SEASONAL ACID MINE DRAINAGE FROM A SURFACE-MINED WATERSHED IN EASTERN KENTUCKY[1]

by

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Abstract. Jacks Branch and nearby streams in Knott County, eastern Kentucky, experienced highly acidic "flushouts" during spring runoff events, but were near neutral or alkaline for the rest of the year. The most acidic and saline discharges occurred a few hours or days following the peak discharge; the least saline discharges occurred near the discharge peaks as a consequence of dilution. The pH of Jacks Branch ranged from 2.7 to 8.1; dissolved solids ranged from 491 to 3,000 mg/l. Water-quality records for the past 11 years indicated little change in pH or dissolved solids over time. Two seams of coal have been mined on the watershed, the lower (Hazard No. 7) by auger mining and the upper (Hazard No. 9 or Hindman) by both strip and auger mining. Strong permanent springs emerged from the lower seam of coal, assuring a dependable supply of good-quality, near neutral or alkaline water in the main stream at base flow. Only at high-flow periods in the spring did enough highly acidic drainage from the upper mined area reach the main stream to seriously degrade the quality of water. These acid discharges from the upper bench had pH values as low as 2.2 and dissolved solids up to 11,650 mg/l. They emerged in brief but strong flows directly from the highwall of the Hindman coal seam, a seam commonly associated with acid discharges in much of eastern Kentucky, and contained the products of pyrite oxidation.

Additional Key Words: Water quality; flushouts; coal mining

Introduction

Acid mine drainages generally do not pose a problem in surface-mined areas of eastern Kentucky since drainage from these watersheds usually is more alkaline than from those which are unmined and otherwise undisturbed (Dyer 1982, 1983; Dyer and Curtis 1977, 1983). Streams affected by acid mine drainage usually are acidic all year; however, Lotts Creek and tributaries in Knott and Perry Counties, Kentucky, tend to have one or more surges of highly acidic drainage in the spring, then are near neutral or alkaline the remainder of the year (Dyer 1983). These seasonal surges of acid water are sufficient to kill most forms of aquatic life, so a healthy aquatic community of living forms can never become well established. Acid streams also are very destructive of metal and concrete structures and objects (Havens 1952). A local informant in 1975 said that an acid surge in Lotts Creek near its mouth would dissolve a "tin can" in a few days except for the reinforced metal rings at the top and bottom.

The purpose of this study was to document the sources of the acid and alkaline discharges and to gain an understanding of the driving forces behind them. Information of this kind might be used to help alleviate the severity of these acid surges, and could help prevent such problems in future mining.

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Description of Area

Figure 1 shows the location of the study area and the locations of stream gaging stations and water quality sampling sites outside the study area. Figure 2 shows the topography, the sampling sites, and the surface drainage boundaries for Jacks Branch above the gage (site 22) and for the older sampling site (site 36) at the highway crossing near the mouth of the branch. The upper bench at an elevation of 1,500 to 1,530 feet resulted from the mining of the Hindman (or Hazard No. 9) coal seam. The lower, narrower bench at an elevation of about 1,350 feet marks the location at which the Hazard No. 7 coal seam was auger mined. This lower bench was largely buried under the overburden material spilled from the upper bench. Buried portions are indicated in Figure 2 by dashed lines. Of the 185 acres of watershed above the Jacks Branch gage, 111, 60 percent of the total, have been disturbed by surface mining. The upper bench occupies about 44 acres, the exposed portion of the lower bench abour 2 acres, and the highwalls about 3 acres.

Mining History and Reclamation

It is believed that no coal, except perhaps "house coal," was mined on Jacks Branch prior to 1954. Sometime between 1954 and 1964, probably about 1962 or 1963, the Hazard No. 7 seam was auger mined. A bench about 30 feet wide was constructed at the level of the base of the coal seam.

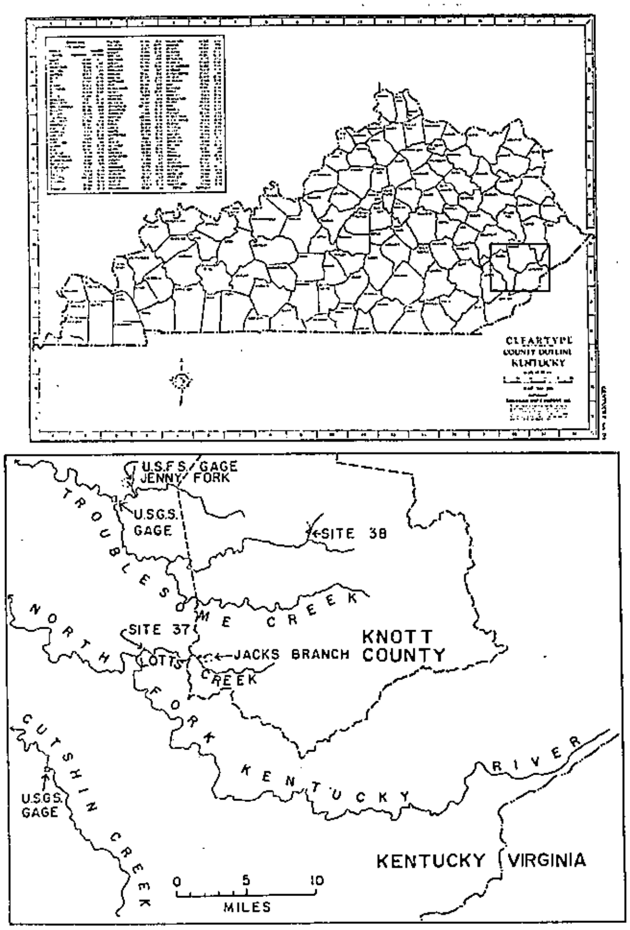

Figure 1. Location maps.

Any unweathered and marketable coal exposed in the process was likely salvaged. The exact thickness of the Hazard No. 7 seam on Jacks Branch is not known; neither is the diameter or length of the auger used to mine it.

