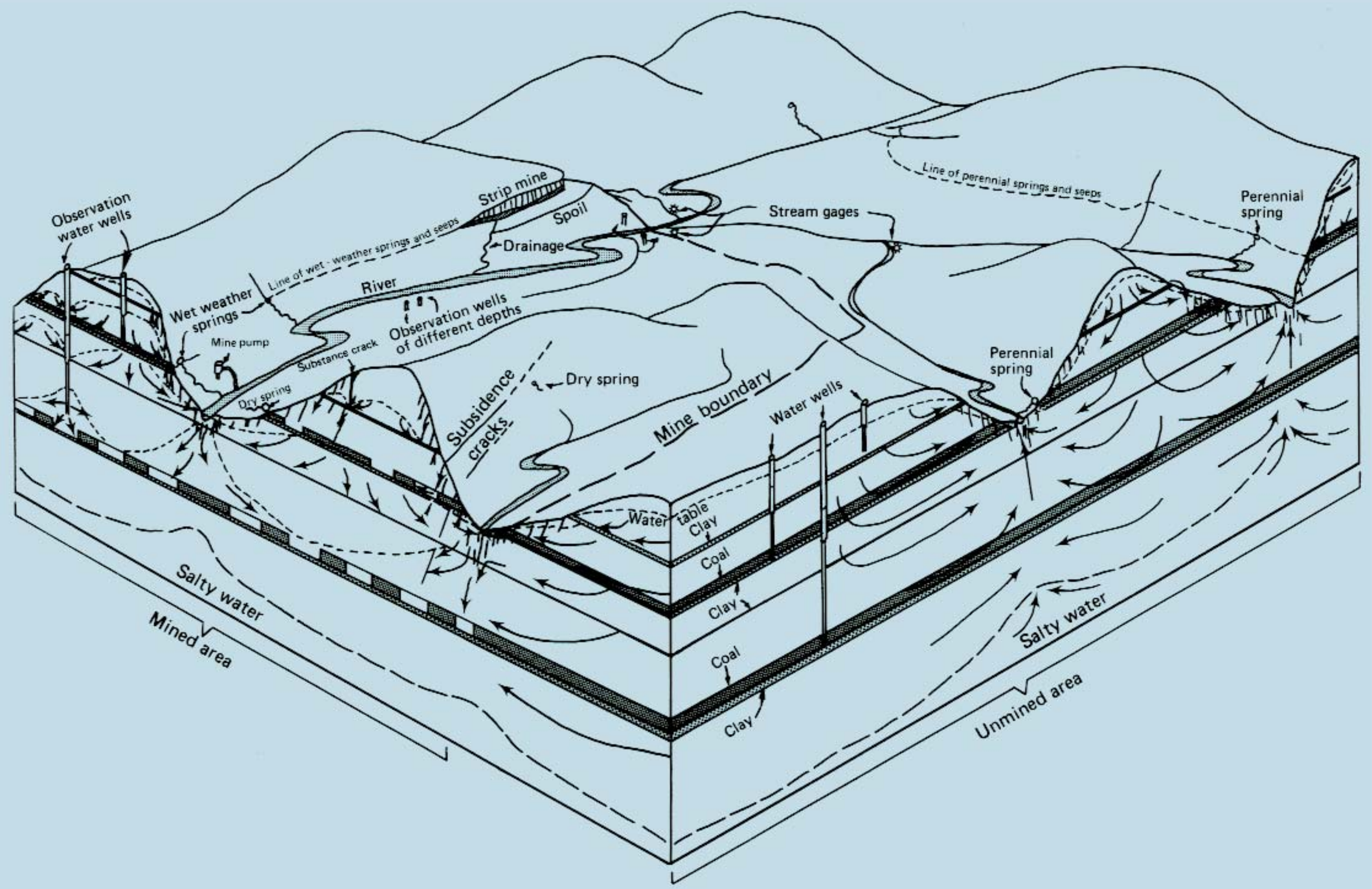
U. S. Department of the Interior
Office of Surface Mining Reclamation and Enforcement

GROUND-WATER INFORMATION MANUAL:

COAL MINE PERMIT APPLICATIONS — VOLUME II



Prepared in cooperation with
U.S. Geological Survey

GROUND-WATER INFORMATION MANUAL: COAL MINE PERMIT APPLICATIONS VOLUME II

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April 1987

TABLE OF CONTENTS

CONVERSION FACTORS AND ABBREVIATIONS

For use of readers who prefer to use metric (SI) units,
conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
Length		
inch (in.)	25.4	millimeters (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047.	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09294	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785.	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
Flow		
Velocity		
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.048	meter per day (m/d)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)
Discharge		
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meters per second (m^3/s)
Mass		
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (oz)	453.6	gram (g)
ton, short	0.9072	megagram (Mg)
Temperature		
degree Fahrenheit (˚F)	˚C =	degree Celsius (˚C)

Use of brand names throughout this manual is for identification purposes only and does not imply endorsement by U.S. Geological Survey.

PREFACE

The Surface Mining Control and Reclamation Act of 1977 requires that hydrologic information on the aquifers above and below the coal beds (or seams) to be mined be submitted with the permit application. With this information, the regulatory authority can evaluate the potential impact of the proposed mine on the aquifer system(s), as well as assess the cumulative hydrologic impacts of the proposed mine, or mines, on the adjoining properties.

The purpose of this manual, consisting of volumes I and II, is to assist applicants for coal mining permits in (1) describing the ground-water conditions in the vicinity of a permit area, and (2) assessing the potential impacts of mining on the ground-water resources in the area adjacent to the proposed site. The manual is directed at a moderately technical audience. The applicant, or the consultant for the applicant, is assumed to have a bachelor's degree in hydrology, engineering, or geology, or its equivalent, with a basic background in science, including mathematics, chemistry, and physics.

This manual describes four principal subjects: (1) the geologic setting of the bedrock units containing the coal to be mined, (2) the hydrologic setting (primarily ground water), including low flow in streams and its relationship with ground water (or lack of); (3) the potential impacts of mining on the ground-water resources; and, (4) the data requirements or monitoring plan for an impact analysis. Detailed discussions of these subjects are presented in volume I.

In volume II, the results of 11 ground-water studies are compiled. Each study is self-contained and is the result of a geohydrologic investigation conducted in cooperation with other State and Federal agencies, in one of the various coal provinces in the conterminous United States (see figure 1). These studies include the geologic and hydrologic settings and other hydrologic information. Their interrelation with volume I is shown in table 1.

In preparing the permit application, the applicant can use the studies in this manual as examples for presentation of ground-water information. However, these studies are not comprehensive in presenting the ground-water situations for all geologic and hydrologic settings. Also, the content of each of these studies is not directed at satisfying the requirements of the State regulatory authority. Thus, some studies may not contain sufficient hydrologic information to satisfy all the requirements of all regulatory agencies.

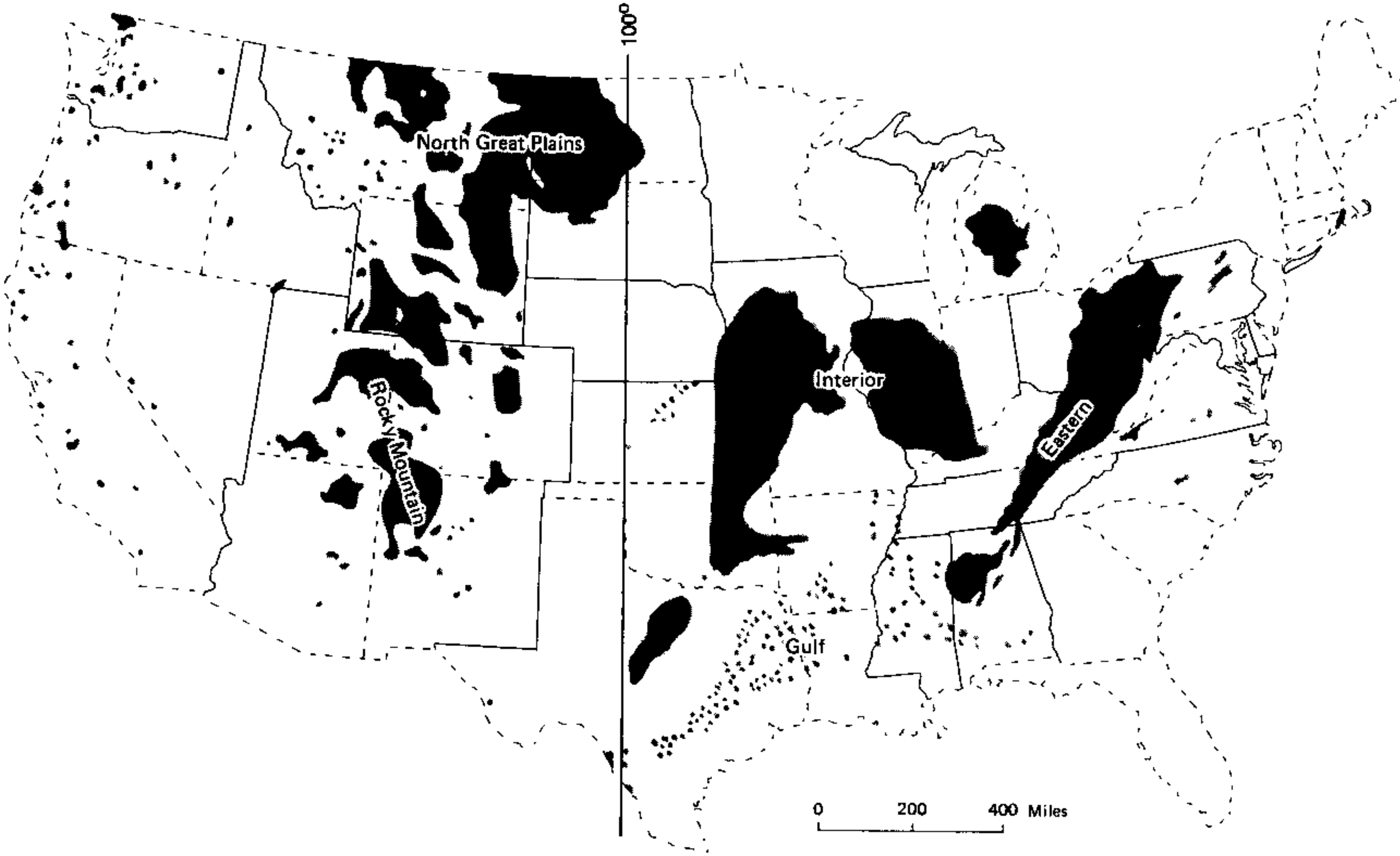


Figure 1. — Location of coal provinces in conterminous United States.
(Modified from Trumbull, 1960, sheet 1.)

Table 1. Selected ground-water studies.

[X, indicates the occurrence of analysis for respective ground-water study.]

Ground-water study number	Geologic 1/ setting	Hydrologic 2/ setting	Mining 3/ method	Availability 4/ of hydrologic data	Pre-mining	During mining	Post-mining	Aquifer properties	Stream-aquifer interaction	Spoils-pile hydrology	Model analysis	Statistical analysis	Remarks (significant features of the study)
Eastern Province													
1	1	D,E	S	G,Q	X		X	X	X				Slug-test analysis; Impacts on hydrologic system.
2	3,8	D,E	S,U	S,G,Q	X	X				X		X	Fracture-trace analysis; hydrologic-budget analysis; detailed water-quality analysis.
3	1	E	S	S,G,Q	X	X	X	X			X		Hydrologic-budget modeling; detailed water-quality analyses.
4	1	G	U	S,G,Q	X	X		X			X		Secondary permeability; aquifer test analyses; cross-sectional aquifer modeling.
5	1,7,8	D	U	S,G,Q	X	X	X	X	X		X		Fracture-trace analyses; subsidence; base-flow modification; detailed aquifer analyses.
Interior Province													
6	6	C,D	S	G	X		X	X	X		X		Alluvial aquifer(glacial); slug-test analysis; analytical dewatering models.
7	1	G	S,U	S,G,Q	X		X		X			X	Flow duration; water-quality regionalization.
Northern Great Plains Province													
8	1	E,G	S	S,G,Q	X	X	X	X		X	X		Geochemical analyses; detailed aquifer analyses and modeling.
9	1	C,D	S	G,Q	X	X	X	X			X	X	Geochemical & aquifer modeling; potentiometric and permeability maps; lignite.
Rocky Mountain Province													
10	1	D,E	S	S,G,Q	X			X		X			Transmissivity map; lignitic coal; detailed water-quality analyses; potentiometric map.
11	1,4	E,G	S,U	G,Q	X	X	X	X			X		Secondary permeability; potentiometric maps; detailed aquifer analysis; aquifer modeling.

1/Geologic Setting:
1, Flat lying coal bed;
3, Synclinal geologic structure;
4, Low-angle dipping coal bed;
6, Coal bed 'under' stream valley;
7, Coal beds and fault structures;
8, Fractured bedrock caused by mine subsidence.

2/Hydrologic Setting:
C, Coal bed in contact with saturated unconsolidated deposits;
D, Coal bed in contact with confined bedrock aquifer;
E, Coal bed in contact with unconfined aquifer;
G, Coal bed within multi-layered aquifer system.

3/Mining Method:
S, Surface;
U, Underground.

4/Availability of Hydrologic Data:
S, Streamflow data;
G, Ground-water data;
Q, Qualilty of water data.

GROUND-WATER STUDY 1

by

Celso Puente

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1.0 ABSTRACT

Geology and the Occurrence of Coal

The Blue Creek area in Tuscaloosa County lies in the Warrior coal field. The basin is principally underlain by nearly flat-lying sedimentary rocks of the Pottsville Formation of Pennsylvanian age. The Pottsville consists chiefly of alternating beds of sandstone, conglomerate, siltstone, and shale, with interbeds of coal and associated underclays. In the Warrior field, the productive part of the Pottsville Formation contains seven coal groups that may contain from 2 to 10 coal beds each. The Utley Coal Group, which consists of three coal horizons within a vertical interval of 20 to 250 feet, crops out in the basin. Two coal beds within the basal horizon are mined in the study area.

Hydrology and Hydrologic Monitoring

Water percolating downward into the Pottsville Formation, the only source of ground water available to wells in the area, is stored primarily in and transmitted through openings along joints, fractures, and bedding planes. Relatively impermeable clay beds underlying the two coal beds mined in the study area from the base of two perched water zones or aquifers above the regional ground-water system. Because of the occurrence of perched water tables and the irregular lensing character of the aquifers, the configuration of the water table over a large area is generally unpredictable. Areal correlations are possible only within short distances. The aquifers are not a source of large quantities of water. Transmissivity and storage coefficients computed using the slug test method at selected wells ranged from about 1 to 450 ft^2/d and from 1 to 10^{-2} to 1 x 10^{-5}, respectively. Premining quality of ground water is extremely variable but generally suitable for most domestic uses. Surface water draining the mined area is very mineralized. The hydrologic monitoring network consists of inventoried and drilled observation wells with continuous water-level recorders, streamflow-gaging stations with continuous water-quality monitors, and precipitation gages.

Mining Methods and Other Stresses on the Aquifer System

Surface coal mining in the general area started in early 1976 and entailed the stripping of two coal beds within the Utley Coal Group. About 250 acres were surface-mined in the basin. The aquifer systems do not have any significant withdrawal demands other than for domestic purposes.

Probable Hydrologic Impacts and Post-Mining Hydrologic Network

The intersection of the surface mine with water-bearing openings or aquifers resulted in draining of the openings and a corresponding decline in ground-water levels adjacent to the mine. Placement of mine spoils in the mined area has created aquifers of the spoils that store and transmit more water than the original aquifers. The spoils aquifers are a source of recharge to underlying aquifers and a source of base flow to Blue Creek. The low flows of Blue Creek exceed those prior to mining. The quality of water in streams draining the mined area and in wells downdip from the mine has been significantly altered. Mineralization of surface drainage leaving the basin has increased by a factor of 27 since mining started. A post-mining hydrologic surveillance network needed to determine the extent, magnitude, rate, and duration of hydrologic change caused by surface mining could consist of ground-water monitoring wells, streamflow gaging stations, and precipitation gages.

2.0 GEOLOGIC SETTING

AREA UNDERLAIN BY COAL-BEARING ROCKS OF PENNSYLVANIAN AGE

The Blue Creek area is underlain by nearly flat-lying rocks of the Pottsville Formation. The strata generally strike northeastward and dip southeastward about 22 feet per mile.

The basin is underlain by nearly flat-lying rocks of the Pottsville Formation of Pennsylvanian age and the Coker Formation of Cretaceous age (fig. 2.0-1). The two formations are sedimentary in origin but contrast greatly; the Pottsville is consolidated, and the Coker is unconsolidated.

Regionally, the strata in the Pottsville Formation strike northeastward and dip southeastward about 5 to 25 ft/mi except where disrupted by faulting and folding (2)*. The unconformable contact between the Pottsville and the overlying Coker Formation strikes northwestward and dips southwestward from 32 to 37 ft/mi (5). The dip and strike of strata in the Coker Formation parallel those of the contact. In the study area, the Pottsville strata generally strike and dip southeast about 22 ft/mi (fig. 2.0-2). The Coker Formation, which dips southwestward about 32 ft/mi, crops out in less than 5 percent of the area, capping the highest hills and ridges along the basin divides.

The Pottsville Formation consists chiefly of alternating beds of gray sandstone, conglomerate, siltstone, and shale, with interbeds of coal and associated underclays. Shale is the dominant rock type. The thickness of the Pottsville in the area is about 4,000 feet. The Coker Formation consists of fine- to coarse-grained sand and gravelly sand separated in places by lenticular beds of gray, sandy clay.

Several intervals in the Pottsville Formation contain beds of coal and underclay. In the Warrior field, the productive part of the formation contains seven coal units that may contain 2 to 10 beds each (2). These units are, in ascending order, the Black Creek, Mary Lee, Pratt, Cobb, Guin, Utley, and Brookwood. Coal beds cropping out in the basin are in the Utley unit.

The Utley Coal unit in the general area consists principally of three coal horizons (7). This unit consists of two to six coal beds within a vertical interval of 20 to 150 feet (2). Sandstone, generally interbedded with some shale and siltstone and ranging in thickness from 40 to 50 feet, composes the lowermost part of the Utley Coal unit. One or more of the coal beds separated by shale partings may be present in each horizon. The basal coal horizon generally contains the most persistent and thickest coal beds. The second horizon is 10 to 20 feet above the basal horizon and the third horizon 30 to 40 feet above the basal horizon. The two upper horizons are inconsistent in that either or both may be absent in a given area. Two coal beds probably within the basal horizon of the Utley unit, a 24-inch seam and a lower 18-inch seam (fig. 2.0-3), are mined in the general area.

* Numbers in parentheses refer to items in the bibliography.

