Effect of Strip Mining on Water Quality in Small Streams in Eastern Kentucky, 1967-1975

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ABSTRACT

Eight years of streamflow data are analyzed to show the effects of strip mining on chemical quality of water in six first-order streams in Breathitt County, Kentucky. All these watersheds were unmined in August, 1967, but five have since been strip mined. The accumulated data from this case history study indicate that strip mining causes large increases in the concentrations of most major dissolved constituents in the runoff waters, the concentration of most of these reaching a maximum some time after mining has ceased, then holding steady for several years. The maximum concentration of dissolved salts occured during the low flow of the dormant season, whereas maximum salt loads occurred during the high flow of the early part of the growing season.

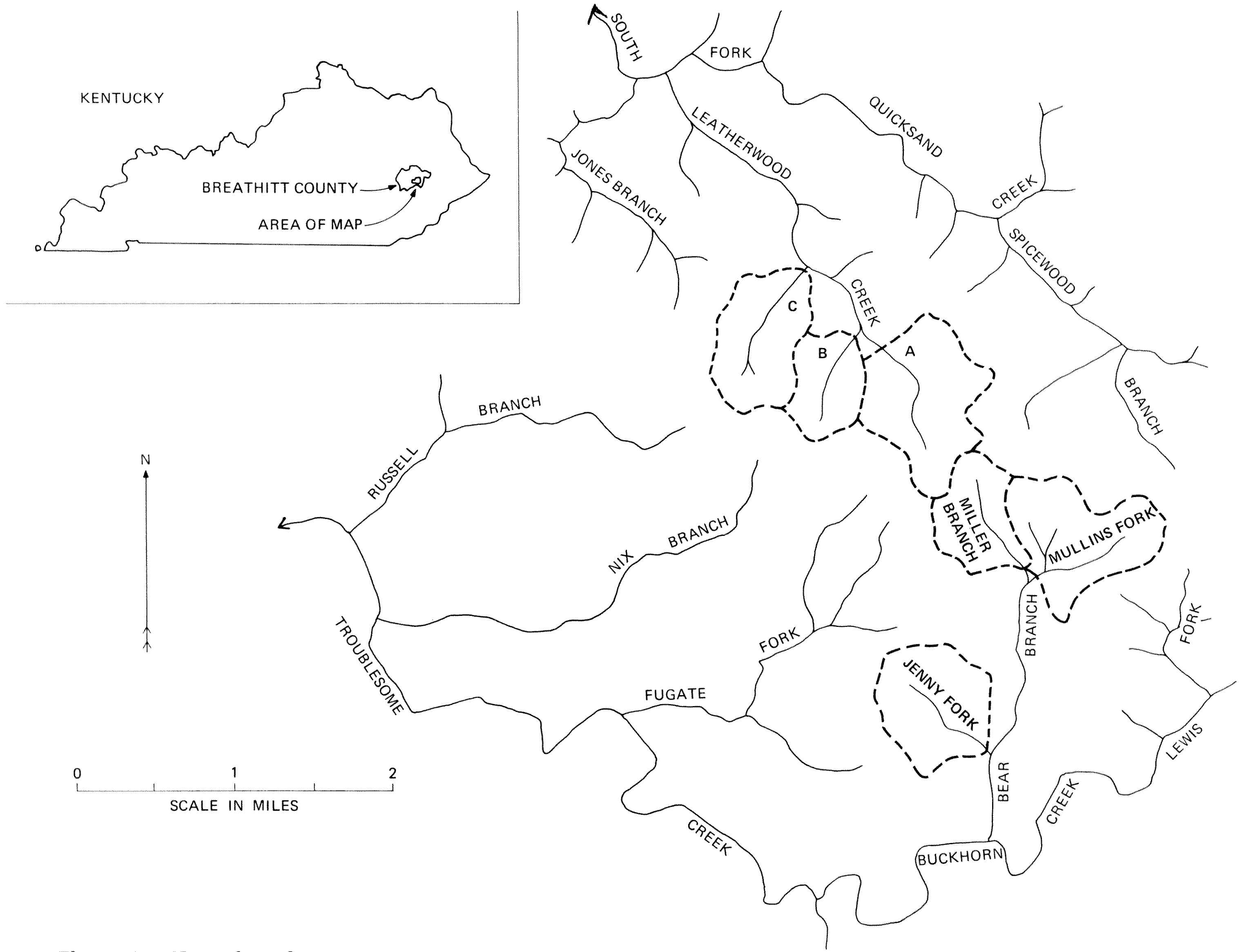

Figure 1.—Map of study area.

STREAM pH values increased from about 6.8 before mining to about 7.4 after strip mining. Acid is formed in the mine spoils of these watersheds, but it is neutralized by contact with spoil, soil, subsoil or aquifer materials before it can enter the streams. Other chemical parameters investigated include Ca, Mg, Na, K, Fe, Al, Mn, Zn, SO_4, Cl, HCO_3 and specific conductance. The salt concentrations and loads in streams draining mine spoils are largely dependent on (1) the rate of pyrite decomposition on the watershed, (2) the chemical nature of the spoil, soil, and aquifer materials contacted by the acid drainage water, and (3) the supply of water available for salt transport and the seasonal distribution of this supply of water.

REVIEW OF METHODS AND EARLIER OBSERVATIONS

Strip mining for coal in Appalachia can have a profound effect on the quality of water downstream from the mining operation. The same may be said of road building, or of any other activity in which large quantities of earth are moved. To evaluate the impact of strip mining on the environment, a case history study of six first-order watersheds ranging in size from 172 to 380 acres was initiated in 1967 (see figure 1 for location map). The three Leatherwood Creek watersheds are separated from the three Bear Branch watersheds by a narrow ridge. The watersheds are adjacent or nearly so and are similar in all respects except aspect; they range in elevation from 800 to 1,500 feet. Average stream slope is 4 percent and average slope of the land is about 30 percent. Three minable coal beds outcrop at altitudes of approximately 1,350, 1,380, and 1,420 feet. There had been a limited amount of deep mining on Miller Branch many years earlier, but any effects of this mining on water quality were not apparent at the beginning of this study in 1967. The area of each watershed and the percentage of it disturbed by mining at different times are given in table 1.

No mining is presently underway on any of the six watersheds. All the spoils have been smoothed and seeded and are now revegetated. There was apparently little attempt made to cover the entire spoil with material from any one stratum, as evidenced by the great variety in type and density of vegetation that now covers these spoils, as well as by the sharp transitions that separate the vegetation zones.

