Effects of Coal Mining on the Water Resources of the Tradewater River Basin, Kentucky

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1940

Prepared in cooperation with the Commonwealth of Kentucky, University of Kentucky, Kentucky Geological Survey

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By HAYES F. GRUBB *and* PAUL D. RYDER

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EFFECTS OF COAL MINING ON THE WATER RESOURCES OF THE TRADEWATER RIVER BASIN, KENTUCKY

By Hayes F. Grubb and Paul D. Ryder

ABSTRACT

The effects of coal-mine drainage on the water resources of the Tradewater River basin, in the Western Coal Field region of Kentucky, were evaluated (1) by synthesis and interpretation of 16 years of daily conductance data, 465 chemical analyses covering an 18-year period, 28 years of daily discharge data, and 14 years of daily suspended-sediment data from the Tradewater River at Olney and (2) by collection, synthesis, and interpretation of chemical and physical water-quality data and water-quantity data collected over a 2-year period from mined and nonmined sites in the basin.

Maximum observed values of 13 chemical and physical water-quality parameters were three to 300 times greater in the discharge from mined subbasins than in the discharge from nonmined subbasins. Potassium, chloride, and nitrate concentrations were not significantly different between mined and nonmined areas. Mean sulfate loads carried by the Tradewater River at Olney were about 75 percent greater for the period 1955–67 than for the period 1952–54. Suspended-sediment loads at Olney for the November–April storm-runoff periods generally vary in response to strip-mine coal production in the basin above Olney. Streamflow is maintained during extended dry periods in mined subbasins after streams in nonmined subbasins have ceased flowing.

Some possible methods of reducing the effects of mine drainage on the streams are considered in view of a geochemical model proposed by Ivan Barnes and F. E. Clarke. Use of low-flow-augmenting reservoirs and crushed limestone in streambeds in nonmined areas seems to be the most promising method for alleviating effects of mine drainage at the present time. Other aspects of the water resources such as variability of water quantity and water quality in the basin are discussed briefly.

INTRODUCTION

Coal mining has affected the streams in the Tradewater River basin in western Kentucky since the late 1800's. Oxidation of iron sulfide minerals in abandoned underground mines causes the formation of sulfuric acid; discharge of this mine water into streams leads to changes in water quality.

By the 1940's, surface mining of coal had become an important industry in the area. The disturbance of earth materials during surface coal-mining operations exposes iron sulfide compounds which increase dissolved solids in streams. In addition, the exposed materials become more easily eroded and sediment loads of streams are increased. The acidic conditions (low pH) along with increased dissolved solids and sediment loads have led to the destruction of fish and other aquatic life and have rendered the affected water undesirable for public, industrial, or domestic supplies. Coal-mining activities have also created such objectionable sights as spoil banks, treekills in bottom lands, red-tinted water in streams and ponds, and stream channels covered with red iron hydroxide.

This study was made to determine the effects of coal mining on the water resources of the Tradewater River basin. The study provides background data for future more intensive investigations and research regarding the causes and control of mine drainage in the basin.

The U.S. Geological Survey conducted this study as a part of the cooperative water-resources-investigation program with the Kentucky Geological Survey. A special note of acknowledgment is due J. E. Palmer and others in the Madisonville office of the U.S. Geological Survey, the Kentucky Geological Survey, and Tennessee Valley Authority for help with the geology of the area; P. H. Murdock of the Kentucky Water Pollution Control Commission, and R. J. Pickering of the U.S. Geological Survey for help in the early stages of water-data collection; and Douglas Griffin of the Division of Water, Kentucky Department of Natural Resources, for assistance in data synthesis and analysis. The cooperation of landowners and companies as exemplified by Ames Oil and Gas Company and Island Creek Coal Company is appreciated.

BASIN CHARACTERISTICS

The Tradewater River basin is in western Kentucky (fig. 1) and the river is the only major tributary to the Ohio River between the Cumberland River on the west and the Green River on the east. It occupies 943 square miles along the southwestern edge of the Western Coal Field in six Kentucky counties—Caldwell, Christian, Crittenden, Hopkins, Union, and Webster. The basin is approximately 52 miles long and is 32 miles wide between the towns of Marion on the west and Madisonville on the east.

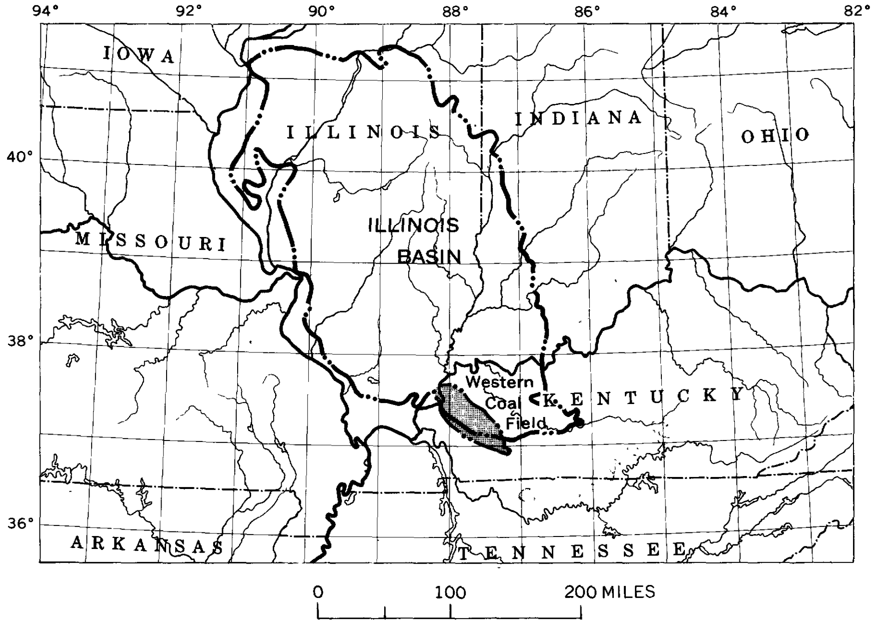

FIGURE 1.—Location of the Tradewater River basin (shaded) with respect to the Western Coal Field and the Illinois Basin. (Adapted from Atherton and others, 1960, fig. 1.)

TOPOGRAPHY AND STREAMS

Basin orientation is northwest-southeast, which is parallel to the western boundary between the Western Coal Field and the Mississippian Plateau (Lobeck, no date) physiographic regions. Approximately 77 percent of the basin is in the Western Coal Field, and the remaining 23 percent is in the Mississippian Plateau region. The basin rises from 320 feet above mean sea level at the pool stage of the Ohio River to 806 feet above mean sea level at the crest of the drainage divide about 5 miles northwest of Hopkinsville. The rugged mature topography west of the Tradewater River and in the southern part of the basin reflects the more resistant coarse-grained rocks of the upper part of the Chester Series and the Caseyville and Tradewater Formations. The effect of less resistant shales in the Tradewater, Carbondale, and Lisman Formations is expressed by the relatively flat upland which lies parallel to the Tradewater River from Madisonville to Sturgis in the northeastern part of the basin.

Sixty-seven percent of the area above the U.S. Geological Survey stream-gaging station at Olney lies below 560 feet above mean sea level (fig. 2), or less than 200 feet above the riverbed at the gage. The

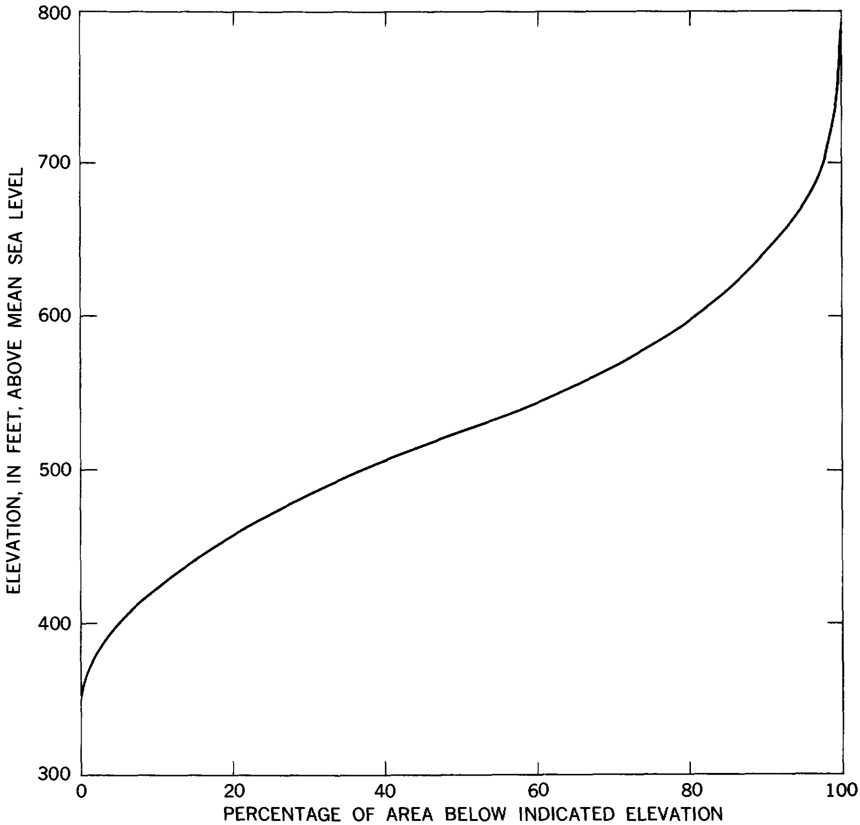

FIGURE 2.—Relationship of area and elevation for the Tradewater River basin above Olney.

average stream gradient of 0.6 foot per mile (fig. 3) from Olney to the Ohio River is the lowest for any major reach of the stream. This is about nine times less than the gradient of 5.4 feet per mile for the reach from Olney upstream to the river's source. Both stream gradient and the distribution of drainage area with respect to elevation are factors which determine the surface-runoff characteristics as they have been observed at Olney since 1941.

The relationship of important tributaries in the basin stream system can be seen on plate 1. Buffalo Creek and Cany Creek, which drain adjacent subbasins and enter the river downstream from Collins Bridge and upstream from Dawson Springs, originate in an intensively mined area on the eastern side of the river. Copperas Creek is a small tributary in the lower part of the Cany Creek subbasin. Piny

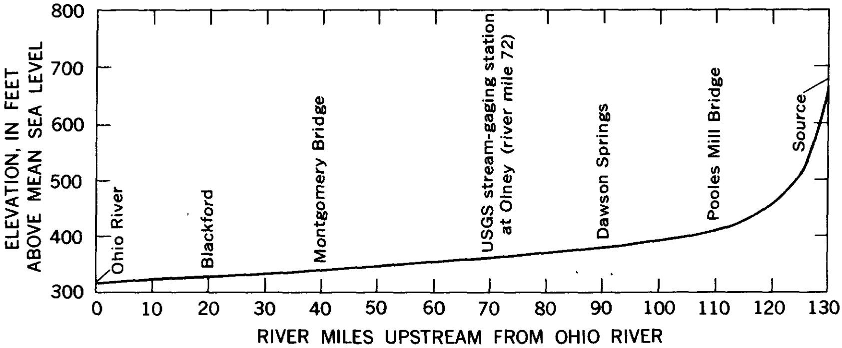

FIGURE 3.—Longitudinal profile of the Tradewater River.

Creek, which is partially regulated by Lake Beshear,[1] flows into the river from the west at Dawson Springs, about 3 miles downstream from Cany Creek. About 15 miles downstream from Piny Creek, the drainage from the Flynn Fork subbasin flows into the river from the west. The next important stream, Clear Creek, flows into the river from the east about 5 miles upstream from Providence and 34 miles downstream from Flynn Fork. Small headwater tributaries to Richland Creek are located in the southern section of the Clear Creek subbasin. Craborchard Creek flows into the river from the east through Vaughn Ditch about 34 miles downstream from Providence.

The rather flat uplands in the eastern section of the basin are drained by Clear Creek and Craborchard Creek. Geomorphologic and geologic conditions are important factors in the development of the extensive swamps and poor surface drainage conditions in these two subbasins. Much of the area in these two subbasins is low lying with respect to the altitude of base level, the Tradewater River. The two streams enter the Tradewater River below Olney where the river gradient is lowest. Area-elevation curves for the two streams indicate that 20 percent of the area in each subbasin is at an elevation less than 40 feet above the elevation of the river at the mouth of the stream.

The swampy conditions in the basin as seen along Craborchard, Clear, and Cany Creeks and near the mouths of other tributaries are attributed to the low relief in the basin and to the flat gradient of the Tradewater River, which serves as the local base level for these tributary streams. Earth materials are eroded from the upland and deposited in low-lying areas and in the stream channels in response to natural geologic processes. However, man's activities such as farming and mining may significantly increase the rate of erosion and sedimentation.

[1] Lake Beshear was constructed after the publishing of the base maps used on plate 1 and is not shown.

GEOLOGY

Consolidated sedimentary rocks of Late Mississippian and Pennsylvanian age are exposed in the Tradewater River basin. Figure 4 shows the outcrop pattern of Mississippian and Pennsylvanian rocks, major faults, and the extent of the area covered by this study. Formational contacts within the Pennsylvanian System are shown; these formations consist mostly of shale, siltstone, sandstone, and thin beds of coal and limestone. Undifferentiated Mississippian rocks, the upper part of the Chester Series, are shown along the western and southern parts of the area. These rocks consist mostly of marine limestone, shale, and sandstone. The general strike of the rocks is from northwest to southeast, and the dip is to the northeast. The outcrop pattern is offset in many places by major eastward-trending high-angle faults.

The generalized geologic column on plate 2 shows the range of thickness of the Pennsylvanian formations as they occur within the study area. Formational contacts and the positions of important coal and limestone beds are also shown. The Caseyville-Tradewater contact is transitional and is often placed arbitrarily on the basis of interval thickness. Formations within the Mississippian Chester Series are shown in the generalized column, but the Mississippian rocks are generally treated as a unit in the text of this report because the emphasis of the report is on mine drainage associated with Pennsylvanian coal beds.

Plate 1 shows the locations of drill holes used in constructing the geologic fence diagram shown on plate 2. Plate 2 covers an area of about 300 square miles that is important in the production of coal. The fence diagram was constructed mainly by using electrical logs of oil and gas test wells. The rocks shown in the diagram are mostly Pennsylvanian in age, and many of the logged sections are more than 1,000 feet thick. The fence diagram shows all major faults, most coal beds, mined-out coal beds (surface and underground), and gross lithologies of Pennsylvanian and Mississippian rocks as determined mainly by interpretation of electrical logs. Many lateral variations in lithology occur within the Pennsylvanian rocks. These lithologic changes are the result of the changing environments of deposition that occurred when the sediments were deposited. The coals were formed in swamp environments, as shown by abundant remains of fossil plants. Reducing conditions associated with swamp environments account for the presence of iron sulfide found in the coals and closely associated beds.

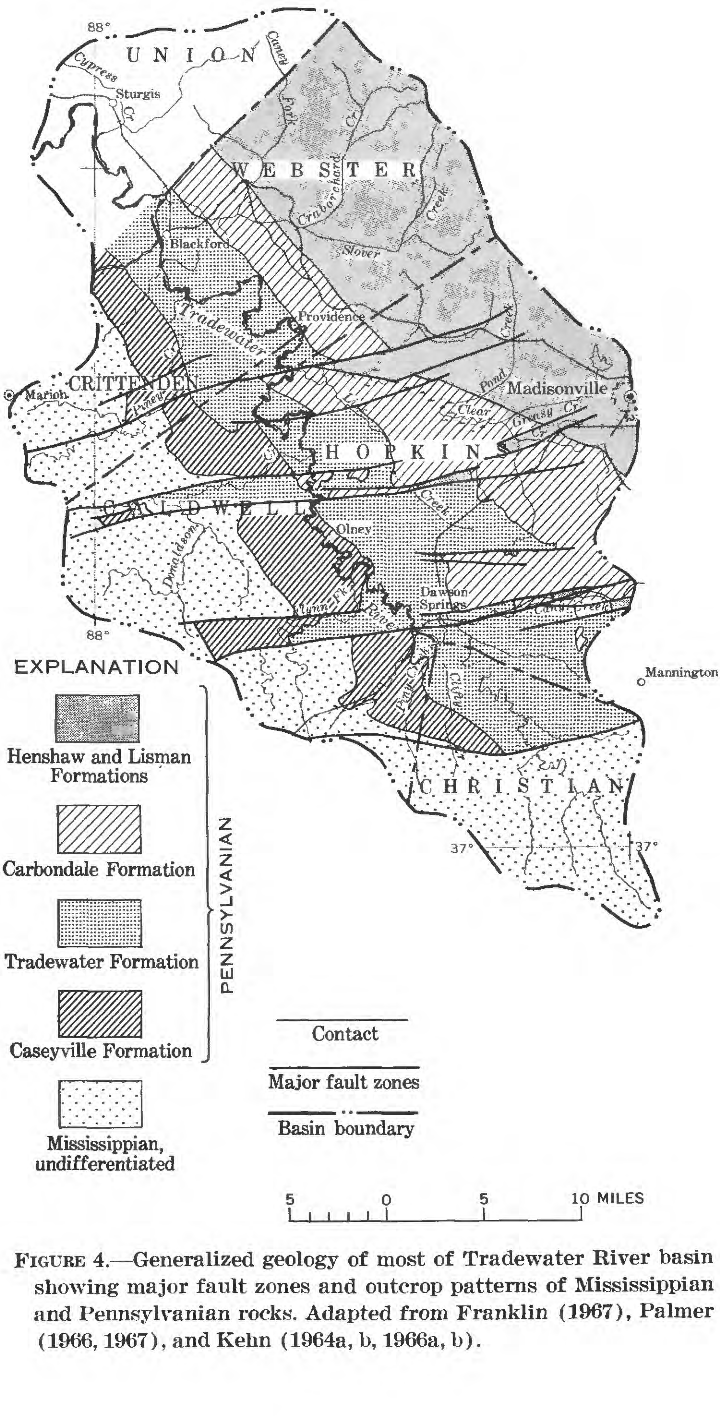

FIGURE 4.—Generalized geology of most of Tradewater River basin showing major fault zones and outcrop patterns of Mississippian and Pennsylvanian rocks. Adapted from Franklin (1967), Palmer (1966, 1967), and Kehn (1964a, b, 1966a, b).

The numerous changes in lithology have an important hydrologic significance. Sandstone aquifers present in one locality may change abruptly into shaly facies. The probability of locating a successful water well in a given area on the basis of existing wells is low, except where extensive sandstones are present in the Caseyville and Tradewater Formations. The fence diagram shows a relatively continuous body of sandstone or shaly sandstone in the Caseyville Formation; in places, a sandstone facies is also present in the lower part of the overlying Tradewater Formation. The sandstone has a maximum thickness of approximately 300 feet in the vicinity of the city of Providence in Webster County.

The changes in lithology also give rise to the highly variable quality of ground water that is the general rule in the Tradewater River basin. Ground-water quality is dependent mainly on the type of geologic materials and the length of time that the water is in contact with these materials.

The fence diagram shows how faults can add to the complexity of the hydrologic condition. Vertical movement along a fault may cause a sandstone aquifer to end abruptly at the fault and be in contact with an impervious rock, or such movement may cause aquifers in different geologic formations to be juxtaposed.

The preservation of minable coal beds in fault blocks has resulted in complex patterns of surface and underground mining. The diagram shows, in part, mined-out areas of various coal beds. The major coal-mining areas in the Tradewater River basin are shown in figure 5; both surface and underground mining areas are included.

Plate 2 shows rather wide thick alluvial deposits in the valleys of the Tradewater River and the major tributaries. In order to determine the approximate thickness and geologic character of the alluvium, 20 test holes were augered into the alluvium along the Tradewater River valley from near the city of Providence upstream to Pooles Mill Bridge, about 9 miles southeast of Dawson Springs. Six holes were augered into the alluvium near the mouths of six major tributaries to the Tradewater River.

The thickness of the alluvium in the auger holes ranges from 22 to 81 feet. Thicknesses average about 60 feet and decrease in an upstream direction. The alluvium, Quaternary in age, consists mostly of clay and silt and minor amounts of sand and gravel. The thickness of the sand and gravel ranges from 0 to 23 feet, and in all holes the sand and gravel deposits directly overlie bedrock. An exception to the thickness range was found in a hole drilled in the Tradewater Range alluvium

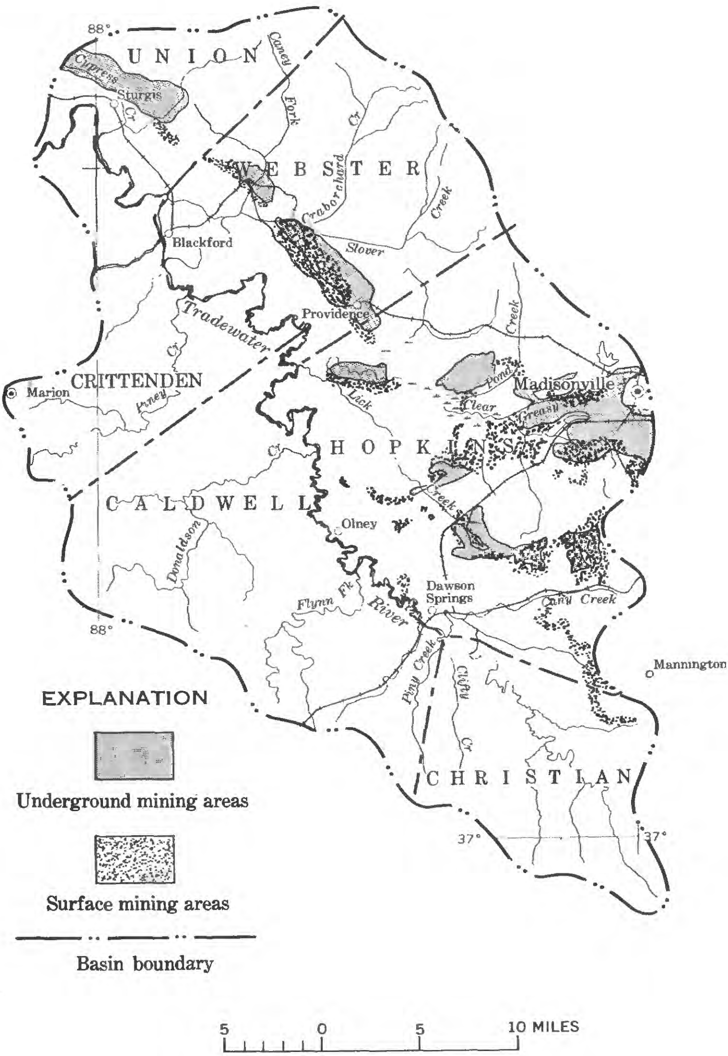

FIGURE 5.—Major coal-mining areas.

near the city of Providence; 55 feet of fine sand and a small amount of coarse gravel were logged in this hole.

No quantitative data on the water-yielding characteristics of the alluvium are available. However, the test drilling shows that saturated sand and gravel deposits are present locally and would probably yield sufficient water for domestic supplies. Water-yielding characteristics of bedrock aquifers and ground-water quality are discussed in the section entitled "Ground Water in Nonmined Areas."

CLIMATE

A wide range of variability is observed in both annual and monthly precipitation and temperature in the Tradewater River basin. This variability is not unexpected since the basin is in a geographic area characterized by mixing and rapid modification of both polar and tropical airmasses throughout the year. The mean monthly temperature for the coldest month (January) at Madisonville is 2.3°C (36.5°F). The greater part of the 44 inches of precipitation received annually over the basin (fig. 6) is produced by tropical airmasses associated with low-pressure systems which move over the area from the western Gulf of Mexico. Approximately 1 inch or less of the annual precipitation is in the form or snow.

The long-term irregularity of precipitation in the basin is illustrated in figure 7, which shows a difference between maximum and minimum annual precipitation of 32 inches at Madisonville, 34 inches at Princeton, and 38 inches at Earlington. No patterns were detected in these cyclic fluctuations which would suggest any long-term climatic change in the basin. However, a comparison of figures 6 and 8 indicates that the basin received from 2 to 4 inches less mean annual precipitation for the period 1951–66 than for the period 1931–52.

Based on data for the period 1951–66, the mean monthly precipitation at Madisonville for the months June–September is exceeded by potential evapotranspiration as estimated by Thornthwaite's method (Criddle, 1958). Potential evapotranspiration exceeds precipitation more than 80 percent of the time for the months of June, July, and August and more than 60 percent of the time for the month of September.

September and October are the driest months, January and March the wettest, on the basis of the long-term mean monthly precipitation (fig. 9). However, the driest and wettest months may vary from year to year as shown by the 1951–66 data for Madisonville. For this period, 4 other months have more precipitation than January. These variations in precipitation and evapotranspiration are major factors in the annual variations of both streamflow and the water levels in wells.

