UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Field Trip Guidebook For Surface-Water Contamination and It's Remediation Near Idaho Springs, Colorado

Prepared for the Annual Meetings of the Soil Science Society of America
Division A-5, Environmental Quality, Denver, Colorado
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This report is preliminary and has not been reviewed for conformity with the U.S. Geological Survey editorial standards and stratigraphic nomenclature. Any use of trade names is for descriptive purposes and does not imply endorsement by the USGS.

Cover Photograph: Clear Creek Canyon taken from Lookout Mountain before highway construction. Photo by L. C. McClure, Denver Public Library Western History Collection (printed with permission).

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INTRODUCTION

Welcome to Colorado and the first field trip sponsored by Division A-5, Environmental Quality in conjunction with the Annual Meeting of the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.

This one-day field trip to the Front Range west of Denver includes commentary and viewing of mountain landscapes, notes on the colorful history of the area related to mining, and discussions on the geology and mining-related environmental hazards near Idaho Springs. In-depth discussions will be conducted at two sites, the Argo Tunnel and a constructed wetland, both near Idaho Springs. The Argo Tunnel drains the large Central City-Idaho Springs hard-rock mining district and is a source of acid-mine drainage, arsenic, and heavy metals to Clear Creek. The constructed experimental wetland demonstrates technology for the remediation of acid-mine drainage and removal of arsenic and heavy metals. Take this opportunity to view and discuss experimental methods for remediation of acid-mine drainage and heavy-metal removal.

A few precautions and suggestions are offered to make the field trip as safe and enjoyable as possible. Idaho Springs is at an elevation of about 7500 feet above sea level and the lower oxygen content of the air (about 50 percent that of sea level) may affect some people. The wetlands are "wet" and participants should bring suitable foot ware. The daily weather patterns are such that the morning in Denver may be sunny and warm, but by afternoon it could be cloudy and windy with rain or snow in Idaho Springs; be prepared for all types of weather. Finally, enjoy the mountain scenery, ask questions, and do not just attend, but participate in the field trip.

FIELD TRIP ROAD LOG

by

Ralph R. Shroba and Kathleen C. Stewart

The field trip begins at the Colorado Convention Center, Stout and 14th Streets, Denver. Denver stands on late Pleistocene terrace deposits (Trimble and Machette, 1979). Proceed to interchange of I-25 and I-70. This route is mostly on Holocene alluvium deposited by Cherry Creek and the South Platte River (Fig. 1).

<u>Mileage</u>

0.0 Road log begins: Interchange of I-25 and I-70. Proceed west on I-70. Under and just south of the interchange, beside the Denver Post building, is the site of the former Boston and Colorado Smelting Works. After the transfer of the smelting operations from Black Hawk to Denver in 1879, the smelter processed ore shipped from the Idaho Springs-Central City mining district (Hale, 1936). Route is mostly on Holocene alluvium and eolian sand (Trimble and Machette, 1979).

3.5 Exit I-70 at Exit 271A. Turn right (north) at exit, proceed north on Sheridan Boulevard (Colorado Highway 95) for a 1/2 block, and turn left (west) into Inspiration Point Park.

3.7 STOP 1. Inspiration Point Park overlook. Outstanding views of Denver and the Front Range. Inspiration Point is capped by a small remnant of middle Pleistocene alluvium that was deposited on a surface cut on the Denver Formation (Paleocene-Upper Cretaceous). The valley of Clear Creek, to the north and west of Inspiration Point, contains late Pleistocene and Holocene alluvium as much as 30 feet thick.

Much of the urban development visible from Inspiration Point postdates World War II. The valley of Clear Creek once contained extensive vegetable farms, but in the past 40 years, they have been displaced by gravel pits, homes, and commercial establishments. Some of the lakes produced by the gravel mining have been converted to recreational uses. Some of the pits produced by gravel mining were used as landfills. Much of the gravel resources along Clear Creek has been lost to urban growth.

The flat tops of North and South Table Mountains to the west, near Golden, are capped by mafic latite lava flows that overlie the Denver Formation. Above and far west of the Table Mountains are Mount Evans and the Continental Divide. In between these features is the rolling topography on a dissected Late Eocene erosion surface. On a clear day, Pikes Peak can be seen 60 miles to the south and Longs Peak can be seen 45 miles to the northwest (Hansen and others, 1976).

4.0 Leave Inspiration Point Park, turn right (south) on to Sheridan Boulevard, go one block to W. 48th Avenue, turn right (west), and continue on W. 48th Avenue to Harlan Street.

4.7 At intersection of Harlan Street and W. 48th Avenue enter westbound I-70. Route is mostly on Holocene and late Pleistocene alluvium of Clear Creek (Trimble and Machette, 1979).

9.2 North Table Mountain and large gravel pit on the right.

13.4 Green Mountain, on the left, is capped by conglomerate of the Green Mountain Conglomerate (Paleocene). Expansive soils and unstable colluvial slopes on Green Mountain have posed problems for housing developments (Robinson and others, 1976).

15.1 Approximate location of 1984 landslide that disrupted a short portion of the eastbound lanes of I-70 (Fig. 2). The landslide developed in the roadfill that was placed on expansive shale and mine tailings (L. McKenzie, Colorado Department of Highways, oral communication, 1991).

15.3 Enter roadcut through hogback which exposed a thick sequence of east dipping sedimentary rocks of Jurassic and Cretaceous age (Trimble and Machette, 1979). The route west of the roadcut crosses the oldest sedimentary rocks in the Denver Area. These rocks are of Jurassic to Pennsylvanian age (Reed and others, 1987).

Dinosaur bones are abundant in Late Mesozoic rocks in the Denver area. They were first discovered in 1877 in Late Jurassic rocks of the Morrison Formation just south of here (Lockley, 1988).

15.9 At overpass over Colorado Highway 26, I-70 crosses the former route of the Denver, Auraria, and Colorado Wagon Road which was built up Mount Vernon Canyon in 1859 to transport supplies to Central City (Scott, 1976).

16.0 The red rocks exposed south of I-70 are resistant beds of conglomeratic sandstone of the Fountain Formation.

16.1 Enter mouth of Mount Vernon Canyon. The rocks exposed along the route between the canyon mouth and Idaho Springs are mostly felsic gneiss, biotite gneiss, hornblende gneiss, and amphibolite of Precambrian age (Bryant and others, 1981).

20.5 Head of Mount Vernon Canyon near Exit 254. For the next 7 miles, I-70 crosses rolling topography on the dissected Late Eocene erosion surface. Remnants of the surface north of Clear Creek Canyon are visible from several points along I-70. Also visible are ridges capped by Pliocene (?) gravel that occupies an ancestral channel of Clear Creek, which is incised several hundred feet into the erosion surface. The channel is about 400 to 600 feet above the present stream. Remnants of the gravel deposit can be traced discontinuously to near the mouth of the canyon, where they lie several hundred feet above the projection of the highest pediment surfaces in the Colorado Piedmont. Roadcuts in the erosion surface expose interlayered felsic gneiss, amphibolite, and hornblende gneiss cut by dikes of pink granite and pegmatite (Reed and others, 1987).

20.6 Exit I-70 just west of Exit 254. Park just west of the overpass.

STOP 2. Panoramic View. View to the west of the Late Eocene erosion surface and the high, snow-capped peaks along the Continental Divide. Behind us is Victory Pass on the old wagon road. This area is part of the Denver Parks system and contains bison that were brought here in 1913. The Patrick House, a former stage stop built in 1860, still stands in the trees to the west. A barn to shelter horses that ascended the wagon road once stood where the windmill is today (M. Homola, Denver Mountain Parks, oral communication, 1991).

Proceed west and enter westbound I-70. The old wagon road is located along I-70 in the trees to the left.

22.0 Near Exit 253, view to the right of Pliocene(?) gravel on the Late Eocene erosion surface.

22.6 The Ruby stage station once stood just north of I-70 near exit 252 (Scott, 1976).

27.1 Cross county line into Clear Creek County.

27.4 Large subdivision on the left. Residential development in the foothills of the Front Range is commonly accompanied by problems of quantity and quality of the water supply and waste disposal (Hansen and Crosby, 1982).

27.9 Floyd Hill summit just beyond overpass.

28.6 Ridge north of Clear Creek is capped by Pliocene (?) gravel. Roadcuts on grade down Floyd Hill are in interlayered felsic gneiss, hornblende gneiss, and amphibolite, cut by dikes of pink granite and pegmatite (Reed and others, 1987).

Clear Creek was previously known as the Vasquez Fork, named for the fur trader Louis Vasquez. He built a fur-trading fort in 1835 on the South Platte River north of Denver (Hafen, 1964).

30.0 Junction of I-70 and U.S. Highway 6. Proceed west on I-70 toward Idaho Springs. The large bedrock mass on the east side of Clear Creek is a landslide that is moving along slip planes that are developed in foliation planes in the biotite gneiss bedrock (Robinson and others, 1976).

30.2 Large roadcuts on right just after crossing Clear Creek expose migmatitic biotite gneiss and schist with abundant pods and deformed layers of pegmatite (Reed and others, 1987).

32.3 Outcrops of felsic gneiss and amphibolite, on right, at the east portal of the highway tunnel (Reed and others, 1987).

32.8 Roadcut in late Pleistocene glacial outwash gravel.

33.3 Exit I-70 at Exit 241A for Idaho Springs. Follow Business 70 about one mile west to a small municipal park on the south side of Clear Creek across from the Argo Mill (Fig. 3). Refer to the report by Stewart in this guidebook for historical information on Idaho Springs.

34.2 STOP 3A. Argo Tunnel. Refer to the reports in this guidebook on the chemistry of the tunnel effluent by Smith and Ficklin and on the history of the tunnel by Stewart.

Leave municipal park and proceed west on Business 70.

34.5 Cross Clear Creek. Much of the town of Idaho Springs is built on late Pleistocene, glacial outwash gravel. The lower limit of late Pleistocene glaciation in the valley of Clear Creek is marked by hummocky moraines near the junction of I-70 and U.S. Highway 40, about 7 miles west of Idaho Springs (Bryant and others, 1981).

35.8 Turn left (south) on 1st Street. Park on right (west) side of street.

STOP 3B. Constructed wetland at the portal of the Big Five tunnel. Refer to the reports in this guidebook on some of the factors that affect the treatment of acid mine discharge at the Big Five tunnel by Emerick and others and on the history of the tunnel by Stewart.

35.9 Leave the wetland. Turn left (east) on the unnamed street and left (north) on 2nd Street. Proceed north on 2nd Street to Business 70.

36.0 Turn right (east) on Business 70 and proceed east.

36.6 Turn right (south) on 13th Street and proceed south.

36.7 Turn left (east) on Miner Street and proceed east. Note the stone mill (arrastre) on the left in front of the library on the northwest corner of Miner and 14th Streets. This Spanish-style mill was used to grind gold ore (Cox, 1989). Continue east on Miner Street.

37.0 Cross Clear Creek.

37.1 Turn right (south) on Soda Creek Road. Proceed south on Soda Creek Road.

37.2 Lunch stop at the hot springs resort. Refer to the report by Stewart in this guidebook for historical information on the resort.

Retrace route to intersection of Soda Creek Road and Miner Street.

37.6 Turn left (west) on Miner Street and proceed west.

38.0 Intersection of Miner and 13th Streets. Turn left (south) on 13th Street and enter eastbound I-70. Across Clear Creek to the right (south) is the site of the discovery of gold on Chicago Creek in 1859 (see report by Stewart in this guidebook).

38.7 Waterwheel on right. Refer to the report by Stewart in this guidebook for historical information on the waterwheel.

39.7 Enter west portal of highway tunnel.

42.8 Exit I-70 at Exit 244 and follow U.S. Highway 6 down Clear Creek Canyon.

43.1 Rock quarry on the left.

Just east of the junction of I-70 and U.S. Highway 6, the road passes from migmatitic biotite schist and gneiss through a sequence of interlayered calc-silicate gneiss, hornblende gneiss, and amphibolite, and into a large body of amphibolite. Here and there along the sides of Clear Creek one can see the bed of the narrow-gauge Colorado Central railroad (Reed and others, 1987). The Colorado Central railroad built this route to Black Hawk along the former route of the Clear Creek Road in 1872 (Fig. 4) (Scott, 1976; Hauck, 1972).

44.2 Cinder block building on the south side of Clear Creek is the site of the former Therapeutic Radium Baths resort.

44.6 Enter west portal of highway tunnel no. 6.

45.2 Enter west portal of highway tunnel no. 5

45.6 Intersection with Colorado Highway 119 which heads northwest to Black Hawk.

45.7 Cross county line into Jefferson County. The Colorado Central railroad built a water tower and station at this location (Fig. 5). Tracks along both forks of Clear Creek once joined at the Y-intersection near here (Hauck, 1972). Just downstream from the intersection is one of four sites for proposed dams on Clear Creek (Colorado Water Resources and Power Development Authority, personal communication, 1991). Continue east on U.S. Highway 6.

46.2 Dredge tailings are conspicuous here and there for the next 2 miles downstream.

47.2 Approximate location where a seven-ton boulder landed on the highway in May 1991 (Fig. 6).

48.0 Nearly 400 feet of Pliocene(?) gravel caps the ridge on the south side of Clear Creek (Reed and others, 1987).

50.1 Note the cribbing along Clear Creek for the bed of the Colorado Central railroad.

50.3 Enter west portal of highway tunnel no. 3.

50.8 Enter west portal of highway tunnel no. 2.

51.0 Exit east portal of highway tunnel no. 2. The Beaver Brook railroad station and dance pavilion were built just upstream from here in 1885 to entertain tourists on day excursions from Denver (Fig. 7) (Hauck, 1972).

52.6 The side valley to the left is the former site of the Guy Gulch railroad station which was built in 1885. Just downstream from here is a site for a proposed dam on Clear Creek.