Data collected from the beginning of the study in November 1967 include stream discharge (continuous), precipitation (continuous), temparature, turbidity, specific conductance, pH, and concentrations of sediment, sulfate, bicarbonate, carbonate, calcium, magnesium, aluminum, manganese, zinc, iron, and copper. When no trace of copper was found over a 2-year

Table 1.—*Physical characteristics of the six watersheds*

Watershed	Acreage	Percentage of land disturbed on			
		4 Feb 1968	9 Oct 1969	20 Oct 1972	30 Oct 1975
Leatherwood Creek					
A	380	0	53	67	67
B	172	0	40	71	71
C	283	17	17	39	39
Bear Branch					
Jenny Fork	287	0	0	0	0
Miller Branch	190	0	29	55	55
Mullins Fork	327	0	7	46	46

period, tests for that element were discontinued. Tests for potassium were begun at that time and tests for chloride and sodium were begun in 1973. Water samples were collected weekly until the end of January 1972 in the Leatherwood Creek watersheds and until the end of October 1972 in the Bear Branch watersheds, after which samples were collected every 4 weeks in both watersheds. Samples were again collected weekly during the 1975 water year (Nov. 1, 1974 to Oct. 31, 1975) on the Bear Branch watersheds. Water quality data are still being collected from all six streams. It was necessary to abandon gages at all three Leatherwood Creek watersheds at the end of the 1971 water year, because a dam constructed downstream obstructed access to them. The three tributaries to Bear Branch (Jenny Fork, Miller Branch, and Mullins Fork) are still being gaged.

Contour strip mining was started on the Leatherwood C watershed on 15 August 1967 and on four other watersheds on or after 1 May 1968. Jenny Fork has still not been mined and serves as a reference or undisturbed watershed. At least 6 months of baseline data were collected on four of the watersheds before they were mined. Both contour stripping and mountaintop removal were used in four of the watersheds, but only contour stripping was used on Miller Branch. The period of active mining on the watersheds ranged from about 1 to 5-1/2 years.

Earlier work in these watersheds by Curtis *(1972a, 1973)* showed that mining increased the concentrations of sulfate, calcium, magnesium, aluminum, manganese, iron, and zinc in streams. He observed that the concentrations of some elements increased to a plateau immediately after the mining, whereas others continued to increase gradually for at least 2 years after mining had ceased. He noted that, although aluminum and manganese concentrations in stream water increased immediately after mining, they returned to normal within a year after mining had stopped. Curtis *(1974)* found that erosion and sedimentation in this area also increased sharply after strip mining, with about half the total sediment yield in the first 6 months. Erosion and sediment yield then declined quickly, having a half-life of about 6 months. Peak streamflow rates increased by a factor of 3 to 5 after surface mining *(Curtis 1972b)*. Branson and Batch *(1971)* studied the effect of mining on fish populations in these streams. They found that the siltation and turbidity associated with strip mining severely reduced the number of benthic food organisms and affected breeding, thus eliminating some species of fish from the affected streams and severly reducing the populations of others.

GEOLOGY

Detailed geologic maps of the Leatherwood Creek and Bear Branch watersheds are not available; however, much of the information published for the nearby Haddix quadrangle *(Mixon 1965)* should be applicable. It appears that the mountaintop removal and deep bench cuts at an altitude of approximately 1,400 feet mark areas in which coal has been mined from the Upper Knob coal zone. The line of strip mine benches or terraces, about 50 feet lower in elevation, probably marks the Lower Knob coal zone. Strata associated with the coal in these zones include sandstone, siltstone, shale, limestone, and underclay. Limestone was reported from only one location in the Haddix quadrangle; however, fragments of a similar gray limestone were observed by the authors in the mine spoil along the divide between Leatherwood Creek and Bear Branch.

WATER QUALITY

All water-quality and discharge data for each watershed have been summarized for the 1968 through 1975 water years and are presented in table 2. Except for pH values, these averages show mean concentrations for each year on a time basis. The pH values were computed from the mean annual hydrogen ion concentrations. The mean concentrations of dissolved solids are considerably higher than those that would have been found had they been calculated as discharge weighted averages, because most of the annual flow occurs in less than 10 percent of the time and is relatively low in dissolved solids. For sediment, the opposite relationship holds true: sediment concentrations generally increase at an even faster rate that does discharge.

To show seasonal changes and long-term trends graphically in each of the six watersheds, calcium, magnesium, sulfate, and bicarbonate concentrations in monthly water samples were plotted with the accompanying discharge data in figures 2 through 7. These first-order streams

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Table 2.—*Summary of annual water-quality and discharge data for individual watersheds, 1968-1975 water years*