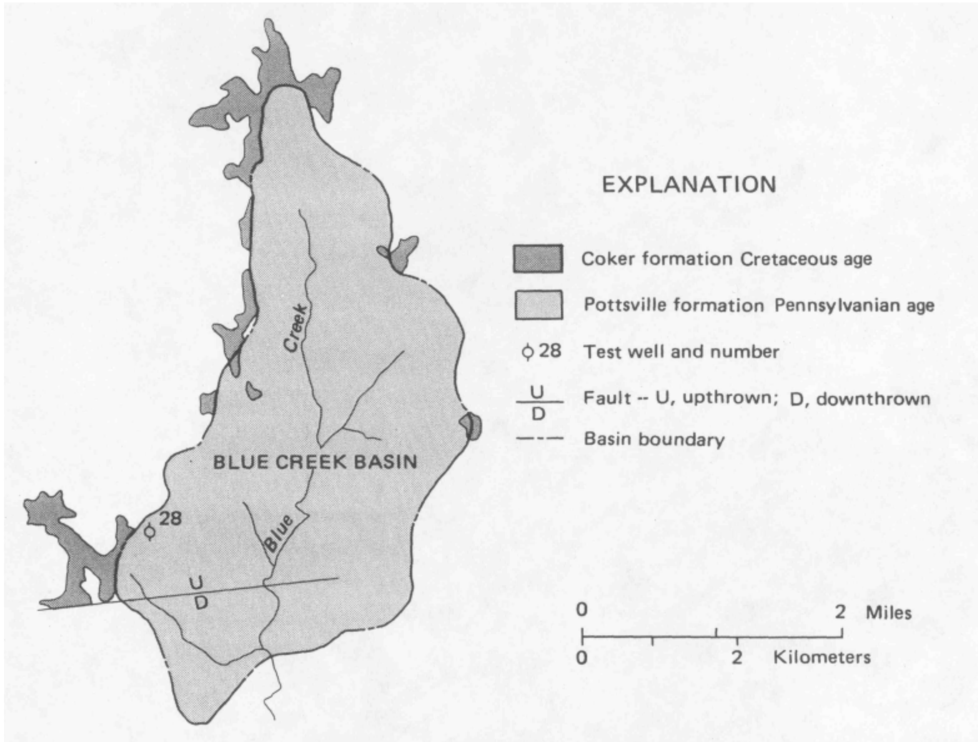


Figure 2.0-1. Geology of general area. (Modified from Puente and others, 1980.)

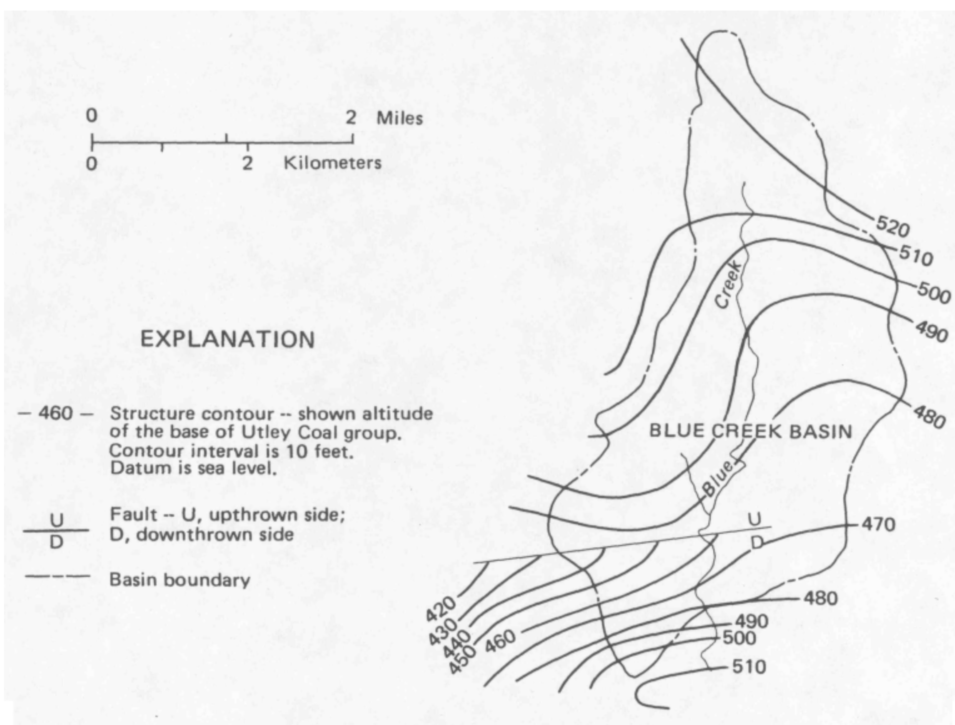


Figure 2.0-2. Contour map showing altitude and configuration of the base of the Utley coal unit. (Structure modified from Semmes, 1929.)

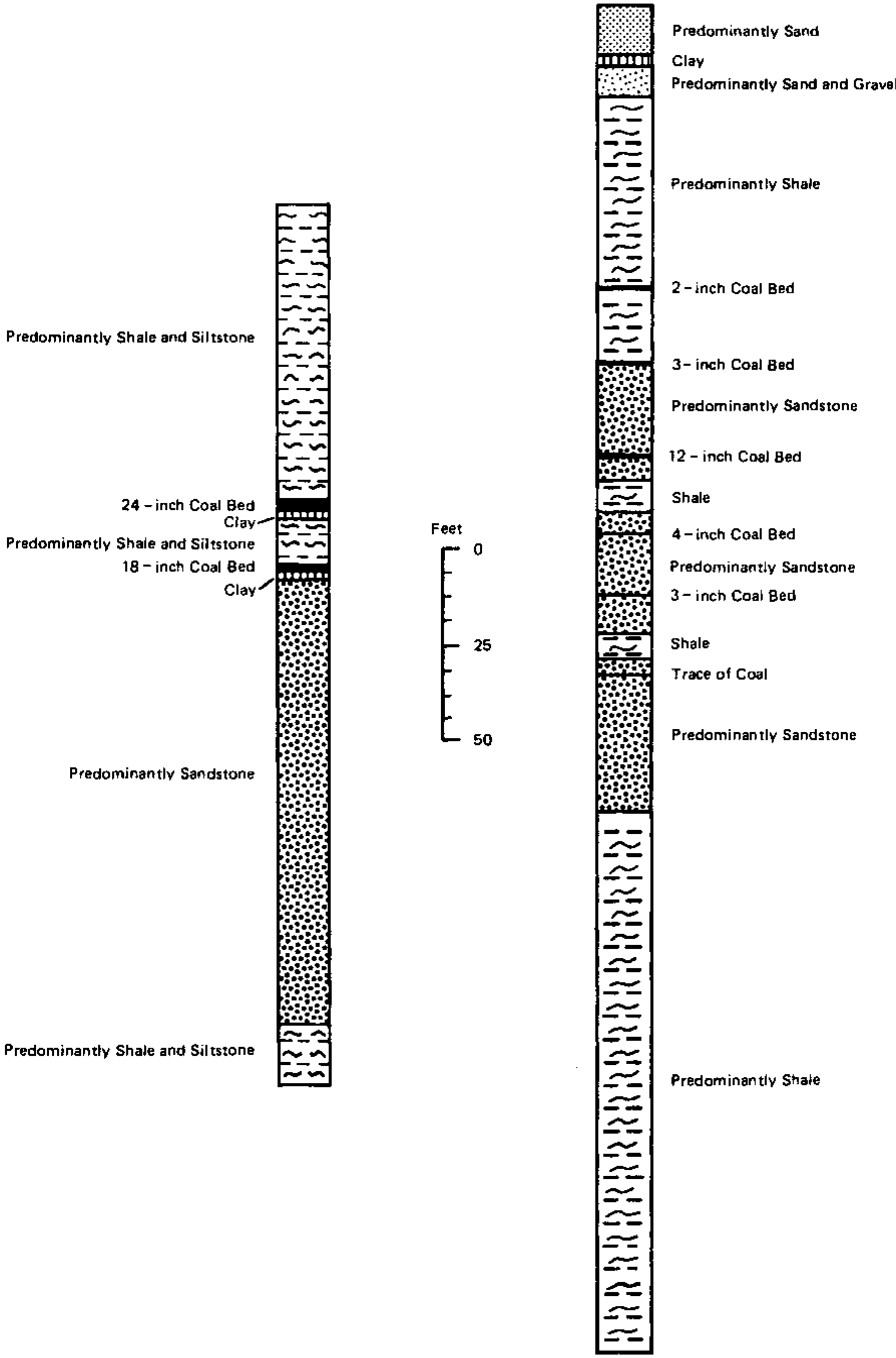


Figure 2.0-3.— Stratigraphic columns for selected test wells in the vicinity of the mine-permit area (see fig. 3.2-1 for test-well locations).

3.0 HYDROLOGIC SETTING

3.1 CLIMATE

AREA CHARACTERIZED BY WARM AND HUMID WEATHER

The average annual temperature is about 63˚F. The average annual precipitation is about 56 inches per year.

The Blue Creek area has a subtropical climate characterized by warm and humid weather. According to National Weather Service records (3), the average annual temperature is about 63˚F. January is generally the coldest month with an average temperature of 44˚F and July, the hottest with an average temperature of 80˚F. The length of the growing season averages 225 days, with the frost-free season occurring from late March through early November.

The average annual precipitation, almost all in the form of rain, is about 56 inches. Snowfall is very light and infrequent. About 55 percent of the average annual precipitation occurs from December through April. The wettest month is March and the driest is October; drought seldom occurs. Monthly precipitation data at sites near the study area are shown in figure 3.1-1. Summer rains, produced by convective storms, are more intense but briefer and smaller in area than rains associated with winter and early spring frontal storm systems.

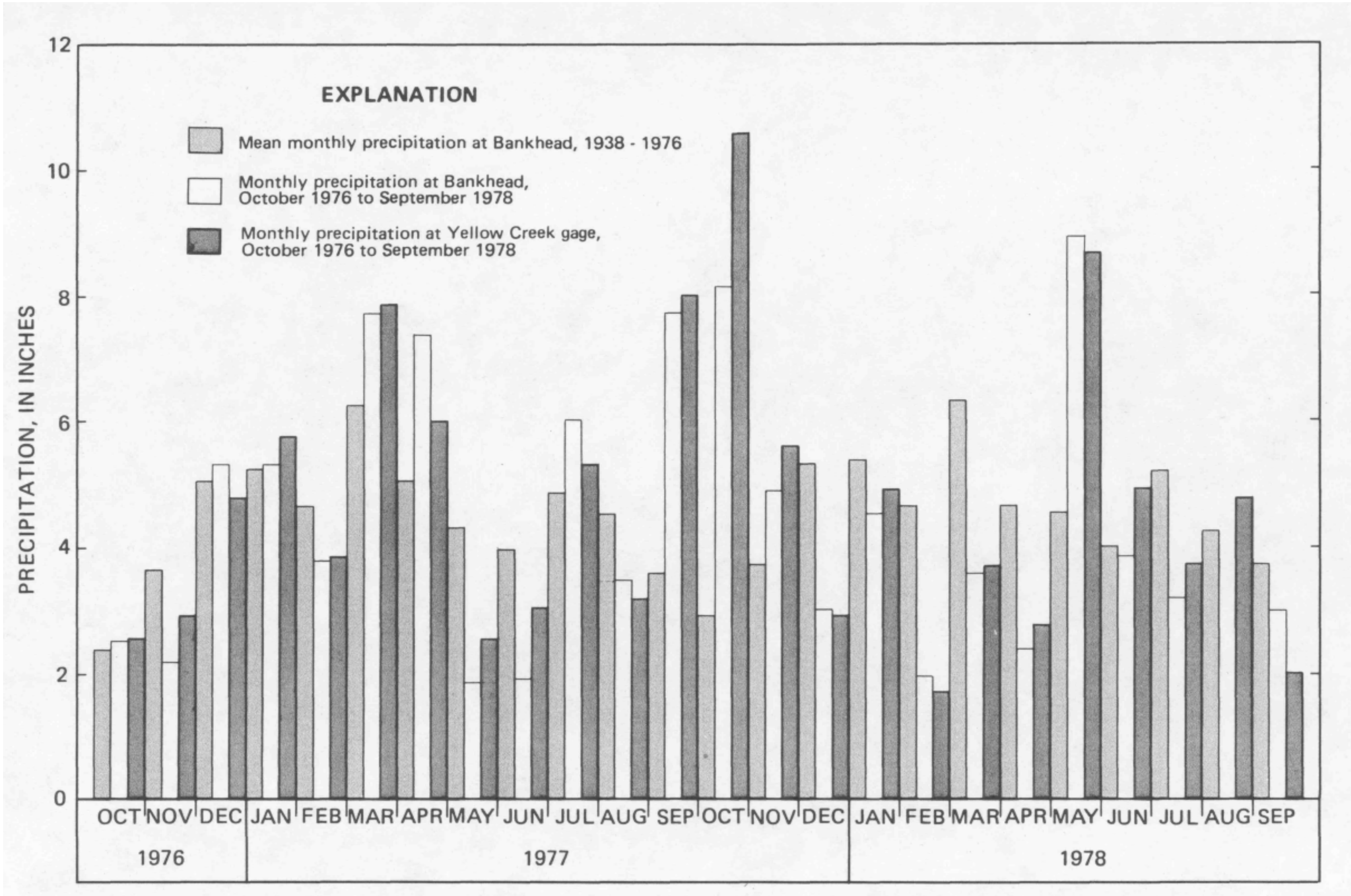


Figure 3.1-1.— Monthly precipitation near the mine permit area. (Modified from Puente and others, 1980.)

3.0 HYDROLOGIC SETTING

3.2 OCCURRENCE AND MOVEMENT OF GROUND WATER

FRACTURED BEDROCK IS THE MAJOR SOURCE OF GROUND WATER

Water is principally stored in and transmitted through openings along joints, fractures, and bedding planes. Well yields are small, reflecting limited ground-water storage and little aquifer permeability.

The principal source of water in the Blue Creek area is from precipitation. Water percolating downward into the Pottsville Formation, the only source of ground water available to wells in the area, is primarily stored in and transmitted through openings along joints, fractures, and bedding planes.

Water in the Pottsville Formation occurs under water-table, artesian, and perched conditions. Aquifers overlain by relatively permeable rocks that permit precipitation to enter directly by percolation are under water-table conditions. Aquifers lying between relatively impermeable rocks, where the water is confined under pressure, are under artesian conditions. Perched water-table conditions occur where rocks of little permeability (unfractured sandstone, soft shale and underclay associated with coal) impede the downward movement of water to the regional water table. Under perched conditions, one or more water tables may exist above the local stream level. All conditions may be present at different levels in the same area.

The occurrence and movement of ground water in the Blue Creek basin is based on geology, well inventory, and information obtained from a test-drilling program in the area. The locations of wells inventoried and test wells drilled are shown in figure 3.2-1. Detailed information for these wells is given in tables 3.2-1 and 3.2-2. Additional data-collection sites to define streamflow (site 3) and rainfall (site A) also are shown in figure 3.2-1. The surface-water site in Blue Creek has been instrumented, since 1976, for continuous monitoring of streamflow, water quality (temperature and specific conductance) and daily suspended sediment.

A schematic diagram illustrating the occurrence and movement of water in the Pottsville underlying the general area is shown in figure 3.2-2. Relatively impermeable clay beds underlying the two coal beds mined in the general area form the base of two perched water zones or aquifers above the regional ground-water system. Recharge to the upper aquifer is from precipitation percolating into the formation. The lower aquifer is recharged by leakage through the overlying clay and precipitation where the clay is absent.

The water in interconnected openings moves downward from the upper aquifers and (or) laterally to the outcrop of the aquifer on hillsides where the water discharges as seeps or springs and becomes a part of streamflow. The seeps or springs most commonly discharge during periods of greatest rainfall, but in most instances, cease to flow in a relatively short time if precipitation is absent.

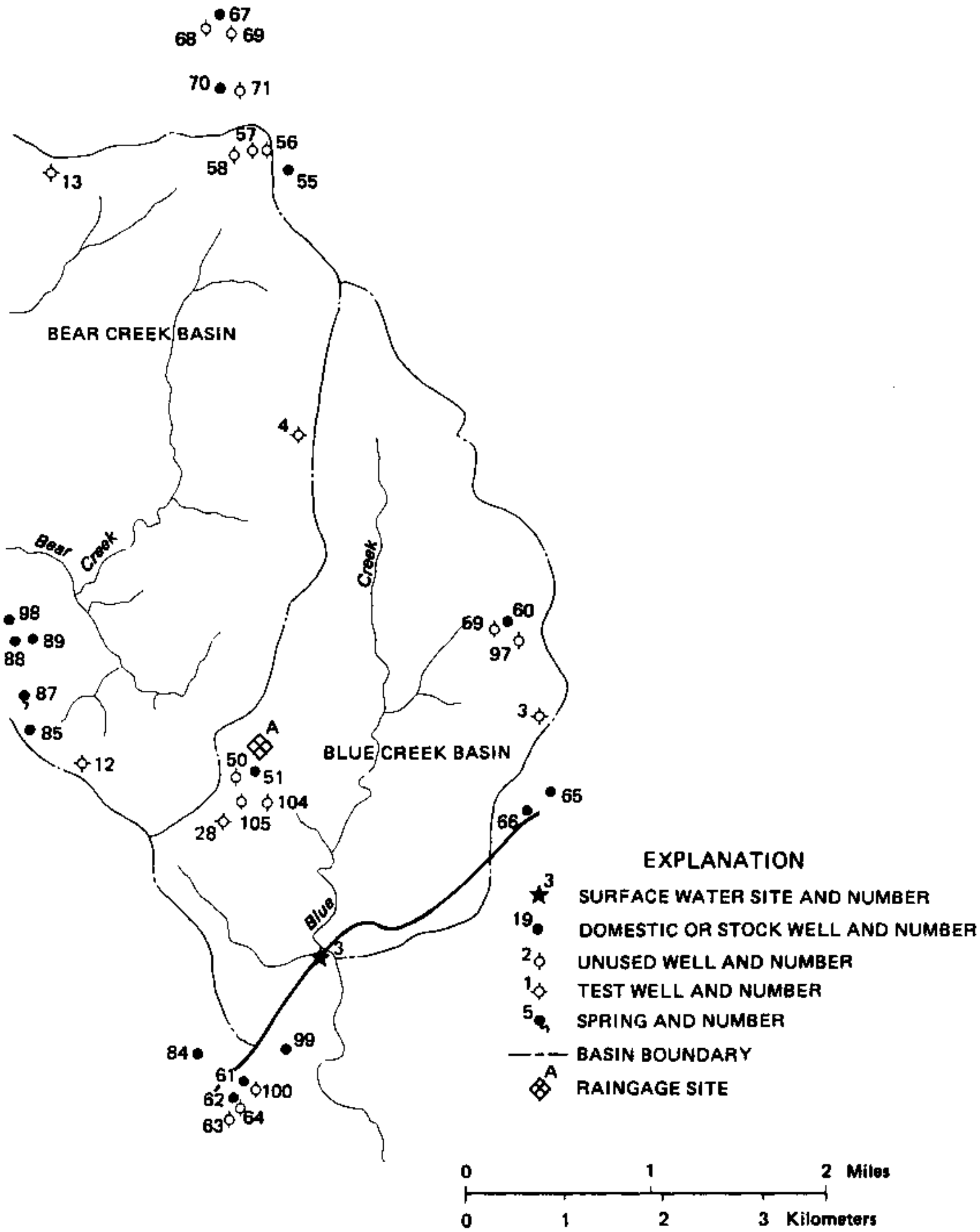


Figure 3.2-1.— Location of wells and springs in the general area. (Modified from Puente and others, 1980.)

