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Water quality impacts from mining in the Black Hills, South Dakota, USA

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Abstract The focus of this research was to determine if abandoned mines constitute a major environmental hazard in the Black Hills. Many abandoned gold mines in the Black Hills contribute acid and heavy metals to streams. In some areas of sulfide mineralization local impacts are severe, but in most areas the impacts are small because most ore deposits consist of small quartz veins with few sulfides. Pegmatite mines appear to have negligible effects on water due to the insoluble nature of pegmatite minerals. Uranium mines in the southern Black Hills contribute some radioactivity to surface water, but the impact is limited because of the dry climate and lack of runoff in that area.

Key words Acid-mine drainage · Water quality · Abandoned mines

Introduction

The generation of acidic waters bearing high concentrations of heavy metals from mining is a great environmental concern. Many stream reaches, such as near Summitville and Leadville, Colorado; Tar Creek, Oklahoma; and Iron Mountain near Keswick, California, USA, show significant toxicity levels. The Comprehensive Environmental Response, Compensation, and Liability Act ("Superfund") has resulted in public awareness of the contamination of many mining areas. The Upper Clark River below Butte, Montana, is possibly the worst Superfund site in the United States.

Contamination by acid-mine drainage is attributed to the reaction of sulfide minerals in the presence of oxygen and water to form sulfuric acid. This allows for the solubilization of metals. As the water travels downgradient in streams, dilution and buffering typically occur, the pH increases (Rahn 1992), and heavy metal concentrations gradually decrease (Dean and Fogel 1982). Studies in Wisconsin (Toran 1987) have shown that acidic mine drainage typically decreases slowly with time following the cessation of mining as the sulfides are consumed by weathering reactions.

This paper focuses on water quality impacts from mining in the Black Hills of South Dakota. The Black Hills were formed by a Laramide domal uplift (Fig. 1). Precambrian metamorphic and igneous rocks are exposed in the core of the uplift, and Paleozoic and Mesozoic sedimentary rocks surround the core and dip outward from it. Laccoliths intruded into the northern Hills in early to middle Tertiary time.

Since gold was discovered in 1874, the Black Hills have been an important mining locale. Most of the mining is associated with gold veins and placers in the northern Black Hills near Lead and Deadwood, South Dakota. The history of mining and descriptions of ore deposits of all kinds were given by O'Harra (1902), Allsman (1940), Gries (1958), and the US Geological Survey (1975). Around the time of World War II, pegmatite mining occurred in the central Black Hills near Keystone and Custer and some still continues today. In the 1950s and 1960s uranium mining occurred in the southern Black Hills near Edgemont. Today there are five operating gold mines, regulated by the South Dakota Department of Environment and Natural Resources. Most mining-related water problems are associated with abandoned gold mines in the northern and central Black Hills. This is the most important mining area, as well as the region where most perennial streams occur. The precipitation ranges from 40 cm yr^{-1} in the lower elevations to 60 cm yr^{-1} in the highest parts of the Black Hills. Perennial streams are few in the lower elevations, especially in the southern part of the Black Hills.

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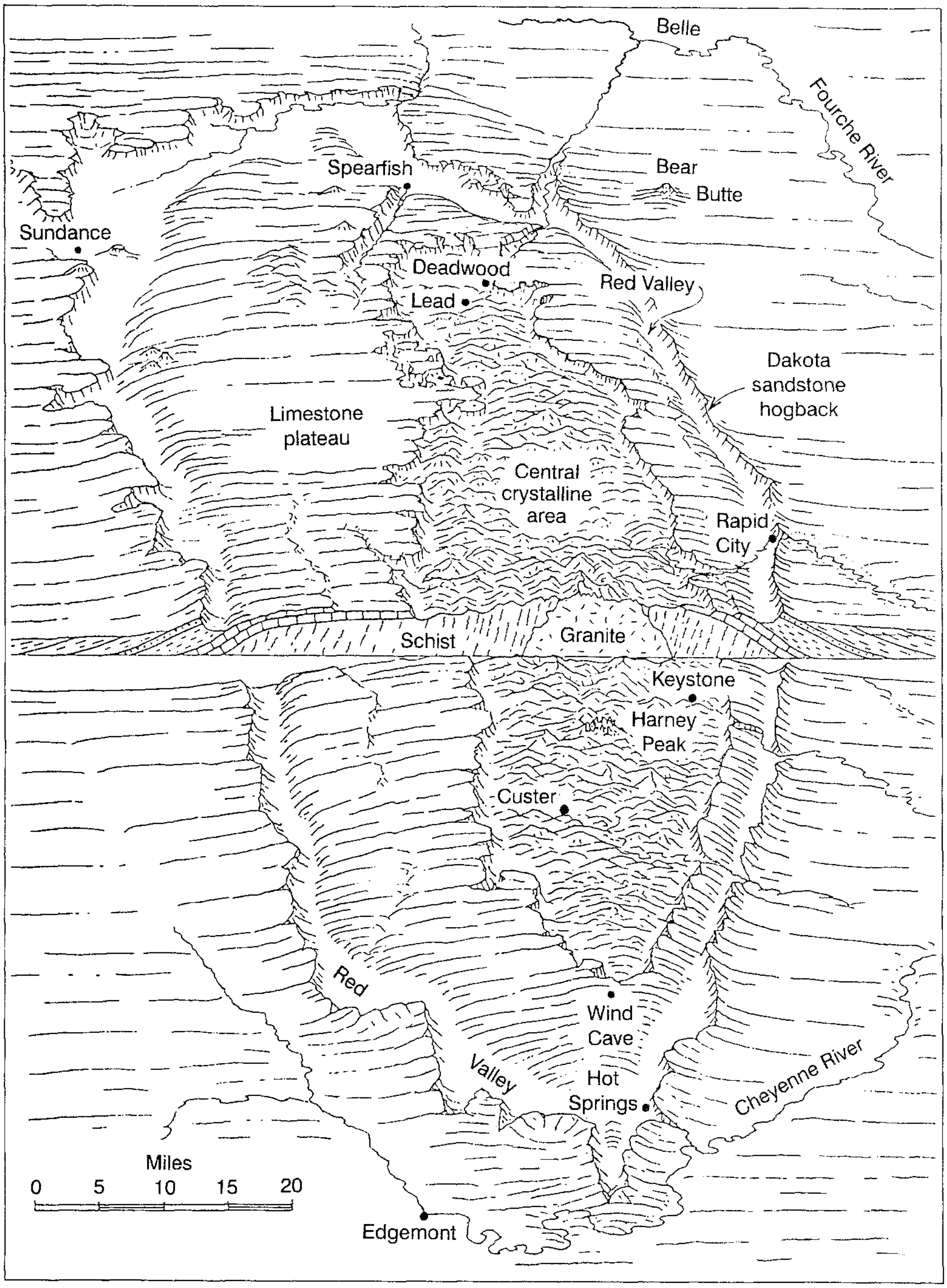
Fig. 1 Geologic diagram of the Black Hills (Strahler 1960)



ral Resources (Groundwater Research and Public Education Program). The primary emphasis of this research was to evaluate the impacts to streams at 11 abandoned gold mine sites in the northern and central Black Hills (Nichols 1994). The 11 sites chosen are on or near US Forest Service land as well as near a stream. Because Whitewood Creek between Lead and the Belle Fourche River (Fig. 1) is a Superfund site and has been studied extensively, its drainage basin (which includes the Homestake Mine) was excluded from consideration. An on-going program of the inventory of environmental impacts of abandoned mines in the Black Hills National Forest is described by Davis and Webb (1995).

History of mining

Gold mining in South Dakota is centered in the northern Black Hills. Most gold ores are associated with veins and strata-bound deposits in Precambrian rocks or replacement deposits in lower Paleozoic rocks (Redden and French 1989). Commencing in the late 1870s placer mining disrupted many streams, and within a decade bedrock mining commenced. Virtually all of these activities had ceased by the late 1930s, with the exception of the Bald Mountain Mining Company on upper False Bottom Creek, which operated until 1959 and the Homestake

Fig. 2 1970 photograph of HMC tailings being disposed into Whitewood Creek below the cyanide mill in Deadwood, South Dakota

Mining Company (HMC) operation in Lead, South Dakota. The production of gold by HMC from 1876 to 1988 totaled more than 36 million troy ounces (Redden and French 1989). About 100 million tons of finely ground gold-mill tailings were discharged into Whitewood Creek between 1876 and 1977 (Fig. 2). Roughly 2500 t d^{-1} of tailings from HMC were dumped directly into Whitewood Creek from about 1900 to 1978 (Rahn 1975). Most of the tailings were sand and silt from the crushing of the quartzitic ore. Mercury originally was used in the amalgamation of gold, and an estimated 15 kg of mercury was lost daily to Whitewood Creek. Other toxics discharged by HMC were a daily average of 140 kg of cyanide, 100 kg of zinc, and 10 tons of arsenopyrite. The tailings now rest in the alluvium along Whitewood Creek, the Belle Fourche River, and the Cheyenne River, constituting a 10-km-long Superfund site. This discharge of tailings ended in 1977 with the enforcement of the Federal Water Pollution Control Act, when HMC built a tailings dam on Grizzly Creek (Rahn 1986). Although the contamination of Whitewood Creek ended in 1977, the deposits of contaminated sediments continue to degrade surface runoff and groundwater with arsenic, iron, and manganese. Goddard (1988) found dissolved arsenic averaged 40 mg l^{-1} in Whitewood Creek, 39 mg l^{-1} the Belle Fourche River, and 10 mg l^{-1} in the Cheyenne River. Some cyanide was found in Whitewood Creek.

