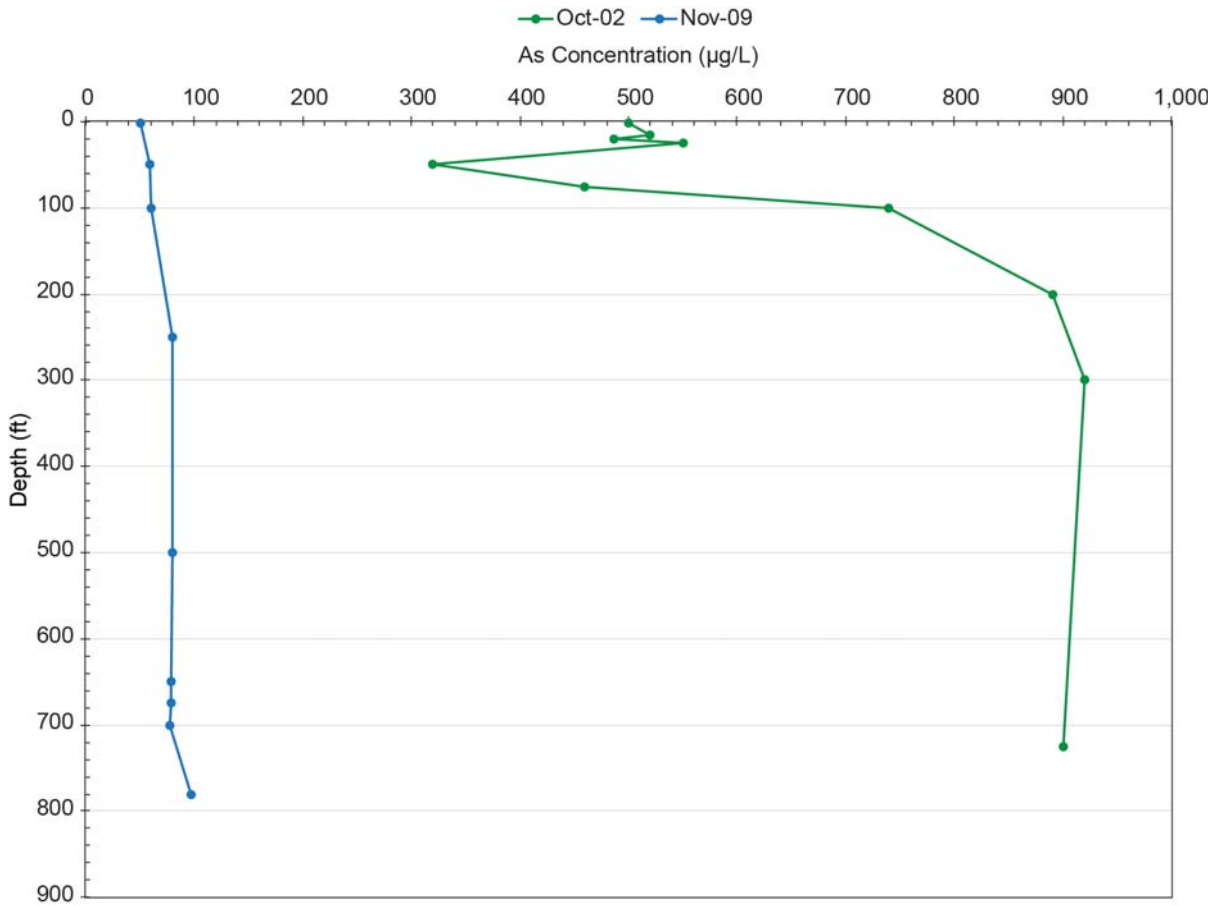


Figure 39. Arsenic concentration with depth in October 2002 and November 2009 Berkeley Pit samples.

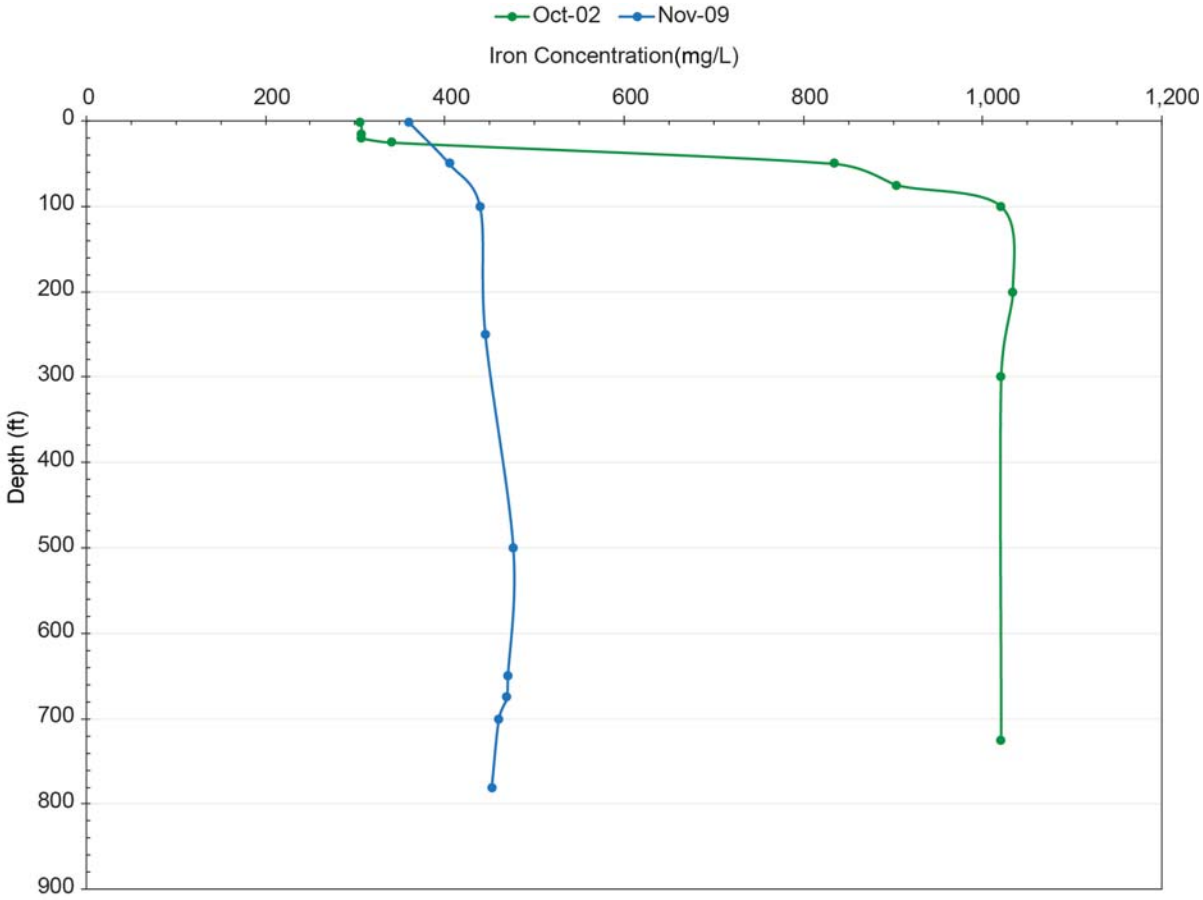


Figure 40. Iron concentration with depth in October 2002 and November 2009 Berkeley Pit samples.

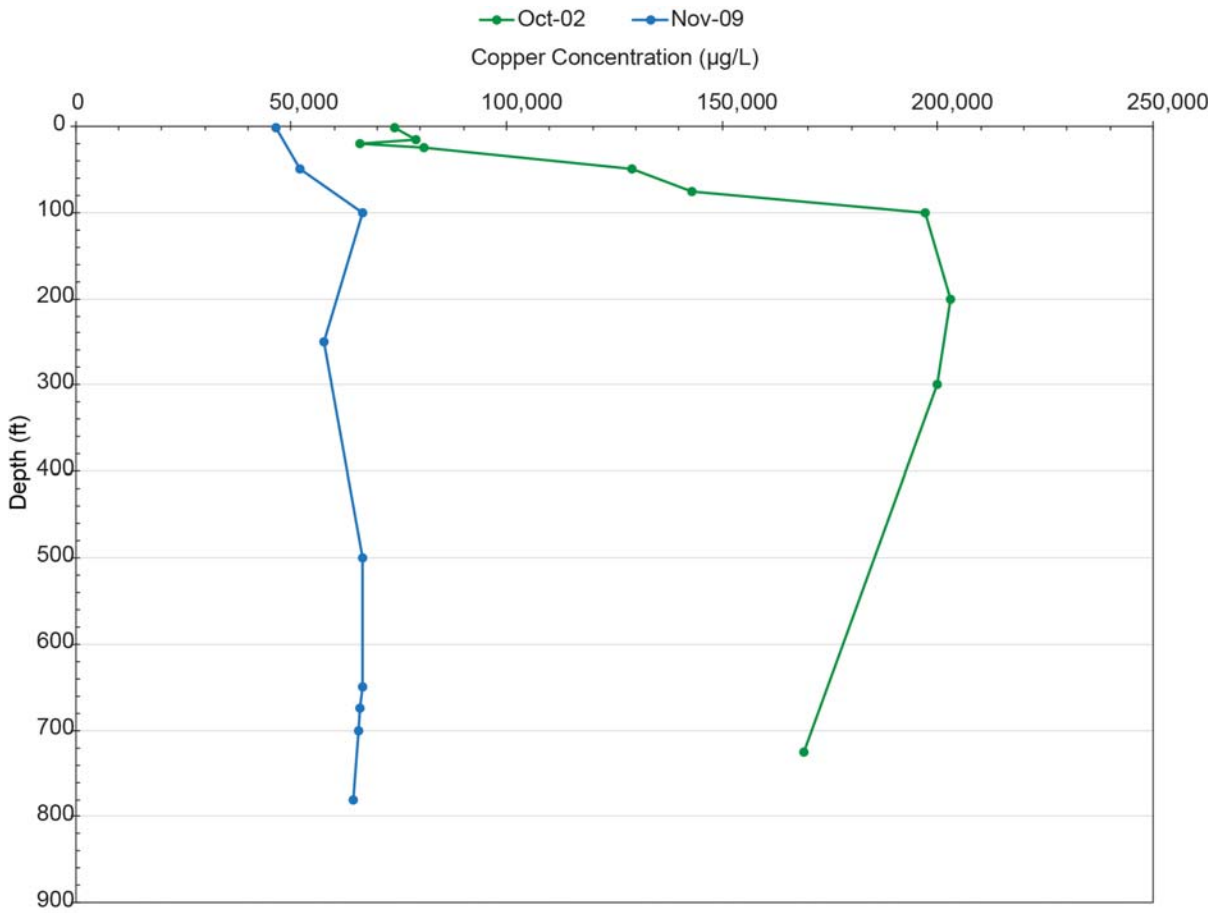


Figure 41. Copper concentration with depth in October 2002 and November 2009 Berkeley Pit samples.