Table 3.2-1 — Records of wells and springs in and near Blue Creek basin completed in Pottsville Formation. (Well numbers correspond with those on figure 3.2-1.)

Depth: Reported depths given in feet.

Water-bearing unit: Ppv Pottsville Formation.

Altitude: Altitude determined by aneroid barometer. In feet above sea level.

Water level: Reported levels given in feet; measured levels given in feet and tenths. Use of water: D domestic; N none.

Field determination: ˚C degrees Celsius

						Water level			Field determinations			
Field well number	Owner	Year com- pleted	Depth of well below land surface (feet)	Diame- ter of well (inches)	Altitude of land surface (feet)	Below land surface (feet)	Date of measure ment	Use of water	Date	Specific conduct -ance (micro- mhos at 25 ˚C)	PH	Tem perat ure (˚C)
50	C. Zeanah	—	61	4	551	25.9	4-21-77	N	4-21-77	265	6.9	17.0
51	C. Zeanah	—	118	4	551	49.2	4-21-77	D	4-21-77	225	6.9	17.5
55	D. Bar net	—	52	6	646	41.7	5-31-77	D	5-31-77	350	6.9	21.0
56	Irvin Realty	—	152	6	656	69.2	5-31-77	N	5-31-77	138	—	17.5
57	Irvin Realty	—	152	6	656	82	5-31-77	N	5-31-77	200	6.7	17.0
58	Irvin Realty	1975	32	36	640	15.1	5-31-77	N	5-31-77	33	—	19.5
59	L. Bagwell	1950	62	6	574	26.2	6- 1-77	D	6- 1-77	255	6.8	18.5
60	L. Bagwell	1928	39	6	574	26.2	6- 1-77	N	——	—	—	—
61	E. Long	—	89	6	492	45.9	6- 1-77	D	6- 1-77	340	7.3	19.5
62	J. Bagwell	—	92	6	492	45.9	6- 1-77	D	6- 1-77	315	6.8	18.0
63	J. Bagwell	1970	328	6	466	72.2	6- 1-77	N	——	—	—	—
64	J. Bagwell	—	210	6	492	33.1	6- 1-77	N	——	—	—	—
65	J. Bolton	—	98	6	525	73.7	6- 1-77	D	6- 1-77	415	7.1	18.5
66	J. Bolton	—	56	6	525	35.1	6- 1-77	D	6- 1-77	422	6.9	20.0
67	J. Baker	—	285	6	653	116.8	6- 2-77	D	6- 2-77	340	7.5	17.5
68	J. Baker	1917	98	6	660	86	6- 6-77	N	6- 6-77	270	7.3	17.5
69	J. Baker	1917	98	6	446	85.3	6- 6-77	N	——	—	—	—
70	W. Baker	—	187	4	660	—	6- 6-77	D	——	—	—	—
71	W. Baker	—	112	6	660	66.3	6- 6-77	N	6- 6-77	126	7.0	17.5
84	J. Smith	—	34	6	499	13.1	6- 9-77	D	6- 9-77	125	6.7	16.5
85	W. Griffin	—	102	6	584	60.0	6- 9-77	D	6- 9-77	112	6.6	19.0
87	J. Neal	—	Spring	—	516	—	6- 9-77	D	6- 9-77	42	6.7	17.0
88	T. Davis	1976	103	6	505	246	6- 9-77	D	6- 9-77	65	6.5	17.0
89	T. Davis	1976	96	6	502	37.7	6- 9-77	D	6- 9-77	75	6.4	17.5
97	L. Bagwell	—	98	6	443	23.0	7-19-77	N	7-19-77	215	6.6	24.0
98	T. Davis	—	Spring	—	476	—	7-27-77	D	——	—	—	—
99	E. Long	—	77	6	495	11.8	8- 8-77	N	——	—	—	—
100	E. Long	—	36	6	492	27.2	8- 9-77	N	——	—	—	—
104	C. Zennah	1977	27	6	535	10.5	8-17-77	N	——	—	—	—
105	C. Zennah	1977	38	6	564	21.0	8-l 7-77	M	——	—	—	—

Table 3.2-2 — Records of test wells drilled in and near Blue Creek basin completed in the Pottsville Formation. (Well numbers correspond with those in figure 3.2-1) Altitude: Altitude determined by aneroid barometer.

						Water level	
Well number	Date completed	Depth of well below land surface (feet)	Diameter of well (inches)	Depth of casing below land surface (feet)	Altitude of land surface (feet)	Below land surface (feet)	Date of measurement
T -3	6-25-78	290	6	29	633	106.0	6-25-78
T -4	6-20-78	47	6	25	640	89.9	6-25-78
T -12	7-26-78	267	6	49	584	—	—
T -13	7-27-78	166	6	40	581	69.6	10-13-78
T -28	9-15-78	248	6	26	607	181.4	9-20-78

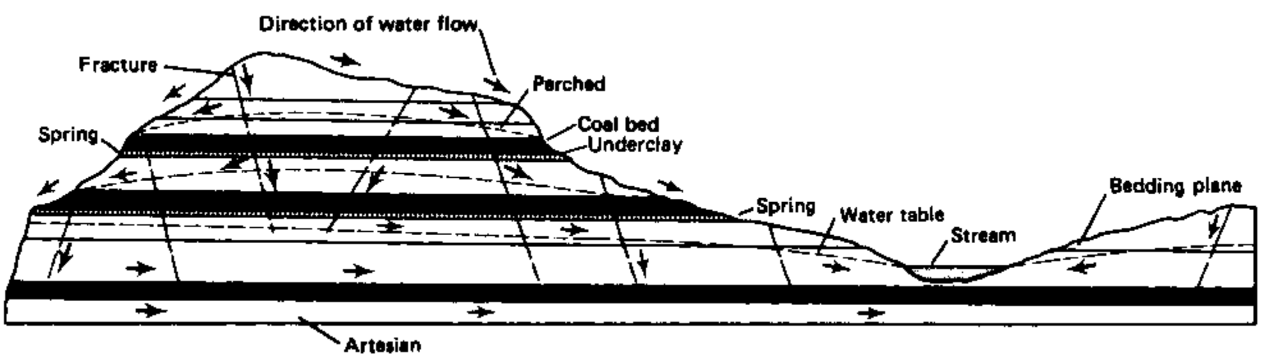


Figure 3.2-2. Schematic diagram showing general occurrence and movement of ground water in the Pottsville Formation underlying the area.

The configuration of the water table in the area generally conforms to the overlying topography. Water levels generally range from 20 to 150 feet below land surface on hilltops, from 5 to 30 feet in lowland areas, and generally between the two extremes on the hillsides. Ground-water movement in the Blue Creek area is generally to the southeast. Water levels typically fluctuate in response to seasonal variations in precipitation and evapotranspiration (fig. 3.2-3). Water levels are usually highest from November through April and lowest from May through October. The decline in water levels during the latter period is due to lack of precipitation and the increase in evapotranspiration during the growing season. Water levels generally rise during the fall when evapotranspiration decreases and precipitation increases. The water-level fluctuations in test well 4 (fig. 3.2-3) are fairly representative of fluctuations in other wells tapping the Pottsville in the general area. Because of the complex occurrence of perched water tables and the irregular lensing characteristics of the aquifers, water levels in wells completed in the Pottsville over a large area are generally unpredictable. Areal correlations are possible only within short distances (4).

The Pottsville Formation is generally not a source of large quantities of water, but does provide enough for domestic use in the Blue Creek area. The yields of wells completed in the formation average less than 5 gal/min; the greatest yields generally are from wells in lowland areas. Yields seldom exceed 25 gal/min (6). The small yields of wells and springs from the Pottsville reflect limited aquifer storage and little permeability.

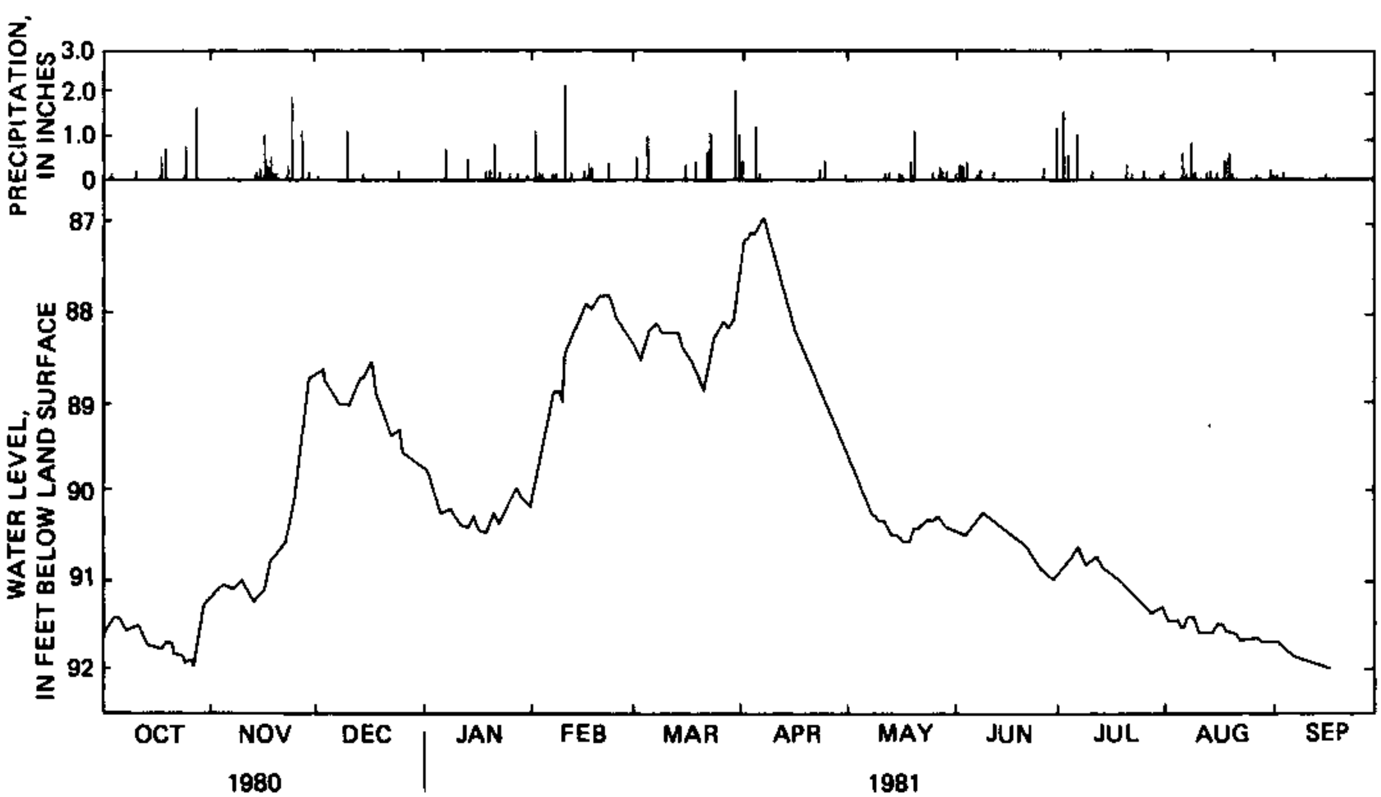


Figure 3.2-3.— Precipitation at site A and daily mean water levels at test well A.

Estimates of the aquifer's ability to store water (storativity) and transmit water (transmissivity) were computed by the "slug test" method (1). This method was used because of the small yields from wells in the area. The more widely used aquifer-test procedures for determining transmissivity and storativity were not practical because of the very small discharge rates required to avoid pumping the wells dry in a very short period of time. Transmissivity (T) and storativity (S) determined for selected wells in the area, ranged from less than one to 450 ft^2/d and from 0.01 to 0.00001, respectively.

The slug test consisted of suddenly dropping a weighted float, having a known volume ($V = 0.195\ ft^3$), into a well and periodically measuring the subsequent water level in the well. Figure 3.2-4 illustrates the initial rise in water level and the well features measured in applying the method. This method makes use of the equations:

$$H/H_o = Tt/r_c^2 \qquad\qquad S = (r_c^2/r_s^2)\ \alpha$$

where H_o = the rise in water level at time of the injection = $V/\pi\ r_c^2$

H = the residual rise in the water-table sometime ‘t’ after the weighted float is added,

r = radius of open hole, r = radius of well casing,

$\alpha = (r_s^2/r_c^2)S$.

Assumptions made in the analyses were (1) the wells fully penetrate a confined aquifer of small transmissivity, and (2) $r_c = r_s$.

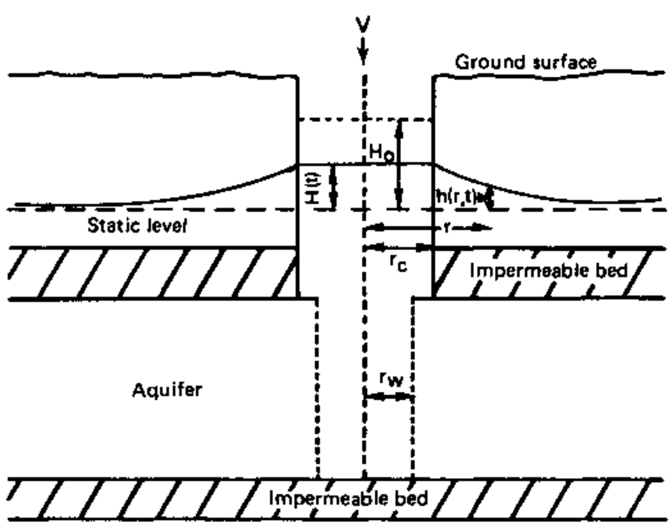


Figure 3.2-4.— Cross section through a well in which a known volume is instantaneously injected.
(Modified from Reed, 1980, fig. 9.1.)

The slug test data for test well 4 are listed in table 3.2-3 and a semi-log plot of H/H_o versus 't' is shown in figure 3.2-5. The field curve (dots representing field-test data) in figure 3.2-4 was superimposed on several type curves (fig. 3.2-6) prepared from data given in table 3.2-4, to achieve a best fit between the field curve and the type curves. Corresponding values of 't' (from the field curve) and Tt/r_c^2 (from the type curve) were read at an arbitrarily selected 'match' point on the horizontal scale. Computations for T and S are shown in figure 3.2-5.

The computed transmissivity and storativity represent only local conditions near the tested well and cannot be extrapolated to other areas in the basin. Because the storativity values depend upon the shapes of the type curves, which differ only slightly when α differs by an order of magnitude, the determinations of storativity are considered to be of limited reliability (1).

Table 3.2-3 – Recovery of water level in test well 4 near Blue Creek basin after instantaneous addition of weighted float.

t (seconds)	Head below land surface datum (feet)	H (feet)	$\frac{H}{H_o}$
-1	91.95	—	—
0	90.96	0.99 (H_o)	1.00
5	91.05	.90	.91
20	91.14	.81	.82
32	91.21	.74	.75
45	91.27	.68	.69
52	91.32	.63	.64
70	91.37	.58	.59
105	91.48	.47	.47
115	91.51	.44	.44
135	91.56	.39	.39
150	91.59	.36	.36
197	91.67	.28	.28
213	91.70	.25	.25
234	91.72	.23	.23
253	91.74	.21	.21
275	91.76	.19	.19
300	91.78	.17	.17
385	91.84	.11	.11
470	91.87	.08	.08
590	91.88	.07	.07
735	91.90	.05	.05

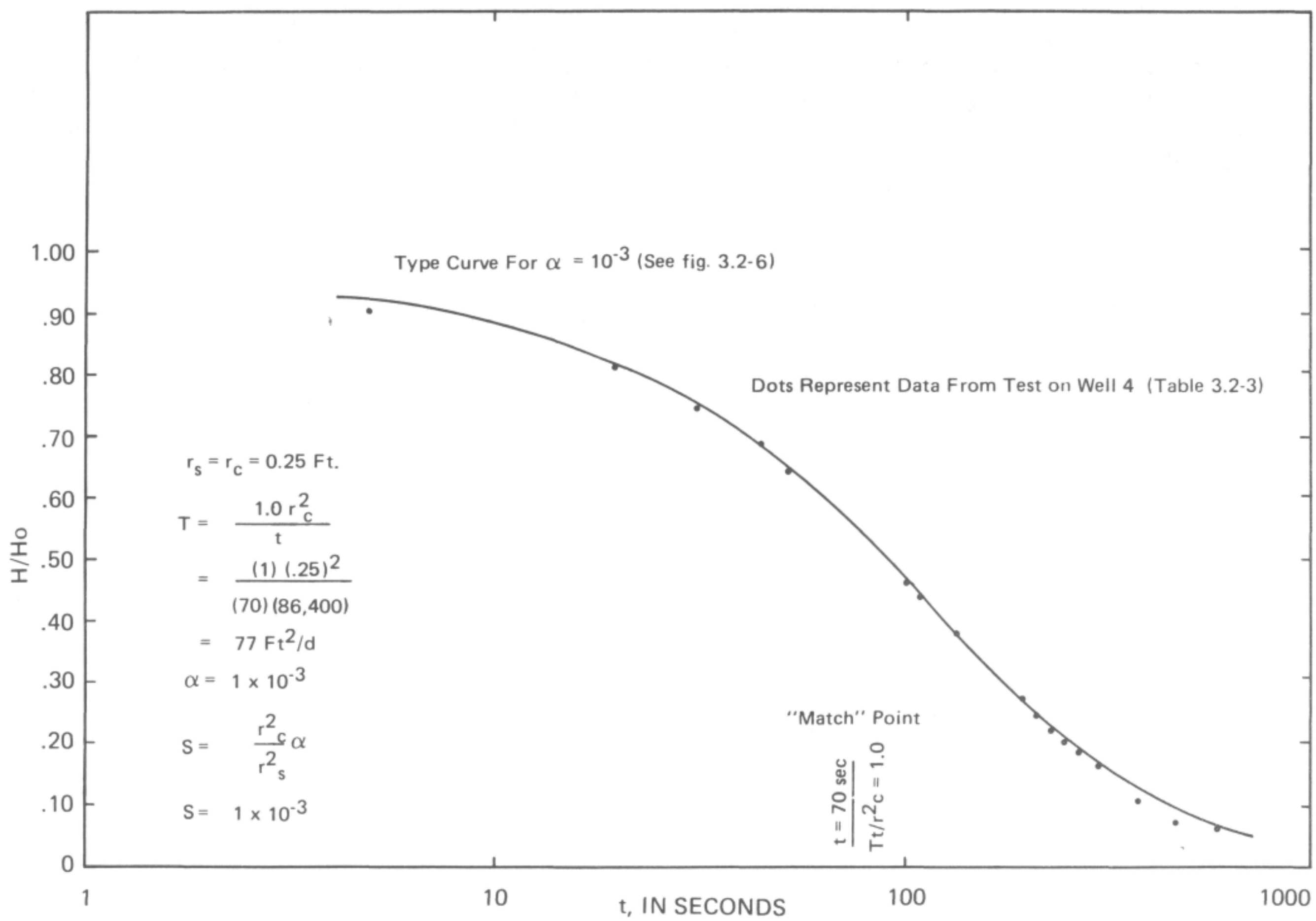


Figure 3.2-5.— Plot of data from slug test at test well 4, September 16, 1980.