It is believed that the Hindman or Hazard No. 9 coal seam was mined largely in 1963 and 1964. The width of coal stripped probably exceeded 100 feet over most of the bench. The exact thickness of this seam of coal is not known, but it appears to have generally exceeded 7 feet since a 7-foot-diameter auger has been used to extract coal from this seam on neighboring watersheds and possibly on part of the Jacks Branch watershed. An early type of continuous miner is thought to have been used on about 1,800 feet of bench to extract coal from under that part of the mountain not removed by stripping. Exactly how much of this 1,800 feet of bench was on the Jacks Branch Watershed is not known; however, this may not be important because the hydrologic effects would have been similar whether mining was by auger or by continuous miner. The continuous miner was operated by remote control and cut either a 10- or 12-foot-wide tunnel under and sometimes through the mountain. These tunnels were separated by pillars of coal about 12 feet wide and, except for being square, resembled large auger holes. All auger holes and/or continuous miner tunnels have been backfilled and are not exposed or visible at the present time.

Aerial photographs taken on 23 October 1964 indicate that mining had been completed on the lower bench and that the upper bench had been completely cut with coal possibly still being extracted. None of the upper bench on the Jacks Branch drainage had been reclaimed at this time; however, it was being partially filled, leveled, and reclaimed just a few hundred feet to the south of the study area. In 1985, the upper bench generally was 165 to 435 feet wide. Topography on the upper bench varied from almost flat to gently rolling. The maximum elevation and divide along this bench generally was about one-third of the distance from the outer edge to the highwall. Several breaks through this divide permitted surface runoff to leave the bench. It was evident that parts of the outer bench periodically slip over the edge in small landslides.

The lower bench had a volunteer cover of native grasses and trees in the northern section while the southern length of bench contained marsh-type vegetation. The upper bench was almost completely grass covered except for a few ponds and marshes near the highwall, and a very few acid spots which were bare of vegetation. Most of the upper bench was covered by locust trees planted at random or set out on an approximately 10 by 10-foot grid. Many deciduous and coniferous trees apparently have seeded themselves on parts of this upper bench. Most of the outslope was covered with a dense sod, hummocky in appearance; much of it has been invaded by deciduous trees. The lower non-vertical slope of the highwall was largely covered by coltsfoot (*Tussilago farfara*). Cattails (*Typha* sp.) were the predominant vegetation in the ponds and larger marshes.

Methods

Beginning on April 11, 1984, and ending November 12, 1985, the author periodically walked

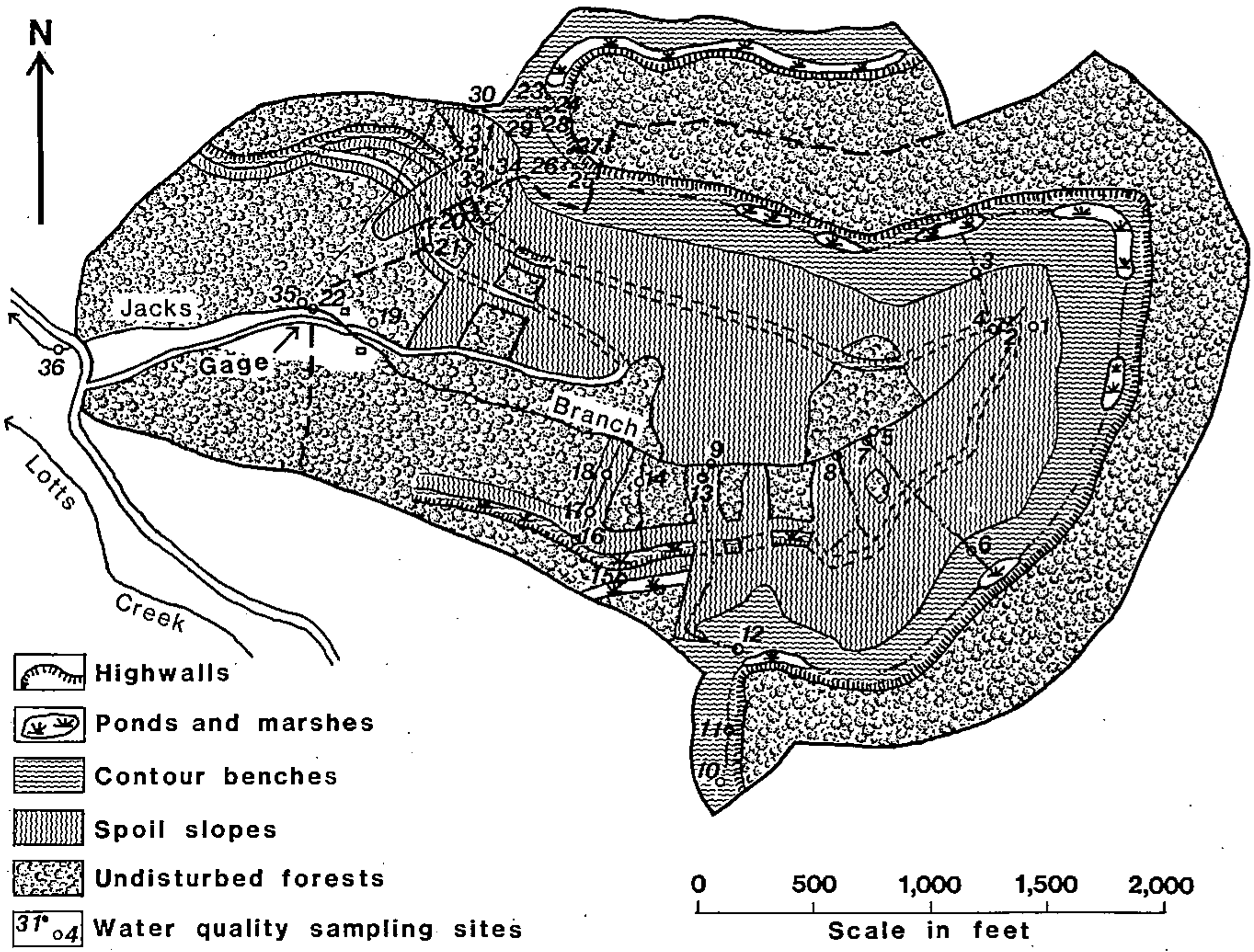

Figure 2. The Jacks Branch watershed showing disturbed areas and sampling points for water samples.