Little thought was given to the environment by the early miners. For example, the description of conditions in the old mining community of Carbonate is revealing. Silver, gold, and lead ore from the Carbonate Mine was hauled to a mill built in 1885 along Rubicon Gulch. According to Fielder (1962): "That old smelter wasn't exactly a bed of roses, if memories of old timers was correct. The arsenic fumes from its operation permeated the clear mountain atmosphere, and all the cats in town died. They simply couldn't stand it. Some throats and lung trouble were blamed on the arsenic fume situation, too."

In the 1980s renewed gold mining occurred, and five large mines are presently operating. According to Durkin (1994a) these mines and their gold production in 1993 were: Homestake, 447,593 oz; Wharf Resources, 102,381 oz; Golden Reward, 35,551 oz; Richmond Hill, 9841 oz; and Brohm Mining, 9421 oz. These giant mines are mostly open pit operations that use cyanide leaching treatment of low-grade ores. Approximately 800 ha are disturbed by these five mines.

The South Dakota Department of Environment and Natural Resources (DENR) regulates the five operating mines. For example, at the Annie Creek Mine owned by Wharf Resources, 2 ha of arsenic-bearing tailings associated with the old Reliance Mining Company (part of the Bald Mountain mining district) are being studied for cleanup. Wharf is working with the US EPA and DENR to mitigate dispersion of tailings down Annie Creek, a tributary of Spearfish Creek.

Annie Creek Mine (Wharf) has had high arsenic associated with the Old Reliance Mine tailings. The Gilt Edge Mine (Brohm) had acid-mine problems associated with old mine workings. These two examples illustrate the complex nature of assessing impacts from past and present mining.

Selection of sampling sites and description of 11 abandoned gold mines

The approach taken by this study was to compare the water quality above 11 abandoned mine sites with the water quality immediately downstream from the abandoned mine. Comparing the two samples provided an estimate of the effects of the mine on water quality. At some sites, water issues from the mine as seepage from waste piles, discharge from adits, etc. This water also was sampled.

The eleven sites were chosen primarily because they were on or near US Forest Service property and hence were accessible. A second criterion was that the mines be near water sources so that water samples could be obtained. Figure 3 shows the location of the 11 sites that were sampled. The field techniques for sampling of water above and below the abandoned mines typically consisted of stream gaging; measurement of temperature, pH, and conductivity; and the collection of a water sample (unpreserved plus one sample preserved with nitric acid). The comparison above and below the site gave an indication of the change in water quality.

The 11 sites and data (Tables 1–15) are described below (in alphabetical order):

Cleopatra Mine

This mine is along Squaw Creek (S16, T5N, R2E). The ore is a replacement deposit in the Cambrian Deadwood Formation (O'Harra 1902). A 40-ton cyanide mill was erected and the total production value estimated at $200,000.

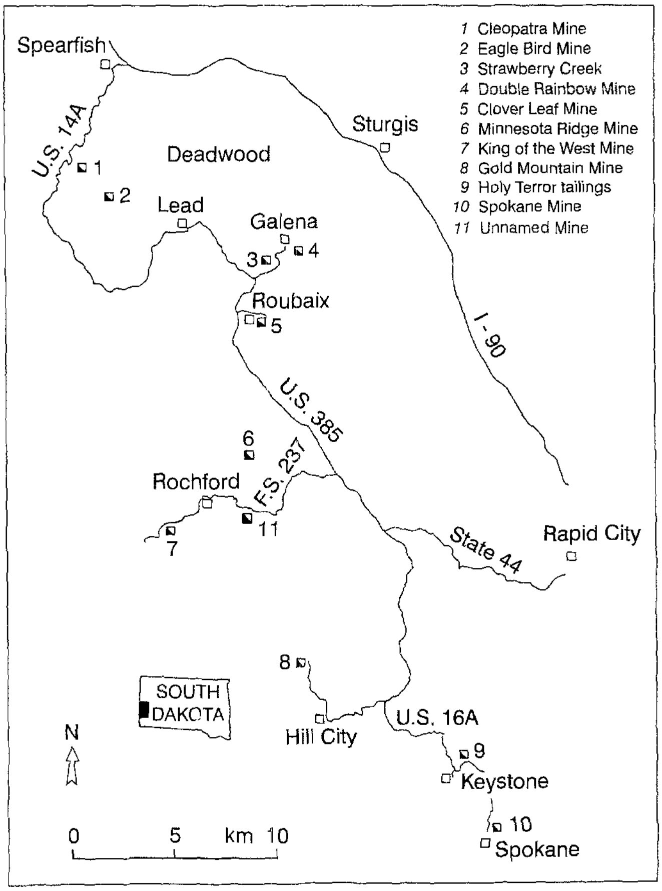


Fig. 3 Map showing the location of 11 abandoned mine sites

Table 1 shows data taken from Squaw Creek above and below the mine. Little change in the water quality was observed, although a slight increase in conductance below the mine occurs. The water is not acidic, a conclusion reached by Gries (1971) in a similar study of Squaw Creek.

In 1992 an active mine at the headwaters of Squaw Creek, the Richmond Hill Mine, was ordered by the DENR to stop mining until it had remedied the acid seep at the base of the waste rock pile. In 1995 the problem was corrected by a $10 million project that involved dumping the sulfide-bearing waste rocks back into the open pit mine and covering them with limestone and a clay cap.

Cloverleaf Mine

This mine (also known as the Uncle Sam Mine) is located along Elk Creek in S29, T4N, R4E. Gold is found in quartz within Precambrian mica/graphitic schist. A 60-stamp mill was erected at the turn of the century. Gold was recovered by cyanidation and amalgamation, but owing to excessive water in the mine at ~210 m depth, operations ceased in 1937 (Allsman 1940). Perhaps $1,000,000 in gold was recovered.

Table 2 shows the results of water analyses in Elk Creek above and below the mine where public access is available. Arsenic concentration increases slightly (Durkin personal

Table 1 Concentrations of constituents in surface water analyzed from Squaw Creek at Cleopatra Mine[a]

	Upstream											
	7/7/92	9/1/92	9/15/92	9/26/92	10/23/92	11/11/92	1/16/93	3/28/93	5/21/93	6/21/93	7/24/91	8/21/93
Properties												
Water temp. (°F)	—	64.5	50.4	51	47.7	31.8	33	41.5	*	*	*	*
Specific conductivity (μS)	356	401	494	427	388	479	—	135	140	110	260	270
pH field	7.6	8.88	8.37	8.43	8.83	—	—	7.19	6.39	8.5	8.2	8.3
Discharge (cfs)	1.2	0.32	0.29	0.31	0.31	0.48	0.31	7.0	4.9	11	1.9	1.8
Trace elements (ppm dissolved)												
Arsenic	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	
Cadmium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	
Copper	0.01	<0.01	<0.01	<0.01	—	<0.03	—	—	<0.03	<0.03	<0.03	
Manganese	<0.01	—	—	—	0.02	<0.01	<0.01	<0.02	<0.01	<0.02	<0.01	
Iron	<0.01	<0.01	<0.01	<0.01	0.22	0.06	0.07	2.45	0.15	0.12	3.16	
Lead	—	<0.03	<0.03	<0.03	0.07	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	
Mercury	—	—	—	—	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	

	Downstream										
	7/7/92	9/1/92	9/15/92	9/26/92	10/23/92	11/11/92	1/16/93	3/28/93	5/21/93	6/21/93	7/24/93
Properties											
Water temp. (°F)	—	—	49.3	51	42.1	31.8	32.1	40.6	*	*	*
Specific conductivity (μS)	390	456	480	444	340	385	**	126	140	130	250
pH field	7.90	7.18	8.07	8.15	8.90	—	—	7.56	7.10	8.00	8.20
Discharge (cfs)	1.2	0.32	0.29	0.31	0.31	0.48	0.31	7.0	4.9	11	1.9
Trace elements (ppm dissolved)											
Arsenic	<0.05	<0.05	<0.05	<0.09	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Cadmium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Copper	<0.01	<0.01	<0.01	<0.01	—	—	—	—	<0.03	<0.03	<0.03
Manganese	<0.01	—	—	—	0.02	0.02	<0.01	0.04	0.10	0.02	<0.01
Iron	<0.01	<0.01	<0.01	<0.01	0.54	0.20	0.06	0.72	0.47	0.15	0.10
Lead	—	<0.03	<0.03	<0.03	0.17	0.10	<0.03	<0.03	<0.03	<0.03	<0.03
Mercury	—	—	—	—	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03