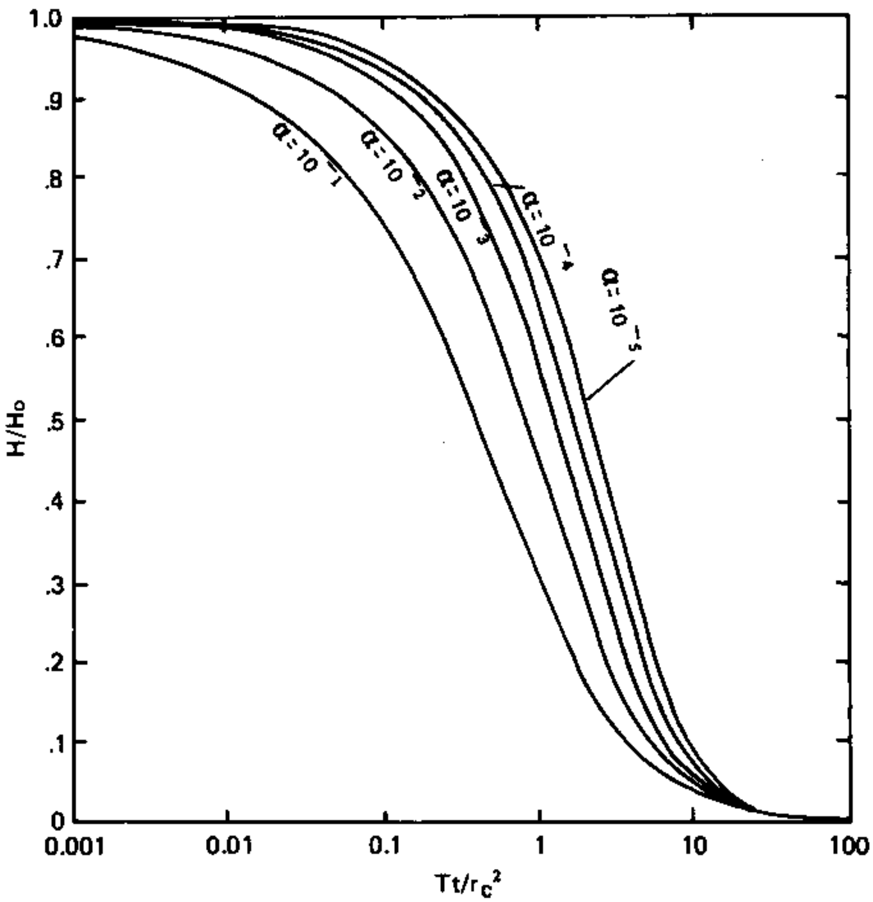


Figure 3.2-6.— Type curves for instantaneous charge in well of finite diameter, for H/HO versus Tt/r_c^2 for five values of α.
(From Lohman, 1972, pi. 2; and Cooper and others,1967, table 1.)

Table 3.2-4. – Values of H/H_O for a well of finite diameter (1)

$\frac{Tt}{r_c^2}$	H/H_O				
	α =0.01	α=0.001	α =0.0001	α=0.00001	α=0.000001
0.0010	0.9771	0.9920	0.9969	0.9985	0.9992
.00215	.9658	.9876	.9949	.9974	.9985
.00464	.9490	.9807	.9914	.9954	.9970
.010	.9238	.9693	.9853	.9915	.9942
.0215	.8860	.9505	.9744	.9841	.9888
.0464	.8293	.9187	.9545	.9701	.9781
.10	.7460	.8655	.9183	.9434	.9572
.215	.6289	.7782	.8538	.8935	.9167
.464	.4782	.6436	.7436	.8031	.8410
1.0	.3117	.4598	.5729	.6520	.7080
2.15	.1665	.2597	.3543	.4364	.5038
4.64	.07415	.1086	.1554	.2082	.2620
7.00	.04625	.06204	.08519	.1161	.1521
10.0	.03065	.03780	.04821	.06355	.08378
14.0	.02092	.02414	.02844	.03492	.04426
21.5	.01297	.01414	.01545	.01723	.01999
30.0	.009070	.009615	.01016	.01083	.01169
46.4	.005711	.005919	.006111	.006319	.006554
70.0	.003722	.003809	.003884	.003962	.004046
100.	.002577	.002618	.002653	.002688	.002725
215.	.001179	.001187	.001194	.001201	.001208

3.0 HYDROLOGIC SETTING

3.3 QUALITY OF GROUND WATER

CHEMICAL QUALITY OF GROUND WATER IS VARIABLE, BUT GENERALLY SUITABLE FOR MOST USES

Water from deep wells tends to be more highly mineralized than water from shallow wells. Water from wells located on hilltops is usually less mineralized than water from wells in valleys.

The quality of ground water in the area is extremely variable, but is generally suitable for most uses. Water-quality data from wells completed in the Pottsville Formation in Blue Creek basin (fig. 3.2-1) and other nearby areas are summarized in table 3.3-1.

Water from deep wells tends to be more mineralized and alkaline than water from shallow wells or springs. Water from wells located on hilltops is usually less mineralized than water from wells in valleys. Important reasons for this variability are (1) the amount of time ground water has been in contact with the rocks and (2) the pattern of ground-water circulation as it moves from points of recharge to areas of discharge. Acidic rain-water in the area remains acidic as it percolates through decaying organic matter on the land surface and through generally acidic soil. This acidic water dissolves and leaches minerals as it moves downward through the rocks towards the discharge areas. The end results are that ground water at shallow depth in recharge areas (hilltops and hillsides) is commonly acidic with little dissolved minerals, and water at greater depth or in the discharge areas (valleys) is commonly alkaline with much dissolved minerals.

Generally, water in the Pottsville Formation is a calcium-magnesium-bicarbonate type. The specific conductance of water in aquifers underlying ridges and at depths less than 50 feet was generally less than 150 umho/cm (micromhos per centimeter at 25˚ Celsius). The specific conductance of water in aquifers in lowland areas or underlying ridges at depths exceeding 50 feet ranged from 150 to about 550 umho/cm. Dissolved-solids concentrations ranged from 50 to 360 mg/L (milligrams per liter), and pH ranged from 5.6 to 8.0 with a median of 6.9. In all but the shallowest wells, the water was moderately hard to very hard and had bicarbonate concentrations ranging from 4 to 280 mg/L.

Locally, dissolved iron and manganese concentrations exceeded 300 and 50 ug/L (micrograms per liter), respectively. Trace-element concentrations, other than those for iron and manganese, were well below maximum concentrations established by the U.S. Environmental Protection Agency (1977).

Table 3.3-1 – Summary of selected chemical and physical properties of water from the Pottsville Formation (6).
[results in milligrams per liter, except as indicated; ug/L, micrograms per liter]

Property	Number of analyses	Mean	Range
Specific conductance (micromhos at 25 ˚C)	37	287	59-555
Temperature (˚C)	34	18.2	16.0-22
pH (units)	38	6.9	5.6-8.0
Color (units) [2]/	27	17	5-100
Hardness as $CaCO_3$	34	117	19-220
Noncarbonate hardness	37	5	0-59
Total Acidity as H+	18	0	0
Total Acidity as $CaCO_3$	26	0	0
Calcium (Ca)	37	26.8	2.5-46
Magnesium (Mg)	37	11.6	2.8-26
Sodium (Na)	37	16.5	2.7-63
Percent Sodium (%)	37	25	8-63
Sodium absorption ratio (SAR)	37	.7	.2-2.8
Potassium (K)	37	2.6	.6-7.0
Bicarbonate (HCO_3)	37	159	4-280
Carbon Dioxide (CO_2)	30	54	3.1-217
Carbonate (CO_3)	37	0	0
Sulfate (SO_4)	34	12	.2-59
Chloride (Cl)	33	3.4	.8-14
Fluoride (F)	32	.1	.0-.3
Silica (SiO_2)	31	20	.1-34
Dissolved Solids (calc.)	21	175	50-360
Total Nitrate (N)	23	.25	.01-2.4
Total Nitrate (NO_3)	18	1.7	.00-5.0
Total Nitrite (N)	15	.00	.00
Total Organic Nitrogen (N)	19	.33	.00-1.1
Total Kjeldahl Nitrogen	21	.42	.00-1.3
Phosphate (PO_4)	5	1.2	.09-2.9
Phosphorus (P)	27	.23	.00-. 96
Arsenic (AS) (ug/L)	28	1	0-4
Boron (B) (ug/L)	5	0	0
Cadmium (Cd) (ug/L)	37	1	0-5
Chromium (Cr) (ug/L)	30	3	0-10
Cobalt (Co) (ug/L)	36	1	0-9
Copper (Cu) (ug/L)	32	3	0-17
Iron (Fe) (ug/L)	34	762	0-11 , 000
Lead (Pb) (ug/L)	37	3	0-65
Lithium (Li) (ug/L)	37	16	0-40
Manganese (Mn) (ug/L)	37	139	0-1,100
Mercury (Hg) (ug/L)	35	.4	.0-.6
Selenium (Se) (ug/L)	27	.1	0-2
Strontium (Sr) (ug/L)	35	278	0-1.000
Zinc (Zn) (ug/L)	37	84	0-370

[1]/ - Median Value
[2]/ - Platinum - Cobalt

4.0 HYDROLOGIC IMPACTS OF SURFACE MINING

4.1 INTRODUCTION OF IMPACTS

HYDROLOGIC ENVIRONMENT ALTERED BY SURFACE COAL MINING

The effects of surface coal mining on the ground-water hydrology include the decline of ground-water levels, increased ground-water discharge, and degradation of ground-water quality.

The hydrologic environment of Blue Creek basin has been significantly altered by surface coal mining. The impacts of mining on the ground-water system are identified as decline of ground-water levels, augmentation of base flow, and degradation of water quality. The impacts resulted from (1) the removal of parts of aquifers during mining, (2) modification of ground-water movement and storage by removal of overburden and replacement of overburden with spoils, and (3) changes in ground-water quality caused by leachate from mine spoils areas and water impoundments (6).

Surface coal mining in the general area started in early 1976 and entailed the surface mining of two coal beds within the Utley Coal Group. The progression of mining, based on aerial photography flown in 1977-79 and the location of selected wells, springs, and streamflow-gaging sites in Blue Creek and Bear Creek basins are shown in figure 4.1-1. About 250 acres were surface mined in the basin during this period.

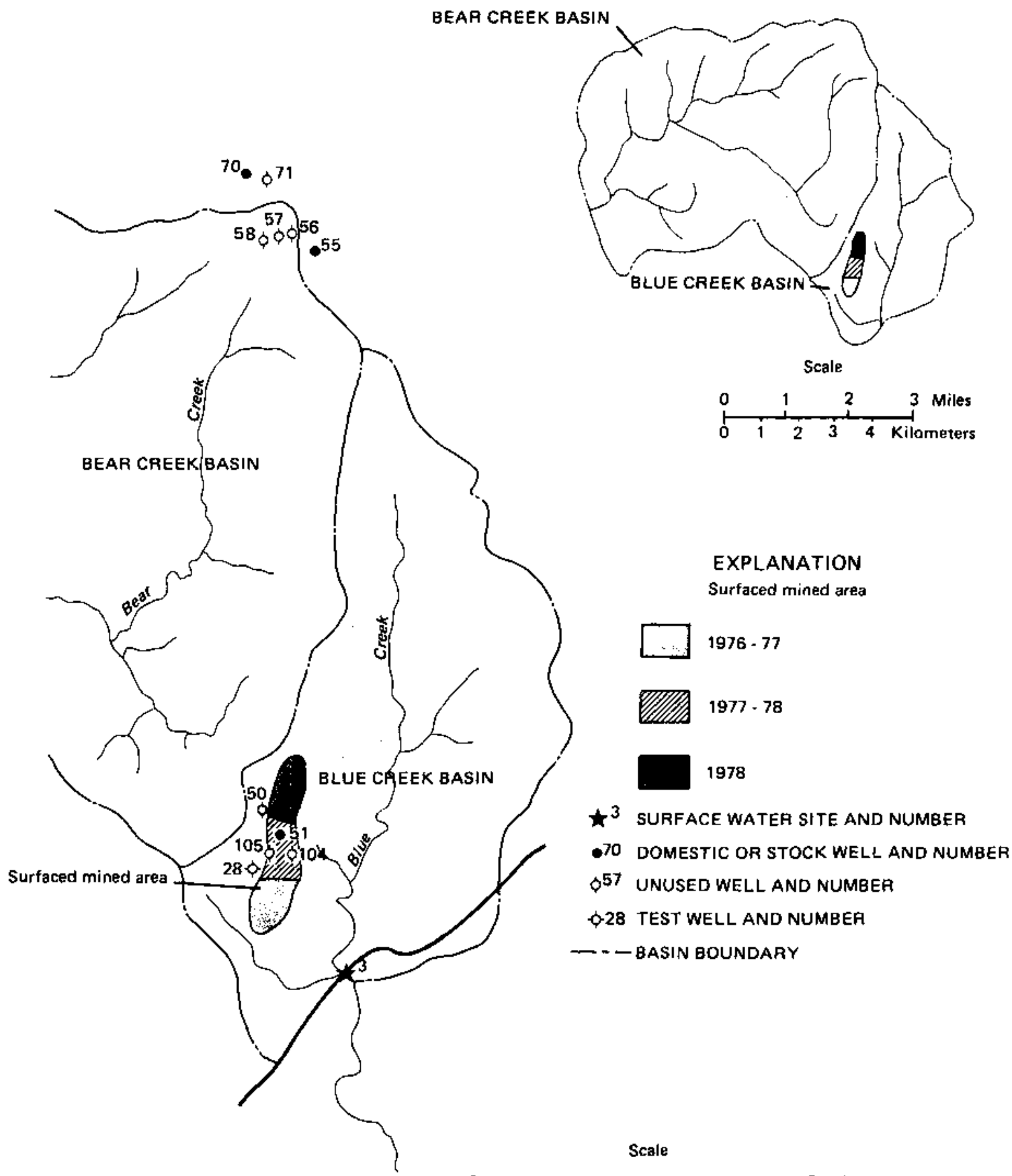


Figure 4.1-1.— Location of selected wells, springs, surface-water sites, and surface-mined areas. (Modified from Puente and others, 1980.)

4.0 HYDROLOGIC IMPACTS OF SURFACE MINING

4.2 DECLINE OF GROUND-WATER LEVELS

DEWATERING OF SURFACE MINES RESULTS IN WATER-LEVEL DECLINES

Penetration of the surface mining operation into aquifers causes the draining of aquifers.

The intersection of the surface mine with water-bearing openings of aquifers resulted in draining of the openings and a corresponding decline in water levels in aquifers adjacent to the mine area. A schematic diagram illustrating the effect of surface mining on the local hydrology is shown in figure 4.2-1. Springs issuing from exposed coal beds in the high walls of the mine indicated that water-bearing zones (fractures) adjacent to and updip from the mine excavations were being dewatered. The resulting decline in water levels is illustrated by the hydrograph for well 50 (fig. 4.2-2). The hydrograph shows a downward trend in 1978. In March 1978, mining progressed northward to within 0.1 mile of the observation well. Since then, the water level in the well has declined periodically to the approximate altitude of the lowest adjacent coal bed mined.

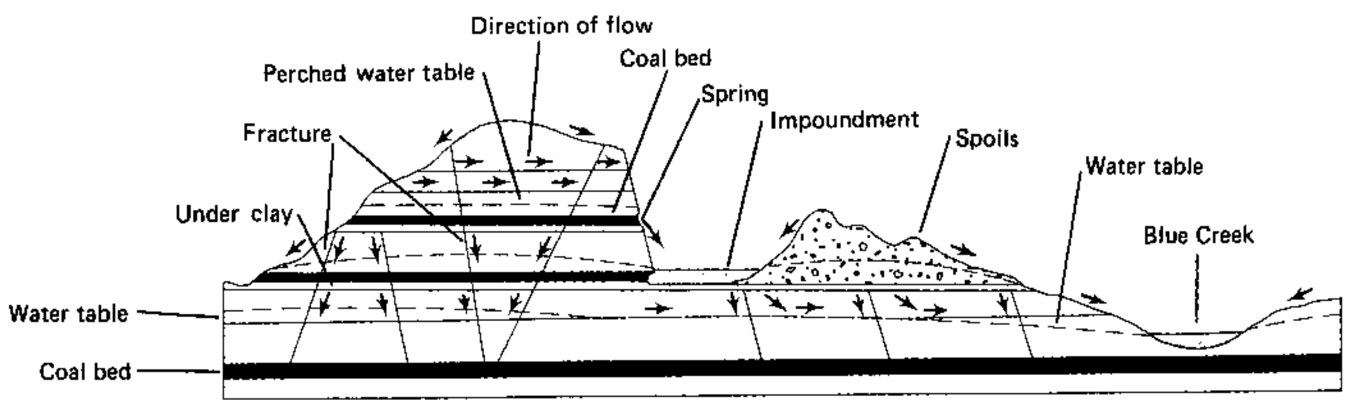
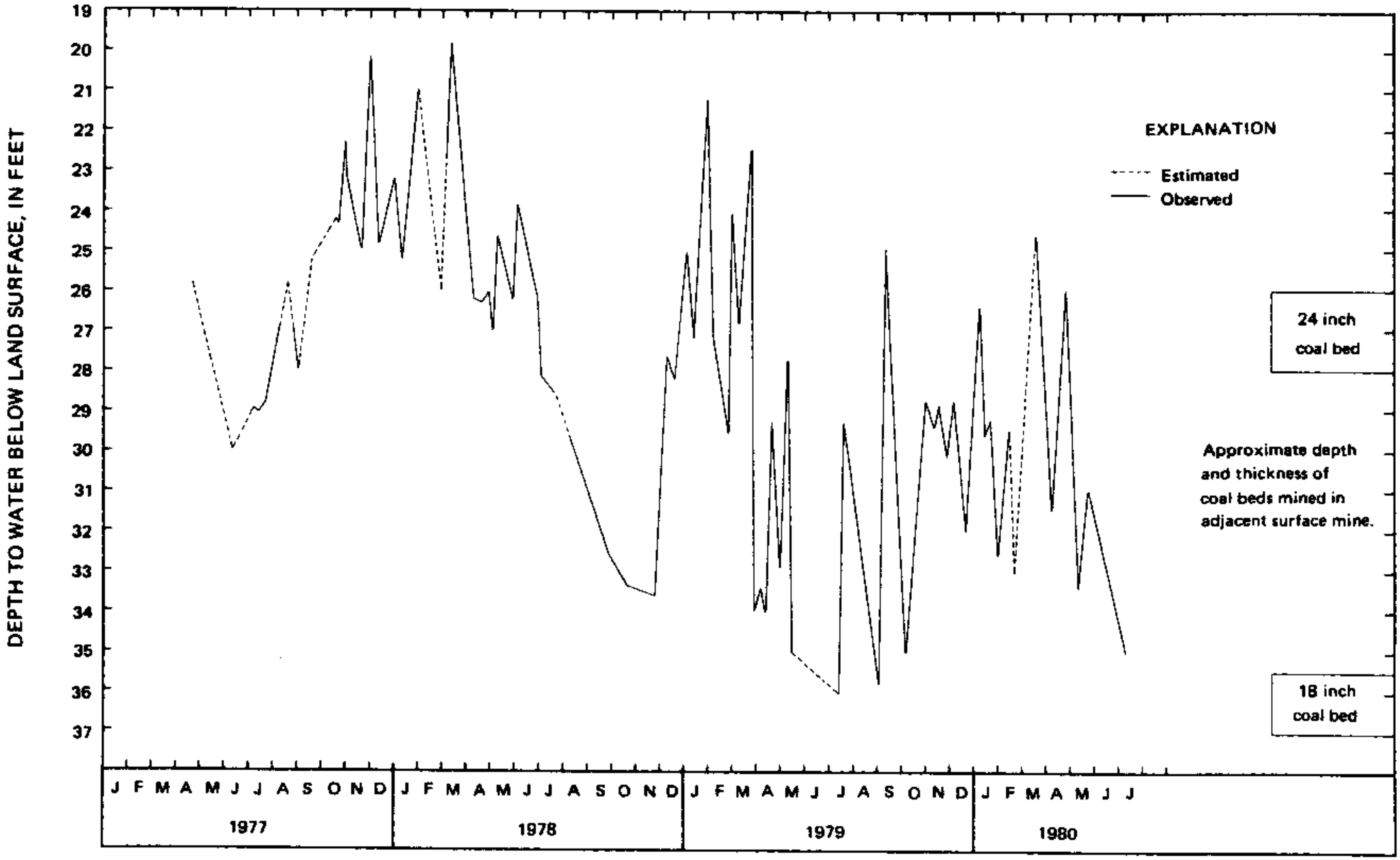


Figure 4.2-1.— Schematic diagram illustrating the effect of surface mining on the hydrology of a mined area in Blue Creek Basin.