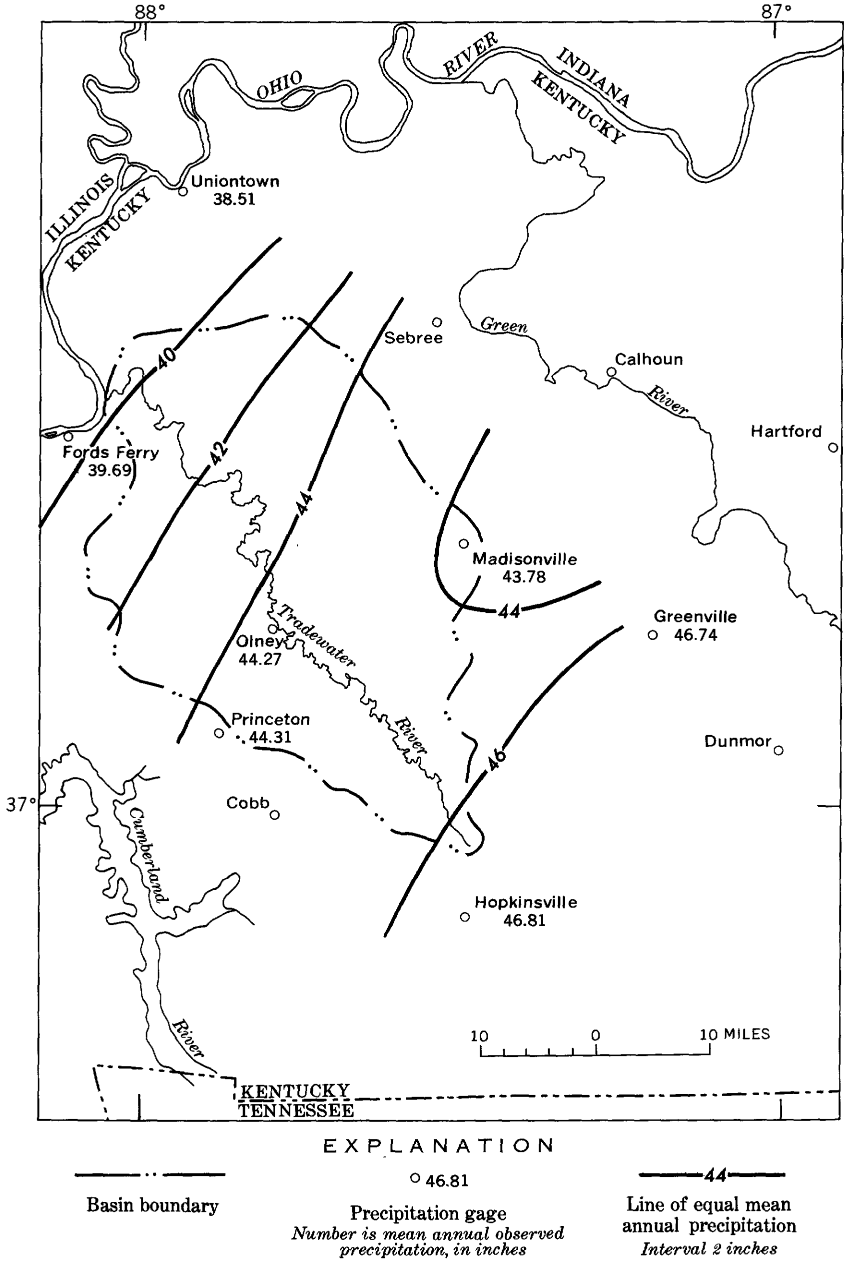

FIGURE 6.—Mean annual precipitation for the Tradewater River basin and vicinity. Based on U.S. Weather Bureau records for the years 1951–66.

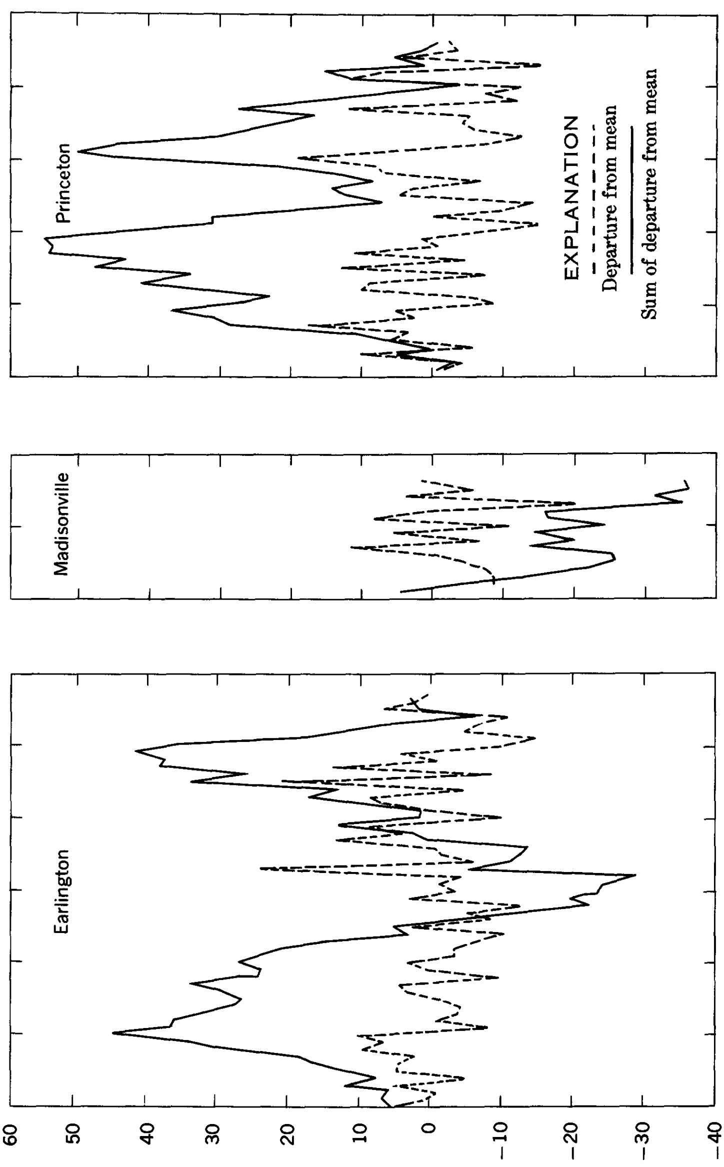

FIGURE 7.—Departure from mean and sum of departure from mean for precipitation at Earlington (1890–1947), Madisonville (1951–66), and Princeton (1921–66).

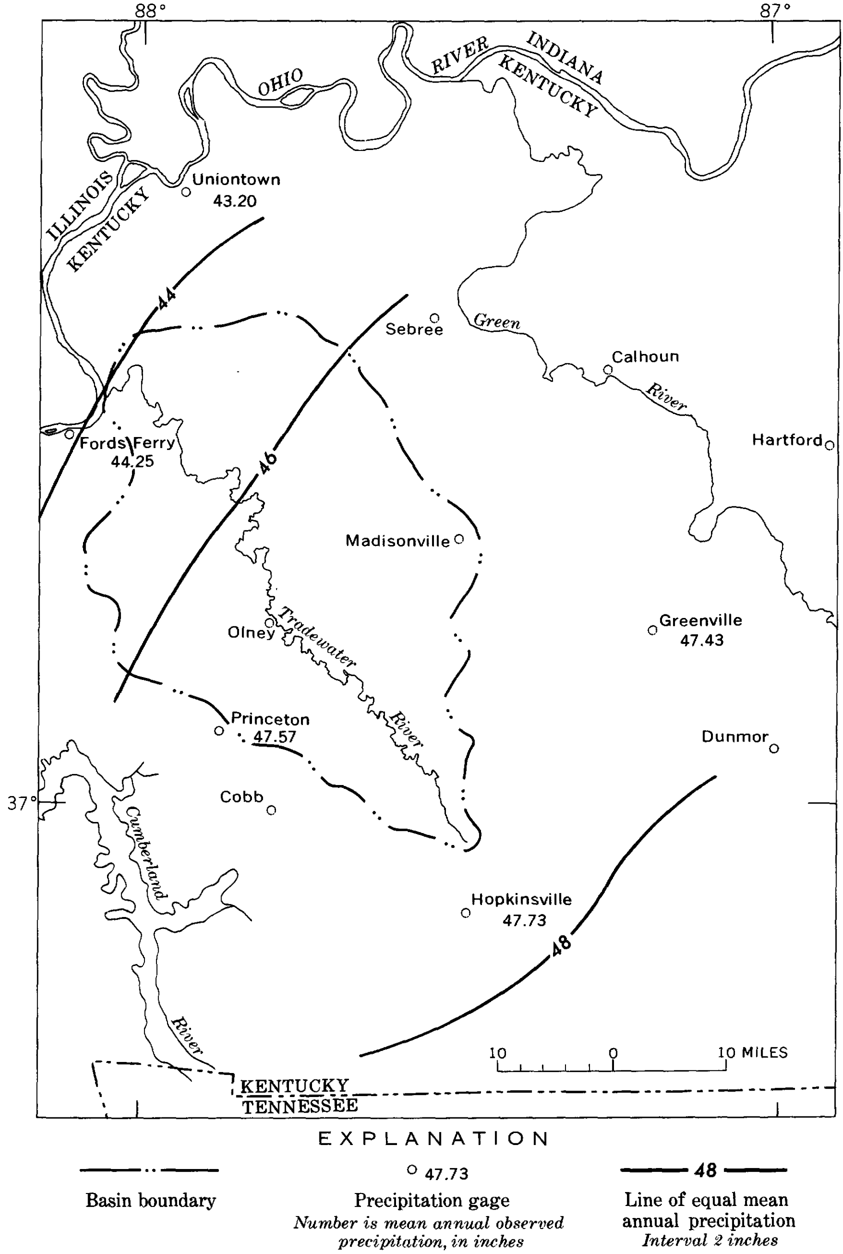

FIGURE 8.—Mean annual precipitation for the Tradewater River basin and vicinity. Based on U.S. Weather Bureau records for the years 1931–52.

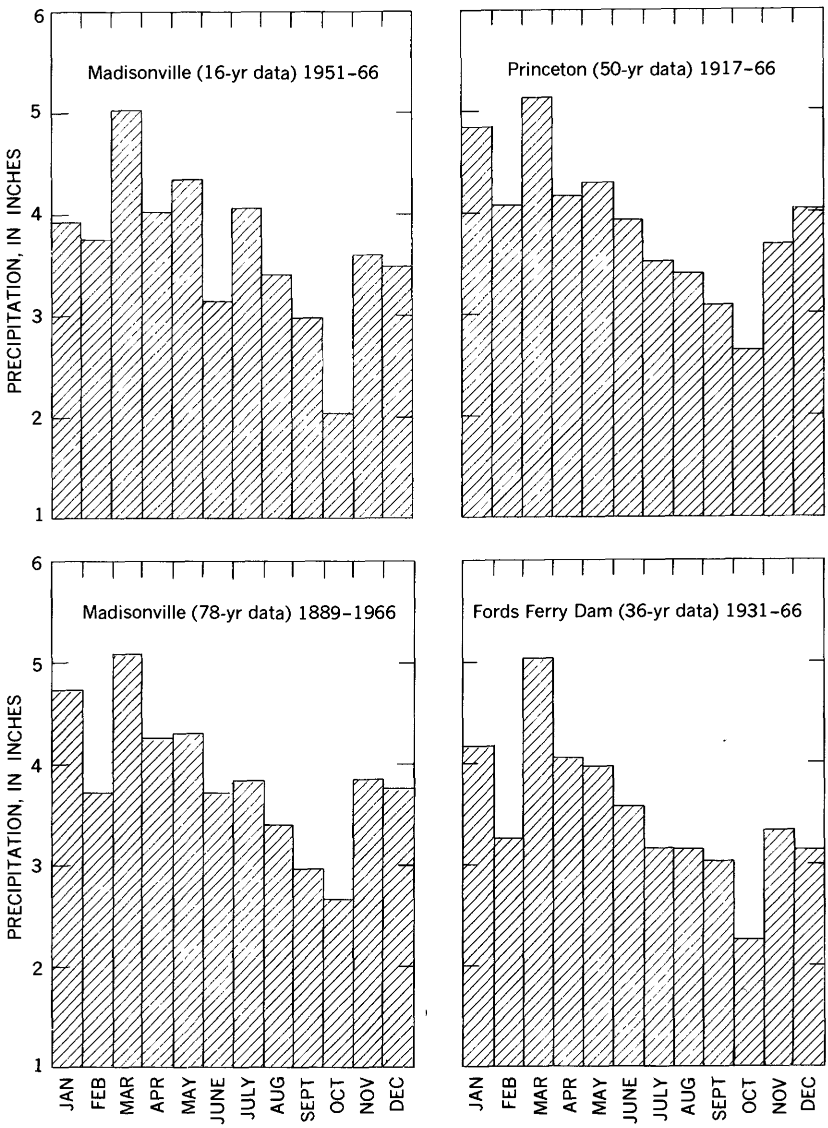

FIGURE 9.—Mean monthly precipitation for Madisonville, Princeton, and Fords Ferry Dam.

ECONOMY AND RESOURCES

The main elements of the economy of the Tradewater River basin are farming, coal mining, and oil and gas production. The chief farm products are corn, soybeans, tobacco, and livestock. In the southern and western parts of the basin, where the topography is rugged, farms are small and most of the crops are used for subsistence.

Bituminous coal is the most important of the mineral resources in the area and is discussed separately below. The petroleum industry was developed rapidly in the 1950's and still contributes substantially to the economy of the area. Hopkins, Webster, and Union Counties account for most of the petroleum production. Exploration for oil and gas in the Tradewater River basin is active at the present time (1969).

COAL

Coal has been mined in the Tradewater River basin for more than 95 years and is extremely important to the economy of the area. The important coal-producing counties in this area include Hopkins, Webster, and Union Counties. Data from the U.S. Bureau of Mines (1945–64) showed that total coal production in Hopkins County has exceeded 10 million tons per year for all years during the period 1950–64. The average yearly total tonnage for this period was 12.1 million tons; average yearly strip-mine tonnage was 4.8 million tons or about 40 percent of the total; average yearly underground-mine tonnage was 7.3 million tons or about 60 percent of the total.

During the period 1950–64 the number of men employed in the coal-mining industry in Hopkins County has varied from a high of 4,901 in 1950 to a low of 1,849 in 1964. The number of men employed in strip mining during the period has averaged about 21 percent of total mine employment; the number of men employed in underground mining has averaged about 79 percent of total mine employment in Hopkins County.

Approximately 17 square miles, or 1.8 percent of the total area of the Tradewater River basin, has been strip mined (see fig. 5). The important commercial coal beds in the basin have been the Nos. 4, 6, 9, 11, 12, 13, and 14. The No. 9 coal bed has been and is the most important coal in the basin because of its relatively good quality, greater thickness, and consistent presence. Analyses by the U.S. Bureau of Mines (1944) showed that the Nos. 9 and 11 coals have a relatively high sulfur content.

Large reserves of coal remain in the Tradewater River basin. Hodgson (1963) estimated coal reserves of more than one-half billion tons in a 410-square-mile area in the upper Tradewater River basin. Modern strip-mining equipment has made it possible to mine many areas in which mining with older equipment was considered marginal or uneconomical.

WATER

During the peak demand month of 1967, the average daily pumpage of water for public and industrial supplies in the Tradewater River basin was about 4.9 million gallons. Public supplies accounted for 63 percent of this total, and industrial supplies, 37 percent. Of the total, 18 percent was supplied by ground water; surface water, nearly all from lakes and reservoirs, furnished 82 percent. Public and industrial supplies included the municipal supplies for six cities in the area, a State hospital and school, a State park, three coal-washing operations, and a water-flooding operation for the secondary recovery of oil.

Other uses of water in the Tradewater River basin include individual domestic and stock supplies and recreation. Ground water furnishes most of the rural domestic supplies and part of the stock supplies. In many areas well yields are inadequate, and water must be hauled in by truck at relatively great expense. Lake Beshear and Pennyrile Lake, and Lake Barkley and Kentucky Lake outside the area. are the major lakes providing water for recreational needs.

Factors that will lead to the demand for more water in the Tradewater River basin are the following: The growth and expansion of towns, cities, and industries; the increased use of water flooding for secondary recovery of oil; and the possible development of supplemental irrigation systems. Development of additional ground-water supplies will be limited in most areas; however, a thick basal Pennsylvanian sandstone acquifer is present in some areas, and a further study of this aquifer system has been initiated by the U.S. Geological Survey. The use of streams for obtaining water supplies is limited because of the variable nature of the flow; most streams in the basin cease to flow during the dry periods of most years. Mine drainage in many parts of the basin presents serious quality problems. However, streams can be impounded above sources of mine drainage, and these reservoirs will be excellent sources for water supplies. Some strip-mine lakes, particularly those associated with the No. 14 coal in the Madisonville area, are potential sources of fresh-water supplies. Large pipelines could bring in water from sources outside the basin; the Green River and Lake Barkley are two such possible sources.

A recent study by the Federal Water Pollution Control Administration (1967) based on population increases and projected industrial activity forecasted that water use in the Tradewater River basin will double every 20 years and that by the year 2020 water use will be six times what it was in 1960.

PHYSICAL AND CHEMICAL CHARACTERISTICS OF WATER IN THE BASIN

GROUND WATER IN NONMINED AREAS

Most aquifers appear to be isolated and generally low yielding—less than 5 gpm (gallons per minute)—and can be defined only for very small areas. Great variation in the thickness and character of geologic units over short distances, numerous faults, and steeply dipping beds present a complex pattern of ground-water occurrence, movement, and quality. Maxwell and Devaul (1962) pointed out that the availability of water in bedrock aquifers of the Western Coal Field depends chiefly on the character, thickness, and depth of the aquifers penetrated and, to a limited extent, on topography. They show effects of depth by the percentage of wells in various depth ranges which yield greater than 500 gpd (gallons per day). For example, few wells (less than 35 percent) 25–75 feet deep yield more than 500 gpd while most wells (over 80 percent) greater than 150 feet deep yield more than 500 gpd. Maxwell and Devaul's discussion of occurrence and movement of ground water in the Western Coal Field generally applies to the Tradewater River basin. Variability in chemical quality in numerous wells is demonstrated by large changes in dissolved-solids concentration over horizontal distances as little as 30 feet. Available subsurface data indicate that some of these wells are open to the same geologic horizons. Examples of three such pairs of wells are given in table 1. Detailed lithologic and mineralogic information which might help to explain these variations in water quality is not available.

TABLE 1.—*Variation in dissolved solids of ground water with distance*

[Compared wells are finished in the same geologic horizon]

Well	Dissolved solids (mg/l)	Depth (feet)	Distance between wells (feet)
372558N0875330-1	335	56	30
372558N0875330-2	758	54	
372110N0873214	360	48	1,000
372107N0873211	3,440	44	
371332N0874629	220	31	2,500
371338N0874638	4,060	42	

Analysis of computer-produced areal plots—by geologic formation—of chemical constituents, physical and chemical ratios, and physical well characteristics revealed no consistent areal patterns of ground-water quality. Plate 1, which shows all wells in the Tradewater River basin for which specific-conductance values are available, illustrates the variability and randomness of ground-water quality in the basin. Table 2 lists the chemical analyses of samples collected from wells in the Tradewater River basin.

TABLE 2.—*Analyses of water from wells*

[Dissolved constituents and hardness in milligrams per liter except where indicated. Aquifer designation: series (1, Lower; 2, Middle; 3, Upper; and 6, Lower and Middle); last letters indicate formation (HE, Caseyville; CA, Caseyville; KI, Kinkaid; VI, Vienna; WL, Waltersburg; TS, Tar Springs; and SG, Department; 6, private laboratory; 8, other]

Latitude N.	Longitude W.	Depth (feet)	Aquifer	Date of collection	Temperature (° C)	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)
37°31′15″,	87°41′59″1	45	N3HE	1940			3	169	80		
37°31′11″,	87°42′ 4″1	55	N3HE	1940			2	180	109		
37°25′ 9″,	87°36′58″1	115	N3HL	8-24-67	15	22	.05	409	367	374	3.6
37°23′48″,	87°33′38″1	56	N3HL	5-23-67	16		1.3				
37°22′42″,	87°34′49″1	54	N3HL	8-24-67	16.5		.07				
37°22′10″,	87°38′40″2	230	N3	8-23-67	25	12	1.3	39	32	457	2.9
37°28′26″,	87°48′33″1	250	N3LI	10-17-58	14.5	33	1.3	67	24	39	1.6
37°28′11″,	87°48′50″1	112	N3LI	10-27-55			18	45	26		
37°28′ 2″,	87°48′55″1	102	N3LI	12- 3-52	14.5		2.0				
37°33′46″,	87°58′35″1	130	N3LI	2-17-53	13		1.3				
37°33′28″,	87°53′25″1	65	N3LI	2-17-53	11.5	10	.64	62	49	26	1.3
37°22′55″,	87°38′31″1	280	N3LI	2-17-53	16.5		.18				
37°22′53″,	87°39′18″1	315	N3LI	6- 7-67	15.5	13	.05	24	3.4	292	2.6
37°22′44″,	87°38′35″1	171	N3LI	10-25-66	18.5		.63			495	
37°21′39″,	87°34′34″1	43	N3LI	3- 8-54		21	6.9	112	61	200	4.1
37°20′54″,	87°43′41″1	47	N3LI	8-23-67	17	21	.76	17	11	47	1.3
37°20′45″,	87°35′ 1″1	156	N3LI	8-24-66	17		3.1				
37°12′43″,	87°37′ 3″1[1]		N3LI	11-26-58	15	37	121	456	234	38	9.3
37°29′30″,	87°54′52″1	165	N2CB	7-13-67	24.5	20	9.7	377	255	121	7.7
37°23′56″,	87°45′25″1[1]	105	N2CB	3-14-58	19.5	18	13	319	287	1,080	17
37°30′27″,	88° 0′38″1	72	N2CB	2-17-53	15.5	12	.45	112	73	28	3.2
37°19′46″,	87°42′37″1	96	N2CB	8-22-67	20.5	20	.80	79	50	131	2.2
37°19′37″,	87°32′53″1[1]	134	N2CB	6- 7-67	15	33	48	556	370	180	12
37°17′21″,	87°41′31″1	76	N2CB	2-14-67	14.5	12	1.0	270	462	166	4.7
37°16′27″,	87°35′32″1	136	N2CB	8-27-66	15.5		.00				
37°12′58″,	87°34′23″1	194	N2CB	7-26-66	19	100	.05	4.1	6.2	18	.8
37°11′42″,	87°36′48″1	115	N2CB	7-23-66	16	24	8.0	101	63	61	1.8
37°11′35″,	87°36′53″1	160	N2CB	7-28-66	20	11	.04	21	16	263	1.3
37°13′ 6″,	87°37′14″1	90	N2TR	7- 7-66	25.5		.06				
37°21′53″,	87°49′35″1	62	N2TR	5-18-67		40	.05	81	33	37	1.0
37°13′16″,	87°40′22″1	400	N2TR	2-17-53	16.5		.12				
37°25′58″,	87°53′30″2	54	N2TR	6- 6-67	14.5	26	.08	89	58	59	4.4
37°21′ 5″,	87°47′44″1	40	N2TR	5-18-67	21	23	8.2	31	8.1	8.2	12
37°18′ 7″,	87°47′26″1	140	N2TR	5-19-67	25.5	14	.08	7.9	.8	652	2.2
37°17′56″,	87°45′54″1	153	N2TR	2-17-53	16.5		.18				
37°16′22″,	87°36′33″1	182	N2TR	8-21-66	17	23	.10	107	36	113	1.9
37°16′20″,	87°36′39″1	150	N2TR	8-24-66	18.5	36	.20	118	45	142	4.1
37°16′ 6″,	87°35′50″1	250	N2TR	10-27-66	16	27	.23	19	8.0	213	1.7
37°16′ 2″,	87°36′25″1	191	N2TR	9-15-65	18		.10	14	6.0		
37°15′34″,	87°41′ 1″1	124	N2TR	9- 5-52	16	12	.06	2.2	.6	200	1.3
37°14′28″,	87°33′47″1	244	N2TR	7-27-66	20	15	.12	188	112	106	9.0
37°13′ 7″,	87°39′55″2	55	N2TR	12- 2-58	14.5		5.0				
37°11′16″,	87°35′19″1	461	N2TR	7-29-66	20		.01				
37°10′59″,	87°33′31″1	100	N2TR	2-17-53	15.5		.24				
37°10′43″,	87°37′ 5″1	260	N2TR	7-19-66	20.5	22	.06	21	11	264	2.1
37°10′38″,	87°40′41″1[1]	110	N2TR	12- 2-58	15	31	21	175	94	145	6.4
37° 9′46″,	87°32′23″1	462	N2TR	7-29-66	23.5	13	.07	4.0	.3	580	1.8
37°20′ 0″,	87°53′50″1	57	N2TR	4-12-67	15.5		.06				
37°19′59″,	87°52′55″1	57	N2TR	4-12-67	15.5	33	.31	6.7	6.0	13	.3
37° 9′30″,	87°40′53″1	249	N1CA	11-14-51	15	11	4.4	16	7.3	14	2.2
37°13′38″,	87°46′38″1	42	N1CA	8-24-66	16.5	14	.03	341	311	436	7.4
37° 9′30″,	87°40′51″1	240	N1CA	1- 3-55		9.4	4.2	16	6.4	13	2.2
37° 8′23″,	87°39′39″1	418	N1CA	9-27-66	15	8.7	5.4	16	8.3	5.9	1.0
37°19′37″,	87°55′25″1	61	N1CA	4-12-67	15.5						
37°18′36″,	87°56′30″1	19	N1CA	3- 3-55	10.5		7.1				
37°18′51″,	87°53′35″1	163	N1CA	4-12-67	14	16	.54	20	12	11	1.1
37°17′31″,	87°50′ 8″1	100	N1CA	5-19-67	15.5	10	.01	36	8.3	74	2.4
37°14′19″,	87°49′51″1	40	N1CA	3- 3-55	16		.80				
37° 8′58″,	87°52′25″1	112	N1CA	10-27-66	15	18	.15	32	10	33	2.3
37° 5′51″,	87°30′26″1	120	N6TC	6-17-66	22		2.3				