Item	Water Year	Bear Branch			Leatherwood		
		Jenny	Miller	Mullins	A	B	C
Discharge	1968	--	--	--	25.8	27.9	24.7
(inches)	1969	11.2	12.6	9.7	11.3	11.7	12.4
	1970	17.6	24.2	16.6	28.2	31.1	19.3
	1971	27.0	35.2	26.5	24.5	32.3	24.4
	1972	34.3	--	31.5	--	--	--
	1973	25.0	23.4+	28.2	--	--	--
	1974	29.3	31.5	33.7	--	--	--
	1975	--	--	--	--	--	--
Turbidity	1968	28	17	37	82	114	147
(J.T.U.)	1969	26	15	100	160	177	45
	1970	19	255	202	127	185	44
	1971	25	466	76	125	179	36
	1972	16	888	205	395	265	31
	1973	11	69	111	128	361	17
	1974	9	45	190	107	112	33
	1975	18	188	125	316	239	5
Conductivity	1968	80	55	58	54	76	92
(micromhos/cm)	1968	80	65	79	100	177	138
	1970	83	145	131	224	250	203
	1971	62	245	102	298	294	385
	1972	85	235	156	297	495	424
	1973	78	317	319	381	664	525
	1974	72	318	424	404	947	568
	1975	73	298	438	388	759	550
pH[a]	1968	6.3	6.5	6.3	6.6	6.5	6.4
	1969	7.0	6.9	6.8	7.0	7.2	7.2
	1970	7.1	7.0	7.1	7.2	7.4	7.2
	1971	7.1	7.3	7.3	7.4	7.5	7.3
	1972	6.6	7.0	6.9	7.1	7.3	6.9
	1973	6.7	7.5	7.5	7.4	7.4	7.2
	1974	6.9	7.4	7.5	7.3	7.5	7.3
	1975	6.8	7.4	7.6	7.4	7.4	7.1
Sulfate	1968	11	7	6	10	11	21
	1969	14	6	7	11	34	33
	1970	15	32	14	81	68	88
	1971	12	77	12	98	81	160
	1972	23	66	17	95	165	169
	1973	16	81	49	125	252	213
	1974	11	79	91	135	426	258
	1975	17	78	103	137	392	251
Chloride	1973	4.4	4.5	4.3	4.6	5.1	5.3
(ppm)	1974	3.2	4.1	5.0	4.4	5.3	4.3
	1975	2.3	2.5	3.0	2.7	3.6	2.7
Bicarbonate	1968	22	18	22	15	23	17
(ppm)	1969	22	25	33	36	57	31
	1970	19	31	46	45	72	34
	1971	15	44	37	49	77	34
	1972	16	56	66	56	83	41
	1973	17	83	105	65	90	41
	1974	14	82	135	72	103	40
	1975	12	101	172	69	91	47
Calcium	1968	5.8	3.8	3.8	3.4	5.3	6.7
(ppm)	1969	6.1	4.7	5.1	6.6	14.0	10.4
	1970	6.5	10.2	8.9	15.5	21.6	13.4
	1971	4.8	19.9	7.3	24.4	31.3	48.5
	1972	6.2	17.4	11.1	23.3	49.6	47.1
	1973	5.3	29.7	27.7	37.0	79.9	67.2
	1974	3.5	26.8	34.7	35.2	117.7	70.4
	1975	4.5	31.2	46.0	38.8	106.2	68.7

continued

Table 2.—*continued*

Item	Water Year	Bear Branch			Leatherwood		
		Jenny	Miller	Mullins	A	B	C
Magnesium (ppm)	1968	3.0	2.2	2.3	2.2	2.8	3.5
	1969	3.5	2.8	4.2	4.7	8.2	5.3
	1970	3.5	7.5	7.5	12.9	12.2	8.1
	1971	2.8	15.9	6.1	19.5	16.2	14.7
	1972	3.3	12.7	8.1	16.4	23.4	14.5
	1973	3.3	17.3	16.6	20.5	34.6	22.7
	1974	2.0	17.3	25.4	22.7	57.7	25.8
	1975	2.6	21.0	33.9	25.7	52.2	30.8
Sodium (ppm)	1973	3.9	4.6	7.8	5.5	6.7	6.2
	1974	2.2	3.1	5.0	3.6	5.8	5.9
	1975	2.0	2.9	4.4	3.3	5.3	5.7
Potassium (ppm)	1970	4.0	7.4	5.3	7.0	6.2	4.9
	1971	2.1	4.2	2.9	4.4	3.7	3.3
	1972	2.4	4.1	3.7	4.5	4.5	3.6
	1973	2.8	4.1	4.9	4.4	4.6	4.3
	1974	1.8	3.8	5.7	4.1	5.1	3.4
	1975	1.5	4.0	5.1	3.2	4.0	3.0
Iron (ppm)	1968	.12	.11	.38	.26	.25	.68
	1969	.15	.17	.78	.46	.35	.18
	1970	.11	.67	.86	.36	.29	.12
	1971	.21	.39	.76	.27	.25	.21
	1972	.02	.16	.44	.08	.05	.01
	1973	.06	.10	.10	.01	.00	.01
	1974	.05	.11	.06	.02	.04	.01
	1975	.07	.04	.04	.03	.02	.02
Aluminum (ppm)	1968	.02	.01	.02	.21	.02	.03
	1969	.03	.03	.04	.44	.04	.03
	1970	.06	.08	.08	.06	.06	.05
	1971	.03	.04	.04	.04	.04	.03
	1972	.02	.03	.03	.03	.03	.02
	1973	.02	.02	.02	.02	.02	.02
	1974	.02	.01	.00	.02	.01	.01
	1975	.03	.03	.02	.01	.00	.00
Manganese (ppm)	1968	.01	.01	.05	.07	.10	.00
	1969	.00	.01	.06	.55	.34	.01
	1970	.01	.29	.26	1.03	.21	.02
	1971	.01	.17	.08	.74	.27	.00
	1972	.00	.42	.23	.49	.46	.13
	1973	.01	.44	.56	.43	.29	.11
	1974	.00	.26	.37	.26	.25	.13
	1975	.00	.16	.38	.18	.12	.12
Zinc (ppm)	1975	.01	.01	.01	.00	.01	.01

[a] The pH averages shown here were computed from the mean hydrogen ion concentrations that had been calculated from the measured pH values.

Figure 2.—Stream discharge and major dissolved ions, Jenny Fork watershed, 1968-1975 water years.

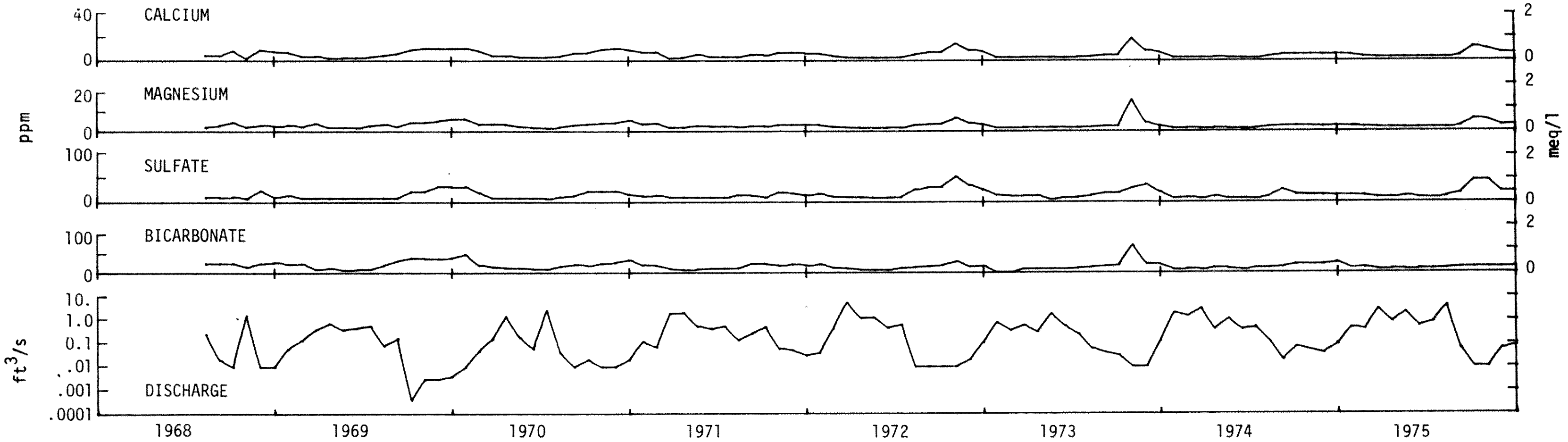


Figure 3.—Stream discharge and major dissolved ions, Miller Branch watershed, 1968-1975 water years. (shaded zones indicate periods of active mining)