In addition to the physical changes to water handling within the mine operations and Berkeley Pit that had significant impacts on pit water chemistry, small landslides in the southeast corner of the pit occurred in August and November 2012. The amount of material that entered the pit was minor in comparison to the 1998 landslide; however, the wave action following the November landslide caused significant damage to the pontoon boat and dock. As a result, no on-water depth sampling or profiling was conducted the fall of 2012.

5.4 Berkeley Pit Vertical Profile Data from Pontoon Boat (1998–2013)

Data from fall profile events in 1999, 2002, 2009, and 2011 (figs. 42–47) show changes in physical parameters in the pit with depth. The 2002 profile was collected during a shutdown period for the mining operation. Circulation from the copper recovery program had ceased, and water from the HSB drainage was discharging to the pit.

Distinct changes (thermocline and chemocline) are apparent on many of these graphs, demonstrating stratification within the pit water column. Figure 44 clearly shows SC increasing at depths between about 20 and 50 ft during each sampling event, although the magnitude of the increase varies throughout time.

The fall 1999 data show the lowest pH and highest SC values throughout the water column; the increasing pH values over time appear to indicate slight improvement in pit chemistry. This corresponds to changes noted in the previous section between copper and iron concentrations in 2002 and 2009 samples.

Profile data for DO, Eh, and turbidity show considerable variation between events. The turbidity profile for October 2002 registered zero for all depths and is considered suspect. The higher DO reading in October 2002 and October 2011 may be due in part to the higher surface and shallow water temperatures, indicating that fall turnover had not occurred. The pH profile for 2011 also indicates that turnover had not occurred.

Tucci and Gammons (2015) discussed the flux of solids occurring throughout the water column as determined through the installation of Imhoff cones at various depths in 2008. The presence of large amounts of precipitates in the Imhoff cones suggests that the higher turbidity readings in the 2009 and 2011 profiles are real.

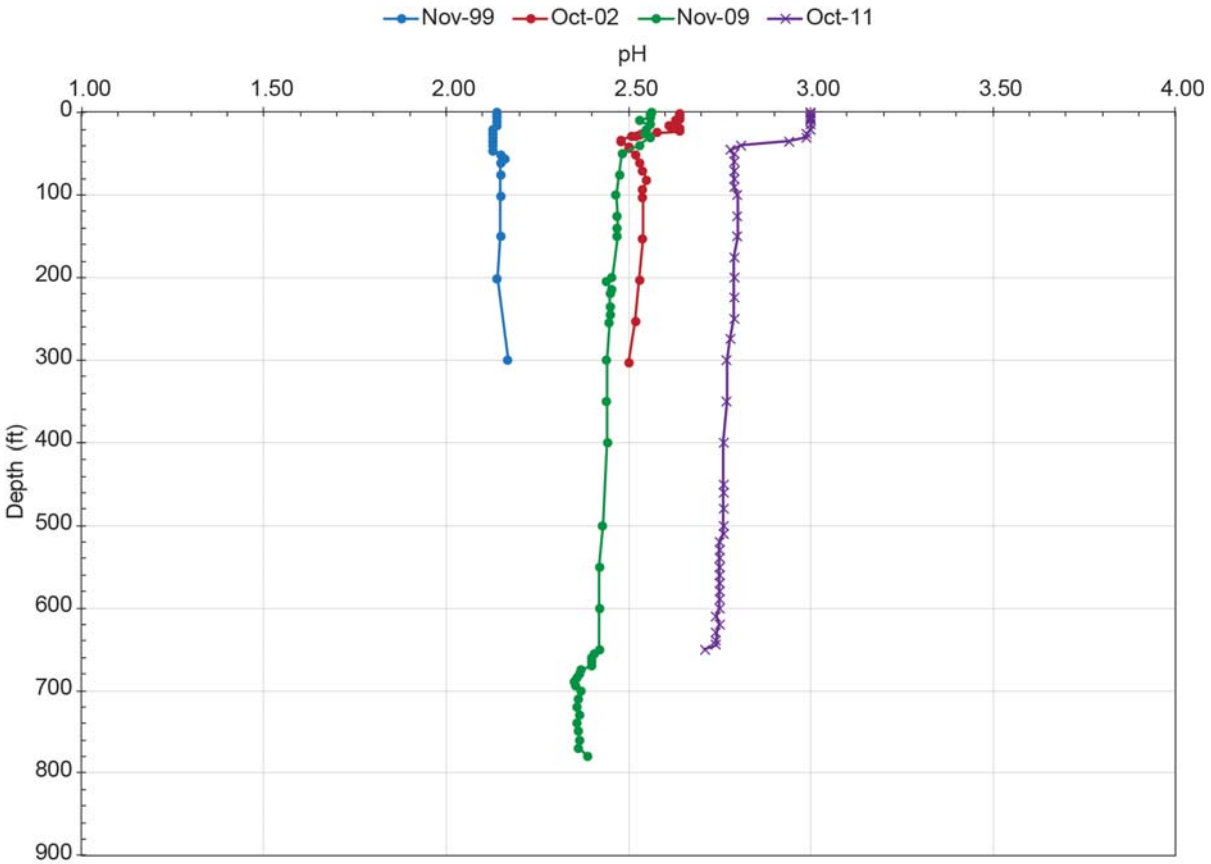


Figure 42. Solution pH with depth profiles for November 1999, October 2002, and November 2009 in the Berkeley Pit.

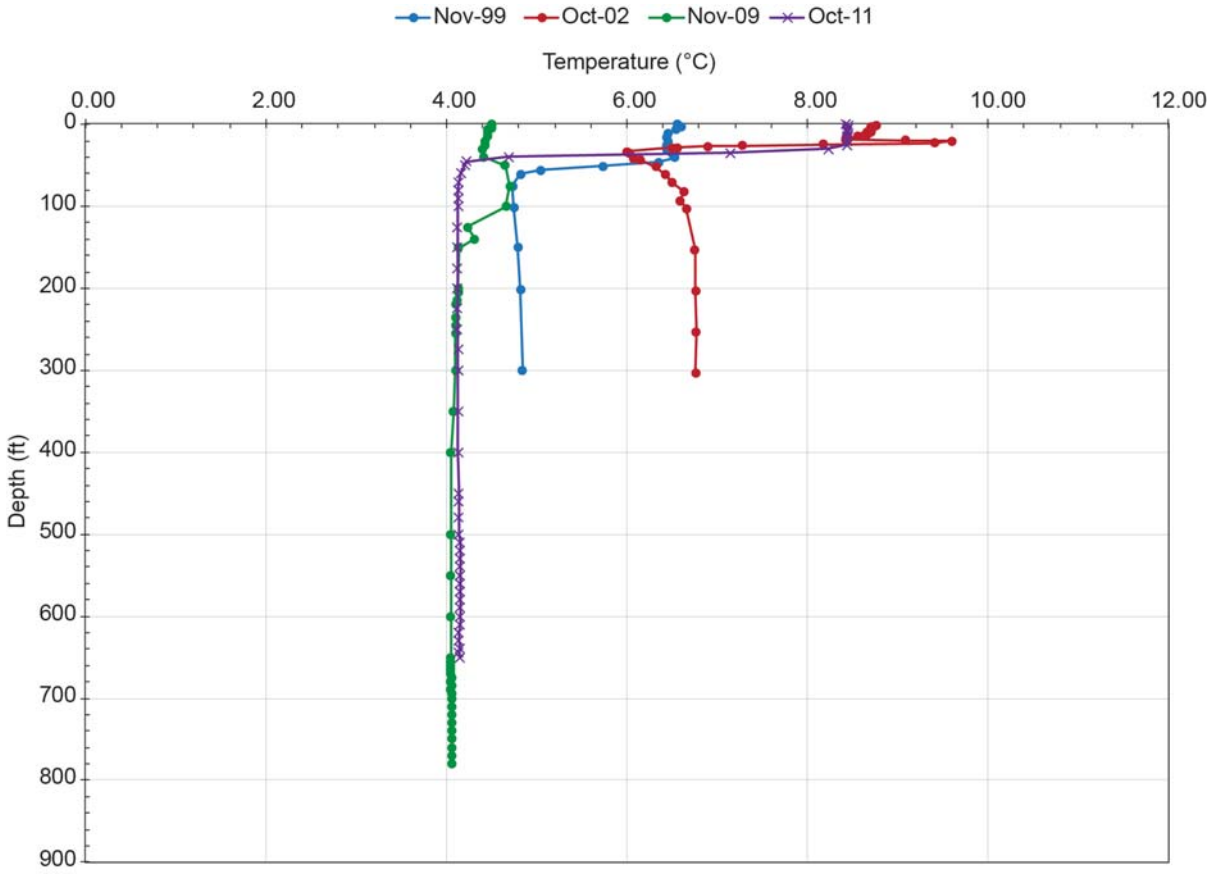


Figure 43. Temperature with depth profiles for November 1999, October 2002, and November 2009 in the Berkeley Pit.

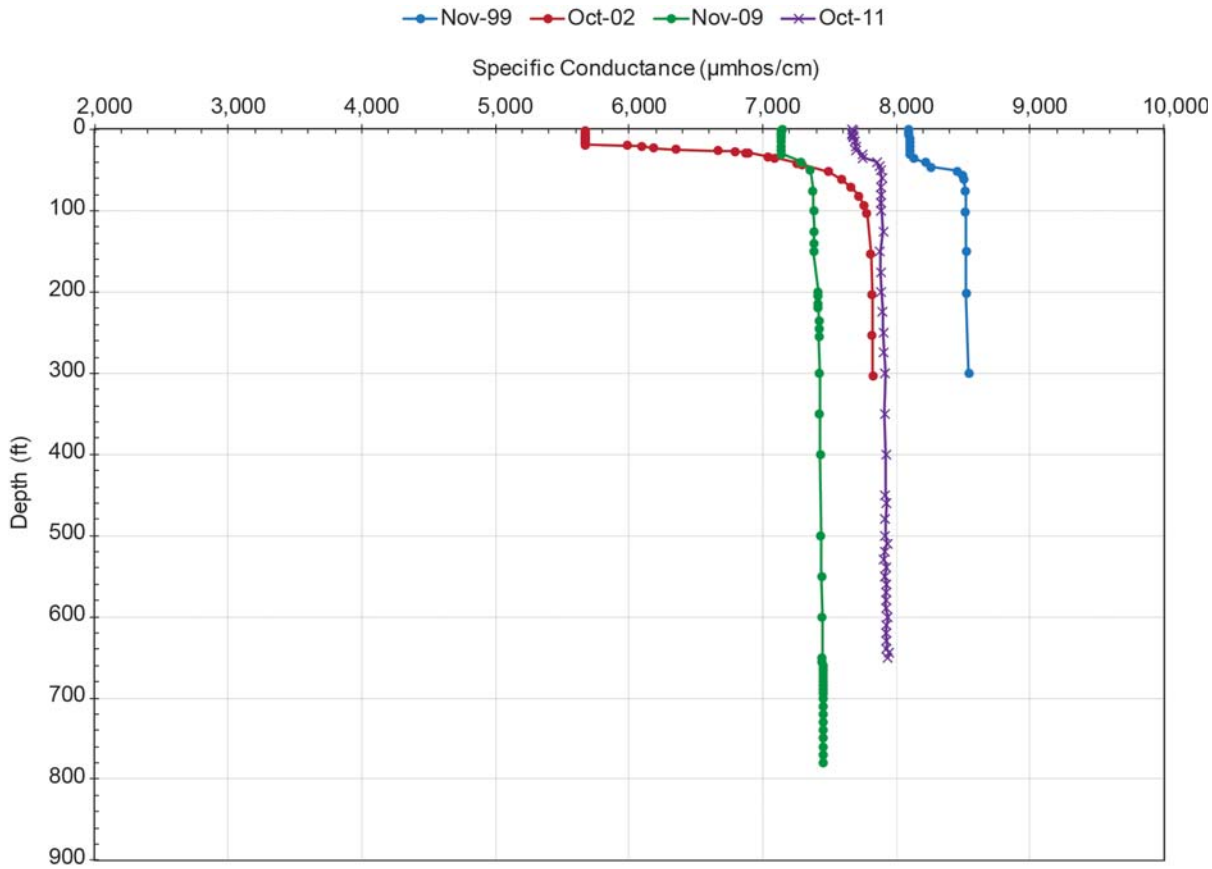


Figure 44. Specific Conductance with depth profiles for November 1999, October 2002, and November 2009 in the Berkeley Pit.