over the entire study area collecting water samples from most streams, seeps, and springs--36 sites in all (Fig. 2). These are all numbered in downstream order. Sites 37 and 38 are shown in Figure 1. Site 37 was on Lotts Creek, about 6 miles downstream from Jacks Branch, and just a few feet above its juncture with Trace Fork. Stream water unaffected by mining could not be found on or near the Jacks Branch watershed, so two typical samples (one of high flow, the other of low flow) from the unmined Board Tree Hollow watershed at Yellow Mountain (11 miles northeast of Jacks Branch) are included in Tables 1 and 2 as site 38. Dyer (1983) showed that there is little variation in water quality in streams draining unmined watersheds in this general area, so these data should be representative of the quality of water discharging from Jacks Branch before mining. Most water samples were analyzed for common ions, trace elements, and acidity. Selected data from these analyses are presented in Tables 1 and 2.

There have been severe seasonal fluctuations in pH in Jacks Branch and Lotts Creek; this is evident from water-quality data collected from 1974 to date. Occasional water samples from Jacks Branch and Lotts Creek at highway crossings were collected in 1974 and 1975, and the partial chemical analyses published by Dyer (1983). Monthly water samples from Jacks Branch near its mouth were collected from June 1977 to July 1979 and analyzed for common ions and trace elements. These data were published by Dyer (1982, p. 146, site 3133). In 1980, a trapezoidal Venturi flume with a recording gage was constructed on Jacks Branch 0.2 mile upstream from the earlier sampling site at the highway crossing. From November 1980 to the present time, samples have been collected at this flume on a monthly basis and analyzed for common ions and trace elements by the methods described by Dyer (1982, p. 6-14) for the earlier samples. Three parameters from these largely unpublished historical data (pH, specific conductance, and instantaneous discharge) are shown in Figure 3 along with monthly runoff from the closest available U. S. Geological Survey gaging station on an unregulated stream (Troublesome Creek at Noble for June 1977 through September 1981, and Cutshin Creek at Wooton from October 1981 through November 1985).

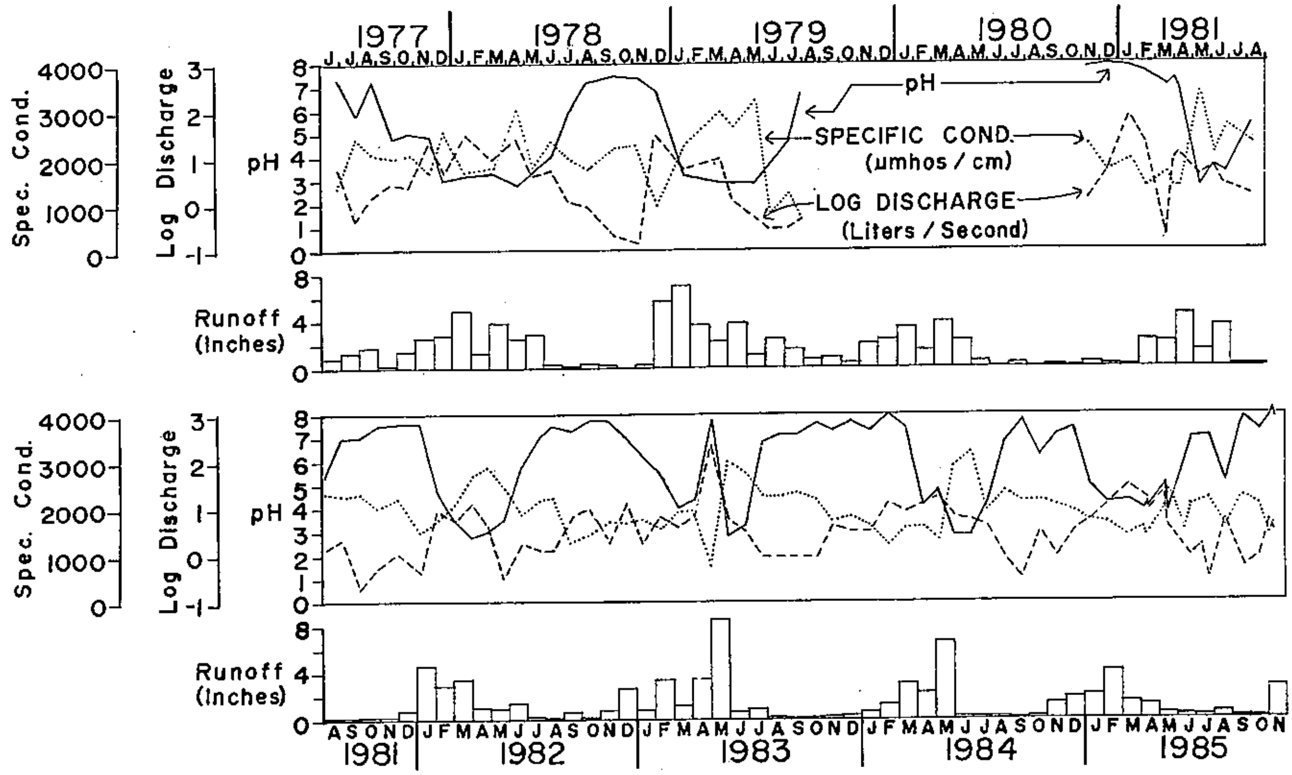

Figure 3. Monthly pH, specific conductance, and instantaneous discharge data for Jacks Branch at the highway (June 1977–July 1979) and for Jacks Branch at the gage (Nov. 1980–Nov. 1985); monthly runoff data for U. S. Geological Survey stations: Troublesome Creek at Noble, Kentucky (June 1977–Sept. 1981) and Cutshin Creek at Wooton, Kentucky (Oct. 1981–Nov. 1985).