4.2-2. — Water levels in observation well 50 in Blue Creek basin.

4.3 AUGMENTATION OF BASE FLOW

FORMATION OF MINE SPOILS CREATES A NEW AQUIFER

The water in the mine spoils within the mined area is a source of base flow to Blue Creek increasing low flow.

Placement of spoils material in the mined area has created spoils aquifers that generally rest on underclay and shale (fig. 4.2-1). The perched water in the spoil is a source of base flow to Blue Creek. In Blue Creek basin, the spoil aquifers store and transmit more water than the original aquifers. Streamflow records for sites 1 (Bear Creek, draining an undisturbed basin) and 3 (Blue Creek, draining a disturbed basin) (fig. 4.1-1) during the water years 1979-80 indicate a substantial increase in base flow at site 3. The increase is reflected by the shape of the annual flow-duration curves for sites 1 and 3 shown in figure 4.3-1. A steep flow-duration curve denotes variable streamflow derived mainly from direct surface runoff, whereas a flatter curve, particularly in the low-flow part, indicates streamflow derived from surface and(or) ground-water storage. The gradual divergence in low-flow parts of the annual flow-duration curves (fig. 4.3-1) indicates an increase in the basin storage that provides larger and more prolonged base flow at site 3. The increase in low flow results from seeps and springs that issue from the spoil areas and impoundments in the mined areas. The storage of water in the mined areas in Blue Creek basin is expected to increase as mining progresses and may result in low flows significantly exceeding those prior to mining.

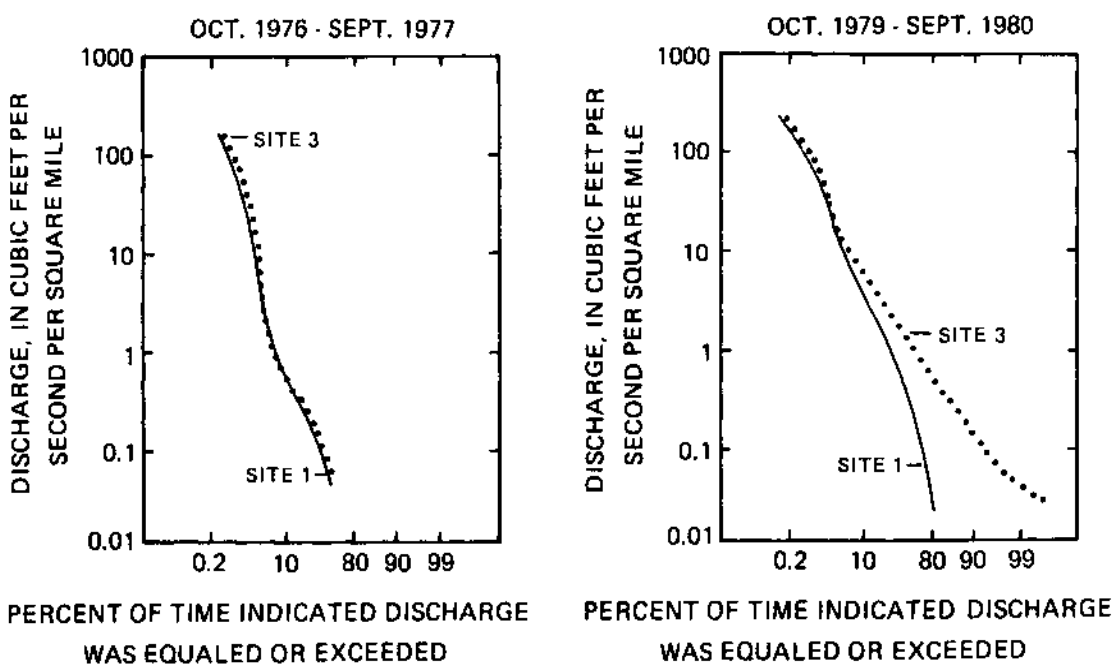


Figure 4.3-1. — Annual flow-duration curves for sites 1 and 3. (Modified from Puente and Newton, 1982.)

4.4 DEGRADATION OF GROUND-WATER QUALITY

GROUND WATER NEAR AND DOWNDIP OF MINE INCREASED IN MINERALIZATION COMPARED TO UNMINED AREAS

Ground-water quality in mined areas has greater dissolved solids, hardness, and concentrations of sulfate, iron, manganese, strontium, and zinc than in unmined areas.

Ground-water-quality degradation was detected in a well near the mined area. Water in well 104 (fig. 4.1-1) near and downdip from the mine, has a specific conductance of 1,180 umho/cm, a sulfate concentration of 338 mg/L, calcium and magnesium concentrations of 110 and 66 mg/L respectively, and a dissolved solids concentration of 864 mg/L. The quality of water in well 104 differed significantly from that in well 28 located updip from the mine (table 4.4-1) and from that in other Pottsville Formation wells in nearby unmined areas (table 3.3-1). As indicated in table 4.4-1, the water in well 104 and site 3 is characterized by much greater hardness, noncarbonate hardness, dissolved solids, and concentrations of sulfate, iron, manganese, strontium, and zinc than water in well 28. The pH of water in wells 28 and 104, and at site 3 was similar. Acid production in the mined area was probably neutralized by calcareous minerals such as siderite, calcite, and ankerite that are commonly present in spoil in the area.

The rate and magnitude of water mineralization in well 104 are probably similar to those of mine drainage sustaining base flow (less than 1.0 ft^3/s) at site 3 on Blue Creek (fig. 4.1-1). As shown in figure 4.4-1, the specific conductance at site 3 increased from 58 umho/cm in November 1976 to 1,550 umho/cm in July 1980. The 1980 value represents a 27-fold increase in mineralization of drainage leaving Blue Creek basin.

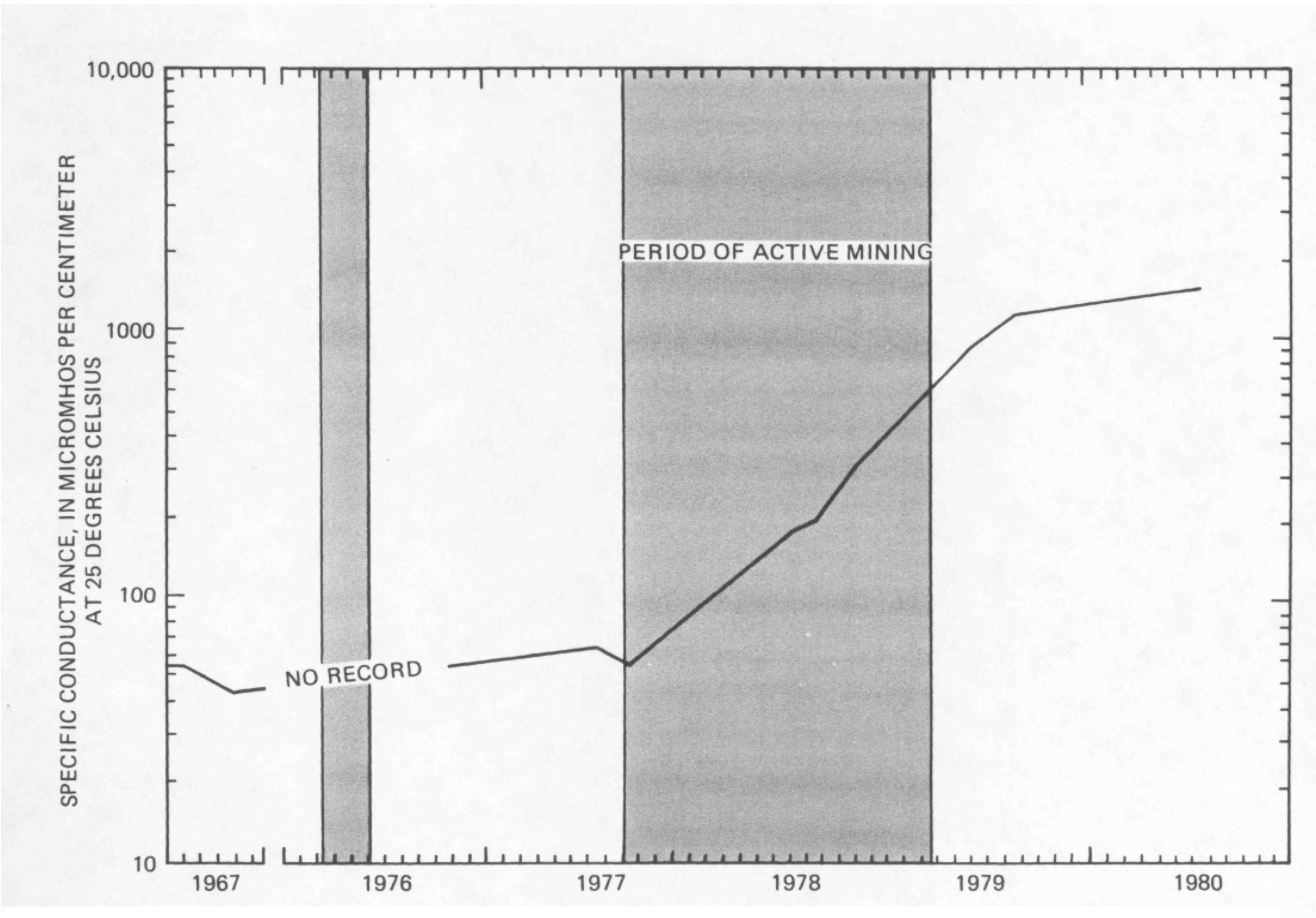


Figure 4.4-1.— Specific conductance in Blue Creek (site 3) during low flow. (Shaded areas indicate time periods of active mining.) (Modified from Harkins and others, 1980.)

Table 4.4-1.– Quality of ground water from observation wells 28 and 104, and Blue Creek (site 3).
[results in milligrams per liter, except as indicated; ug/L, micrograms per liter]

SITE ——— DATE SAMPLED ———	WELL 28 12/2/79	WELL 104 5/13/80	SITE 3 7/24/80
Specific conductance micromhos at 25˚ C)	415	1180	1550
Temperature (˚C)	17.0	16.0	30
pH (units)	6.6	6.9	7.9
Color (units):[2]/	35	0	2
Hardness as $CaCO_3$	210	550	830
Noncarbonate Hardness	0	260	730
Total Acidity as H^+	0	—	—
Total Acidity as $CaCO_3$	0	—	—
Calcium (Ca)	46	110	150
Magnesium (Mg)	22	66	110
Sodium (Na)	14	57	15
Percent Sodium (%)	20	18	4
Sodium adsorption ratio (SAR)	0.4	1.1	—
Potassium (K)	4.4	3.8	5.6
Bicarbonate (HCO_3)	260	360	130
Carbon Dioxide (CO_2)	105	71	2.5
Carbonate (CO_3)	0	0	0
Sulfate (SO_4)	8.3	338	860
Chloride (Cl)	3.6	11	2.2
Fluoride (F)	.1	0.2	0.2
Silica (SiO_2)	—	27	6.8
Dissolved solids (calc.)	227	864	1210
Total Nitrate (N)	1.1	.70	.05
Total Nitrate (NO_3)	4.7	3.1	.22
Total Nitrite (N)	—	—	0
Total Organic Nitrogen (N)	.78	.38	.01
Total Kjeldahl Nitrogen	.88	.53	—
Phosphate (PO_4)	2.0	0	.03
Phosphorus (P)	.66	0	.01
Arsenic (AS) (ug/L)	1	1	0
Boron (B) (ug/L)	0	40	7
Cadmium (Cd) (ug/L)	4	0	5
Chromium (Cr) (ug/L)	10	10	10
Cobalt (Co) (ug/L)	1	0	0
Copper (Cu) (ug/L)	4	5	0
Iron (Fe) (ug/L)	0	60	10
Lead (Pb) (ug/L)	0	1	0
Lithiim (Li) (ug/L)	20	80	9
Manganese (Mn) (ug/L)	100	460	140
Mercury (Hg) (ug/L)	.1	.2	.1
Selenium (Se) (ug/L)	0	0	0
Strontium (Sr) (ug/L)	280	1200	520
Zinc (Zn) (ug/L)	270	620	3

[1]/ - Median Value
[2]/ - Platinum - Cobalt

5.0 POST-MINING HYDROLOGIC MONITORING

MONITORING PLAN COULD DETERMINE HYDROLOGIC CHANGES CAUSED BY SURFACE MINING

A monitoring plan consisting of ground-water monitoring wells, streamflow-gaging stations, and precipitation gages could be used to determine the extent, magnitude, rate, and duration of hydrologic impacts caused by surface mining.

Hydrologic impacts of surface mining previously identified in Blue Creek basin were decline of ground-water levels, augmentation of base flow, and degradation of water quality. Additional ground-water-monitoring wells and surface-water-sampling sites could be used to:

(1) Better define the local geology, and the location, depth and extent of aquifer systems in the area,

(2) Determine the basin ground-water budget (recharge - discharge + change in ground-water storage),

(3) Delineate the lateral and vertical areal extent of water-quality degradation and the gradation in concentration away from the mined area, and

(4) Determine the rate and direction of movement of ground water.

The proposed observation wells, which would supplement the existing surveillance network, would be sited along the perimeter of the mined area and would be constructed so that only water from a selected aquifer can enter each well (fig. 5.0-1). This arrangement would enable observation of water-level fluctuations and water quality in specific aquifers that may be affected by mining. Land-surface altitudes at all observation-well sites and points from which water levels are measured would be referenced to a stable benchmark reference datum in a nearby offsite location.

Aquifer tests would be performed at all wells to determine the transmissivity and storage characteristics, and the hydrologic boundaries of the specific aquifer systems. The data are useful to determine flow velocities, which help in assessing the spread and dilution of degraded ground water from the mined area. Monthly water-level measurements at all observation wells in addition to the continuous water-level records at well 50 would better define the extent of water-level declines and modification of the direction of ground-water movement.

Water samples collected from wells upgradient from the mine (wells W1-W4) would define baseline ground-water quality, whereas samples from wells down-gradient from the mine (wells W6-W10) would measure changes in ground-water chemistry resulting from the mining operation. Additional wells could be added around the perimeter and at greater distance from the mine if ground-water-quality degradation is found to be extensive.

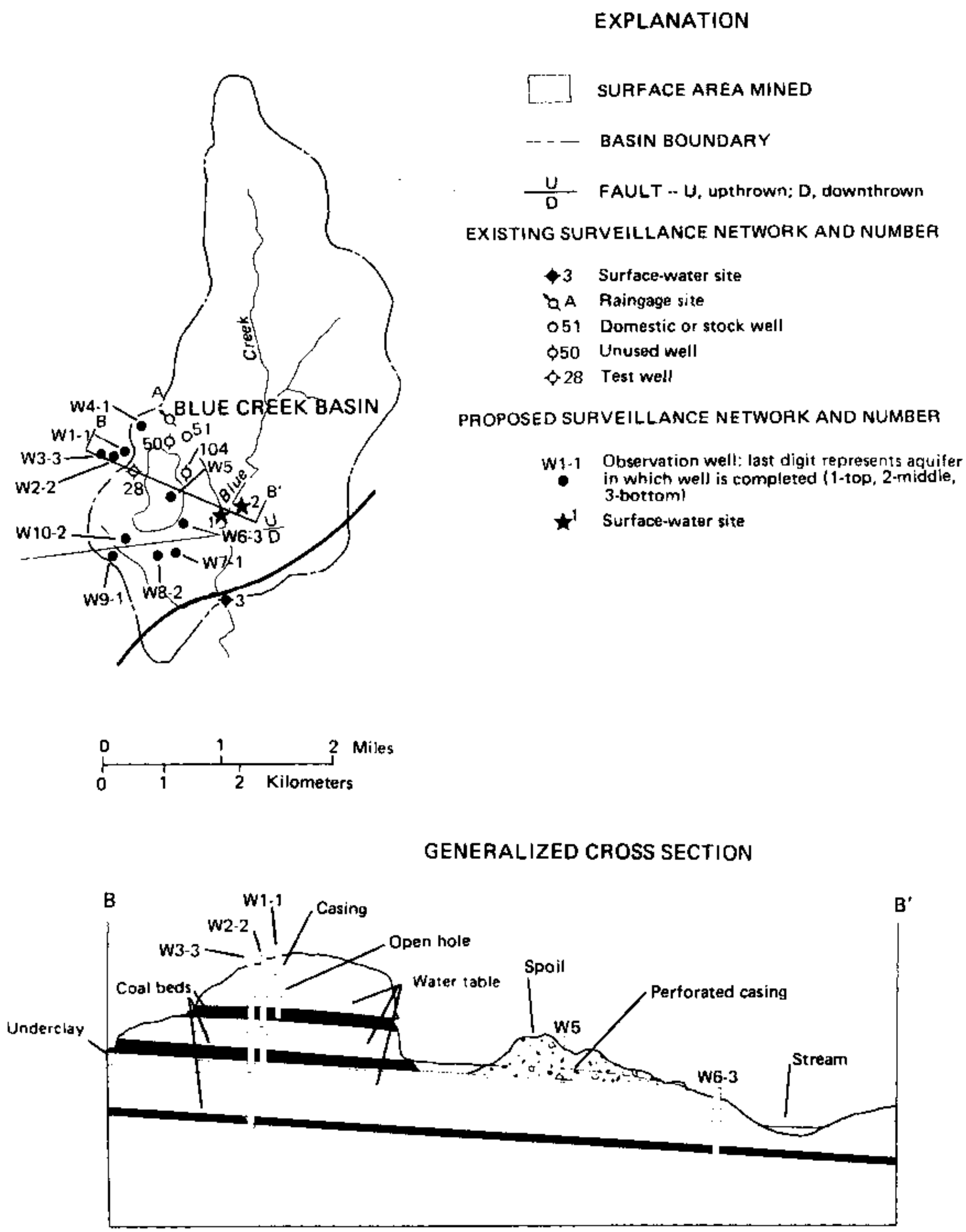


Figure 5.0-1.—Hypothetical hydrologic surveillance network for Blue Creek basin.