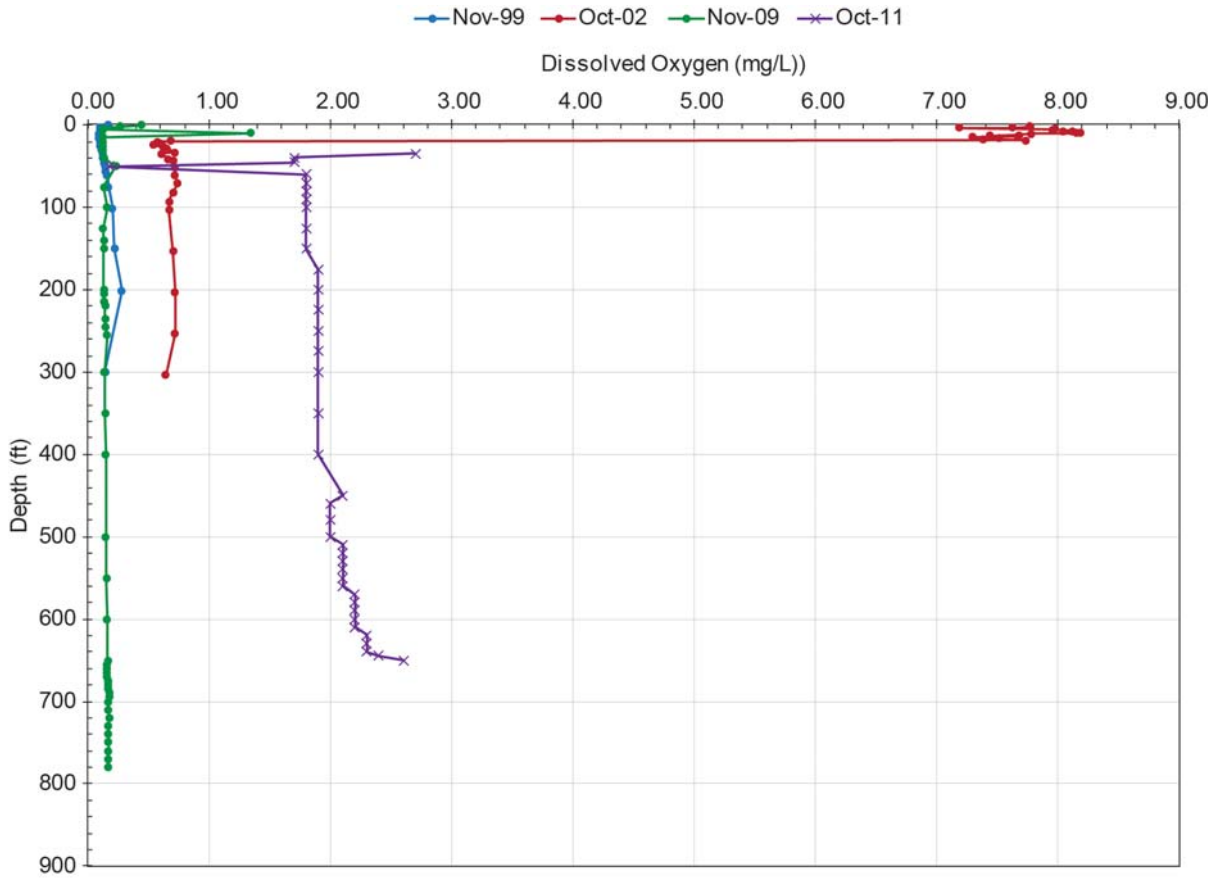


Figure 45. Dissolved oxygen with depth profiles for November 1999, October 2002, and November 2009 in the Berkeley Pit.

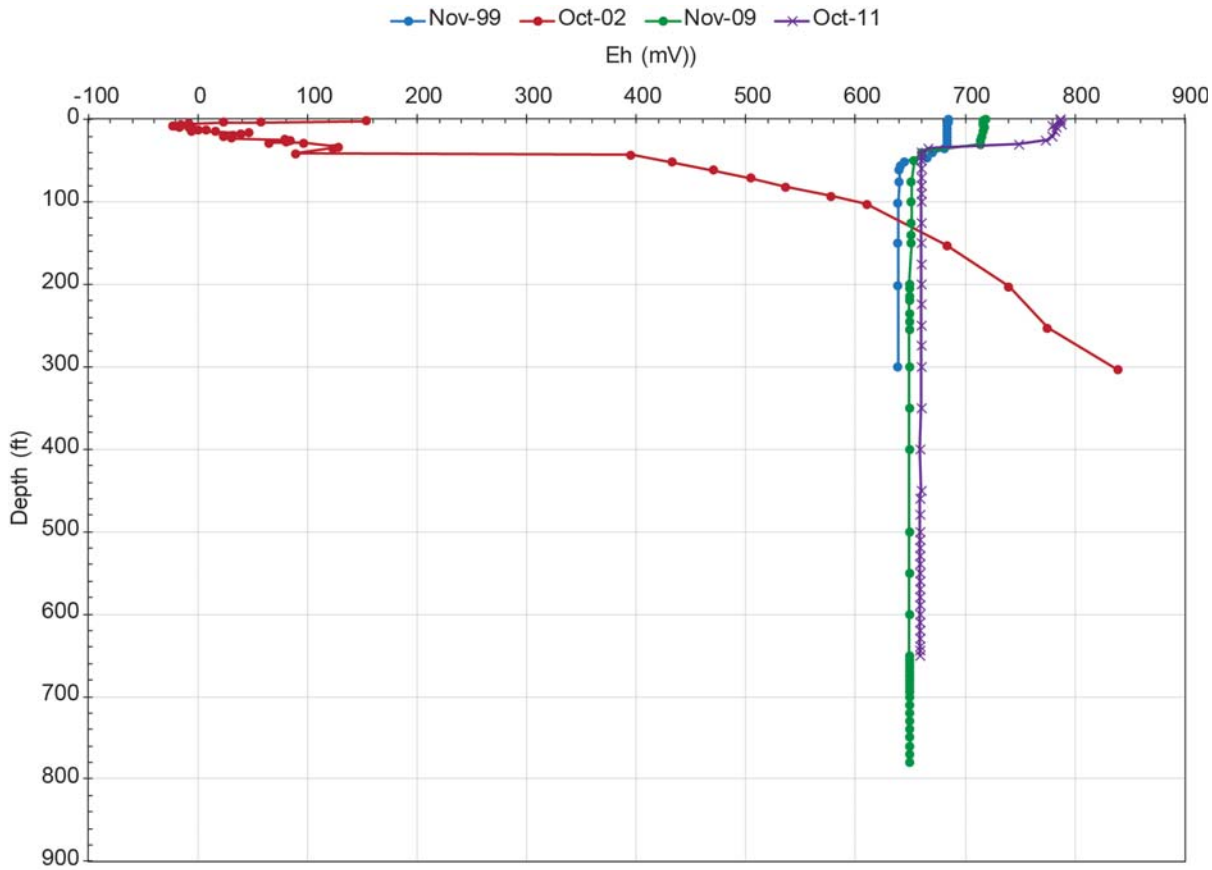


Figure 46. Eh with depth profiles for November 1999, October 2002, and November 2009 in the Berkeley Pit.

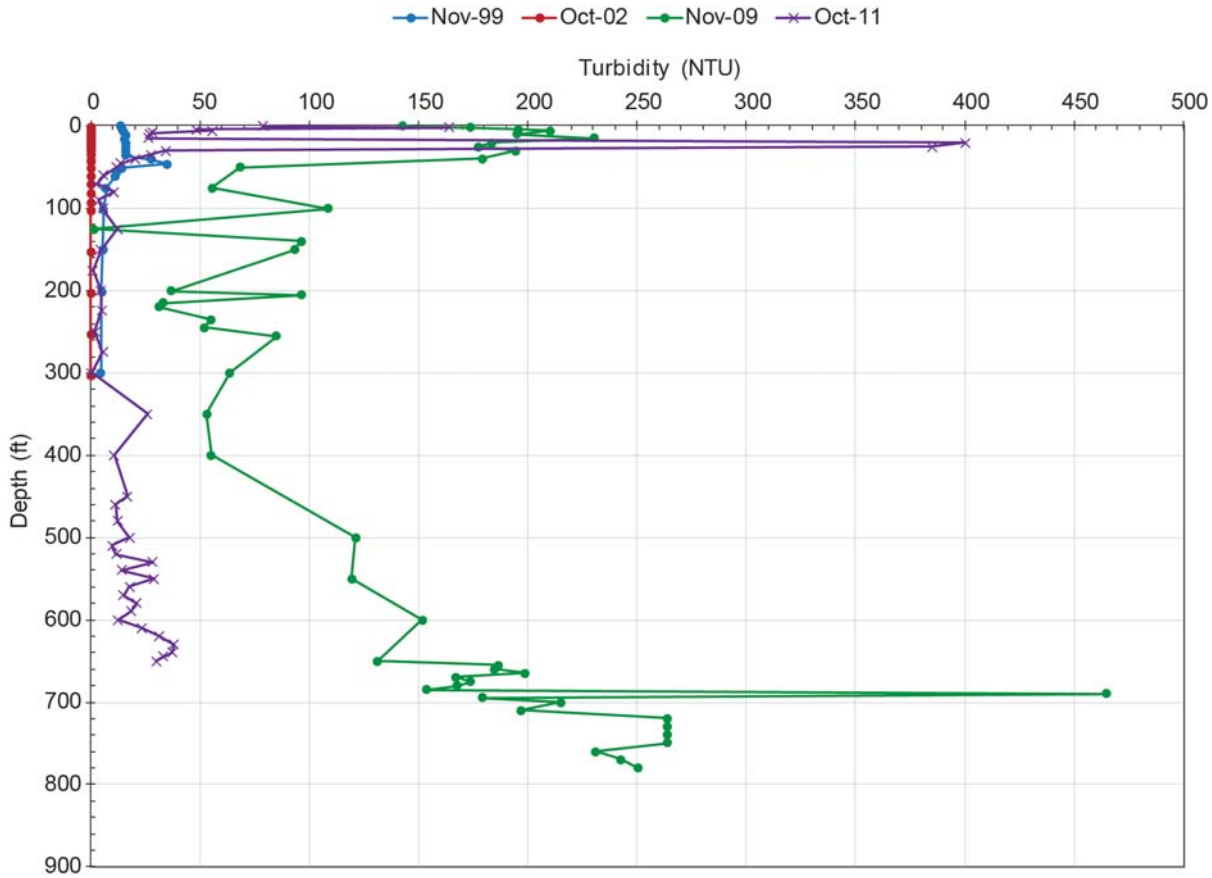


Figure 47. Turbidity with depth profiles for November 1999, October 2002, and November 2009 in the Berkeley Pit.