See footnotes at end of table.

in the Tradewater River basin

First letter indicates geologic system (N, Pennsylvanian; M, Mississippian); numeral indicates geologic
Henshaw; HL, Henshaw-Lisman; LI, Lisman; CB, Carbondale; TR, Tradewater; TC, Tradewater-
Ste. Genevieve). Analyst codes: 1, U.S. Geological Survey; 3, Commonwealth of Kentucky Health

Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids: Calculated	Dissolved solids: Evaporated at 180° C	Hardness as $CaCO_3$: Calcium, magnesium	Hardness as $CaCO_3$: Noncarbonate	Specific conductance (micromhos at 25° C)	pH	Analyst
385	--	428	25	--	--	1,160	--	750	365	--	--	8
500	--	554	36	--	--	1,485	--	950	450	--	--	8
185	0	2,570	298	0.3	5.5	4,140	4,600	2,530	2,380	4,710	6.7	1
428	0	288	13	--	2.0	--	810	500	149	1,180	7.4	1
498	0	443	23	--	4.5	--	1,130	620	212	1,560	7.3	1
1,040	0	352	34	3.2	.3	1,440	1,430	229	0	2,110	8.0	1
370	0	11	22	.1	.6	382	378	266	0	629	7.0	1
269	--	15	150	.0	--	450	--	218	7	--	7.6	3
358	--	124	39	.1	.8	--	--	398	--	906	--	1
638	--	26	8.5	.6	5.1	--	--	230	--	968	--	1
468	0	15	7.0	.3	.6	384	--	356	--	702	6.8	1
1,156	20	52	128	3.0	.1	--	--	93	--	2,120	--	1
660	0	131	19	.4	2.0	811	840	74	0	1,310	8.0	1
1,170	30	2.8	66	5.0	.1	--	1,160	18	0	1,880	8.4	1
632	0	372	21	.1	4.8	1,107	1,077	530	12	1,580	7.0	1
42	0	71	26	.1	56	272	272	88	53	424	6.5	1
638	0	325	184	.3	220	--	1,460	878	352	2,260	7.5	1
0	0	2,260	5.0	6.3	1.4	3,180	3,230	2,100	2,100	3,500	2.80	1
275	0	1,800	76	.6	1.2	2,800	3,060	1,990	1,770	3,190	6.6	1
705	0	3,550	37	1.1	7.4	5,800	5,980	1,980	1,400	6,350	6.6	1
508	0	156	42	.2	21	702	--	580	--	1,120	7.0	1
200	0	400	60	.3	30	871	952	403	239	1,360	6.8	1
0	0	3,470	10	.5	19	4,720	5,240	2,910	2,910	4,790	3.6	1
14	0	2,760	66	2.1	.9	3,760	4,120	2,580	2,560	4,010	5.1	1
282	0	122	18	--	12	--	482	118	0	750	7.7	1
2	0	62	12	.1	2.8	213	--	36	34	203	5.0	1
178	0	465	16	.5	1.4	832	816	512	365	1,130	6.8	1
644	2	138	9.0	3.2	.2	782	776	119	0	1,240	8.3	1
32	0	48	4.0	--	.5	--	118	60	34	171	6.4	1
28	0	250	42	.1	100	598	624	338	315	879	6.2	1
747	18	25	10	1.2	.0	--	--	14	--	714	--	1
146	0	343	45	.2	44	741	758	461	341	1,080	6.9	1
0	0	136	5.0	.2	.8	234	228	111	111	344	4.6	1
710	0	214	440	1.3	.2	1,680	1,720	23	--	2,840	8.5	1
456	26	16	12	1.2	.1	--	--	17	--	798	--	1
288	0	380	23	.2	15	841	862	415	179	1,230	7.9	1
324	0	470	34	.6	19	1,030	1,030	480	214	1,440	7.8	1
515	0	37	86	.8	.1	646	640	80	0	1,100	7.8	1
288	3	64	7.0	--	--	--	--	62	--	--	7.6	6
511	0	1.2	9.0	1.5	.0	480	477	8	0	782	7.2	1
328	0	872	12	.2	.5	1,480	1,570	930	661	1,940	7.1	1
142	0	64	3.2	.1	.3	--	--	154	38	380	7.8	1
1,210	1,000	2.8	164	4.2	1.8	--	1,520	12	0	2,560	9.0	1
386	--	30	10	.3	.1	--	--	105	--	649	--	1
614	0	127	16	2.1	.2	768	736	98	0	1,220	7.9	1
0	0	1,280	15	.5	2.5	1,750	1,750	824	824	2,670	2.70	1
1,400	5	1.2	71	3.4	.1	1,370	1,340	11	0	2,190	8.3	1
20	0	85	8.0	--	3.8	--	190	74	58	260	6.3	1
30	0	36	7.0	.2	.2	118	118	41	16	158	5.8	1
92	0	18	5.0	.2	.1	124	112	70	0	200	6.5	1
520	0	2,160	258	.5	1.5	3,780	4,060	2,130	1,700	4,510	7.2	1
98	0	14	3.0	.1	1.0	168	--	--	--	194	7.2	1
66	0	31	4.5	.3	.1	114	128	74	20	184	6.4	1
388	0	104	22	--	.6	528	--	396	78	820	7.0	1
60	0	17	4.0	.1	.6	--	--	67	18	146	6.7	1
50	0	69	11	.1	.9	166	166	100	58	282	6.0	1
298	0	35	8.0	.8	.5	321	328	124	0	548	7.9	1
54	0	28	52	.2	167	--	--	250	206	678	6.8	1
32	0	17	58	.1	85	272	284	121	95	450	6.2	1
540	0	862	45	.0	.6	--	1,760	1,240	797	2,140	7.1	1

TABLE 2.—*Analyses of water from wells in*

Latitude N.	Longitude W.	Depth (feet)	Aquifer	Date of collection	Temperature (° C)	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)
37° 4′26″,	87°39′45″[1]	210	N1	2-13-53		10	4.2	3.6	3.2	2.8	1.1
37°20′24″,	87°59′34″[1]	90	M3VI	5-17-67	18.5	12	.04	17	6.3	549	2.0
37°11′48″,	87°55′42″[1]	97	M3WL	4-11-67	17	11	45	341	321	82	8.7
37°12′ 7″,	87°53′35″[1]	192	M3TS	4-11-67	15.5	15	.14	11	4.0	233	1.4
37°11′48″,	87°55′40″[2]	280	M3TS	4-11-67	26.5	14	.28	162	106	209	3.2
37°20′41″,	87°59′ 5″[1,2]	1,052	M3SG	10-20-64	20	.5	.44	2,470	1,450	16,100	460
37°10′48″,	87°56′32″[1]	47	M3SG	4-11-67	10.5	12	.07	97	18	8.8	3.0
37° 7′ 4″,	87°51′57″[1]	104	M3SG	9- 4-52	16	14	.12	125	16	30	2.1
37°16′22″,	87°56′18″[1]	36	M3	3- 3-55			1.7				
37°16′23″,	87°56′18″[1]	32	M3	4-12-67	15.5						
37°16′ 9″,	87°54′22″[1]	60	M3	4-11-67		21		318	148	80	2.9
37°24′28″,	87°37′29″[1]	50	N3LI	6-25-54			.05				
37°13′54″,	87°36′46″[1,3]		N2TR	7- 6-66	25.5	20	4.0	472	318	177	5.2
37°12′38″,	87°50′44″[1,3]		M3KI	3- 3-55	12		.08				
37° 1′43″,	87°52′17″[1]	95	M3SG	3-31-55			.45				

[1] Underground mine. [2] Data in parts per million. [3] Spring.

Water quality in the Lisman, Henshaw, and Carbondale Formations and the Mississippian formations is shown in tables 3, 4, and 7 (data in the "Number of observations" column include more than one chemical analysis on some wells). The mean water quality in these formations is slightly saline—mean dissolved solids greater than 1,000 mg/l (milligrams per liter). The mean quality in the Caseyville and Tradewater Formations (tables 6 and 5) is classified as fresh water—

TABLE 3.—*Summary of selected physical and chemical parameters for water from the Lisman and Henshaw Formations*

Parameter	Mean	Minimum	Maximum	Standard deviation	Number of observations
Well depth ... feet	120	11	315	88	20
Specific conductance (micromhos at 25°C)	1,442	424	4,710	1,001	18
pH	7.3	6.5	8.4	.54	14
Iron (Fe) ... mg/l	2.1	.05	18.0	4.0	21
Manganese (Mn) ... mg/l	.14	0.0	.83	.24	12
Dissolved solids ... mg/l	1,103	272	4,140	945	15
Hardness as $CaCO_3$ (calcium, magnesium) ... mg/l	458	18	2,530	543	21

the Tradewater River basin—Continued

Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids: Calculated	Dissolved solids: Evaporated at 180° C	Hardness as $CaCO_3$: Calcium, magnesium	Hardness as $CaCO_3$: Noncarbonate	Specific conductance (micromhos at 25°C)	pH	Analyst
10	0	21	1.5	0.0	0.0	--------	47	22	--------	70	6.1	1
567	15	708	12	.2	1.1	1,600	1,640	68	0	2,430	8.4	1
348	0	1,970	46	.1	.2	3,000	3,210	2,170	1,890	3,240	6.9	1
414	0	179	10	1.9	.5	660	658	44	0	1,040	7.3	1
598	0	746	32	.4	3.0	1,570	1,600	841	350	2,140	7.5	1
688	0	562	31,800	2.5	--------	53,200	70,400	12,100	11,600	73,800	7.0	1
332	0	36	14	.3	14	366	372	316	44	638	7.3	1
342	0	116	26	.4	10	513	--------	376	--------	805	7.3	1
464	0	407	46	.6	.5	--------	--------	554	174	1,530	7.1	1
402	0	397	48	--------	6.4	--------	994	470	140	1,440	7.9	1
644	0	990	38	.2	.1	1,920	2,060	1,400	875	2,360	7.2	1
290	0	244	106	.3	5.9	--------	--------	369	--------	1,530	------	1
152	0	2,600	55	1.8	2.7	3,740	4,020	2,490	2,360	3,940	6.2	1
182	0	20	1.9	.2	2.5	--------	--------	166	--------	326	7.4	1
216	0	7.8	16	.2	40	--------	--------	235	58	473	7.4	1

mean dissolved solids less than 1,000 mg/l. The chemical water type varies among wells and among geologic formations. This variability in water type reflects the variable geologic materials in contact with the water and length of time that the water is in contact with these materials. The relative importance of major chemical constituents in water from the various geologic formations is shown by the Ropes diagrams in figure 10.

TABLE 4.—*Summary of selected physical and chemical parameters for water from the Carbondale Formation*

Parameter	Mean	Minimum	Maximum	Standard deviation	Number of observations
Well depth feet	125	72	194	48	7
Specific conductance (micromhos at 25°C)	1,625	200	4,010	1,290	8
pH	6.7	5.0	8.3	1.14	8
Iron (Fe) mg/l	2.5	0.0	9.7	3.95	8
Manganese (Mn) mg/l	1.6	0.0	8.1	2.8	8
Dissolved solids mg/l	1,300	213	3,760	1,260	8
Hardness as $CaCO_3$ (calcium, magnesium) mg/l	790	36	2,580	955	8

TABLE 5.—*Summary of selected physical and chemical parameters for water from the Tradewater Formation*

Parameter	Mean	Minimum	Maximum	Standard deviation	Number of observations
Well depth……feet..	170	40	460	128	23
Specific conductance (micromhos at 25°C)……	1,260	158	3,940	1,020	22
pH……	7.1	2.7	9.0	1.4	22
Iron (Fe)……mg/l..	1.65	.01	21	4.48	25
Manganese (Mn)……mg/l..	1.03	0.0	11	2.77	18
Dissolved solids……mg/l..	970	120	3,740	880	18
Hardness as $CaCO_3$ (calcium, magnesium)……mg/l..	280	8	2,490	522	25

TABLE 6.—*Summary of selected physical and chemical parameters for water from the Caseyville Formation*

Parameter	Mean	Minimum	Maximum	Standard deviation	Number of observations
Well depth……feet..	250	19	800	210	15
Specific conductance (micromhos at 25°C)……	720	70	4,510	1,170	15
pH……	6.9	6.0	8.8	.76	16
Iron (Fe)……mg/l..	3.87	.01	13	4.31	14
Manganese (Mn)……mg/l..	.25	0.0	.62	.25	11
Dissolved solids……mg/l..	770	47	4,060	1,230	11
Hardness as $CaCO_3$ (calcium, magnesium)……mg/l..	320	10	2,130	590	15

TABLE 7.—*Summary of selected physical and chemical parameters for water from the Mississippian formations*

Parameter	Mean	Minimum	Maximum	Standard deviation	Number of observations
Well depth……feet..	100	32	280	77	10
Specific conductance (micromhos at 25/C)……	1,220	330	3,240	930	15
pH……	7.5	6.9	8.4	.38	15
Iron (Fe)……mg/l..	3.71	.01	45	12.4	13
Manganese (Mn)……mg/l..	.08	0.0	.24	.09	6
Dissolved solids……mg/l..	1,330	370	3,000	880	8
Hardness as $CaCO_3$ (calcium, magnesium)……mg/l..	500	44	2,170	580	15

Exceptions to the preceding discussion of locally defined, low-yielding aquifers of highly variable water quality include three areas of deep-lying aquifers which are potential large sources of fresh-water supplies (fig. 11). These areas contain extensive sandstones lying between 200 and 1,000 feet below the surface. Water yields from these aquifers may be in excess of 50 gpm per well.

The water in the western part of area 1 in figure 11 is a calcium-magnesium bicarbonate-sulfate type and has up to 14 mg/l iron. Yields of up to 195 gpm have been reported from this aquifer from the municipal wells at Dawson Springs. Water in the same formation (eastern part of the area 1) just outside the basin at Mannington is a sodium bicarbonate type containing up to 0.36 mg/l iron. A yield of

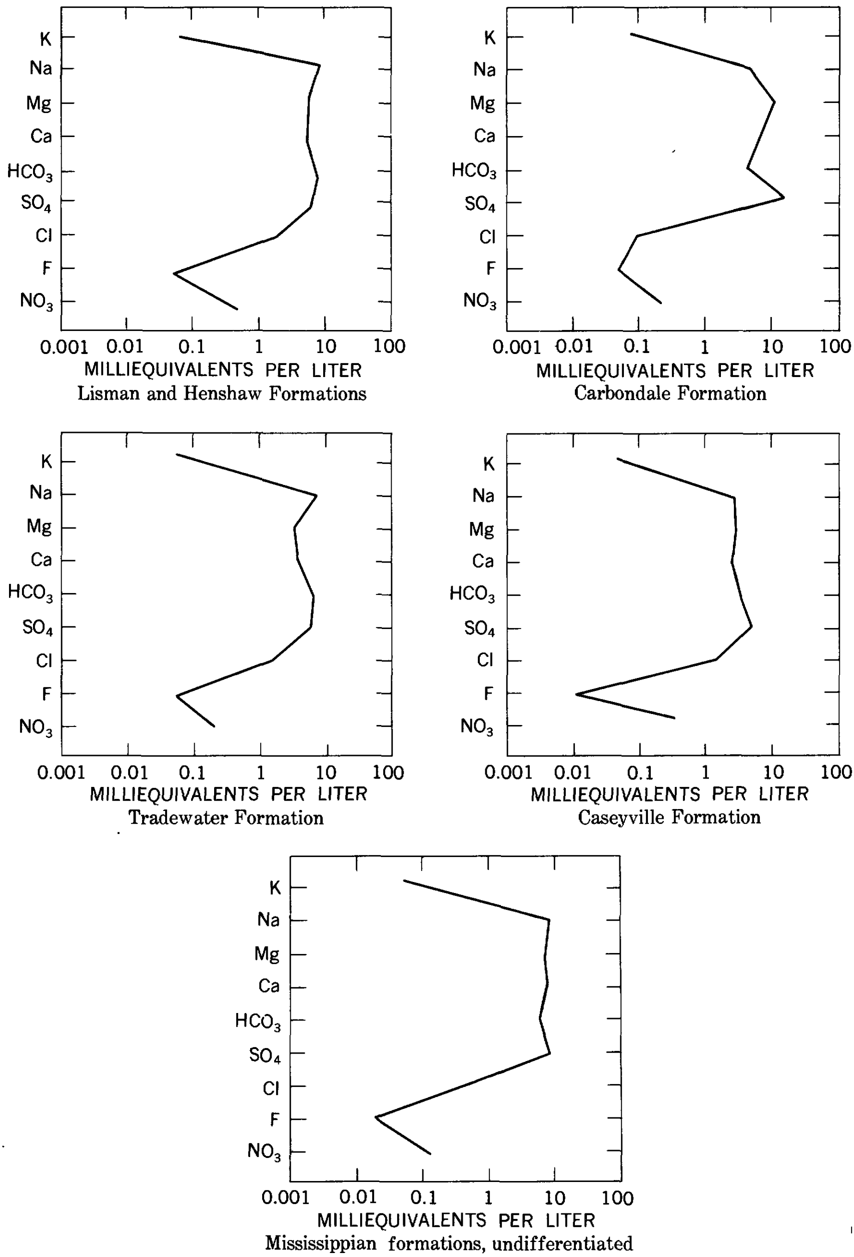

FIGURE 10.—Ropes diagrams showing the mean water type for water in the various geologic formations. (Based on Ropes and others, 1969.)

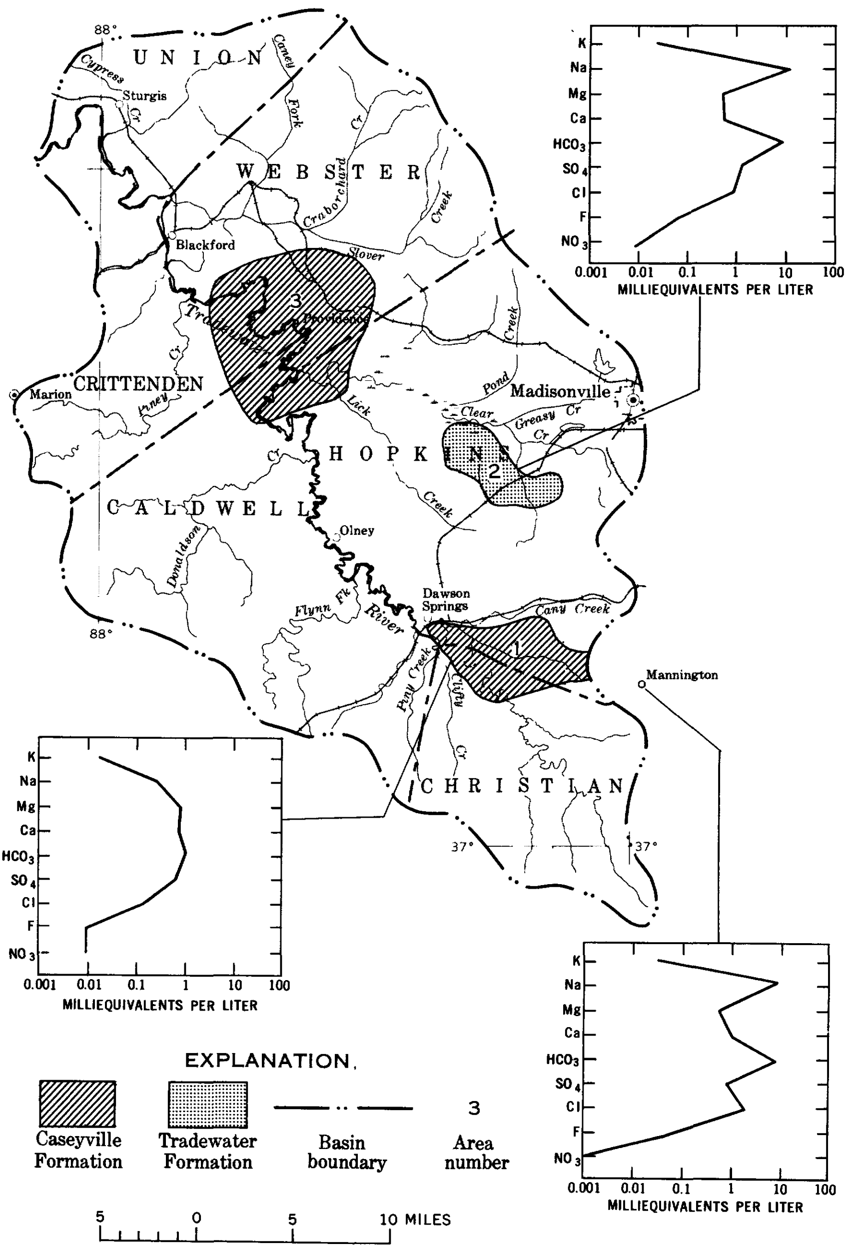

FIGURE 11.—Potential areas of deep fresh-water aquifers and Ropes diagrams showing representative quality of the water.

50 gpm is reported for a well at Mannington. The dissolved-solids concentration in area 1 ranges from 126 mg/l in the western part to 662 mg/l at Mannington.

In area 2 of figure 11 the Ames Oil and Gas Company uses two wells for water-flooding operations. Yields of 41 and 73 gpm are reported. The water is a sodium bicarbonate type containing 0.2 mg/l iron. The dissolved-solids concentration is 640 mg/l.

Subsurface data show a thick sandstone unit in area 3 of figure 11. No wells are presently developed in this aquifer. However, water was found in the aquifer during the construction of an oil-test well and was considered a possible source of supply for the city of Providence. Tests made in this well reportedly show the aquifer to be high yielding and the water to be of good quality.

GROUND WATER AFFECTED BY MINING

Coal-mining activities might be expected to affect the ground-water resources in the Tradewater River basin in at least three ways: (1) by altering flow patterns (a) in fractures and joints by use of heavy explosives and (b) in areas upslope from the deep cuts at strip pits, (2) by causing movement of highly mineralized water from mines into nearby fresh-water aquifers, and (3) by providing increased storage space for water in underground mines and in spoil banks created by strip mining.

Alteration of flow patterns due to explosives used in mining was reported at three locations in the basin. This seems to occur infrequently and in very localized areas.

A change in the ground-water flow patterns in the vicinity of strip-mine high-wall cuts (vertical rock walls created by final cut in mining operation) could be predicted from the principles of ground-water flow. However, the destruction of wells in strip-mined areas prevented field documentation in the Tradewater River basin. Altered flow patterns could conceivably increase the volume of water released to local streams during periods of low flow. This aspect needs further study since the critical limiting process (infiltration rate or discharge rate) in these areas has not been defined.

The movement of highly mineralized water from mines into fresh-water aquifers has not been detected in the basin. In some areas (east and south of Coiltown) wells have been filled and abandoned because of underground mining. It is not known whether this action, completed over a period of several years, was taken because of dewatering of the shallow aquifer while the mine was in operation, a change in water quality, or a combination of the two factors. High sulfate concentrations were observed in water from all sampled geologic formations in the basin (fig. 10 and table 2). In some areas not affected by coal mining, sulfate is the predominant ion. Therefore, an intensive study of flow patterns and water quality in the vicinity of underground mines would be necessary to determine the extent of water movement from mines into fresh-water aquifers in any given area.

In the underground-mining process, the removal of coal over large areas creates storage space for large volumes of water. In the Tradewater River basin many abandoned underground mines are filled with water that is either stagnant and has no points of discharge or is circulating through the mine and discharging at the surface. The large amounts of water that may enter and circulate through these mines is attested by the presence in the basin of several large springs that are discharge points of underground mines. Three such springs are found near Ilsley in Hopkins County at the heads of Copper Creek, Copperas Creek, and Tributary 2 to Richland Creek. The flow in the last stream is discussed further in the next section, entitled "Surface Water." The point of discharge from the underground mine to Tributary 2 was created by a surface-mining operation which cut into the abandoned mine. Similar occurrences in other parts of the basin have been reported. Analysis of a water sample from this spring taken July 26, 1966 (table 8, station 3–3837.8) shows the water to be of a calcium-magnesium-sulfate type. The 36 mg/l iron, which is much higher than concentrations in any of the samples taken at the regular sampling site a short distance downstream, is iron in solution in the ferrous state at the spring. As the water moves downstream it is exposed to the air, and much of the iron is precipitated as ferric hydroxide.

Water is also stored in spoil banks created by the strip-mining process. Some spoil banks may drain rather quickly after periods of precipitation; others may store significant amounts of water and release this water slowly to streams.

The amount of water that is stored in the basin in underground mines and spoil banks and the relative importance of discharge from these sources to the streams for any given period of time are not known. General observations in this basin and studies of other areas (Collier and others, 1964; Corbett, 1965) indicate that the relative importance of discharge from abandoned underground mines, spoil banks, and aquifers intercepted by strip-mine high-wall cuts may vary greatly from one area to another, depending upon topographic and geologic characteristics of the area and the areal extent of spoil banks and underground mines.

