GROUND-WATER STUDY 5

by

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1.0 ABSTRACT

The general area is underlain by numerous coal beds, and large areas of coal have been removed by underground mining. This case history is based on a recent investigation of the effects of underground mining and subsidence on the hydrology of three selected basins.

Geology and the Occurrence of Coal

The general area is underlain by alternating layers of shale, sandstone, some limestone, and more than 15 beds of coal and underclay, all Permian and Pennsylvanian age. The minable coals generally have been the Kittanning, the Pittsburgh, and the Waynesburg of the Allegheny Formation, the Monongahela Group, and the Dunkard Group, respectively. The bedrock is generally jointed and fractured, but in areas of abandoned underground mines, subsidence has increased fracturing and opening of surficial cracks. Regional lineaments control orientation of subsidence cracks, location of serious roof falls, and water and gas problems in underground mines.

Hydrology and Hydrologic Monitoring

Sedimentary rocks form a series of perched and semiperched aquifer systems. Interconnection between the systems is variable. Sandstones and coals are generally the best sources of ground water. Water tends to be perched on semipermeable beds of clay and shale.

Fractured zones along lineaments are generally zones of increased permeability. Saline water occurs at shallow depths (greater than 300 feet) under some major valleys where water is moving through these fractured zones or through oil and gas wells with defective casings. The chemical composition of fresh ground water inside the valleys is generally more highly mineralized than outside the valleys.

Mining Methods and Other Stresses on the Aquifer System

The Pittsburgh and Kittanning coal beds are the major seams developed by underground mining. Room and pillar mining was the primary mining technique used. The Kittanning coal was surface mined in many places at the outcrop. The Waynesburg coal was locally strip mined in some places as a source of domestic fuel. The less persistent Sewickley coal seam is not known to have been mined.

Probable Hydrologic Consequences and Proposed Hydrologic Monitoring Network

In mined areas, ground-water levels fluctuate more rapidly and greatly than in unmined areas. Underground mining and mine subsidence increase ground-water drainage to streams and create annual water-level fluctuation of as much as 100 feet. Mine subsisdence caused increased infiltration of precipitation, lowering of the natural water table, and increased mineralization of water. Sixteen-hundred surface subsidence holes or cracks were mapped in one basin. These subsidence features occurred mostly where overburden was less than 150 feet.

At low flows (ground-water base flow), one-half of the total streamflow may be mine pumpage or mine drainage. Also, at low flow, streams in the mined areas transport more dissolved solids than those streams in unmined areas.

The proposed hydrologic-monitoring plan includes streamflow-gaging stations upstream and downstream from the area affected by mining. Gaging stations are also located on tributaries; one monitors the effluent from a mine dump. Observation wells are located in abandoned mine areas and in the mine-permit area. The specific well sites are controlled by the location of interpreted lineaments, mine-subsidence cracks, nonfractured sites and streams, and proximity to water-supply wells.

2.0 GEOLOGIC SETTING

AREA UNDERLAIN BY ROCKS CONTAINING MORE THAN 15 COAL BEDS THAT GENERALLY DIP NORTHWEST

Three basins in the study area are underlain by alternating layers of shale, sandstone, some limestone, and more than 15 beds of coal and underclay.

The three basins lie within the Monongahela River basin on the east limb of a broad synclinorium that dips generally less than 5 to the northwest. The basins are underlain by rocks of Permian and Pennsylvanian age that contain beds of coal with associated underclays (figs. 2.0-1 and 2.0-2 and table 2.0-1).

Generally, the upper or youngest rocks (Dunkard Group) contain more shale than sandstone. The percentage of sandstone beds increases from about 50 percent in the Dunkard Group to about 75 percent in the lower part of the Conemaugh Group. The Dunkard and Monongahela Groups crop out in Buffalo Creek and Indian Creek basins.

The Monongahela Group underlies the Dunkard Group and the Waynesburg coal bed lies at the top of the Monongahela Group. This coal has been mined in places for domestic use, but nowhere is the mining extensive. The geologic column in figure 2.0-2 shows two coal beds above the Pittsburgh coal, but there could be as many as nine. The Pittsburgh coal, which lies at the base of the Monongahela Group, is 6 to 12 feet thick and is heavily mined in Buffalo Creek basin.

The Conemaugh Group and Allegheny Formation crop out in Roaring Creek-Grassy Run basins. The Conemaugh Group is the uppermost rock unit in the mined area. It is predominantly shale with interbedded sandstone, siltstone, and limestone in the upper part, and predominantly thin-bedded fine-grained sandstone in the basal part. Coal is largely absent from the 100-foot thick section of Conemaugh rocks found in the Norton area.

The Allegheny Formation underlies the Conemaugh Group. The Upper Freeport coal is usually found at the top of this group but is missing in this area. The Allegheny Formation is predominantly sandstone with some interbedded shale, siltstone, and clay in the upper part. The Kittanning coal units are near the center of the formation. They range in thickness from 0 to 12 feet thick and are underlain primarily by shale with thin beds of coal, underclay, and some sandstone.

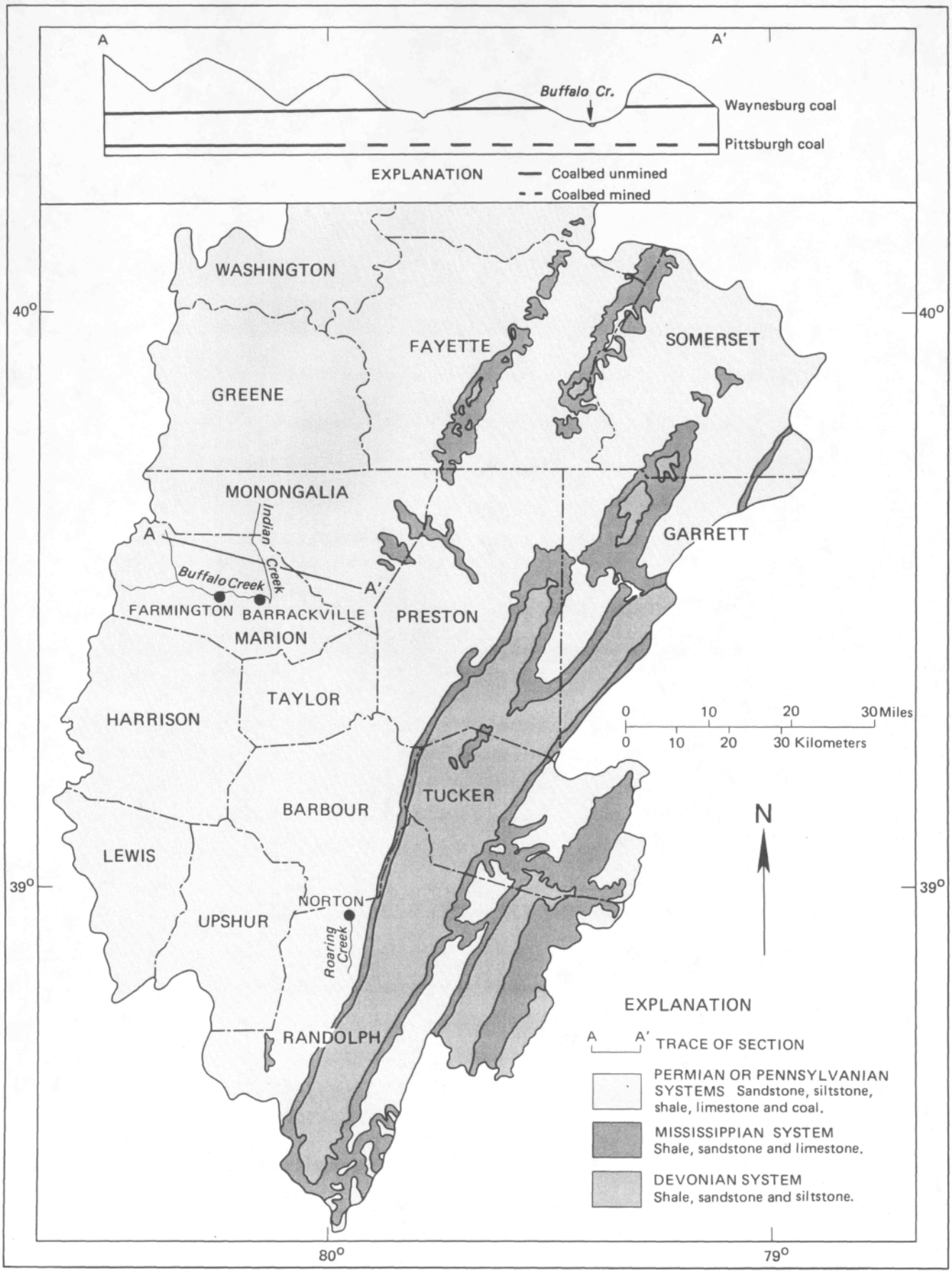


Figure 2.0-1— Surface geology and cross section.
(Modified from Herb and others, 1981, fig. 4.1-1.)

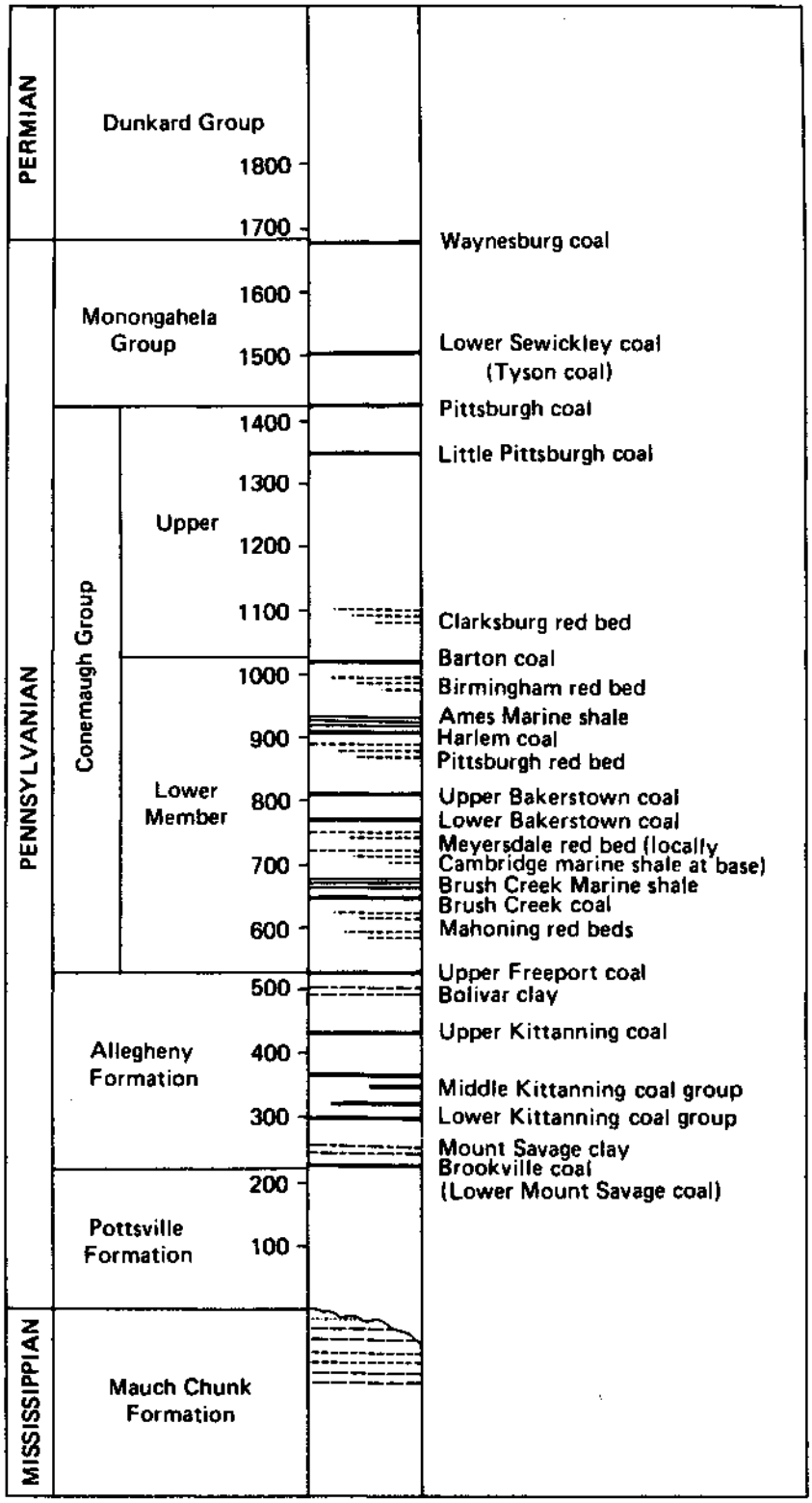


Figure 2.0-2.— Generalized geologic section of the Pennsylvanian-age strata. (From Amsden and others, 1954, p. 48)

Table 2.0-1. – Geologic and hydrologic framework of Farmington area.