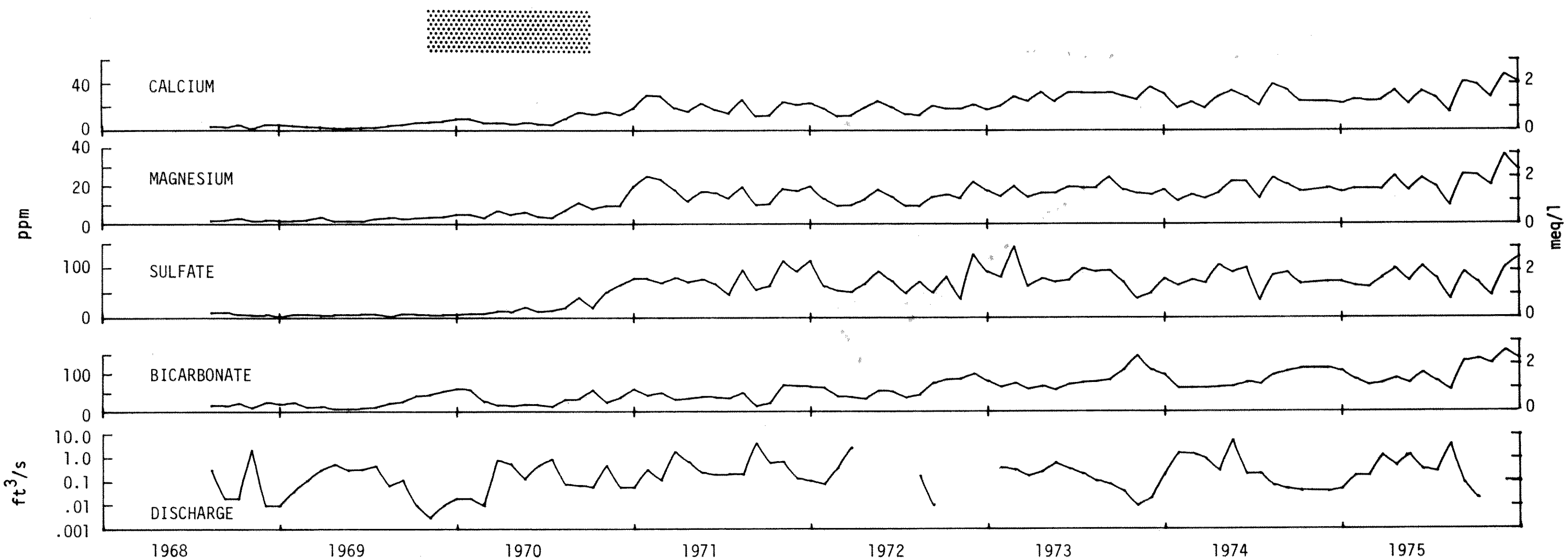


Figure 4.—Stream discharge and major dissolved ions, Mullins Fork watershed, 1968-1975 water years. (shaded zones indicate periods of active mining)