6.0 ROUTINE SAMPLING AND PROFILING WITH AN AUTONOMOUS DRONE BOAT (2017)

6.1 Events during 2013–2017

The sampling hiatus created by the 2013 landslide ended with the development of an autonomous drone boat in 2017. The events during this period are outlined in table 15.

The minor landslides that occurred in the Berkeley Pit in 2012 were followed by a more significant landslide in February 2013. This landslide raised water levels in the Berkeley Pit about several tenths of a foot, while depositing an estimated 0.45 million cubic yards of material into the pit. Figure 48 shows the southeast corner of the pit after the landslide. The landslide damaged the pipeline used in the copper recovery process and raised concerns about worker safety in the event of additional slope failure. MR terminated the copper recovery operation, and on-water sampling and profiling activities were suspended due to these safety concerns.

In 2015 MR entered into an agreement with Montana Tech (Electrical Engineering Department and the MBMG) for the design and construction of an autonomous (drone) boat for use in sampling/profiling the Berkeley Pit. The boat was equipped with a modified ISCO 3700 automatic sampler, 700 ft of sample hose, reel with 600 ft of cable for vertical profiling, two electric motors, an on-board computer, two cameras, and wireless communication antennas. The boat was controlled from a base station on the rim of the pit, using computer code to operate monitoring equipment and guide the boat to sample locations within the pit. The boat became operational in 2017 (fig. 49) once it was demonstrated that personnel could launch and dock the boat without having to enter the water.

In 2017, the Berkeley Pit conditions were different from previous years in which sampling was conducted. There was a dramatic change in water color, from a dark reddish-brown to a light green (fig. 50). The clarity of the water also changed. Prior to 2017, it was difficult to see more than 1 ft in depth due to the dark water color. In spring 2017, it was possible to see tens of feet out into the water. This is demonstrated in figure 51, in which the pipeline from the former MR copper recovery project is visible.

Table 15. Timeline for operational changes and natural occurrences that may have influenced Berkeley Pit water quality, 2013–2017.

Date	Event	Significance
February 2013	Relatively large landslide occurred in southeast corner of Berkeley Pit.	Estimated that 0.45 million cubic yards of material entered the pit, resulting in about a 1 ft water-level rise. Wave action in pit damaged copper recovery pipeline. Copper recovery operation suspended.
February 2013–April 2017	Safety concerns related to potential pit wall failures caused cancellation of semi-annual Berkeley Pit water sampling activities.	No water quality or profiling performed in Berkeley Pit.
May 2017	MBMG/Montana Tech drone boat used for Berkeley Pit sampling/monitoring.	Semi-annual sampling/monitoring schedule resumed. Physical parameter monitoring and water-quality data reveal significant changes in water pH and iron concentrations when compared to previous pit samples.

Figure 48. Looking northeast at area of February 2013 Berkeley Pit landslide.

Figure 49. MBMG drone boat returning to shore following November 2017 sample/profiling event.

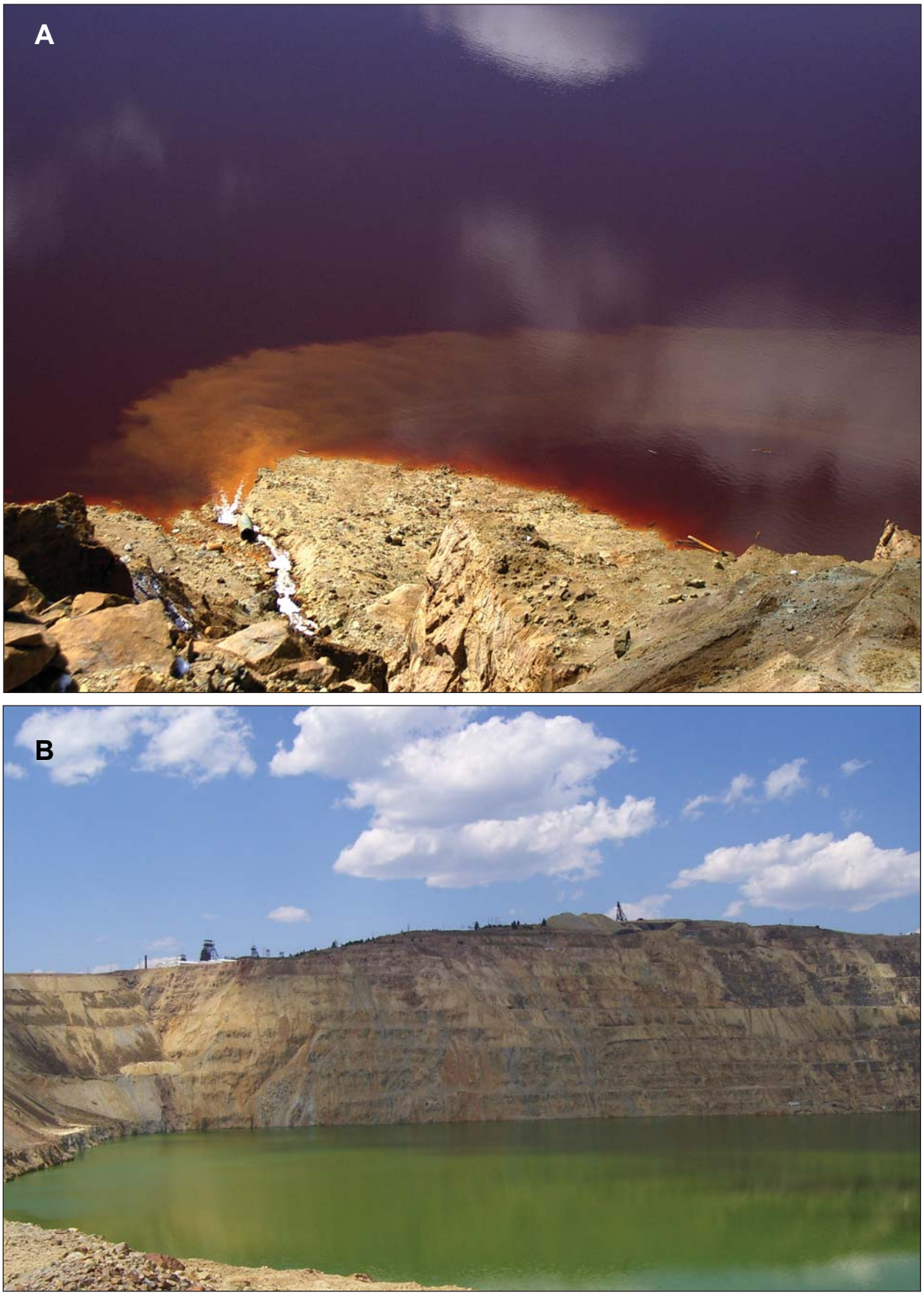


Figure 50. Contrast in Berkeley Pit water color between 2006 (A) and 2017 (B). Note sludge discharged from the Horseshoe Bend water treatment plant in the top photo.

Figure 51. Clarity of Berkeley Pit water in spring 2017.

6.2 Sampling and Profiling with the Autonomous Drone Boat (2017)

The drone boat was used in July and November 2017 to sample the pit. Sample depth during July was limited to 125 ft due to equipment issues. These issues were resolved by the November sampling, and samples were collected to 450 ft.

6.3 Berkeley Pit Water-Quality Results (2017)

Table 16 contains selected water-quality data for July and November 2017 sampling events.

The data from 2017 (table 16) differ from the June 2012 data (table 13):

- pH increased by more than a half unit from 2012 to 2017, and increased several tenths of a unit between July and November 2017 (fig. 52);
- iron and arsenic concentrations decreased by an order of magnitude, continuing the downward trend observed between 1999 and 2012;
- aluminum increased slightly, while cadmium, copper, and zinc concentrations were similar to those of previous years;
- concentrations were similar throughout the profile; and
- no stratification was observed.

Figures 52 through 56 depict the concentration differences between 2012 and 2017 sample events and the lack of stratification in the 2017 sample profile.

The increasing pH and decreasing arsenic and iron concentrations between the 2012 and 2017 sampling events indicate an important change in the Berkeley Pit water chemistry. During this time period, the only high-volume and consistent input to the pit was sludge discharged from the HSB water treatment plant. The change in water quality is likely attributable to the alkaline nature of this material and its flow rate of 0.26 MGD over 14 years (2003–2017).

Table 16. Dissolved water-quality concentrations for selected analytes from July and November 2017 Berkeley Pit sampling events.

Sample Date	Sample Depth (ft)	Field pH (+/- 0.2)	Field Temp. (°C)	Sulfate (mg/L)	Iron (mg/L)	Aluminum (µg/L)	Arsenic (µg/L)	Cadmium (µg/L)	Copper (µg/L)	Zinc (µg/L)
							MCL	MCL	MCL	MCL
							10	5	1,300	7,400
07/19/17	3	3.44	12.9	6,895	11.2	329,800	7.5	1,878	62,302	606,800
07/19/17	30	3.53	5.57	6,916	5.3	341,775	10.8	1,779	60,217	623,050
07/19/17	100	3.64	2.73	6,919	3.3	332,250	4.1	1,953	58,232	612,900
07/19/17	125	3.63	2.73	6,923	2.7	349,650	4.3	1,950	59,560	623,350
11/09/17	3	3.93	3.10	6,932	1.9	310,925	4.5	1,834	56,056	597,500
11/09/17	20	3.92	3.82	7,025	1.8	312,175	4.0	2,061	59,901	599,000
11/09/17	60	3.95	4.20	7,010	1.6	312,125	4.6	2,019	57,716	599,750
11/09/17	200	4.00	4.15	7,012	1.3	311,650	4.2	2,085	59,812	601,200
11/09/17	450	4.02	4.15	7,027	1.2	311,300	5.7	2,094	57,794	598,250

Note. MCL, maximum contaminant level for human health standards in surface water. DEQ-7 Montana Numeric Water Quality Standards, May 2017.