System	Series	Geologic Unit	Approximate Thickness (feet)	Lithologic and Structural Characteristics(16&25)	Hydrologic Characteristics (7)
Quaternary	Holocene	Alluvial Deposits	0- 20 (?)	Unconsolidated stream deposits of gravel, sand, clay, and silty clay. Deposits poorly-sorted to well-sorted and may form thin water-table aquifer along stream.	Source of few domestic supplies. Yields range from less than 1 to 10 gal/min and average about 5 gal/min in Monongahela basin.
Pennsylvanian and Permian	Upper Pennsylvanian and Lower Permian	Dunkard Group	0-550	Alternating layers of shale, sandstone, siltstone, limestone, coal, and underclay. Top and middle of unit comprised of nearly equal amounts of shale and sandstone beds. Most shale beds range from 10-60 feet thick. Sandstone beds range from 20-40 feet thick with numerous interbeds of thin limestone, coal, underclay, shale, and sandstone. Basal part is about 55% sandstone; ranges 10-50 feet thick. This part also contains shale beds 4-60 feet thick, and numerous thin beds of limestone, coal, and clay. Some clay beds over 10 feet thick. Fracturing locally developed in siltstone, shale, and limestone; joints are blocky and closely spaced in finer-grained rocks, moderately spaced in sandstone. Joints vertical and open. Subsidence fractures are encountered in underground coal mining.	Yields adequate water for many domestic and farm supplies and a few small-to-moderate industrial supplies in Monongahela basin. Yields of wells range from less than 1 to 75 gal/min and averages about 12 gal/min. Wells drilled as deep as 321 feet, average depth 77 feet. Extensive mining in underlying Monongahela Group has partly drained some areas; ground-water conditions stable in some areas, but continually changing where heavy mine pumpage is maintained and periodically altered.
Pennsylvanian	Upper Pennsylvanian	Monongahela Group	350-400	Alternating layers of shale, sandstone, siltstone, limestone, coal, and underclay. Unit is domestic and capped by coal bed 5 feet thick, underlain by clay and beds of shale 10-13 feet thick alternating with sandstone beds 35 feet thick and thin beds of limestone and coal. Middle part generally contains thin beds of shale and siltstone and two beds of limestone 20-40 feet thick, streaks of clay. Lower part contains two thick beds of coal separated by about 120 feet of shale and limestone beds that are 20-25 feet thick, alternating with thin sandstone beds and several beds of clay or slaty clay 2-30 feet thick. Mined Pittsburgh coal is 6-12 feet thick and lies at the base of unit. Joints vary from poorly-to- moderately-well developed in limestone. Fracturing widely spaced in irregular intervals, generally blocky or platy patterns, and spacing closer in fine-grained rocks. Joints usually open and vertical. Subsidence fractures are encountered in underground coal mining.	Yields enough water for many farm and small-to- moderate industrial supplies in Monongahela basin. Yields range from less than 1 to 75 gal/min and average about 13 gal/min. Wells drilled as deep as 385 feet, with average depth 98 feet. Extensive coal mining in Monongahela Group has partly drained some areas; ground-water conditions stable in some areas, but continuously changing where heavy mine pumpage is maintained and periodically altered.
		Conemaugh Group	550-600	Alternating layers of shale, sandstone, siltstone, limestone, coal, and underclay. Top of unit capped by about 5 feet of underclay, of Pittsburgh coal of Monongahela Group. The clay, in turn, is underlain by about 35 feet of massive sandstone. Upper part of unit is nearly 50% massive sandstone with several thick beds of shale and thin beds of limestone, coal, and clay. Middle part largely shale with alternating beds of massive sandstone 20-40 feet thick, thin beds of limestone, shale, coal, and underclay. Basal part about 75% massive sandstone with beds 15-60 feet thick. Beds of shale are up to 20 feet thick and there are numerous thin beds of limestone, shale, coal, and underclay. Joints poorly-to-moderately well-formed, open and vertical.	Most-developed aquifer in the Monongahela basin. Adequate yield for domestic, farm, and small-to moderate industrial supplies. Yields of wells range from less than 1 to as much as 400 gal/min; however, average is about 18 gal/min. Highest yields reported from wells in valleys and tapping massive sandstones at base of Group. Wells drilled as deep as 985 feet, average depth 107 feet

3.0 HYDROLOGY

3.1 CLIMATE

BASINS HAVE MILD SUMMERS AND COLD WINTERS

Average daily temperatures range from about 80°F in July to about 26˚F in January and average annual precipitation is more than 43 inches.

In general, the climate of the area is a continental mountainous type characterized by mild summers and cold winters (7). Variations in temperature and precipitation are caused mainly by variations in altitude and topographic exposure. The average annual temperature ranges from about 45°F at higher elevations to about 55°F at lower elevations. The average maximum temperatures range from about 80˚ to 88˚F in July. The average minimum temperatures range from about 20° to 26°F in January. The annual precipitation ranges from about 40 to 70 inches, depending on altitude, terrain, and exposure.

3.0 HYDROLOGY

3.2 OCCURRENCE, MOVEMENT, AND QUALITY OF GROUND WATER

DOMINANT OCCURRENCE OF GROUND WATER IS IN FRACTURED ROCK

Water enters pores and fractures in the rocks and moves slowly down gradient. Chemical composition of ground water is variable and depends chiefly on the types of rock through which it has moved.

The sedimentary rocks in the Monongahela River basin form a series of aquifer systems, each composed of several hydraulically connected beds (22). The degree of hydraulic connection ranges from direct contact with free hydraulic connection to very little connection through relatively impermeable intervening strata.

Joints, the fractures of most importance to ground-water occurrence, are sets of approximately parallel linear cracks that are spaced from several inches to several feet apart. Joint systems usually are best developed in coal, sandstone, and limestone.

Because the sandstones in the basin contain both intergranular and joint openings, they generally yield the most water to wells. However, where the pores are filled with secondary minerals and jointing is relatively undeveloped sandstones will transmit little water. Shales ordinarily yield little water because they lack the characteristics that permit the rapid transmission of very large quantities of water.

Ground water occurs under both water-table and artesian conditions. Where the aquifers are overlain by relatively permeable rocks and precipitation enters directly by percolation, water-table conditions exist.

In general, the differences in rock permeability and the nearly horizontal attitude of the strata are conducive to perched and semiperched ground-water conditions in the hills throughout the area (fig. 3.2-1). Shale and clay are relatively impermeable and impede the downward movement of water causing perched conditions in many places in the summer and early fall, when ground-water recharge is at a minimum. However, during winter and spring, when recharge is generally greatest, saturated (semiperched) conditions are more likely to persist.

Stress-relief fracturing can modify the hydrology along valleys in the Appalachian Plateaus physiographic province (23). The stress-relief phenomenon causes near-vertical tensile fractures to develop along valley walls. These fractures, in turn, allow the valley walls to slump, causing increased compressional force beneath the valley walls. This compressional force, combined with the expansion of rocks in the valley floor due to erosion, causes upward arching of the rocks in the valley floor. The results are fracturing along the arched rock and the opening of fractures along bedding planes. A significant amount of water enters underground mines along stress-relief fractures, particularly those mines that penetrate hillsides through the zone broken by the stress-relief fractures.

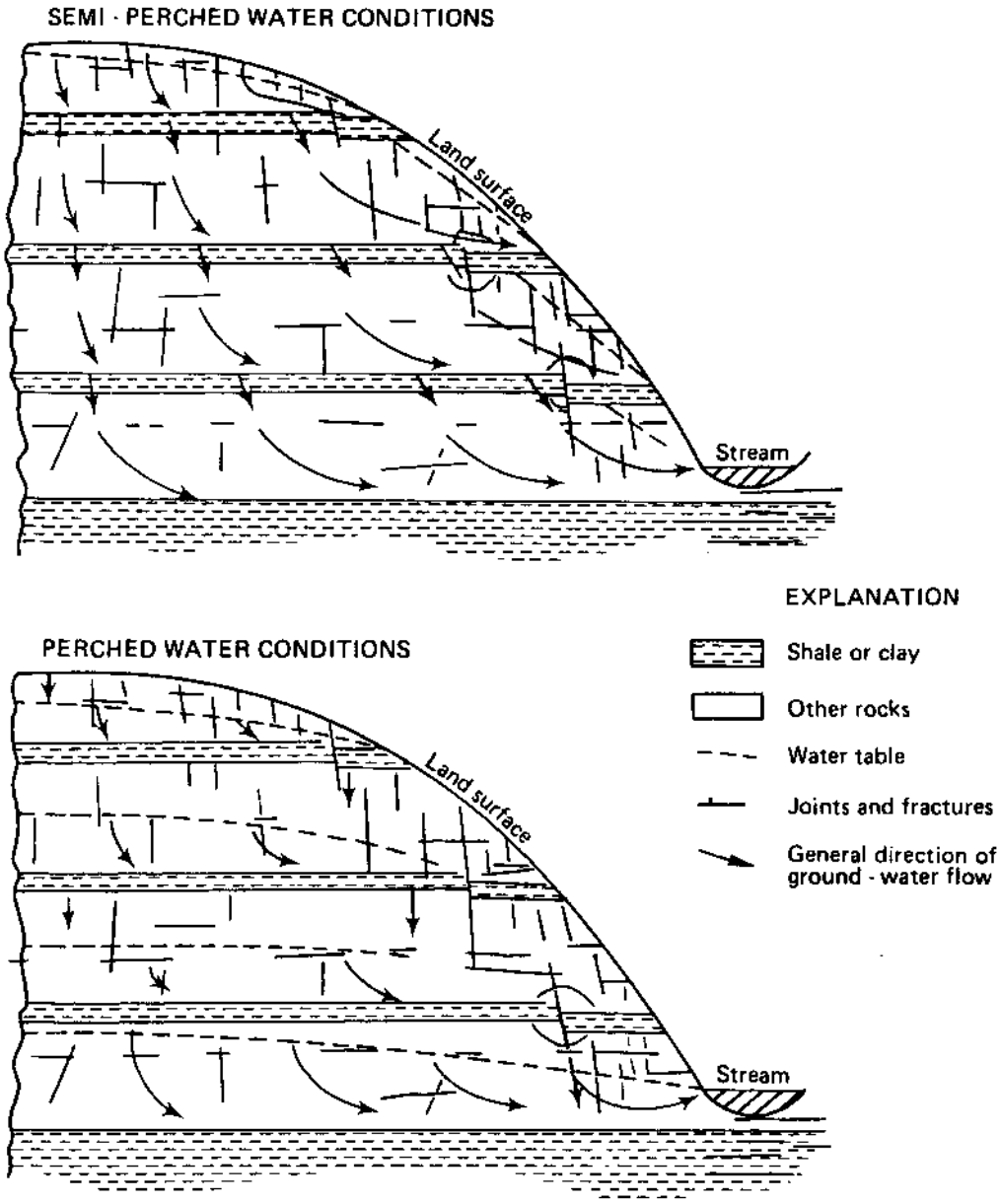


Figure 3.2-1.— Diagrams showing idealized semiperched and perched water conditions in the Monongahela River basin.
(Modified from Ward and Wilmoth, 1968, p. 11)

The greatest changes in, and acceleration of, ground-water drainage caused by coal mining usually take place after the supporting coal pillars are removed (22). With the mining of these pillars, the overlying rocks may settle and fracture. Some fractures may extend vertically to the land surface and cause slumping. The slumping increases permeability, thereby making it easier for water in the overlying rocks and at places on the land surface to infiltrate the mine (9). Ordinarily, most of the water collecting in mines drains from the overlying rocks. In places, however, the water in rocks beneath the mine may be under sufficient artesian pressure to cause upward movement of ground water. Figure 3.2-2 schematically shows the idealized pattern of ground-water flow to a hypothetical mine drift. Underclay or shale beneath the coal impedes upward movement of water to the mine.

Local ground-water movement and quality are affected by faults and other linear fracture zones (lineaments) throughout the Monongahela River basin. The major stream valleys are the principal discharge areas for both fresh and saline ground water. In some places, deep saline water moves upward and mixes with the fresh ground water at relatively shallow depths (100-300 feet). However, in most places freshwater can be obtained from shallow zones above the saline water. The occurrence of saltwater below the streams throughout much of the western part of the Monongahela River basin limits the occurrence of fresh ground water to relatively shallow depths.

Most of the saltwater contamination of shallow aquifers probably is caused by natural interformational seepage of saline water from deeper aquifers. However, some is undoubtedly caused by oil and gas wells with leaky casings that permit discharge of saline water or natural gas to the shallow freshwater aquifers.

Because stream valleys function as sumps for the discharge of both fresh and saline ground water, the contact between the fresh and saline ground water probably "cones up" beneath the stream and lies at successively greater depths away from the stream. Mining activity and practices for controlling water quality or quantity may alter the depth to saline water and the amount of discharge of saline water to the streams.

Table 3.2-1 shows that the chemical character of ground water in the basin for different grouping of geologic units. The chemical quality is variable—ranging from soft to hard, acidic to basic, and containing small to large concentrations of iron and chloride.

The coals and associated black shales in the basin contain small but significant amounts of pyrite and marcasite--both iron disulfide minerals. Coal mining exposes much larger quantities of these minerals to weathering than are exposed naturally. Sulfuric acid is formed by the action of air and water on the disulfide minerals. Also, metals are dissolved and transported in solution by ground water circulating through mined areas. Thus, the natural ground water moving into a mine opening undergoes chemical changes which increase the hardness and dissolved solids. Commonly, acidity also is increased; pH values as low as 2.5 have been measured in underground pools.