Hydrology

Young (1986) found that total annual runoff for 1982 and 1984 on a mined watershed in Ohio (Dorr Run) averaged 20.4 inches, 6.8 inches (or 50 percent) higher than the 13.6 inches on a nearby unmined watershed (Fivemile Creek). The additional runoff from the mined watershed was attributed to the lower evapotranspiration and lower infiltration rates on the mined lands. Discharge records at USDA Forest Service gaging stations on Jacks Branch and Jenny Fork (13 miles NNW of Jacks Branch) were not complete; however, the 19 months of complete data for these two stations which could be compared indicated that runoff from Jacks Branch was 14 percent higher than that from the unmined Jenny Fork. An overstory of deep-rooted young trees now covers most of the disturbed portion of the Jacks Branch watershed, so it seems reasonable that evapotranspiration and total runoff should be approaching that of an unmined watershed.

Young also found that the groundwater discharge for 1982 and 1984 on the mined watershed was 15.2 inches, more than double the 6.8 inches observed on the unmined watershed. The higher groundwater discharge would be associated with a higher base flow. Young (1986), Curtis (1977), and Agnew and Corbet (1973) all noted that streams from mined watersheds had a more dependable flow than streams from unmined watersheds. From personal observations, the author determined that the summer base flow of Jacks Branch was higher than that of unmined watersheds of similar size in this area. Streams from unmined watersheds with similar drainage areas may be dry at times in the summer; yet Jacks Branch was never observed to be dry.

Water Quality

The data in Figure 3 illustrate interesting relationships between water chemistry and discharge. The most apparent of these was the seasonal cycling of pH, which dropped from a high of 8.1 during low flow to a low of 2.8 during and immediately after periods of high flow centered around the spring of the year. The inverse correlation of pH to the log of the discharge was significant at the 5 percent level for both stations together for the entire period of record and for 1977-79 at the lower station near the mouth of Jacks Branch. There was one serious anomaly observed in which both pH and discharge increased together in a sharp peak on May 3, 1983. This discharge event was unique for the study in that it was the only real flood observed and sampled at the gage. The very high pH of this sample indicates this water was coming from areas largely unaffected by acid drainage--presumably because the flood of acid water from the upper bench simply had not had time to reach the gage. The very low specific conductance would likely be due to the dilution effect of relatively nonsaline surface runoff water from the lower elevations. A sample taken only an hour or two later would likely have been higher in specific conductance and much lower in pH because inflow from the upper bench would have had time to reach the sampling site by then.

An inverse correlation of pH to specific conductance, statistically significant at the 0.01 level, was observed for the entire group of samples plotted in Figure 3. This also was true for both the 1977-79 and 1980-85 subgroups evaluated as separate units. This means that the acid discharges tend to have higher levels of dissolved solids (largely sulfates) than the nonacid discharges.

An inverse correlation of specific conductance to the log of the discharge was significant at the 0.01 level for the entire period of record plotted in Figure 3. This also was true for the 1980-85 subgroup. This would seem to indicate an apparent dilution effect on the dissolved solids at the higher discharge rates, an effect especially evident in the May 3, 1983, March 9, 1985, and December 7, 1978, samples (Fig. 3). However, the opposite effect was noted on other occasions, especially the April 18, 1978, January 14, 1981, and December 2, 1981, samples. These differing relationships are believed to be due to the fact that different kinds of water from different portions of the watershed required different lengths of time to reach the lower parts of the watershed. The dilution effect would be most evident on streamflow occurring early in the runoff event from the lower parts of the watershed, while increases in specific conductance and salinity associated with increased discharge would be attributable to flows from the acid-producing areas high on the watershed that do not reach the sampling point until later in the runoff event.

The data in Table 1 show that water from the upper bench was almost always more acidic than that draining from other portions of the watershed. It was also higher in sulfates, iron, aluminum and manganese, and, as shown in Table 2, most trace elements. This was especially evident on the main, and more or less permanent, drains at sites 3, 6, 12, and 30. Partially neutralized acid water from these same drains reaches Jacks Branch most of the year at sites 4, 7, 13, and 35. Small ponds on the upper bench, such as at site 29, were nearly neutral in pH, though still moderately high in specific conductance. The most acidic discharge observed during this study was at site 27, where a strong flow issued from the rubble a foot or more above the base of the highwall. This flow had a pH of 2.17 and an acidity of 5,300 mg/l as $CaCO_3$. Sulfate, iron, aluminum, and manganese concentrations also were extremely high. Most concentrations of trace elements were much higher than in other samples (Table 2). Flows such as this from the highwall were observed on only one occasion during the study and are believed to last only a few hours after heavy rains saturate the unmined top of the mountain. Auger holes and fractures in the Hazard No. 9 or Hindman seam of coal probably interconnect to lead drainage from the overburden to the group of discharge points clustered around site 27. Discharge from the upper bench toward the highwall at site 26 was very acidic. Also, springs at sites 31 and 34, discharging from the outslope spoil from this upper bench were very acidic. During dry seasons, little or none of the surface drainage water from this upper bench reached Jacks Branch.

Those samples that contain large concentrations of soluble iron could become much more acidic when this ferrous iron oxidizes to the insoluble ferric form and precipitates out as "yellow boy." Almost half the samples tabulated in Table 1 show high concentrations of iron. The sample from site 27 contained 1,300 mg/l iron, which, if oxidized, would release 47 mg/l hydrogen, enough to lower the pH of this sample from 2.17 to about 1.3, provided the action of buffers in the water is not taken into consideration.