[a] —, not available; *, temperature corrected; **, meter inoperable

Table 2 Concentrations of constituents in surface water analyzed from Elk Creek at Clover Leaf Mine[a]

	Upstream									Downstream								
	9/26/92	10/31/92	11/10/92	3/27/93	4/25/93	5/9/93	6/26/93	7/25/93	8/20/93	9/26/92	10/31/92	11/10/92	3/27/93	4/25/93	5/9/93	6/26/93	7/25/93	8/20/93
Properties																		
Water temp. (°F)	52	42	34	46.4	49.7	51	*	*	*	48.6	45.4	32.2	46	47.5	51.5	*	*	*
Specific conductivity (μS)	580	430	519	279	141	300	230	270	310	450	418	499	285	133	300	220	270	310
pH field	6.8	-	7.58	6.26	7.98	7.73	8.5	8.5	8.2	7.5	—	8.24	8.62	8.17	7.24	8.5	8.6	8.5
Discharge (cfs)	1.0***	1.2***	1.8***	13***	15***	56***	20***	9.2***	0.4***	1.0***	1.2***	1.8***	13***	15***	56***	20***	9.2***	0.4***
Trace elements (ppm dissolved)																		
Arsenic	0.02	<0.05	<0.05	<0.05	<0.05	0.10	<0.05	0.07		<0.05	<0.05	0.05	<0.05	0.2	0.25	0.1	<0.05	
Cadmium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	
Copper	0.02	—	<0.03	-	0.04	<0.03	<0.03	<0.01		<0.01	—	<0.03	—	0.06	0.08	<0.03	<0.03	
Manganese	—	0.02	0.01	0.19	0.04	0.04	0.04	<0.03		—	0.01	0.01	0.17	0.08	0.4	0.05	0.04	
Iron	<0.01	0.27	0.2	2.58	0.84	2.72	0.48	0.45		0.11	0.22	0.18	2.15	0.93	1.01	0.50	0.41	
Lead	0.51	<0.03	<0.03	<0.03	0.1	0.08	0.03	0.22		<0.03	<0.03	<0.03	<0.03	0.08	0.24	0.05	0.06	
Mercury	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	1.78		<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	

[a] —, not available; *, temperature corrected; ***, USGS data

communication) but overall little was observed, which is somewhat surprising considering the several acres of unvegetated tailings in the flood plain below the mine. The lack of vegetation is presumably due to high sulfides.

Double Rainbow

This mine (near the Richmond and Sitting Bull Mines) is located along Bear Butte Creek in S3 and 4, T4N, R4E. The ore is a replacement deposit within the Cambrian Deadwood Formation. The ore consisted of gold and argentiferous galena in arsenopyrite, pyrrhotite, and quartz. Between 1881 and 1983, it produced $410,000 in silver. In 1968 Homestake Mining Company did considerable exploratory drifting and sank the Double Rainbow shaft. In 1994 HMC did considerable remediation at this site.

Today the abandoned mine has several collapsed adits from which acidic water seeps into Bear Butte Creek. Table 3 shows the results of water analyses from Bear Butte Creek above and below the mine. Table 4 shows the data from a broken pipe draining the Double Rainbow shaft discharging effluent directly into the creek, intermittent runoff from an ore stockpile removed in 1994, and an adit. The addition of trace metal solutes to Bear Butte Creek is shown in Table 16 (below). (A discussion of the annual loadings is given later in this paper.) The overall quality of Bear Butte Creek in this reach is not very good, probably because of the influence of numerous mines upgradient in the watershed and natural chemical weathering of this mineralized area. The discharge from the pipe is elevated in dissolved minerals including arsenic. The runoff from the stock pile is very polluted, with acid conditions and elevated arsenic and other metals. Bear Butte Creek normally loses all its discharge to sinkholes in the Madison Limestone about 3 km downstream.

Eagle Bird Mine

The Eagle Bird Mine is located in Squaw Creek, S22, T5N, R2E, about 3 km upstream from the Cleopatra Mine. In the 1920s the mine had a 750-m drift onto Precambrian schist; the pyrritiferous ore was reportedly hauled to a local mill. The adit (Fig. 4) is partially collapsed today, and water drains from it into Squaw Creek.

Table 5 shows data from Squaw Creek sampled above and below the mine. Table 6 shows data directly from the mine adit. Large iron deposits ("yellow boy") occur across the dump. This water is quickly diluted by Squaw Creek; the overall quality of Squaw Creek is little changed as it flows past the mine.

Gold Mountain

Located near Newton Fork of Spring Creek in S2, T1S, R4E, the Gold Mountain Mine followed a quartz vein in Precambrian schist. The ore consisted of gold, arseno-

Table 3 Concentrations of constituents in surface water analyzed from Bear Butte Creek at Double Rainbow Mine[a]

	Upstream												Downstream											
	9/8/92	9/15/92	10/31/93	11/10/92	12/23/92	2/6/93	3/27/93	4/25/93	5/9/93	6/26/93	7/25/93	8/20/93	9/8/92	9/15/92	10/31/92	11/10/92	12/23/92	2/6/93	3/27/93	4/25/93	5/9/93	6/26/93	7/25/93	8/20/93
Properties																								
Water temp. (°F)	56.1	60.6	39.6	32.4	—	34.0	46.1	47.7	48.8	*	*	*	55.4	59.6	39	32.2		34.7	47.3	47.8	48.2	*	*	*
Specific conductivity (μS)	603	806	355	431	—	1157	398	136	170	200	250	280	663	810	384	467	—	1311	448	140	330	170	230	280
pH field	8.49	8.21	9.36	8.68	—	8.34	7.28	7.36	7.99	8.20	8.10	7.80	8.60	8.25	9.45	9.04	—	8.27	7.09	7.76	—	8.30	8.10	8.00
Discharge (cfs)	1.1***	0.55***	0.54***	1.0***	0.8***	0.84***	12***	16***	71***	22***	7.1***	5.7***	1.105	0.6	0.59	1.05	0.85	0.89	12.05	16.05	71.05	22.05	7.15	5.75
Trace elements (ppm dissolved)																								
Arsenic	<0.05	0.09	<0.05	<0.05	<0.05	<0.05	<0.05	0.14	<0.05	0.25	0.17	—	<0.05	0.10	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.18	0.08	0.18	—
Cadmium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.01	<0.01	—	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.01	<0.01	—
Copper	<0.01	<0.01	—	<0.03	—	—	—	0.14	0.08	0.18	0.09	—	<0.01	<0.01	—	—	—	—	—	0.05	0.16	0.15	0.04	—
Manganese	—	—	0.02	0.02	<0.01	0.04	<0.01	0.12	0.17	0.08	0.03	—	—		0.10	0.20	0.18	0.23	0.08	0.10	0.25	0.06	0.09	—
Iron	<0.01	<0.01	0.17	0.18	<0.01	0.19	<0.01	1.15	2.10	1.19	0.71	—	0.14	0.07	0.27	0.26	0.17	0.18	<0.01	1.19	2.49	0.78	0.59	—
Lead	<0.03	<0.03	0.06	<0.03	<0.03	<0.03	<0.03	0.22	<0.03	0.22	0.15	—	<0.03	0.03	0.08	0.05	<0.03	<0.03	<0.03	<0.03	0.22	0.13	<0.03	—
Mercury	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	—	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	—

[a] —, not available; *, temperature corrected; ***, USGS data

Table 4 Concentrations of constituents in surface water analyzed from various locations at Double Rainbow Mine[a]