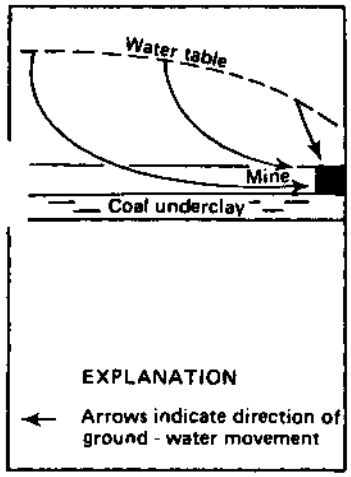


Figure 3.2-2.— Diagram showing general ground-water flow to a mine drift. (From Ward and Wilmoth, 1968, p. 17)

Table 3.2-1. – Summary of chloride, iron, hardness, and pH of ground water in the Monongahela River basin, [mg/L, milligrams per liter]

Geologic-age grouping	Water bearing unit	Number of samples analyzed	Chloride concentration (mg/L)		Iron concentration (mg/L)		Hardness (mg/L) as $CaCO_3$		Hydrogen-ion concentration (pH)	
			Range	Median	Range	Median	Range	Median	Range	Median
Quaternary	Alluvium	2	0 – 14	7.0	0.2 – 7.5	3.5	60 – 68	64.0	5.1 – 6.0	5.6
Permian and Upper Pennsylvanian	Dunkard Group	39	0 – 1,610	16	0 – 16	2	5 – 720	112	6.0 – 8.5	7.5
	Monongahela Group	42	0 – 105	6	0 – 18	.2	0.5 – 1,212	124	5.8 – 8.8	7.1
	Conemaugh Group	161	0 – 1,700	5	0 – 24	.1	0 – 1,479	102	4.8 – 9.0	7.0
Middles-Lower Pennsylvanian	Allegheny Formation	38	0 – 237	4	0 – 12	1.0	1 – 1,650	81	5.0 – 8.4	6.7
	Pottsville Group	49	0 – 688	4	0 – 20	1.5	5 – 242	46	4.3 – 8.1	6.6
Pre-Pennsylvanian	Mauch Chunk Group	3	3 – 4	3.5	0	.01	70 – 136	77	5.0 – 6.8	5.9
	Greenbrier Limestone	21	1 – 8	3	0 – 10	.01	8 – 188	81	6.3 – 8.0	6.8
	Pocono Formation	17	1 – 32	6	0 – 3	.01	3 – 208	124	4.5 – 7.0	6.8

3.3 GROUND-WATER/SURFACE-WATER RELATIONSHIPS

GROUND-WATER DISCHARGE TO STREAMS IS GREATEST IN SPRING

Ground-water discharge to streams may be affected by mining.

Precipitation is partly returned to the atmosphere by evaporation or transpiration, part runs overland and enters streams, and part infiltrates into the earth and becomes ground water. Surface runoff reaches the streams quickly, and is usually discharged from a drainage basin within a few days. In contrast, ground water is discharged over a prolonged period. It is greatest in the spring when the water table is high, but decreases through the summer and autumn when there is little or no ground-water recharge and the water table is declining.

Grassy Run and Roaring Creek are adjacent drainage basins. However, Grassy Run basin (2.86 mi^2) is only about 10 percent the size of Roaring Creek basin (29.2 mi^2). Streamflow in both streams is derived from overland runoff and ground-water discharge. The western two-thirds of Roaring Creek basin is completely mined, and nearly the entire Grassy Run basin has been mined. The rocks and mines in the Kittanning coal bed slope from Roaring Creek toward Grassy Run. At low flow (percentage greater than 90), the slope of the curve for Grassy Run flattens, indicating that low flow is being sustained by water draining from storage in the rocks and mines (fig. 3.3-1). The duration curve for Roaring Creek, on the other hand, does not show this condition. A part of the ground water within Roaring Creek basin is flowing into Grassy Run basin. In effect, this flow increases the recharge area of Grassy Run and more stored ground water is available to maintain flow. Conversely, the recharge area of Roaring Creek is decreased, and less stored ground water is available to maintain its low flow. Above the 96-percent duration point, the flow of Grassy Run is higher than Roaring Creek despite the much larger drainage area of Roaring Creek.

Sand Run drains an unmined area of 14.5 mi^2 located several miles west of Roaring Creek and Grassy Run. Sand Run basin is geologically, topographically, and vegetatively similar to the Grassy Run and Roaring Creek basins, and average annual precipitation is about the same. Thus, the shape of the flow-duration curve for Sand Run should closely approximate the shape of the duration curves for Grassy Run and Roaring Creek before mining. Because the shapes of the curves of Sand Run and Roaring Creek are similar, mining may have had little effect on the flows of Roaring Creek. The dissimilarity of the shapes of the Sand Run and Grassy Run curves may indicate the effects of mining on flows of Grassy Run.

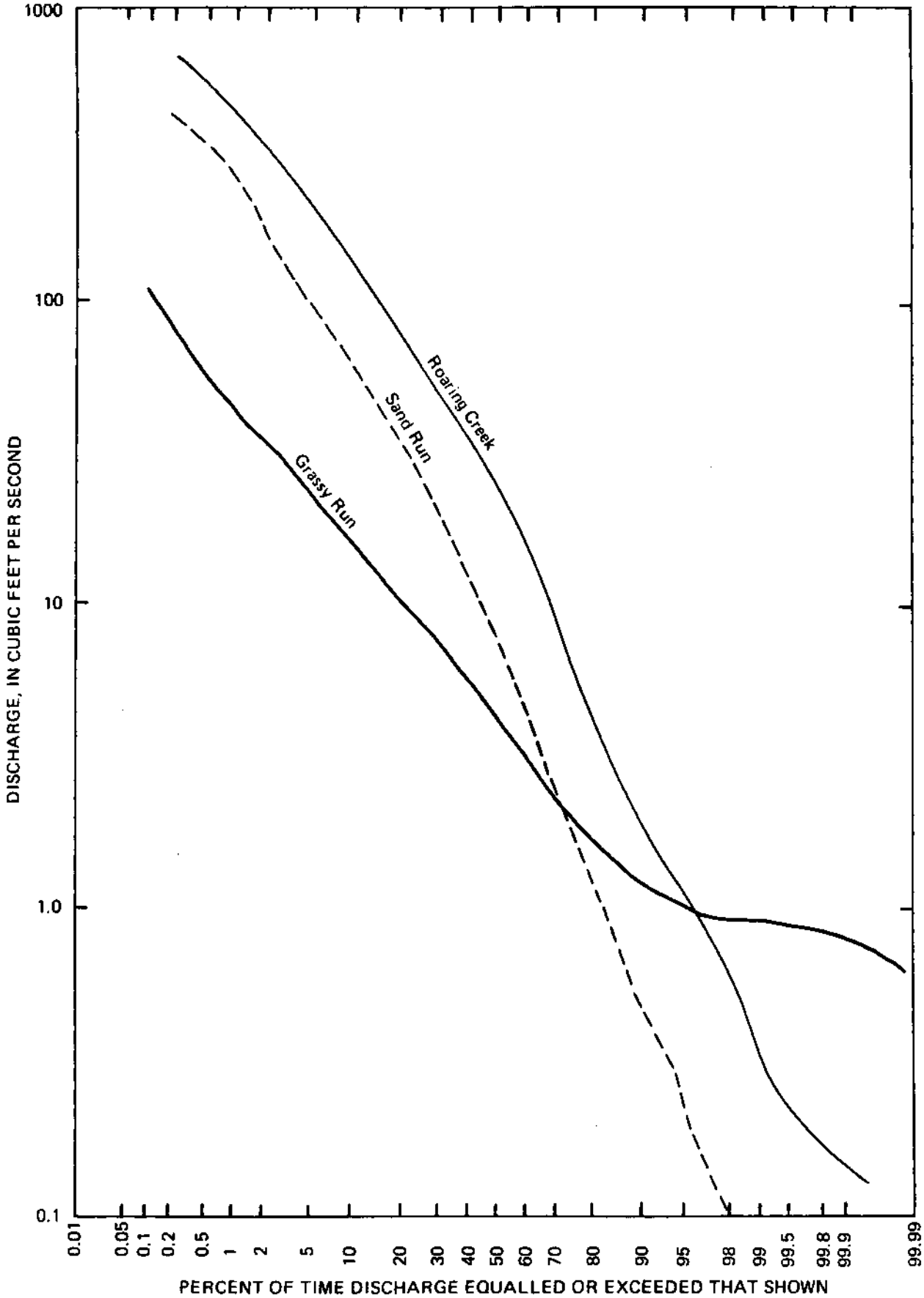


Figure 3.3-1.— Flow-duration curves of Roaring Creek, Grassy Run, and Sand Run. (From Hobba, 1981, fig. 2.2.2-B.)

4.0 AQUIFER CHARACTERISTICS

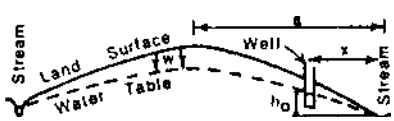
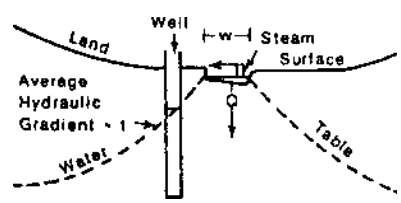
4.1 AREAL AQUIFER ANALYSIS

AREAL AQUIFER ANALYSIS INDICATES AREAS OF MINE SUBSIDENCE HAVE INCREASED ROCK PERMEABILITY

Transmissivity values from area aquifer analysis range from 2.2 to 55 feet squared per day; the smaller values are from undisturbed areas and the greater values from areas affected by mine collapse.

Two methods of determining areal transmissivity were used in the Buffalo Creek basin to relate the gain or loss of streamflow over a given stream reach to the height of the water in wells or to the slope of the water table at some distance from the stream. These methods are summarized in table 4.1-1. The steady-state flow method (13) is an equilibrium method of analysis, which assumes ground-water conditions do not change with time.

Table 4.1-1.– Methods used for areal aquifer analysis
[ft, feet; d, day; in, inches; yr, year; gal/pin, gallons per minute; ft^2/d, square feet per day]

Method	Steady-State Flow (13)	Darcy's Law (6)
Equation	$T = 0.000229\ W\left(\frac{aX}{h_o} - \frac{X^2}{2h_o}\right)$	$K = \frac{Q}{IA}$
Explanation of Symbols	T = transmissivity (ft^2/d) W = constant rate of recharge to water table (in/yr) a = distance from stream to ground-water divide (ft) X = distance from stream to observation well (ft) h_o = elevation of water table at the observation well with respect to mean stream level (ft)	K = hydraulic conductivity (ft/d) Q = flow rate loss (ft^3/d) I = hydraulic gradient (ft/ft) A = area of streambed (ft^2) T = transmissivity (ft^2/d)
Transmissivity Computation	Compute value for W by the equation $W = 4.22(10^5)Q_b/a$ where Q_b = streamflow in gal/min per foot of stream channel. Substitute the value of W into the above equation and compute T.	T = K x aquifer thickness
Assumptions	1. Aquifer is homogeneous and isotropic. 2. Aquifer recharged at a rate of accretion, w, that is constant with respect to time and place. 3. Stream penetrates full aquifer thickness.	1. I is average slope of water table as measured in wells near stream. 2. A is estimated width of streambed times length over which loss is measured.
Diagram		

Three values of transmissivity were computed for Little Laurel Run near Farmington by the steady-state flow method using the discharge from one reach of the stream and the water level in three different observation wells. Table 4.1-2 shows that transmissivity ranged from 45 to 55 ft^2/d. Little Laurel Run is the only small stream measured in the mine subsided area near Farmington. The transmissivity in this area is larger than Brush Run, Rex Run, and Mahan Run, which are in unmined areas. Transmissivity for rocks adjacent to these streams in the unmined areas ranges from 2.2 to 20 ft^2/d (table 4.1-2).

Another method of determining an areal estimate of transmissivity is made using a form of Darcy's law (table 4.1-1). The average width of Buffalo Creek is about 30 feet through the Farmington area. A 1-mile reach of the streambed covers about 158,400 ft^2. By using this area and 120,960 ft^3/d for water loss, (l.4 ft^3/s or 630 gal/min from a seepage run)(section 5.1), and an approximate hydraulic gradient of 1 (approximate average gradient based on water levels in wells A-E in fig. 4.1-1), the hydraulic conductivity is computed to be 0.76 ft/d. Transmissivity equals hydraulic conductivity times aquifer saturated thickness. If a saturated thickness of 30 feet (equal to the width of the stream) is assumed, the approximate transmissivity is 23 ft^2/d. Table 4.1-2 and the block diagram on figure 4.1-1 summarize the various permeability and transmissivity values.