The stream at site 23 drained a long marshy area on the upper bench that had been diverted into the Jacks Branch watershed. Water here was either neutral or alkaline, perhaps because the acid-producing spoil materials remained immersed beneath the water table and could not oxidize (Dyer 1984). Larger ponds and marshes with similarly good-quality water lay on the upper bench just south of the Jacks Branch watershed. Small acid seeps entered the stream a few feet below site 23, and when these were flowing it was sufficient to severely acidify the water sampled at site 24, only 20 feet downstream from site 23, without significantly increasing the discharge.

Water sampled at sites 8, 14, 16, 17, and 18 on the north-facing slope drained largely from the augered coal seam (Hazard No. 7) on the lower bench. This lower bench produced a relatively steady supply of nearly neutral to slightly alkaline water, which is the main component of base flow in Jacks Branch most of the year. Data in Tables 1 and 2 show this water to be high in dissolved solids, yet low in iron, aluminum, manganese, and trace elements. During wet seasons, the strong discharges of acid water from the upper bench first neutralized and then frequently overwhelmed this relatively constant supply of better quality water, turning it acidic.

The acid discharge from site 3 on the upper bench was consistently neutralized before it reached site 5 on Jacks Branch, regardless of the season. It is believed that this was due to alkaline seeps reaching Jacks Branch from the buried portion of the lower bench in the head of Jacks Branch. The stream at site 5 always exhibited a grayish turbidity; however, a few feet away, the highly acidic stream at site 7 was always clear as it flowed over clean rocks. The formation of abundant "yellow boy" at and immediately downstream from the juncture of the two streams sampled at sites 5 and 7 was apparent when both were flowing. It can be deduced that the water at site 7 was always acidic enough to keep the iron in solution; however, once its pH was raised by mixing with the neutral or alkaline water from site 5, large quantities of yellow boy immediately precipitated out, frequently covering the stream bottom downstream to the gage and beyond.

There commonly is a water table underneath spoils, both on the benches and on the outslopes, so seepage is observed frequently at spoil bank toes (Dickens and others 1983). Springs discharging from spoil placed on the outslope were observed at sites 1, 31, and 34 at a considerable distance above the toes of the spoils. Old landslides had removed most of the spoil at sites 31 and 34, so bedrock probably was no more than a foot or two beneath the surface. Orange-brown deposits of yellow boy had accumulated to an unknown depth for 100 feet or more downstream of the essentially perennial and highly acidic spring at site 31. The spring at site 34 was only about 100 feet farther east and in a similar topographic setting, yet it was less saline and much less acidic except on April 11, 1984. The spring at site 1 discharged from a gray, largely barren spoil of unknown depth. The reasons for alkaline water surfacing at this point are not known. The water from the puddle and pool on the outslope at sites 32 and 33 was alkaline in both instances. This would seem to indicate that the spoil spilled here from the upper bench also was somewhat alkaline. The good cover of grass on spoil outslopes from the upper bench indicated no acidity problems here.

Discussion

Hollyday and McKenzie (1973) deduced from their study in western Maryland that, on the average, 70 percent of the acidity of underground mine drainage had been neutralized before discharge at the land surface. Similar calculations on the Jacks Branch watershed indicated that only 28 percent of the acid initially produced had been neutralized at the time water was released from the highwall at site 27. Average neutralization of water from the upper bench at sites 3, 6, 12, and 30 was 60 percent; water from the lower bench at sites 8, 14, 16, 17, and 18 was about 100 percent neutralized. The water in springs at sites 31 and 34 on the outslope spoil was about 80 percent neutralized, presumably because it had dissolved carbonates from calcareous spoil and/or had been partly neutralized by ion exchange processes as it leached through less acidic soils and spoils.

Agnew and Corbett (1973) described in detail a "flushout" of acidic water on Mud Creek in southern Indiana associated with storm runoff which caused an increase of 1,150 percent in acidity, 1,300 percent in total iron, and 180 percent in sulfate. The pH increased from 4.3 to 5.0, then dropped to 2.5 while specific conductance first dropped from 2,450 micromhos/cm to 1,000 (due to dilution), then increased to 3,400 when the surge of acid-saline water from the more distant parts of the surface-mined watershed arrived. These changes were similar to those observed in Jacks Branch, and the processes occurring on these two watersheds are thought to be very similar. Agnew and Corbett defined a flushout as a hydrologic event in which the precipitation falling on a watershed is sufficient in quantity and intensity to cause storm runoff; this, in turn, can drastically change the quality of water in the streams. They found that flushouts were most effective when caused by intense rains occurring at the end of sustained periods of low flow and drought. This statement no doubt would apply to Jacks Branch also, but samples were not taken at close enough intervals to show the entire cycle.

Young (1986) found the broken rock material comprising the spoil at Dorrs Run was high in pyrite and concluded that the near surface pyrite will continue to oxidize and contribute to acid mine drainage until it has been depleted. This would appear to be the process now operating in the spoil from the Hindman coal seam on the upper bench. This seam was mined in 1964, yet data from 1974 through 1985 indicate there has been little or no improvement or change in water quality in Jacks Branch over a period of 11 years. Eventually, the effects of acid mine drainage will lessen and then disappear from Jacks Branch; however, judging from the lack of improvement thus far, it will likely be many years before there is significant improvement in water quality.

It would have been difficult to prevent acid mine drainage from the Hindman (Hazard No. 9) seam from reaching Jacks Branch regardless of how the mining and reclamation had been carried out. Practices that might have helped reduce oxidation of pyritic materials and the resulting formation of acid mine drainage area include: (1) removing all coal from the Hindman seam so the mountaintop could have been lowered--thus reducing exposed surface areas; (2) segregating the more toxic spoils at the base of the highwall and covering them with finer textured spoils and soils; and (3) manipulating water on the upper bench to keep the toxic spoils immersed as much of the time as possible. All of these practices would help limit access of oxygen to pyritic materials; however, the immersion technique would be the most effective and permanent (Dyer 1984).