55.8 Diversion dam on the right is for the Welsh irrigation ditch.

57.1 Canyon mouth. End of road log. Return to Denver via U.S. Highway. 6 and I-25.

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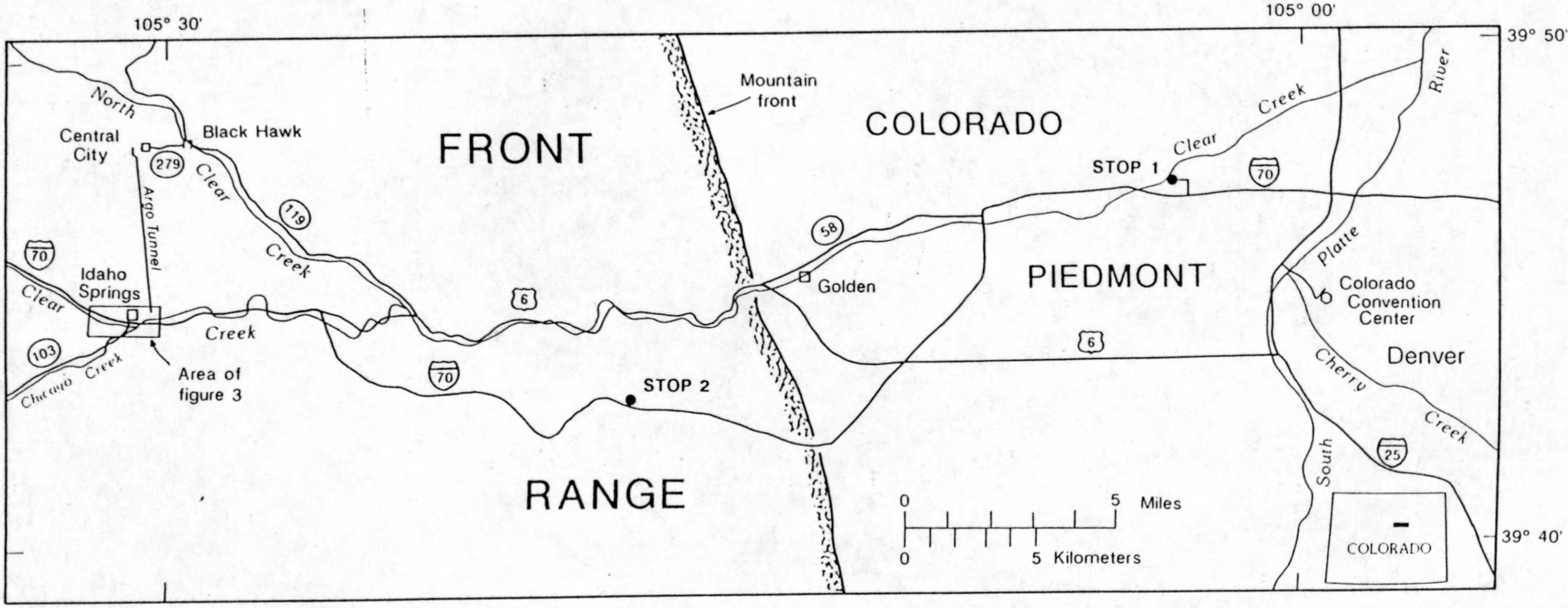

Figure 1. Map of field trip route

Figure 2. Landslide with prominent tension fractures that disrupted a portion of the eastbound lanes of I-70 in 1984. Colorado Department of Highways photograph (printed with permission)

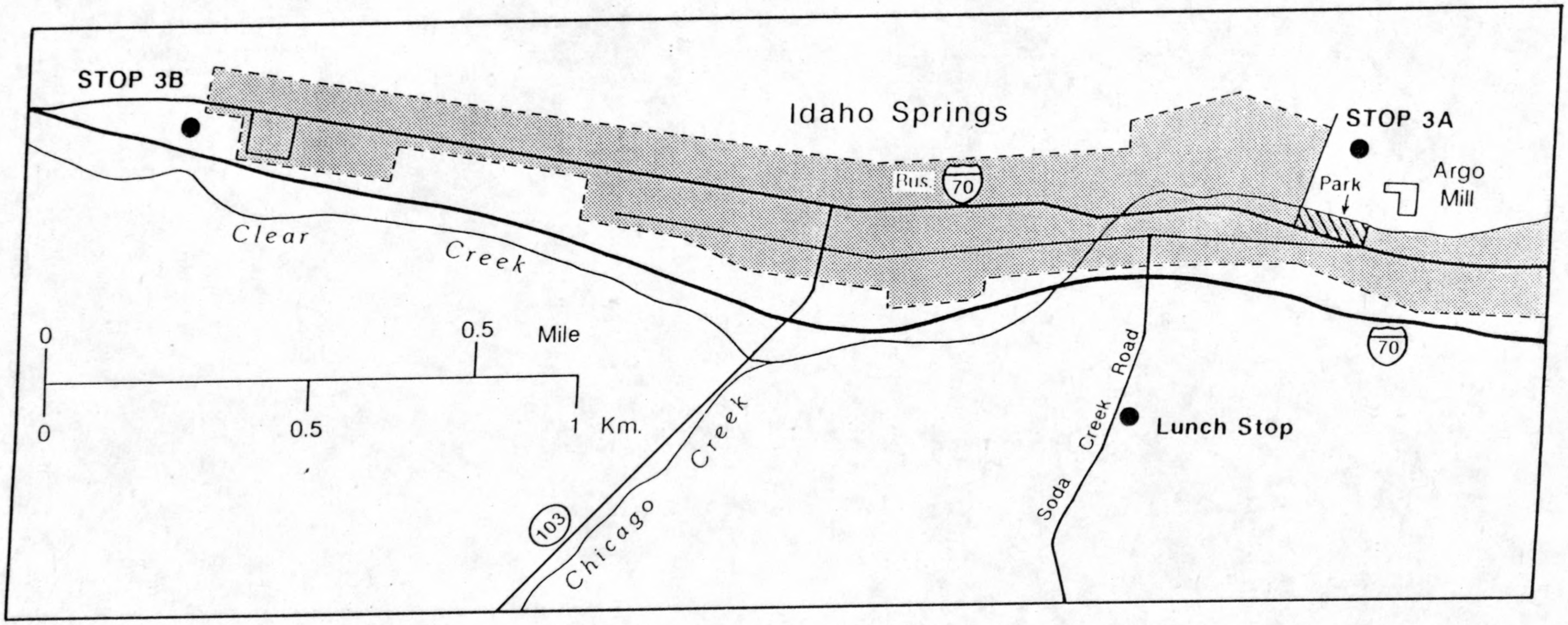

Figure 3. Map of the Idaho Springs area

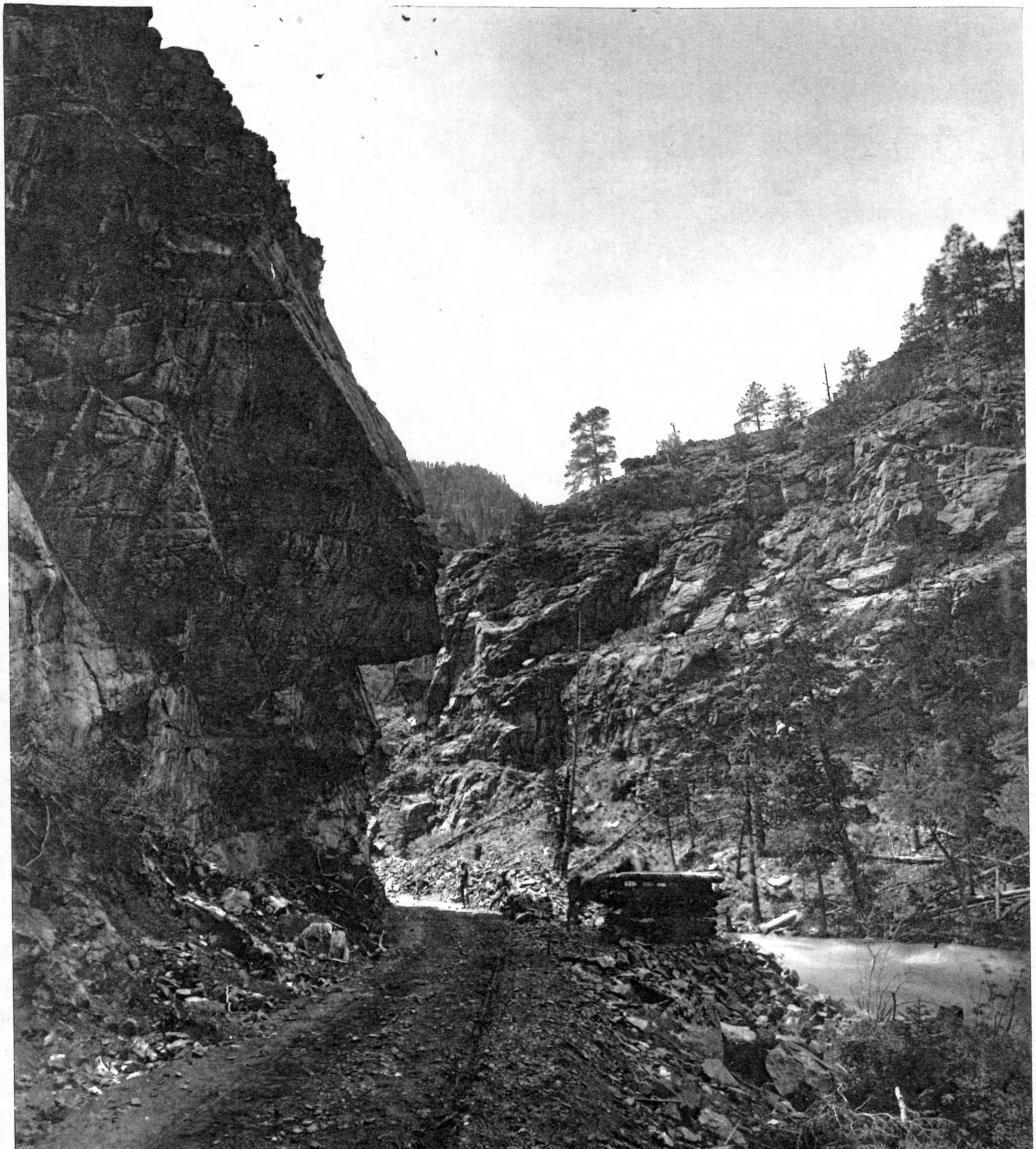

Figure 4. Clear Creek Road, 1872. Ties to be laid for railroad are at edge of embankment . (U.S. Geological Survey photo by W.H. Jackson)

Figure 5. Narrow gauge railroad tracks at the junction of Clear Creek and North Clear Creek before they were replaced by standard gauge tracks. Photo by Collier. Denver Public Library Western History Collection (printed with permission)

Figure 6. Seven-ton rock that fell on U.S. Highway 6 in May 1991. Denver Post photograph by John Epperson (printed with permission)

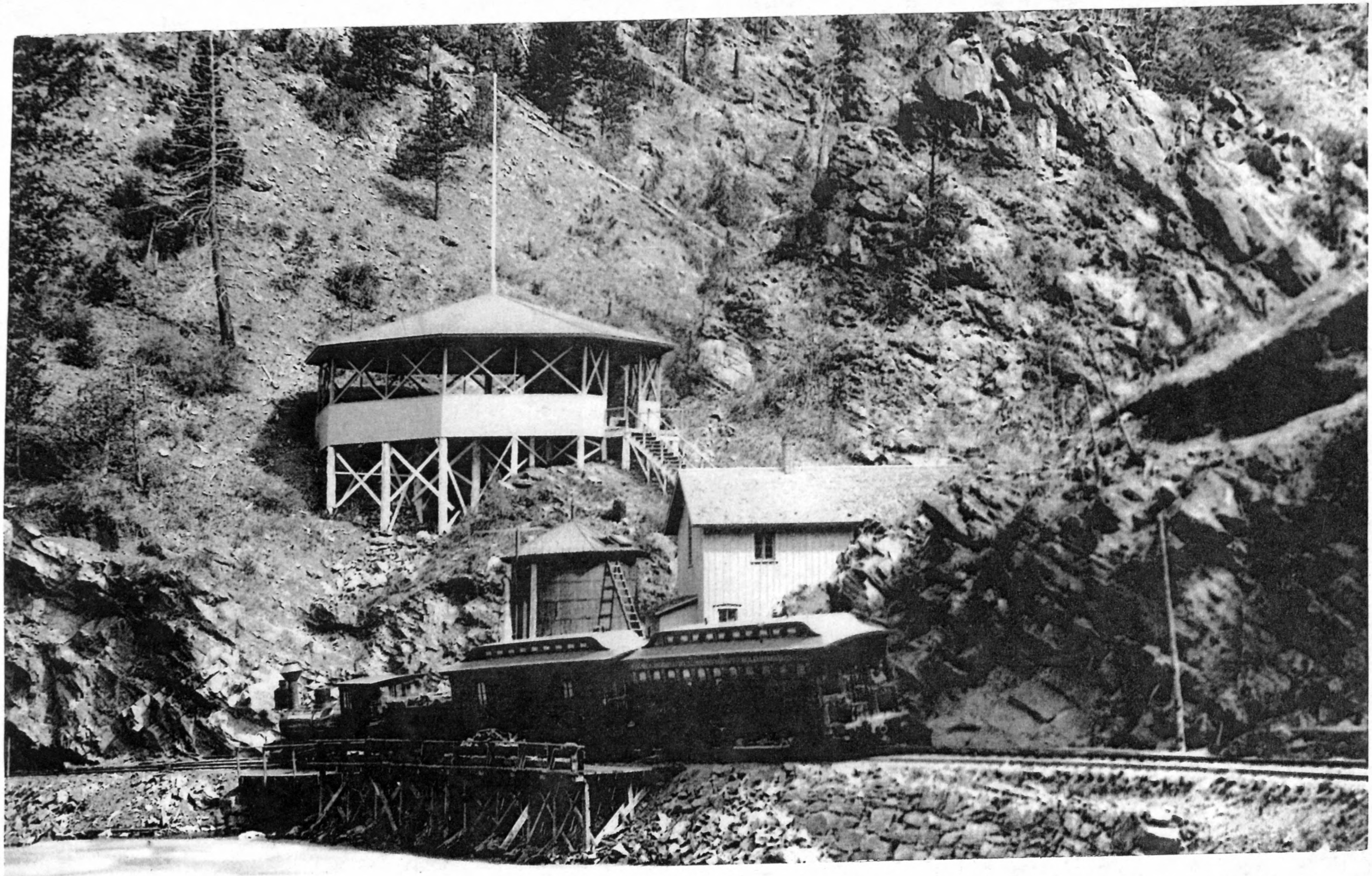

Figure 7. Beaver Creek railroad station and dance pavilion in the late 1800's. Denver Public Library Western History Collection (printed with permission)

HISTORICAL NOTES

by

Kathleen C. Stewart

IDAHO SPRINGS

Before the discovery of gold and the resultant influx of miners, abundant grass growing in the valley of Idaho Springs attracted many bighorn sheep. The sheep enabled George A. Jackson (Fig. 8) to survive in January, 1859 as he sought placer gold. He camped on Soda Creek (Fig. 3) to take advantage of the hot springs, ate "plenty fat meat" and shot wolverines and mountain lions who also wanted his meat. After camping there several nights and exploring a few miles to the west, Jackson moved his camp one drainage upstream to Chicago Creek. He built a raging fire on the bar to thaw the gravel for panning and on January 7, 1859 discovered gold. Five days later with an injured dog and moccasins shredded by Clear Creek ice, he limped into camp near present-day Golden and told his partner, Tom Golden, the news. Due to the winter conditions and the difficult accessibility of the area, they were unable to return until April (Hollister, 1867; Jackson, 1935).