Samples would be collected quarterly to describe seasonal changes in ground-water quality in response to changes in seasonal recharge rates to the specific aquifers in the area. More frequent sampling may be needed if significant changes in water quality (sulfate, iron, manganese, pH, acidity, and dissolved solids) are detected. Water-quality constituents analyzed could be the same as those given in table 3.3-1.

Aquifer tests and continuous-recorder measurements of water levels would help define the ability of mine spoils to store and transmit water. Monthly water-quality sampling at observation well W5, completed in the spoils would help define the quality of its stored water, which is a source of recharge to underlying aquifers and a source of base flow to nearby streams.

Measurements of the quantity and quality of water at sites 1 and 3 would determine changes in streamflow regime and changes in chemistry of water leaving Blue Creek basin. Surface-water site 2 would define baseline water-quality conditions upstream from the mined area.

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GROUND-WATER STUDY 2

by

Mark T. Duigon

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 ABSTRACT

Geology and the Occurrence of Coal

The Allegheny Plateau contains broadly folded sedimentary rocks of Devonian through Permian age. The general area, located in the southwest corner of Garrett County, contains part of one of the synclinal basins--the Upper Potomac basin. This area is underlain by sandstones, siltstones, shales, and coals of Pennsylvanian age, which lie disconformably above the Mauch Chunk Formation of Mississippian age. The coal beds of economic importance in the area are the Upper Freeport coal (Allegheny Group) and the less continuous, stratigraphically higher, Lower Bakerstown coal (Conemaugh Group). No significant faults are known in the area, but numerous photo-interpreted lineaments (fracture traces) are present. The rocks are jointed and fractured, resulting in secondary porosity and permeability.

Hydrology and Hydrologic Monitoring

Ground water in the area occurs in shallow, water-table aquifers and in deeper, artesian aquifers. Brackish water underlies the fresh ground-water system at depths of less than 1,000 feet. The deeper aquifers yield small quantities of water to wells; thus, pumping tests of long duration are difficult to perform. Hydraulic conductivity seems to decrease logarithmically with depth. Drawdown effects adjacent to dewatered mine excavations probably are localized. The ground-water flow patterns are complicated by fracturing, underclays, and the discontinuous nature of the rock units. Surface-water quality is affected by discharge from abandoned mines and from treated mine pumpage. The hydrologic monitoring network consists of sites with a cluster of wells equipped with water-level recorders, streamflow-gaging stations with stage and water-quality recorders, a precipitation gage, and miscellaneous observation wells, springs, and stream sites.

Mining Methods and Other Stresses on the Aquifer System

The area has abandoned surface and underground mines in the Upper Freeport coal and abandoned underground mines in the Lower Bakerstown coal. At present (1985), only one mine is operating in the area; it began underground extraction of the Upper Freeport coal in 1977. Other land uses in the area include agriculture and lumbering. Other than for mine dewatering, ground-water withdrawals are not significant.

Probable Hydrologic Impacts and Proposed Hydrologic Monitoring Network

Large quantities of water must be pumped to allow underground mining operations. Water levels in aquifers near the mine heading declined as much as 350 feet within a 1-month period. The magnitude of the decline diminished as the distance from the bottom of the well to the coal increased. Some springs and shallow wells may become dry as a result of mine dewatering. Impacts of mine dewatering include increases in streamflow due to discharge of treated pumpage into streams, decreases in streamflow due to reversal of ground-water gradients adjacent to streams, and alterations in water chemistry. Streamflow alterations are also caused by interbasin transfers of water. Treatment of mine pumpage and wastewaters decreases the acidity of stream water, but may increase concentrations of dissolved solids. A post-mining hydrologic monitoring network will include observation wells completed at various depths, streamflow-gaging stations, and water-quality sampling sites.

2.0 GEOLOGIC SETTING

2.1 PHYSIOGRAPHY

AREA LOCATED IN BROAD UPLAND WITH NORTHWEST TRENDING RIDGES AND VALLEYS

The general area is characterized by relief and steep slopes.

The general area is located within the Allegheny Plateau division of the Appalachian physiographic province and is a broad upland with northeast trending ridges and valleys. Land slopes are steep along parts of the streams and along Backbone Mountain. Swamps have formed in several locations where channels and land slopes are slight. Beaver dams have ponded some stream reaches.

The soils are chiefly gently sloping to steep, moderately deep, well drained to moderately well drained, and very stoney, having formed over acid, gray to yellowish sandstone and shale (20). Steep slopes and stoniness limit suitability for cultivation. Areas that have been surface mined for coal or have been covered with mine spoils from underground mining also may be unsuitable for cultivation. However, some of the abandoned mined areas, as shown in figure 2.1-1, have recently been regraded, seeded, and improved.

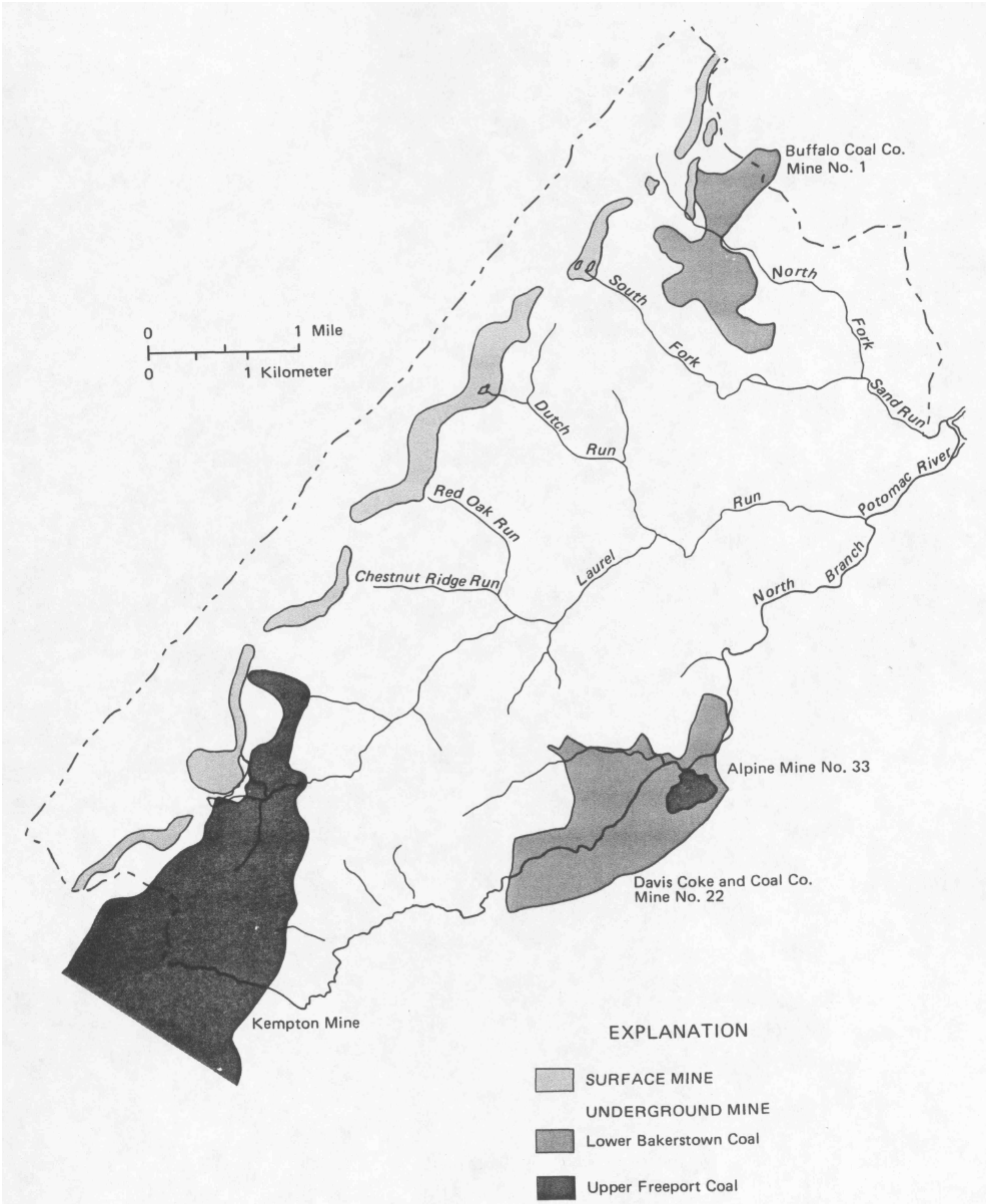


Figure 2.1-1— Abandoned coal mines in the general area.

2.0 GEOLOGIC SETTING

2.2 GEOLOGY

SEDIMENTARY BEDROCK IS OF LATE PENNSYLVANIAN AGE

Exposed rocks in general area consist of sandstones, siltstones, shales, limestones, and coals.

The sedimentary rocks exposed in the general area consist of sandstones, siltstones, shales, limestones, and coals and are of Late Pennsylvanian age. The formations and important coals are identified in the stratigraphic column shown in figure 2.2-1. Detailed lithologic descriptions of rock units composing the formations are shown in figure 2.2-2. These rocks represent a transition from an alluvial plain to a shallow marine environment (17).

The oldest exposed rocks, which belong to the Pottsville Group, and lie disconformably on the Mauch Chunk Formation of Mississippian age. The Pottsville Group consists primarily of sandstones and siltstones and includes some thin coals that are not economically important. This group was formed by sediments deposited in a braided fluvial environment. The well indurated basal conglomerate of the group forms the crest of Backbone Mountain.

The sedimentary rocks of the Allegheny Group are difficult to distinguish from the rocks of the Pottsville Group. The Allegheny Group includes several coal beds, but only the Upper Freeport coal is economically significant.

The Conemaugh Group underlies the rest of the general area, but erosion has removed much of the upper part. This group consists of siltstones, sandstones, shales, and coals deposited in a shallow marine environment. Red shales, which are characteristic of the Conemaugh, are absent in the older rocks. The Lower Bakerstown coal is the only coal in this group of economic importance, but a minable thickness is present in less than one-third of the area. Floodplain sediments along the streams and colluvial deposits at the toeslopes of hills are of limited extent and thickness.

The sedimentary rocks in the county have been folded to form five synclinal coal basins, as shown in figure 2.2-3. The broad folding produced general to moderate dips; the maximum dip in the general area is about 20˚. The geologic structure in the general area is shown in figure 2.2-4 by the contours on the base of the Upper Freeport coal. The axis of the Upper Potomac syncline plunges to the northeast.

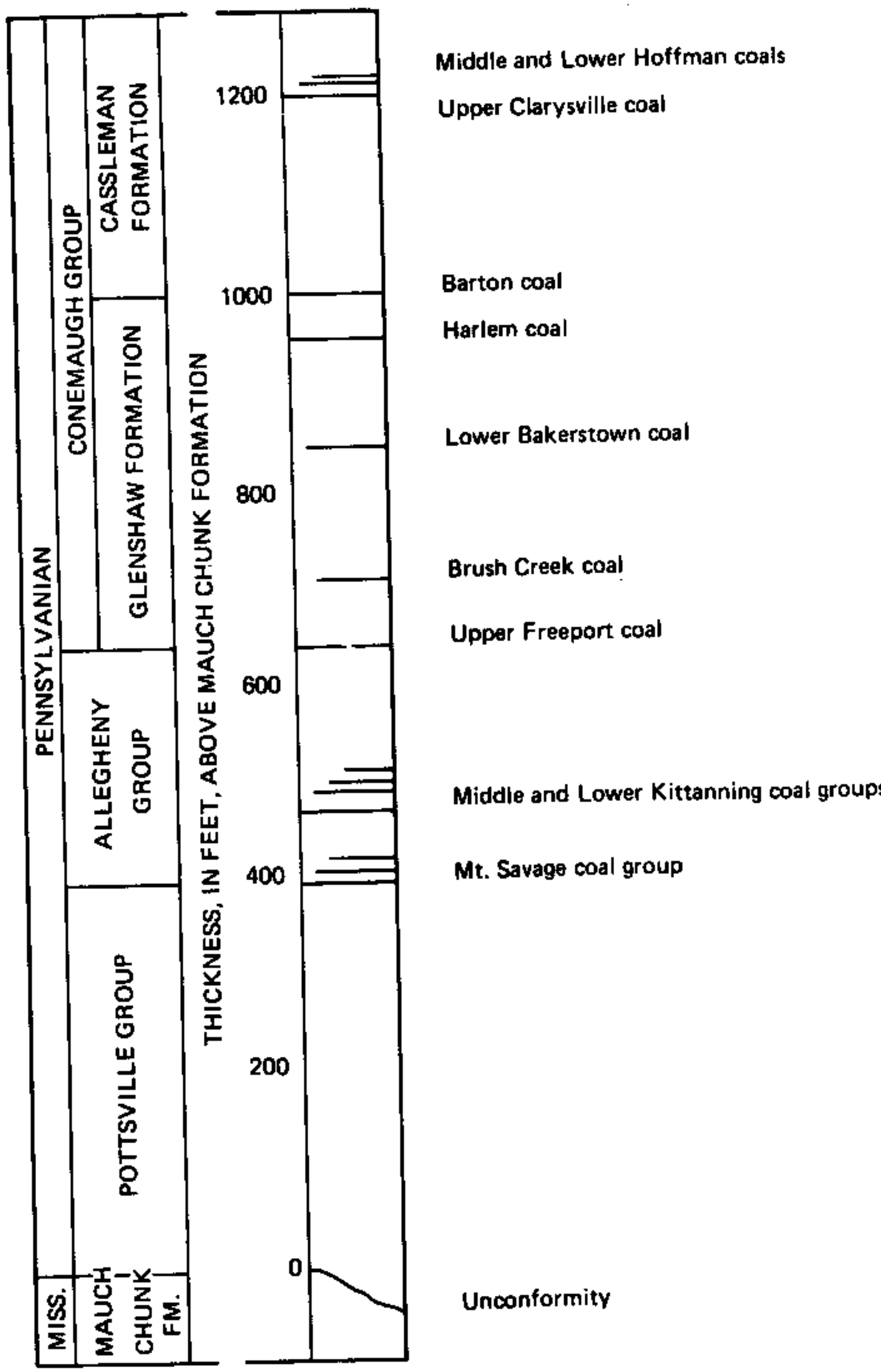


Figure 2.2-1. — General stratigraphic column for the Upper Potomac coal basin in the general area.

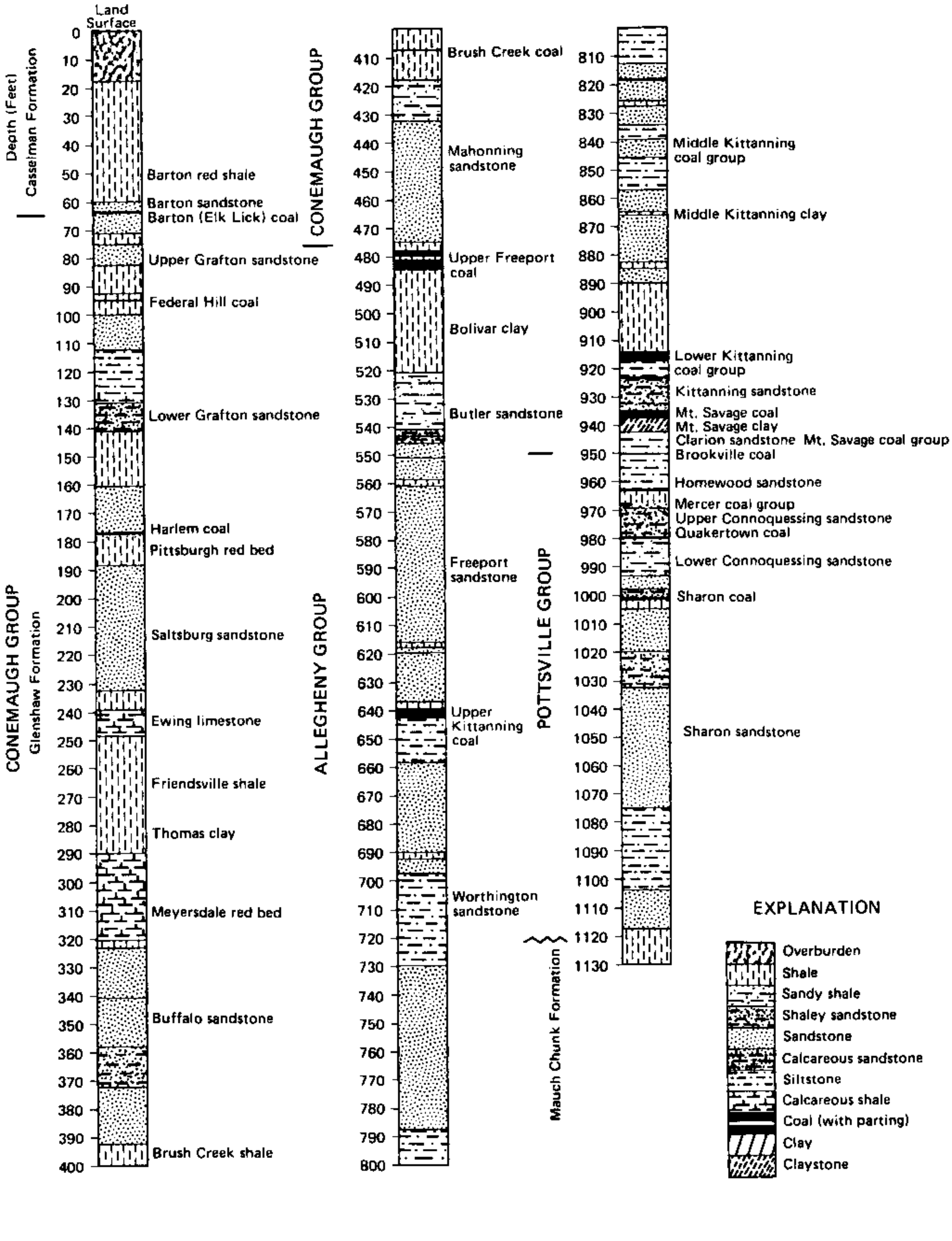


Figure 2.2-2.— Lithologic log of well FA 31. Depth below land surface is shown in feet.