The Hindman seam on the Clear Fork watershed (adjoining the Jacks Branch watershed on the north) was strip and auger mined in 1963-64, the same as the Jacks Branch watershed. In 1985, the upper part of the Clear Fork watershed was reclaimed and reseeded, possibly as part of the orphan lands reclamation program. Rock cores were constructed, wetlands drained, and the upper bench regraded and smoothed. These practices might have stabilized the outslope and improved the appearance of the land, though it is doubtful that they could have reduced oxidation of pyrite and improved water quality. The improved drainage could have exposed additional pyritic materials to oxygen and in this way may have aggravated the water quality problem.

Little can be done to alleviate the production of acid mine drainage from old mined areas such as the Jacks Branch watershed once the pyritic materials have been scattered. For pyrite still in place in the old auger tunnels, flooding might sometimes be a practical solution (Dyer 1984). Water could be held on the upper bench with small dams on drainage outlets at sites 3, 6, 12, 30 and similar sites on the other side of the mountain. This would largely flood the auger tunnels and associated pyritic materials; however, it is doubtful that any resulting improvement in water quality could be justified by the storage of such large quantities of water high on a mountain. If materials high in pyrite are to be exposed during a mining operation, it is best to plan in advance techniques for segregating them from nonpyritic spoils and then protecting them from oxygen after mining has been completed. Careful planning in the beginning can make unnecessary the expensive treatment of acid mine drainage later.

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Table 1. Water quality data: physical parameters and common ions

Site No.	Site	Date	Disch. gpm	Spec. Cond. µmhos per cm	Calc. Diss. Solids mg/l	Lab pH	Acidity (mg/l as $CaCO_3$)	Alkalinity (mg/l as $CaCO_3$)	Cl (mg/l)	NO_3 (mg/l)	SO_4 (mg/l)	Al (mg/l)	Ca (mg/l)	Fe (mg/l)	K (mg/l)	Mg (mg/l)	Mn (mg/l)	Na (mg/l)
1	Spring	4-12-84	0.5	3700		7.7*												
2	Jacks Br	4-12-84	0	3100		7.0*												
3	Upper Bench	4-11-84	2.2	2580	2490	2.9	338	0	0.5	0.27	1900	39	290	59	9.1	180	3.2	6.4
		5-10-84	4.5	3480	3670	2.6	599	0	.4	.01	2800	47	370	140	11	240	4.6	9.4
		6-13-85	.02	1600	1480	3.4	99	0	.5	.05	1200	9.9	160	3.3	11	83	2.7	3.9
		11-8-85	.6	1580	1290	3.2	108	0	.4	.14	1000	12	160	15	10	69	1.3	2.7
4	Tributary	4-12-84	2.0	3400		4.5*		0										
5	Jacks Br	4-12-84	4.5	2250	2150	8.1	-83	107	.7	.08	1500	.79	320	1.3	13	190	1.2	8.7
		6-13-85	.7	1950	2190	7.2	-88	100	.5	.08	1700	1.5	280	6.9	8.8	150	3.8	7.9
		9-24-85	.1	2210	1900	8.0	-232	260	1.7	.21	1200	1.3	330	1.7	12	150	12	11
		11-8-85	1.0	1900	1540	8.2	-122	143	.6	.00	1000	.74	290	1.3	9.5	100	1.4	5.8
6	Upper Bench	4-11-84	18	3990	4340	2.5	1225	0	.5	.30	3200	66	380	370	3.8	230	4.5	11
		5-10-84	90	3290	3200	2.8	440	0	.7	.30	2500	27	370	102	8.0	220	3.4	11
		6-13-85	.5	4900	6070	2.6	1590	0	.2	.00	4900	77	460	250	2.9	270	7.3	13
		11-8-85	.6	3260	3170	2.6	564	0	.1	.04	2500	47	310	76	4.6	170	5.0	7.8
7	Tributary	4-12-84	18	3970	4230	2.5	1065	0	.4	.04	3220	61	380	270	4.4	220	4.6	11
		6-13-85	.3	3200	4090	2.9	516	0	.2	.02	3320	36	430	41	6.0	200	5.8	8.1
		11-8-85	2.0	2640	2770	3.5	183	0	.2	.04	1700	22	350	5.1	5.8	160	4.0	6.3
8	Tributary	4-12-84	4.5	1790	1630	8.3	-133	161	.8	.02	1100	.34	240	.22	8.0	150	.02	4.6
		11-8-85	1.5	1740	1610	8.4	-120	140	.8	.01	1100	.50	260	.09	7.8	110	.03	4.6
9	Jacks Br	4-12-84	54	2750		3.1*		0										
		5-10-84	180	380		3.9*		0										
10	Upper Bench	11-8-85	0	3260	2540	2.6	750	0	.2	.03	2000	42	250	110	3.2	120	1.8	3.0

Table 1. Water quality data: physical parameters and common ions (Continued)