Only a month later news came from Denver of John Gregory's lode discovery near Central City--just over the mountains to the north. Men scrambled up Virginia Canyon (Fig. 9) in a mad rush to reach and confirm the discoveries on the other side. Soon both valleys were filled with placer claims or "poor man's diggings", and in this valley every available gravel bar with room to stand was taken--Spanish Bar to the west, Illinois Bar, Payne's Bar and Idaho Bar in addition to Jackson's Bar (Hall, 1889; Hall, 1891; Mathews, 1940).

Over the next two years the individual camps blurred into one another. In 1860, F.W. Beebee moved from Illinois Bar to Idaho Bar and opened a hotel where some of the early bachelor miners could get out of their tent for a couple of days. People also came to "spectate" and see if all they had heard was true. Across the street was the log cabin saloon where miners "squandered their hard earned dust in fiery liquids, suggestive of insanity and murder" (Hall, 1891). The Colorado Territorial Legislature made "Idahoe" the county seat of newly-formed Clear Creek County in 1861, but the distinction moved to Georgetown in 1867, after silver discoveries there and in Silver Plume (Hall, 1891; Bauer and others, 1990; Wright, 1986).

The placer mines survived until 1865, but were gradually replaced by ore mining. By 1861 several stamp mills for crushing ore were already in the area, including a "20-stamper" on Spanish Bar near the Stanley Mill west of Idaho Springs. The difficulty of recovering gold from ores increased as the surface, weathered ores gave out. Sulfide or "sulfuret" mining became increasingly uneconomic until a smelter was built in Black Hawk in 1867-1868. Ores were then transported over the mountains for processing by way of Virginia Gulch (Cushman and Waterman, 1876; Hall, 1891; Hale, 1936).

ARGO MILL AND TUNNEL

By the 1890's many of the mines around Central City to the north had become so deep it was no longer economic to pump water or hoist blasted material to the surface (Fig. 9.) (Cox, 1989). Since Clear Creek was nearly 1000 feet lower than Gregory Gulch by Central City, Samuel Newhouse and some associates had the idea of boring a tunnel through the mountains to drain mines and transport ores at the lower level. Articles of incorporation for the Argo Mining, Drainage, Transportation and Tunnel Company were filed with the Secretary of State in January, 1893. The Idaho Springs News noted in October that a road had been built and that Newhouse was "preparing for work on the tunnel" (Secretary of State Incorporation Recordings, Colorado State Archives, v. 33, p. 474, Idaho Springs News, 1893). Locally it was referred to simply as the Newhouse tunnel. Mines operating through the tunnel paid drainage and transportation fees to the company. The tunnel reached its maximum length of 4.16 miles and average depth of 1500 feet below the surface by 1910, extending just north of Prosser Gulch west of Central City (Fig. 9) (Bastin and Hill, 1917).

The company re-organized with new financing in 1899 and by 1910 the volume of ore being processed had become so large stockholders decided to build their own mill. Articles of incorporation for the Argo Reduction and Ore Purchasing Company were filed with the Secretary of State in July, 1912 and by 1913 the mill was in operation with special features to process the low-grade ores encountered (The Denver Republican, 1899, Secretary of State Incorporation Recordings, Colorado State Archives, v. 157, p. 477, The Idaho Springs Siftings-News, 1912, 1913).

The tunnel also benefitted schools indirectly. As a young teacher around 1905, Beatrice Rule rode the train a little over a mile into the tunnel and took the platform hoist up the Gem shaft to her first job in Gilson Gulch (History of Clear Creek County, 1986).

Business waned after World War I due to disputes with mine owners. The tunnel was cleaned and unwatered in 1926 (Fig. 10) and was eventually acquired by George Collins, owner of some mines in Nevadaville. He wanted to intersect the Kansas shaft (Fig. 9) which had a good vein but had been allowed to flood since the 1880's. Miners were aware of the extreme hazard from such deep workings and were very cautious with every charge set and squirt of water encountered. After Merle Sowell had worked a drift for 160', he "found a drier job and flew the coop" (Sowell, 1974). When water pressure did not increase after working a stope (step-like excavation) for some weeks, a decision was made to use 10 minute fuses instead of the 30 minute fuses used previously. The decision was fatal to four men. On the afternoon of January 19, 1943, about four o'clock, power went out and a huge roar was heard. One man raced 200 yards to the entrance escaping in waist-deep water. According to Merle Sowell, in several minutes the water was flowing to the top, shooting across Clear Creek into downtown Idaho Springs. After the water subsided, the body of one miner was found covered with mud and gravel--three other bodies were found later. The tunnel was subsequently closed to mining because of lawsuits and, although attempts have been made to clean it out, it has not been used for mining since (The Denver Post, 1943; Sowell, 1974).

BIG FIVE TUNNEL

The origin of the "Big Five" is shrouded in mystery--men and companies become confused. The minutes of the Dew Drop Mine in Boulder County taken on September 2, 1892 state that a certificate of organization for the Orphan Boy Extension Mining and Milling Company, also in Boulder County, was filed with the Secretary of State in 1892. The incorporators were five men--N.C. Merrill, Sidney Williams, Charles H. West, Frank C. Smith and Edwin E. Ives, but their board of directors included four additional people (one of them the sister-in-law of Merrill). By 1893, William P. Daniels appears on the board and also on letterheads for the two companies. A letterhead mailed in February 1898, shows five companies listed under "The Big Five"--The Dew Drop Mining Company, The Dew Drop Mill Company, the Adit Mining Company, The Adit Tunnel Company and The Ni Wot Mining Company, all in Boulder County. Minutes for the Big Five Tunnel, Ore Reduction and Transportation Company state that the charter was filed with the Secretary of State of Colorado in August 1900. The first shovel-full of dirt was thrown for their "Central Tunnel" in December of that year, seven years after the start of the Newhouse (Argo) Tunnel (The Denver Times, 1900; Big Five Tunnel, 1906).

Negotiations had been rather secretive, but the tunnel was to be excavated in direct competition with the Newhouse (Fig. 9). According to advertising, the "Big Five" had acquired ownership of mining claims to be intersected, thereby circumventing the bookwork needed to keep track of fees and handling charges used by the Newhouse. It was also advertised they would encounter ore within half a mile in contrast to the Newhouse, which had blasted for a mile and a half before cutting into a good vein (The Big Five in Pen and Pencil, 1901).

By 1901, the Big Five consisted of seven or eight major stockholding companies and several minor ones. In addition to tunnels in Boulder, Gilpin and Clear Creek Counties, they operated several in the San Juan Mountains in southern Colorado. The names of Merrill and Daniels appear on letterheads, minutes and boards of directors, in various combinations with other names which appear and disappear (Big Five Tunnel, 1906).

Despite grandiose claims to stockholders; the Big Five evidently had an image problem. In a letter dated July 1901, Merrill admonishes Williams to put up billboards in addition to the big "5" carved in the stone over the tunnel. He says, "When they receive it (advertising circular) they have never heard of the Big Five" (Merrill, 1901). It seems that even the tailings pile of the Newhouse was better publicity than the Big Five's small, inconspicuous bore.

They also had legal problems. A stockholder from Boston sued the company in February, 1904 to prevent incorporation of yet another company and to be allowed to examine the books of the Big Five. A receiver was appointed and mining operations ceased. In March, the Colorado Supreme Court issued an injunction to allow operations to continue, but news of the Big Five disappeared from mining journals after November, 1904 (Mining Reporter, 1904a,b,c). The tunnel was extended to about 9000 feet in the 1920's or 1930's and was mined some in the 1960's. It is now owned by George Groves Jr. who lives in New York city. The Big Five is scarcely referred to in historical accounts of Idaho Springs and mostly in reference to the hot springs, another of Merrill's ventures. In August, 1970 fire destroyed the remnants of their properties in Boulder County at Ward (Al Hoyl, Clear Creek Mining Company, personal communication, 1991; Rocky Mountain News, 1970).

CHARLEY TAYLER WATER WHEEL

The original wheel was built by Charley Tayler in 1893 (Fig. 11) to power a stamp mill on Ute Creek, about four miles southwest of Idaho Springs on the way to Mount Evans. In 1945, it was donated to Idaho Springs, moved and reassembled in its present location by the Chamber of Commerce, as a tourist attraction. In 1973, the Henderson Mine made drawings of the individual pieces and rebuilt the wheel using much of the old structure. By this time it was badly deteriorated and the partial reconstruction served only as a temporary measure before it ground to a halt again. In 1988, many Idaho Springs residents started a major reconstruction effort. Using donated time, materials and expertise, massive concrete foundations were poured, new supports were constructed, and the hub and axle were hoisted into place. Based on drawings from the previous reconstruction, new wooden components were cut and attached to the hub with many of the original metal parts. The hub and axle constitute fully one quarter of the total weight of 6000 pounds. Because of its tremendous weight, the wheel is furnished with solder-like bearings which prevent wear of the axle and can be poured in place when replacement is needed. The wheel is also equipped with special fittings for greasing from ground level.

Water powering the wheel and the waterfall to its left come from an overflow pipe of the water supply to Idaho Springs. The water is diverted from its natural path either to the falls, the wheel, or both. During the winter, all water flow is diverted to the falls to prevent ice damage to the wheel (Wendell Upright, Colorado Department of Highways, and Bruce Bell, Idaho Springs Historical Society, personal communication, 1991).

HOT SPRINGS

The hot springs Jackson used were known to Ute, Arapahoe, Apache, Kiowa and Comanche Indians since the territory had shifted hands many times. The best theories of the origin of "Idaho" are based on various corruptions of Indian words. In 1861, the area was "ceded" to the United States by the Arapahoe and Cheyenne Indians and shortly became part of Colorado Territory (Matthews, 1940; Dawson, 1954; Erickson and Smith, 1985). The first attempt to commercialize the springs was two years later in 1863 when a Dr. E.M. Cummings acquired the land and built a wooden bathhouse over the springs. From that time forward people had to pay to use the springs. It was some compensation, however, to be indoors and out of the cold. In 1866, the property was sold to Harrison Montague who built a more substantial stone structure. Montague's son-in-law replaced the bathhouse in 1899 with the "natatorium" (Fig. 12). Around this time it also became popular for tourists to stop and drink the mineral water (Hall, 1891; The Denver Times, 1899).

Operators of the Big Five Tunnel bought the property in early 1900 and made the tunnel network in the mountain that is present today. About 1910, a property-holding company acquired it and in the 1920's attempted to develop it as a sanitarium for polio called The Radium Hot Springs . During this time the main hotel was built. Today it is owned and operated as Indian Hot Springs by Jim Maxwell. Among the celebrities whose names have appeared in guest books over the years are Frank and Jesse James, H.A.W. Tabor and Walt Whitman (History of Clear Creek County, 1986; Radium Hot Springs Records, 1924-1930).

ACKNOWLEDGMENTS

I would like to thank the following for their help with this history: Marjorie Bell of Idaho Springs was a very patient initial and continuing source of information; Mary Jane Loevlie, also of Idaho Springs, kindly obtained the print of Charlie Tayler; the entire staff of the Denver Public Library's Western History Collection was generous with their help to obtain documentation and photographs; the staff of the U.S. Geological Survey and Bureau of Mines Libraries helped obtain and reproduce photographs and documentation; the staff of the Colorado State Archives assisted with document verification; Dick Walker skillfully adapted the figure from Terry Cox; and my sister Mary Lindsey edited the first draft.

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Figure 8. George A. Jackson. Denver Public Library Western History Collection (printed with permission)

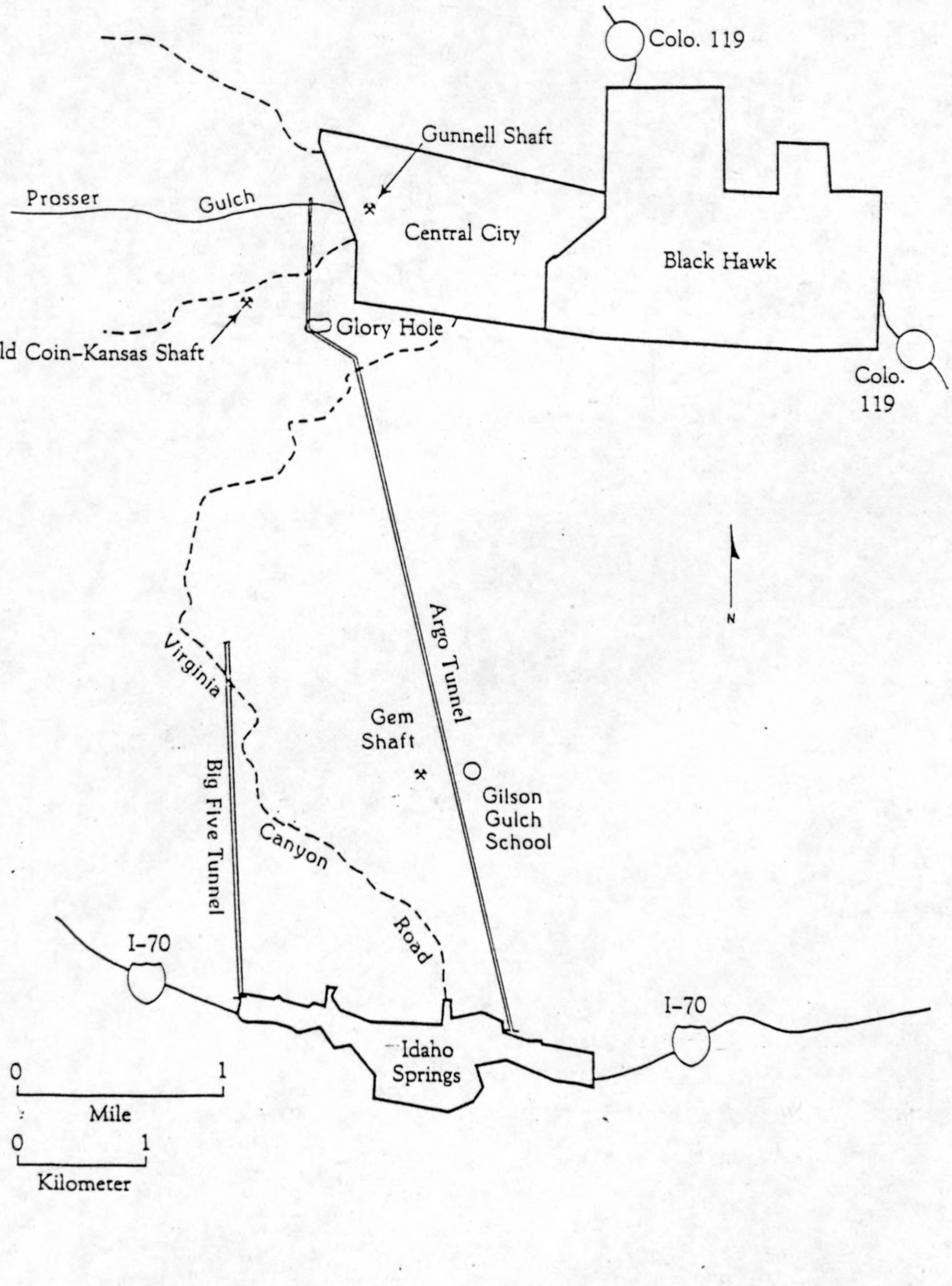

Figure 9. Map showing Argo and Big Five Tunnels in relation to Idaho Springs and Central City. Adapted from Terry Cox (printed with permission)