SURFACE WATER

Observations of streamflow and selected water-quality parameters have been made in the Tradewater River basin at several sites and with varying frequencies prior to and during this study. A summary of the sites where these observations have been most frequent is presented in table 9, and all streamflow observation sites are shown on plate 1.

TABLE 9.—*Summary of selected streamflow and water-quality observation sites in the Tradewater River basin*

[Frequency: M, monthly; I, intermittent; C, continuous; D, daily; Site number refers to location on pl. 1]

Observation site	Streamflow		Water quality		Site number
	Year begun	Frequency	Year begun	Frequency	
Tradewater River at Collins Bridge	1966	M	1966	M	03-3826.80
Buffalo Creek at Highway 1338	1965	M	1965	M	03-3827.20
Copperas Creek at Ilsley	1966	M	1966	M	03-3828.35
Cany Creek at mouth	1965	M	1965	M	03-3828.55
Tradewater River at Dawson Springs at Highway 109	1966	M	1966	M	03-3828.70
Piny Creek	1966	I	1966	I	03-3828.90
Tradewater River at Dawson Springs Dam	1965	I	1965	I	03-3828.92
Flynn Fork	1966	M	1966	M	03-3829.80
Tradewater River at Olney	1941	C	1952	D	03-3830.00
Richland Creek aobve Tributary 1	1966	M	1966	M	03-3837.70
Tributary 1 to Richland Creek	1966	M	1966	M	03-3837.75
Tributary 2 to Richland Creek	1966	M	1966	M	03-3837.80
Rose Creek at Nebo	1952	C	1966	I	03-3840.00
Tradewater River at Providence	1966	M	1966	M	03-3840.72

The mean annual discharge of the Tradewater River at Olney is 317 cfs (cubic feet per second); daily mean discharge for the period of record varied from 0 to 13,200 cfs. A station mean annual flood of 3,700 cfs at Olney was reported by McCabe (1962, p. 18). Flood magnitude and frequency can be estimated for ungaged sites in the basin by using results of regional analysis of flood data (McCabe, 1962; Speer and Gamble, 1965). Analyses of stage records at Olney show that during flood periods the river stage rises slowly, attains a broad flattened peak, and slowly recedes. This characteristic can be attributed to the fairly flat gradient of the river channel.

The Tradewater River above Olney does not intercept any groundwater aquifer having large enough yields to maintain flow at Olney in the months of low mean precipitation preceded by long periods when potential evapotranspiration exceeds precipitation. The flow-duration curve for the Tradewater River at Olney (fig. 12) shows the percentage of time during which specified discharges were equaled or exceeded during the period 1941–66. Six percent of the time the flow at Olney is less than 0.1 cfs; it is less than 1.0 cfs 15 percent of the time (fig. 12). A mean low flow of zero for 7 consecutive days occurs at

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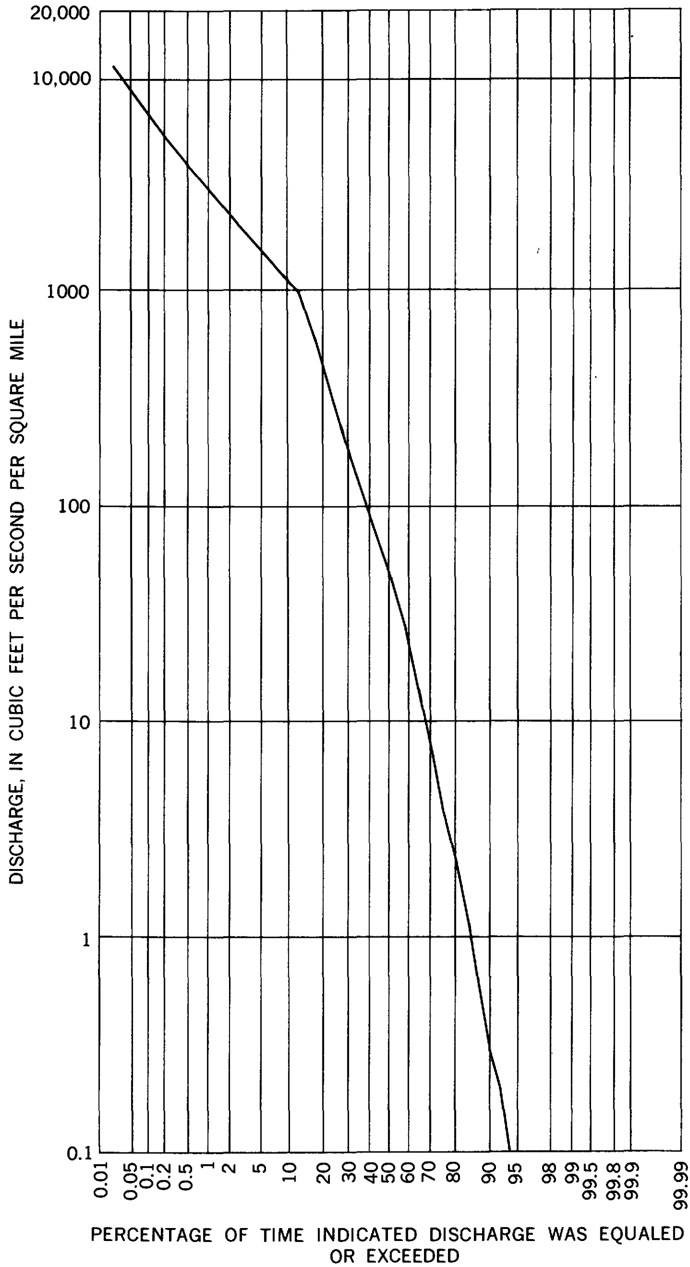


FIGURE 12.—Duration curve of daily flow, Tradewater River at Olney, 1941–66.

average intervals of 1.93 years on a long-term basis (table 10). Moreover, the average occurrence of a mean low flow of zero for 30 consecutive days is once in every 3.4 years.

TABLE 10.—*Magnitude and frequency of annual low flow for the Tradewater River at Olney*

[Data for period 1941–67 water years]

Period (consecutive days)	Annual low flow (cfs) for indicated recurrence interval (yr)						
	1.04	1.23	1.35	1.93	3.4	9.0	13.5
7	8.1	0.6	0.4	0	0	0	0
30	19.6	3.1	1.9	.6	0	0	0
60	53.9	12.1	6.9	3.3	.7	0	0
120	261.3	37.2	18.3	9.4	3.3	1.5	0

The relationship of streamflow at Olney to streamflow at several other sites in the basin as developed by correlation and regression analysis is summarized in table 11. Searcy (1959) showed that differences in the geologic characteristics of drainage basins are reflected by the shape of the low-flow ends of flow-duration curves of streams in adjacent basins.

TABLE 11.—*Summary of correlation and regression analyses of streamflow, Tradewater River at Olney and nine miscellaneous sites*

[Regression equation: $\log Y = \log a + b \log X$. X=independent variable (discharge at Tradewater River at Olney); Y=dependent variable (discharge at miscellaneous measuring site)]

Miscellaneous measuring site	log *a*	*b*	Standard error	Correlation coefficient
Tradewater River at Collins Bridge	−1.033	1.082	±0.417	0.914
Buffalo Creek at Highway 1338	−.263	.481	±.153	.974
Cany Creek at mouth	−.197	.589	±.188	.937
Tradewater River at Dawson Springs	.138	.712	±.578	.946
Flynn Fork	−.185	1.410	±.445	.844
Copperas Creek at Ilsley	−.646	.200	±.324	.578
Richland Creek above Tributary 1	−.342	1.046	±.298	.951
Tributary 1 to Richland Creek	−2.033	.615	±.153	.956
Tributary 2 to Richland Creek	−.477	.144	±.154	.806

Flow-duration curves for the streams in table 11 were estimated by the method given by Hunt (1963). These curves, when plotted as cubic feet per second per square mile as in figures 13 and 14, permit a comparison of the geologic characteristics of each subbasin. The curves are based on the period 1958–66 because of an apparent increase in low flow at Olney beginning about 1958; this increase is believed to have been caused by strip-mining operations.

Figure 13 shows the flow-duration curves of five streams: two streams—Cany Creek and Buffalo Creek—drain basins in which sub-

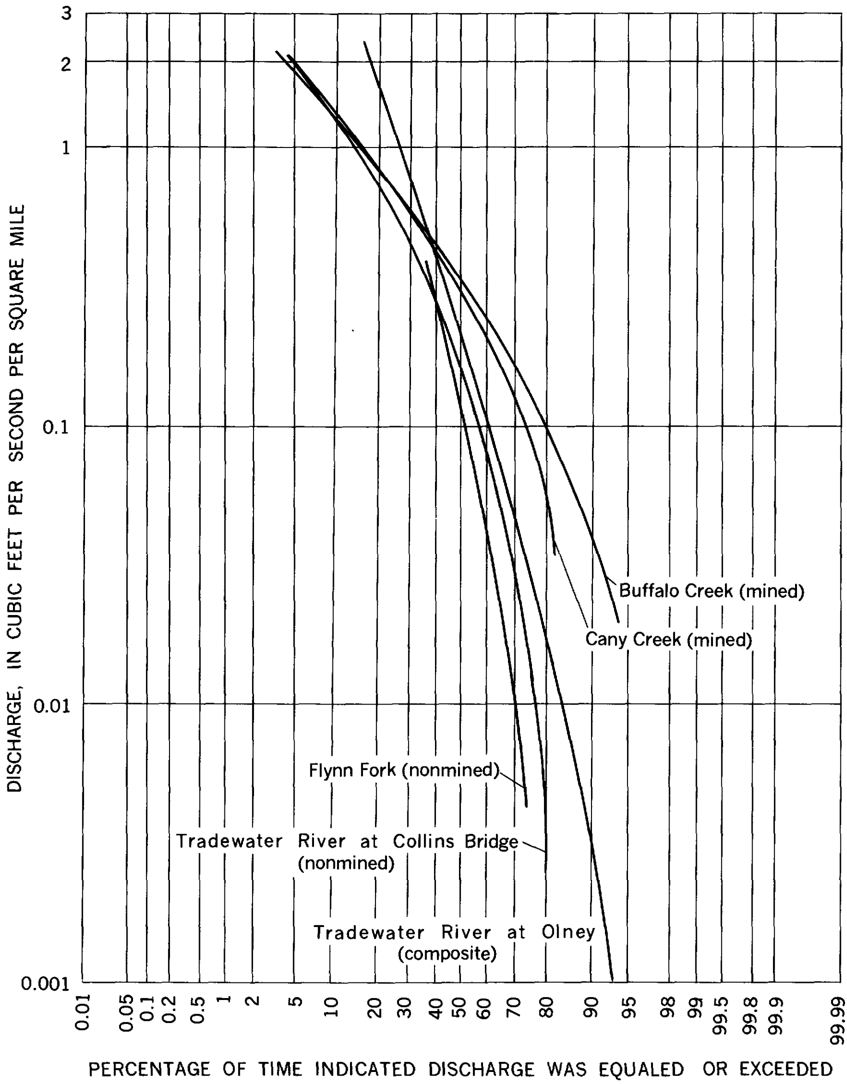


FIGURE 13.—Comparison of flow-duration curves for selected streams in the Tradewater River basin based on streamflow measurements, 1966–67, and correlation with Olney gaging station, 1958–66.

stantial coal-mining activity has occurred; two streams—the Tradewater River above Collins Bridge and Flynn Fork—drain areas in which no coal-mining activity has occurred; the remaining stream is the Tradewater River at Olney, which receives drainage from mined and nonmined areas.

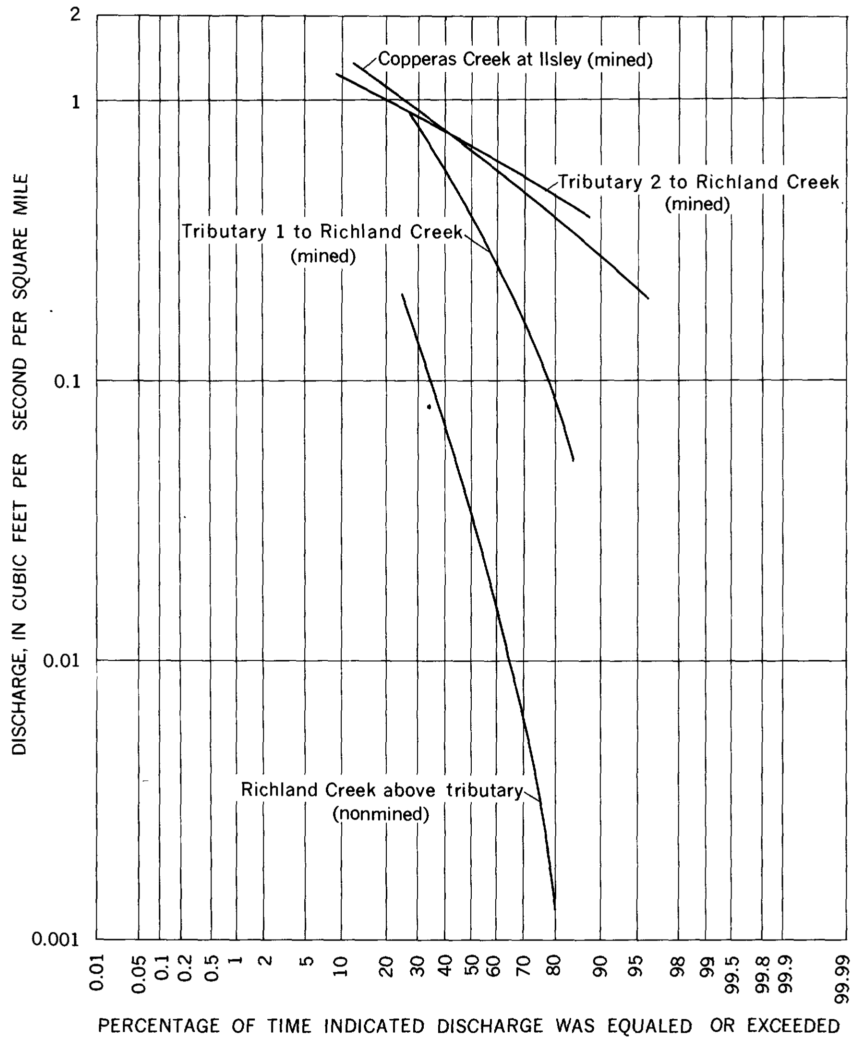


FIGURE 14.—Comparison of flow-duration curves for four adjacent streams near Ilsley based on streamflow measurements, 1966–67, and correlation with Olney gaging station, 1958–66.

The curves in figure 13 are nearly convergent above 0.5 cfs per square mile, but below this point the curves diverge. Topography, geologic structure, and rock types in the areas drained by these streams are virtually the same. The differences in the low-flow ends of the flow-duration curves are attributed to the presence or absence of coal-mining activity. The curves for Cany Creek and Buffalo Creek show relatively higher low flows for a greater percentage of time than the curves for the streams draining nonmined areas. Accounting for this fact are the storage of water in abandoned underground mines, strip pits, and spoil banks and the slow release of this water during ensuing dry periods. The curve for the Tradewater River at Olney, where drainage from mined and nonmined areas is received, falls between the other two sets of curves.

Field observations during an extended dry period in September 1966 showed that the only streams having noticeable flow were in the mined basins of Clear Creek, Cany Creek, and Buffalo Creek. The flows were traced to their sources, which were found to be areas of surface or underground coal-mining operations or both. No flow was observed in streams draining nonmined areas.

Figure 14 shows the flow-duration curves of four streams in four small adjacent basins: Richland Creek above Tributary 1 drains a nonmined basin, Tributary 1 drains an area in which only strip mining of coal has occurred, and both Tributary 2 and Copperas Creek drain areas which have undergone extensive underground mining and strip mining. Geology and topography are very similar in all four basins.

The curves of Tributary 2 and Copperas Creek are relatively flat and nearly identical. The position and flatness of these two curves show that the low flows are relatively high and constant compared with the other two streams. These low flows are sustained almost entirely by discharge from abandoned underground coal mines. The curve for Tributary 1 is in an intermediate position. The storage and slow release of water from strip-mine spoil banks sustain low flows, but the magnitude is less and the variability greater than flows sustained by underground-mine drainage. Richland Creek above Tributary 1 is typical of streams draining nonmined areas. The low-flow end of the flow-duration curve is steep, and the magnitude of flow (on a per-square-mile basis) is relatively small. During dry-weather periods the flow decreases rapidly to zero while the other three streams still have measurable flows.

Surface-water sampling sites were chosen in the basin (see pl. 1) in order to study water-quality characteristics and compare and contrast water quality from mined and nonmined subbasins. The analyses resuting from the sampling study, given in table 8, show that nearly all serious problems of surface-water quality in the Tradewater River basin are due to drainage from coal mines. Chemical indicators of contamination from sewage—nitrate and chloride concentrations—were not observed to be excessive below sewage outlets at Dawson Springs and Providence when compared with the magnitude of sulfate concentrations resulting from mine drainage. Another potential source of serious water-quality problems is producing oil fields. Oil containing associated brines is pumped from wells and into large separator tanks where the brines are separated from the oil and later drained into evaporation pits. These brines have caused serious pollution of ground water and streams in other areas of the State. Analyses of water samples collected at sites downstream from oil-field activity and in other parts of the basin do not show the high chloride concentrations that would be indicative of contamination by brines. Flushing of the brines and accumulated salts from the evaporation pits may occur during periods of precipitation. Continuous water-quality monitoring at selected sites would be needed for proper detection and evaluation of such events.

ORIGIN AND CHARACTERISTICS OF DRAINAGE FROM COAL MINES

The increase of dissolved constituents in coal-mine drainage begins with the breakdown of iron sulfide minerals (pyrite and marcasite) present in the earth materials disturbed by mining activities and the subsequent breakdown of clays and other minerals. In the Tradewater River basin, these minerals are present in strip pits and spoil banks, in underground mineworks, and in waste materials from coal washing (gob piles). High concentrations of the dissolved products of chemical breakdown are found in streams draining coal-mine areas. Increased concentration of suspended sediment resulting from surface-mining operations and from spoil-bank erosion is another change attributable to coal-mining activities; this will be described only for the Tradewater River at Olney.

A commonly postulated reaction for the oxidation of pyrite in the presence of atmospheric or dissolved oxygen is:

$$2FeS_2 + 7O_2 + 2H_2O = 2FeSO_4 + 2H_2SO_4. \quad (1)$$

Barnes and Clarke (1964) discussed the assumption and conditions required for this reaction and propose the following reaction in the absence of atmospheric or dissolved oxygen, a condition which may exist in abandoned underground coal mines:

$$FeS_2 + 8H_2O = Fe^{+2} + 2SO_4^{-2} + 2H^{+1} + 7H_2. \qquad (2)$$

The water in contact with the minerals oxidized by either of the above reactions would be acid (low pH); it would also have high concentrations of sulfate (SO_4^{-2}) and ferrous iron (Fe^{+2}). The acid water accelerates the breakdown of clay, other silicate minerals, and carbonate minerals, thus increasing the concentrations of silica (SiO_2), aluminum (Al), calcium (Ca^{+2}), magnesium (Mg^{+2}), and manganese (Mn) in mine waters. The acid water also tends to maintain a low bicarbonate (HCO_3^{-1}) concentration.

The concentrations of iron, manganese, aluminum, and silica and the pH are among the more variable water-quality characteristics in streams of the Tradewater River basin with respect to distance from coal-mine areas. As distance increases and as dilution and neutralization of a stream occur, these parameters are among the first to return to levels observed in the water of nonmined areas of the basin.

Some acidity levels measured at varying distances from sources of coal-mine drainage in the basin were the same as those observed in water from nonmined areas. Concurrent sulfate concentration was as much as 75 times greater than the level measured in water from nonmined areas of the basin. Rainwater and Thatcher (1960, p. 88), in their discussion of methods for analysis of acidity in water samples, said, "Determinations of acidity are among the least reliable in water analysis in respect to accuracy and reproducibility of results."

In contrast, the sulfate ion (the final sulfur product of iron sulfide oxidation) is very persistent and is chemically stable in most environments to which natural waters are subjected (Hem, 1959, p. 100). The above considerations, the type of data in greatest abundance, and the reliability of sulfate concentrations estimated from relationships between specific conductance and sulfate clearly demonstrate the utility of sulfate concentrations as the most reliable indicator of coal-mine drainage in streams of the Tradewater River basin.

STREAMS TRANSPORTING MINE DRAINAGE

The Tradewater River above Olney receives mine drainage from the Cany Creek, Buffalo Creek, Hurricane Creek, and Bull Creek subbasins. Although there has been some shallow strip-mining activity in the Castleberry Creek subbasin, the highest sulfate concentration observed on the main stem of this creek is of the same order of magnitude as that observed on Richland Creek above Tributary 1, where no known mining has occurred. No coal-mining activity is known in the other major subbasins above Olney, which include Flynn Fork, Montgomery Creek, and Piny Creek.

Below Olney, the major contribution of coal-mine drainage comes from the Clear Creek, Owens Creek, and Craborchard Creek (Vaughn Ditch) subbasins. The Donaldson Creek and Piny Creek subbasins are largely underlain by formations in the Upper Mississippian or Lower Pennsylvanian Systems which contain no commercial coals. No indication of coal-mine drainage was observed in these two subbasins.

Effects of coal-mine drainage can be demonstrated by comparing chemical water types. Analysis of the data in table 8 shows three distinct water types in streams in the Tradewater River subbasins (fig. 15). An areal distribution of water types is presented by quality

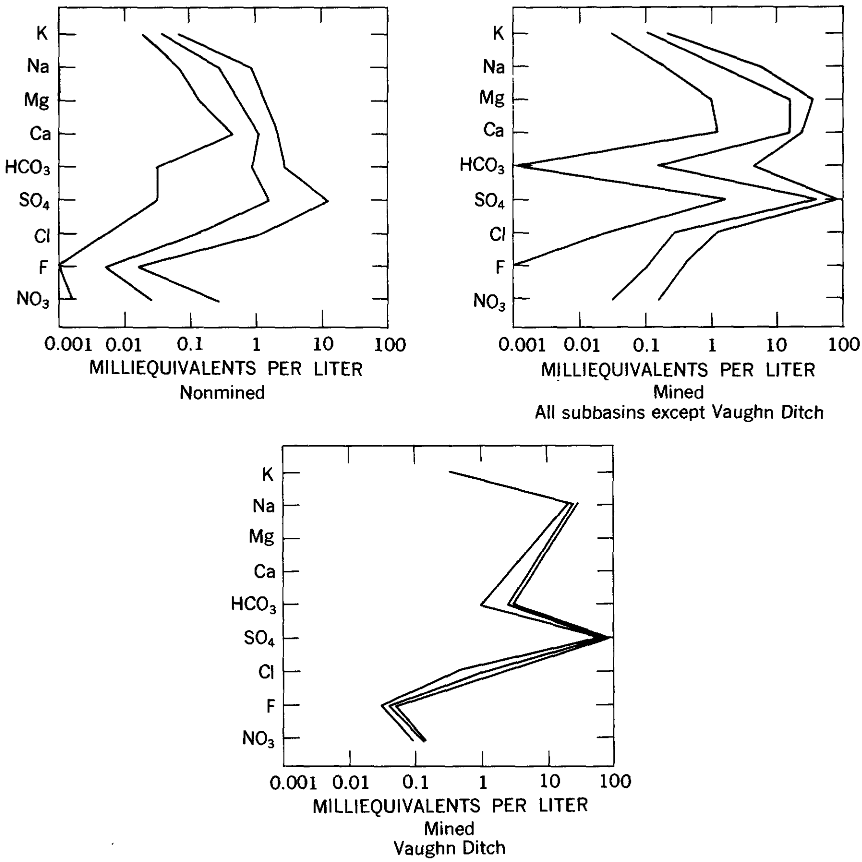


FIGURE 15.—Ropes diagram showing variations in water type between subbasins that are nonmined and mined. Lines are from left to right—minimum, mean, and maximum values observed. (Based on Ropes and others, 1969.)

diagrams (pl. 1) that show water-quality type in six major tributaries to the Tradewater River. Four of these tributaries drain mined areas; Buffalo Creek, Cany Creek, Clear Creek, and Vaughn Ditch. Two of the tributaries drain nonmined areas: Piny Creek and Flynn Fork. The quality diagrams represent, with the exception of Vaughn Ditch, the mean of several samples taken over a 2-year period at nearly regular intervals.

The diagrams on plate 1 show that the mean concentrations of major ions in Buffalo Creek, Cany Creek, and Clear Creek are strikingly similar. These streams are typed as calcium-magnesium-sulfate water. The fourth stream draining a mined area, Vaughn Ditch, has a greater concentration of most ions except fluoride (including a substantial amount of bicarbonate, which is persistently low in the above three streams), a greater proportion of sodium to calcium and magnesium, and a relatively high pH of 6.6. The source of this peculiar type of water in Vaughn Ditch was traced to an abandoned strip-mine operation on the No. 13 coal. Here, water overflows constantly from a lake formed by the mining operation. The lake covers a thick calcareous shale which is present in the high wall above the No. 13 coal. Large amounts of the shale constitute the spoil banks adjacent to the lake. A laboratory experiment shows that the shale can neutralize acid mine water. An exchange of calcium ions for sodium ions in the shale probably accounts for the relatively high sodium content.