Site No.	Site	Date	Disch. gpm	Spec. Cond. µmhos per cm	Calc. Diss. Solids mg/l	Lab pH	Acidity -----mg/l----- (as $CaCO_3$)	Alkalinity -----mg/l----- (as $CaCO_3$)	Cl	NO_3	SO_4	Al	Ca	Fe	K	Mg	Mn	Na
									mg/l									
11	Upper Bench	5-10-84	0			2.7*		0										
		11-8-85	0	2930	2580	3.2	324	0	.7	.00	1900	42	450	12	12	105	4.6	2.7
12	Upper Bench	4-12-84	9	3300	2770	3.3	209	0	.8	.01	2100	32	360	28	9.3	200	2.9	6.9
		5-10-84	40	2710	2700	2.9	328	0	.5	.06	2100	25	290	80	11	200	2.5	6.8
		6-13-85	TR	2650	2840	3.5	90	0	.3	.01	2200	9.9	370	3.1	18	180	3.1	6.3
		11-8-85	.4	2220	2100	7.1	-10	13	.4	.11	1600	1.6	320	.3	12	140	1.1	5.0
13	Tributary	4-12-84	18	3200		3.1*		0										
		5-10-84	12			4.2*		0										
		6-13-85	.5	2650	2890	3.0	327	0	.3	.12	2300	25	360	25	5.9	160	6.1	5.1
		11-8-85	.6	2510	2100	3.3	168	0	.3	.12	1600	18	310	5.8	9.6	110	4.2	7.4
14	Lower Bench	4-12-84	4.5	2700		7.4*												
		5-10-84	9.0			6.5*												
		6-13-85	1.4	2100	2420	7.6	-48	61	.6	.01	1900	1.1	300	.18	11	170	.17	9.5
		9-24-85	2.2	2650	2340	8.1	-46	60	1.5	.04	1700	.42	380	.35	15	190	.45	12
		11-8-85	2.7	2250	2080	7.9	-35	45	.9	.00	1500	.85	320	.22	16	160	.36	9.7
15	Road Cut	5-10-84	.045			6.3*												
16	Lower Bench	5-10-84	1.2	1100	757	7.6	-5	24	.9	.01	530	.38	130	.08	4.8	73	.01	4.7
		9-24-85	.7	2570	2290	7.3	-10	13	1.9	.07	1700	1.4	370	.14	13	180	.13	14
17	Lower Bench	9-24-85	.1	2400	2220	8.2	-64	78	2.6	.02	1600	1.8	330	.10	22	170	.03	16
18	Lower Bench	4-12-84	2.2	1510	1350	7.6	-28	39	.6	.01	1000	.28	170	.11	7.2	120	.01	7.5
		5-10-84	5.4			7.0*												
		6-13-85	.7	1590	1370	7.8	-47	61	.2	.01	1200	.92	200	.08	6.2	120	.03	6.1
		9-24-85	.5	2190	2070	8.1	-64	75	1.1	.02	1500	.40	310	.11	12	150	.09	10
		11-8-85	1.2	1770	1420	7.7	-40	52	.7	.06	1000	.35	200	.12	7.4	120	.01	8.3
		11-12-85	1.2															
19	Road Ditch	4-12-84	1.3	423	244	7.4	-6	12	1.1	.01	160	.07	35	.06	2.2	27	.01	4.1
		11-8-85	0	439	309	7.5	-13	19	1.0	.00	220	.09	35	.04	3.1	27	.00	5.5
20	Lower Bench	4-11-84	0	700		6.0*												
		5-10-84	0	441	330	6.5	6	3	1.4	.01	250	.22	40	.09	5.1	29	.03	3.1
		11-8-85	0	823	728	6.5	3	1	1.4	.07	520	.43	94	.71	8.1	97	.75	5.7
21	Road Cut	4-11-84	.22	840		6.7*												
		5-10-84	1.2	680	500	7.1	-6	14	1.2	.03	370	.22	59	.23	5.1	52	.05	5.6
		11-8-85	0	1180	941	7.4	-22	30	1.8	.03	710	.23	110	.19	7.4	79	.55	9.7
22	Jacks Br at gage	4-11-84	240	1520	1390	4.2	51	0	.8	.05	1100	9.4	170	21	6.3	97	1.0	5.6
		4-12-84	135	1670	1520	4.0	58	0	6.3	.08	1100	9.2	210	1.5	6.5	120	1.0	17
		5-10-84	360	1980	2010	3.6	77	0	.4	.09	1500	4.3	280	26	7.1	150	2.0	5.8
		6-13-85	26	1500	1820	6.7	4	7	1.3	.07	1500	1.5	210	.73	8.3	114	2.2	9.0
		9-24-85	8.7	2210	2090	7.8	-12	22	1.1	.01	1600	.5	320	.22	14	150	.6	11
		11-8-85	80	1380	1100	7.8	-30	41	.8	.34	810	.4	160	.17	6	89	.7	5.4
		11-12-85	50	1580	1130	8.1	-42	48	4.8	.04	790	.4	180	.10	7.5	100	.6	18
23	Upper Bench	6-13-85	.5	1400	1050	5.9	9	2	.2	.00	830	1.7	130	.26	5.8	71	.53	2.5
		11-8-85	1.2	1100	888	8.2	-48	61	.3	.07	650	.28	110	.04	10	71	.06	2.3
24	Upper Bench	5-10-84	10			3.5*												
		6-13-85	.5	1680	1370	3.2	137	0	.1	.00	1100	12	150	14	5.7	84	1.5	3.0
		11-8-85	1.2	1120	887	7.9	-40	55	.3	.04	650	.41	113	.05	11	72	.2	2.4
25	Upper Bench	4-11-84	0	2340	2450	5.5	10	6	1.0	.21	1830	8.0	410	1.8	12	150	5.0	3.8
		11-8-84	.6	2580	2460	3.7	237	0	.4	.07	1840	39	400	3.2	12	110	4.2	5.9
26	Upper Bench	4-11-84	0	2260	1910	2.7	234	0	1.3	.28	1500	45	240	43	5.2	74	2.0	2.8
		5-10-84	.18			2.6*		0										
		11-8-85	.07	2390	1710	2.6	443	0	.8	.42	1400	42	180	15	7.8	59	2.6	2.9
27	Highwall Spring	5-10-84	6.7	6390	11700	2.2	5310	0	1.2	.02	9200	250	460	1300	1.0	360	20	10
28	Upper Bench	4-11-84	0	2300	1940	3.0	276	0	.9	.05	1400	36	320	16	9.3	100	3.9	3.4
		11-8-85	.6	2400	2220	3.6	240	0	.8	.18	1700	40	370	5.1	19	110	3.6	4.0
29	Upper Bench	4-11-84	0	860		5.7*												
		5-10-84	0			7.0*												
30	Upper Bench	5-10-84	90	5400	7730	2.4	3350	0	1.0	.30	6000	170	440	760	4.0	320	16	9.1
31	Spring	4-11-84	.18	4200		3.1*		0										
		5-10-84	.05			2.8*		0										
		9-24-85	.02	3830	3560	2.9	238	0	.7	.01	2700	12	490	49	10	230	18	15
		11-8-85	.001	3720	3320	2.9	211	0	.6	.20	2500	16	490	17	8.0	220	16	13
32	Puddle	4-11-84	0	3000		7.4*												
33	Pool	5-10-84	0	1980	2060	7.9	-145	161	.4	.01	1400	.70	380	.40	6.5	140	.11	8.7