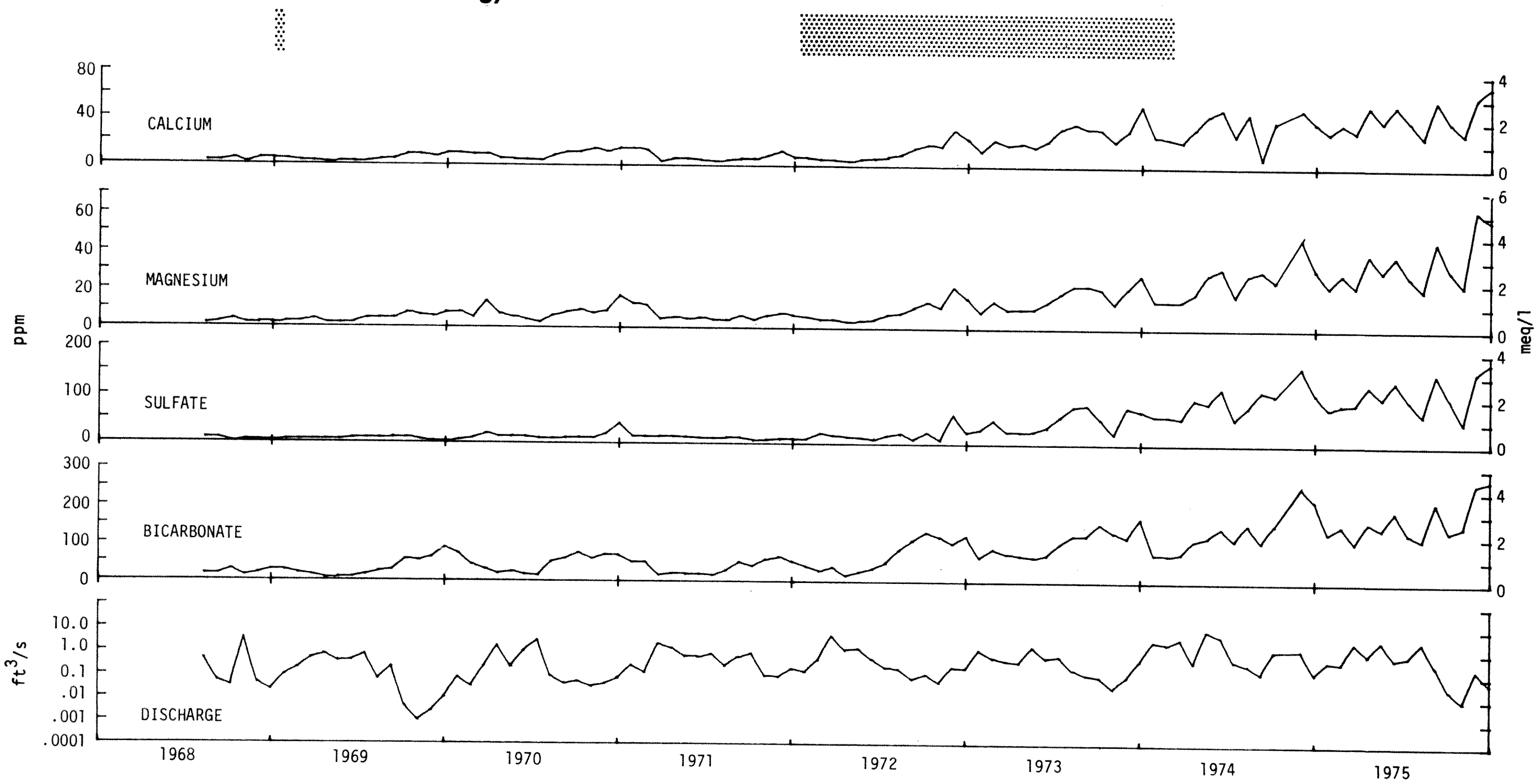


Figure 5.—Stream discharge and major dissolved ions, Leatherwood A watershed, 1968-1975 water years. (shaded zones indicate periods of active mining)

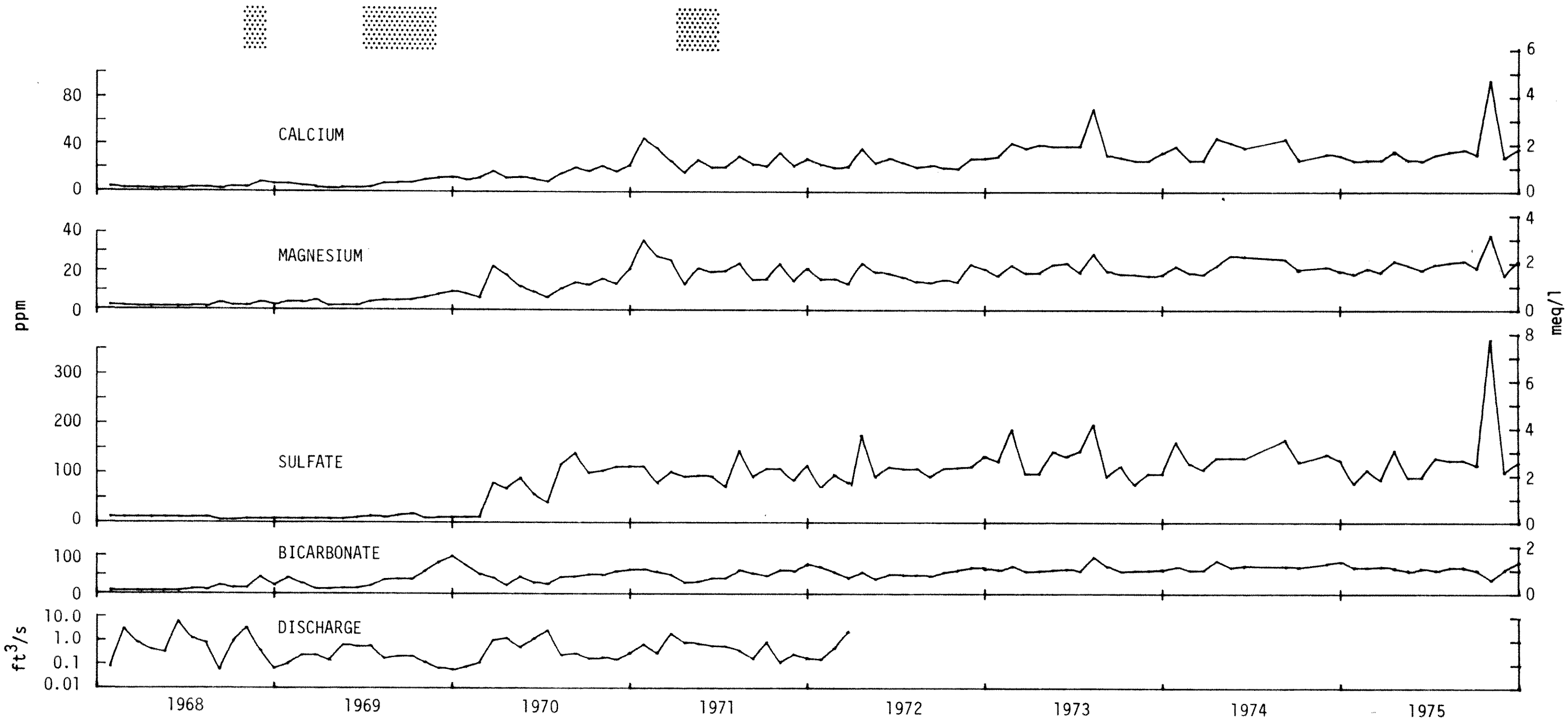


Figure 6.—Stream discharge and major dissolved ions, Leatherwood B watershed, 1968-1975 water years. (shaded zones indicate periods of active mining)