	Pipe													Stockpile runoff						Adit
	3/29/92	6/26/92	9/8/92	9/15/92	10/31/92	11/10/92	12/23/92	2/6/93	3/27/93	4/25/93	6/26/93	7/25/93	8/20/93	3/27/93	4/25/93	5/9/93	6/26/93	7/25/93	8/20/93	6/26/92
Properties																				
Water temp. (°F)	—	—	54.1	52.5	49.1	46.6	—	48.4	50.7	49.4	*	*	*	55.5	56.1	59.8	*	*	*	—
Specific conductivity (μS)	—	533	975	1173	704	928	—	2970	1027	422	490	550	480	8780	6200	>scale	490	>1000	>1990	10,600
pH field	—	7.33	8.05	7.87	8.92	8.18	—	7.61	6.64	7.02	7.00	7.10	6.2	2.51	1.64	5.04	7.00	2.20	2.20	1.59
Discharge (cfs)	0.05	0.05	0.05	0.05	0.05	0.05	—	0.0	0.05	0.05	0.05	0.05	0.05	—	—	0.005	0.0011	stagnant	stagnant	stagnant
Trace elements (ppm dissolved)																				
Arsenic	0.13	0.57	0.12	0.23	0.13	0.06	0.10	0.10	<0.25	0.24	0.24	0.22	—	18.55	20.65	18.99	18.99	18.39	—	16.89
Cadmium	<0.01	<0.01	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	—	1.57	2.53	2.70	1.92	2.03	—	2.88
Copper	<0.01	<0.01	<0.01	<0.01	—	<0.03	—	—	—	—	<0.03	<0.03	—	—	20.34	28.63	30.20	21.58	—	20.75
Manganese	0.35	0.63	—	—	0.42	0.01	0.42	0.45	0.28	0.55	0.36	0.37	—	20.82	20.59	22.03	22.03	21.48	—	17.38
Iron	3.61	9.25	5.98	3.94	3.69	0.14	3.42	3.94	<0.01	5.46	3.34	3.38	—	212.87	192.42	214.73	214.73	185.71	—	215.48
Lead	<0.03	<0.03	<0.03	<0.03	0.07	<0.03	<0.03	<0.03	<0.03	0.20	<0.03	<0.03	—	2.49	2.90	3.54	2.02	2.13	—	3.89
Mercury	—	—	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	—	0.07	0.08	0.25	0.13	<0.03	—	—

[a] —, *, and *** as in Table 3

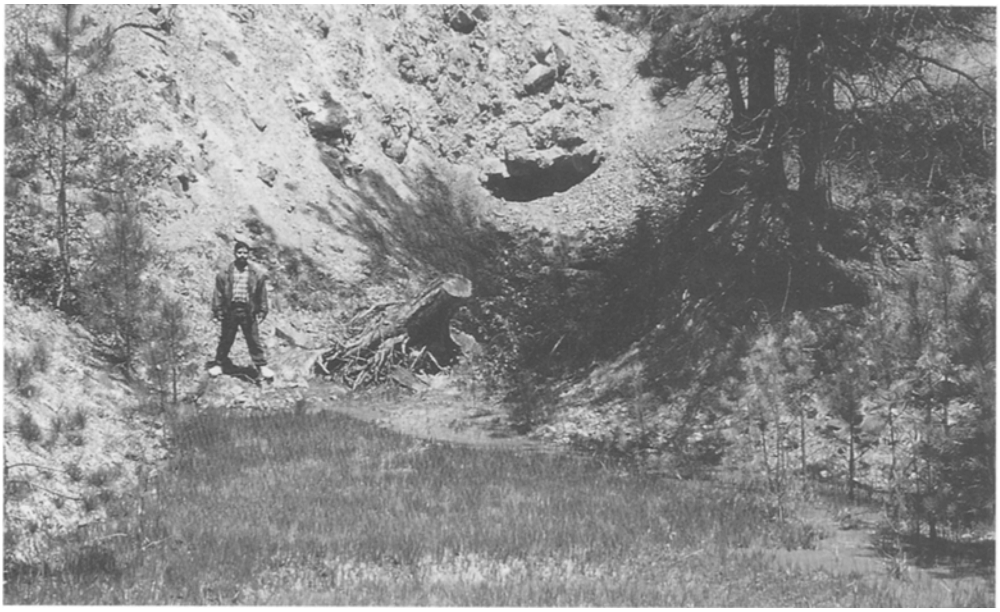


Fig. 4 Adit at Eagle Bird Mine. Groundwater flows from the collapsed adit

Table 5 Concentrations of constituents in surface water from Squaw Creek at Eagle Bird Mine[a]

	Upstream						Downstream					
	9/9/92	9/15/92	5/21/93	6/21/93	7/24/93	8/21/93	9/9/92	9/15/92	5/21/93	6/21/93	7/24/93	8/21/93
Properties												
Water temp. (°F)	49.8	52.2	*	*	*	*	49.5	53.4	*	*	*	*
Specific conductivity (μS)	877	824	80	<detection	160	190	789	907	330	100	200	210
pH field	8.01	7.68	6.50	7.60	7.80	7.40	7.79	7.69	6.40	7.30	7.30	7.30
Discharge (cfs)	—	—	—	—	0.07	0.078	—	—	—	—	0.08	0.10
Trace elements (ppm dissolved)												
Arsenic	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.05	0.07	0.07
Cadmium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Copper	<0.01	<0.01	<0.03	<0.03	<0.03	<0.01	<0.01	<0.01	<0.03	<0.03	0.03	0.05
Manganese	—	—	0.01	0.02	0.02	<0.01	—	—	0.06	0.06	0.15	0.03
Iron	<0.01	<0.01	0.10	0.13	0.09	<0.01	0.56	1.48	0.14	0.20	0.25	<0.01
Lead	<0.03	<0.03	0.07	0.08	0.23	0.06	<0.03	<0.03	0.05	0.08	2.62	0.09
Mercury	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	5.48	<0.03

[a] —, not available; *, temperature corrected

Table 6 Concentrations of constituents in surface water analyzed from Eagle Bird Mine adit[a]

	Date						
	9/9/92	9/15/92	10/23/92	5/21/93	6/21/93	7/24/93	8/21/93
Properties							
Water temp. (°F)	53.4	49.3	51.8	*	*	*	*
Specific conductivity (μS)	1187	1040	803	100 –220	260	530	310
pH field	7.29	7.27	7.41	5.90	6.40	6.20	6.40
Discharge (cfs)	—	0.01	0.01	0.01	—	0.01	0.022
Trace elements (ppm dissolved)							
Arsenic	<0.05	<0.05	<0.05	<0.05	<0.05	0.21	0.07
Cadmium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Copper	<0.01	<0.01	—	0.03	<0.03	0.06	0.07
Manganese	—	—	4.06	3.81	0.06	3.89	0.77
Iron	25.38	26.27	23.13	20.79	0.20	22.29	3.27
Lead	<0.03	<0.03	0.07	0.08	0.08	0.013	0.15
Mercury	<0.03	<0.03	<0.03	<0.03	<0.03	0.09	<0.03

[a] —, not available; *, temperature corrected

pyrite, and some pyrite in quartz. In 1938 the mine was developed from a vertical shaft. Today the mill and headframe are still standing, along with a large steel boiler in its brick enclosure. The US Forest Service has taken measures to reduce the physical hazards at the caved-in shafts.

Table 7 shows water quality above the mine and in a stock pond just below the mine. The water quality of the unnamed stream at this mine is not affected. Apparently there were few sulfides in the ore, and not much mercury was lost in the tailing.

Holy Terror Mine

This is a famous gold mine along Battle Creek in Keystone, South Dakota, S5, T2S, R6E. The mine produced free gold from a quartz vein in Precambrian schist. The well-defined quartz vein was mined underground at various levels, with a maximum depth of 366 m. A five-stamp mill was built at the turn of the century, but the workings were flooded in 1903 because the owners were unable to pump out groundwater. Between 1894 and 1903, about 150,000 tons of ore were milled (Allsman 1940). The ore had a high arsenic content, and the nearby Bullion Mine produced 50 tons of white arsenic. Tailings from the Holy Terror Mine (mainly quartz sand) are located above an ephemeral stream just northeast of the mine.

Table 8 shows water quality data from a seep beneath the tailings and in the same stream about 1 km downstream. Slightly elevated concentrations of arsenic were found in the ephemeral stream draining the tailings.

King of the West

This mine is located on an ephemeral tributary to Rapid Creek in S33, T2N, R3E and was mainly operated from 1908 to 1909 and 1934 to 1936. The ore is found in calcareous units of the Precambrian chert-grunerite schist. The gold is associated with quartz, siderite, arsenopyrite, and pyrite. A 10-m length ore shoot had values of about 30 g t^{-1} of gold. About 7000 t of ore were milled. Today a 1-ha deposit of tailings rests on an ephemeral gulch about 1 km S of Smith Spring (Fig. 5). The lack of vegetation on the tailings is presumably from the high sulfide content.

Table 9 shows water quality data from this area. No perennial stream exists at the site; however, during snowmelt and following a rain, runoff was sampled. Smith Spring, sampled on a regular basis, still has good quality in spite of the fact that tailings periodically are washed down toward it. Physical hazards such as caved in shafts and a collapsed head frame are present.