Although pH varies in streams affected by coal-mine drainage as noted above, pH values do give some indication of mine drainage as shown in figure 16. Craborchard Creek (Vaughn Ditch) is the only major subbasin in the upper pH range (fig. 16) which is a contributor of mine drainage to the Tradewater River.

MAGNITUDE AND EFFECTS OF MINE DRAINAGE IN STREAMS

The effects of drainage from coal mines vary from no apparent effect at several sites in the basin to concentrations of sulfate in excess of 2,000 mg/l and pH values well below 4.0 in the Buffalo Creek, Cany Creek, and Clear Creek subbasins. The effects of coal-mine drainage are variable over the basin, and the factors and processes involved are complex. Therefore, the following discussion will be concerned first with the Tradewater River at Olney, then with the subbasins

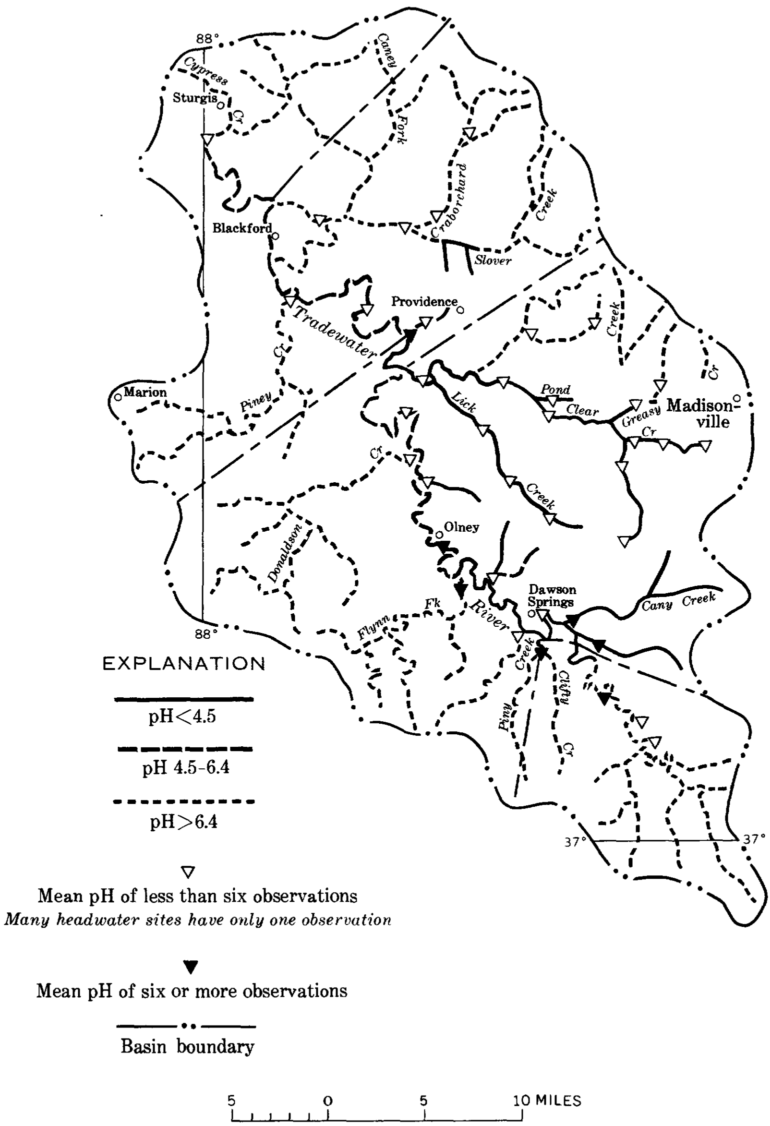


FIGURE 16.—Variation in mean pH of surface water (includes data from Kentucky Water Pollution Control Comm.).

contributing coal-mine drainage to the Tradewater River, and finally with the variations in water quality at selected sites along the Tradewater River.

TRADEWATER RIVER AT OLNEY

DISSOLVED CONSTITUENTS

The maximum values of several selected physical and chemical parameters observed in the Tradewater River at Olney are from two to more than 100 times greater than the maximum observed values of the same parameters at any of the other five selected rivers in Kentucky shown in table 12. Except for the North Fork Kentucky River at Hazard (pH 3.8), the minimum pH observed at the sites in table 12 was about two times greater than the minimum pH of 3.3 observed at Olney. A minimum bicarbonate (HCO_3) concentration of zero has been observed at Olney in 11 of the last 16 water years (through water year 1967). The minimum bicarbonate concentration observed at the sites listed in table 12 was 26 mg/l, with the exception of the North Fork Kentucky River at Hazard which is affected by mine drainage (Schneider, 1965).

The data from the five Kentucky rivers that are compared to Tradewater River data in table 12 are not for the same periods of time. However, the comparison illustrates to some degree the changes in water quality due to coal-mine drainage in the Tradewater River

TABLE 12.—*Maximum observed values for selected water-quality parameters for selected periods from five Kentucky rivers compared to maximum observed values from the Tradewater River at Olney*

[Milligrams per liter, except as indicated]

Parameter	Maximum observed value for indicated site—					
	1	2	3	4	5	6
Silica (SiO_2)	10	0.1	0.1	13	16	37
Iron (Fe)	.45	.91	.92	.36	.32	5.7
Manganese (Mn)		.27	.26			39
Calcium (Ca)		55	70			159
Magnesium (Mg)		15	7.0			150
Sulfate (SO_4)	442	20	16	38	62	1,600
Fluoride (F)		.2	.5			1.5
Dissolved solids	810	566	235	347	377	2,400
Hardness as $CaCO_3$:						
Calcium, magnesium	360	199	202	170	169	1,380
Noncarbonate	360	106	180	103	113	1,380
Specific conductance (micromhos at 25°C)	1,060	1,020	405	636	635	2,480

1. North Fork Kentucky River at Hazard.
2. Green River, Greensburg.
3. Little River, Cadiz.
4. Licking River, McKinneysburg.
5. Kentucky River at Frankfort.
6. Tradewater River at Olney.

at Olney as related to some major streams in Kentucky. The magnitude of change in water quality is even greater at Olney when compared with other points in the Tradewater River stream system that are not affected by coal-mine drainage.

CORRELATION OF WATER-QUALITY PARAMETERS WITH SPECIFIC CONDUCTANCE

Observations of several physical and chemical characteristics of water in streams not affected by mining show that some of these parameters had already been changed at Olney by coal-mine drainage before the first daily observations of specific conductance were made there in 1951. Changes in some water-quality parameters are not so apparent from the chemical analyses of samples collected in the early part of the sampling period (beginning in 1949) as they are from some of the analyses of recently collected samples. However, a correlation analysis using data from October 1949 to September 1966 (table 13) shows that 8 of the 11 parameters considered in table 12 are highly correlated (correlation coefficient > 0.8), the more obviously changed parameters being specific conductance and sulfate. Therefore, variations in magnitude of water-quality changes at Olney will be considered in terms of the most frequently observed parameter, specific conductance, and the relationship between this parameter and sulfate concentration.

TABLE 13.—*Correlation coefficients of sulfate and specific conductance with 18 selected water-quality parameters, Tradewater River at Olney*

[Analysis of 259–465 observations for the period Oct. 1949–Sept. 1966]

Parameter	Sulfate	Specific conductance
Silica (SiO_2)	0.54	0.63
Aluminum (Al)	.75	.87
Iron (Fe)	.35	.31
Manganese (Mn)	.93	.86
Calcium (Ca)	.96	.98
Magnesium (Mg)	.99	.98
Sodium (Na)	.85	.89
Potassium (K)	.57	.60
Carbonate (HCO_3)	−.38	−.32
Sulfate (SO_4)	----	.92
Chloride (Cl)	.57	.63
Fluoride (F)	.86	.86
Nitrate (NO_3)	−.12	−.10
Dissolved solids	.90	.99
Hardness as $CaCo_3$:		
Calcium, magnesium	.92	.99
Noncarbonate	.92	.99
Acidity	.73	.84
Specific conductance (micromhos at 25°C)	.92	----
pH	−.74	−.74

SHORT-TERM AND SEASONAL VARIATIONS

Continuous records on the Tradewater River at Olney during 1966–67 show no diurnal changes in specific conductance. Therefore, less frequent changes such as those associated with storm-runoff events and time of the year will be considered in this section. Changes in specific conductance are the result of transport of water of higher or lower dissolved-solids concentration from upstream areas. Daily specific-conductance records were plotted against mean daily discharge for the Tradewater River at Olney for the period 1952–66. Analysis of these records permits generalizations to be made concerning the variation of specific conductance with stream discharge and with time.

In nearly all streams, specific conductance varies inversely with stream discharge; during periods of rainfall and runoff, the water entering streams is more dilute than is the water that has circulated through rocks and soils before entering streams during periods of base flow. However, for the Tradewater River at Olney during the period 1952–66, the records show that in at least 17 instances of precipitation an increase in discharge was associated with a concurrent increase in specific conductance; after these flows peaked and began falling, conductances also fell. The conditions associated with these 17 occurrences showed several similarities. Streamflow was relatively low for a period of at least several days preceding the concurrent increase in discharge and conductance. The peak discharges of the events, all occurring within the months August–January, ranged between 14 and 350 cfs with a mean of 151 cfs.

These events can be interpreted as a "flushing-out" action. Acid salts accumulate in coal-mined areas during periods of little or no precipitation, and highly concentrated acid water accumulates in strip-mine cuts and abandoned underground mines. Rainfall over these mined areas may dissolve acid salts and flush out acid ponds and underground mines and then move this acid water as a body downstream toward Olney. The amount of rainfall must be sufficient to flush out and transport the acid loads, but too great an amount of precipitation will cause dilution of the acid water being transported and result in an immediate decrease in conductance at Olney as discharge increases. Many occurrences of this decrease in conductance can be observed in the record at Olney.

These effects of the amount, duration, and areal distribution of rainfall on the relation of specific conductance and discharge at Olney are illustrated by the examples in figures 17–19. During the period February 6–19, 1964, rainfall of relatively low volume occurred much of the time and was evenly distributed over the basin (figs. 17 and 18).

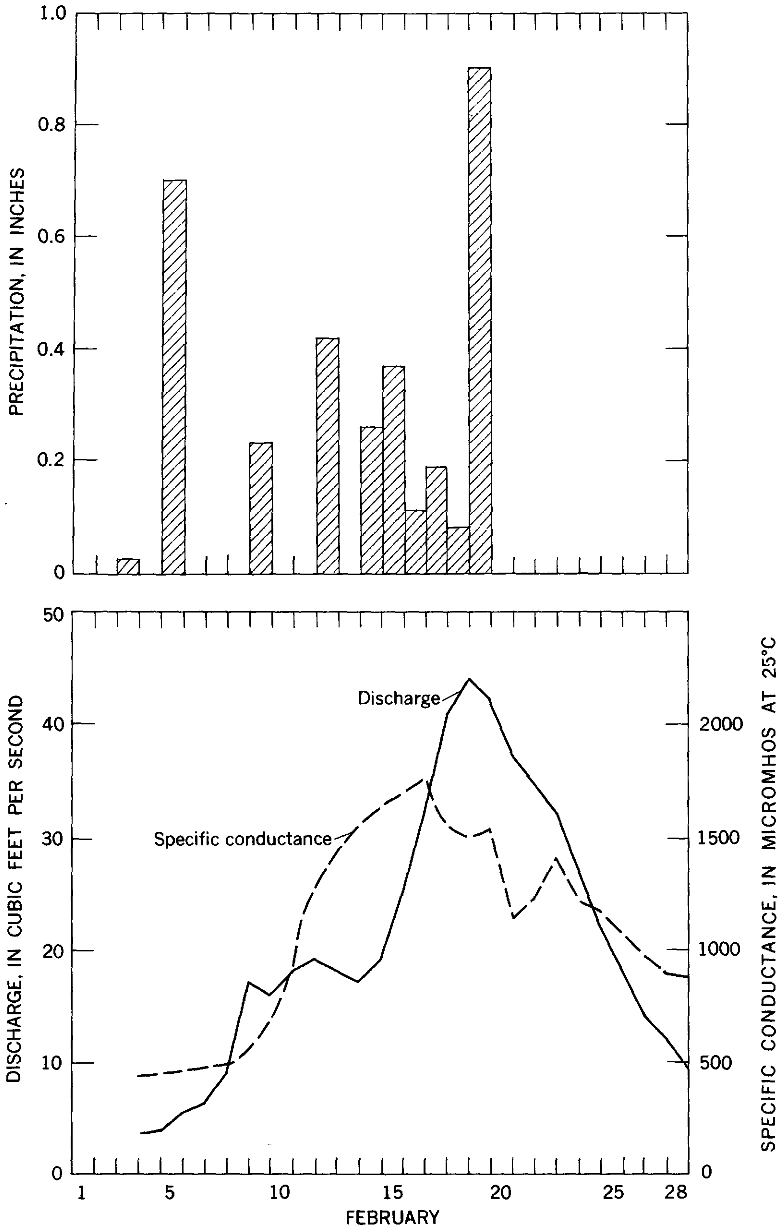


FIGURE 17.—Daily distribution of precipitation at Princeton and relation between specific conductance and discharge for the Tradewater River at Olney, February 4–29, 1964.

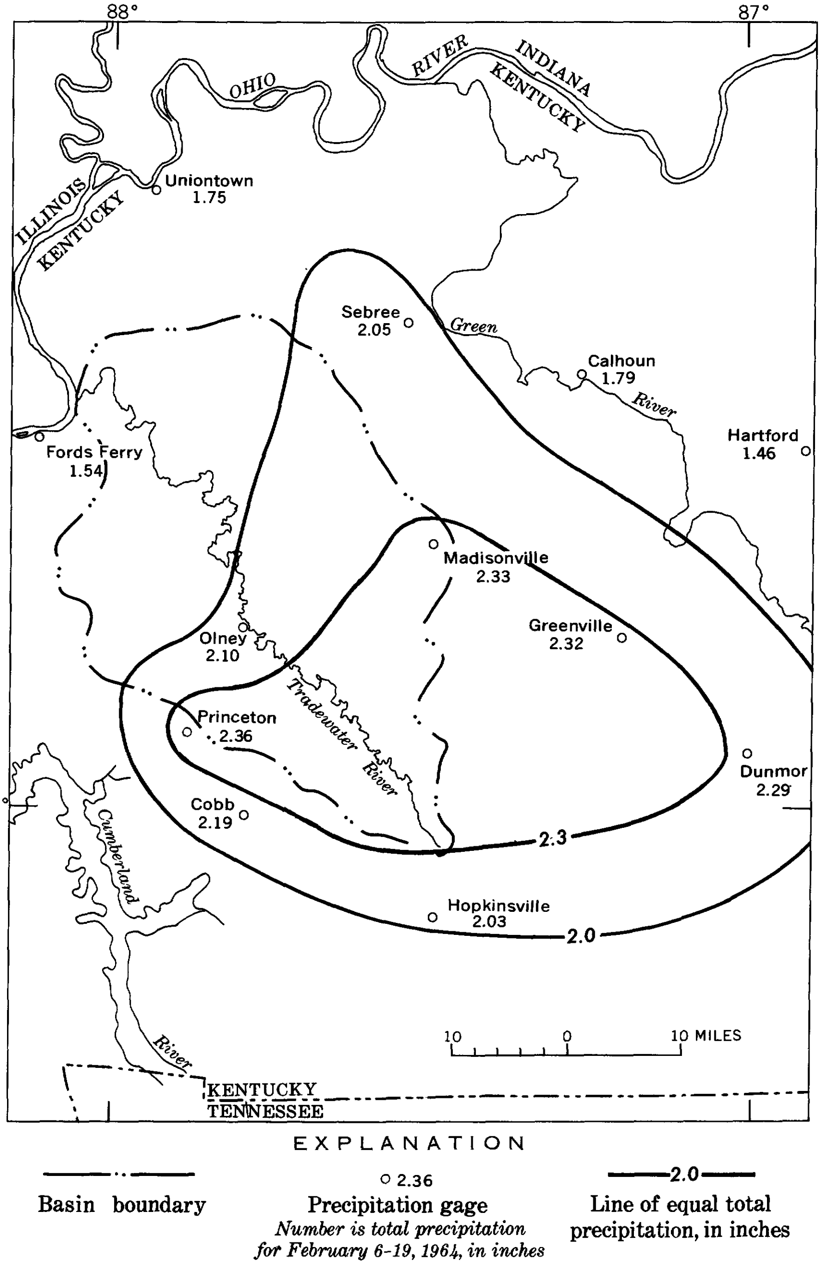
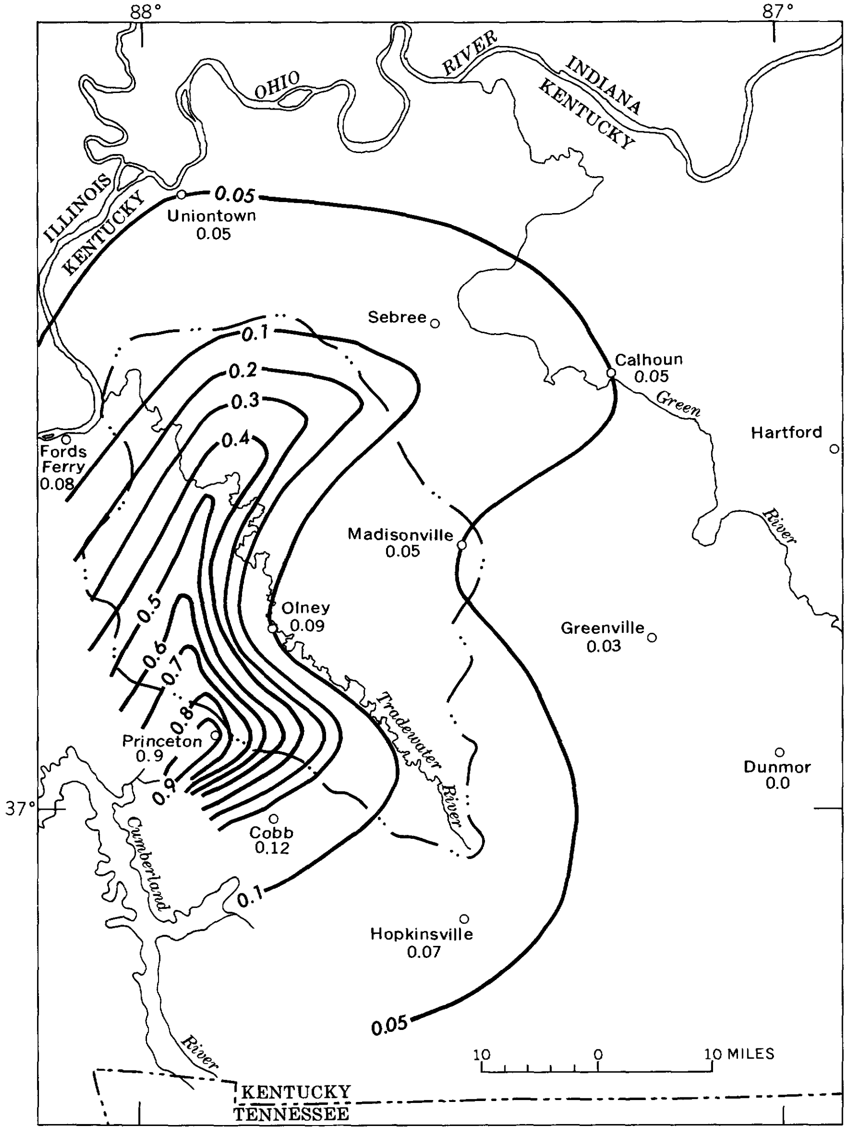


FIGURE 18.—Total precipitation for the Tradewater River basin and vicinity, February 6–19, 1964.



EXPLANATION

Basin boundary	Precipitation gage	Line of equal total precipitation
	0.05 — *Number is total precipitation for February 20, 1964, in inches*	0.3 — *Interval 0.05 and 0.1 inch*

FIGURE 19.—Total precipitation for the Tradewater River basin and vicinity, February 20, 1964.

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The specific conductance (fig. 17) increased steadily until a peak was reached on February 17. Further rainfall which brought a peak discharge on February 19 served to dilute the acid water and cause a decrease in specific conductance. Falling discharge on February 20 brought a slight rise in conductance in a normal inverse relationship; however, a sharp decrease in conductance on February 21 was associated with a heavy rainfall which was highly concentrated in the western (nonmined) part of the basin (fig. 19). The passing of this surge of dilute water by February 23 was followed by a return to a higher conductance level and then a gradual fall in conductance as the effects of the initial flushing action diminished.

These interpretations of the relationship of specific conductance, discharge, and rainfall distribution are based on discharge and conductance data for the Tradewater River at Olney, which is many miles downstream from mined areas; thus damping and lagging effects are included in the data. Rainfall data are collected at widely scattered points in the basin, as can be seen in figures 18 and 19. Closer control, in the form of stream-gaging and conductance-monitoring installations and networks of recording rain gages in the larger mined and nonmined subbasins, is needed to define accurately the mechanism of flushing, transport, and dilution of acid water.

Specific-conductance measurements are useful not only in indicating the concentration of mine drainage but also in establishing relationships with other indicators of the concentration of mine drainage. Such relationships were developed at Olney (table 14) from the 460 chemical analyses which cover a 15-year period; these relationships can be used to estimate sulfate concentration, dissolved solids, and hardness from a specific-conductance measurement.

Using the relationship of specific conductance and sulfate shown in table 14 and shown graphically in figure 20, a daily sulfate concentration was calculated for the 16 years of daily specific-conductance observations. The calculated daily sulfate concentration and daily

TABLE 14.—*Summary of regression analysis of water-quality parameters, Tradewater River at Olney*

[Regression equation: $Y=a+bX$]

X	Y	a	b	Correlation coefficient	Standard error of estimate of Y	Observations
Specific conductance	Sulfate	−63.8	0.61	0.99	±24.3	460
Do	Dissolved solids	−54.62	.87	.99	±29.2	458
Do	Hardness (calcium, magnesium).	−26.55	.52	.99	±17.8	460

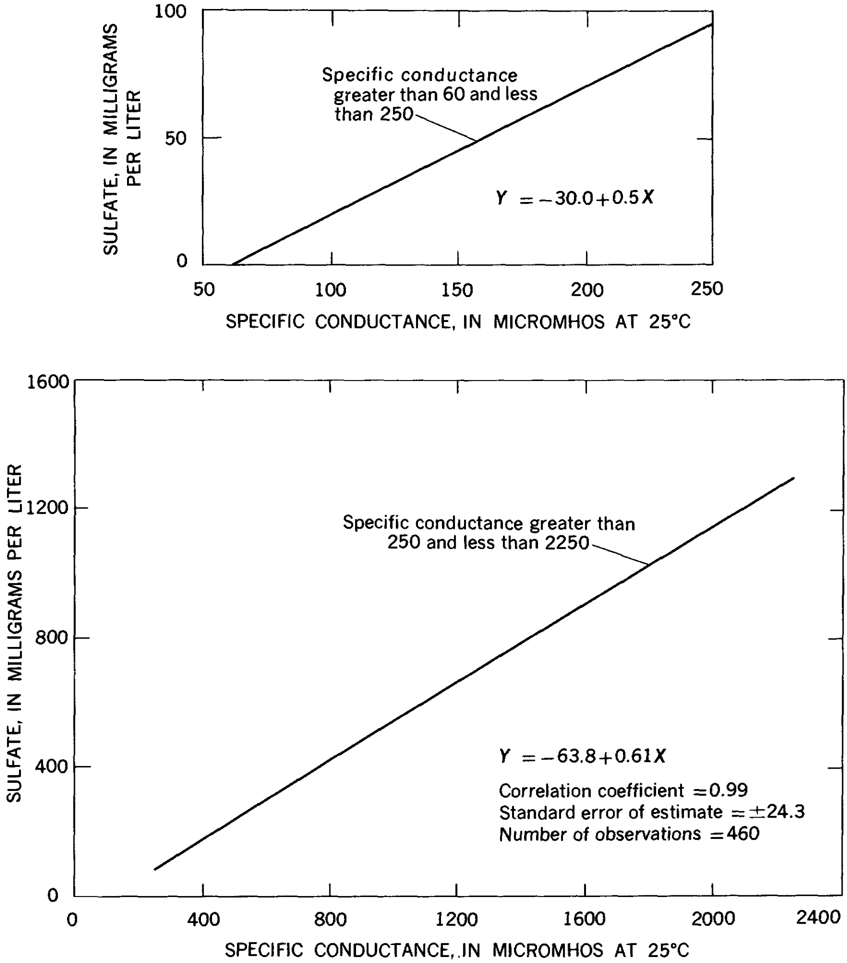

FIGURE 20.—Relationships of sulfate concentration to specific conductance used to estimate sulfate concentration from daily specific conductance data, Tradewater River at Olney. Upper curve used for specific-conductance range of 60–249 micromhos; lower curve used for specific-conductance range of 250–2,250 micromhos.

mean discharge data were used in the following relationship to compute daily sulfate loads:

Load (tons) = discharge (cfs) × sulfate concentration (mg/l) × 0.0027.