Table 1. Water quality data: physical parameters and common ions (Continued)

Site No.	Site	Date	Disch. gpm	Spec. Cond. μmhos per cm	Calc. Diss. Solids mg/l	Lab pH	Acidity -----mg/l----- (as $CaCO_3$)	Alka- linity	Cl	NO_3	SO_4	Al	Ca	Fe --mg/l--	K	Mg	Mn	Na
34	Spring	4-11-84	.22	3600		3.2*		0										
		5-10-84	.27			4.0*		0										
		11-8-85	0	1920	1710	5.2	4	0	1.0	.02	1300	.8	270	1.0	9.7	100	3.2	11
35	Tributary	4-11-84	4.5	1110	884	4.6	20	1	.7	.10	670	3.9	130	.61	6.3	68	2.7	5.2
		4-12-84	4.5	1070	700	4.5	26	0	.9	.25	500	3.0	110	.08	5.6	63	2.3	5.0
		5-10-84	90	5000	6780	2.4	2514	0	.6	.36	5400	150	430	410	6.2	290	20	9.2
		6-13-85	.5	1300	1370	3.9	57	0	.7	.28	1100	8.6	160	.15	6.1	85	4.4	4.7
		11-8-85	.3	1110	855	4.8	16	1	.8	1.2	630	3.4	130	.08	7.5	67	2.8	5.2
		11-12-85	.25															
36	Jacks Br	12-18-74	45	1630		6.6*			2.3		1000							
		2-28-75	76	2710		3.4*			5.0		1800							
		7-24-75	13	2030		7.5*			1.2		1300							
		5-10-84	450	2990	2580	2.7	623	0	.7	.19	1900	40	290	120	6.9	180	5.9	6.5
		9-24-85	6.1	2120	2010	7.4	-8	15	3.1	.23	1500	.42	300	.14	13	140	.42	15
		11-12-85	30	1520	1440	7.7	-25	34	2.8	.17	1100	.33	200	.12	7.1	110	.53	15
37	Lotts Creek	4-12-84	900	694	440	7.3	-1	11	2.5	.35	300	.11	72	.09	4.1	38	1.1	6.7
		5-10-84		892	666	3.9	83	0	1.3	.62	490	6.1	97	2.8	5.2	49	2.2	5.6
		9-24-85	1440	1500	1270	8.1	-51	61	8.5	.03	930	.32	180	.09	12	81	.2	22
		11-12-85	1800	905	738	7.7	-26	34	6.4	.54	520	.17	120	.06	4.7	56	1.2	15
38	Board Tree Hollow	3-7-78	315	53	35	6.8		6	.7	.1	14	.1	3.2	.11	1.2	3.0	.02	2.0
		11-7-78	.09	66	48	6.7		16	.8	0	14	.1	5.4	.11	2.0	3.4	.17	3.6

*Field pH

Table 2. Trace element and silica analysis for selected samples

Site No.	Site	Date	B	Co	Cr	Cu	Ni --mg/l--	P	Pb	Si	Ti	Zn
3	Tributary	5-10-84	0.05	0.22	0.10	0.20	0.51	0.3	0.66	16	1.1	0.92
		6-13-85	.01	.07	.01	.03	.20	0	.20	3.5	.2	.36
5	Jacks Branch	4-12-84	.04	.04	.03	.00	.15	0	.43	3.7	.5	.05
		9-24-85	.03	.06	.04	.00	.12	.3	.33	3.3	.4	.17
6	Tributary	5-10-84	.05	.18	.08	.12	.40	.3	.61	8.3	.8	.63
		6-13-85	.08	.34	.10	.17	1.0	.4	.51	29	1.4	2.1
8	Tributary	4-12-84	.02	.01	.01	.00	.11	.4	.80	1.4	.8	.01
		11-8-85	.02	.02	.01	.00	.06	.1	.23	2.1	.4	.00
12	Tributary	5-10-84	.04	.10	.04	.13	.32	.1	.43	7.5	.6	.49
14	Tributary	6-13-85	.01	.02	.03	.00	.05	.1	.33	3.1	.4	.02
		11-8-85	.02	.00	.00	.00	.04	.0	.18	6.5	.2	.00
22	Jacks Branch (at gage)	5-10-84	.02	.07	.04	.05	.17	.0	.32	3.8	.4	.21
		11-12-85	.02	.02	.02	.00	.08	.8	.25	3.3	.3	.02
27	Highwall Spring	5-10-84	.27	.86	.31	.81	2.3	14	1.0	23	3.0	4.6
31	Spring	9-24-85	.08	.36	.05	.02	.53	.4	.48	18.7	.8	.80
34	Spring	11-8-85	.01	.02	.00	.01	.12	.0	.15	3.2	.2	.07
35	Tributary	5-10-84	.15	.78	.17	.63	1.7	5.1	.83	18	2.1	2.9
36	Jacks Branch (at highway)	5-10-84	.04	.25	.08	.17	.50	.7	.60	6.5	.9	.81
38	Board Tree Hollow	3-7-78	.00	.01	.02	.01	.01	.0	.00	3.3	.0	.00
		11-7-78	.00	.07	.10	.02	.04	.4	.07	3.9	.2	.00