Table 4.1.2.– Comparison of transmissivity and yields determined by aquifer analysis for unmined and mined areas.
[gal/min, gallons per minute; ft^2/d, square feet per day]

Stream name	Date	Yield of reach (gal/min)	Transmissivity (ft^2/d)
Unmined area			
Brush Run	11/3/77	23	8
Rex Run	11/3/77	97	20
Mahan Run	11/3/77	28	2.2
Mined area			
East Run	11/3/77	94	7.7
Little Laurel Run	11/8/77	53	47
(known subsidence)	11/8/77	53	45
	11/8/77	53	55
Buffalo Creek	5/11/79	630 (loss)	23

Well	Depth	Diameter (inches)	Depth cased (feet)	Water level		
				Below land surface (feet)	Below creek (feet)	Date measured
A	98	8	30	70.2	60	6/28/79
B	80?	8	–	71.6	60	3/ 9/79
C	145?	8	20-30	14.0	3-4	6/28/79
D	52	8	–	22.5	10	6/28/79
E	132	8	–	25.3	12	6/28/79
F	265	8	252	196.2	165	6/28/79

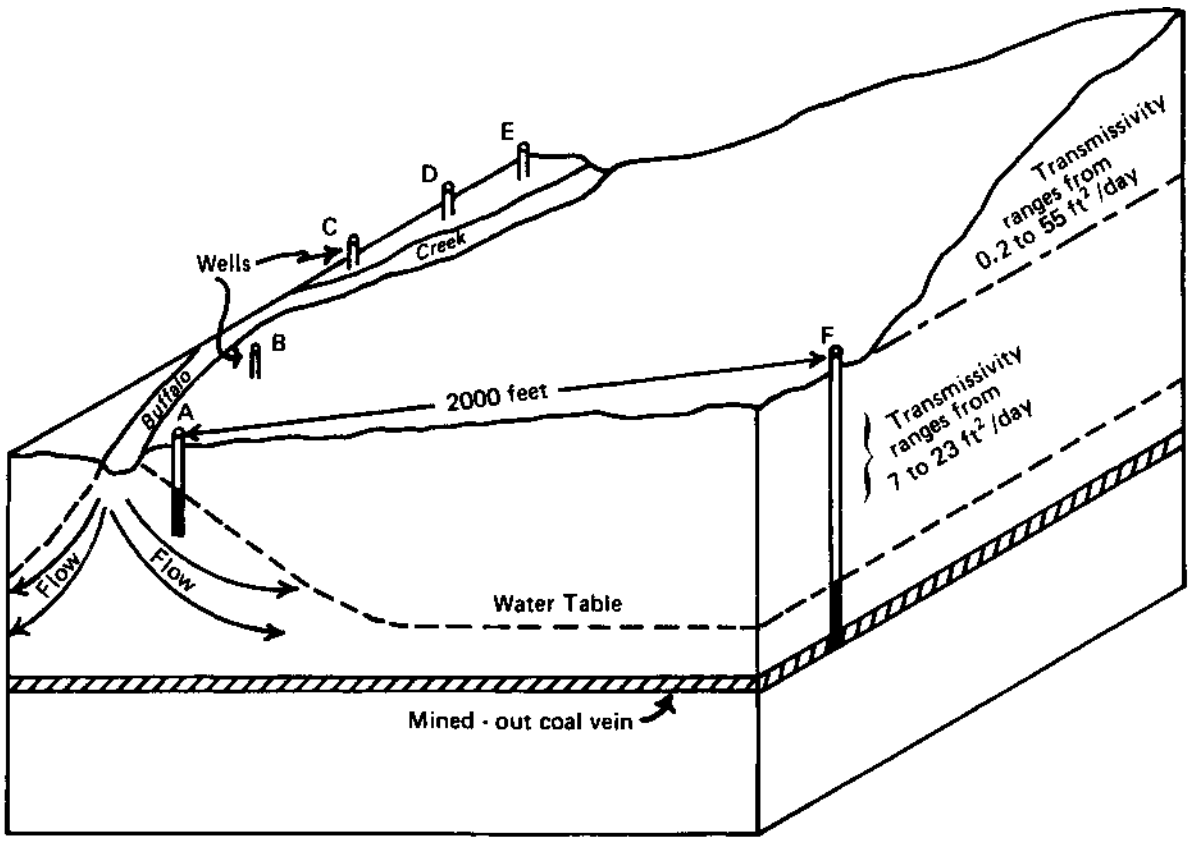


Figure 4.1-1.— Block diagram showing wells, water table, and computed ranges of transmissivity at Farmington where Buffalo Creek was losing about 1.4 cubic feet per second per mile. (From Hobba, 1981, fig. 3.5.1-B.)

4.0 AQUIFER CHARACTERISTICS

4. 2 SINGLE-WELL AQUIFER TESTS

WELL AQUIFER TESTS INDICATE ROCK PERMEABILITY IS GREATEST IN AREAS OF MINE SUBSIDENCE

Transmissivity values from well aquifer tests range from 0.20 to 65 square feet per day in areas of mine subsidence.

Recovery tests were performed on wells A and C, former public water-supply wells at an area of mine subsidence (fig. 4.1-1). These wells are 10 and 30 feet from Buffalo Creek, respectively. As shown in table 4.2-1, the transmissivity (T) computed from the recovery test is the same for both wells. However, water can enter about 115 feet of well C, whereas it can enter through only 68 feet of well A. Because transmissivity is equal to the product of permeability and length of hole open to the aquifer, the rocks at well A are more permeable than at well C. This greater permeability also is indicated by the lower water level; that is, more water is leaking from well A and into the mine below, than from well C.

The recession of ground-water level and a water-injection test (slug test) were used to estimate transmissivity at an observation well at Farmington using the equation (15):

$$T/S = 0.933 \frac{a^2 \log (h_1/h_2)}{t_2 - t_1}$$

where T/S = transmissivity divided by storage coefficient, feet squared per day;

a = distance from stream to ground water divided along a line passing through the observation well, in feet;

h_1, h_2 = the beginning and ending water levels in the well above stream level at time t_1 and t_2 respectively, in days.

The computed diffusivity (T/S) was 647 ft^2/d. Assuming a storage coefficient of 0.1, which is commonly representative of water-table aquifers, a transmissivity of 65 ft^2/d is calculated.

However, at this same well, hydraulic conductivity values of 0.0045 and 0.0062 ft/d were computed using variable-head permeability methods with data obtained from (1) a slug injection test, and from (2) a water-level recession hydrograph. Transmissivity values of 0.20 and 0.21 ft^2/d were calculated, using the values of hydraulic conductivity times the length of well tested. These small values indicate that the rocks are not very permeable, at least from the depth of 25 feet to the bottom of the well (the injected water slug filled the well to about 25 feet below land surface). However, after subsidence, a swampy area near the well became dry, indicating that subsidence cracks are permitting local ground-water drainage. Using the recession hydrograph and the T/S equation, the hydraulic conductivity computed is greater higher than that using the injection test, probably because: (A) the hydrograph data are of longer term and reflect the effect of a larger volume of rock (some of which probably contains subsidence fractures), (B) the assumed storage coefficient is too large, or (C) the conditions at the well do not meet the assumed aquifer conditions that are required to make the equations valid. During wet periods, the rapid rises in water levels in the well are attributed to water entering the well through fractures

between depths of 6 and 25 feet. During dry periods, the water drains from the well through the less permeable rocks in the saturated part of the well toward the more permeable subsidence cracks or joints some distance away.

Table 4.2-1. – Results of single veil aquifer tests
[ft^2/d, square feet per day; ft/d, feet per day; ft, feet]

Site and Method	Transmissivity, T (ft^2/d)	Hydraulic Conductivity, K (ft/d)	Assumed Aquifer Thickness (ft)
Well A			
Recovery test	7	0.25	28
Permeability test[1]	10 .9	0.39	28
Permeability test[2]	23	0.82	28
Specific capacity[3]	14	0.50	28
Well C			
Recovery test	7	–	–
Permeability test[1]	20	0.18	112
Specific capacity[3]	15	–	–
Observation Well			
Ground-water recession[4]	65	0.51	128
Permeability tests[2]	0 .20	0.004	49 .5
	0 .21	0.0006	35 .5

[1](19)
[2](18)
[3]Transmissivity estimated from 10-minute specific capacity (21)
[4](15)

4.0 AQUIFER CHARACTERISTICS

4.3 BORE-HOLE HYDRAULIC CONDUCTIVITY

AVERAGE HYDRAULIC CONDUCTIVITY FOR WELLS LOCATED IN MINED AREAS IS HIGHER THAN WELLS LOCATED IN UNMINED AREAS.

The U.S. Soil Conservation Service collected borehole hydraulic-conductivity data at dam sites in Buffalo Creek and Middle Wheeling Creek basins. These data were separated into two groups: (1) sites underlain by mines (28 holes), and (2) sites not underlain by mines (53 holes). The data indicated that average hydraulic conductivity for aquifers penetrated by valley wells in mined areas was greater than that for valley wells in unmined areas. Similarly, average hydraulic conductivity for aquifers penetrated by hillside wells in mined areas was greater than that for hillside wells in unmined areas. These findings of increased hydraulic conductivity of near-surface rock in mined areas agree with findings from areal and well aquifer-testing methods described in previous sections.

5.0 HYDROLOGIC CONSEQUENCES

5.1 MINE DRAINAGE AND DEWATERING

AT BASE FLOW, MINE PUMPAGE OR DRAINAGE MAY BE ONE-HALF OF TOTAL STREAMFLOW

Most of base flow in Grassy Run is from mine drainage; 35 percent of base flow in Indian Creek and 10 percent of base flow in Buffalo Creek is from mine pumpage.

About 50 streams and 20 mine-discharge sites were measured and sampled during 5 days of low flow in Buffalo and Indian Creek basins. The drainage area for each stream site was determined from topographic maps. After subtracting the mine discharge from the stream discharge, the yield (discharge per square mile of drainage area) was computed for each site (fig. 5.1-1). The yields ranged from 0.12 to 0.78 $(ft^3/s)/mi^2$. As shown in figure 5.1-1, the larger yields are in the lower parts of both basins, which are largely underlain by abandoned mines. The smallest yields are from central Buffalo Creek basin and Upper Indian Creek basin, which are largely underlain by active mines. Median yields are found in Upper Buffalo Creek basin, which is largely unmined.

A comparison of base-flow measurements with mine discharge in Buffalo Creek and Indian Creek basins showed that 10 percent of the flow of Buffalo Creek at Barrackville came from mine pumpage, whereas 35 percent of the flow of Indian Creek at Crown came from mine pumpage. At the time of base-flow measurements, a part of the mine water discharging into Indian Creek came from a mined area outside the basin. At this location, pumpage from the mine ceased sometime after these base-flow measurements were made, and the water level in the mine rose about 2 feet. The fact that the water level rose no farther indicates that water from this area now drains to another pump-site outside the drainage basin.

Base-flow measurements were made at 18 stream sites and 5 mine sites on April 20, 1979, in Roaring Creek and Grassy Run basins. Base-flow measurements were also made at some of the same sites in October 1965. Figure 5.1-2 shows the ranges of yield based on measured flows and surface-drainage area for April 1979. The basins with yields of less than 0.5 $(ft^3/s)/mi$ are areas shown by dye tracing to be losing water underground through joints, fractures, and subsidence cracks to Grassy Run basin (12). Flow measurements on May 17, 1979, show that the yield for Roaring Creek at its mouth was 1.44 $(ft^3/s)/mi^2$, or, in the same range as the unmined basins. At the same time, the yield of Grassy Run basin was 3.09 $(ft^3/s)/mi^2$ —more than twice the yield of Roaring Creek basin. The flow measurements in October 1965 show the yield of Roaring Creek basin to be 0.035 $(ft^3/s)/mi^2$ and the yield of Grassy Run basin to be 0.27 $(ft^3/s)/mi^2$ —nearly eight times the yield of Roaring Creek basin.