Figure 21 is a graph of total daily sulfate loads, daily specific conductance, and mean daily discharge for the 1966 water year. Sulfate loads vary almost directly with discharge regardless of time of year or magnitude of discharge. This is in contrast to specific con-

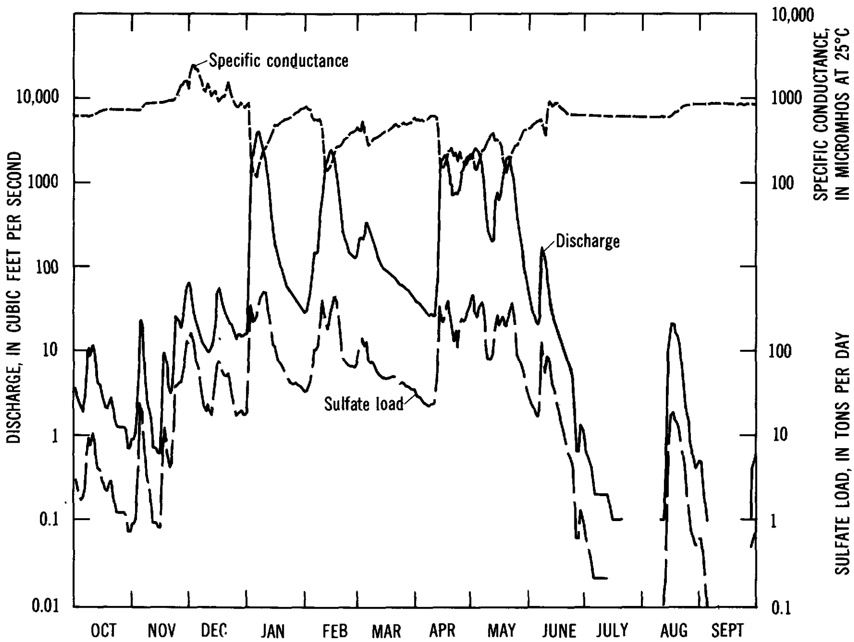

FIGURE 21.—Relationship of daily sulfate load, daily specific conductance, and mean daily discharge for the Tradewater River at Olney, for the water year 1966.

ductance, discussed above, which may vary directly or inversely with discharge or show little response to discharge. Thus, although mine drainage becomes less concentrated and presents less serious quality problems at higher flows, the magnitude of mine drainage as represented by total sulfate loads varies in direct response to stream discharge.

Figure 21 also shows the monthly variation in magnitude and concentration of mine drainage. The months of January–May show higher flows, higher sulfate loads, and lower concentration. Figure 22 is a graph showing the variation in mean monthly sulfate loads for the Tradewater River at Olney for the period 1952–67. The months of January through May are consistently high in the production of sulfate loads. Minimum loads have gone to zero for several months of the year in response to zero discharge.

LONG-TERM TREND

The mean sulfate load carried by the Tradewater River at Olney for the period 1955–67 was about 75 percent greater than the mean sulfate load for the period 1952–54 (table 15). A significant difference

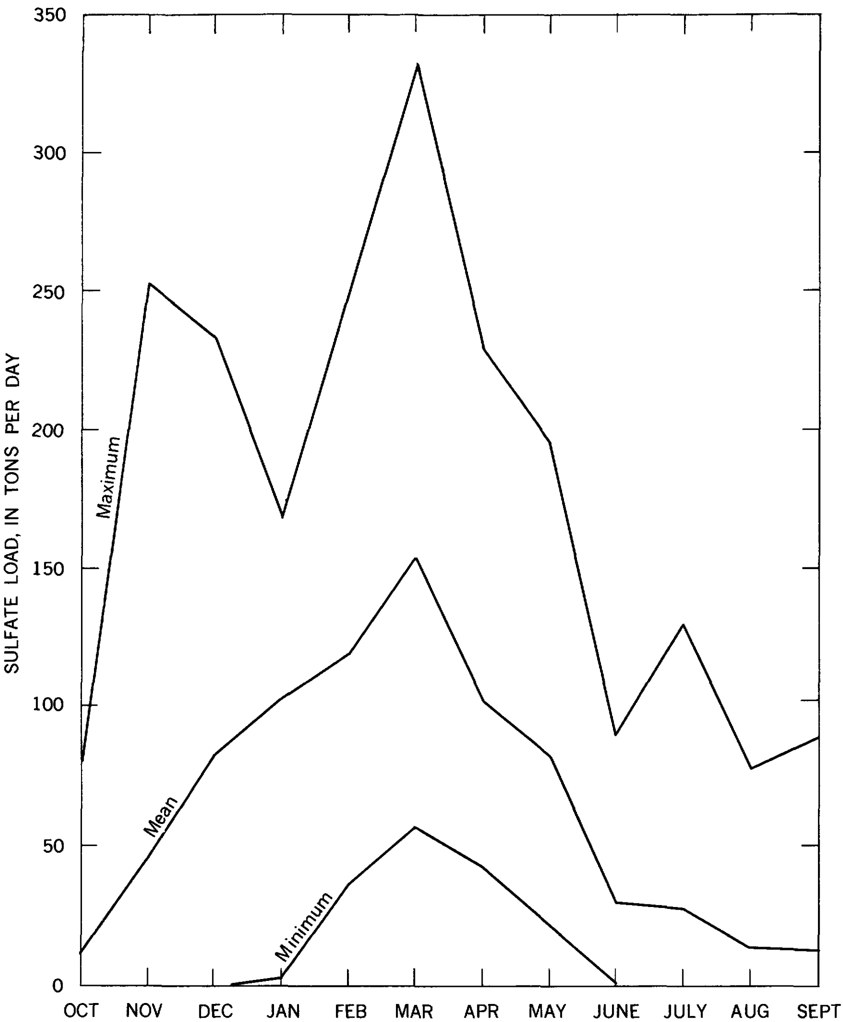

FIGURE 22.—Variation in mean monthly sulfate loads for the Tradewater River at Olney, 1952–67.

in the means of these two periods, which has a probability of 99.9 percent of not being due to chance alone, is shown by an analysis of covariance of the data (table 16). This increase in sulfate loads may reflect either a change in the amount of material exposed to accelerated chemical weathering or a change in the transporting mechanism. Representation of the transport mechanism and amount of material exposed by gross quantities, such as mean discharge and annual coal production respectively, does not explain the observed increase in sulfate loads. Mean discharge for the two periods is virtually the same, and figure 23 shows a similar range between the maximum annual discharges for each period. Moreover, coal-production data (fig. 24) used as an indicator of the amount of material exposed to accelerated weathering show the total amount of material exposed increasing at a decreasing rate. Thus, other aspects of the transport mechanism and more accurate measurements of the amount of material exposed to accelerated chemical weathering must be considered.

Several factors which may be proposed to account for the significant increase in sulfate loads between the periods 1952–54 and 1955–67 include the following: (1) intersection of abandoned underground mines by strip-mine operations, (2) mining of coals with higher sulfur content, and (3) timelag between peak coal-production period and maximum equilibrium rate of sulfate-load output.

TABLE 15.—*Annual sulfate loads and annual discharge for the Tradewater River at Olney, water years 1952–67*

[Sulfate loads calculated from conductance determinations of daily samples]

Water year	Annual discharge (cfs)	Annual sulfate load (tons per day)
Period 1		
1952	468	56.6
1953	295	41.1
1954	136	27.5
Mean	299.7	41.7
Period 2		
1955	284	51.7
1956	262	54.9
1957	328	68.6
1958	523	106.9
1959	182	61.6
1960	277	75.7
1961	382	87.4
1962	387	92.9
1963	165	52.7
1964	223	50.4
1965	374	94.6
1966	297	71.1
1967	231	77.2
Mean	301.2	72.8

TABLE 16.—*Analysis of covariance for sulfate loads and discharge for the Tradewater River at Olney, 1952–67*

	df	Σx^2	Σxy	Σy^2	*df*	$\Sigma \hat{y}^2$	Mean square	
Between periods	1	5.39	112.42	2,344.46	1	2,313.77	2,313.77	F=22.42.[1]
Within periods	14	170,484.36	23,294.14	4,524.23	13	1,341.43	103.19	$F_{(1,13).999}$=17.81.
Total	15	170,489.75	23,406.56	6,868.69	14	3,655.20		

[1] Significant at the 99.9-percent level.

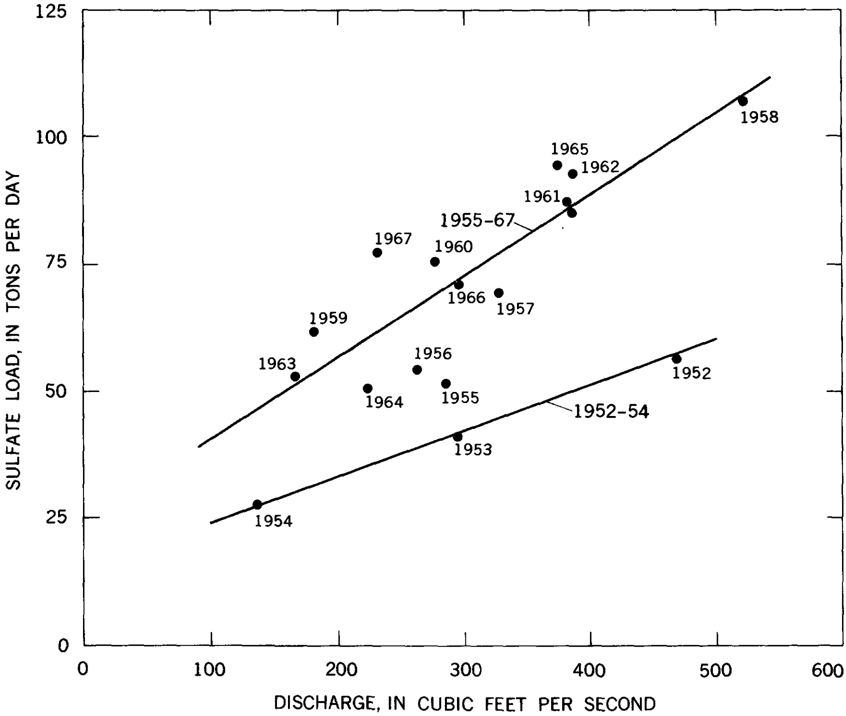

FIGURE 23.—Relationship of sulfate loads to discharge as represented by least square lines fitted to the data of table 15.

The increase in sulfate loads approximately coincides with the advent of "scavenger" strip-mine operations. These operations consist of entering previously strip-mined areas and working coal beds which were too deeply covered with overburden to be economically mined in the previous operations. In many instances coal beds are worked back to where they may have been mined out by the underground method. The barrier of rock and coal that once separated the underground mine from the surface is thus intersected, and mine water which previously had no outlet, a very restricted outlet, or an outlet at a higher altitude, is now allowed to enter streams at increased rates carrying large sulfate loads. Occurrences of these types are known, but the incidence of occurrence is not known. A few such intersections of large abandoned mines that contain water under great hydrostatic pressure could produce large sulfate loads, but data which could ascribe the significant increase in sulfate loads at Olney to these occurrences are lacking.

Coal which is of lower quality and has a higher sulfur content was being mined in increasing quantity by the late 1950's. Whether the

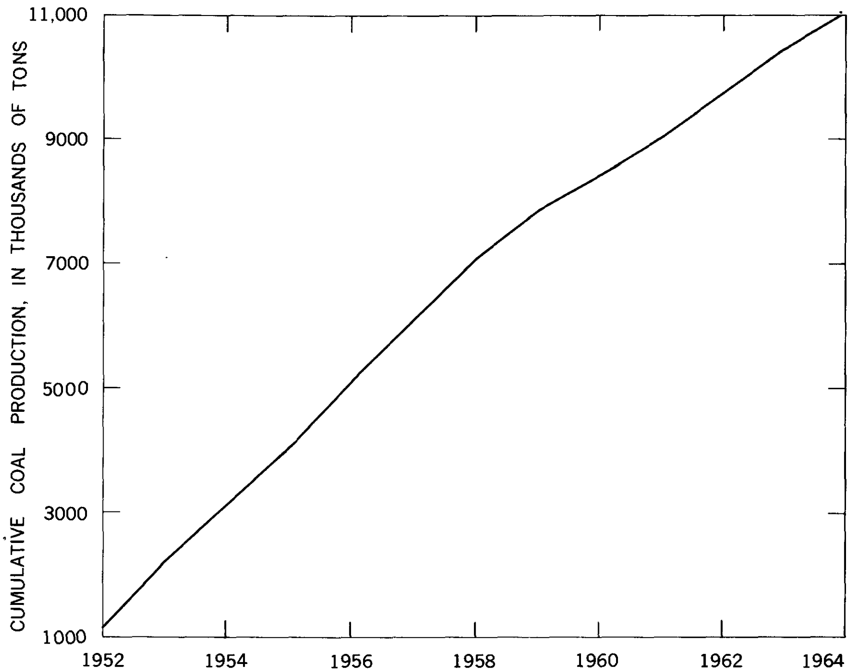

FIGURE 24.—Trend of total coal production in the Tradewater River basin above Olney, 1952–64. Data from Kentucky Department of Mines and Minerals.

overburden associated with lower quality coals is also higher in sulfuritic materials is not known; the sulfide contents of coals and disturbed overburden must be considered together when attempting to assess the magnitude of mine drainage as represented by sulfate loads from particular coal beds. However, high-sulfur coals considered by themselves would give rise to more concentrated sulfates and higher sulfate loads and must be mentioned as a factor in this discussion of increased sulfate load at Olney.

The last factor to be considered is a possible timelag between the peak strip-mine production period prior to 1952 and the increase in sulfate loads at Olney during the mid-1950's. The effects of mine drainage are initiated as soon as earth materials are disturbed, pyrite is exposed to air and water, and precipitation carries the sulfate loads to streams. Sulfate-load output increases toward a maximum equilibrium rate. The time required for attainment of this maximum equilibrium rate and its detection at Olney is not known; it probably varies with the various geologic and topographic conditions present in each mined-out area. The time required for the filling of lakes and ponds, the breaching of spoil dams by erosion, and neutralization by calcium carbonate materials—if any are present—are several important factors which must be considered in a timelag discussion.

SUSPENDED SEDIMENT

The trend of sediment loads for the November–April storm-runoff periods at Olney generally follows the trend of strip-mine coal production in the basin above Olney (fig. 25). November–April storm-runoff sediment loads for the period 1953–56 averaged 30 percent higher than for the period 1957–61 (table 17); average annual strip-mine coal production for this earlier period was 86 percent greater than for the later period. Moreover, sediment loads for the period 1962–66 averaged 51 percent higher than for the period 1957–61, while strip-mine coal production for the later period (1962–66) averaged 20 percent greater than for the 1957–61 period.

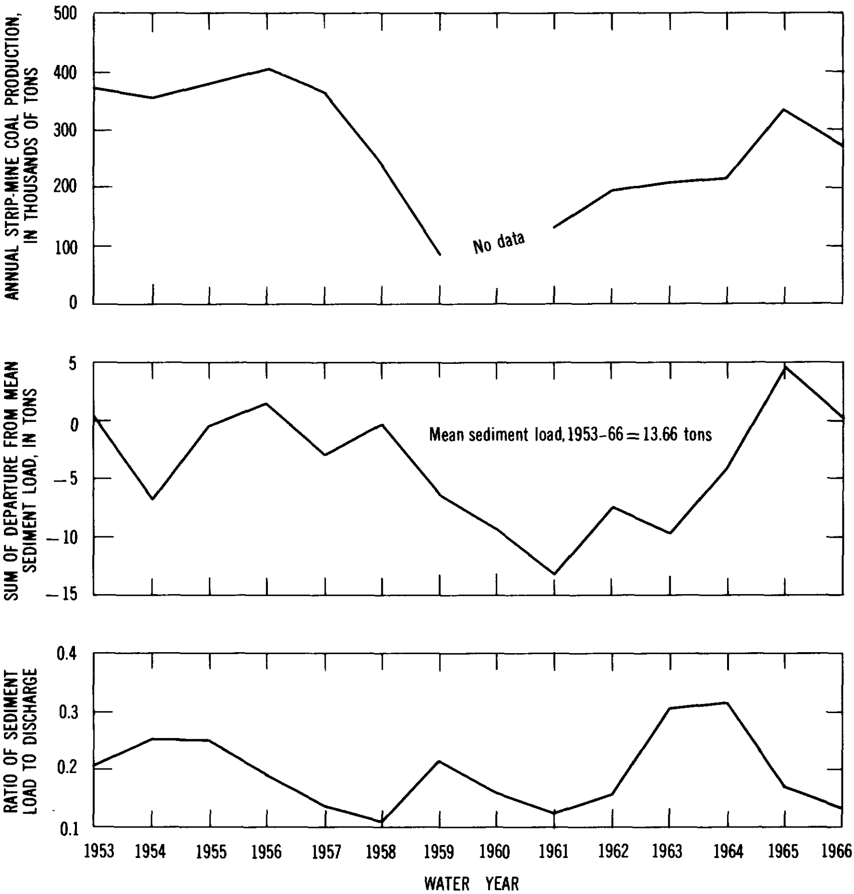

FIGURE 25.—Relation of annual strip-mine coal production in the Tradewater River basin above Olney, trend of November–April storm-runoff sediment loads carried by the Tradewater River at Olney, and ratio of sediment loads to discharge for water years 1953–66. Coal-production data from the Kentucky Department of Mines and Minerals. Data for 1960 are unavailable.

TABLE 17.—*November-April sediment loads and discharge for periods of storm runoff for the Tradewater River at Olney for the period October 1953–September 1966*

Water year	Total discharge (thousands of cfs-days)	Total sediment load (thousands of tons)
Period 1		
1953	65.90	13.69
1954	27.60	6.87
1955	82.76	19.99
1956	81.34	15.41
Mean	64.40	13.99
Period 2		
1957	68.34	9.34
1958	147.66	16.09
1959	36.68	7.83
1960	67.51	10.64
1961	82.39	9.95
Mean	80.52	10.77
Period 3		
1962	122.35	19.29
1963	36.93	11.29
1964	62.64	19.46
1965	136.16	22.22
1966	70.50	9.22
Mean	85.72	16.30

An analysis of covariance (table 18) of the data in table 17 (and presented graphically in fig. 26) shows that there is a difference in the mean sediment loads for the three periods when adjusted for differences in stream discharge. This difference has a probability of 90 percent of not being due to random variation and is explained in part by variations in strip-mining activities. The position of the plotted points in figure 26 seems to be extremely sensitive to changes in strip-mining activity as represented by the trend of strip-mine coal production from one year to the next shown in figure 25. This is illustrated by the 1954 and 1966 water-year data which plot along the curve representing a lower sediment production and transport rate, typical of the 1957–61 period, and the corresponding decrease in strip-mine coal production for these years compared with the preceding year. The increased strip-mine coal production in 1961 as compared with 1959 may indicate that the sensitivity of sediment production and

TABLE 18.—*Analysis of covariance of November-April sediment loads and discharge for periods of storm runoff for the Tradewater River at Olney*

	df	Σx^2	Σxy	Σy^2	*df*	$\Sigma \hat{y}^2$	Mean square	
Between periods	2	1,068.42	47.40	76.94	2	78.01	39.01	F=3.98.[1]
Within periods	11	15,762.13	1,586.82	257.68	10	97.93	9.79	$F_{(2,10).90}$=2.92.
Total	13	16,830.55	1,634.22	334.62	12	175.94	-------	$F_{(2,10).95}$=4.10.

[1] Significant at the 90-percent level.

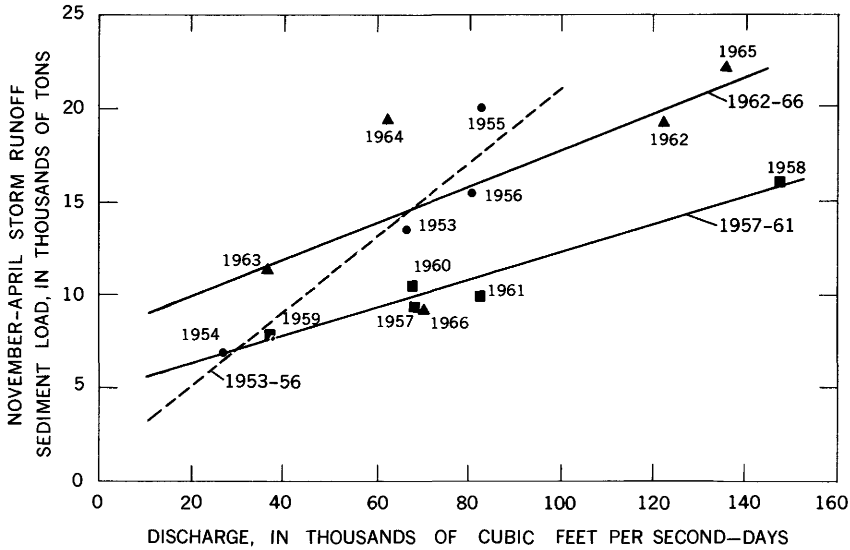

FIGURE 26.—Relationship of November–April storm-runoff sediment load to discharge for the Tradewater River at Olney as represented by least square lines fitted to data for the three periods.

transport to strip-mining activity is decreased below some threshold value of strip-mine coal production. However, the absence of data on strip-mine coal production for water year 1960 adds some uncertainty to the interpretation, especially in regard to the value of the threshold quantity.

The ratio of sediment load to discharge inadequately demonstrates rates of erosion and sediment transport at Olney. The 1954 data plot along the line representing a lower rate of sediment production and transport in figure 26, while the 1955 data plot well above the line representing a higher rate. The ratio of sediment load to discharge for these 2 years, however, is only slightly different as shown in figure 25. Other comparisons of this nature can be made between figures 25 and 26.

Furthermore, two levels of sediment production and transport may adequately represent the sediment regime as indicated by figure 26. Included in the lower level would be the years 1954, 1966, and the period 1957–61. Remaining years of data would be included in the higher level of sediment production and transport. Estimates of material exposed to accelerated erosion that are better than those based on annual strip-mine coal production would tend to quantify the relationship of the two levels.

SUBBASINS

The concentration of sulfate, one of the primary products of the oxidation of iron sulfide minerals, was 70 times higher in water discharged from the mined subbasins of Buffalo Creek and Cany Creek than the maximum observed in the water discharged from the nonmined subbasins of Piny Creek and Flynn Fork (table 19). Moreover, maximum observed concentrations of silica, iron, and aluminum were at least three, 30, and 300 times greater, respectively, in the water discharged from mined subbasins than in that discharged from nonmined subbasins.

Maximum fluoride concentration observed in water discharged from the mined subbasins was 10 times greater than in water discharged from the nonmined subbasins. The specific minerals which account for these higher fluoride concentrations are not known. However, a high correlation coefficient (>0.9) with total dissolved solids suggests that the minerals are well distributed among the materials giving the high dissolved-solids concentrations from the mined subbasins (maximum dissolved-solids concentration was 17 times greater than from nonmined subbasins).

Of all the observed chemical constituents in the streams of these four subbasins, only the concentrations of potassium, chloride, and nitrate were not significantly different between mined and nonmined areas. Bicarbonate concentration and pH values were the only chemical water-quality properties observed in these streams which were lower in the mined basins than in the nonmined basins.

Concentrations of mine drainage on the same order of magnitude as in Buffalo Creek and Cany Creek were observed at several sites in the Clear Creek subbasin. However, at low flows the discharge from Clear Creek near the mouth (at State Highway 293) is less than that observed in Richland Creek at State Highway 70 or in Clear Creek at State Highway 70 (table 8). This loss in flow, attributed to evapotranspiration in the extensive swamp along Clear Creek and to some temporary storage, means that the chemical constituents carried in the water from the mines are being concentrated (stored) in the swamp. These chemical constituents are not all temporarily stored and discharged into the Tradewater River during high flows; some may be taken out of solution by the soils. Preliminary data indicate that the pH of the soil in the swamp area is much lower than commonly observed in similar soil types in the basin (H. H. Bailey, University of Kentucky, oral commun., 1968).