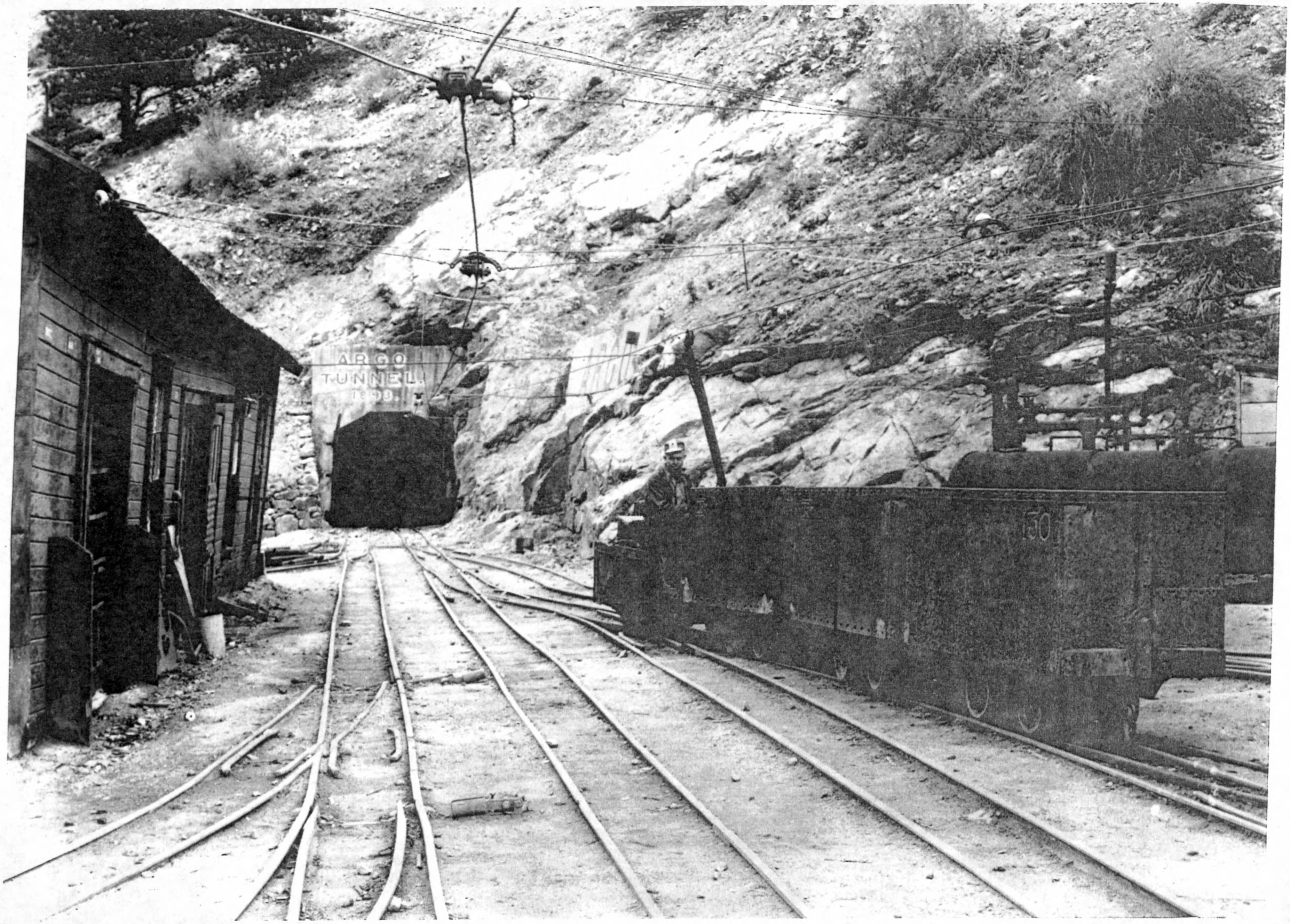

Figure 10. Argo Tunnel in operation during the 1930's. Denver Public Library Western History Collection (printed with permission)

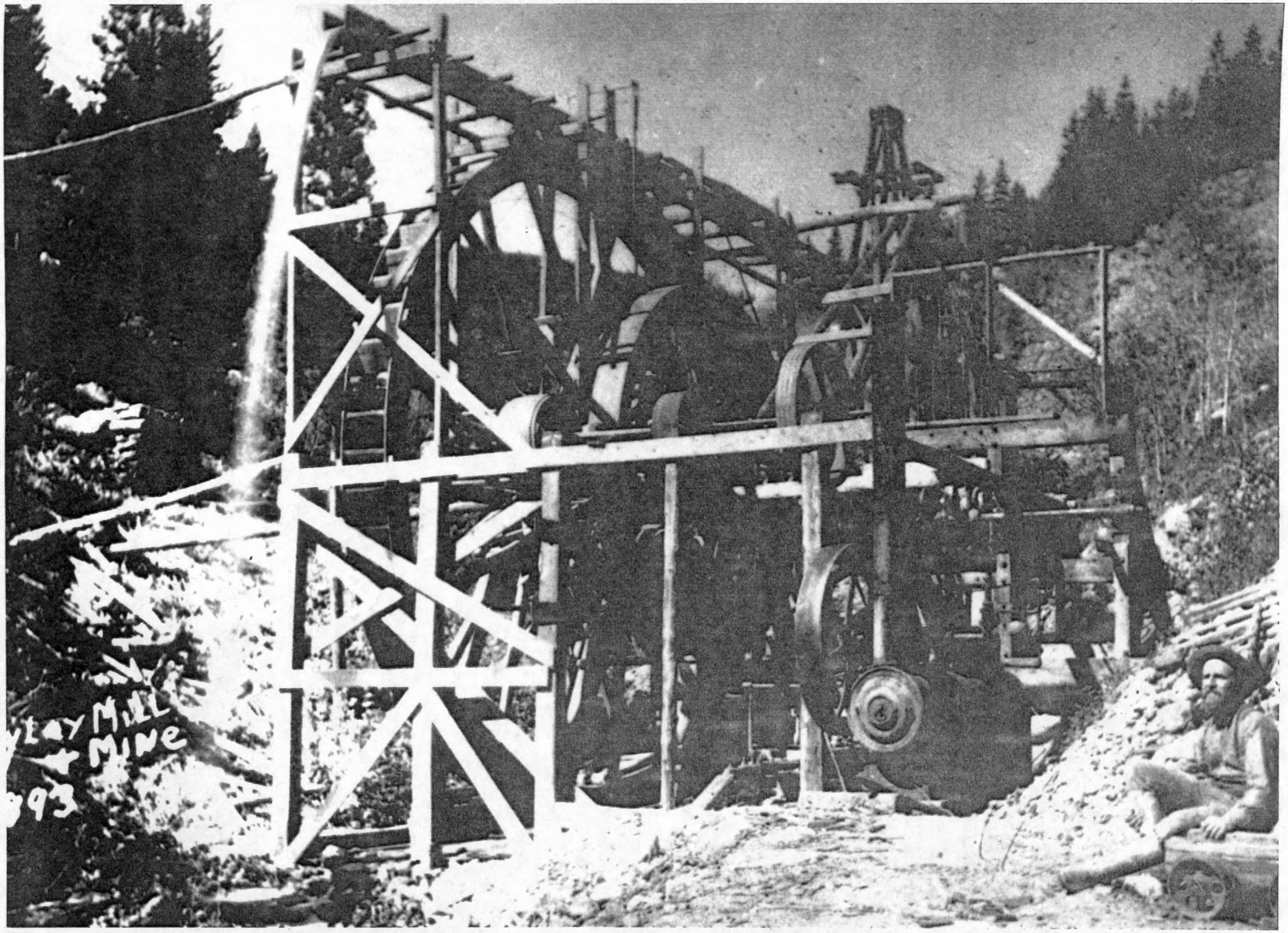

Figure 11. Charley Tayler with his water wheel. Idaho Spring Historical Society (printed with permission)

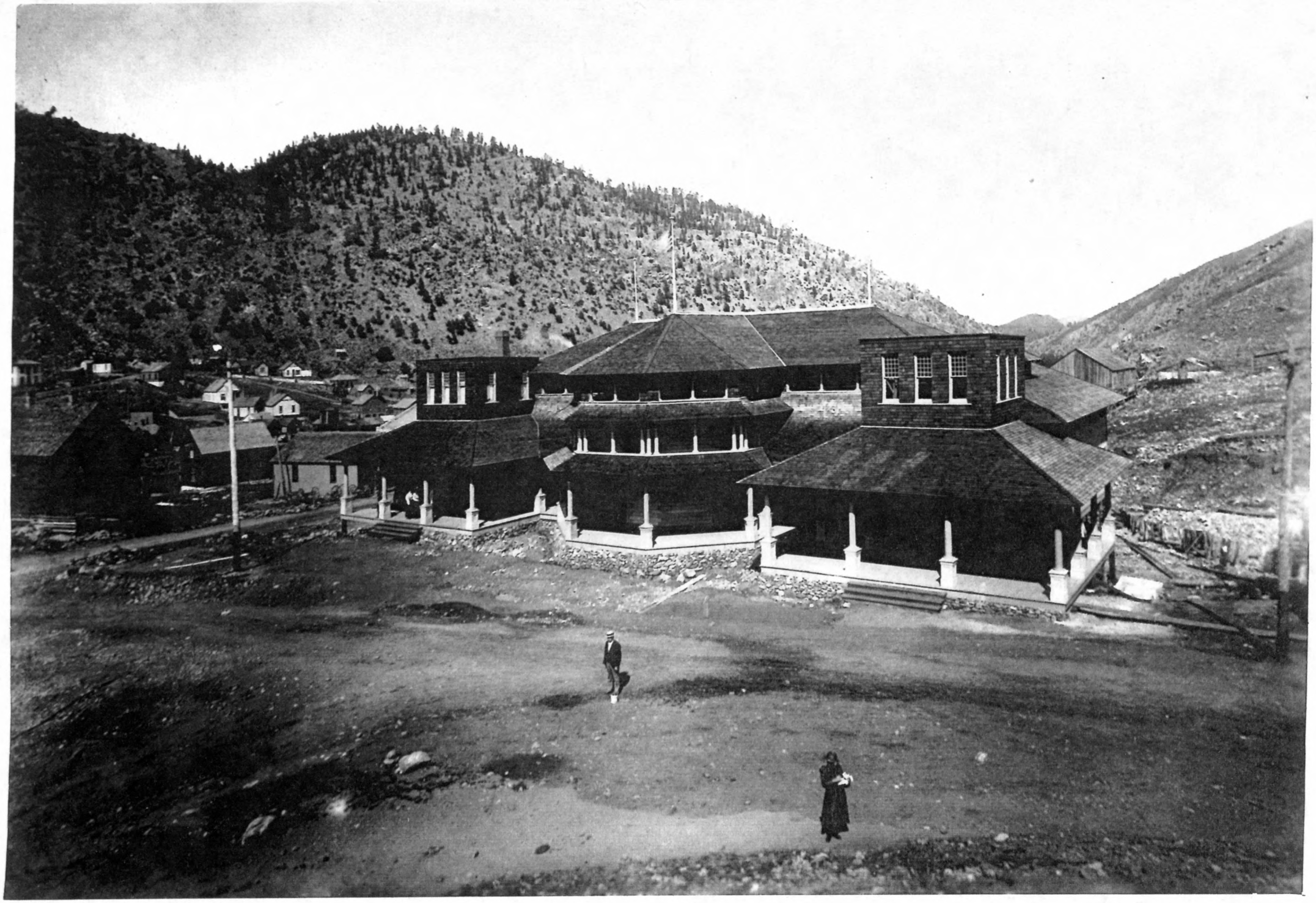

Figure 12. The Idaho Springs Natatorium. Denver Public Library Western History Collection (printed with permission)

INFLUENCE OF ACID-MINE DRAINAGE ON CLEAR CREEK, COLORADO

by W. H. Ficklin and K. S. Smith

FORMATION OF ACID-MINE DRAINAGE

Acid-mine drainage is a serious environmental problem in Colorado. The State of Colorado has determined that over 1300 miles of its streams are impacted by metals as a result of acid-mine drainage. Acid-mine drainage most commonly forms from the oxidation of iron-containing sulfide minerals. When sulfide minerals are exposed to air and water, iron sulfide [pyrite (fool's gold), FeS_2] is oxidized to dissolved ferrous iron (Fe^{2+}), sulfate (SO_4^{2-}), and acidity (H^+). This is referred to as the "initiator" reaction. Ferrous iron can then be oxidized to ferric iron (Fe^{3+}) in the presence of oxygen and bacteria. Normally, the oxidation of ferrous iron takes place fairly slowly. However, in the presence of common *Thiobacillus* bacteria, oxidation of ferrous iron takes place rapidly--about a million times faster than it does abiotically (Singer and Stumm, 1970). The resulting ferric iron is able to oxidize pyrite and can take over the initial role of oxygen. This bacterially-catalyzed oxidation of ferrous iron and the subsequent oxidation of pyrite by ferric iron is referred to as the "propagation cycle" of acid-mine drainage. The propagation cycle can produce acid-mine drainage as long as there are available pyrite, water, oxygen, and bacteria.

Acid-mine drainage often carries high concentrations of dissolved metals and metalloids. These high concentrations are caused both by the oxidation of metallic sulfides and by the acid dissolution of the country rock. Oxidation of metallic sulfides can cause elevated concentrations of elements such as iron, zinc, copper, lead, cadmium, and arsenic. Acid dissolution of the country rock can result in the release of elements such as aluminum, silicon, calcium, magnesium, sodium, and potassium. Many of these elements can be harmful to the ecology of the receiving waters.

CHARACTERIZATION OF WATER QUALITY IN CLEAR CREEK

There are many Clear Creeks in Colorado. This one originates at the continental divide west of Georgetown, Colorado, in the pristine alpine environment found at 11,0000 feet of elevation near Torrey's Peak. Along its path through the front range of the Rocky Mountains it traverses a section of the Colorado Mineral Belt. Many old mines and mine dumps can be seen along Interstate Highway 70 which follows the course of Clear Creek throughout most of Clear Creek County, Colorado. Eventually, Clear Creek empties into the South Platte River just north of Denver. During periods of low flow most of the water is removed from the stream at Golden, Colorado, for domestic, agricultural, and industrial use.