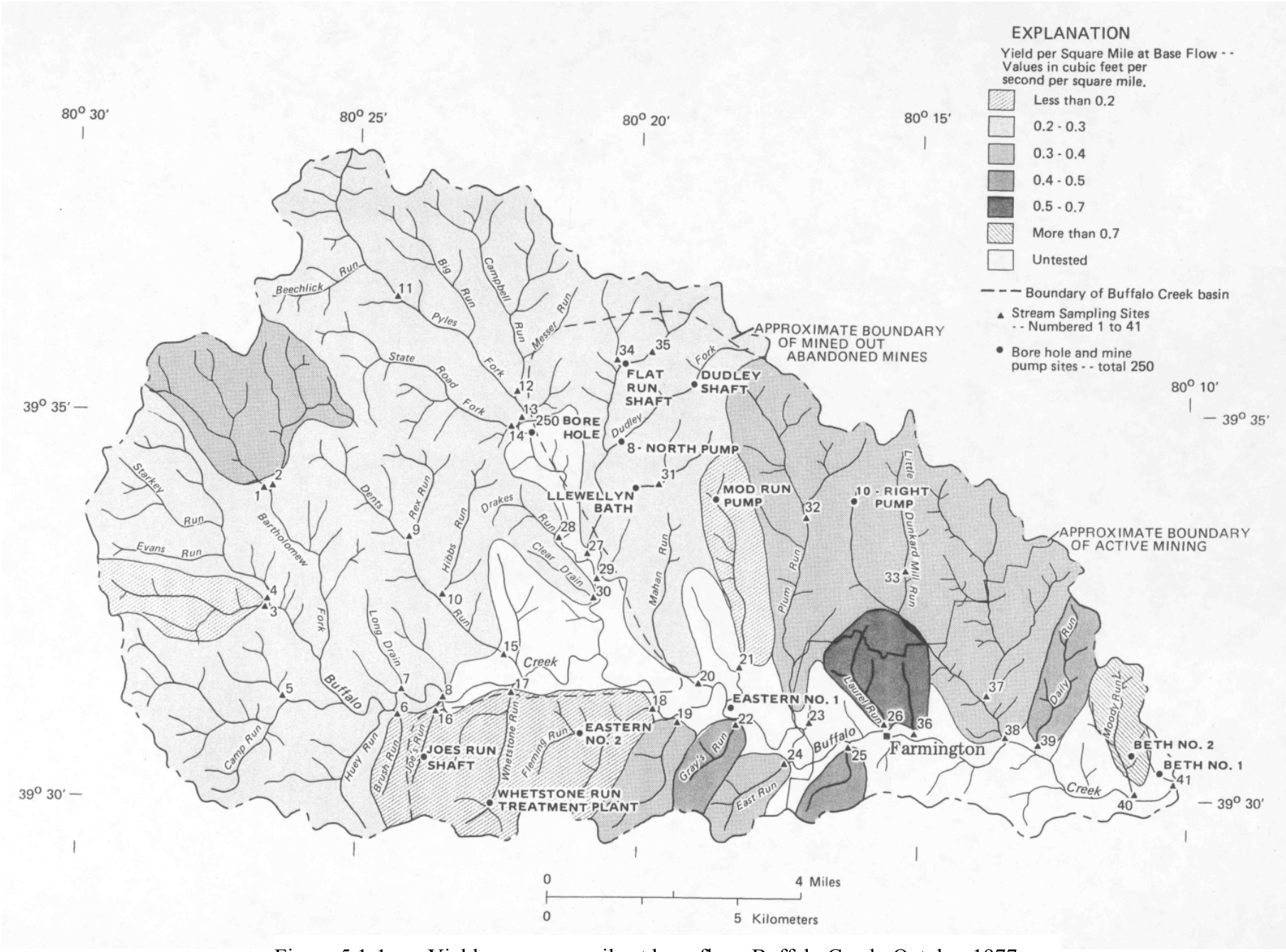


Figure 5.1-1.— Yield per square mile at base flow, Buffalo Creek, October 1977. (From Hobba, 1981, fig. 3.2.1-A.)

Figure 5.1-3 shows flows measured on Buffalo Creek and some tributaries near the collapsed area at Farmington. A loss of about 1.4 ft^3/s is measured between sites A and B, and between sites F and J, although this measured loss was 1.7 percent of the total flow (less than the accuracy of most flow measurements). The loss between sites A and B may be due to a fractured zone along the downstream part of this reach, which follows a lineament. Also, dewatering the coal bed by mine pumpage at Rachel may induce water from Buffalo Creek downward along the lineament. The low water level in wells near the Creek verify that there is a potential for water loss from Buffalo Creek.

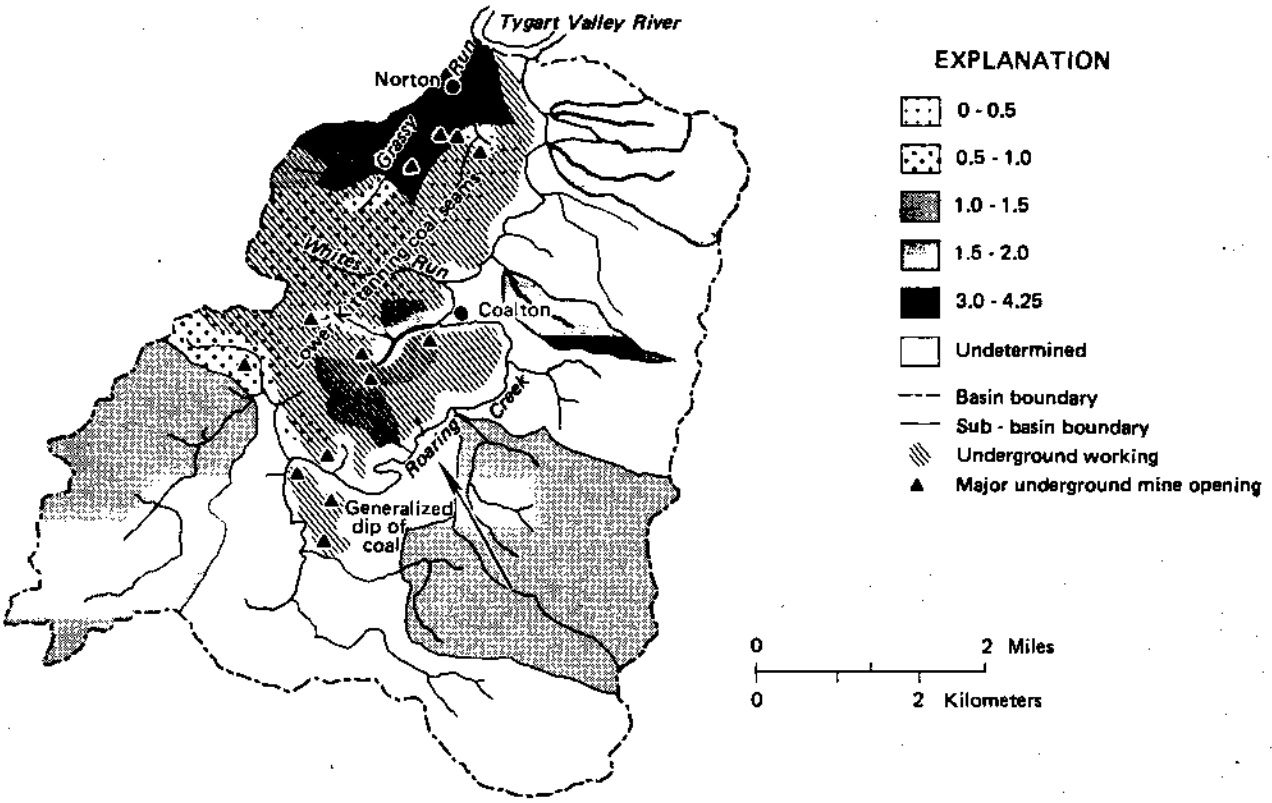


Figure 5.1-2.— Yield per square mile of small drainage basins, April 1979. (From Hobba, 1981, fig. 2.2.1-A.)

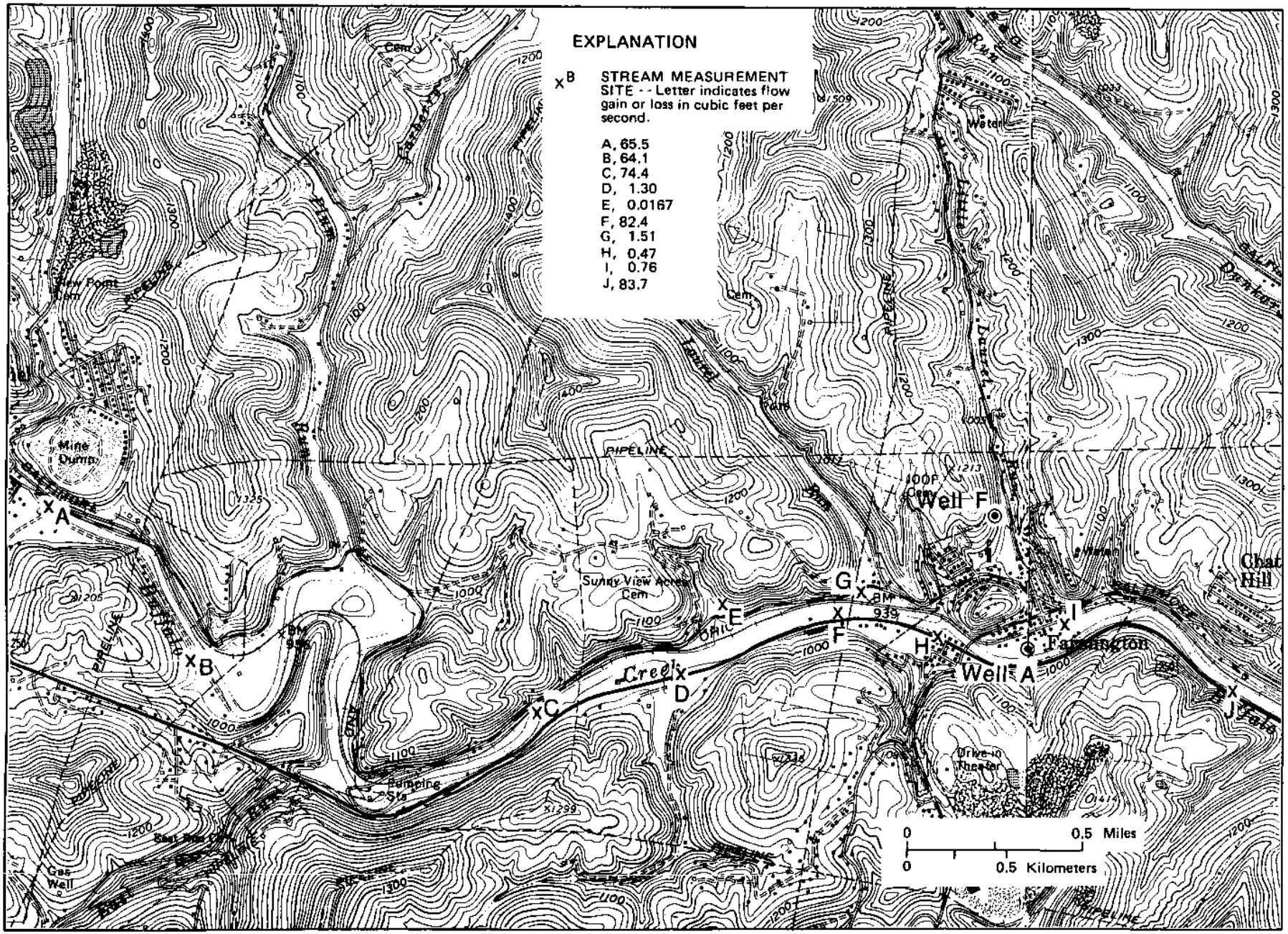


Figure 5.1-3.— Stream sites measured to determine flow gain or loss in Buffalo Creek near Farmington.
(From Hobba, 1981, fig. 3.2.3-A.)

5.0 HYDROLOGIC CONSEQUENCES

5.2 WATER QUALITY

STREAMS IN MINED AREAS TRANSPORT MORE DISSOLVED MINERALS AT LOW FLOW THAN THOSE IN UNMINED AREAS

Streams in mined areas carry more dissolved minerals at low flow than those in unmined areas even when no mine pumpage enters the stream; treated mine water contributes large amounts of dissolved minerals to streams.

The effects of mining on the quality of the water in streams are particularly noticeable in autumn, when streamflow is largely sustained by pumpage from coal mines and drainage from aquifers. In October 1977, 50 streams and 20 mine-discharge points were sampled in Buffalo Creek and Indian Creek basins. Analysis of the water-quality data shows that specific conductance is a good indicator of mine-water discharges. The western part of the Buffalo Creek basin is essentially unmined, and specific conductance of streams there ranged from 95 to 155 micromhos (fig. 5.2-1). The central and eastern parts of the basin are underlain by mines, and specific conductance of streams there ranged from 150 to 3,600 micromhos. Nearly the entire Indian Creek basin either has been undermined, or is currently being mined, and specific conductance of streams in this basin ranged from 165 to 2,300 micromhos. The largest conductance value measured in Indian Creek is at the most downstream site and below a point where mine discharge was entering from Stewart Run. The specific conductance of streams, such as Laurel Run and Little Laurel Run near Farmington, is high because of suspected increased infiltration of water arid solution of limestone along subsidence cracks.

Although most of Indian Creek and Buffalo Creek basins are undermined, the smallest stream pH value measured was 6.2 at base flow in October 1977. The pH of streams unaffected by mining or mine pumpage ranged from 6.7 to 7.6. The pH of streams affected by mine pumpage ranged from 6.2 to 8.5. This greater range of pH in streams affected by mine pumpage may be due to (1) variations in the treatment processes of mine water, (2) limestone dusting in the mines, or (3) more limestone beds in the eastern parts of the basins.

Basins, such as Laurel Run and Little Laurel Run, contain numerous subsidence cracks and have pH values larger than most streams, and large specific conductance. Hardness is generally high in water from these streams, perhaps as a result of water percolating down along subsidence cracks and joints dissolving carbonate minerals from the rock. In dissolving the carbonate minerals, calcium and magnesium are released resulting in increased carbonate hardness and pH. In summary, coal mining may be causing higher-than-normal pH rather than low pH in streams in Buffalo Creek basin.

Of the 50 streams sampled for dissolved minerals most (42) could be separated into four groups: (1) streams unaffected by mining, (2) streams undermined and having low flow but receiving no pumpage, (3) streams undermined and having high flow but receiving no mine pumpage (may receive some drainage from old drift mines in Waynesburg coal), and (4) treated and untreated mine pumpage.