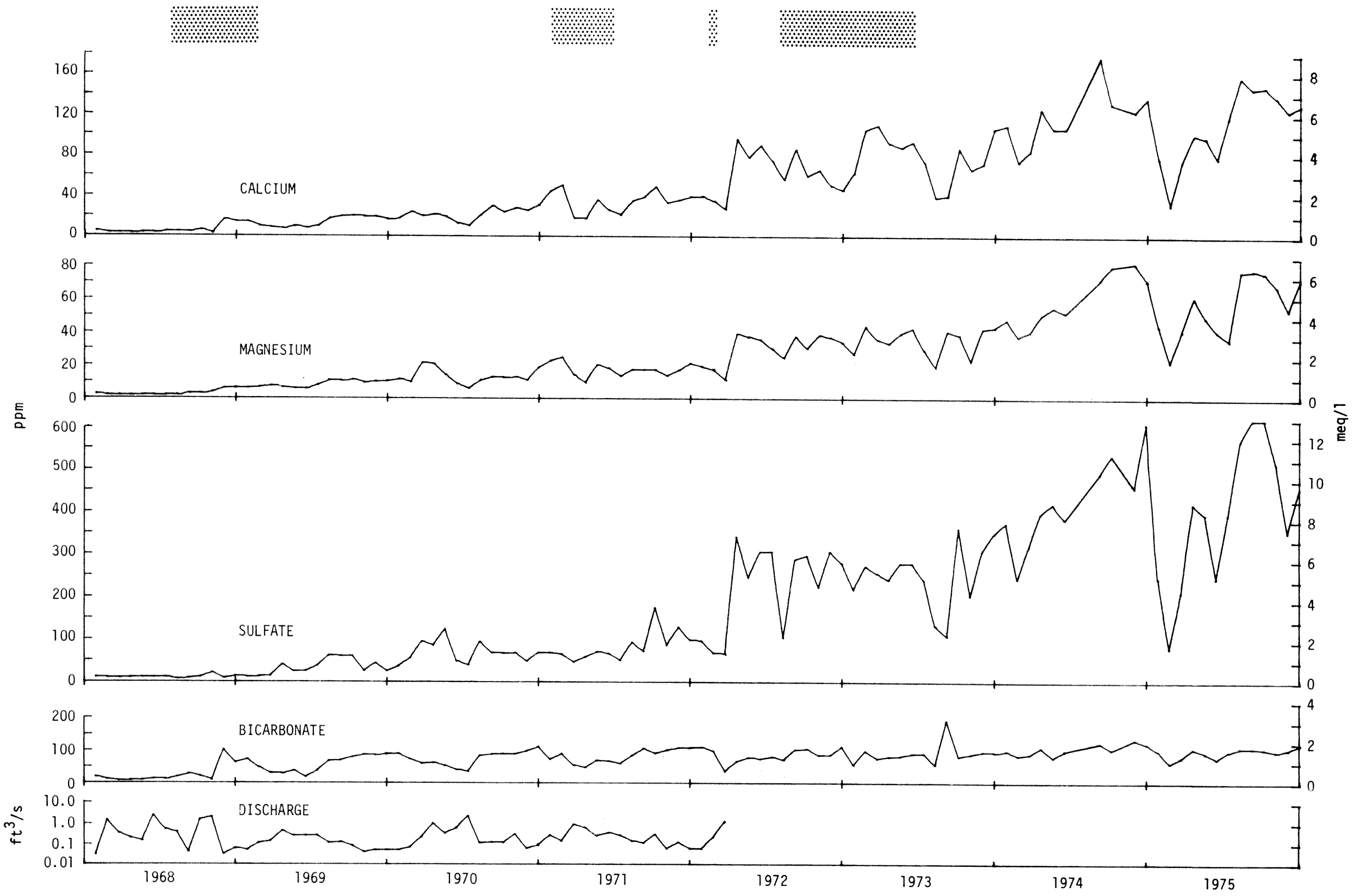
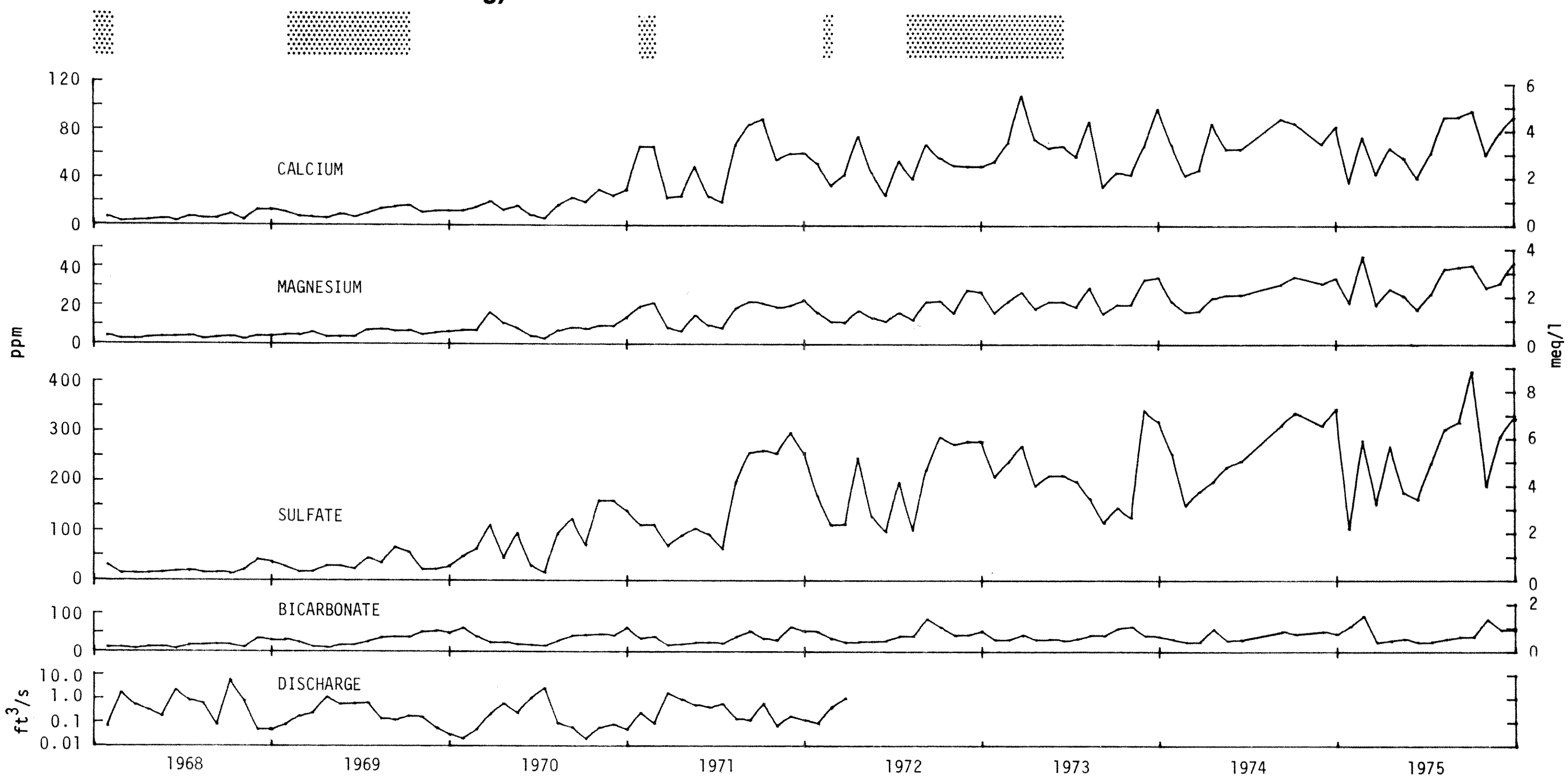


Figure 7.—Stream discharge and major dissolved ions, Leatherwood C watershed, 1968-1975 water years. (shaded zones indicate periods of active mining)



rise quickly in response to precipitation or smowmelt sufficient to cause runoff. The concentrations of most chemical constituents change almost as quickly in response to runoff events, but the changes in concentrations are of a lesser magnitude than are the changes in runoff. It is apparent from figures 2 through 7 that the concentrations of these four major constituents show approximately inverse relationships to the log of the discharge.