Acidic metal-rich drainage from the Argo Tunnel in the city of Idaho Springs enters Clear Creek and has a profound effect on the concentration of dissolved constituents, the amount of suspended sediment, and on the metal loads in the bed sediment. The concentration of several constituents found in the Argo Tunnel water is presented in table 1. The South Fork of Clear Creek receives waters draining the Argentine Mining District near the city of

Georgetown. The West Fork of Clear Creek receives mine drainage from an area near the town of Empire. The North Fork of Clear Creek passes through the Central City mining district. The waters and sediment of the North Fork are affected by the mining and add additional metals to Clear Creek.

In June of 1986, during high flow, we collected 27 water and sediment samples from Clear Creek at about two-mile intervals. Sample locations are shown in figure 13. The distribution of samples covered almost the entire length of the stream. In October of that same year when low flow was re-established we collected samples at the same locations. Field observations included pH, temperature, and conductivity.

Metals and metalloids are transported in streams and rivers as dissolved constituents and as suspended sediment. In Clear Creek, dissolved concentrations were determined from samples that had been filtered through a 0.45 micron filter and total concentrations were determined from samples that had not been filtered. Both filtered and unfiltered samples were acidified. Graphical results for dissolved and total concentrations of iron, manganese, copper, and zinc are presented in figure 14 for June, 1986, and figure 15 for October, 1986. At both sampling times the dissolved concentrations of iron were below the detection limit of 0.1 mg/L and are not shown on the graphs. The results clearly demonstrate the addition of these elements to the stream system by the acid water of the Argo Tunnel and the partitioning of these elements between the dissolved phase and the suspended load. The amount of an element carried in the suspended load is the difference between the unfiltered water and the filtered water.

FACTORS INFLUENCING METAL TRANSPORT AND ATTENUATION IN CLEAR CREEK

Downstream declines in dissolved metal concentrations can occur due to oxidation, precipitation, and adsorption reactions and to dilution effects. For example, dissolved ferric iron is fairly soluble under acidic conditions. However, when conditions are less acidic (pH>3.5), dissolved ferric iron becomes more and more insoluble and will precipitate as hydrous iron oxides. These hydrous iron oxides appear as red-orange-yellow precipitates and can be seen forming where drainage from the Argo Tunnel enters Clear Creek. Hydrous iron oxides can settle to the bottom of the stream and coat the streambed or they can be carried downstream in the suspended load. Similar precipitation reactions can take place for aluminum at pH>5 and for manganese at pH>8.

Many metals are known to adsorb on hydrous iron, aluminum, and manganese oxides. Upon adsorption, the metals become associated with the oxide surfaces and are either attenuated or transported with the oxides. Adsorption of metals on oxide surfaces is very pH dependent. The pH range of adsorption is different for different metals and different oxides. For positively-charged metal cations, the extent of adsorption on oxides generally increases with increasing pH of the stream water. Figure 16 demonstrates that the amount of copper and zinc associated with the suspended load in Clear Creek in June, 1986, downstream of the Argo Tunnel increases with increasing stream pH. This figure indicates that both copper and zinc may be adsorbed on hydrous iron oxides that precipitate when drainage from the Argo Tunnel enters Clear Creek. As shown in figure 14, the suspended load of copper and zinc increases downstream of the Argo Tunnel. However, pH-dependent metal transport is not apparent in data from October, 1986 (Fig. 16).

Arsenic is also added to Clear Creek at the Argo Tunnel and at the North Fork. The dissolved concentration of arsenic is less than 1 lg/L throughout the sampling region. However, as demonstrated in figure 17, the concentration of arsenic found loosely bound to the bed sediment shows that arsenic is adsorbed by the hydrous iron oxides in the system and is increased dramatically downstream from the Argo Tunnel and the North Fork. The loosely bound arsenic was defined as that which dissolves in 1 M hydrochloric acid.

Detailed information on the extent of contaminated mine drainage in Colorado can be found in Wentz (1974). A very technical discussion of the chemistry of natural waters can be found in Stumm and Morgan (1981). Ferguson and Gavis (1972) discuss the chemistry of arsenic in natural waters. Kimball and Wetherbee (1988) report on the instream chemical reactions of acid mine water entering a neutral stream. Benjamin and Leckie (1981) discuss pH-dependent adsorption of metals on hydrous iron oxide.

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Table 1. Results for chemical analysis of Argo Tunnel water, August 1985, and Clear Creek, October, 1985.

Constituent, concentration	Argo Tunnel Water	Clear Creek at Argo Tunnel	
		Upstream	Downstream
Sulfate, lg/L	2,000,000	29,000	44,000
Calcium, lg/L	400,000	14,000	15,000
Magnesium, lg/L	110,000	3,000	3,300
Iron, lg/L	37,000	<100	<100
Manganese, lg/L	31,000	640	1,070
Sodium, lg/L	19,000	8,300	8,700
Zinc, lg/L	9,600	190	430
Copper, lg/L	5,400	18	14
Potassium, lg/L	4,000	1,700	1,700
Molybdenum, lg/L	170	no data	no data
Arsenic, lg/L	120	<1	<1
pH, std. units	3.2	7.5	7.6

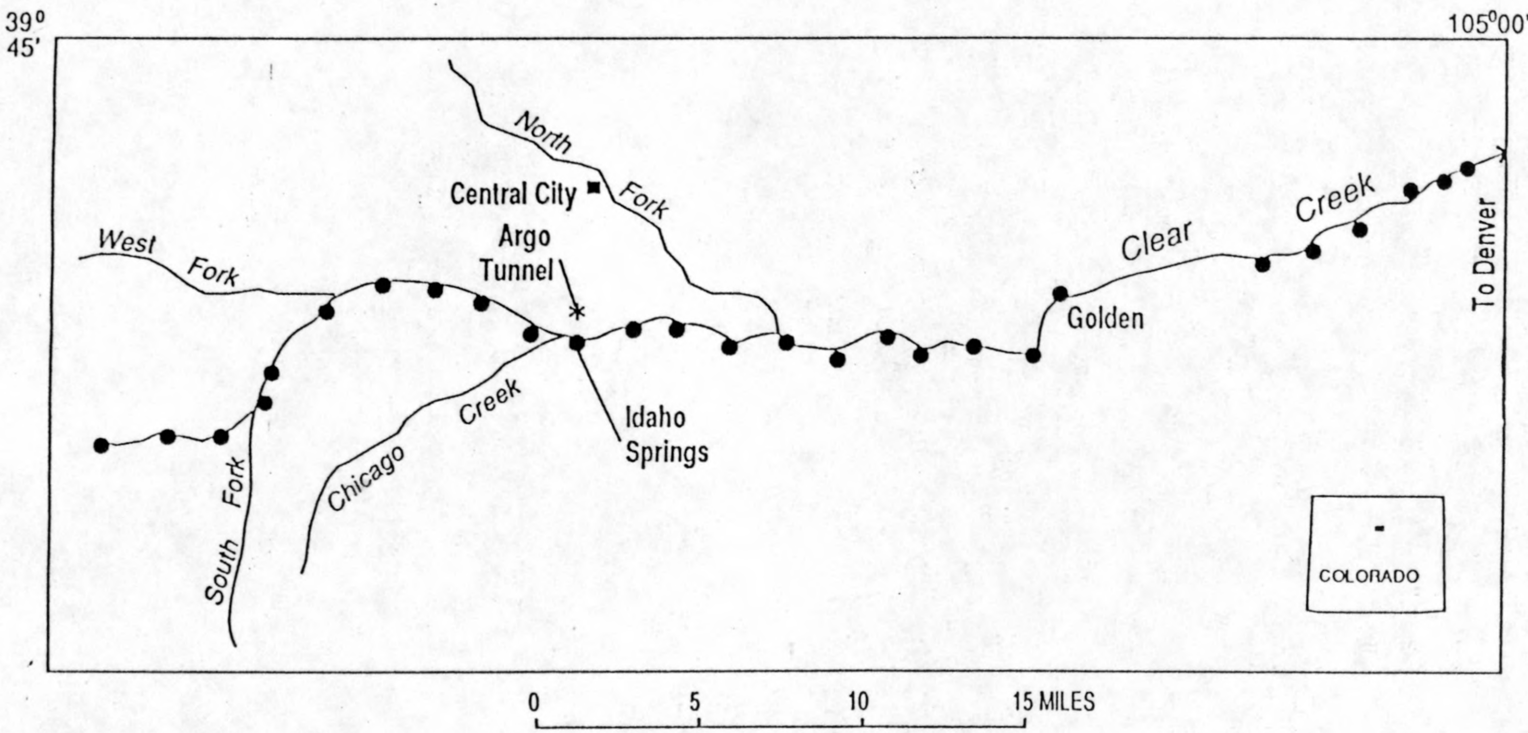


Figure 13. Map showing general location of Clear Creek, Colorado, and sample collection sites

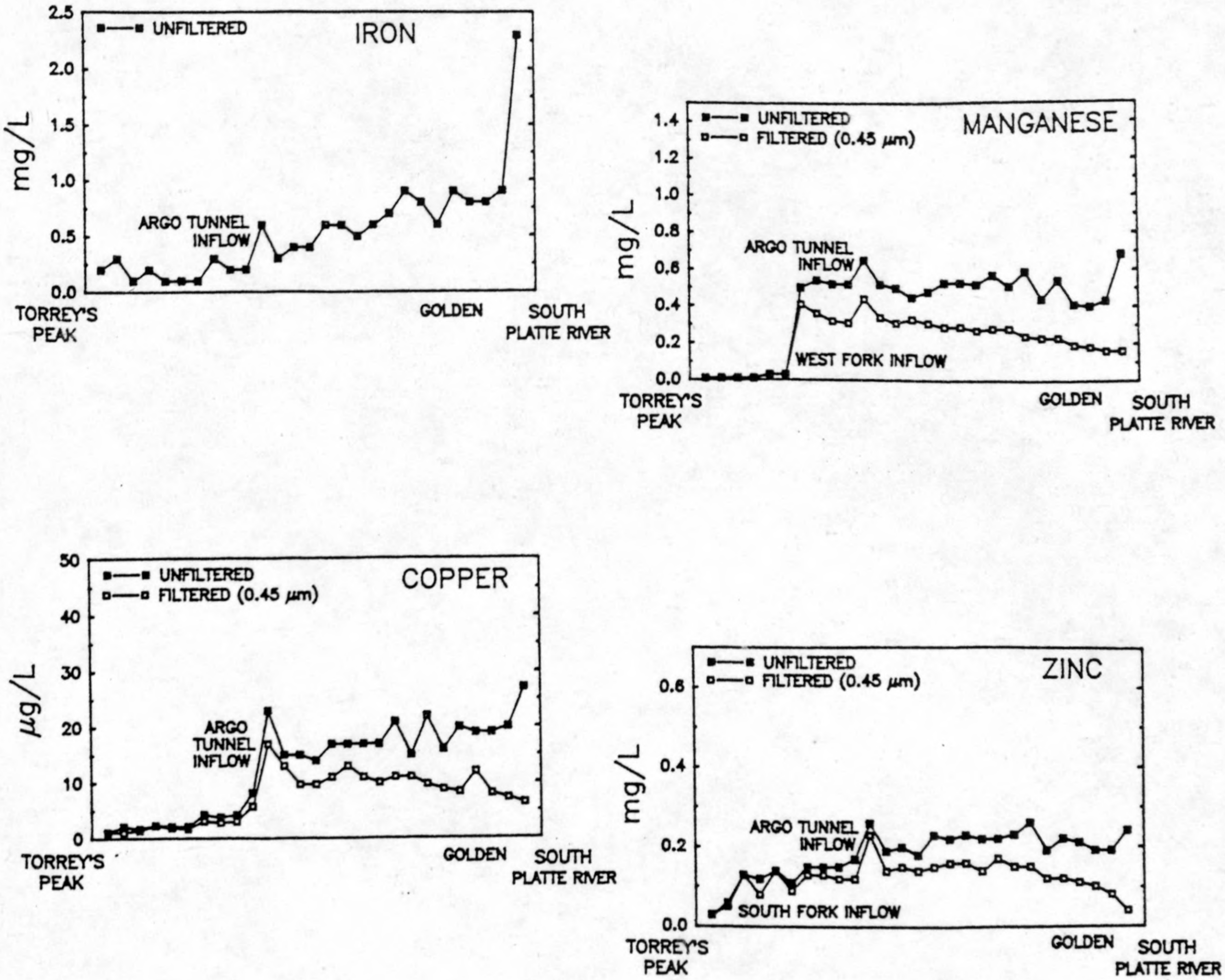


Figure 14. Influence of various inflows on the dissolved (passed through 0.45 1m filter) and total (unfiltered) concentrations of iron, manganese, copper, and zinc in water collected from Clear Creek in June, 1986.