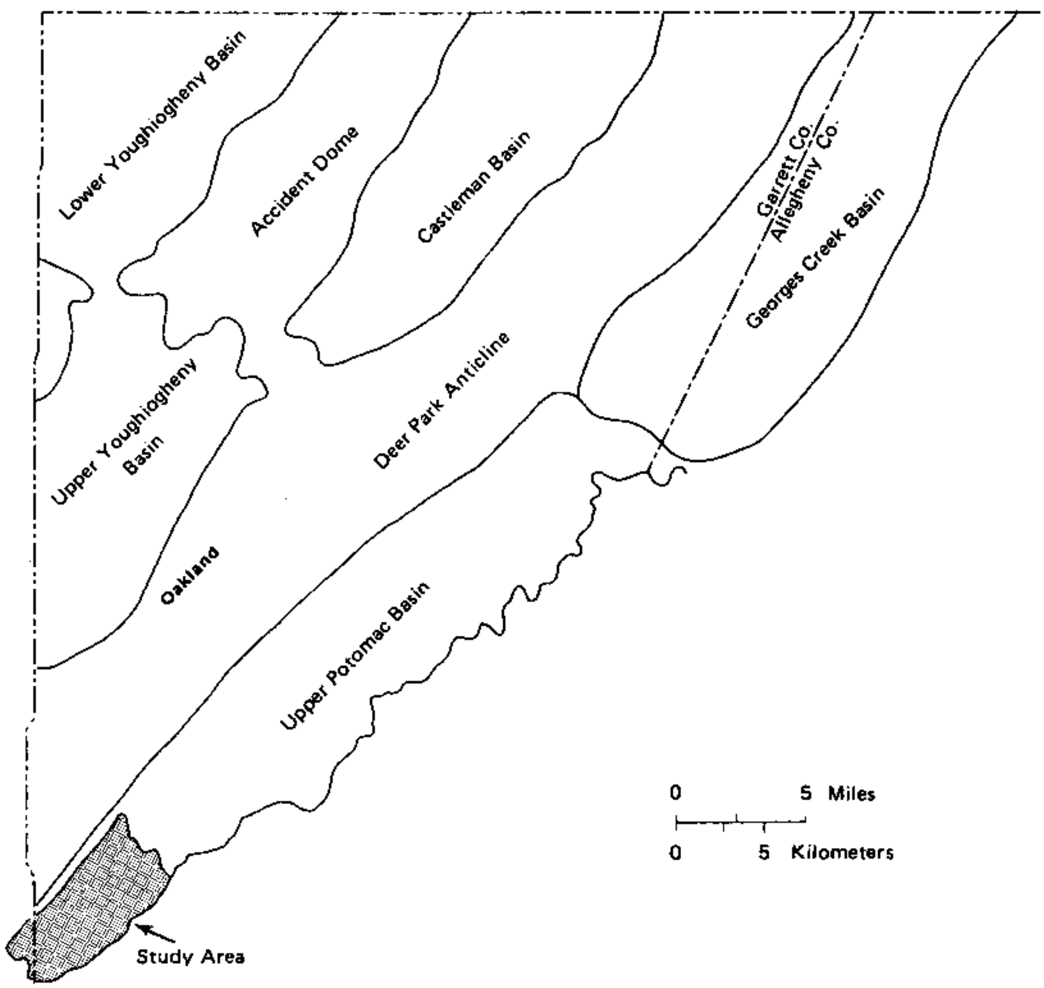


Figure 2.2-3.— Geologic structure in Garrett County.

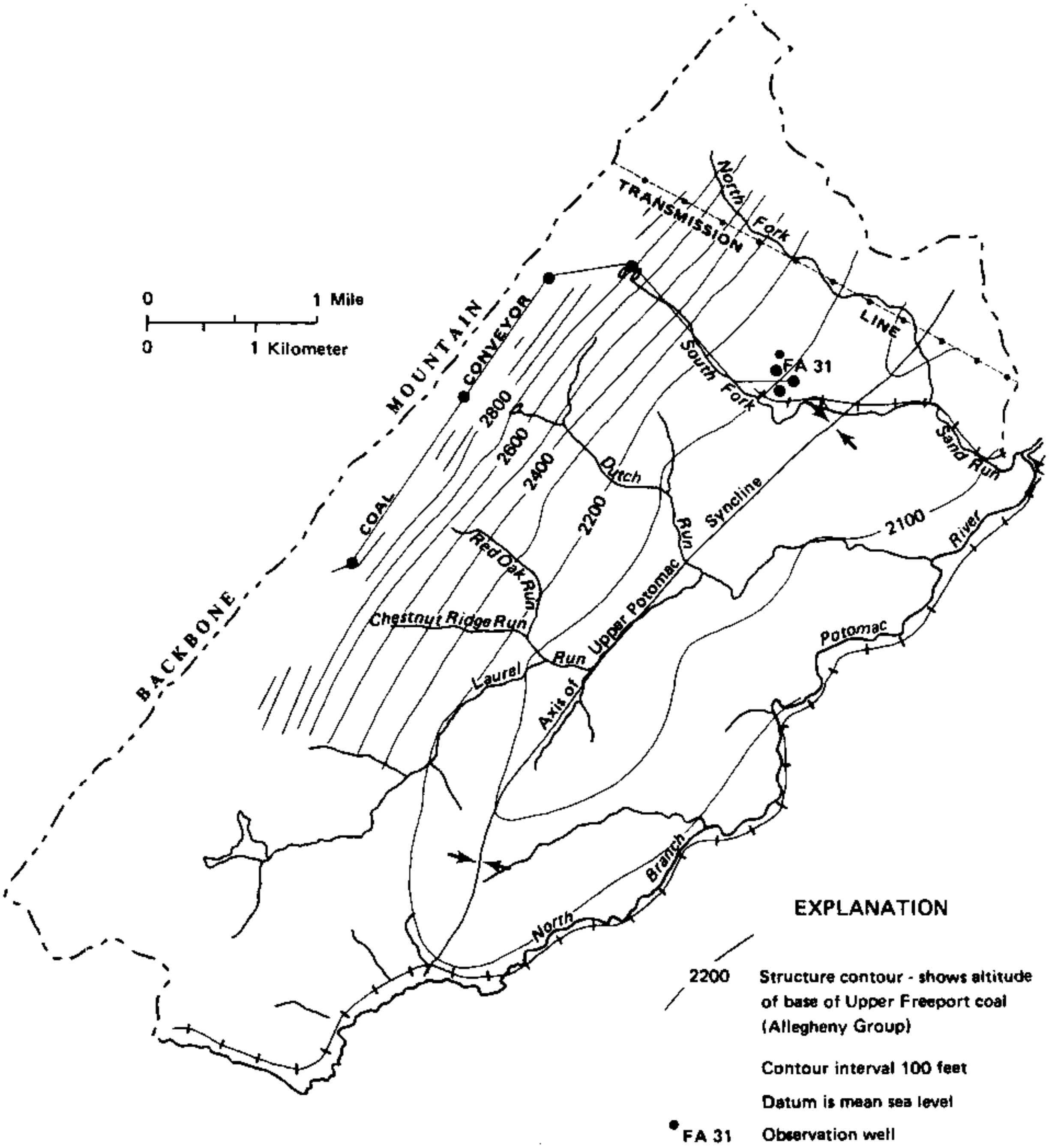


Figure 2.2-4.— Altitude of the base of the Upper Freeport coal of the Allegheny Group. (From Duigon and Smigaj, 1985, fig. 9.)

3.0 HYDROLOGIC SETTING

3.1 CLIMATE

HUMID CONTINENTAL CLIMATE CHARACTERISTIC OF AREA

The mean annual temperature is about 48˚F and the mean annual precipitation is about 47 inches.

Air masses from the interior of the continent provide the area with a humid continental climate. The prevailing winds are from the west and northwest but become more southerly in the summer. The mean annual precipitation, during 1941-70, is 47.11 inches at the nearest National Weather Service station, which is about 11 miles north-northeast of the area. The mean annual temperature at this station during the same period is 47.8˚F. Mean monthly temperatures exceed the mean annual from May through October, peaking in July at 67.4˚F. January is the coldest month, at 27.5˚F.

Mean monthly precipitation for March through August exceeds the average mean monthly (3.93 inches); mean monthly precipitation for the rest of the year, although less than average, is still abundant. Much of the annual precipitation occurs as snow, which may fall as early as September and as late as May. Snow cover may be as much as several feet in places.

3.0 HYDROLOGIC SETTING

3.2 OCCURRENCE AND FLOW OF GROUND WATER

OCCURRENCE OF GROUND WATER GOVERNED BY ROCK FRACTURES IN BEDROCK

Secondary porosity and permeability due to fracturing provide for storage and transmission of water.

Most of the water within the sedimentary rocks is related to the fractures within the rock mass. The secondary porosity and permeability provide storage and transmission of the ground water. The number of open fractures decreases with depth. Wells that are open at greater depths, with the shallow zones cased off, generally have smaller yields than shallow wells. Also, fractures are not evenly distributed among rock types. Plastic underclays provide very effective barriers to ground-water flow.

Zones of bedrock fracturing are interpreted from linear features observed on stereophotographs. These linear features are called fracture zones and are shown for the general area in figure 3.2-1. The orientation-frequency rosette shows some north-northwest south-southeast preference for the linear features.

The ground-water flow system in the general area consists of three major subsystems: shallow, intermediate, and deep. Associated with these subsystems are four interpreted open-hole water-bearing zones: zone 1 with the deep flow, zones 2 and 3 with the intermediate flow, and zone 4 with the shallow flow. The ground-water flow system, interpreted from water levels, is shown in figure 3.2-2.

The shallow flow system underlies the hills, discharges to the local streams, and, to some extent, leaks downward into the deeper, intermediate system, which discharges into higher order streams at lower altitudes. The shallow flow system also is perched above beds of lower permeability in places, and most of this ground water flows laterally to springs that discharge above stream levels.

The main water table probably is indicated by the water levels in the shallow wells. The source of most of the ground water in the flow system is precipitation, but some stream water also leaks into the shallow aquifers. At site 1 near the middle of South Fork Sand Run (fig. 3.2-2), the water table was generally several feet above the level of the stream. At site 2, near the downstream reach of South Fork Sand Run, the water table generally was near, or several feet below, the level of the stream. At site 3, on the hilltop, the water table was generally about 30 feet below the surface, where the water level in the next shallowest well (zone 4) is about 60 feet lower. These differences in water levels indicate perching of the shallow aquifer, with some leakage downward. The dissected terrain results in a number of local, independent shallow subsystems. In some parts of the area, very shallow systems perched above the main water table may be important contributors to streamflow following periods of precipitation. These localized, ephemeral systems may be perched on impervious soil zones, such as fragipans, or they may be zones of concentrated seepage developed by piping near the lower areas of the hillslopes.

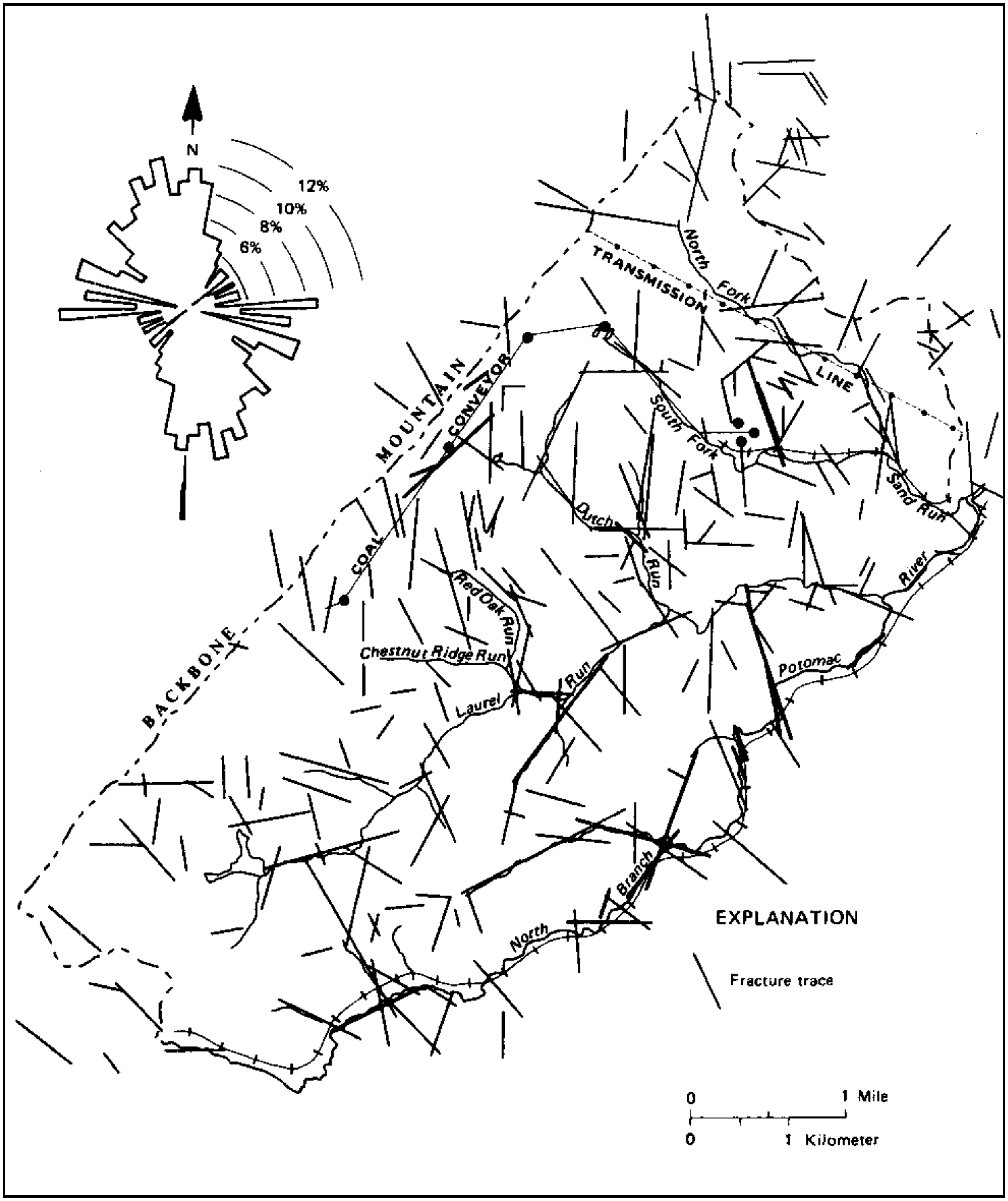


Figure 3.2-1.— Fracture traces and orientation rosette. (From Duigon and Smigaj, 1985, fig. 10.)

The intermediate flow system does not interact with the lower order streams within the area. Confining beds, such as the underclays of the Lower Bakerstown coal, separate some of the flow paths. These confining beds are not continuous throughout the area, and in some places may be hydraulically breached by fracturing. The bottom of the intermediate system may be at the underclay of the Upper Freeport coal. The water from this system may be discharged by upward leakage into stream valleys at lower altitudes outside of the area.

Water below the Upper Freeport coal may be part of a regional flow system extending from a high area southeast of the county and discharging to the Cheat River to the west. Although the regional system may receive some leakage from above, it is fairly well sealed by the underclay of the Upper Freeport coal.

The base of the fresh water in well FA 31 was at a depth of 940 feet. Figure 3.2-2 shows possible flow paths prior to April 1981. Flow into the plane of the figure is not shown, although such a component exists. The zone of salty water is below the lowest level shown in the illustration.

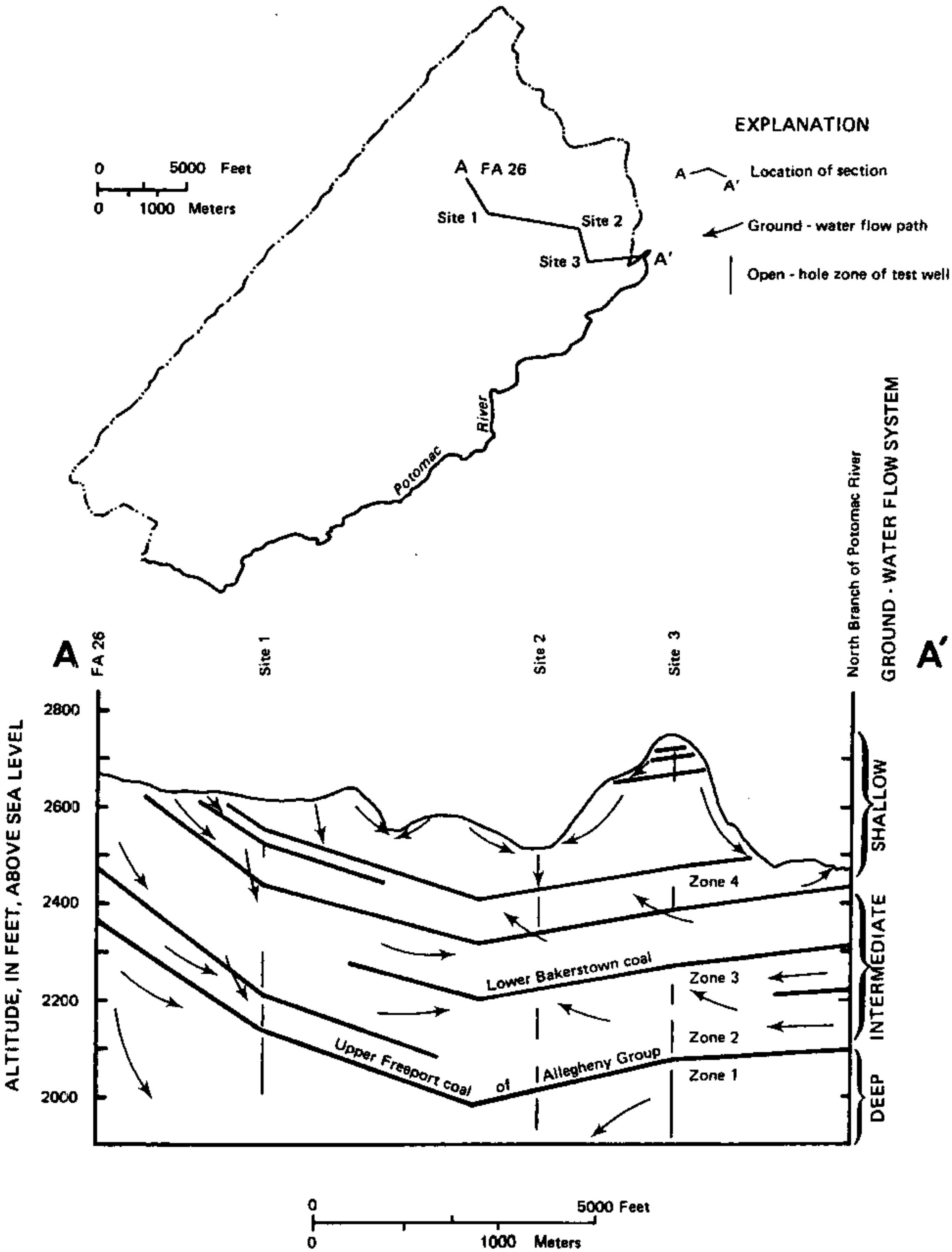


Figure 3.2-2.— Possible ground-water flow paths prior to April 1981. (From Duigon and Smigaj, 1985, figs. 22 and 30.)