Minnesota Ridge

This mine is located about 5 km west of Rochford, in the upper reaches of Gimlet Creek S6, T2N, R4E. It was first worked in the 1880s, and additional mining and milling

Table 7 Concentrations of constituents in surface water analyzed from Gold Mountain Mine[a]

	Stream							Pond						
	7/17/92	9/2/92	9/22/92	4/24/93	6/11/93	7/18/93	8/18/93	7/17/92	9/2/92	9/22/92	4/24/93	6/11/93	7/18/93	8/18/93
Properties														
Water temp. (°F)	—	—	60.2	62.9	*	*	*	—	—	64.0	54.7	*	*	*
Specific conductivity (μS)	118	199	183	63	<detection	<detection	140	145	198	205	70	<detection	100	100
pH field	7.75	7.40	7.85	6.40	7.00	7.40	7.40	7.34	7.40	7.92	6.78	7.10	7.70	8.00
Discharge (cfs)	0.17	0.05	0.053	—	0.22	0.089	0.067	0.13	0.05	stagnant	stagnant	stagnant	stagnant	stagnant
Trace elements (ppm dissolved)														
Arsenic	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.08	<0.05	0.11	<0.05	<0.05	<0.05	<0.05	—
Cadmium	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	—
Copper	<0.01	<0.01	—	<0.03	<0.03	<0.03	<0.03	<0.01	<0.01	<0.01	<0.03	<0.03	<0.03	—
Manganese	<0.01	—	<0.03	0.06	0.01	0.02	0.01	0.03	—	—	0.01	0.03	0.01	—
Iron	0.01	<0.01	0.52	0.86	0.54	0.18	0.08	0.53	<0.01	<0.01	0.73	0.52	0.34	—
Lead	—	0.23	<0.03	<0.03	0.05	<0.03	<0.03	<0.03	0.19	<0.03	0.05	<0.03	<0.03	—
Mercury	—	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	—	<0.03	<0.03	<0.03	<0.03	<0.03	—

[a] —, not available; *, temperature corrected

Table 8 Concentrations of constituents in surface water at Holy Terror tailings[a]

	Below tailings					Downstream											
	6/9/92	5/14/93	6/10/93	7/18/93	8/18/93	6/9/92	10/26/92	11/8/92	11/21/92	1/6/93	2/5/93	3/18/93	4/23/93	5/14/93	6/10/93	7/18/93	8/18/93
Properties																	
Water temp. (°F)	—	53.5	*	*	*	—	49.8	49.7	39.6	35.2	45.7	50.9	52.0	51.7	*	*	*
Specific conductivity (μS)	501	220	120	220	200	650	502	366	682	381	361	310	314	340	240	330	250
pH field	6.91	4.59	6.00	6.50	6.40	6.28	5.48	9.64	—	—	7.27	7.31	7.04	5.61	6.8	6.60	6.20
Discharge (cfs)	—	0.09	0.045	0.027	0.0014	—	0.0018	0.0018	—	—	—	—	—	0.09	0.045	0.027	0.0014
Trace elements (ppm dissolved)																	
Arsenic	<0.05	<0.05	0.09	<0.05	0.09	<0.05	<0.05	<0.05	0.11	<0.05	<0.05	0.05	<0.05	0.08	0.14	<0.05	0.22
Cadmium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Copper	<0.01	<0.03	<0.03	<0.03	<0.03	<0.01	—	<0.03	—	—	<0.03	—	<0.03	<0.03	<0.03	<0.03	0.06
Manganese	0.53	0.29	0.13	0.43	0.53	<0.01	0.04	0.01	0.24	0.06	0.01	0.27	0.03	0.01	0.02	0.01	0.15
Iron	<0.01	2.57	0.50	0.09	<0.01	0.01	0.29	0.12	3.14	1.04	0.19	2.65	2.17	0.17	0.32	0.04	1.10
Lead	<0.03	<0.03	<0.03	<0.03	0.06	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0.07
Mercury	—	<0.03	<0.03	<0.03	<0.03	—	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03

[a] —, not available; *, temperature corrected

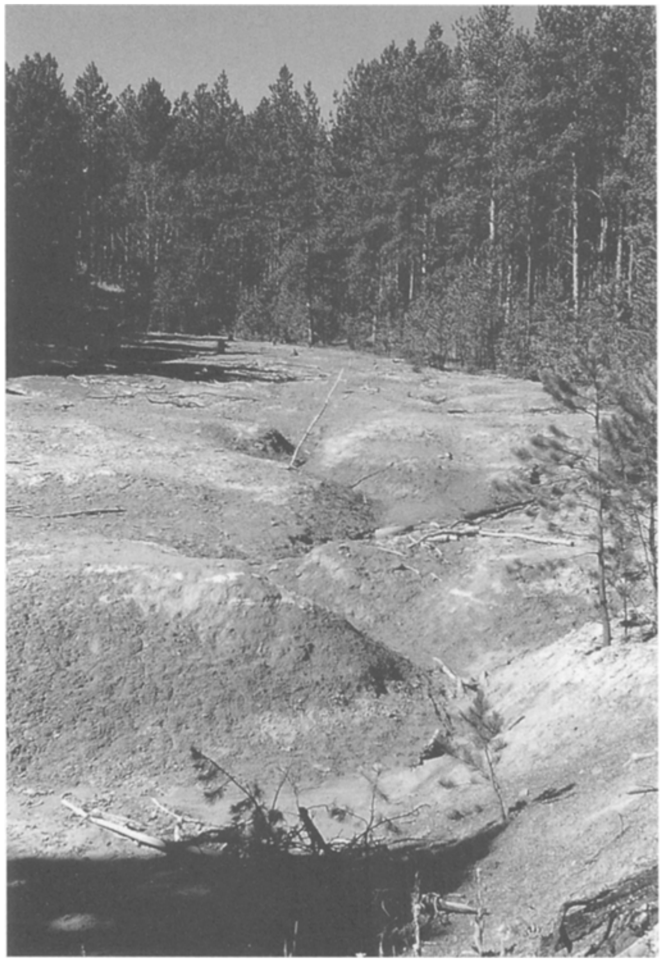


Fig. 5 Unvegetated tailings at King of the West Mine

occurred sporadically until 1938. A 10-stamp amalgamation mill was built in 1934. Numerous drifts were installed to intersect a steeply dripping shear zone in the Precambrian schist. Ore from the lower levels was unoxidized and contained abundant sulfides including copper.

Today the mill building and assay office are still standing. Like many abandoned mines in low topographic elevations, the extensive underground workings inadvertently serve as a collection system for groundwater. Water seeps from the collapsed adit (Fig. 6) and crosses a waste rock dump area (approximately 1 ha in size) where nothing grows. The distinct odor of sulfides in the dump area is unmistakable. Durkin (1995) describes this site and the problems associated with deep mines that are below the oxidized zone and hence are more prone to acid mine drainage due to sulfides.

Table 10 shows water quality data from the portal of the main adit from the same stream of water below the dump. Extensive ferric hydroxide deposits coat the bed of the stream. The pH drops from about 6 to 2 as it flows through the tailings and waste rock. Eventually the stream sinks into alluvium about 1 km below. The contaminated acidic water has high levels of sulfate and dissolved metals.

Table 9 Concentrations of constituents in surface water analyzed from King of the West Mine[a]

	Mine runoff, 3/1/92	Smith Gulch Spring, 6/19/92	Smith Gulch Spring, 9/3/92	Smith Gulch Spring, 9/22/92	Smith Gulch Spring, 10/20/92	Smith Gulch Spring, 11/10/92	Smith Gulch Spring, 1/7/93	Smith Gulch Spring, 2/4/93	Smith Gulch Spring, 3/18/93	Mine runoff, 4/24/93	Smith Gulch Spring, 4/24/93	Mine runoff, 5/8/93	Smith Gulch Spring, 5/14/93	Smith Gulch Spring, 6/11/93	Smith Gulch Spring, 7/19/93	Smith Gulch Spring, 8/19/93
Properties																
Water temp. (°F)	—	—	62	61.4	40.6	38.7	37.5	37.6	41.5	51.3	47.3	—	56.6	*	*	*
Specific conductivity (µS)	—	400	570	502	366	272	703	—	708	99	202	—	—	240	290	210
pH field	4.65	7.60	8.20	7.79	6.78	8.91	—	9.71	6.47	4.07	6.28	—	9.60	6 90	7.10	7.60
Discharge (cfs)	—	0.025	0.014	0.025	—	—	—	—	—	—	—	—	0.02	0.045	0.033	0.067
Trace elements (ppm dissolved)																
Arsenic	<0.05	<0.05	0.05	0.10	<0.05	<0.05	<0.05	<0.05	<0.05	0.42	<0.05	17.78	<0.05	0.22	<0.05	0.14
Cadmium	<0.1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.15	<0.01	<0.01	<0.01	<0.01
Copper	<0.01	<0.01	<0.01	<0.03	—	<0.03	—	—	—	0.04	<0.03	6.07	0.03	0.03	<0.03	0.03
Manganese	0.38	0.16	—	—	0.05	0.06	0.08	0.06	0.27	0.29	0.04	21.23	0.06	1.27	0.12	0.04
Iron	<0.01	9.49	2.02	1.26	1.19	1.70	5.70	2.72	4.54	28.42	1.57	498.70	0.79	4.39	0.74	0.09
Lead	—	—	0.06	0.23	<0.03	<0.03	0.03	<0.03	<0.03	<0.03	<0.03	3.34	<0.03	<0.03	<0.03	0.09
Mercury	—	—	—	—	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0.67	<0.03	<0.03	<0.03	<0.03