Salt loads were not calculated for inclusion in this paper, but in the cumulative data it is apparent that the highest total daily loads of dissolved constituents occurred during periods of high flow, when concentrations of these constituents were at or near their minimum levels.

pH AND ACIDITY

The summary of data in table 2 indicates that strip mining in the study area consistently caused an increase in the pH of stream water. In the 1973 through 1975 water years, Jenny Fork was slightly acid, with an average pH of 6.8, whereas the five mined watersheds were all slightly alkaline, with an average pH of 7.4. The maximum pH observed was 8.3 on 28 September 1975 in Mullins Branch; the minimum observed was 5.4 on 7 October 1968 in Leatherwood C. Both extremes occurred during low flow, 0.22 and 0.16 ft^3/s respectively.

Acid water is a common problem in mined areas. It develops as a byproduct of the oxidation of pyrite (ferrous sulfide) through the following overall reaction.

$$FeS_2(solid) + 3\tfrac{3}{4}O_2 + 3\tfrac{1}{2}H_2O \rightarrow 4H^+ + 2SO_4^{=} + Fe(OH)_3(solid) \quad [1]$$

Although large quantities of acid are produced in the mined portions of Leatherwood Creek and Bear Branch, it is quickly neutralized, apparently before it leaves the spoil material and before it enters the streams. This is common throughout much of Appalachia. Part of this neutralization occurs when acid ground water contacts carbonate minerals we know to be present in the overburden on the Bear Branch and Leatherwood Creek watersheds. Additional neutralization probably occurs when the hydrogen ion (acid) from the water replaces the exchangeable bases (calcium, magnesium, sodium, potassium, etc.) from the soils, spoils, and aquifer materials that it contacts.

SULFATE

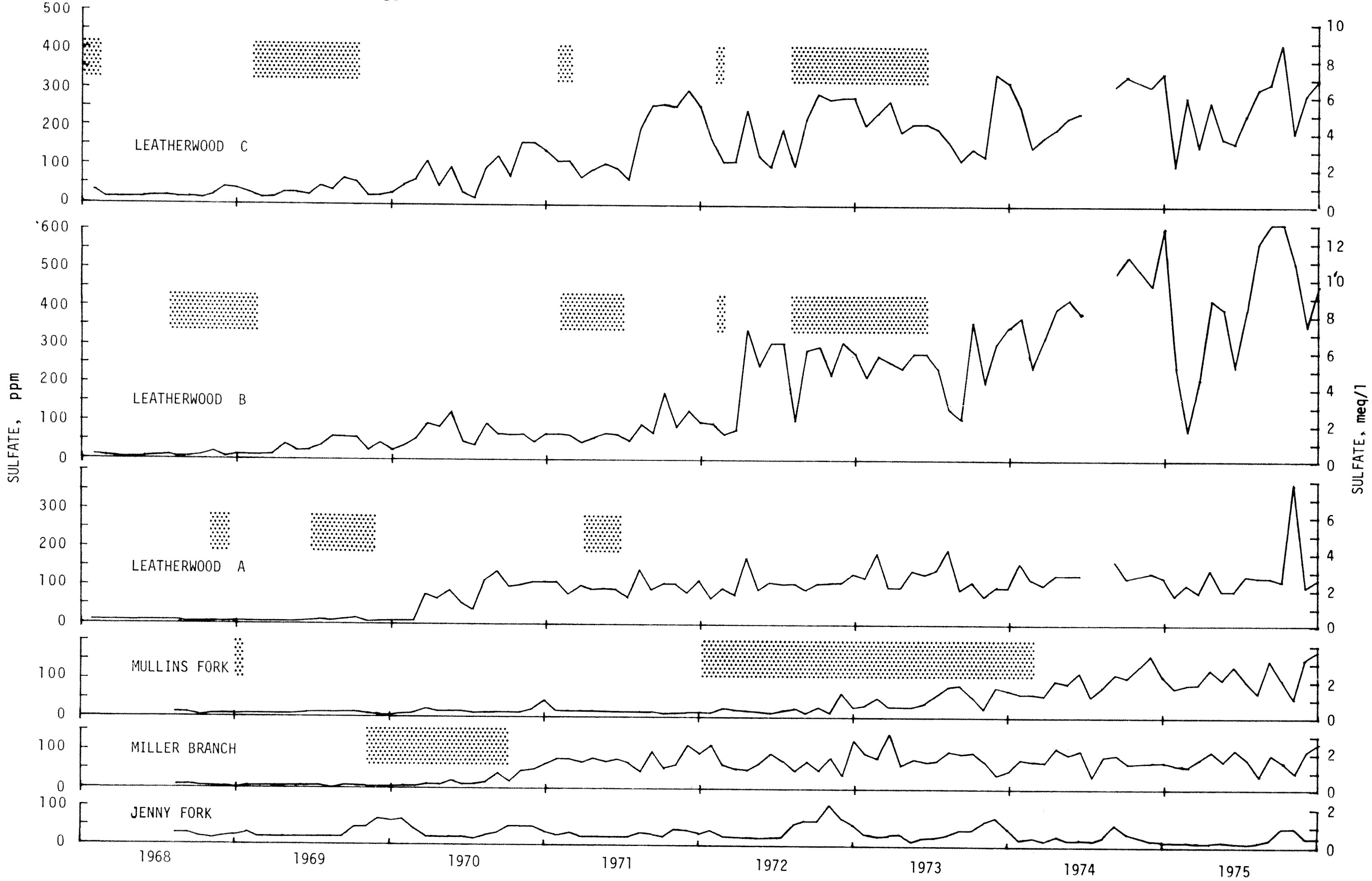
In the six small streams under investigation, sulfates show the greatest, though perhaps not the most immediate, response to mining and other earth-moving activities. Data from all six watersheds are graphically compared in figure 8. Before mining, the mean concentration of sulfates in these streams was generally less than 15 parts per million (ppm), but after mining the concentrations were generally in excess of 100 ppm. The sulfates observed in Jenny Fork and in the other streams before mining were contributed jointly by precipitation, dry atmospheric fallout, and natural geologic weathering processes. Aside from the small quantities of sulfates from the precipitation and atmospheric fallout, essentially all the sulfates observed in Appalachian streams originate from the dissolution of pyrite through the process described in equation 1.