Craborchard Creek, which discharges into the Tradewater River through Vaughn Ditch, carries concentrations of sulfate, iron, manganese, and dissolved solids of the same order of magnitude as ob-

TABLE 19.—*Summary of selected physical and chemical parameters at sampling sites on Buffalo Creek at State Highway 1338, Cany Creek near mouth, Flynn Fork near mouth, and Piny Creek near mouth below Lake Beshear reservoir, 1965–67*

[Data from table 8. Data in milligrams per liter, except as indicated]

Parameter	Buffalo Creek				Cany Creek				Piny Creek				Flynn Fork			
	Minimum	Maximum	Mean	Number of observations	Minimum	Maximum	Mean	Number of observations	Minimum	Maximum	Mean	Number of observations	Minimum	Maximum	Mean	Number of observations
Discharge (cfs)	0.01	35	7.7	16	0.50	44	10	13	0.10	95	15	10	0.10	34	8.3	10
Silica (SiO_2)	12	30	23	6	18	56	39	5	4.9	6.4	5.6	4	9.5	9.8	9.6	3
Aluminum (Al)	9.3	36	25	6	15	87	39	6	.0	.10	.02	4	.00	.10	.03	3
Iron (Fe)	.22	25	5.2	6	3.3	39	15	6	.16	.22	.19	4	.00	.79	.48	4
Manganese (Mn)	4.7	85	41	6	5.2	28	15	6	.0	.37	.14	4	.07	3.2	.90	4
Calcium (Ca)	83	353	237	4	85	278	190	3	9.5	14	12	3	42	46	44	2
Magnesium (Mg)	61	450	300	4	50	156	109	3	1.7	2.6	2.2	3	5.4	5.9	5.6	2
Sodium (Na)	8.3	30	21	5	10	24	18	3	1.6	2.3	1.9	2	6.0	6.1	6.0	2
Potassium (K)	2.1	6.2	4.4	4	1.8	3.9	2.9	3	.80	1.3	1.0	2	2.1	2.9	2.5	2
Bicarbonate (HCO_3)	0	0	0	6	0	0	0	6	28	46	35	5	102	149	135	4
Carbonate (CO_3)	0	0	0	6	0	0	0	6	0	0	0	5	0	0	0	4
Sulfate (SO_4)	530	3,130	1,842	6	548	2,060	1,264	6	12	15	13	5	18	29	23	4
Chloride (Cl)	4.0	12	7.0	6	5.0	18	9.0	6	.0	2.0	.80	5	4.0	6.0	4.7	4
Fluoride (F)	.60	3.0	1.9	6	.80	2.1	1.6	6	.0	.10	.04	5	.10	.30	.20	4
Nitrate (NO_3)	.30	2.2	1.5	6	.20	1.9	.80	4	.30	1.0	.72	5	.40	1.8	1.1	3
Dissolved solids	768	4,590	2,741	6	796	3,040	1,911	6	50	60	55	5	144	175	160	4
Hardness as $CaCO_3$:																
Calcium, magnesium	458	2,730	1,693	6	418	1,600	1,030	6	34	46	38	5	110	139	126	4
Noncarbonate	458	2,730	1,693	6	418	1,600	1,030	6	8.0	11	9.4	5	6.0	26	16.2	4
Total acidity as H^{+1}	1.5	7.2	4.0	6	2.6	14	7.6	6	---	---	---	0	---	---	---	0
Specific conductance (micromhos at 25°C)	974	4,100	2,370	16	1,120	3,220	2,183	13	89	220	117	10	240	360	286	10
pH	3.2	4.6	3.9	15	2.8	3.5	3.1	12	6.0	7.5	7.0	10	6.0	8.2	7.0	10

served in Buffalo Creek and Cany Creek. Observed aluminum and silica concentrations in Craborchard Creek were less than in other mined subbasins—this may be related to the relatively high pH observed in this stream. Bicarbonate concentrations in Craborchard Creek below Clay were of the same order of magnitude as the maximum bicarbonate concentration observed in the nonmined subbasins.

A comparison of sulfate loads contributed by Buffalo Creek and Cany Creek during periods of base flow permits an evaluation of some of the important differences which exist in the two subbasins (see table 20). Cany Creek has a drainage area approximately 1.7 times as large as Buffalo Creek and a total strip-mined area about one-half as large.

Base flows are greater at Cany Creek than at Buffalo Creek in the medium to high range; base flow in Buffalo Creek recedes to about 1 cfs, whereas base flow in Cany Creek generally recedes to zero. Sulfate concentrations are equal on both streams at high base flows (above 6 cfs at Cany Creek); they are greatly increased in Buffalo Creek at low base flows (less than 3 cfs at Buffalo Creek) but only slightly increased in Cany Creek (table 20).

Cany Creek has about three times the sulfate load per square mile of stripped area as Buffalo Creek at high base flows (table 20); the values are nearly equal at low base flows of about 1 cfs in both streams. One important difference between the two basins is the total absence of known drainage from underground mines in the Buffalo Creek basin. Both streams receive drainage from strip-mined areas, but Cany Creek receives a significant amount of drainage from underground mines as well.

TABLE 20.—*Comparison of Cany Creek and Buffalo Creek at base-flow periods showing stream discharge, sulfate concentration, and sulfate load per square mile of strip-mined area*

Date of measurements	Cany Creek (3-3828.55) Drainage area: 25.6 sq mi Strip-mined area: 0.77 sq mi			Buffalo Creek (3-3827.2) Drainage area: 15.1 sq mi Strip-mined area: 1.43 sq mi			Ratio of loads per square mile (Cany Creek: Buffalo Creek)
	Discharge (cfs)	Sulfate concentration (mg/l)	Sulfate load (tons per square mile of strip-mined area)	Discharge (cfs)	Sulfate concentration (mg/l)	Sulfate load (tons per square mile of strip-mined area)	
1966							
Feb. 15–16	44	548	84.4	26	530	25.9	3.2
June 14	5.5	1,160	22.1	3.1	1,740	9.8	2.2
Dec. 1	5.3	1,410	26.2	1.7	1,950	6.3	4.2
Dec. 14	30	775	81.6	11	920	19.1	4.3
1967							
Jan. 5	6.8	1,025	24.4	6.5	1,090	13.4	1.8
Feb. 9–10	13	725	33.0	6.8	850	10.9	3.0
Mar. 30	11.8	908	37.7	5.7	1,090	11.9	3.2
Apr. 24–25	10	1,200	42.1	5.3	1,310	13.1	3.2
June 13	.92	1,260	3.0	1.1	2,040	3.0	1.0
Oct. 4	1.0	1,375	4.8	1.3	2,300	4.0	1.2

The greater sulfate load per square mile of strip-mined area at Cany Creek is at least partly due to the load contributed from underground mines. The smaller difference between the sulfate loads in Cany Creek and Buffalo Creek at very low flows reflects a relative decrease in flow at Cany Creek and a relative increase in sulfate concentration at Buffalo Creek. These factors may reflect the location of the two sampling and gaging sites (index Nos. 3–3828.55 and 3–3827.2 on pl. 1): Cany Creek is measured near the mouth after flowing through an extensive swampy area; Buffalo Creek is measured nearer to the source of mine drainage in a channel that has a relatively steep gradient. Under such conditions the mine drainage in Cany Creek may undergo considerable loss in volume due to evapotranspiration and perhaps dilution in the swamp area; in contrast, Buffalo Creek continues to receive a relatively undiminished contribution of mine drainage.

MAIN STEM OF THE TRADEWATER RIVER

The magnitude of water-quality changes due to mine drainage in the main stem of the Tradewater River for three selected periods is shown in the graph on plate 1 by large increases in concentrations of sulfate, calcium, and magnesium and decreases in concentration of bicarbonate at Dawson Springs. This change in water quality is the result of the discharge of Buffalo Creek and Cany Creek into the river just upstream from Dawson Springs. The concentrations of sulfate, calcium, and magnesium decrease with distance downstream from Dawson Springs. This decrease in concentration below Dawson Springs is the result of dilution from the major nonmined-area tributaries of Flynn Fork and Donaldson Creek and from other nonmined areas during the February period. Water remaining in numerous pools in the Tradewater River after the high flow periods is less mineralized than the water which enters the river from the major mined subbasins of Buffalo Creek and Cany Creek. Mixing of this more highly mineralized mine water with the less mineralized water in the pools appears to be the most significant factor involved in the decrease in concentrations during periods when the nonmined streams are not flowing. These decreased concentrations together with decreased flow downstream, mainly the result of evapotranspiration from the numerous pools, result in a decrease in sulfate loads between Dawson Springs and Olney during low-flow periods.

Water from the Clear Creek subbasin enters the Tradewater River below Highway 293 and results in increased concentrations of calcium, magnesium, and sulfate observed at Providence and Montezuma Bridge. During the November period the concentration of sodium, as well as the concentrations of sulfate, magnesium, and calcium, increased from Providence to Highway 60–641. This increase was due to a relatively high sodium content in water from Vaughn Ditch (Craborchard Creek), which enters the river a few miles upstream from Highway 60–641.

METHODS FOR REDUCING EFFECTS OF MINE DRAINAGE ON STREAMS

Prevention of the adverse effects of mine drainage cannot be realized in the Tradewater River basin by application of only one of the numerous methods which have been proposed by researchers in this field. In view of experience in other areas and the present understanding of the geochemical processes in mined areas, the possible effects of any method of prevention or control of this problem should be carefully evaluated.

The various prevention and control methods used elsewhere in the Nation can be grouped into two broad categories: (1) the prevention or minimization of acid formation, and (2) the treatment and regulation of acid water once it has formed. Results which might be expected by the application of these methods in the Tradewater River basin will be considered in this section.

PREVENTION OR MINIMIZATION OF ACID FORMATION

Two methods that have been suggested for prevention or minimization of acid formation are flooding and air sealing of abandoned underground mines. The effectiveness of general application of the two methods is questionable. Pollio and Kunin (1967) described the air-sealing method as not generally effective. The effectiveness of the flooding method has been questioned by Barnes and Clarke (1964) who proposed a geochemical model for the oxidation of iron minerals in the absence of air. Barnes, Stuart, and Fisher (1964) presented field observations from underground mines in Pennsylvania which verify the theoretical model. An implication of this model is that an actual increase in concentration of iron, sulfate, and other chemical constituents in the water may result from the flooding of abandoned underground mines in an attempt to exclude air. (The increase in concentration could be due to the reaction of pyrite with water; the reaction would continue until equilibrium is reached.) In addition, the amount of water discharged from underground mines which are sealed may not be changed, since hydrologic isolation of mines is impractical.

The diversion of water from mined areas, a third method which is often proposed and is beneficial in some cases, has limited applicability in the absence of practical methods of isolating large areas hydrologically.

The covering of sulfide materials in strip-mined areas as required by present Kentucky laws and regulations may not significantly reduce concentrations of iron, sulfate, and other chemical constituents in the water discharged from these mined areas, particularly where a permanent impoundment maintains a high water level in the spoil banks. The reaction of pyrite with water in the spoil bank may increase the dissolved solids as noted above.

An understanding of geochemical processes in mined areas is essential before methods of prevention or minimization of acid formation can be expected to give consistently desirable results.

TREATMENT AND REGULATION OF ACID WATER

The application of methods of treatment and regulation of acid water appears to hold more promise in the Tradewater River basin than application of those in the category just considered. However, the methods of treatment and regulation are not ideal solutions to the problem and are less desirable than those prevention methods which do give predictable improvement in water quality.

Neutralization and dilution of the drainage from coal mines in the Tradewater River basin may be improved by putting limestone in the beds of selected streams and by building low-flow regulating reservoirs in nonmined areas. The use of limestone in the streambed of Montgomery Creek, Flynn Fork, Donaldson Creek, Piny Creek, and the Tradewater River above Collins Bridge may increase the capacity of these streams to neutralize the acidic water from the mined subbasins. This placement of limestone in streams draining nonmined areas would avoid the problem of iron hydroxide precipitating on the limestone (which has been found in some areas when the limestone is placed in streams carrying drainage from coal mines). The use of limestone would be ineffective at the time when pH values are lowest in the main stem of the river, owing to conditions of no flow in the above-mentioned streams, unless low-flow augmentation reservoirs are constructed. Impoundments which are upstream from the areas treated with limestone and are capable of releasing water during periods of low flow may both neutralize and dilute the mine drainage during the periods when streams from nonmined areas are normally dry.

The diversion of mine drainage presents only a localized avoidance of the problem. This method is used to protect local high-value areas, such as Loch Mary Reservoir at Earlington, where water from a strip-mined area is diverted around the town's water supply.

Some proposed methods of treatment which may become important in the future but are either uneconomical now or require further

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evaluation include biological treatment with sulfate-reducing bacteria and treatment by ion-exchange processes. Further references on the prevention and treatment of mine-drainage pollution are given in Brant and Moulton (1960), Lorenz (1962), Moulton (1957), and Pollio and Kunin (1967).

SUMMARY AND CONCLUSIONS

The impact of coal-mining activity on the water resources of the Tradewater River basin is summarized below:

1. The major subbasins contributing mine drainage to the Tradewater River are Buffalo Creek, Cany Creek, Clear Creek, and Craborchard Creek (Vaughn Ditch).
2. Streamflow is sustained during extended periods of no precipitation in Buffalo Creek, Cany Creek, and Craborchard Creek, owing to drainage from mined areas, while streams in nonmined subbasins cease flowing.
3. The water from streams in the mined areas is highly mineralized. Total dissolved-solids concentrations were 17 times greater in the water discharged from mined subbasins than in the water discharged from nonmined subbasins.
4. The maximum observed values of 13 chemical and physical water-quality parameters were three to 300 times greater in the discharge from mined subbasins than in discharge from nonmined subbasins. Potassium, chloride, and nitrate concentrations were not significantly different between mined and nonmined areas. Minimum bicarbonate concentrations and pH values were lower in mined subbasins than in nonmined subbasins.
5. A sulfate water having a relatively high pH and high sodium content compared with other water affected by mine drainage is discharged into the Tradewater River from the Craborchard Creek subbasin.
6. The effects of coal-mine drainage in the Tradewater River decrease from Dawson Springs to Olney in response to dilution and neutralization.
7. The mean sulfate load carried by the Tradewater River at Olney was about 75 percent greater in the period 1955–67 than in the period 1952–54.
8. The trend of sediment loads carried by the Tradewater River at Olney for the November–April storm-runoff period generally follows fluctuations in strip-mine coal production in the basin above Olney.

9. The combined use in nonmined subbasins of crushed limestone in the streambed and low-flow augmenting reservoirs appears to be the most promising method for alleviating the effects of mine drainage in the basin.
10. Water type similar to that found in coal-mine drainage occurs naturally in the ground water of the basin.
11. Contamination of ground water by waters from coal-mining areas was not observed in this study.

The great variability in ground-water quality, the generally low yield of the aquifers in the basin, and a frequent condition of no flow in the Tradewater River at Olney limit alternatives for major water-resources development in the basin. Other limitations are the result of the quality of water in the stream system of the basin as noted above. Large coal reserves are present in the basin, and the demand for coal and for water supplies is increasing. Thus, intensive studies are needed for obtaining the optimum development of deep aquifers and surface reservoir sites and for finding ways of alleviating the problems caused by coal-mining activities. Fruitful areas for study seem to be (1) evaluation of the effects of recent strip-mine laws and regulations on the total quality of the water resources, and (2) an intensive study of geochemical processes in mined areas, both surface and subsurface. A study should be made of the transport mechanism of mine drainage and the optimum mix of water-quality-control alternatives such as neutralization, dilution, and possible control of geochemical processes at the source.

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TABLE 8

TABLE 8.—*Miscellaneous analyses of*

[Chemical analyses

Date of collection	Discharge (cfs)	Silica (SiO_2)	Aluminum (Al)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Bicarbonate (HCO_3)
3-3826. Tradewater River at Pooles Mill Bridge,											
Feb. 15, 1966	107			0.52	0.11						42
June 13											
3-3826.5. Castleberry Creek at bridge at mouth,											
Feb. 15, 1966	23			0.06	1.0						12
May 10	7.3	11	.0	.19	.63	24	12	4.4	1.2		18
June 13	.37	12	.00	.0	.77						14
3-3826.8. Tradewater River at Collins Bridge,											
Nov. 18, 1965 [1]	0.35	8.7	0.0	2.0	4.8						120
Feb. 15, 1966	155			.26	.20						34
May 10	38	12	.1	.22	.24	19	6.6	3.6	0.9		52
June 14	3.2	8.3	.0	.10	.74						73
July 18	.02										
Aug. 18	.21	7.4	.0	.44	2.7	24	5.0	4.9	2.4		98
Sept. 13	.01	17	.0	.32	1.9	27	6.2	4.7	2.2		116
Oct. 20	.003										
Dec. 1	5.0										
Dec. 14	53										
Jan. 5, 1967	32										
Feb. 9	38										
Mar. 29	34	8.1	.0	.56	.00	19	5.2				48
Apr. 24	28										
Apr. 26	35										
June 13	2.1	7.3	.1	.28	.26	26	4.3	4.9	1.8		88
Oct. 5	.2										
3-3826.85. Tradewater River at Murphy Ford,											
Sept. 14, 1966	0.01		0.0								130
3-3827.2. Buffalo Creek at State Highway 1338,											
Feb. 15, 1966	26	12	9.3	1.9	15	83	61	8.3	2.1		0
June 14	3.1	26	27	.22	4.7						0
July 19	.26										
Aug. 18	1.0	30	36	25	70	254	386	29	6.2		0
Sept. 14 [2]	.09	30	34	1.8	85	353	450	30	5.2		0
Oct. 20	.83										
Dec. 1	1.7										
Dec. 14	11										
Jan. 5, 1967	6.5										
Feb. 9	6.8										
Mar. 30	5.7	18	16	1.0	29			12			0
Apr. 24	5.3										
Apr. 26	18										
Apr. 26	35										
June 13	1.06	25	26	1.3	45	258	304	25	4.1		0
Oct. 4	1.3										

See footnotes at end of table.

streams in Tradewater River basin

in milligrams per liter]

Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphorus as PO_4	Dissolved solids (residue at 180° C)	Hardness as $CaCO_3$: Calcium magnesium	Hardness as $CaCO_3$: Noncarbonate	Total acidity as H^{+1}	Specific conductance (micromhos at 25°C)	pH	Color	Turbidity	Temperature (°C)
near Dawson Springs (lat 37°04'30", long 87°34'46")														
0	21	2.0	0.0	1.3		80	52	18		128	6.9			
										170	7.1			
near Dawson Springs (lat 37°05'22", long 87°35'12")														
0	89	2.0	0.0	0.6		158	89	79		225	6.9			5.5
0	102	2.0	.1	.3		166	110	94		275	6.5	2		12
0	168	2.0	.1			272	174	163		398	6.7	3		
near Dawson Springs (lat 37°07'00", long 87°37'20")														
0	4.0	4.0	0.1			132	102	4	0.3	210	6.8	16	3	8
0	32	2.0	.0	1.3		94	56	28		143	7.1			5.5
0	39	3.0	.0	.8	0.20	128	74	32		184	6.8	3		14.5
0	34	4.0	.0			125	84	24		208	7.3	5		
										220	7.3			
0	7.2	4.5	.1	2.1		101	80	0		184	6.8	7		
0	4.4	5.0	.2	1.3		124	93	0		204	7.1			21
										220	6.2			
										225	6.0			
										190	6.6			
										190	7.0			
										180	7.0			
0	37	4.0	.0	.3		107	69	30		177	7.1			
										200	5.9			
										180	6.9			
0	19	3.0	.1	1.2		112	82	10		192	7.4	4		23
										250				
near Dawson Springs (lat 37°08'49", long 87°39'00")														
0	6.0	6.0	0.2	1.7		116	94	0		237	6.9			20
near Dawson Springs (lat 37°08'29", long 87°36'54")														
0	530	6.0	0.6	0.3		768	458	458	1.5	974	4.2			5
0	1,740	8.0	1.7			2,590	1,740	1,740	3.5	2,630	3.6	3		
										3,400	3.4			
0	2,520	12	2.7	2.0		3,810	2,220	2,220	7.2	3,540	3.3	5		31.5
0	3,130	8.0	3.0	1.8		4,590	2,730	2,730	5.6	4,100	3.9	10		24.5
										3,500	3.5			
										2,800.	3.2			
										1,500	4.2			
										1,700	4.4			
										1,400	4.6			
0	1,090	4.0	1.2	1.2		1,670	1,110	1,110	2.8	1,740	4.4			
										2,000	3.5			
										1,275	4.3			
										1,200	4.4			
0	2,040	4.0	2.4	2.2		3,020	1,900	1,900	3.4	2,910	3.6	2		30
										3,250				

TABLE 8.—*Miscellaneous analyses of streams*

Date of collection	Discharge (cfs)	Silica (SiO_2)	Aluminum (Al)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Bicarbonate (HCO_3)
3-3827.25 Buffalo Creek at Hamby Ford, near											
Nov. 18, 1965	0.90	29	46	3.5	80						0
3-3827.35. Cany Creek 0.8 mile above Fox Run, near											
Dec. 21, 1965	0.02	30	23	0.27	19			36	2.5		0
3-3827.39. Unnamed tributary to Cany Creek at Highway											
Dec. 21, 1965	0.46	12	1.6	0.78	21			55	7.2		6
3-3827.55. Fox Run Creek at U.S. Highway 62,											
Dec. 21, 1965	0.31	52	74	91	26						0
3-3827.7. Cany Creek at bridge at St.											
Dec. 22, 1965	0.58	44	65	54	22						0
3-3827.8. Unnamed tributary to Cany Creek at Highway											
Dec. 22, 1965	0.05	57	45	16	13			18	3.2		0
3-3828. Cane Run Creek at mouth near St.											
Dec. 22, 1965	0.10	36	33	3.5	26						0
3-3828.35. Copperas Creek at highway bridge											
June 9, 1966	0.74	40	80	29	13						0
July 6	.23	51	149	218	19	508	195	62.	9.0		0
Oct 21	.13		217	687	26						0
Dec. 2	.19		211	551	44						0
Dec 15	.79	52	146	320	1.2	387	166				0
Jan. 4, 1967	.50	51	138	279	21	357	160				0
Mar. 31	.74		84	76	16						0
Apr. 25	.68		107	202	37						0
June 14	.36	43	87	212	15	516	158	30	4.7		0
Oct. 5	.19										
3-3828.45. Copperas Creek at U.S. Highway 62											
Dec. 22, 1965	0.24	56	150	180	32						0

See footnotes at end of table.

in Tradewater River basin—Continued

Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphorus as PO_4	Dissolved solids (residue at 180° C)	Hardness as $CaCO_3$: Calcium magnesium	Hardness as $CaCO_3$: Noncarbonate	Total acidity as H^{+1}	Specific conductance (micromhos at 25°C)	pH	Color	Turbidity	Temperature (°C)
Dawson Springs (lat 37°08′52″, long 87°38′13″)														
0	2,710	10	2.5			4,040	2,640	2,640	5.8	3,660	3.5	3	10	5.5
St. Charles (lat 37°11′03″, long 87°31′33″)														
0	1,030	6.0	1.4			1,500	840	840	3.1	1,650	4.3	5	0.2	7
62, near St. Charles (lat 37°11′06″, long 87°31′30″)														
0	2,160	6.0	0.7	165		3,240	2,320	2,310	0.6	3,280	5.3	3	3.10	2
near St. Charles (lat 37°11′14″, long 97°32′22″)														
0	2,450	12	2.0			3,610	2,040	2,040	5.8	3,850	2.8	10	2	6.5
Charles (lat 37°10′51″, long 87°33′16″)														
0	2,080	8.0	1.7			3,020	1,760	1,760	9.9	3,340	2.9	5	4	1
62, at St. Charles (lat 37°10′57″, long 87°33′21″)														
0	1,020	10	2.4	2.4		1,660	900	900	6.4	2,000	3.1	3	9	6.5
Charles (lat 37°10′51″, long 87°34′41″)														
0	1,150	10	2.0			1,700	1,030	1,030	4.8	1,860	3.7	3	1	6
near Ilsley (lat 37°12′08″, long 87°37′26″)														
0	2,640	4.0	3.1			3,680	1,820	1,820	19	4,550	2.5	10		29
0	3,670	6.0	3.0	0.9		5,480	2,070	2,070	42	5,680	2.6	25		34
0	4,460	15		3.7		6,030	2,040	2,040	21	5,920	2.6			13
0	4,160	5.0		5.2		5,810	1,900	1,900	18	5,450	2.7			3
0	2,960	2.0	2.6	1.8		4,190	1,650	1,650	34	4,610	2.8			
0	2,760	4.0	2.8	2.6		3,850	1,550	1,550	27	4,410	3.2			6
0	2,290	10	3.0	2.8		3,290	1,700	1,700	17	3,980	2.7			
0	2,260	4.0		.6		3,170	1,400	1,400	19	3,940	2.6			13.5
0	2,800	36	3.2	4.8		4,050	1,940	1,940	20	4,460	2.7	10		30.5
										4,500				
near St. Charles (lat 37°11′08″, long 87°36′57″)														
0	2,670	34	2.6			3,760	1,880	1,880	11	4,000	2.7	35	15	7