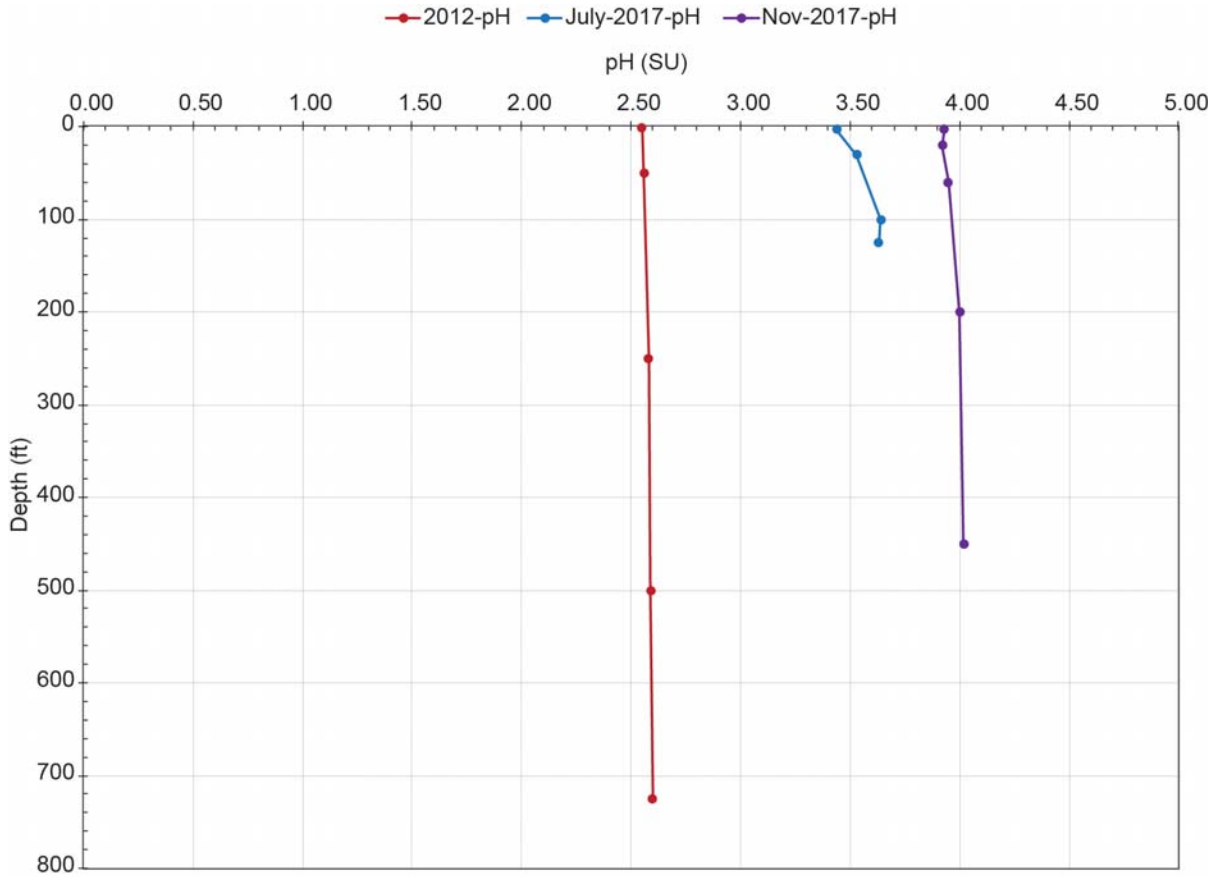


Figure 52. Comparison of pH values as a function of depth between spring 2012 and July and November 2017.

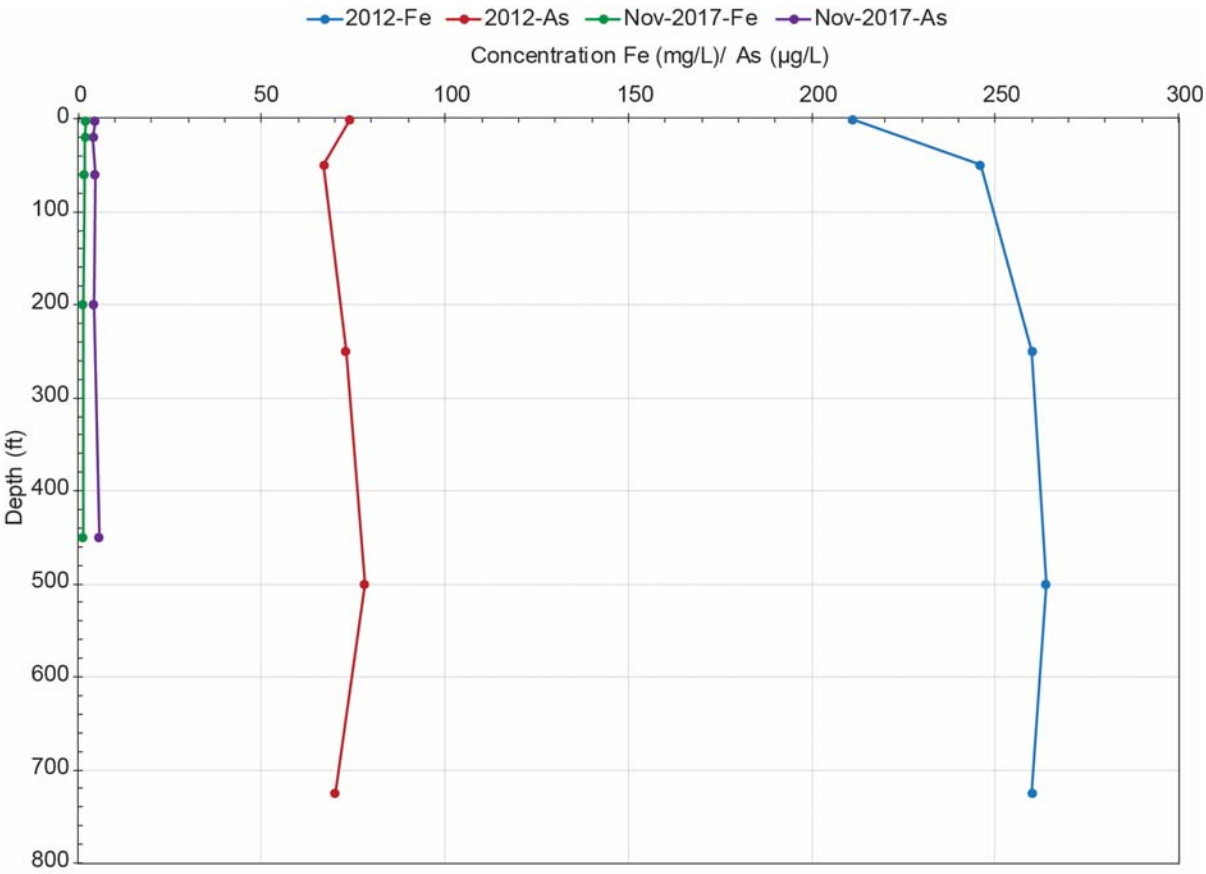


Figure 53. Iron and arsenic concentrations with depth, spring 2012 and fall 2017.

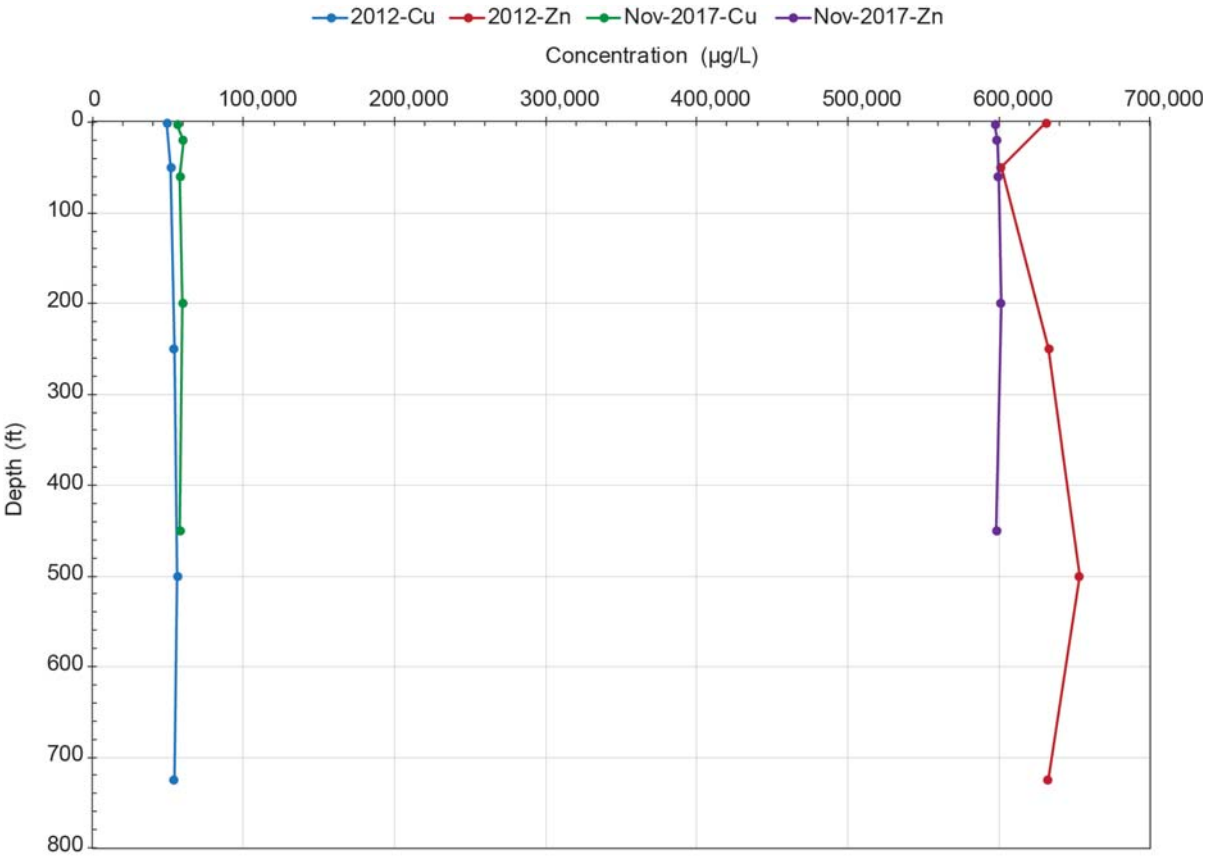


Figure 54. Copper and zinc concentrations with depth, spring 2012 and fall 2017.