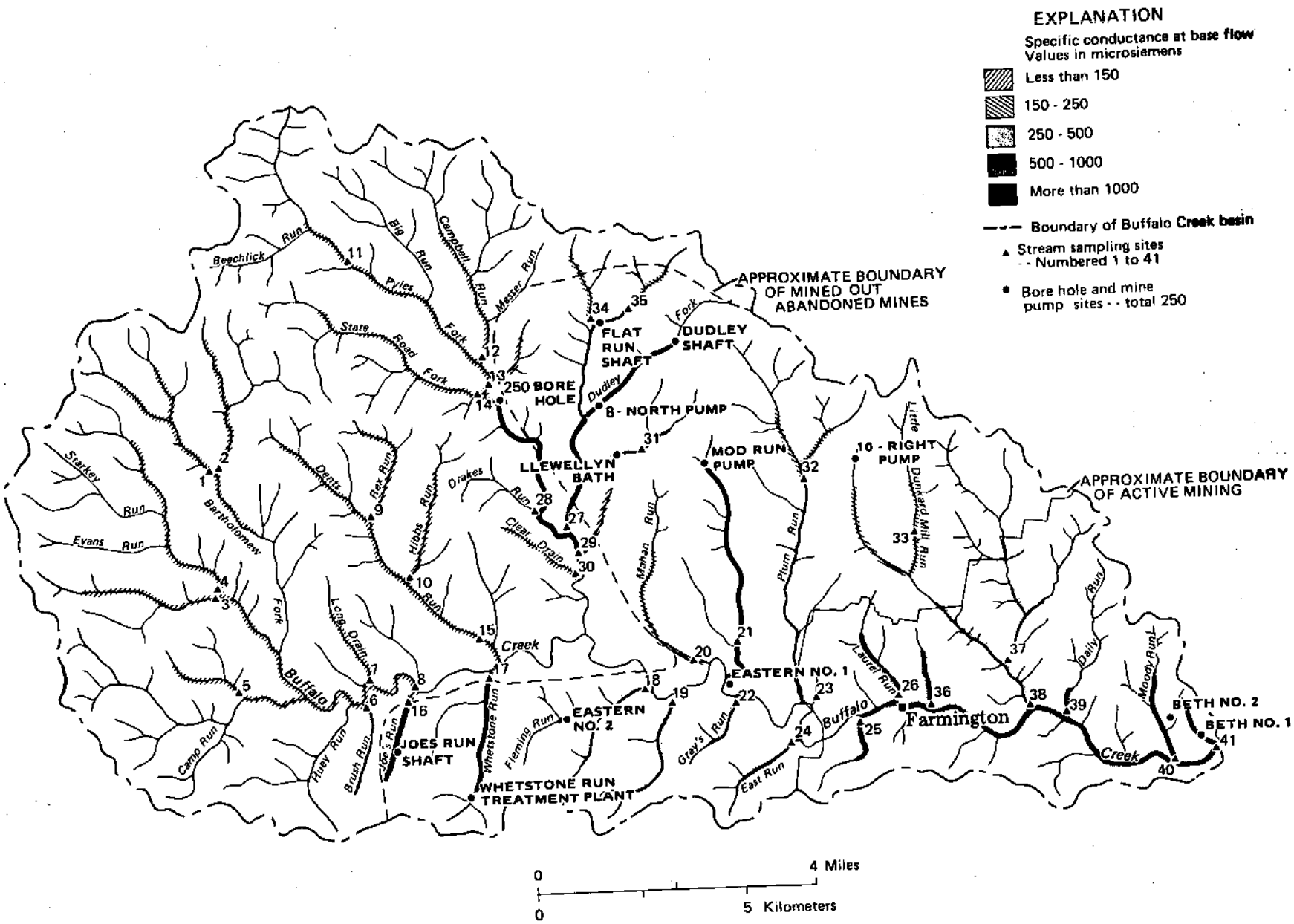


Figure 5.2-1— Specific conductance at base flow, Buffalo Creek, October 1977. (From Hobba, 1981, fig- 3.3.1-A.)

These four groups were analyzed and duration curves (figs. 5.2-2 and 5.2-3) prepared for sulfate, iron, hardness, and chloride. With the exception of iron, the sequential ordering of the groups on the graphs is also the order of increasing concentration for each chemical parameter. For iron, the order of increasing concentration is 3, 2, 1, and 4, respectively. The general reversal of order of groups 1, 2, and 3 may be due to the increase in pH from the unmined area to the completely mined area. As pH increases, iron generally cannot be dissolved and will not remain in solution. Thus, the iron curve for group 4 (treated and untreated mine pumpage) ranges from 30 to 45,000 ug/L. Because the mine-water treatment increases pH, iron concentration in the treated mine water is less than that in streams unaffected by mining.

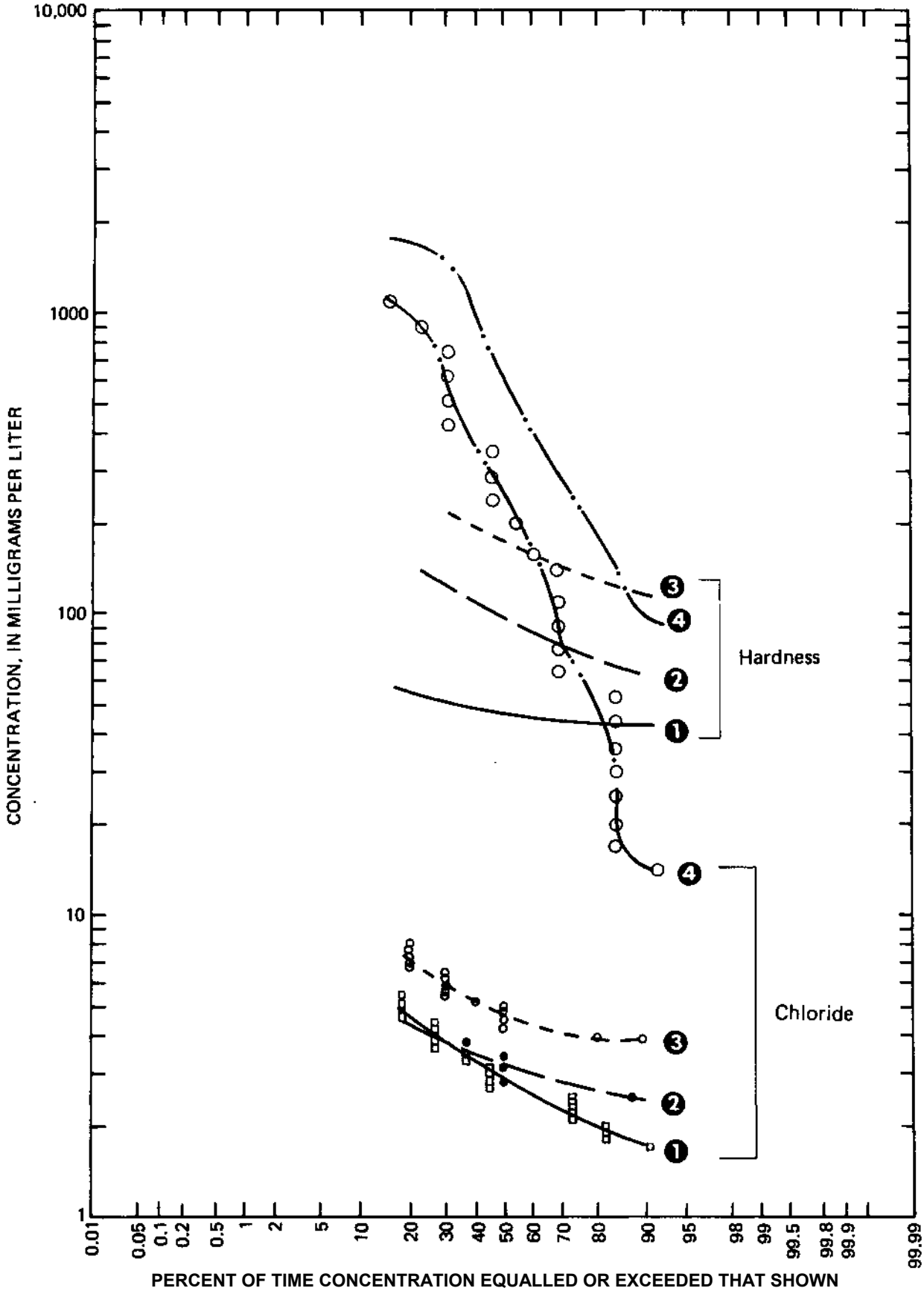


Figure 5.2-2.— Duration curves for hardness and chloride for streams in (1) unmined basins, (2) mined basins with low water yield, (3) mined basins with high water yield and (4) for treated and untreated mine water. (From Hobba, 1981, fig. 3.3.3-B.)

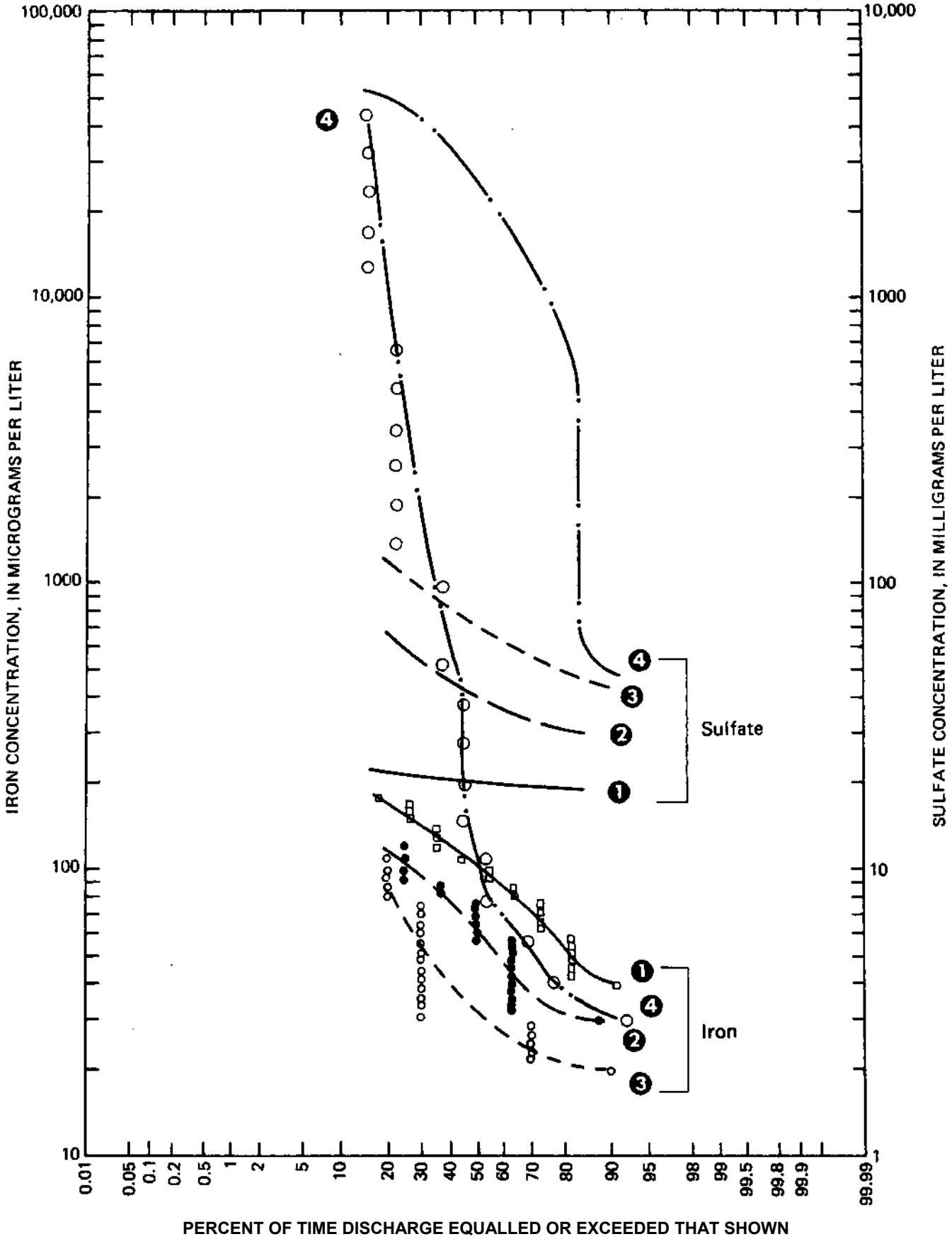


Figure 5.2-3.— Duration curves for sulfate and iron content for streams in (1) unmined basins, (2) mined basins with low water yield, (3) mined basins with high water yield, and (4) for treated and untreated mine water. (From Hobba, 1981, fig. 3.3.3-A.)

5.0 HYDROLOGIC CONSEQUENCES

5.3 SUBSIDENCE

SURFACE CRACKS CAUSED BY MINE SUBSIDENCE GENERALLY DEVELOP ALONG EXISTING JOINTS IN ROCKS

Mine subsidence cracks may cause increased infiltration of precipitation or runoff, lowering of the local water table, and increased mineralization of the ground water.

In the Farmington area of Buffalo Creek basin, subsidence began about 12 years after mine abandonment, but it was not confined to the vicinity of Farmington. Surface-subsidence fractures were found 1 mile or more from Farmington and 600 feet or more above the mine. Some investigators (8) believe that subsidence in the Farmington area may have been caused by the coal pillars pushing into the underlying clay. Another possible contributing condition is that the synclinal (downwarped) rock structure in the area might have less supporting strength than an anticlinal (arching) structure. Still another possible contributing condition is a linear fracture zone in the rock as interpreted from lineaments on aerial photographs. Thus, the combined effects of soft underclay, synclinal structure, and fractured zones may have caused considerable subsidence.