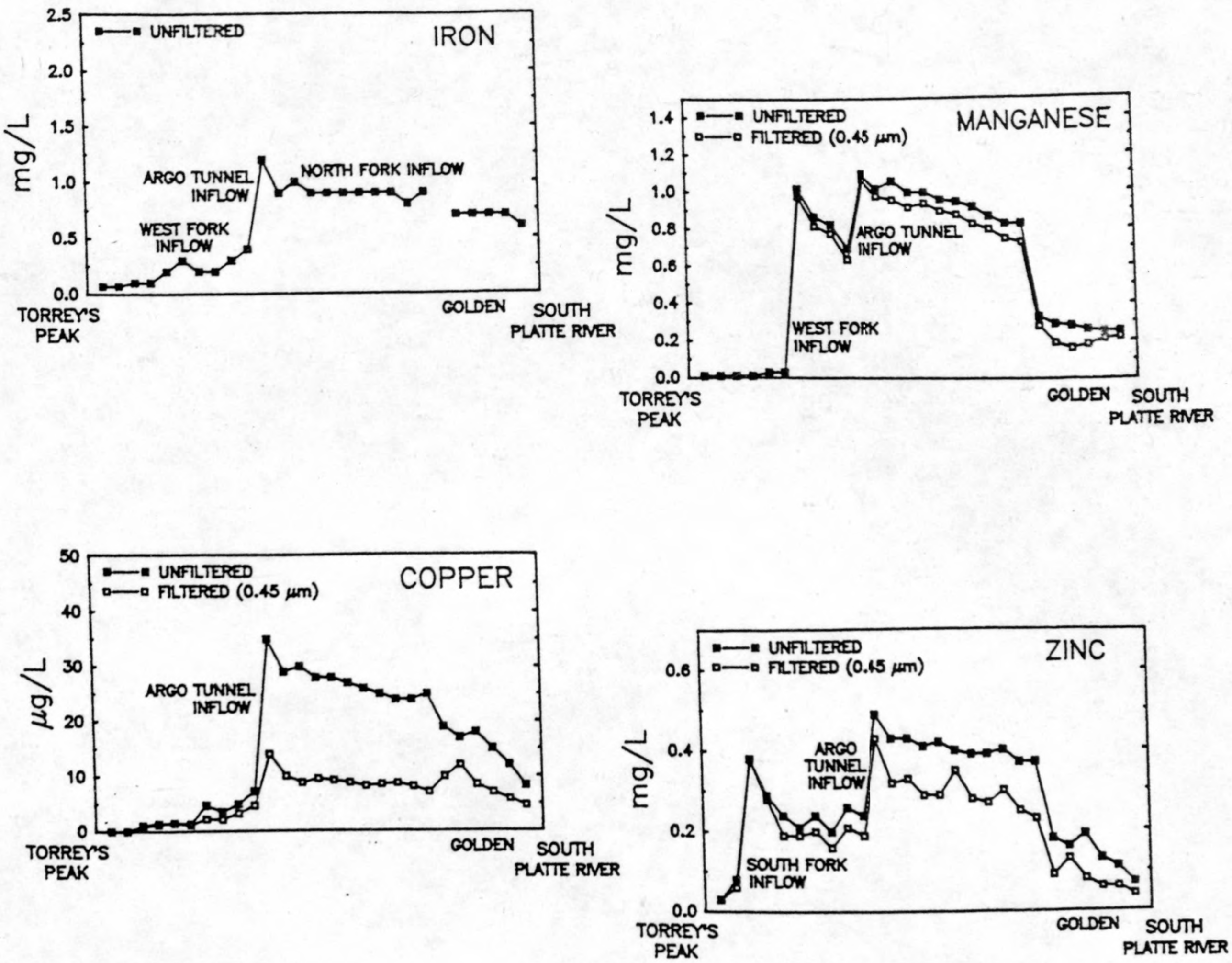
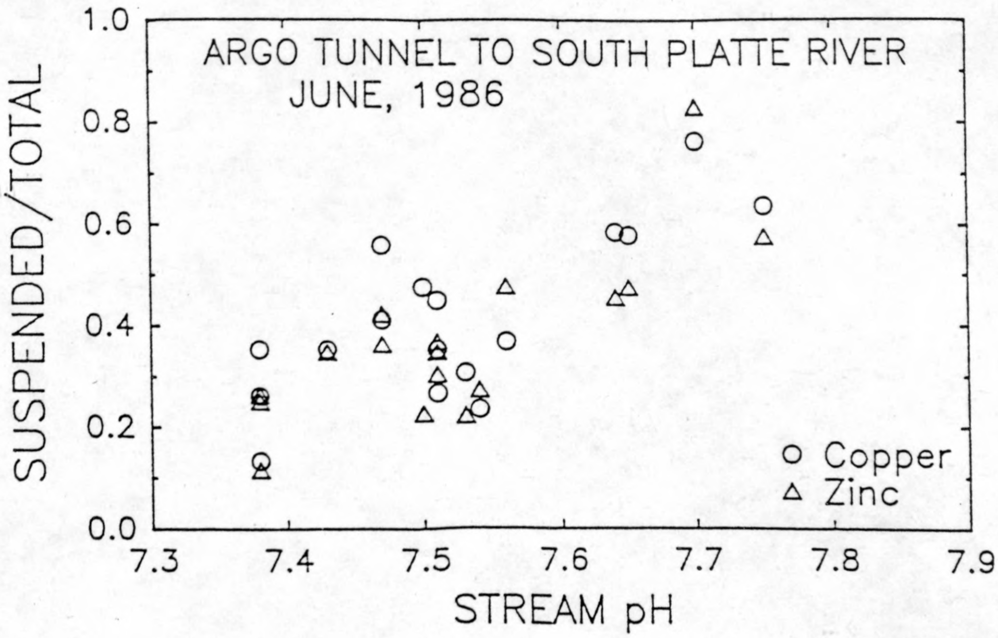


Figure 15. Influence of various inflows on the dissolved (passed through 0.45 1m filter) and total (unfiltered) concentrations of iron, manganese, copper, and zinc in water collected from Clear Creek in October, 1986.



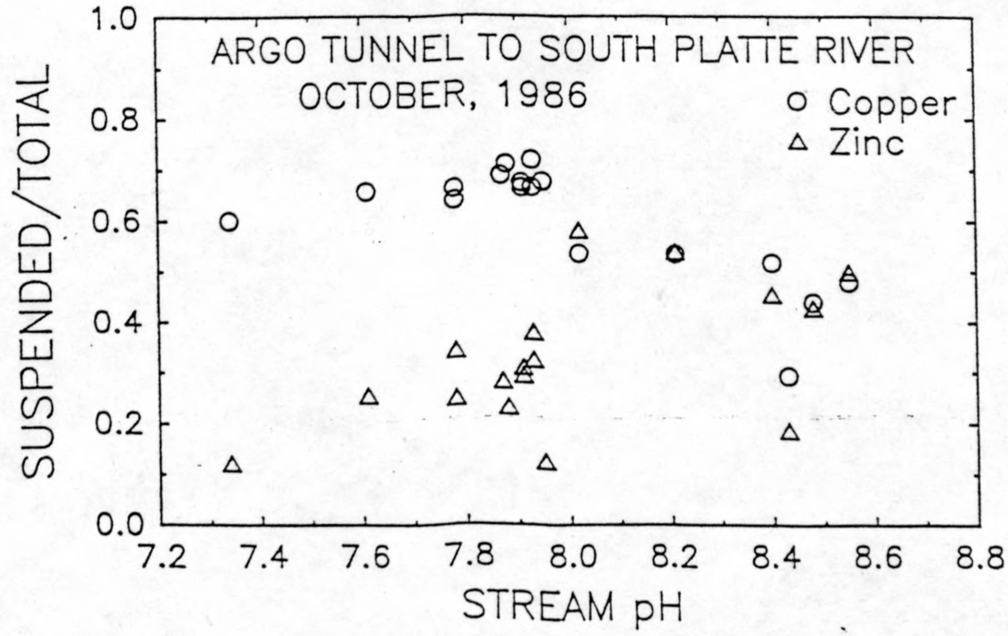


Figure 16. Proportion of suspended load of copper and zinc versus stream water pH downstream of the Argo Tunnel drainage into Clear Creek.

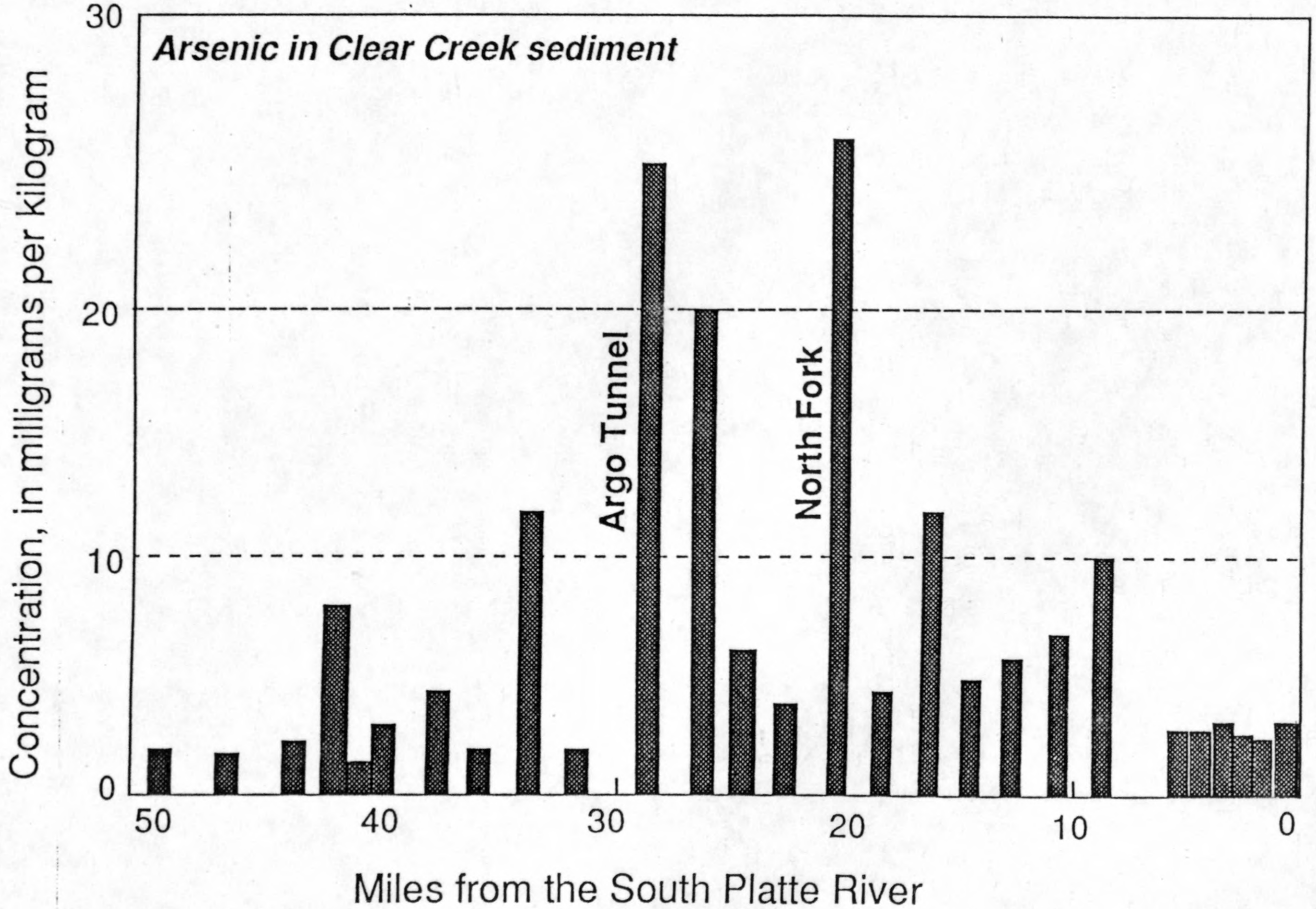


Figure 17. Distribution of loosely bound arsenic in Clear Creek sediment

RESULTS OF EXPERIMENTS USING A PILOT-SCALE CONSTRUCTED WETLAND FOR REMEDIATION OF ACID MINE DISCHARGE AT IDAHO SPRINGS, COLORADO

J.C. Emerick, T.R. Wildeman, R.R. Cohen, and R.W. Klusman

ABSTRACT

Acid mine drainage affects the water quality and aquatic resources of a significant proportion of streams and rivers in the mineral belt of the Southern Rocky Mountains. In an effort to develop low-cost effective methods to treat mine discharge using constructed wetlands, a pilot-scale treatment system has been maintained at the Big Five tunnel in Idaho Springs, Colorado, since October 1987. This experimental system has been used to assess the importance of substrate type, different flow characteristics, vegetation, and other factors on treatment effectiveness. During the life of the pilot system, various modifications and additions have been made in an effort to refine knowledge of treatment processes and to develop design criteria for large-scale systems. The system is effective at removing most metals studied, including iron, zinc, and copper. In general, results indicate that treatment systems incorporating a mechanism forcing vertical flow of the mine drainage through the soil substrate are more effective than systems relying on lateral flow. Low flow rates provided more effective metal removal than high flow rates.

INTRODUCTION

One of the most serious surface water quality problems in the Rocky Mountain region is the presence of waters having low pH and high heavy metal concentrations associated with mineralized zones. These waters are formed as a result of natural geochemical processes involving the oxidation of metal sulfides nearly always found in mineralized rock, with the processes being initiated by exposure of the rock to moisture and oxygen. This occurs naturally in places where the host rock is fractured and results in so-called "iron seeps" or "iron bogs", the presence of which has been used in geochemical exploration for minerals. Of greater concern are situations where the geochemical sulfide weathering processes have been exacerbated as a result of mining activity, where sulfide-bearing rock has been exposed in underground mine workings, or at the surface in mine dumps or mill tailings. These situations often promote the formation of acid drainage, and acid leachate from surface waste piles. In all of these cases, water quality concerns include the suitability of the receiving waters for fisheries habitat, and the potential threat to human populations.

State and federal agencies have been particularly concerned with inactive mines because of the lack of adequate treatment, poor records of ownership, and the large numbers of these sites in western mineral belts. In Colorado, several mining districts have been placed on the National Priority List for action under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (known as CERCLA or Superfund), including the Idarado Mine near Telluride, the Eagle Mine near Minturn, the California Gulch district near Leadville, and the Central City-Idaho Springs district.

These problems have highlighted a need for a technology to treat acid mine drainage and acid leachate that is effective and relatively inexpensive to construct and maintain. Although various methods of conventional treatment exist, these technologies have either a high equipment cost, a high maintenance cost, or both. For several years, we have been examining the potential of using natural biogeochemical processes in a constructed wetland scheme to treat acid mine drainage. Such a concept has been used in coal mining regions of the eastern U.S. with some success, but there has been uncertainty regarding the effectiveness of this type of treatment in mountain climates for metal mine discharges.

In 1987, as part of the remedial investigation connected with the Central City - Idaho Springs Superfund Project, an experimental pilot-scale constructed wetland was built to evaluate a wetland treatment approach and to determine the most important biogeochemical processes involved in metal removal and remediation of acid conditions. The work was initially funded through a subcontract with Camp, Dresser, and McKee, who was the prime Superfund contractor with the Environmental Protection Agency (EPA) for the project, and funded later through the Emerging Technology Program of the EPA. The experimental wetland was constructed at the portal of the Big-Five tunnel, located at the western edge of Idaho Springs, Colorado. This paper summarizes results of some of the studies at the wetland, and presents some of our perspectives on the design of operational systems. It is not intended to provide a detailed description of methods, or even a synopsis of all of the numerous studies that have been conducted at the site; much of that information will be available in a forthcoming EPA report (Handbook for Constructed Wetlands Receiving Acid Mine Drainage, T.R. Wildeman (Ed.), Risk Reduction Engineering Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati Ohio, 45268) that at the time of this writing is in the review process.

SITE CONDITIONS AND CONSTRUCTION OF THE ORIGINAL TREATMENT SYSTEM

The Big Five tunnel was constructed in 1901 as a drainage tunnel for several gold and silver mines in the Idaho Springs district. The elevation of the site is approximately 2280 m (7600 ft). The site is located in the valley bottom less than 100 meters from Clear Creek. Because of its location, the climate is cool, and cold air drainage from the surrounding slopes can produce freezing conditions even during the summer. Water flow from the tunnel is relatively constant throughout the year, averaging 1.34 L/sec. The chemical characteristics also are relatively uniform over time. Table 2 shows mean concentrations for the more important metals in the drainage. Mean temperature is approximately 13^{o}C, and pH is usually within a few tenths of 2.6. The major anion is sulfate, with an average concentration of 2100 mg/L.