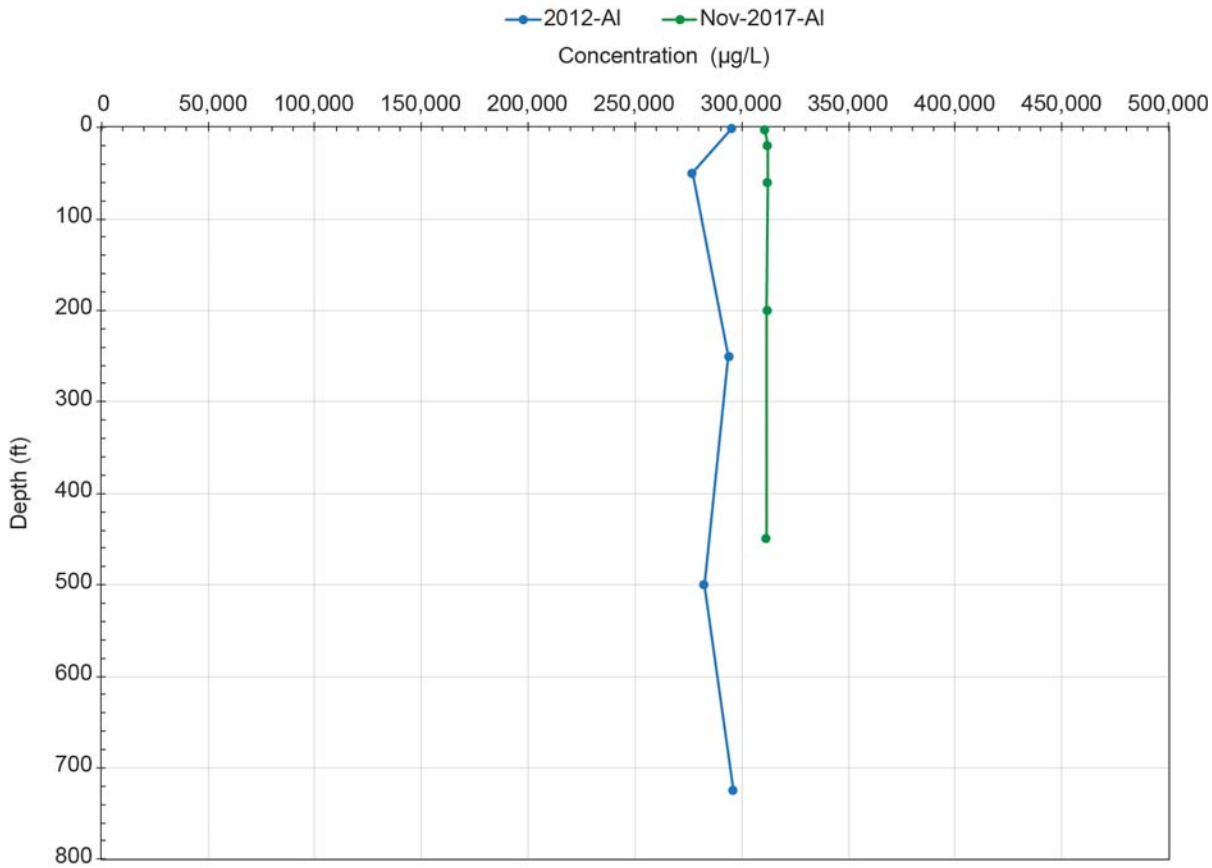


Figure 55. Aluminum concentrations with depth, spring 2012 and fall 2017.

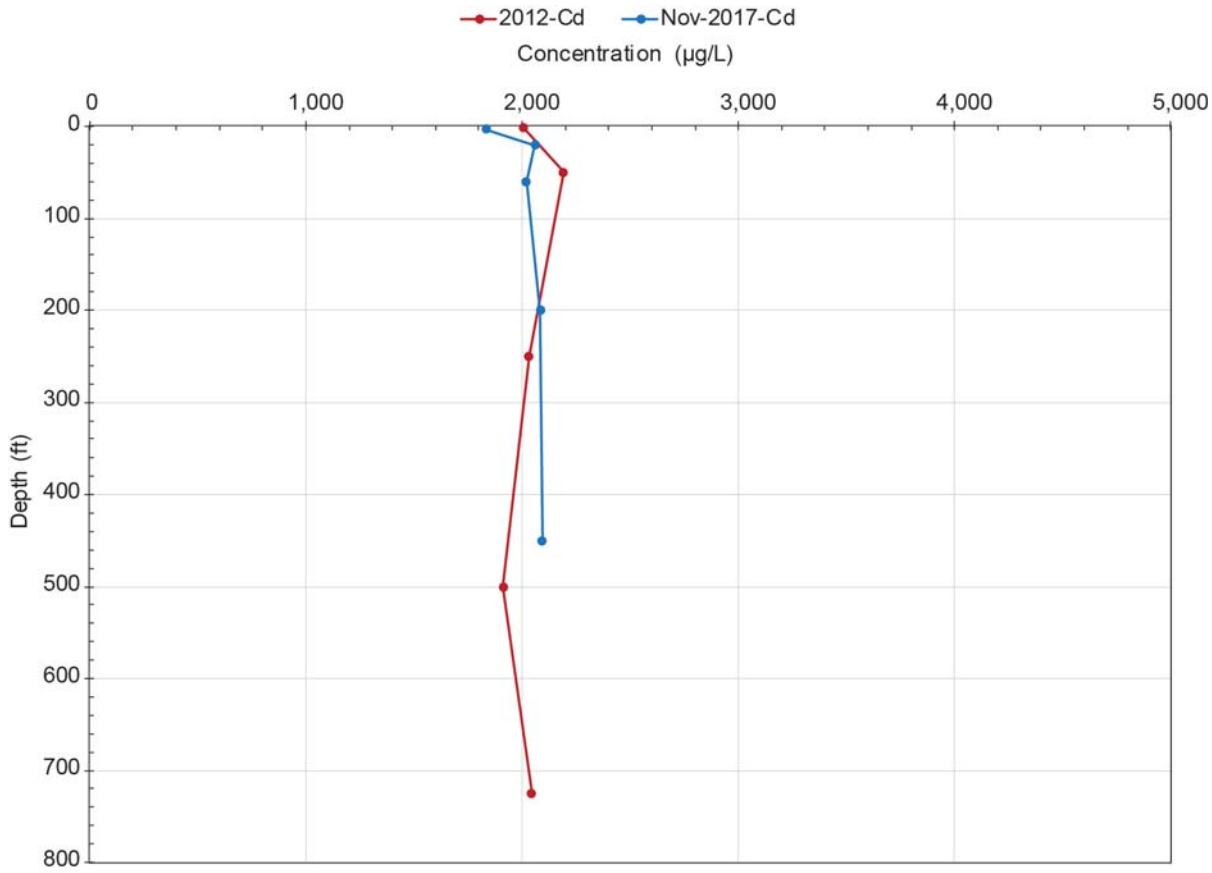


Figure 56. Comparison of cadmium concentrations as a function of depth between spring 2012 and fall 2017 samples.

6.4 Berkeley Pit Vertical Profile Data (2017)

Three vertical profiles were conducted using the drone boat in 2017. Profiles were conducted in May, October, and November using the Hydrolab DataSonde MS5. The data collected included: (1) pH; (2) SC; (3) temperature; (4) DO; (5) Oxidation–reduction potential, or ORP as Eh; and (6) turbidity. Profiles were conducted to depths up to 625 ft. Figures 57 through 61 present a comparison of these data for the six physical parameters.

The 2017 vertical profiles denote an increase in pH values between the spring and fall monitoring events (fig. 57). In the spring profile, the near-surface pH varied between 3.4 and 3.5, while pH values from 50 ft to 600 ft were in the 3.6–3.7 range. These values are approximately a full pH unit higher than those observed in the spring 2012 profile. Both fall profiles showed pH values between 3.9 and 4.0, an increase of 0.3 to 0.4 tenths higher than observed in the spring profile. The pH of the pit water did not vary below 100 ft during both fall profiles.

The spring SC profile (fig. 58) showed minor stratification in the upper ~40 ft, with values similar throughout the water column to those measured in November. The October profile had slightly higher values, with no changes in concentrations throughout the profile.

The spring temperature profile (fig. 59) showed the effects of thermal heating (thermocline) in the upper ~40 ft, with surface temperatures about 13°C. Below 40 ft the water temperature was stable near 3°C. The two fall profiles show the effects of seasonal turnover and cooling of the near-surface waters, i.e., November surface-water temperatures were colder than those measured in October. Below ~40 ft the water temperature was ~4.1°C to a depth of 570 ft in both the October and November profiles.

All three 2017 DO profiles (fig. 60) show concentrations between 8 and 9 mg/L in the near-surface water. These gradually decrease to about 8 mg/L in the May profile and 6 mg/L in the fall profiles, from about 100 ft to the total depths. These vary markedly from the 2012 and previous profiles. Prior to 2017, very little DO was present at depth, while near-surface concentrations were typically less than 3 mg/L. Turnover probably plays a role in distributing oxygen at depth, where lack of oxygen demand allows a higher concentration to exist than in the past.

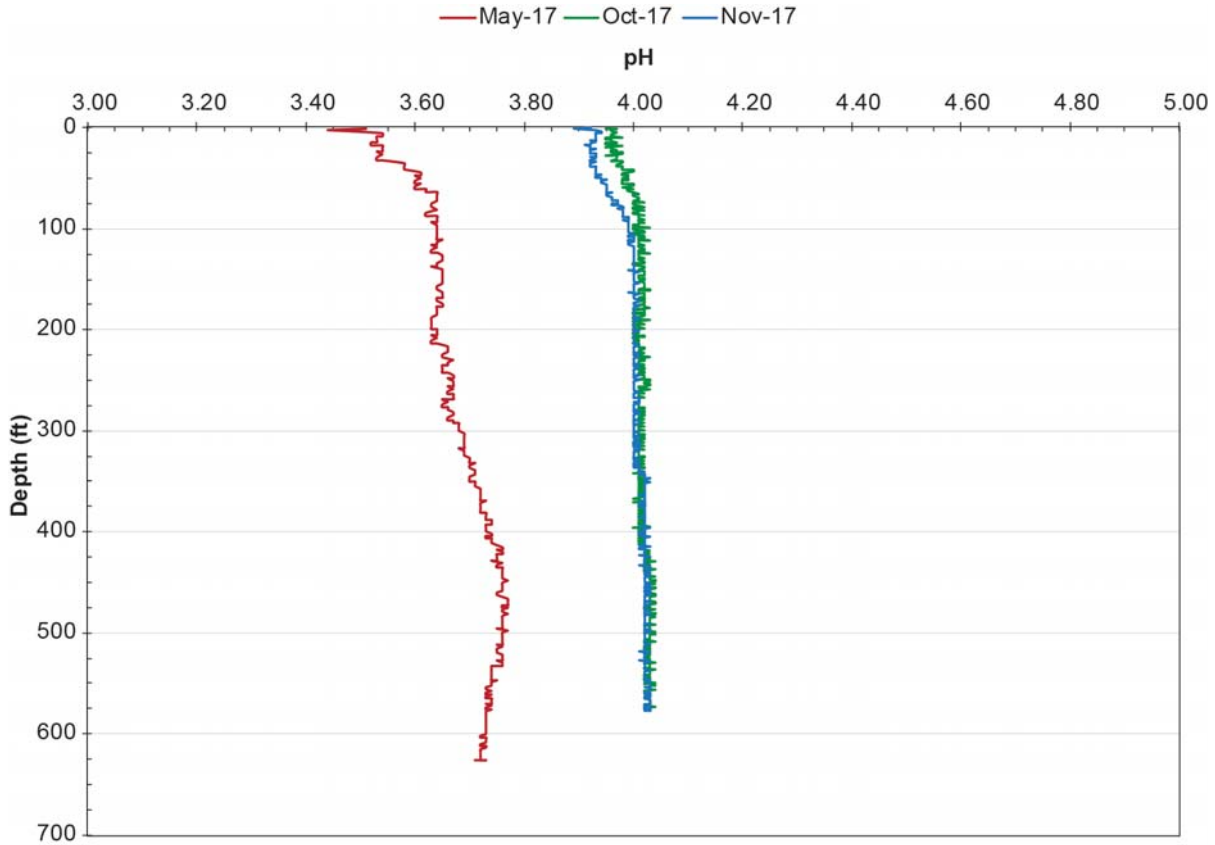


Figure 57. Berkeley Pit vertical depth profiles showing pH trends.