TABLE 8.—*Miscellaneous analyses of streams*

Date of collection	Discharge (cfs)	Silica (SiO_2)	Aluminum (Al)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Bicarbonate (HCO_3)
3-3828.55. Cany Creek at mouth near Dawson											
Nov. 17, 1965 [3]	0.48	56	87	39	28						0
Feb. 16, 1966	44	18	15	6.8	5.2	85	50	10	1.8		0
June 14	5.5	36	27	5.0	12						0
Aug. 18	4.6	44	46	20	17	278	156	24	3.1		0
Oct. 20	2.1										
Dec. 1	5.3										
Dec. 14	30										
Jan. 5, 1967	6.8										
Feb. 10	13										
Mar. 30	11.8		23	3.3	11						0
Apr. 25	10										
June 13	.92	40	36	18	16	208	121	21	3.9		0
Oct. 4	1.0										
3-3828.7. Tradewater River at State Highway 109, at											
Sept. 15, 1966	0.24	24	26	5.4	23	21.1	146	13	3.7		0
Oct. 20	2.6										
Dec. 1	7.3										
Dec. 15	95										
Jan. 5, 1967	65										
Feb. 10	65										
Mar. 30	59	10	5.5	.47	.0	53	42				0
Apr. 24	59										
June 13	6.9	16	8.7	5.5	13	94	88	10	2.4		0
3-3882.9. Piny Creek below Lake Beshear Dam, near											
Feb. 17, 1966	95										32
June 15	1.2	6.0	0.0	0.16	0.00						34
July 19	.02										
Sept. 14	.44	6.4	0	.20	.37	14	2.6	2.3	0.8		46
Oct. 20	.35										
Dec. 15	13										
Jan. 5, 1967	18										
Mar. 28	16	5.2	.1	.18	.14	9.5	2.4				28
Apr. 25	1.8										
June 13	.59	4.9	.0	.22	.04	12	1.7	1.6	1.3		33
3-3828.92. Tradewater River at Dam at Dawson											
Nov. 18, 1965	0.84	31	28	20	31						0
June 13, 1966	25	13	5.4	.03	6.2						0
July 19	.34										
Sept. 14	.49	22	31	1.6	26	214	175	17	3.4		0
Dec. 1											
3-3828.94. Tradewater River at abandoned bridge, below											
Feb. 16, 1966	466	8.3	1.9	0.59	2.6	24	20	4.8	1.4		1
June 13	25	14	5.3	.15	6.0						0
Aug. 17	11	21	24	2.1	24	206	165	20	4.0		0
3-3829. Montgomery Creek near mouth, at Illinois Central											
June 15, 1966	0.13	5.5	0.0	0.03	0.61						113

See footnotes at end of table.

in Tradewater River basin—Continued

Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphorus as PO_4	Dissolved solids (residue at 180° C)	Hardness as $CaCO_3$: Calcium magnesium	Hardness as $CaCO_3$: Noncarbonate	Total acidity as H^{+1}	Specific conductance (micromhos at 25°C)	pH	Color	Turbidity	Temperature (°C)
Springs (lat 37°09′49″, long 87°39′47″)														
0	2,060	10	2.1			3,040	1,600	1,600	14	3,220	2.8	10	0.4	10
0	548	5.0	.8	0.2	0.28	796	418	418	2.6	1,120	3.4			6
0	1,160	6.0	1.4			1,720	1,040	1,040	6.4	2,330	2.9	4		
0	1,650	18	1.9	1.9		2,560	1,340	1,340	12	3,020	2.8	5		25.5
										2,900	2.9			
										2,400	2.8			
										1,450	3.4			
										1,850	3.5			
										1,400	3.5			
0	908	10	1.3	0.5		1,350	760	760	4.2	1,820	3.2			
										2,100	3.1			
0	1,260	5.0	1.9	.6		2,000	1,020	1,020	6.7	2,420	3.0	4		24.5
										2,350				
Dawson Springs (lat 37°09′03″, long 87°40′29″)														
0	1,340	10	2.0	0.6		1,980	1,140	1,140	4.6	2,220	3.7	5		20
										2,600	3.5			
										2,200	3.2			
										700	4.6			
										600	5.0			
										580	4.5			
0	338	6.0	.2	.1		524	305	305	.8	719	4.5			
										690	4.3			
0	620	3.0	.7	.9		934	597	597	1.6	1,210	3.6	1		23.5
Dawson Springs (lat 37°08′53″, long 87°40′55″)														
0	12	0.0	0.0	0.9		50	34	8		90	7.3			
0	14	2.0	.1	.7		51	39	11		91	6.9	15		26.5
										135	7.2			
0	13	1.0	.1	.3		60	46	8		104	7.0			24.5
										110	6.9			
										110	6.9			
										120	6.7			
0	15	1.0	.0	1.0		57	34	10		100	7.5			
										220	6.0			
0	13	.0	.0	.7		55	37	10		89	7.5	6		25.5
Springs (lat 37°09′42″, long 87°41′50″)														
0	1,450	8.0	0.8			2,160	1,360	1,360	6.0	2,390	3.2	5	10	11.5
0	380	3.0	.4			577	336	336	1.1	851	3.6	2		
										1,450	3.6			
0	1,440	10	2.0	1.2		2,120	1,260	1,260	5.3	2,290	3.8	5		22
										2,100	3.0			
Dawson Springs Dam, at Dawson Springs (lat 37°09′39″, long 87°42′01″)														
0	158	2.0	0.1	0.5	0.04	234	142	142	0.4	368	4.8			5.5
0	374	4.0	.4			576	342	342	1.2	806	3.7	2		
0	1,320	10	1.5	.6		1,930	1,190	1,190	5.0	2,200	3.5	3		25.5
Railroad near Dawson Springs (lat 37°09′12″, long 87°42′11″)														
0	28	2.0	0.1			150	113	20		258	7.3	5		

TABLE 8.—*Miscellaneous analyses of streams*

Date of collection	Discharge (cfs)	Silica (SiO_2)	Aluminum (Al)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Bicarbonate (HCO_3)
3-3829.1. Tradewater River at bridge at West Kentucky											
Sept. 14, 1966	0.66	17	22	0.96	24	206	165	17	3.8	--	0
3-3829.25. Tradewater River at bridge southwest of Union Grove											
July 13, 1966	0.29	--	--	--	--	--	--	--	--	--	--
Sept. 14	.04	2.8	0.8	0.80	18	113	103	12	3.2	--	0
Oct. 20	4.1	--	--	--	--	--	--	--	--	--	--
3-3829.8. Flynn Fork (creek) at Creekmur Bridge,											
June 16, 1966	2.7	9.5	0.0	0.00	0.16	--	--	--	--	--	140
Aug. 17	1.04	9.5	--	.60	3.2	42	5.4	6.0	2.9	--	148
Oct. 20	.004	--	--	--	--	--	--	--	--	--	--
Nov. 30	.2	--	--	--	--	--	--	--	--	--	--
Dec. 15	11	--	--	--	--	--	--	--	--	--	--
Jan. 6, 1967	7.4	--	--	--	--	--	--	--	--	--	--
Mar. 29	17.7	--	.0	.53	.17	--	--	--	--	--	102
Apr. 25	8.4	--	--	--	--	--	--	--	--	--	--
Apr. 26	34	--	--	--	--	--	--	--	--	--	--
June 13	.97	9.8	.1	.79	.07	46	5.9	6.1	2.1	--	149
3-3830. Tradewater River at Olney											
Nov. 18, 1965 [4]	6.3	12	9.1	0.39	11	--	--	--	--	--	0
3-3835. Tradewater River at Wilson Bridge on State											
Nov. 18, 1965 [5]	3.3	10	3.2	0.34	10	--	--	--	--	--	2
Feb. 17, 1966	1,200	--	--	.12	.94	--	--	--	--	--	7
Sept. 13	.045	2.1	0.0	.02	1.6	59	37	8.5	2.1	--	14
Oct. 21	.26	--	--	--	--	--	--	--	--	--	--
3-3837. Donaldson Creek at bridge on State Highway											
Feb. 17, 1966	121	--	--	0.10	0.02	--	--	--	--	--	72
3-3837.1. Tradewater River at State Highway											
Nov. 19, 1965 [6]	0.45	7.6	0.8	0.24	10	--	--	--	--	--	4
Feb. 17, 1966	1,960	--	--	.18	.24	--	--	--	--	--	10
Sept. 13	.14	5.0	.0	.01	1.6	52	30	8.5	1.9	--	20
Oct. 21	.07	--	--	--	--	--	--	--	--	--	--
3-3837.55. Clear Creek at State Highway 70, near											
Sept. 15, 1966	2.6	--	--	--	--	--	--	--	--	--	--

See footnotes at end of table.

in Tradewater River basin—Continued

Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphorus as PO_4	Dissolved solids (residue at 180° C)	Hardness as $CaCO_3$: Calcium magnesium	Hardness as $CaCO_3$: Noncarbonate	Total acidity as H^{+1}	Specific conductance (micromhos at 25°C)	pH	Color	Turbidity	Temperature (°C)
Parkway near Dawson Springs (lat 37°10′43″, long 87°43′48″)														
0	1,310	8.0	1.9	3.4		1,860	1,190	1,190	3.4	2,030	4.1	3		21.5
Church, near Dawson Springs (lat 37°11′58″, long 87°44′42″)														
										890	4.0			
0	740	6.0	0.7	2.2		1,080	706	706	0.6	1,320	4.3	2		19.5
										1,775	4.4			
near Dawson Springs (lat 37°11′23″, long 87′45′43″)														
0	22	4.0	0.2			166	130	16		286	7.5	5		
0	18	4.0	.3	1.8		156	127	6		283	8.2	25		24.5
										315	6.4			
										360	6.0			
										240	6.8			
										280	6.8			
0	29	6.0	.1	.4		144	110	26		245	7.8			
										290	6.7			
										260	6.8			
0	24	5.0	.2	1.2		175	139	17		296	7.4	6		23.5
(lat 37°13′26″, long 87°46′53″)														
0	481	5.0	0.6			724	441	441	1.2	905	4.5	7	0.8	10.5
Highway 70, near Dalton (lat 37°16′28″, long 87°47′48″)														
0	354	4.0	0.2			528	340	338	0.6	709	4.8	5	0.2	9.5
0	100	4.0	.1	0.8		168	99	94		244	6.6			6
0	294	5.0	.4	.8		442	299	288	.2	621	6.5	3		23.5
										560	6.1			
293, near Dalton (lat 37°17′03″, long 87°48′37″)														
0	26	2.0	0.0	2.4		128	80	21		185	7.2			6
293, near Dalton (lat 37°19′00″, long 87°48′40″)														
0	288	4.0	0.3			444	294	291	0.2	606	6.0	20	1	8.5
0	76	2.0	.1	0.6		144	82	74		206	6.6			6
0	251	4.0	.4	.8		368	253	237	.2	550	6.7			21.5
										520	6.0			
Richland (lat 37°17′46″, long 87°34′18″)														
										3,900	3.1			

TABLE 8.—*Miscellaneous analyses of streams*

Date of collection	Discharge (cfs)	Silica (SiO_2)	Aluminum (Al)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Bicarbonate (HCO_3)
3-3837.7. Richland Creek above Tributary 1, near											
May 12, 1966	15.0	8.6	0.1	0.22	0.28	8.6	6.2	2.5	1.2		2
June 9	.06	13	.1	.06	.10						7
Oct. 21	.002		.2	.18							24
Dec. 2	.01		.1	.19	1.4						8
Dec. 15	.27	12	.0	.54	.00	31	17				10
Jan. 4, 1967	.07	11	.1	.16	.06	33	18				8
Mar. 31	.25		.0	.09	.43						6
Apr. 25	.70		.1	.05	.23						6
June 14	.003	11	.2	.14	.00	9.3	3.4	5.5	1.2		16
3-3837.75. Unnamed Tributary 1 to Richland Creek,											
May 12, 1966	4.24	7.6	0.2	0.27	0.21	132	84	9.3	2.4		64
June 9	.12	8.3	2.7	.00	2.5						124
Aug. 19	.002	24	3.0	.19	18	373	243	28	5.3		0
Oct. 21	.015		17	.52							0
Dec. 2	.05		1.0	1.2	12						6
Dec. 15	.21	7.1	.6	56	.00	283	188				38
Jan. 4, 1967	.27	6.3	.9	3.9	.06	297	205				76
Mar. 31	.21		.2	.20	3.2						98
Apr. 25	.13		.1	.12	3.0						56
June 14	.02	8.0	.2	.22	12	250	117	24	3.4		4
Oct. 5	.024										
3-3837.8. Unnamed Tributary 2 to Richland Creek,											
May 12, 1966	5.1	26	13	1.0	8.5	186	99	14	3.4		0
June 9	1.1	3.5	19	1.7	9.1	345	197	26	5.0		0
July 6	.46	42	19	2.2	19	381	224	28	5.2		0
July 26	.4	33	9.3	86	12	500	209	35	7.2		0
Aug. 19	4.6	14	.2	5.2	3.2	468	229	52	7.9		102
Sept. 15	.17										
Oct. 21	.35		.3	.23							261
Dec. 2	.06		.0	4.5	24						6
Dec. 15	.16		18	12	14						0
Jan. 4, 1967	.53	37	21	16	.03	319	164				0
Mar. 31	.55		24	3.4	20						0
Apr. 25	.27		22	8.6	18						0
June 14	.38	32	12	1.8	1.4	417	231	33	5.8		0
Oct. 5	.35										
3-3838. Richland Creek at Highway 70, near											
Sept. 29, 1965[7]	1.13	42	68	169	28						0
Sept. 15, 1966	.58										
3-3839.01. Unnamed tributary to Clear Creek near Beulah (lat 37°16′49″,											
Feb. 14, 1966[8]		66	95	49	27	318	321	33	2.8		0
3-3839.02. Unnamed tributary to Clear Creek near Beulah (lat 37°16′49″,											
Feb. 14, 1966		66	102	46	28	349	321	35	2.7		0

See footnotes at end of table.

in Tradewater River basin—Continued

Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphorus as PO_4	Dissolved solids (residue at 180° C)	Hardness as $CaCO_3$: Calcium magnesium	Hardness as $CaCO_3$: Noncarbonate	Total acidity as H^{+1}	Specific conductance (micromhos at 25°C)	pH	Color	Turbidity	Temperature (°C)
Ilsley (lat 37°17′34″, long 87°35′53″)														
0	50	1.0	0.0	0.9		81	47	46	0.2	135	5.6	10		16.5
0	79	1.0	.0			136	70	64		200	6.5	3		30
0	25	2.0	.2	.4		69	35	16		168	7.0			10
0	602	5.0		.2		864	568	562		1,100	6.6			3.5
0	158	4.0	.2	1.2		254	148	140		369	7.2			
0	166	2.0	.1	.7		276	157	150		432	7.2			1
0	139	4.0	.1	.2		224	135	130	.0	349	6.3			
0	132	1.0		.1		220	128	123	.0	319	6.7			11.5
0	36	1.0	.2	.7		83	37	24	.1	118	6.7	10		36
near Ilsley (lat 37°13′31″, long 87°35′53″)														
0	606	3.0	0.3	0.2		876	676	623		1,170	6.7	3		16.5
0	1,820	8.0	.6			2,750	1,940	1,840		2,840	7.4	7		30
0	1,970	10	1.0	1.0		2,820	1,930	1,930	0.8	2,850	4.5	3		34
0	2,090	12	2.0	.1		2,970	2,000	2,000	2.2	2,850	4.4			6.5
0	1,870	11		.1		2,620	1,840	1,830	.6	2,680	5.1			1.5
0	1,490	6.0	.5	.3		2,160	1,480	1,450	.1	2,240	6.4			
0	1,550	6.0	.3	.2		2,300	1,580	1,520	.1	2,350	6.9			1
0	1,440	8.0	.4	.4		2,210	1,560	1,480		2,270	7.3			
0	1,010	5.0		.1		1,590	1,120	1,070		1,720	7.6			11.5
0	1,080	6.0	.5	.4		1,650	1,110	1,100	.1	1,770	6.0	4		30
										3,300				
near Ilsley (lat 37°13′39″, long 87°35′29″)														
0	1,040	4.0	1.5	0.2		1,560	872	872	2.6	1,810	3.3	2		
0	1,780	8.0	2.6	.7		2,630	1,670	1,670	5.1	2,920	3.1	5		33
0	1,940	12	2.5	.4		2,930	1,870	1,870	4.8	3,070	3.2	3		31.5
0	2,270	7.0	3.5	1.8		3,360	2,110	2,110	8.5	3,840	3.1	5		18.5
0	2,050	6.0	1.3	6.6		3,100	2,110	2,030		3,020	7.0	15		29
											5.8			
0	2,080	7.0	.7	9.5		3,170	2,100	1,880		3,180	7.3			11.5
0	1,690	5.0		1.5		2,360	1,660	1,660	.1	2,430	5.9			0
0	1,660	13		.2		2,360	1,520	1,520	3.2	2,440	3.9			
0	1,790	6.0	2.2	.4		2,610	1,470	1,470	3.4	2,640	4.2			4
0	1,570	10	2.7	.4		2,360	1,550	1,550	3.6	2,440	3.4			
0	1,600	1.0		.2		2,490	1,560	1,560	3.2	2,510	3.4			10.5
0	1,970	12	2.3	4.5		3,000	1,990	1,990	1.7	2,840	4.5	37		29
										2,800				
Richland (lat 37°16′26″, long 87°36′15″)														
0	3,390	16	5.3			4,860	2,840	2,840	19	5,100	2.6	30	5	25.5
										5,400	2.7			
long 87°41′11″) (near stripmine highwall where water flows into auger hole)														
0	2,910	10	7.3	2.4		4,270	2,120	2,120	16	4,180	2.8			
long 87°41′11″) (near stripmine highwall where water flows from auger hole)														
0	2,910	10	7.0	2.4		4,280	2,190	2,190	18	4,200	2.6			

TABLE 8.—*Miscellaneous analyses of streams*

Date of collection	Discharge (cfs)	Silica (SiO_2)	Aluminum (Al)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Bicarbonate (HCO_3)
3-3840. Rose Creek at Nebo											
May 11, 1966	0.03	2.4	0.1	0.16	0.10	27	9.0	20	1.7		26
3-3840.5. Clear Creek at bridge on State Highway 293,											
Feb. 18, 1966	452	9.0	5.3	1.5	4.5	44	28	11	2.2		0
Sept. 13 [9]	<.02	29	6.6	3.3	24	349	209	65	6.4		0
May 16, 1967	1,392		2.7	2.4	3.0						0
3-3840.6. Tradewater River at dam, near											
Nov. 19, 1965 [10]	2.8	24	36	2.7	19						0
July 20, 1966	.88										
Aug. 19	3.02	13	1.6	.19	11	108	63	24	2.9		0
Sept. 15	2.9	4.3	.0	.40	5.2	82	45	15	2.5		6
Oct. 5	14										
Oct. 21	3.2										
Nov. 30	23										
3-3840.7. Owens Creek at mouth, near											
Nov. 19, 1965 [11]	0.42	14	0.3	0.50	3.3			126	3.9		62
3-3840.72. Tradewater River at bridge below dam,											
Dec. 15, 1966	884										
Jan. 6, 1967	683										
Mar. 29	665	7.6	2.0	0.20	1.8	44	24				2
3-3841. Tradewater River at Highway 120 (Montezuma Bridge),											
Sept. 30, 1965		20	9.1	1.3	13						0
Feb. 17, 1966				.11	1.1						4
3-3841.1. Piny Creek at mouth, near Blackford											
Nov. 19, 1965	0.1	14	0.0	3.1	7.7						170
3-3841.3. Unnamed tributary to Slover Creek, near											
July 14, 1966	<0.1										
3-3841.33. Unnamed tributary to Slover Creek, near											
July 14, 1966											
3-3841.5. Craborchard Creek at Highway 270,											
Sept. 30, 1965	[12]<0.001	4.6	0.3	1.0	1.0						60

See footnotes at end of table.

in Tradewater River basin—Continued

Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphorus as PO_4	Dissolved solids (residue at 180° C)	Hardness as $CaCO_3$: Calcium magnesium	Hardness as $CaCO_3$: Noncarbonate	Total acidity as H^{+1}	Specific conductance (micromhos at 25°C)	pH	Color	Turbidity	Temperature (°C)
(lat 37°22′58″ long 87°37′59″)														
0	100	10	0.1	16	--	218	105	83	--	354	7.0	3	--	--
near Providence (lat 37°20′33″, long 87°48′00″)														
0	280	8.0	0.2	0.1	0.10	412	225	225	1.1	641	3.7	--	--	6
0	1,930	15	1.3	1.0	--	2,770	1,730	1,730	2.4	3,040	3.7	5	--	29
0	252	6.0	--	1.4	--	380	220	220	.7	568	3.8	--	--	19.5
Providence (lat 37°22′42″, long 87°48′05″)														
0	1,150	9.0	1.1	--	--	1,740	1,080	1,080	2.8	1,990	3.6	3	9	10.5
--	--	--	--	--	--	--	--	--	--	1,150	4.0	--	--	--
0	580	8.0	.6	4.9	--	840	529	529	.5	1,120	4.1	3	--	28
0	401	6.0	.6	1.5	--	600	390	385	.1	804	5.6	10	--	22
--	--	--	--	--	--	--	--	--	--	1,900	--	--	--	--
--	--	--	--	--	--	--	--	--	--	1,650	5.0	--	--	--
--	--	--	--	--	--	--	--	--	--	2,100	3.9	--	--	--
Providence (lat 37°22′44″, long 87°47′57″)														
0	1,240	44	0.4	--	--	1,960	1,220	1,170	0.4	2,350	6.4	10	15	4
at Providence (lat 37°22′51″, long 87°48′01″)														
--	--	--	--	--	--	--	--	--	--	580	5.2	--	--	--
--	--	--	--	--	--	--	--	--	--	900	4.7	--	--	--
0	238	8.0	0.4	0.3	--	365	209	207	0.5	515	4.7	--	--	--
near Providence (lat 37°23′48″, long 87°50′42″)														
0	890	8.0	1.0	--	--	1,340	920	920	2.4	1,630	3.5	3	1	19
0	105	2.0	.0	0.7	--	166	100	97	.1	258	5.8	--	--	6.5
(lat 37°24′09″, long 87°55′07″)														
0	1.6	46	--	--	--	184	146	6	--	303	7.0	35	10	5
Providence (lat 37°25′55″, long 87°45′23″)														
--	--	--	--	--	--	--	--	--	--	3,500	3.3	--	--	--
Providence (lat 37°26′17″, long 87°47′05″)														
--	--	--	--	--	--	--	--	--	--	5,900	2.8	--	--	--
near Clay (lat 37°27′44″, long 87°46′46″)														
0	19	6.0	0.3	--	--	106	62	13	--	182	7.4	80	45	20

TABLE 8.—*Miscellaneous analyses of streams*

Date of collection	Discharge (cfs)	Silica (SiO_2)	Aluminum (Al)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Bicarbonate (HCO_3)
3-3841.52. Craborchard Creek, 200 feet upstream from unnamed											
July 14, 1966								641			184
3-3841.53. Unnamed tributary to Craborchard Creek											
July 14, 1966								630			174
3-3841.54. Craborchard Creek at State Highway 85,											
July 14, 1966	1.19							635			174
July 14	1.2										
3-3841.62. Vaughn Ditch at State Highway 143,											
Nov. 19, 1965	2.3	13	0.5	14	11			445	14		60
3-3841.8. Tradewater River at U.S. Highway 60-641,											
Nov. 19, 1965		12	5.3	0.13	16			175	8.9		2
Furgerson Strip Mine Lake, near Beulah											
Dec. 2, 1958				699							0
Industrial Strip Mine Lake, near Dawson Springs											
Dec. 4, 1958				13							0
Bell and Zollar Strip Mine Lake, near Madisonville											
Dec. 3, 1958				0.54							24

[1] Includes 1.8 mg/l dissolved oxygen; 15-percent saturation.
[2] Includes 1.0 mg/l copper and 1.2 mg/l zinc.
[3] Includes 1.4 mg/l copper and 3.4 mg/l zinc.
[4] Includes 6.0 mg/l dissolved oxygen; 54-percent saturation.
[5] Includes 7.2 mg/l dissolved oxygen; 63-percent saturation.
[6] Includes 7.6 mg/l dissolved oxygen; 64-percent saturation.
[7] Includes 1.4 mg/l copper and 2.3 mg/l zinc.
[8] Includes 9.2 mg/l zinc.
[9] Includes 0.84 mg/l copper and 0.49 mg/l zinc.
[10] Includes 8.8 mg/l dissolved oxygen; 78-percent saturation.
[11] Includes 6.6 mg/l dissolved oxygen; 50-percent saturation.
[12] Estimated.

in Tradewater River basin—Continued

Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphorus as PO_4	Dissolved solids (residue at 180° C)	Hardness as $CaCO_3$: Calcium magnesium	Hardness as $CaCO_3$: Noncarbonate	Total acidity as H^{+1}	Specific conductance (micromhos at 25°C)	pH	Color	Turbidity	Temperature (°C)
tributary at Clay (lat 37°27′38″, long 87°49′15″)														
0	3,620	16	0.9	5.4	0.26	5,880	2,620	2,470	......	5,480	6.8	......	......	34
at Clay (lat 37°27′38″, long 87°49′16″)														
0	3,410	72	0.8	8.8	0.93	5,620	2,460	2,320	......	5,440	7.8	......	......	34
at Clay (lat 37°27′38″, long 87°49′17″)														
0	3,550	24	0.8	8.0	0.92	5,720	2,540	2,400	......	5,460	6.7	......	......	28.5
......	......	......	......	......	......	......	......	......	......	5,500	......	......	......	......
near Blackford (lat 37°27′48″, long 87°53′54″)														
0	3,110	48	0.6	......	......	4,820	2,480	2,430	0.2	4,690	6.6	3	55	6.5
near Sullivan (lat 37°28′46″, long 87°57′10″)														
0	1,670	28	0.8	......	......	2,570	1,480	1,480	0.5	2,740	5.1	3	5	8.5
(lat 37°15′25″, long 87°40′55″)														
0	4,480	4.0	......	0.4	......	......	1,840	1,840	40	5,480	2.4	......	......	......
(lat 37°14′35″, long 87°40′26″)														
0	800	4.0	0.5	0.2	......	......	682	682	1.6	1,500	3.2	......	......	......
(lat 37°20′55″, long 87°36′10″)														
0	83	5.0	0.2	0.8	......	......	92	72	......	253	6.6	......	......	......

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