Construction of the treatment system was completed in the fall of 1987. In its original configuration, the system was 3.05 m (10 ft) wide by 18.3 m (60 ft) long, with a foundation constructed of concrete and wood to allow a total depth of 1.22 m (4 ft). The system was divided into three equally sized cells, A, B, and C, each 6.1 m (20 ft) long. Each cell was lined with Hypalon, an acid-resistant liner fabric, to prevent leakage. A distribution system made of PVC pipe and valves carried mine drainage from the portal to each cell. The mine drainage was allowed to flow into a 30-cm (12-in) wide rock basket at the head of each cell, which extended across the entire width, held in place with plastic fencing. A PVC drain pipe was installed at the downstream end of each cell. Figure 18 shows a schematic of the system. Cell A was filled with mushroom compost consisting of approximately 50% animal manure and 50% barley mash wastes from a local brewery. Cells B and C were filled with a substrate consisting of equal parts of peat, aged steer manure, and decomposed wood shavings and sawdust. In addition to the above substrate, the bottom of cell C was filled to a depth of 12 cm (5 in) with limestone rock prior to laying the organic substrate. Following installation of the organic substrate, several species of aquatic plants were transplanted into each cell. These species were primarily cattail (*Typha latifolia*), sedges (*Carex aquatilis* and *C. utriculata*) and arctic rush (*Juncus arcticus*). These plants were obtained from nearby wetland areas and from Shadow Mountain Reservoir near Grand Lake, Colorado.

The cells were initially put into operation using a flow rate of 3.8 L/min (1 gallon/min), according to guidelines published by the U.S. Bureau of Mines, based on similar investigations on treatment systems in eastern coal mining areas. Mine drainage entered each cell via the rock basket, which distributed the water over the entire face of the substrate, and allowed the water to flow laterally through the substrate toward the drain at the downstream end of each cell. Saturation of each cell was controlled by overflow into a standpipe attached to the drain. Water eventually percolated to the top of the substrate, where it was drawn off by the standpipe. During most of the project, monthly samples of water, substrates, and plants were collected for analysis of major cations and trace elements. Water samples were analyzed for principal anions, cations, trace elements and nutrients.

Several conclusions resulted from the first year of operation. We found that an unacceptable degree of "short-circuiting" and channelization was occurring, allowing the mine drainage to rise to the surface close to the rock box and flow over the top of the cell to the drain. Flow rates also appeared to be too high for the cells. Because of these problems, we felt that there was insufficient contact with the substrate, and that metal removal was below the potential of the system.

DESIGN MODIFICATIONS

During late 1988, cell A was rebuilt with a system of longitudinal walls to increase the flow path, and transverse redistribution baffles that were designed to collect water from the top surface and return it to the bottom (Fig. 19). During the summer of 1989, cell B was divided into two 3.05-m by 3.05-m (10 ft by 10 ft) cells, redesigned to promote vertical flow. Each half of cell B was fitted with a perforated PVC distribution system at the top and at the bottom of each cell, so that mine drainage could either be admitted to the top of the cell and drawn off the bottom (downflow system), or be admitted to the bottom of the cell and drawn off the top (upflow system) (Fig. 20). A plastic stock tank was also added to the inlet circuit of each subcell to allow additional precipitation of ferric oxyhydroxides from the mine drainage before the water entered the cell. This was done to further minimize potential clogging of the system by iron precipitates. The original peat-based substrate of cell B was replaced by mushroom compost identical to that used in cell A. No vegetation was transplanted into cell B after it was rebuilt. At the same time that cell B was being reconstructed, two other cells were built. Cell D was designed to polish the effluent of cell A, and was constructed as a surface flow cell, approximately 1.22 m (4 ft) wide by 12.2 m (40 ft) long by 45 cm (1.5 ft) deep. Cell E was designed as a downflow cell, with a circular shape approximately 3.05 m (10 ft) in diameter by 0.61 m (2 ft) deep. It was constructed by excavating a small impoundment, lining it with hypalon, installing a PVC drain at the bottom under a layer of gravel, and placing filter fabric over the gravel. Both cells D and cell E were filled with the used peat-based substrate and vegetation that was removed from cell B. Figure 21 shows the approximate location of all cells at the Big Five site.

SUMMARY OF RESULTS

While a number of interrelated studies on the hydrology, microbiology, geochemistry, and vegetation of the system were conducted, only a general summary of the behavior of the various wetland cells will be presented here. Table 3 presents data from the 11-month period following the last of the major modifications. Values showing percentage removal of manganese, iron, copper, and zinc are given to illustrate the effectiveness of the various treatment cells.

Cell A, in spite of its reconstruction, continued to show poor removal of manganese and iron. In part, this was due to the design of the modifications. Some leakage occurred around the walls, and clogging of screened ports in the redistribution baffles limited flow in some sections of the system.

The modifications to cell B incorporating a vertical flow design produced promising results, removing more manganese in general than the other cells, as well as a larger proportion of the other elements. The downflow subcell initially performed better, however, when flow problems were solved in the upflow subcell, the latter system seemed to produce the best overall performance.

Cell C is the only cell that has remained unmodified since the treatment system was initially constructed. Although cell C has not performed as well as the other cells, it has been in operation longer than the rest, and an examination of some of the data from that cell is informative. Figure 22 shows the percentage removal of manganese, iron, zinc, and copper by cell C, plotted with pH of the cell's effluent and flow rate. There perhaps is more uncertainty regarding the flow rate because it was monitored and adjusted only every few weeks, and partial or complete clogging of the inlet valve was a frequent occurrence. However, the figure shows a relatively clear inverse relationship between flow rate and pH, and a direct relationship between pH and removal of iron, zinc, and copper. These relationships have been observed in other cells as well. Figure 22 also shows that manganese behaves differently from the other elements, principally because it tends to precipitate more effectively in an oxidizing environment, rather than in a reducing environment typical of the Big Five systèm. Manganese will not precipitate in a reducing environment unless the pH in the wetland increases significantly.

Some success was achieved with cell D, which received the output of cell A, and which dramatically increased the removal of most metals. However, because cell D is a relatively shallow surface flow cell, freezing problems were experienced during the winter.

Cell E was constructed almost as an afterthought to use up extra substrate and plants that were left over from the reconstruction of cell B and construction of cell D. Its effectiveness in removing metals and raising pH has been relatively good throughout most of its operation. Its good performance may be significant in that considerably less expense was involved in its construction and it may represent a more realistic prototype of future small treatment systems.

CONCLUSIONS

The past three years of studies associated with the pilot treatment system have provided a substantial data base to support a number of conclusions. We present some of these here, with the caveat that ongoing studies at Colorado School of Mines and elsewhere on wetland treatment systems will probably produce results that will cause us to modify and refine some of the statements below.

Metals such as iron, copper, and zinc can be removed, and pH can be increased on a long-term basis. Copper and zinc, in particular, are removed effectively. However, iron removal is a key aspect in the functioning of the system. We believe that flow rates must be adjusted so that total acid flow is limited, so as not to "shock" the microorganisms, which require a higher pH than is usually typical of the drainage at the Big Five tunnel.

The major metal removal process is dissimilatory sulfate reduction, mediated by microbial activity. This process, active at pH 5 and above, allows precipitation of metal sulfides. The metal sulfides are a stable form for long-term retention of metals by the wetland substrate, as long as a reducing environment is maintained.

Adsorption of metals onto an organic substrate is an important transitional retention phase, increasing the residence time, but is relatively unimportant for long-term retention. This adsorbed form provides a readily available source of metals for microbially mediated reactions. The adsorption of metals and protons by the substrate will also help buffer pH shocks to the system.

Anaerobic microbial processes are critical for maintaining high pH. Organic decomposition is a particularly important process, releasing ammonia, bicarbonate ions, and methane. Production of these substances promotes higher pH in the substrate, which in turn enhances the substrate environment for sulfate reduction and metal precipitation.

Plants function mainly to stabilize the substrate surface, reduce channelization, and provide a source of organic matter for the microbes. Although plants absorb metals through their roots, they are relatively unimportant for direct long-term removal of metals. Most of the metals that are absorbed by the plant tissues return to the soil when the plants die and decompose.

Many plant species would probably work well in constructed wetlands, as long as the species used can tolerate saturated soils, low pH, and high metal concentrations. Ideally, the plants should have high biomass production to provide a suitable source of carbohydrates for microbial populations. Of the species studied at the Big Five wetland, cattails worked best. A possible negative influence of plants is to pump oxygen into the upper part of what is intended to be an anaerobic environment.

The use of peat in the substrate is discouraged because of its low hydraulic conductivity and its tendency to buffer the aqueous phase to a low pH. In particular, substrates that have a natural buffering capacity to pH 5.5 or greater enhance sulfate reduction and allow a new wetland to function effectively from the beginning. Desired lower limits of hydraulic conductivity of the substrate is 10^{-5} cm/sec. Natural peat often has a buffering level below pH 5 and a hydraulic conductivity of less than 10^{-5} cm/sec.

A vertical saturated flow design was more effective than a design relying on lateral flow. Lateral systems appeared to be prone to poor circulation in the substrate and a tendency toward surface flow, as well as channelization. These problems, which limited contact of the mine drainage with the substrate, were minimized in vertical flow systems.

Removal efficiency depends strongly on loading factors; more than 24 m^2/L/min (1000 ft^2/gal/min) was needed for reasonable removal at the Big Five system, assuming a substrate depth of 0.61-1 m (2-3 ft). Mine drainage having different metal and acidity concentrations would require a different volume of substrate, which can be determined using bench-scale tests.

Plumbing should be kept simple to avoid clogging by ferric oxyhydroxides, and some parts may need insulation to prevent freezing. Sharp bends and vertical rises are particularly vulnerable to accumulations of iron precipitates. Locating plumbing, if not the entire system, in areas that receive winter sun is desirable to minimize freezing.

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Table 2. Average concentrations and daily output (loading) for selected metals in the Big Five effluent.

Element	Concentration (lg/L)	Loading (kg/day)
Iron	51,000	5.58
Manganese	28,733	3.13
Aluminum	14,067	1.54
Zinc	8,235	0.907
Copper	1,420	0.140
Nickel	239	0.027
Lead	40	0.005
Cadmium	27	0.003
Chromium	14	0.001
Arsenic	8	0.001
Silver	6	0.001

Table 3. Treatment effectiveness of all cells at the Big Five constructed wetland site for selected metals. Data are means of monthly observations and analyses of samples collected during the period from October 1989 through August, 1990. Metal values are shown as percentage of removal compared to concentrations in the mine drainage.

Cell	*N*[1]	Mn	Fe	Zn	Cu	Effluent	Flow
		Percentage Removal				pH	(L/min)
A (Lateral flow)	11	0.2	35.5	60.7	83.4	4.7	1.04
D (Surface flow)[2]	7	13.1	72.7	98.7	100	6.3	0.84
B (Upflow half)[3]	10	18.4	54.7	51.7	65.1	5.1	0.63
	5	34.4	91.2	97.2	100	6.8	0.34
B (Downflow half)	11	22.5	76.0	40.1	82.5	5.4	0.50
C (Lateral flow)	9	1.9	50.1	35.0	65.4	4.4	1.04
E (Downflow)	11	10.7	86.0	100	96.8	6.2	0.51

[1] *N* is the number of monthly observations during the period. Although the total period of observation was 11 months, the number of monthly observations was fewer for cells C and D (due to winter freezing problems) and for the upflow half of cell B (flow problems).

[2] Cell D was receiving the effluent from cell A.

[3] Problems with vertical channelization and flow were experienced during the first 6 months of operation. The second row of values reflects the operation of the cell during the last 5 months after the problems were rectified.