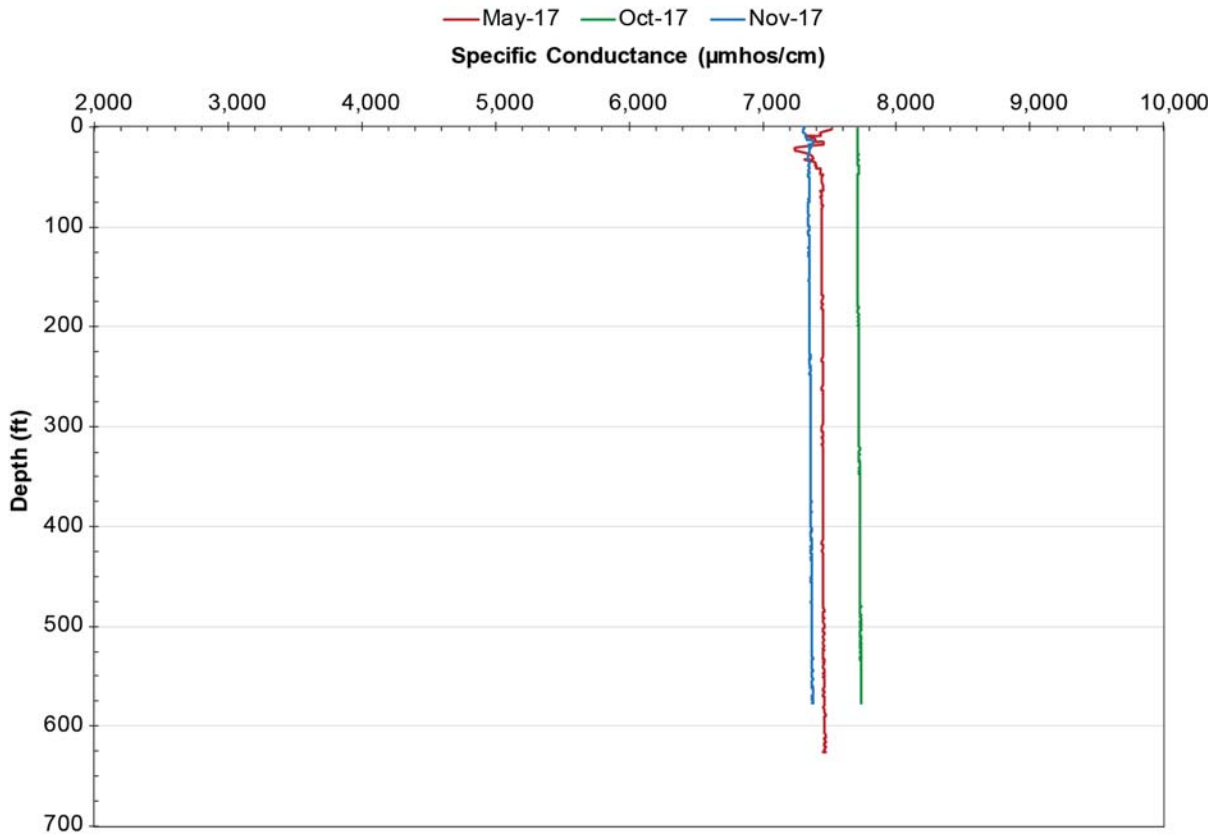


Figure 58. 2017 Berkeley Pit vertical depth profiles showing specific conductance trends.

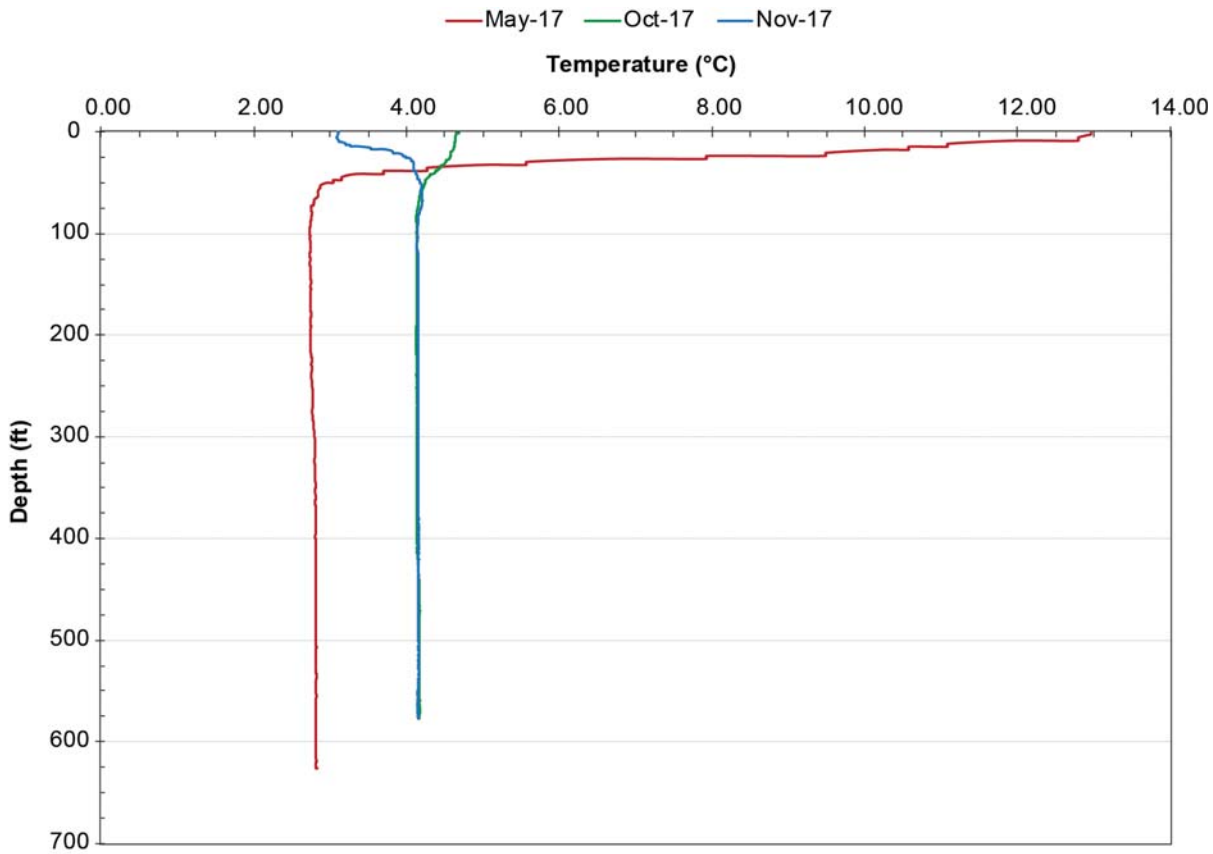


Figure 59. Berkeley Pit vertical depth profiles showing temperature trends.

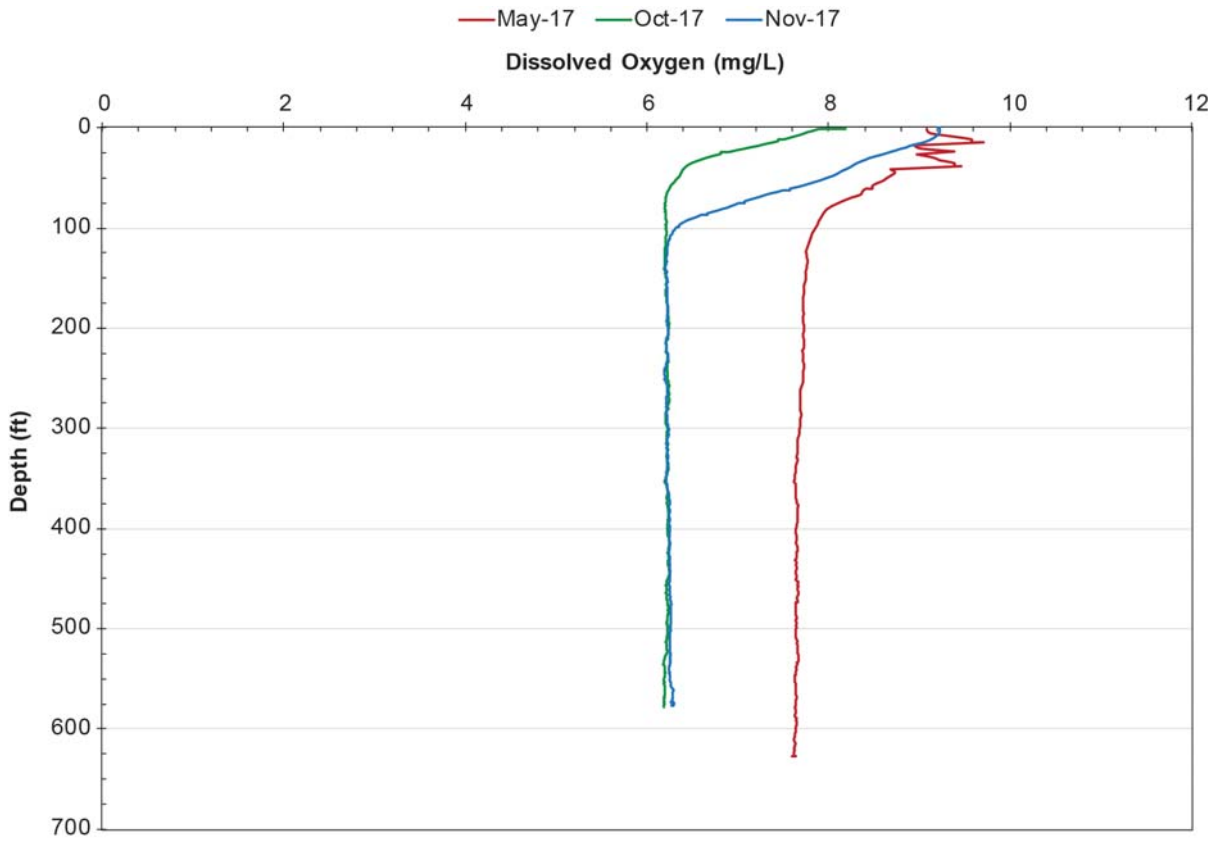


Figure 60. Berkeley Pit vertical depth profiles showing dissolved oxygen trends.