[a] —, not available; *, temperature corrected

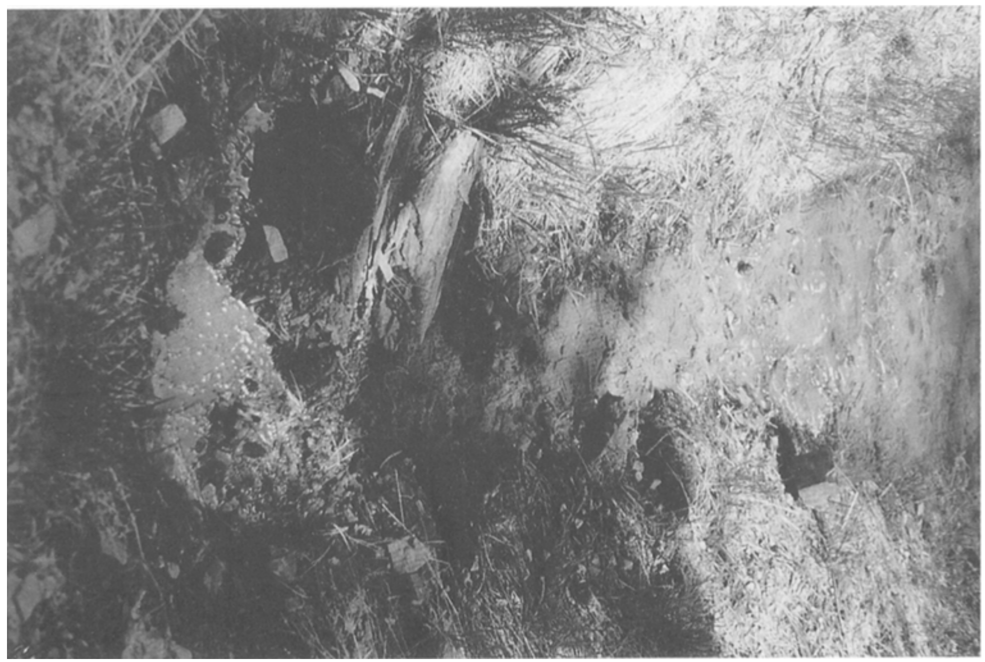


Fig. 6 Water flow from the adit at the Minnesota Ridge mine

Spokane Mine

This large mine is located along Spokane Creek in S26, T2S, R6E. The ore body was a fissure vein in Precambrian schist and pegmatite. The ore included silver and gold with galena and sphalerite in quartz and pyrite. Mining occurred from 1891 until 1940. Ore was processed mostly on the site, with some sent to smelters in Helena, Montana.

In the 1980s the US Forest Service was concerned about a chemical waste pit and tailings pond that had been eroding. The debris was being transported during periodic flood events toward Spokane Creek. Following a forest fire in 1987, the USFS reclaimed the site. Lead, arsenic, and cadmium were found in the tailings (Davis and Webb 1995), as well as potassium xanthate (left from milling operations), which was loaded into barrels and shipped to an EPA-approved disposal site. The cost of this cleaning was $420,000 (Davis and others 1994). The land was seeded with grass and has been closed to the public.

Table 11 shows Spokane Creek quality data above and below the mine. Table 12 shows water quality in the gully draining the mine, just above its confluence with Spokane Creek. Spokane Creek is not measurably affected by the

Table 10 Concentrations of constituents in surface water analyzed from Minnesota Ridge Mine[a]

	Mine Portal											
	6/19/92	6/24/92	8/4/92	9/21/92	10/20/92	11/10/92	3/27/93	4/24/93	5/9/93	6/8/93	6/23/93	8/19/93
Properties												
Water temp. (°F)	—	—	—	54.2	43.9	40.6	50.3	49.2	51.1	—	50.4	*
Specific conductivity (μS)	1050	652	700	1142	833	435	662	373	510	—	337	480
pH field	6.20	6.80	5.43	7.36	7.56	8.27	5.89	6.35	5.70	5.78	6.04	6.3
Discharge (cfs)	0.01	0.005	0.012	0.0097	stagnant	stagnant	—	—	0.0024	stagnant	—	0.0024
Trace elements (ppm dissolved)												
Arsenic	0.06	0.19	0.14	0.23	0.08	0.23	0.15	0.28	0.12	0.24	<0.05	
Cadmium	<0.01	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.01	<0.01	
Copper	<0.01	0.11	0.11	<0.01	—	0.16	—	0.13	0.05	0.15	0.07	
Manganese	0.35	0.34	—	—	0.44	0.34	0.38	0.25	0.23	0.33	0.36	
Iron	59.68	21.09	32.23	53.52	61.79	46.73	51.34	30.02	20.25	26.38	42.69	
Lead	<0.03	0.30	0.59	0.16	<0.03	0.14	<0.03	0.19	0.05	0.15	<0.03	
Mercury	—	—	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	

	Below tailings											
	6/19/92	6/24/92	8/4/92	9/21/93	10/20/92	11/10/92	3/27/93	4/24/93	5/9/93	6/8/93	6/23/93	8/19/93
Properties												
Water temp. (°F)	—	—	—	55.3	49.5	41.9	38.3	50.8	50.3	—		*
Specific conductivity (μS)	880	1140	1435	930	697	401	1517	245	620	—		410
pH field	4.6	2.45	3.35	3.7	5.23	5.27	3.03	3.82	3.1	4.58		3.5
Discharge (cfs)	0.005	—	0.008	0.0014	stagnant	stagnant	0.03	—	0.08	overflow		0.0024
Trace elements (ppm dissolved)												
Arsenic	<0.05	0.08	0.11	<0.05	<0.05	<0.05	0.24	0.16	0.15	0.23		
Cadmium	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.01		
Copper	0.02	0.35	0.3	0.07	—	—	—	0.13	0.16	0.2		
Manganese	0.67	0.22	—	—	0.24	0.23	0.82	0.1	0.3	0.07		
Iron	4.63	2.76	7.67	2.26	0.87	0.72	104.68	7.12	19.9	4.25		
Lead	<0.03	<0.03	0.64	0.48	<0.03	0.03	<0.03	0.23	0.09	0.45		
Mercury	—	—	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03		

[a] —, not available; *, temperature corrected

Table 11 Concentrations of constituents in surface water analyzed from Spokane Creek[a]

	Upstream												
	7/14/92	8/6/92	10/26/92	11/8/92	12/21/92	1/6/93	2/5/93	3/18/93	4/23/93	5/14/93	6/10/93	7/18/93	8/18/93
Properties													
Water temp. (°F)	—	—	46.3	40.1	33.4	34.5	34.9	38.3	47.9	54.4	*	*	*
Specific conductivity (μS)	350	211	193	123	227	345	96	98	82	—	<detection	100	140
pH field	6.3	8.05	9.59	9.44	9.54	—	7.32	7.49	7.32	—	7.20	7.40	6.60
Discharge (cfs)	0.75	0.46	—	—	—	—	—	—	—	—	0.45	0.2	0.17
Trace elements (ppm dissolved)													
Arsenic	<0.05	<0.05	<0.05	0.10	<0.05	<0.05	<0.05	0.10	<0.05	<0.05	0.04	<0.05	0.26
Cadmium	<0.01	0.06	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Copper	<0.01	<0.01	—	<0.03	—	—	—	—	<0.03	<0.03	<0.03	<0.03	0.05
Manganese	<0.01	—	0.34	0.14	0.10	0.11	0.81	0.08	0.04	0.03	0.03	0.07	<0.01
Iron	<0.01	<0.01	0.59	0.56	0.62	1.06	0.52	0.35	0.71	0.53	0.50	0.42	<0.01
Lead	0.25	<0.03	0.12	0.09	<0.03	<0.03	<0.03	0.23	<0.03	<0.03	0.06	0.04	0.11
Mercury	<0.03	—	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03