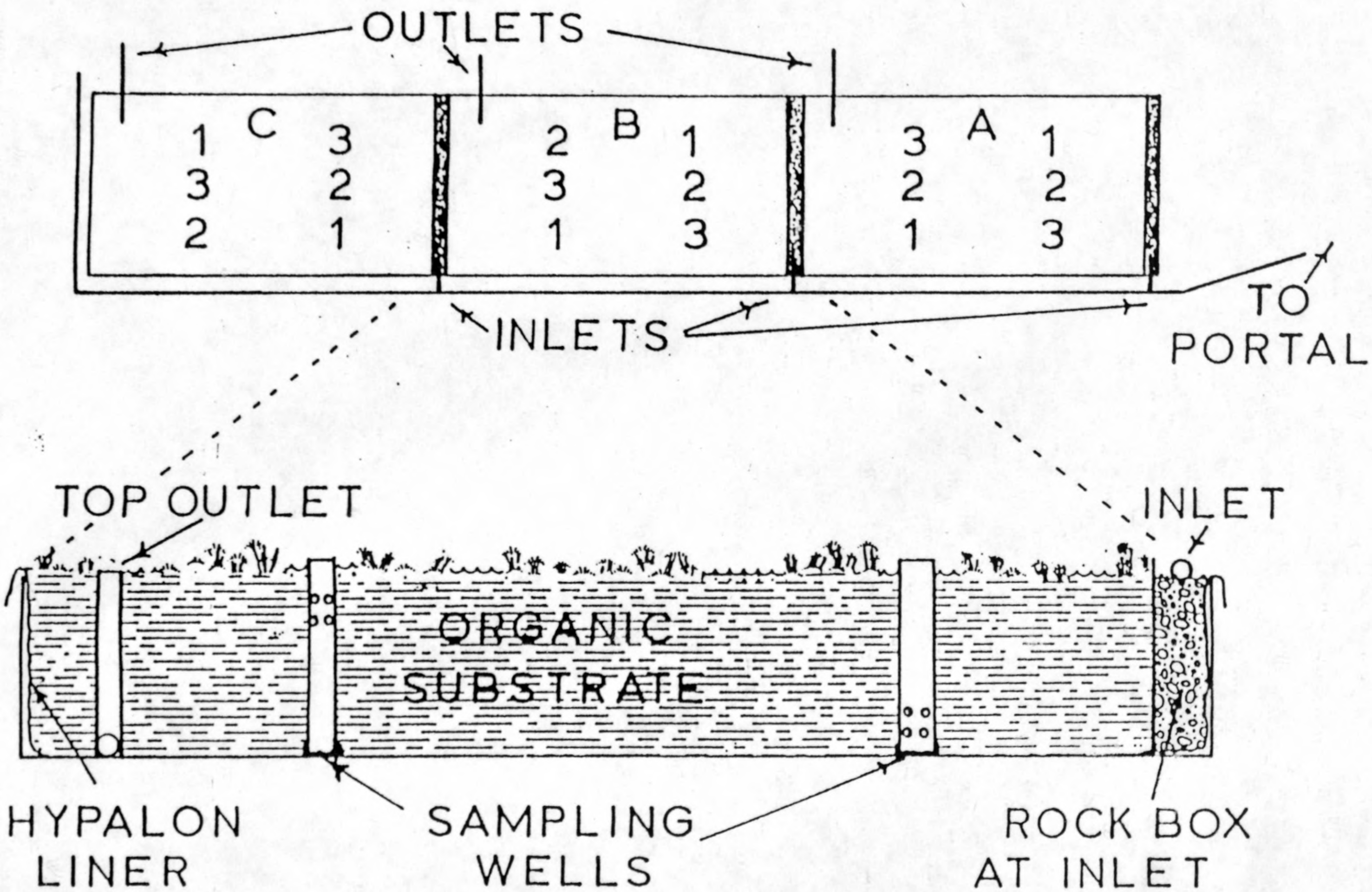

Figure 18. Plan view and cross section of the Big Five constructed wetland

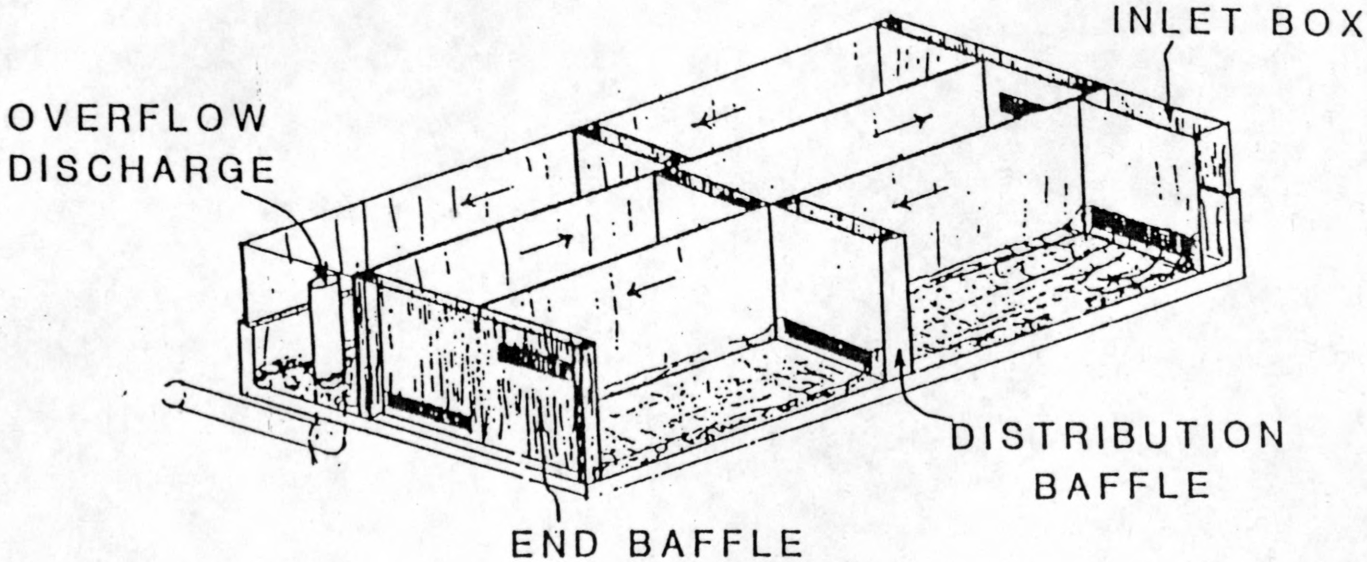

Figure 19. Cut-a-way view of the modified design of cell A

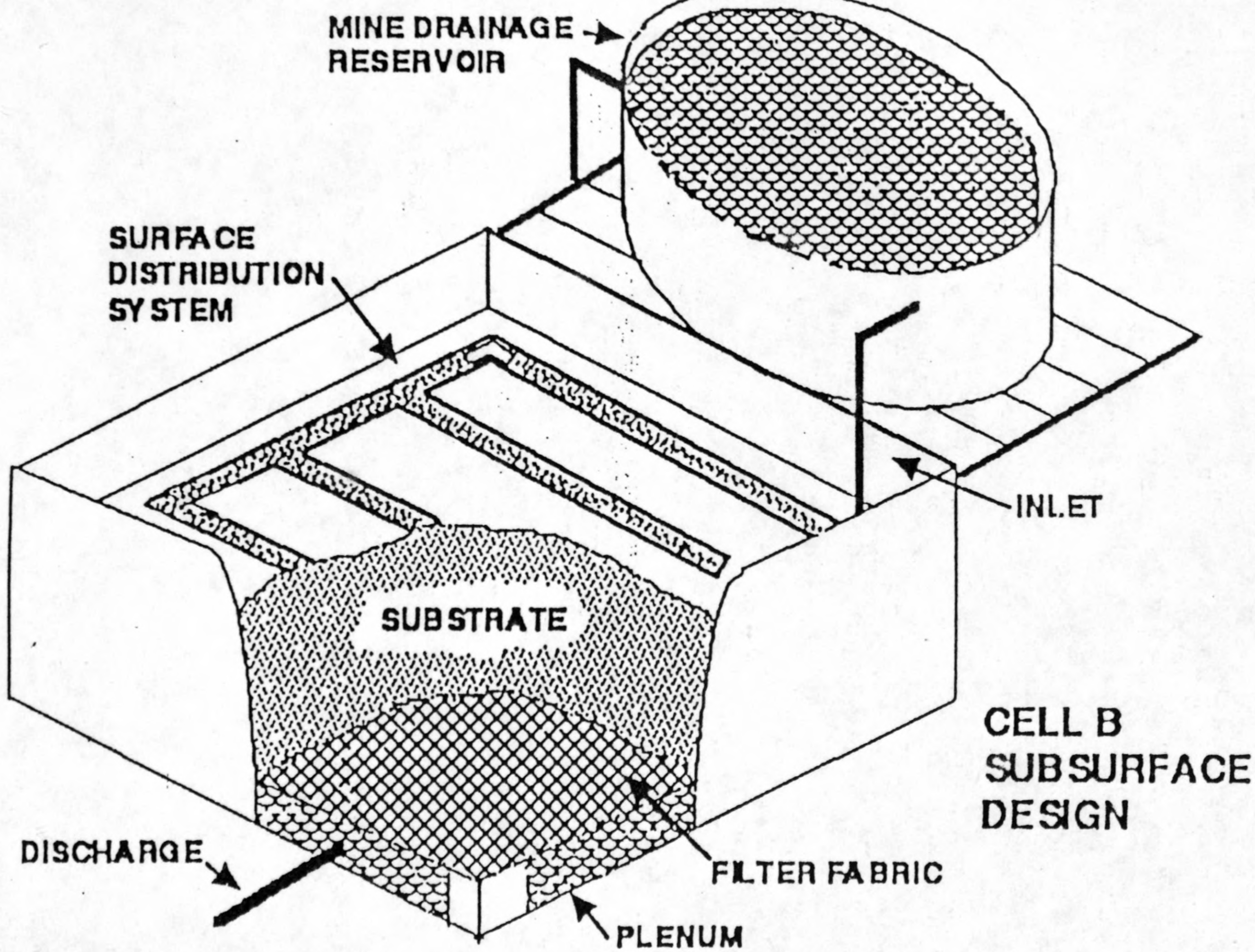

Figure 20. Cut-a-way view of the modified design of a cell B subcell

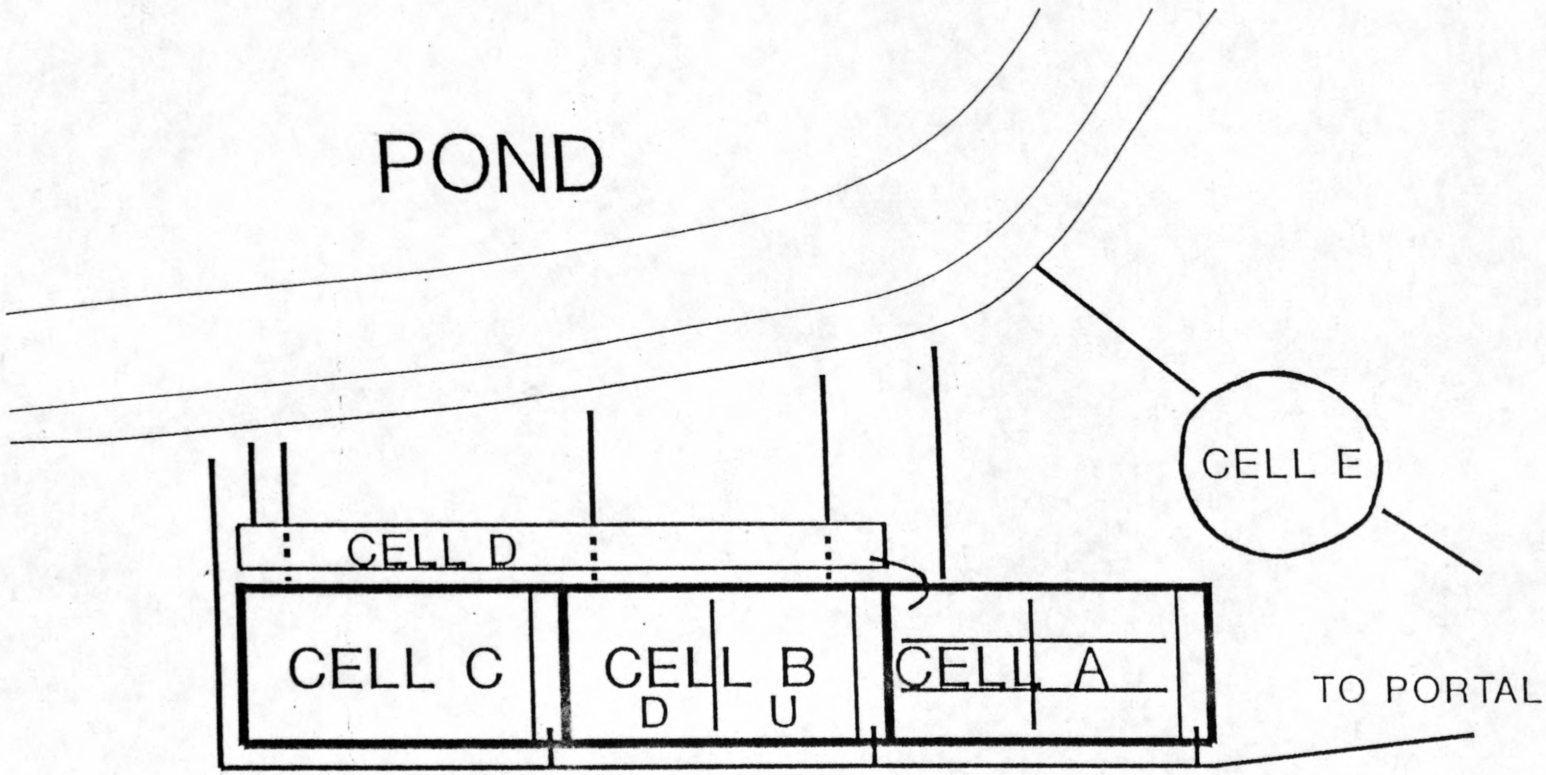

Figure 21. Location of the treatment cells of the Big Five system as of spring, 1991

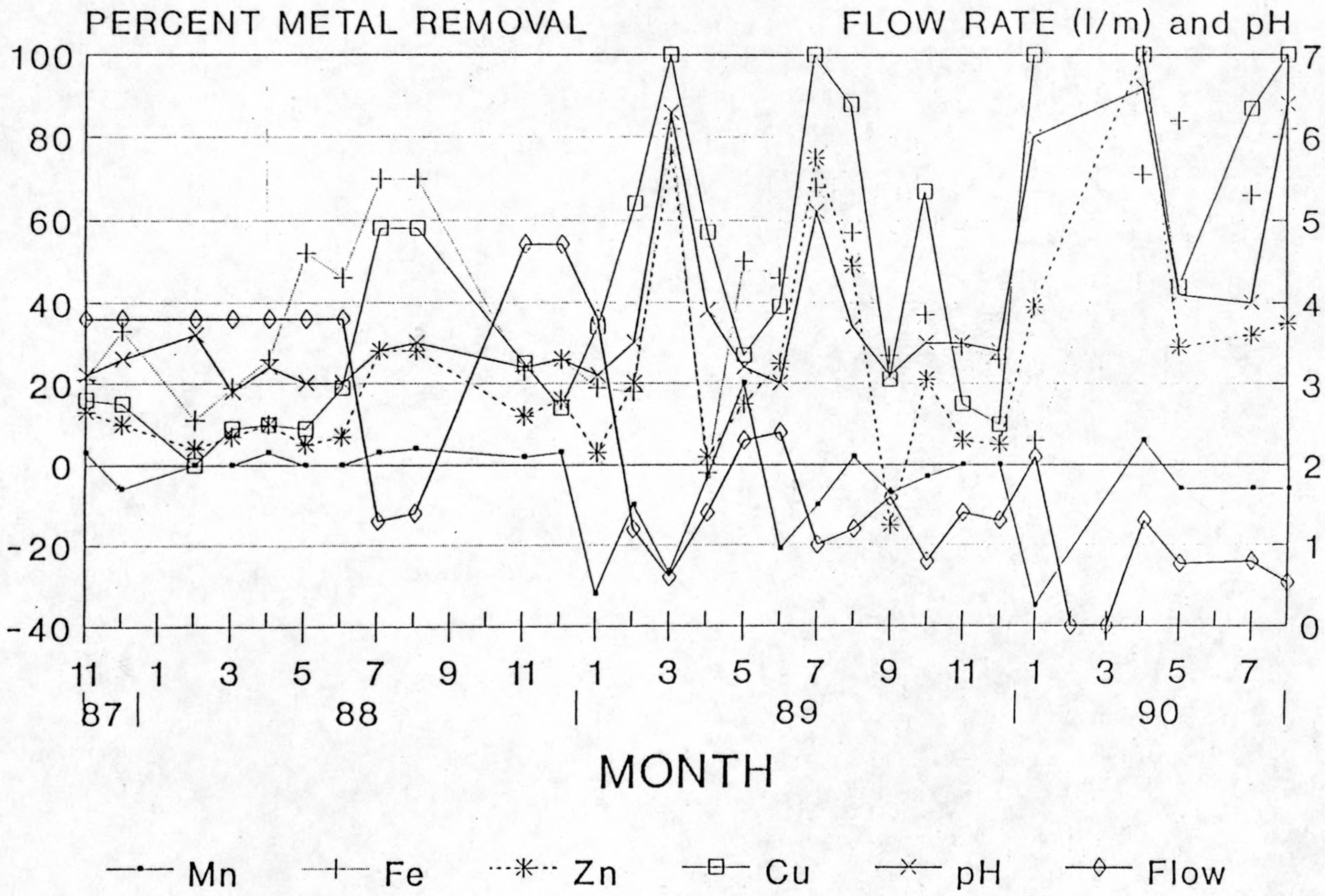

Figure 22. Treatment effectiveness of cell C. Metal values are shown as percentage of removal compared to concentrations in the mine drainage.