Underground mining in the Norton area of the Roaring Creek-Grassy Run basins began in the Lower Kittanning coal about 1895 and continued until 1971; surface mining continues to the present (1982). About one-half the mine area underlies a ridge drained on the east by Roaring Creek and on the west by Grassy Run. The rest of the area is drained by Roaring Creek. The Lower Kittanning coal of the Pennsylvanian Allegheny Formation is the principal coal bed mined.

More than 1,600 surface-subsidence holes or cracks were mapped in the Norton area. Most subsidence features were located where the overburden is less than 150 feet thick. Data from test drilling also indicate that where the overburden is thin, rock was mostly fractured near the surface; where the overburden is thick, rock was mostly fractured at greater depths. Some wells penetrated so much fractured rock at depth that water entering the wells at shallow depths drained down the well bore and out along the deeper fractures.

Nearly all consolidated rocks contain joints and fractures or faults. Joints are nearly vertical planar fractures (except for those which parallel bedding) along which there has been no apparent movement parallel to the joint plane. Joints may be a few inches to several feet in length and commonly develop in parallel sets that reflect stresses applied to the rocks. For example, if horizontal or vertical pressure or release of pressure, such as that caused by erosion, is exerted on this rock, then joints may develop in response to these stresses. Joint orientation is apparently independent of rock type. Thus, joint orientation is approximately the same in sandstone, shale, limestone, or coal.

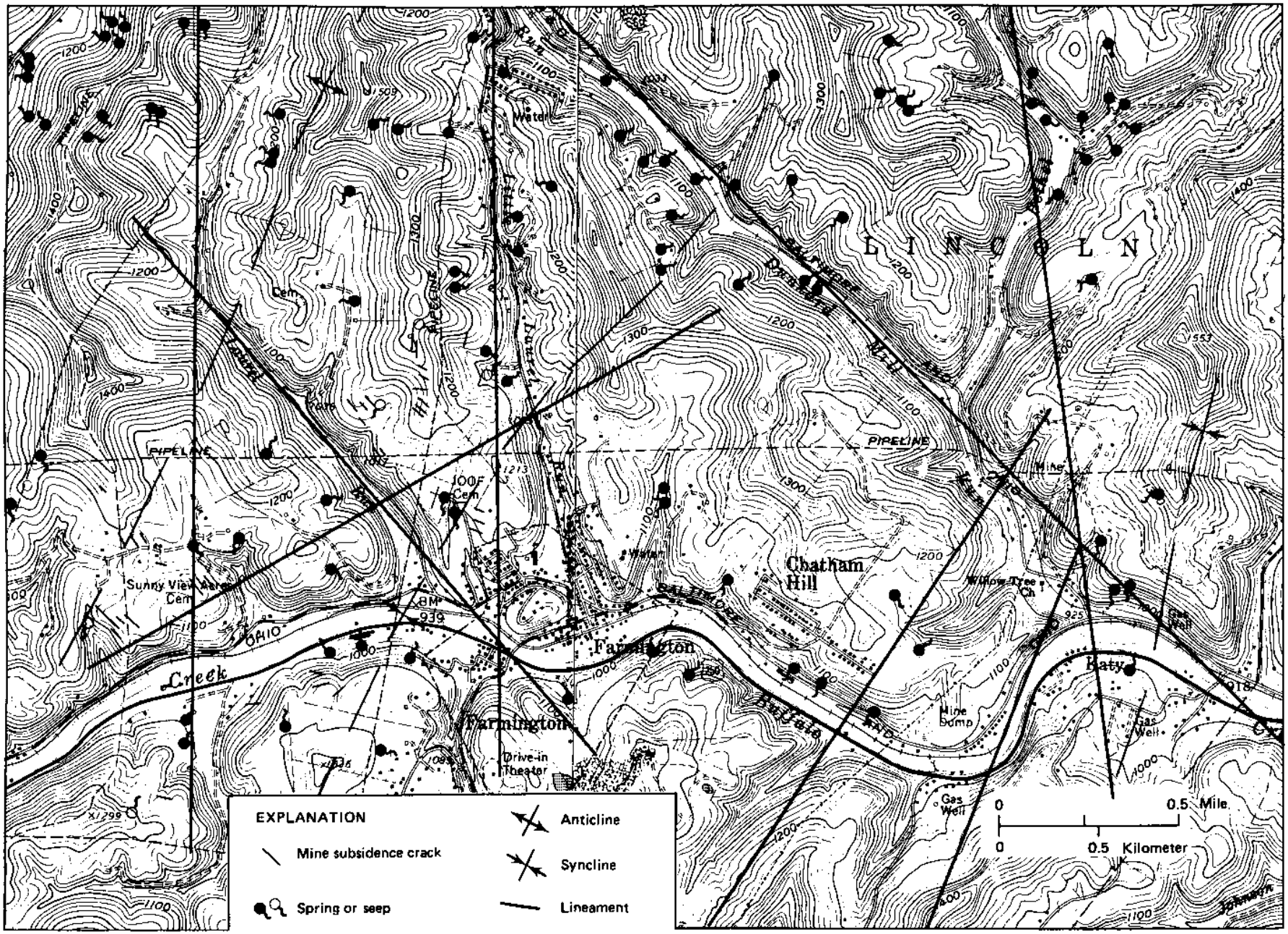


Figure 5.3-1.— Map showing mine-subsidence cracks, wet and dry springs, geologic structure, and lineaments. (From Hobba, 1981, fig. 3.1.3-A.)

Lineaments are linear features visible on photographs or other imagery that generally cannot easily be recognized or mapped on the ground. Lineaments are recognized from imagery by differences in plant types, soil tone or moisture content, alignment of disrupted rock outcrops, or alignment of topographic features, such as straight segments of stream channels. Lineaments commonly reveal underlying fractures, faults, or joint systems which generally are zones of structural weakness and of increased permeability. Three lineaments pass through the Farmington area (fig. 5.3-1). The Mine Safety and Health Administration officials report a correlation between roof falls in mines and intersections of lineaments mapped from aerial photographs and satellite images. Also water and gas problems have been noted in mines beneath surface lineaments.

Investigators (4) have reported that the orientation of lineaments reflect the orientation of major joints in bedrock and the "cleat" in coal beds. The straight linear mine subsidence cracks indicate that they may develop along existing joints. The orientations of 55 subsidence cracks were measured near Farmington, and are shown in figure 5.3-1. Comparing the orientation of these cracks to the orientation of major joints in the accompanying rose diagram (fig. 5.3-2) shows that the orientation of 71 percent of the subsidence cracks falls within the shaded ranges of the major joint trends.

Subsidence cracks 3 or more feet wide seem to be more common on hillsides and to be nearly parallel to the adjacent valley. These cracks may be wider because downslope movement of the rock may accompany subsidence.

Numerous springs and seeps were mapped from thermal imagery of the area (fig. 5.3-1). Most of the springs are above clay layers. Several springs were dry because the water table was lowered by downward leakage of water along subsidence cracks. These open cracks not only lower the local water table by partly draining perched aquifers, but also intercept overland runoff. This interception increases ground-water recharge and reduces evapotranspiration. The subsidence cracks also expose fresh mineral surfaces to weathering by the water; thus, concentrations of dissolved minerals in the ground water increase.

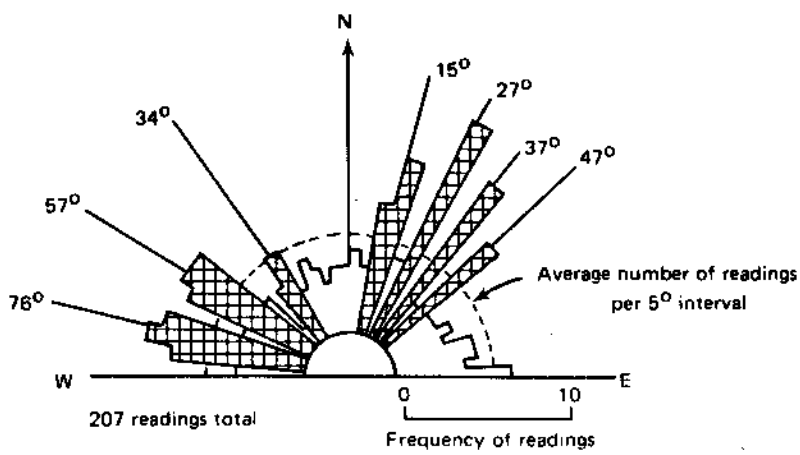


Figure 5.3-2.— Composite rose diagram of principal bedrock joint trends. (Modified from Bench and others, 1977, p. 19.)

5.0 HYDROLOGIC CONSEQUENCES

5.4 WELLS AND SPRINGS

UNDERGROUND MINING HAS LOWERED GROUND-WATER LEVELS IN THE VICINITY OF THE MINE; LITTLE EFFECT IN OTHER AREAS

Underground mining and subsequent collapse of overlying rocks increase ground-water drainage and can cause annual water-level fluctuations of as much as 100 feet.

Water levels have been measured in wells adjacent to mines and in wells completed directly over or penetrating a mine coal bed. Hydrographs show water-level fluctuations in a well penetrating rocks where the coal bed is unmined (fig. 5.4-1) and completely mined (fig. 5.4-2).

Wells 18-3-21A and 21C (fig. 5.4-1) are adjacent to each other and are about 100 feet west of the limit of underground mining. The water level in the deep well (21A) is about 15 feet above the top of the coal bed, and the water level in the shallow well (21C) is about 25 feet below land surface. Annual fluctuation is 1.5 feet in the shallow well and 4.7 feet in the deep well. The small fluctuations in these wells indicate limited recharge and discharge, which, in turn, reflects relatively impermeable rocks. The greater fluctuation in the deep well is probably in response to leakage into the mines. Note that, here and in similar situations, a mine-roof collapse could propagate more fissures, which could transect water-bearing units in the overburden and increase the potential for ground-water drainage and lowering of water levels in shallow wells.

The water-level measurements made as well 21A was drilled show that the water level continuously declined as the well was drilled deeper (fig. 5.4-1). When the well depth reached the level of the coal bed, the water level declined at an increased rate. Later, when the muck was bailed out of the well, effectively increasing the well depth, the water level dropped to between 135 and 140 feet. The well is cased to a packer set at 155 feet and is open from 155 feet to 175 feet. If this well were not cased, it would provide a path for ground water, which is at a higher head near the surface, to flow down the well bore out through the coal and into the abandoned mine, thus lowering local ground-water levels. Open vertical subsidence fractures where water can drain downward along the fractures may lower local ground-water levels in much the same way.

Wells 18-3-26A and 26C (fig. 5.4-2) are in areas where the coal has been removed. The water level in well 26C is about 38 feet below land surface during summer and fall, and fluctuates 9.2 feet annually, which suggests avenues of recharge to the well from the surface and leakage of ground water downward to the mine.

The hydrograph for well 26A (fig. 5.4-2) shows annual fluctuations of nearly 100 feet. This well is cased only to 18 feet, but it is 198 feet deep and penetrates a pillar of coal in the mine. Large fluctuations in water level indicate that the rocks near land surface are fractured and permeable, permitting rapid recharge. Also, the rocks and coal near the bottom of the well are permeable enough to permit rapid discharge of water into the abandoned mine. Monthly measurements at well 26A show that the water level has dropped as much as 85.5 feet in 21 days. Part of the annual fluctuation of water level in shallow well 26C is undoubtedly caused by

discharge of shallow ground water downward through well 26A. During winter and spring of 1966 and 1967, the water level in well 26A was relatively high, and the measurements for the same seasons in 1977 and 1978 show a low water level. Precipitation for 1966 and 1977 was less than average, but was more than average for 1967 and 1978. The low water level in 1977 and 1978 suggests that additional subsidence cracks may have opened at depth to permit better drainage of water from the overlying rocks.