2017 Eh (ORP) values (fig. 61) ranged from 650 to 750 mV and showed little change with depth. These values are consistent with previous profiles; however, previous profiles showed the presence of stratification in the upper 40 ft that was not observed in the 2017 data.

Turbidity profiles in 2017 (fig. 62) depicted some of the most striking changes from those collected in 2012 and prior, with turbidity values being less than 5 NTU in the fall and about 25 NTU in the spring profile. Earlier data (fig. 47) showed turbidity values ranging from 20 to more than 300 NTU in the near surface, and decreasing with depth, showing stratification in the pit. The lower turbidity values confirm the visual observations of improved clarity in the water surface (fig. 51).

7.0 SUMMARY

The cessation of underground mine dewatering and open-pit mining in the Berkeley Pit in 1982 initiated use of the Berkeley Pit for disposal of surface water associated with ancillary Butte mining operations. Sources of water to the Berkeley Pit included HSB and leach pad pond water, and in June 1983, surface water from the East Berkeley Pit. Water levels in the underground mines rose over 2,100 ft before reaching the bottom elevation of the Berkeley Pit. By early 1984, the water level in the mines had risen another 100 ft, effectively reversing the hydraulic gradient, and underground mine waters started flowing into the Berkeley Pit, increasing the pit's filling rate. Total water-level rise as measured in the Kelley Mine exceeded 3,200 ft by the end of 2017. By the end of 2017, the depth of water in the Berkeley Pit was approximately 1,000 ft, although the material added to the pit by landslides and slumps adds some uncertainty to this estimate. The pit contained over 47.8 billion gallons of water in 2017. Over the 35 years of underground mine flooding and filling of the Berkeley Pit, many operational changes in water handling and landslides of material into the pit appear to have impacted pit water chemistry. Analysis and interpretation of the water-quality changes in the pit over the past 35 years will rely on this history of the development and operation of the pit and mine shafts.

Improvements in sampling and monitoring techniques have led to better characterization of physical and chemical conditions within the pit water body over time. Results presented in this report demonstrate the value of a robust and flexible program that can continually adapt to the harsh mine environment

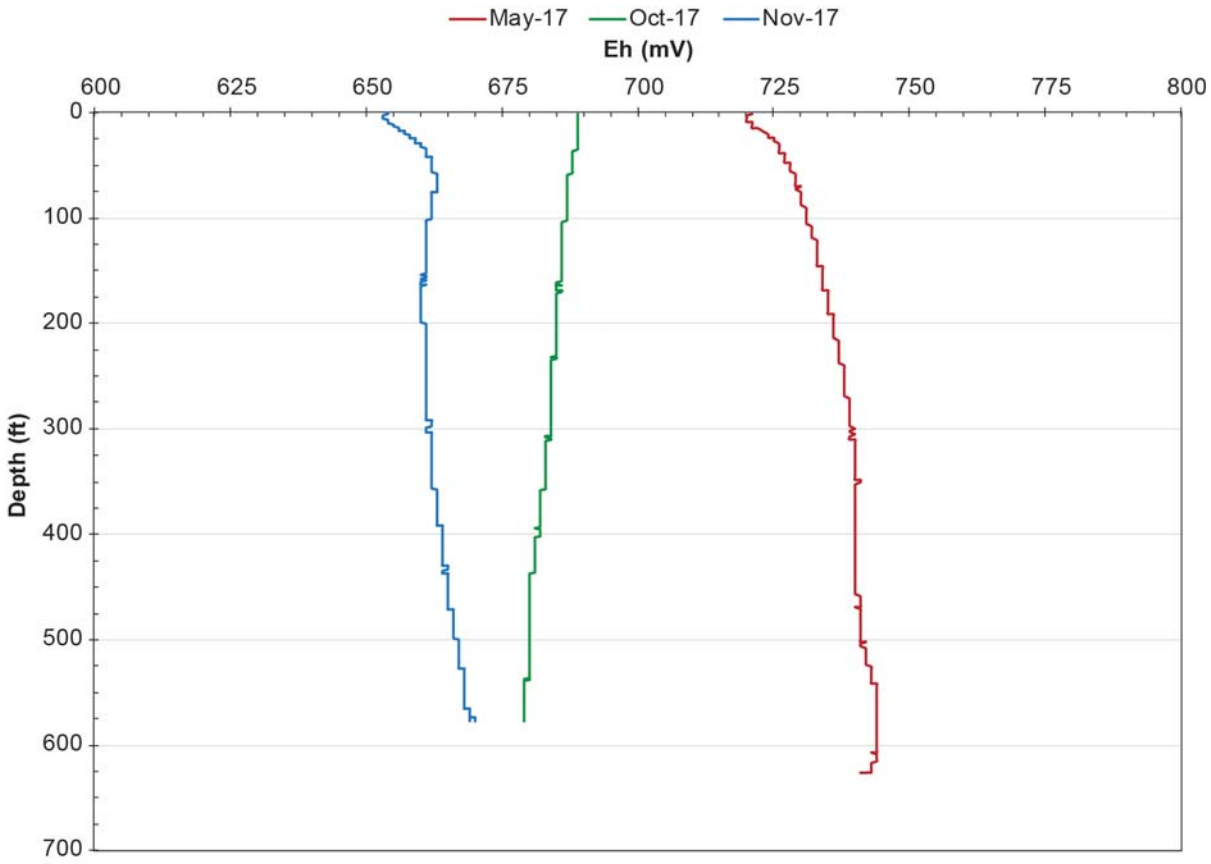


Figure 61. 2017 Berkeley Pit vertical depth profiles showing Eh trends.

Figure 62. 2017 Berkeley Pit vertical depth profiles showing turbidity trends.

and challenging access conditions. The lack of data collection from the fall of 2012 to the spring of 2017 due to safety concerns, and the significant change in water-quality conditions during this period, indicates the value of semi-annual sampling both at the surface and at multiple depths within the pit water column.

Vertical profiling of the Berkeley Pit for physical parameters provides additional information for interpretation of chemical changes in the pit. The water pH increased over a full pH unit from 1984 to 2017. DO concentrations have increased and, by 2017, DO was present at greater depths than previously observed. A decrease in water turbidity in 2017 corresponded to the decrease in iron and arsenic concentrations.

The long sampling record, from 1984 to 2017, documents decreases in iron, arsenic, and copper concentrations of up to an order of magnitude or more. Chemical stratification noted during the 1986 multiple depth sampling was no longer present in 2017.

The increase in aluminum concentration accompanied by the increase in pH between 2012 and 2017 argues for the role of the Horseshoe Bend Water Treatment Plant sludge in the evolution of water quality in the pit. Prior to the cessation of the copper recovery, the sludge served to increase the amount of iron oxyhydroxide formed, which removed arsenic. After the cessation of the copper recovery, the sludge removed residual iron and started to raise the pH. Clearly, much remains to be understood about the mechanisms underlying the observed pH increase in the pit. This problem will doubtless be addressed in future research.

As of this writing, the Berkeley Pit continues to fill, and a water polishing plant capable of producing discharge-quality water is scheduled to come online in 2019. As the remedial measures are implemented over the next several years, continued sampling and monitoring of the pit will ensure water-quality trends are noted and provide for the efficient operation of the water treatment systems and related activities.

8.0 ACKNOWLEDGMENTS

The authors thank the former AMC employees who assisted with initial sampling activities and provided access for specific MBMG sampling activities; these employees also provided information on AMC operations and process water handling. We are especially grateful to Sam Stephenson (deceased), Phil Doughty, Roger Gordon, and Frank Gardner.

Similarly, a heartfelt thank you is extended to the MR employees who have assisted the MBMG since 1986 with site access and technical information regarding MR's operations, specifically Frank Gardner, Steve Walsh, Ray Tillman (deceased), Steve Czehura, Ralph Driscoll, George Burns (deceased), John Burk, Mark Thompson, Tad Dale, Mike McGivern, Mary Anne Antonioli, and Travis Chiotti. Without the assistance and information provided by the above individuals, much of the initial sampling could not have been performed; their knowledge of specific site operations helped greatly in providing information relating to operational changes that may have influenced water-quality conditions in the pit.

Many MBMG employees, both current and past, have assisted with monitoring and sampling throughout the past 35 years, and their assistance is appreciated. Special acknowledgment and thanks is extended to Marvin Miller, John Sonderegger, John Metesh, Fred Schmidt, Herman Moore, Nick Tucci, and Gary Icopini.

Not to be forgotten are the DEQ and EPA employees who have been insightful and supportive of the MBMG activities and allowed modifications in Superfund-related sampling and monitoring activities and procedures throughout the years, specifically Russ Forba and Nikia Greene, EPA, and James Scott (deceased) and Daryl Reed, DEQ.

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10.0 UNPUBLISHED SOURCES

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APPENDIX

List of Acronyms Used in Text

ACM	Anaconda Copper Mining Company
AMC	Anaconda Mining Company
AR	Atlantic Richfield Company
BMFOU	Butte Mine Flooding Operable Unit
CD	Consent Decree
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
DEQ	Montana Department of Environmental Quality
DO	Dissolved Oxygen
EPA	U.S. Environmental Protection Agency
Eh	Oxidation-reduction-potential, when measured relative to the Hydrogen electrode cited as Eh.
gpm	Gallons per Minute
GN	Great Northern
GWIC	MBMG Ground Water Information Center
HSB	Horseshoe Bend Drainage
IECO	International Engineering Company
MBMG	Montana Bureau of Mines and Geology
MCL	Maximum Contaminant Level
MGD	Million Gallons per Day
mg/L	Milligrams per liter
MR	Montana Resources
NAVD29	North American Vertical Datum of 1929
NTU	Nephelometric turbidity unit
ORP	Oxidation-Reduction Potential when measured relative to the Hydrogen electrode cited as Eh.
RI/FS	Remedial Investigation/Feasibility Study
ROD	Record of Decision
SC	Specific Conductance at 25°C
µg/L	Microgram per liter
µmhos	Micromhos per centimeter at 25°C
USGS	United States Geologic Survey