	Downstream												
	7/14/92	8/6/92	10/26/92	11/8/92	12/21/92	1/6/93	2/5/93	3/18/93	4/23/93	5/14/93	6/10/93	7/18/93	8/18/93
Properties													
Water temp. (°F)	—	—	46.2	39	32.5	32.9	34.4	37.1	47.8	54.6	*	*	*
Specific conductivity (μS)	400	214	189	120	222	293	625	316	81	—	<detection	150	140
pH field	6.30	8.09	9.15	9.01	9.83	—	7.32	7.59	7.54		6.60	6.40	7.10
Discharge (cfs)	0.75	0.46	—	—	—	—	—	—	—		0.47	0.22	80 gpm
Trace elements (ppm dissolved)													
Arsenic	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.11	0.07	<0.05	0.03	0.05	
Cadmium	<0.01	0.07	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	
Copper	<0.01	<0.01	—	—	—	—	—	—	0.05	<0.03	<0.03	<0.03	
Manganese	0.06	—	0.44	0.12	0.03	0.59	0.12	0.22	0.01	0.12	0.03	0.19	
Iron	1.68	<0.01	3.14	0.52	0.21	1.08	0.79	0.85	0.14	0.59	0.78	0.43	
Lead	0.22	<0.03	0.17	0.15	<0.03	<0.03	<0.03	0.25	0.23	0.12	0.04	0.03	
Mercury	<0.03	—	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	

[a] —, not available; *, temperature corrected

Table 12 Concentrations of constituents in surface water analyzed from Spokane Mine gully[a]

	Date										
	7/14/92	8/6/92	10/26/92	11/8/92	2/5/93	3/18/93	4/23/93	5/14/93	6/10/93	7/18/93	8/18/93
Properties											
Water temp. (°F)	—	—	47.5	42.9	37.6	40.7	51.8	58.2	*	*	*
Specific conductivity (μS)	2700	3010	2018	1790	1442	4170	1233	—	1250	1700	1700
pH field	3.00	4.42	5.72	5.92	3.34	3.57	4.12	—	4.00	3.70	3.50
Discharge (cfs)	0.00029	0.0014	stagnant	stagnant	stagnant	stagnant	stagnant	stagnant	0.022	0.018	4 gpm
Trace elements (ppm dissolved)											
Arsenic	<0.05	0.05	0.11	0.09	0.11	0.07	0.13	0.11	0.15	<0.05	
Cadmium	0.02	0.07	0.30	0.12	0.10	0.12	0.20	0.15	0.10	0.11	
Copper	<0.01	0.01	—	—	—	—	0.17	0.13	0.09	<0.03	
Manganese	5.97	—	18.03	16.6	13.06	13.41	18.85	11.69	7.80	14.21	
Iron	0.14	7.06	2.05	7.54	1.88	2.45	2.90	0.97	1.04	1.08	
Lead	0.13	0.46	0.37	0.57	0.44	0.59	0.41	0.43	0.34	0.19	
Mercury	<0.03	—	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	

[a] —, not available; *, temperature corrected

mine. However, elevated arsenic and other metals in acid water drain from the mine in a small gully that leads to Spokane Creek. The creek loses its flow to the Madison Limestone downstream.

Strawberry Creek

The confluence of Strawberry Creek with Bear Butte Creek is in S9, T4N, R4E, about 3 km downstream from the large existing gold mine operated by Brohm Mining Corporation, where Brohm Mining is working presently with the DENR to mitigate acid-mine drainage. Strawberry Creek drains the historic Gilt Edge Mining area. The milky color (aluminum hydroxide) of Strawberry Creek primarily reflects the impact of past mining activities. Numerous mines on the watershed are located in brecciated Tertiary porphyry intrusives, originally cemented with auriferous pyrite, now weathered to limonite near the surface. Brohm Mining Co., at the old Gilt Edge Mine at the head of Strawberry and Ruby Creeks, is regulated by the South Dakota Department of Environment and Natural Resources and has a "zero-discharge" permit for their leach pad and process ponds.

Table 13 shows Bear Butte water quality above and below the confluence of Strawberry Creek. Table 14 shows Strawberry Creek quality just above its confluence with Bear Butte Creek. Strawberry Creek is acidic and has detectable concentrations of metals. The overall quality of Bear Butte Creek has been degraded.

Unnamed Mine

About 1 mile east of Rochford along Rapid Creek is a large old mine (S24, T2N, R3E). For years this mill was used as a recreational stop for photography and painting, but in 1992 it was torn down.

Table 15 shows water quality data for water discharging from the main adit. The water quality is good, with somewhat high total solids but few heavy metals.

Discussion

The field pH values for surface waters at the 11 sites ranged from 1.6 to 9.7. The most acidic waters were associated with low discharge on dumps with sulfide-rich ores at sites such as the Double Rainbow and Minnesota Ridge mines.

The concentrations of trace metals in water were typically low. Arsenic is found in numerous ores, but rarely exceeded the drinking water standard (50 ppb) in water samples. Low concentrations of cadmium, lead, manganese, and copper were detected in some analyses. Five sites had elevated mercury.

Iron concentrations were high in many water samples. The EPA drinking water standard of 0.3 ppm was exceeded at many locales. The highest concentration (498 ppm) was from ephemeral runoff at the King of the West Mine.

Pyrite is an abundant sulfide mineral within the Precambrian rocks. High iron concentrations can occur either at reducing sites of ferric oxyhydroxides or oxidizing sites of ferrous sulfides. As ferrous sulfide oxidizes, the sulfur oxidized to sulfate, releasing the ferrous ion. This oxidation process also produces sulfuric acid, which further reduces the pH of the system and increases the solubility of pyrite. The "yellow-boy" deposits found at many mines are a result of the oxidation of ferrous to ferric ions and resulting precipitation of ferric hydroxides.

Table 13 Concentrations of constituents in surface water analyzed from Bear Butte Creek at Strawberry Creek[a]

	Upstream									
	9/15/92	10/31/92	11/10/92	12/23/92	2/6/93	3/27/93	4/25/93	6/26/93	7/19/93	8/20/93
Properties										
Water temp. (°F)	57.9	40.0	32.3	32.3	34.9	46.9	48.0	*	*	*
Specific conductivity (μS)	665	301	390	296	1038	278	84	120	700	210
pH field	8.21	—	8.70	—	8.18	6.49	6.95	8.00	8.30	7.60
Discharge (cfs)		—		—	—	—	—	—	3.9	—
Trace elements (ppm dissolved)										
Arsenic	<0.05	<0.05	<0.05	0.06	<0.05	<0.05	<0.05	<0.05	<0.05	
Cadmium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	
Copper	<0.01	—	<0.03	—	—	—	<0.03	<0.03	<0.03	
Manganese	—	0.02	<0.01	0.01	0.02	0.05	0.04	0.04	0.04	
Iron	<0.01	0.29	0.04	0.13	0.13	0.85	0.94	0.49	0.36	
Lead	<0.03	0.09	<0.03	<0.03	<0.03	<0.03	0.06	<0.03	0.09	
Mercury	—	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	

	Downstream										
	9/15/92	10/31/92	11/10/92	12/23/92	2/6/93	3/27/93	4/25/93	6/26/93	7/19/93	7/25/93	8/20/93
Properties											
Water temp. (°F)	57.1	39.4	32.2	32.1	34.1	44.6	46.9	*	*	*	*
Specific conductivity (μS)	722	343	416	889	1105	439	148	180	600	250	270
pH field	8.21	9.72	8.74	—	8.27	6.39	6.81	7.50	8.00	8.10	8.20
Discharge (cfs)	0.55	0.54	1	0.8	0.84	12	16	22	5.4	7.1	—
Trace elements (ppm dissolved)											
Arsenic	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.03	0.1	<0.03	
Cadmium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	
Copper	0.07	—	<0.03	—	—	—	0.06	0.16	0.15	0.17	
Manganese	—	0.13	0.06	0.11	0.04	0.45	0.27	0.18	0.17	1.86	
Iron	<0.01	0.90	0.15	0.24	0.07	2.50	2.92	1.46	0.65	1.30	
Lead	<0.03	0.08	<0.03	<0.03	<0.03	<0.31	0.31	<0.03	0.02	<0.03	
Mercury	<0.03	<0.03	<0.03	<0.03	<0.03	<0.05	<0.03	<0.03	<0.03	<0.03	

[a] —, not available; *, temperature corrected

Sulfide minerals in waste rock are a problem not only in the Black Hills. At the Summitville Gold Mine, Colorado, the waste rock was inaccurately characterized during the permitting procedure in the 1980s. It was believed the waste rock would come from the oxidized zone, but today 2.5 pH water drains from waste material containing base metal sulfides (Pendleton 1995).