As figure 8 shows, sulfate concentrations continue to increase after mining has ceased, sometimes for as long as 2 years. There are at least three reasons for this delay: (1) A certain amount of time is required for pyrite to oxidize once it has been exposed to the atmosphere and water; but once the reaction is underway, it should proceed at a fairly constant rate except for small seasonal variations caused by temperature differences. (2) Time is required for ground water to transport sulfates from the mine spoils to the streams. (3) Anion exchange with other anions in soil, spoil, and aquifer materials will delay transport of sulfate relative to movement of the water *(Thomas 1960; Yaalon 1964)*.

The continued presence of high levels of sulfate may possibly be explained by the following: If the initial oxidation of pyrite is extremely rapid, gypsum may precipitate from solution in the spoil banks, then redissolve when the oxidation of pyrite slows to the point at which the drainage water is no longer saturated with gypsum. This process allows a fairly steady level of sulfate to be maintained in the drainage waters from the time of mining until the gypsum has all dissolved.

Sulfate concentrations reached a maximum of 625 ppm in Leatherwood B, the most heavily

Figure 8.—Comparison of dissolved sulfate concentrations in six streams, 1968-1975 water years (shaded zones indicate periods of active mining).



mined watershed. Although this is more than twice the suggested maximum concentration (250 ppm) of sulfate in drinking water for humans *(U.S. Public Health Service 1962, p. 7)*, it is considered satisfactory for livestock or aquatic life *(McKee and Wolf 1963)*.

CHLORIDES

Chloride data were collected only for the 1973 through 1975 water years. From table 2, it is apparent that the chloride concentrations were very low in all six streams. Strip mining caused an increase in chloride concentration of approximately 1 ppm or less, a negligible increase.

BICARBONATES

The concentration of bicarbonates in stream water samples increased immediately after mining, approximately in proportion to the percentage of disturbed land on the watershed. Mullins Fork was exceptional in that, with a relatively small percentage of the land disturbed (41 percent), it still produced by far the largest concentrations of bicarbonate ion. The reason for this is not known, but it may be that a stratum of limestone or dolomite was uncovered in the Mullins Fork watershed that did not extend to the others, or there may have been a different arrangement of strata in the spoil material. Abnormally high concentrations of bicarbonate ion in stream water were sometimes noted immediately prior to mining on the watershed; these may have been due to natural variability or caused by road building or other, relatively minor, earth-moving activities.

CARBONATES

Carbonates were not detected in any stream water samples before or after mining. Unless the pH of the sample exceeds 8.3, measurable quantities of carbonate will not be present; in no case did the pH of the sample exceed 8.3.

CALCIUM AND MANGNESIUM

Calcium and magnesium together account for more than 90 percent of the dissolved cations (on a chemical equivalent basis) in waters from mined watersheds, but for only 70 percent of those in waters from unmined watersheds. Measured in terms of chemical equivalents, the concentrations of calcium and magnesium are roughly equal in the study watersheds, each being greater in some cases. The concentrations of both ions increase in response to strip-mining activities; much of this response is immediate, but some of it may be delayed for 2 years or longer. The immediate response is associated largely with the increase in bicarbonate concentration, whereas the delayed response accompanies an increase in sulfate concentration.

SODIUM AND POTASSIUM

Sodium and potassium together account for about 30 percent of the dissolved cations (on a chemical equivalent basis) in waters from unmined watersheds, but for only 10 percent or less of those in waters from mined watersheds. The concentrations of both ions in stream samples from mined watersheds are about twice those in samples from unmined watersheds; even so, this concentration does not significantly degrade the quality of the water.

IRON, ALUMINUM, MAGANESE, AND ZINC

All four cations are dissolved in low concentrations in stream water samples from both mined and unmined watersheds. With the possible exception of zinc, all seem to increase somewhat in concentration during and immediately after mining, then return to normal within about 1 year after cessation of mining. From 1968 through 1975 annual zinc concentrations averaged less than 1 ppm on all watersheds. Only the 1975 data are reported in table 2 because the atomic absorption unit used before that time is known to have erred on the high side in zinc determinations, probably because of an additive interference from other ions.

DISCUSSION

Rate of recovery

Once mining and other earth-moving disturbances have ceased on a watershed, the quality of water in the streams will gradually return to normal. For water chemistry, this is proving to be a very slow recovery in the watersheds under study. At the end of the 1975 water year, the Leatherwood A watershed had not been mined in more than 4-1/2 years and the Miller Branch watershed had not been mined in almost 5-1/2 years, yet it is apparent from figures 3 and 5 and table 2 that very little recovery had taken place. Other researchers have found faster recoveries in other mined areas. For example, Collier and others (*1970*, p. C21-C30) observed a quick decline in sulfate and dissolved solids loads in Cane Branch (McCreary County, Kentucky) in the first 1 or 2 years after strip mining had ceased, but found little additional recovery during the next 5 years.

Time of travel of dissolved constituents

The data in figures 3 through 8 show a lag of 6 to 12 months or longer between mining activity and a full response in stream-water chemistry to the mining.

Two of the reasons for this lag are (1) the time required for the oxidation and solution of pyritic minerals, and (2) the time required for transport of the dissolved spoil minerals. Nearly all the dissolved solids originating in the mine spoils of the watersheds under study must travel at length through soil and/or aquifer materials before they enter a stream. Gang and Langmuir (*1974*, p. 54) demonstrated that the major pollution sources on certain Pennsylvania streams were shallow ground-water discharges that drained mine spoils. There is every reason to believe that this is also true in the Leatherwood Creek and Bear Branch watersheds. It is during the period of travel as ground water that the acids produced by oxidation of pyritic materials are either neutralized by contract with limestone or other calcareous materials or else are replaced by exchangeable bases associated with spoil, soil, or aquifer materials.

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