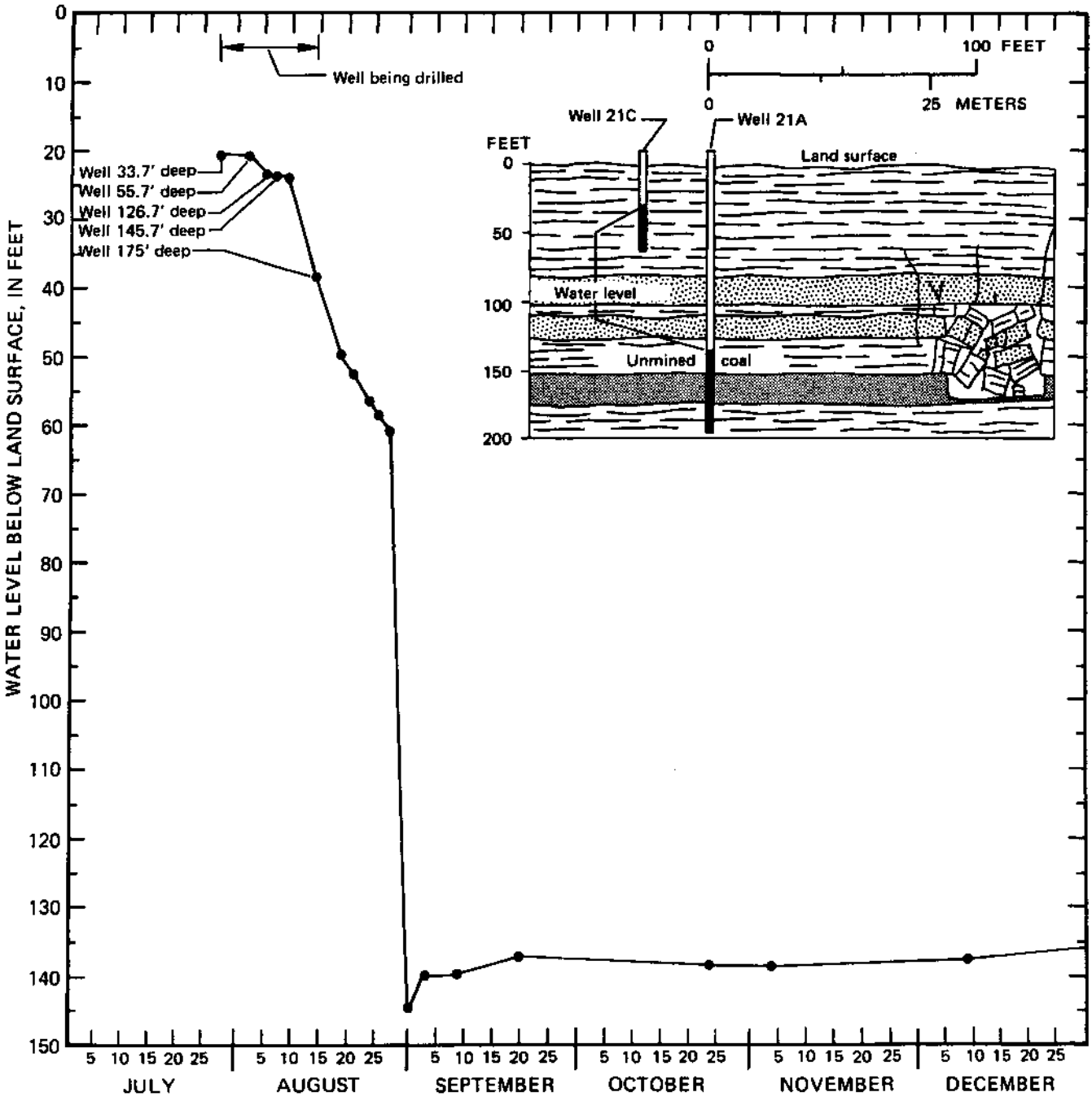


Figure 5.4-1.— Hydrograph of well 18-3-21A as it was being drilled, and for the following four months; and approximate physical setting at wells 21A and 21C. (On August 29, 1964, well 21A was bailed and muck removed from bottom; packer set at 155 feet.)
(From Hobba, 1981, fig. 2.4.2-A.)

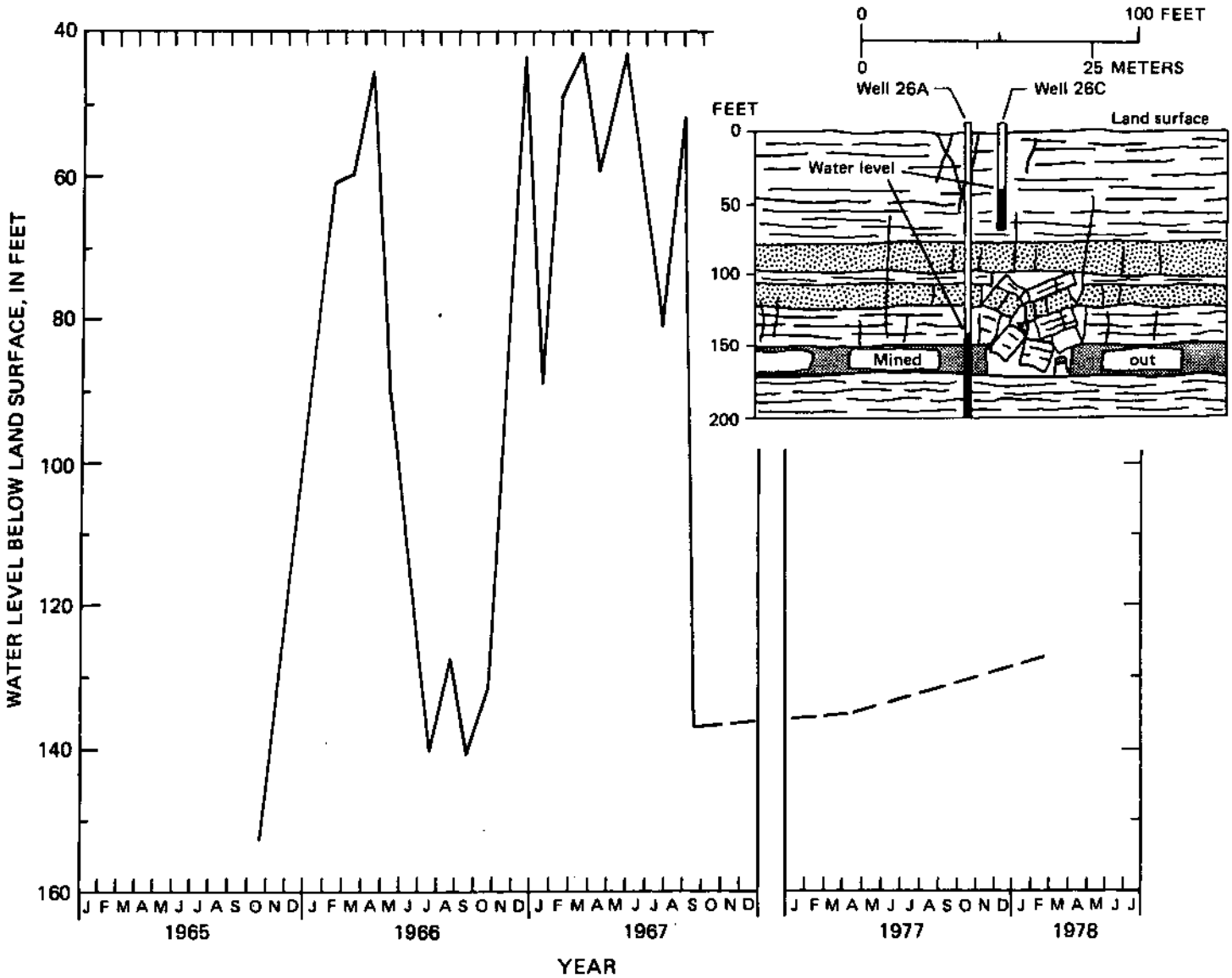


Figure 5.4-2. — Hydrograph of well 18-3-26A and approximate physical setting at wells 18-3-26A and 26C.
(From Hobba, 1981, fig. 2.4.2-B.)

6.0 POST-MINING HYDROLOGIC MONITORING

MONITORING PLAN MUST CONSIDER SOURCES OF LOCAL WATER SUPPLIES

Important considerations for monitoring plans are the effects of mining on domestic water supplies, both surface water and ground water and on streams and springs that may be reduced in flow and quality.

The impacts on local domestic water supplies are of primary concern. Previous sections have illustrated that in mined areas, ground-water levels fluctuate more rapidly, and in greater amounts, than in unmined areas. Underground mining and mine subsidence increase ground-water drainage to streams and create annual water-level fluctuations as much as 100 feet. Mine subsidence caused increased infiltration of precipitation, lowering of the natural water table, and increased mineralization of water. In designing a well-monitoring plan it is important to identify what formations are used primarily as a source of domestic water. Monitoring wells should be located close enough to measure any dewatering of this formation but still be sufficiently far away from the actual mining area as to lessen the radical fluctuations known to occur when in close proximity to a mine or mine subsidence. These wells should be cased and sealed to reflect water level changes just in the formation of concern. Deeper companion wells (fig. 6.0-1) also cased and sealed should be placed to ascertain effects on deeper formations, which might be needed as replacement wells for local domestic use if the shallower wells are dewatered. Wells need to be located upgradient and downgradient from the proposed mining. All wells should be sampled prior to mining for selected water-quality constituents. During mining and after mining and reclamation, wells downgradient from mining should be sampled quarterly for water quality. The frequency of sampling and the number of constituents tested may be less frequent and more selective depending on the results of sampling and during the post-mining recovery and stabilization of the hydrologic system.

Although the ground-water monitoring plan is primarily concerned with the impacts on local water supplies and availability, a limited number of observation wells may be located in abandoned mine areas and in the mine-permit area. The specific well sites are controlled by the location of interpreted lineaments, mine-subsidence cracks, nonfractured sites, and streams. These are temporary wells that will provide an overall understanding of mining impacts during mining and immediately after mining; they would be abandoned or selected for yearly sampling once post-mining effects are clearly identified.

At low flows (ground-water base flow), one-half of the total streamflow may be mine pumpage or mine drainage. Also, at low flow, streams in the mined areas transport more dissolved solids than those streams in unmined areas. The proposed hydrologic-monitoring plan includes streamflow-gaging stations upstream and downstream from of the mine-affected area (fig. 6.0-1). Monitoring stations need to be located on tributaries where effluent from an abandoned mine dump or spoils pile is evident. Finally, baseline water-quality and quantity measurements are needed prior to mining to allow subsequent assessment of post-mining changes, particularly the effects of subsidence.

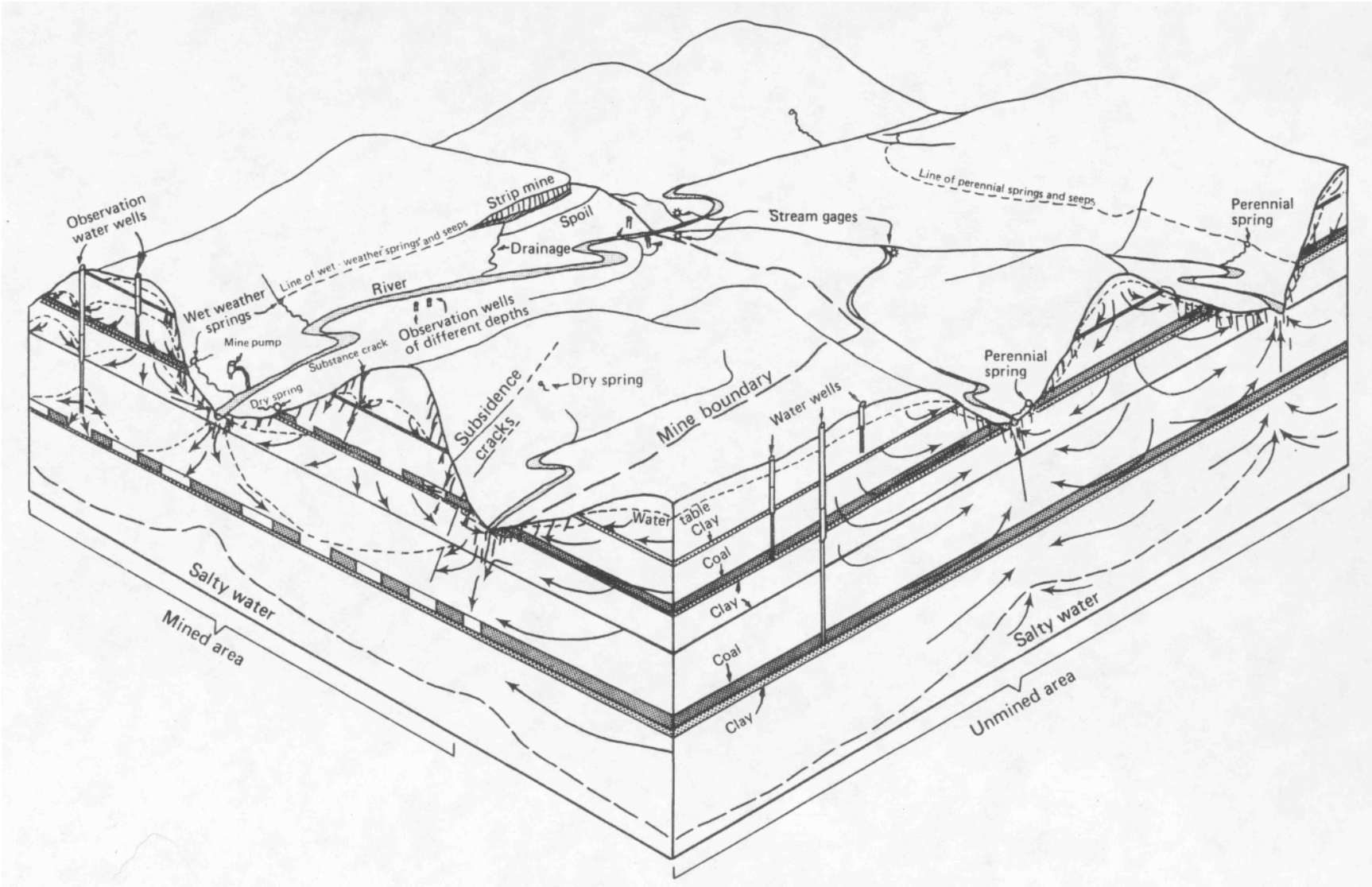


Figure 6.0-1.— Block diagram of hypothetical area showing hydrology of both mined and unmined areas, and possible well- and stream-monitoring sites.
(Modified from Hobba, 1981, fig. 4.0-B.)

7.0 REFERENCES

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