Annual trace element loadings can be calculated if the stream discharge and metal concentrations are known. Many analyses showed no detected trace metals at all. The 11 mines studied are near streams where the discharge is variable; since the measurements were only made on a monthly basis, the data are not continuous and annual loadings are estimated from monthly calculations. The pipe outflow at the Double Rainbow Mine into Bear Butte Creek provides an example of an annual loading determination. Using the nearly constant discharge of 0.001 $m^3 s^{-1}$ and an average arsenic concentration of 0.2 mg l^{-1} yields an annual loading of 9 kg of arsenic. Based Based on analyses of solutes above and below, the Double Rainbow Mine adds an estimated 2400 kg of trace metals annually to Bear Butte Creek, including 58 kg of arsenic (Table 16). Because Bear Butte sinks into the Madison aquifer within a few kilometers downgradient, these solutes ultimately contaminate this aquifer. The Eagle Bird Mine adit water contributes an estimated 100 kg of trace metals to Squaw Creek. An estimated 1800 kg of dissolved trace metals (mostly iron, but including arsenic and lead) are being removed from the Minnesota Ridge Mine area by surface water. These solutes are carried towards the West Fork of Gimlet Creek. Some solutes precipitate out in the alluvium but some presumably reach Rapid Creek. An estimated 3200 kg of trace metals are being dumped annually into Bear Butte Creek by Strawberry Creek. Most of this is iron, but arsenic, copper, manganese, and lead also are included.

Uranium mines

The uranium mines in the Edgemont district have relatively little impact on water resources because of the overall aridity and lack of streams in the southern Black Hills. However, some open pit mines have standing water with high dissolved elevated metals, and pH near 4. Analyses of standing water in several mines (Webb and others 1995) showed dissolved uranium as high as 2.6 ppm and high concentrations of rare earth elements (e.g., lanthanum at 1.7 ppm).

Rahn and Hall (1982) reported 24 large open-pit uranium mines on US Forest Service land, representing over 200 ha of disturbed ground. Soil samples show radium in excess of 5 pCi l^{-1} and radon in underground adits greater than recommended working levels. The radiological and toxicological hazards are small because of the remoteness of the area and the fairly low levels of radionuclide concentrations in the ore. Physical hazards are significant due to

Table 14 Concentrations of constituents in surface water analyzed from Strawberry Creek above Bear Butte Creek[a]

	Date										
	6/26/92	9/15/92	10/31/92	11/10/92	2/6/93	3/27/93	4/25/93	6/26/93	7/19/93	7/25/93	8/20/93
Properties											
Water temp. (°F)	—	53.4	38.8	33.1	35.4	36.2	47.2	*	*	*	*
Specific conductivity (μS)	767	984	535	584	665	776	349	350	500	470	410
pH field	4.70	7.71	9.83	8.51	3.12	4.86	5.44	5.50	6.70	6.90	7.60
Discharge (cfs)	—	—	—	—	—	—	—	0.33	0.36	0.089	0.134
Trace elements (ppm dissolved)											
Arsenic	2.60	<0.05	<0.05	0.15	<0.05	<0.05	—	0.17	<0.05	<0.05	
Cadmium	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	—	0.01	0.01	0.01	
Copper	1.35	0.24	—	0.07	—	—	—	1.46	1.05	1.19	
Manganese	2.59	—	0.52	0.40	0.18	1.94	—	1.09	0.90	1.17	
Iron	14.49	<0.01	0.14	0.15	0.01	9.49	—	7.38	2.79	2.98	
Lead	<0.03	<0.03	0.04	<0.03	<0.01	0.03	—	<0.03	0.03	0.34	
Mercury	—	<0.03	<0.03	<0.03	<0.03	<0.03	—	<0.03	<0.03	0.04	

[a] —, not available; *, temperature corrected

Table 15 Concentrations of constituents in surface water analyzed from Unnamed Mine[a]

	Date							
	9/8/92	9/22/92	10/20/92	11/10/92	4/25/93	5/14/93	6/11/93	7/19/93
Properties								
Water temp. (°F)	47.5	47.1	47.1	35.1	—	47.7	*	*
Specific conductivity (μS)	1118	950	950	549	—	—	440	510
pH field	8.36	8.14	8.14	8.95	—	—	7.40	7.80
Discharge (cfs)	0.01	0.01	0	—	—	0.25	0.016	0.011
Trace elements (ppm dissolved)								
Arsenic	<0.05	0.02	<0.05	<0.05	0.15	<0.05	<0.05	<0.05
Cadmium	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01	<0.01
Copper	<0.01	<0.01	—	<0.03	—	<0.03	<0.03	<0.03
Manganese	—	—	0.08	0.04	1.57	0.18	0.07	0.16
Iron	<0.01	<0.01	0.67	0.21	6.49	1.97	0.73	0.36
Lead	<0.03	<0.03	<0.03	<0.03	0.37	<0.03	<0.03	<0.03
Mercury	—	—	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03

[a] —, not available; *, temperature corrected

Table 16 Estimated annual loadings at selected mines

	Amount (kg)			
	Double Rainbow	Eagle Bird	Minnesota Ridge	Strawberry Creek
Arsenic	58	0	60	40
Cadmium	40	0	0	0
Copper	270	0	60	270
Manganese	600	10	20	450
Iron	600	100	1540	2390
Lead	730	0	120	10
Mercury	60	0	0	0
Total	2400	100	1800	3200

unstable open-pit walls, unmarked pits, partially caved adits, and unmarked ventilation shafts and test holes.

Physical dispersion of waste rock occurs (Fig. 7) from the mining area during flash floods, but no data are available to quantify this impact on the fluvial systems. Presumably much of the fine-grained waste rock ends up in Angostura Reservoir.

Pegmatite mines

Spot sampling of stagnant water was conducted in pegmatites of the Black Hills. On 3 August 1993, the Shamrock, St. Louis, and Bull Moose mines were studied. The pH of these three mines was 9.0, 8.2, and 8.0; and the conductivity was 90, 10, and 130 μS, respectively.

The reason for the alkalic nature of pegmatite mine waters can be explained by the equilibrium pH (abrasion pH), the pH eventually attained when minerals are pulverized in distilled water. Laboratory values of abrasion pH for the common pegmatite minerals orthoclase are 8 and for plagioclase, 8–10 (Ritter and others 1995).

Fig. 7 Abandoned uranium mine dump near Edgemont

The pegmatites contain silicates and some phosphates, oxides, sulfides, and rare metals such as tin, beryllium, uranium, lithium, and columbium (Lingard and Roberts 1968). Yet the water associated with these mines is basic and contains low concentrations of heavy metals. The reason for the low dissolved metals is because the metals are mainly associated with minerals of low solubility such as the silicate minerals.

Conclusion

It is impossible to recreate premining water quality in areas that are heavily affected by historic mining activity. In order to assess the impacts of mining, recourse can be made to a comparison of water quality in a stream above and below a mining site.

The primary emphasis of this study was to evaluate the water quality impacts of selected abandoned mines in the northern and central Black Hills. The mines chosen are moderate-sized sites near streams. The mines can be considered "typical," although their selection should not be considered random in the statistical sense.

Most of the mines in this study had no measurable effect on the water quality. The mines that had the greatest impact are: (1) The Double Rainbow Mine, which dumps about 58 kg of arsenic annually into Bear Butte Creek. This water recharges the Madison aquifer downstream (Rahn and Gries 1973); (2) Strawberry Creek, which delivers 3200 kg of trace metals annually into Bear Butte Creek; (3) the Minnesota Ridge Mine, from which 1800 kg of trace metals are leached into the drainage of Rapid Creek; and (4) the King of the West Mine, where leaching of tailings occurs in an ephemeral drainage above Smith Gulch Spring in the Rapid Creek drainage.

Generally, the impacts of these 11 mines are localized. For example, the Minnesota Ridge Mine is located far from any population centers, and any water that reaches Rapid Creek is diluted by the larger discharge of that stream.

This study shows that mines associated with sulfide-rich ores generally had higher levels of surface-water degradation. Because most of the abandoned mines were in small quartz veins with few sulfides, water draining the disturbed lands does not produce much acid or metals today. Another factor is the presence of carbonate minerals; their presence can temporarily help buffer sulfide minerals. Runoff from snowmelt and thunderstorms generally was not measured in this study, but runoff from these events presumably carries large amounts of mine waste that could adversely affect water resources.

The impacts to surface waters from mining of pegmatites in the central Black Hills are negligible because pegmatites are essentially granitic in composition and they consist largely of silicate minerals of very low solubility.

The impacts to mining of surface waters in the Edgemont uranium district is limited due to the absence of streams. Physical dispersion of mine dumps is more of a concern than water contamination of perennial streams.

One of the most significant water quality problems that will be present for a long time to come is the Whitewood Creek Superfund site, which has arsenic contamination far in excess of any other area.

In the future, care must be exercised to safeguard the contamination of water by additional mining in the Black

Hills. Because the gold mines presently operating are many times larger than the abandoned gold mines cited in this study, and because of the abundance of sulfidic ore at two of the mines, environmental vigilance must be exercised. The fact that the potential for contamination from the presently active mines exists is exemplified by the 1992 release of water with a pH less than 3 into a tributary of Squaw Creek below the Richmond Hill Mine (Durkin 1994b) and the 1993 release of acidic drainage in Ruby Gulch below Brohm's Gilt Edge Mine.

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