3.0 HYDROLOGIC SETTING

3.3 WELLS, SPRINGS, AND STREAMS

WATER QUANTITY AND QUALITY VARIATION DETERMINED FROM INVENTORIED AND INSTRUMENTED WELLS, SPRINGS, AND STREAMS

The location of water-bearing zones within the bedrock and the relevance to the hydrologic setting of the coal beds to be mined is determined from wells, springs, and streams.

The data-collection sites within the general area are shown in figure 3.3-1. Daily records of precipitation are provided by a rain gage in the area. Streamflow-gaging stations were constructed on the four main streams-Laurel Run, South Fork and North Fork Sand Run, and North Branch Potomac River. These stations were equipped to record stage, water temperature, and specific conductance. Onsite measurements of water-quality characteristics were made periodically at these sites, and samples were collected for laboratory analysis. Discharge measurements, onsite field determinations, and water samples were obtained at six additional sites. The streamflow-gaging stations and the precipitation gage are within the boundaries of the Beaver Run Mine. The location of the operational mine boundaries is shown in figure 3.3-2.

Thirteen wells drilled in three clusters were chosen to provide data across the syncline (fig. 3.2-2). This drilling had to accommodate property constraints and projected phases of mining. The three clusters are located within the boundaries of the Beaver Run Mine. At each cluster, wells are open to different zones, including the sandstone below the Upper Freeport coal. Four-inch casing was used in the construction of each well to provide room for the float and counterweight of the water-level recorder. This size also allows for the use of a small diameter submersible pump, which is used to pump test the wells and obtain samples for water-quality analyses. Water-level recorders were installed on all 13 wells. Additional water-level measurements were made in six other wells. Well FA 31 was drilled to a depth of 1,131 feet, as shown in figure 2.2-2, primarily to determine the depth to the Mississippian-Pennsylvanian contact and to the top of the salty-water zone that underlies the region. This well was subsequently grouted back to a depth of 606 feet.

At well site FA 35 is an abandoned underground coal mine in the Lower Bakerstown coal, where mine discharge was sampled and measured. Mine discharge was also measured at sites GA 3 and GA 6 from abandoned mines in the Upper Freeport coal. Discharge, pH, and specific conductance were measured at three springs. The records of wells, mine discharges, and springs are presented in table 3.3-1.

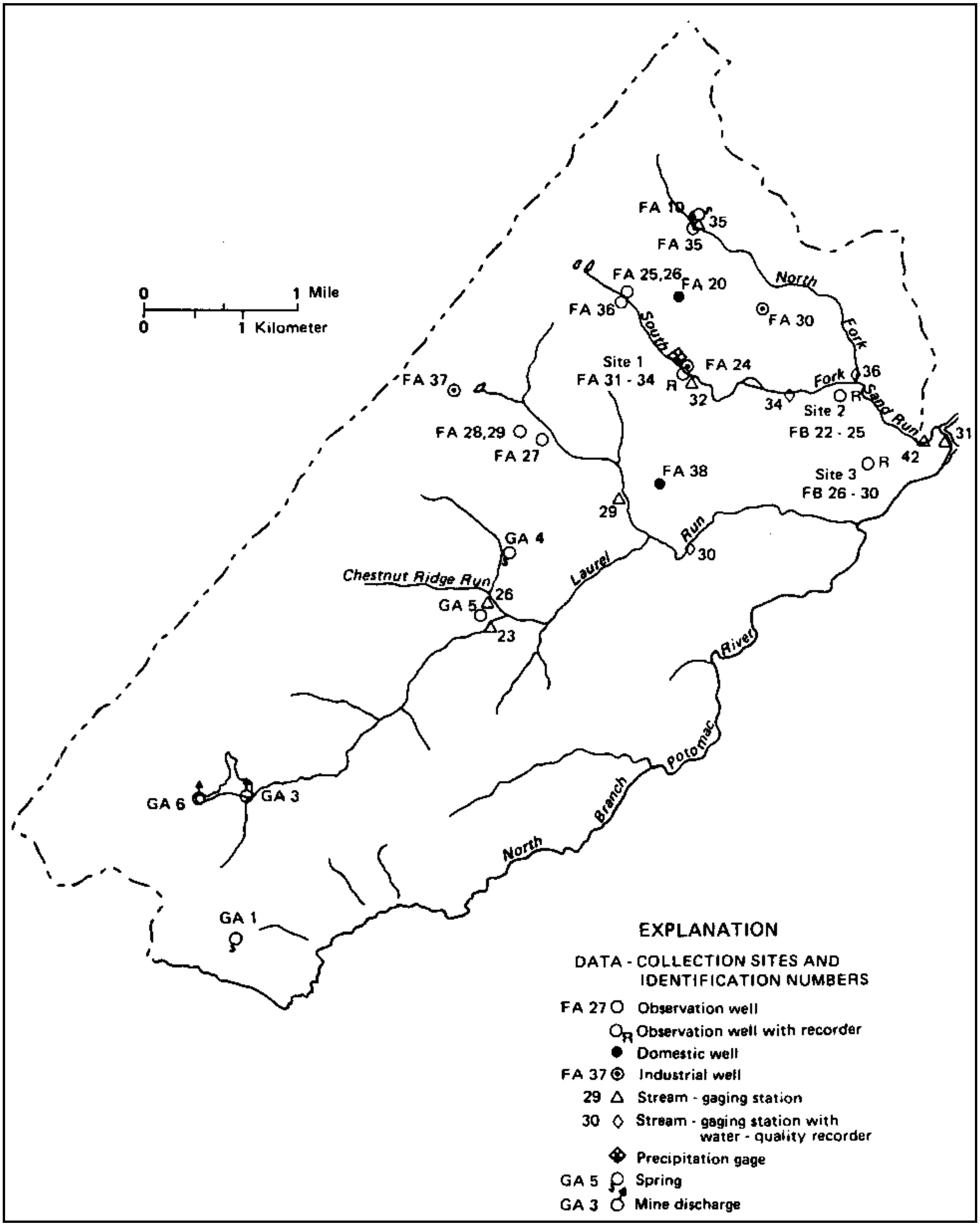


Figure 3.3-1.— Data-collection network.
(From Duigon and Smigaj, 1985, fig. 2.)

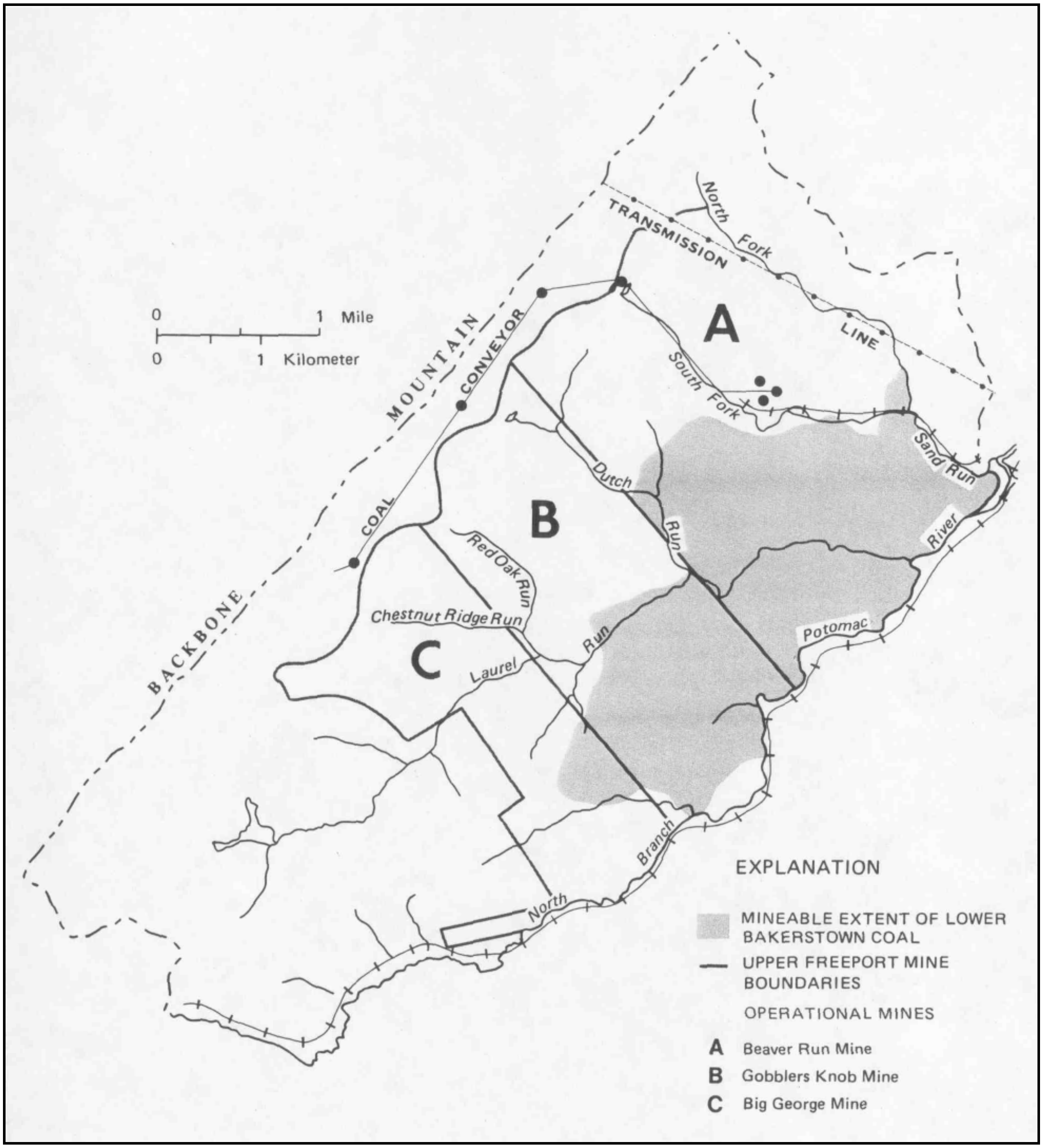


Figure 3.3-2.— Mine boundaries and approximate extent of mineable Lower Bakerstown coal.
(From Duigon and Smigaj, 1985, fig. 12.)

Table 3.3-1. – Records of wells, mine-discharge sites, and springs.

[ft, feet; in., inch; gal/min, gallons per minute; gal/min/ft, gallons per minute per foot of drawdown]
[U.S.G.S., U.S. Geological Survey; H, domestic use; N, industrial use; 0, observation; PS, public supply; U, unused]

WELLS

Site number	Owner	Altitude of land surface (ft)	Depth of well (ft)	Depth cased (ft)	Casing diameter (in.)	Aquifer	Water level (Depth ft)	Water level Date measured	Draw-down (ft)	Discharge Rate (gal/min)	Discharge Date measured	Discharge Hours pumped	Specific capacity (gal/min/ft)	Use of well
FA 20	Cooper, Charles	2,750	78	22	5	Conemaugh	28	6/17/73	12	8.0	6/17/73	2.0	0.7	H
FA 24	Mettiki Coal Co.	2,610	229	30	8	Conemaugh	170	11/23/77	59	30	11/23/77	.5	.5	N
FA 25	do.	2,650	315	304	6	Conemaugh	301	6/23/78	-	-		-	-	O
FA 26	do.	2,650	170	150	6	Conemaugh	16	6/23/78	-	-		-	-	O
FA 27	do.	2,860	215	190	6	Conemaugh	169	6/23/78	-	-		-	-	O
FA 28	Mettiki Coal Co.	2,890	341	317	6	Conemaugh	105.50	6/23/78	-	-		-	-	O
FA 29	do.	2,890	226	203	6	Conemaugh	130.75	6/23/78	-	-		-	-	O
FA 30	do.	2,730	447	417	6	Conemaugh	440	5/20/78	7	50	5/20/78	-	7.1	N
FA 31	U.S.G.S.	2,618	606	470	4	Allegheny	11.54	10/09/80	107	2.0	3/11/81	.2	.02	O
FA 32	do.	2,618	473	430	4	Conemaugh	13.69	10/09/80	103	3.6	3/12/81	.4	-	
FA 33	U.S.G.S.	2,618	391	318	4	Conemaugh	17.94	10/09/80	93	2.0	5/22/81	1.5	-	O
FA 34	do.	2,618	115	96	4	Conemaugh	16.15	10/09/80	2	6.0	5/07/81	2.0	3.6	O
FA 36	Mettiki Coal Co.	2,650	210	46	8	Conemaugh	-2	6/20/78	-	200	6/20/78	.5	-	O
FA 37	do.	2,780	253	40	8	Conemaugh	50	1/17/79	203	100	1/17/79	.5	.5	N
FA 38	Glofelty, Curtis	2,680	118	39	6	Conemaugh	31	10/10/79	87	7.0	10/10/79	1.0	.1	H
FB 22	U.S.G.S.	2,530	640	517	4	Allegheny	78.18	10/09/80	65	3.0	4/21/81	.3	.05	O
FB 23	do.	2,530	495	460	4	Conemaugh	19.70	10/09/80	54	2.0	4/22/81	.5	.04	O
FB 24	do.	2,530	400	340	4	Conemaugh	20.05	10/09/80	117	4.0	4/23/81	.4	.03	O
FB 25	do.	2,530	180	120	4	Conemaugh	29.07	10/09/80	5	7.5	4/24/81	1.5	1.4	O
FB 26	do.	2,755	832	687	4	Allegheny	269.33	10/09/80	-	-		-	-	O
FB 27	U.S.G.S.	2,755	656	590	4	Conemaugh	4.60	10/09/80	167	4.0	5/04/81	.6	.02	O
FB 28	do.	2,755	556	517	4	Conemaugh	216.09	10/09/80	-	-		-	-	O
FB 29	do.	2,755	360	316	4	Conemaugh	252.69	10/09/80	-	-		-	-	O
FB 30	do.	2,755	85	82	4	Conemaugh	32.47	10/09/80	8	6.3	5/05/81	2.3	.8	O

MINE-DISCHARGE SITES

Site Number	Altitude of land surface above sea level (ft)	Discharge Rate (gal/min)	Discharge Date measured	Coal seam drained
FA 35	2,630	58	6/30/81	Lower Bakerstown
GA 3	2,640	690	10/29/81	Upper Freeport
GA 6	2,650	1,659	8/25/70	Upper Freeport

SPRINGS
(Aquifer–Conemaugh Formation)

Site Number	Owner	Altitude of land surface above sea level (ft)	Discharge Rate (gal/min)	Discharge Date measured	Improvements	Use of water
GA 1	Town of Kempton	2,860	750	7/ 50	Spring house	PS
GA 4	Radeheaver, Paul	2,660	40	10/29/81	Concrete basin	H
GA 5	-	2,660	5	10/29/81	Pipe	U

3.0 HYDROLOGIC SETTING

3.4 AQUIFER PROPERTIES

AQUIFER TEST METHODS USED TO DETERMINE TRANSMISSIVITY AND STORAGE COEFFICIENTS

Aquifer properties indicate most ground-water circulation occurs in the shallow flow system and hydraulic conductivity decreases logarithmically with depth.

Aquifer properties were determined for 10 wells using a submersible pump. However, slug or pressure tests would have been more efficient because of the small well yields, except for the shallow aquifer wells. Geophysical logs also gave some indication of aquifer properties. The base of the fresh ground-water system was determined, from fluid resistivity and electric logs, to be at a depth of about 940 feet at well FA 31. Neutron logs run in wells FA 31 and FB 26 indicated porosities less than about 6 percent in the sandstones. Porosity, calculated using a formation factor (13), was determined to be about 5 percent.

Table 3.4-1 lists values of hydraulic conductivity (K) and transmissivity (T) calculated by several methods: the slug test method (3), time-drawdown plot (5), and the one-drawdown estimation method (15). The procedures, assumptions, and requirements of these methods depend upon the hydraulic and physical conditions at a given site. As shown in table 3.4-1, the various methods can give results that differ by an order of magnitude. The Cooper-Jacob time-drawdown method probably gave the most reliable results for the shallower, larger yielding wells, but the Bouwer and Rice slug-test method probably gave better results for the deeper, smaller yielding wells.

Despite the ranges of the computed transmissivities, hydraulic conductivities determined for the shallow wells at each site are about an order of magnitude greater than the values determined for the deeper wells. Figure 3.4-1 shows the relationship of decreasing hydraulic conductivity with depth below land surface. This rapid decrease in hydraulic conductivity indicates that most of the ground-water circulation occurs within a few hundred feet of the land surface or in the shallow flow system.

Table 3.4-1. – Aquifer test results
[ft, feet; ft/d, feet per day; ft^2/d, square feet per day]

Site number	Well number	Aquifer	Well depth (ft)	Assumed aquifer thick-ness (b) (ft)	Assumed storage coeffi-cient[1] (S)	Hydraulic conduc-tivity[2] (K) (ft/d)	Transmissivity (T) (ft^2/d)		
							Kb	Time-drawdown[3]	Single drawdown[4]
1	FA 31	Allegheny	606	76	0.00008	0.3	22	2	25
	FA 32	Conemaugh	473	43	.00004	.5	22	.7	2
	FA 33	Conemaugh	391	66	.00007	.2	13	3	3
	FA 34	Conemaugh	115	64	.00006	9	580	570	1,100
2	FB 22	Allegheny	640	120	.0001	.05	6	3	6
	FB 23	Conemaugh	495	48	.00005	.3	14	8	10
	FB 24	Conemaugh	400	83	.00008	.2	16	11	12
	FB 25	Conemaugh	180	61	.00006	7	430	241	320
3	FB 27	Conemaugh	656	61	.00006	.05	3	9	6
	FB 30	Conemaugh	85	78	.00008	7	550	280	380

[1] S = assumed aquifer thickness (b) x 10^{-6} (from Lohman, 1972, p. 8)
[2] Bower and Rice, 1976
[3] Cooper and Jacob, 1946
[4] Ogden, 1965

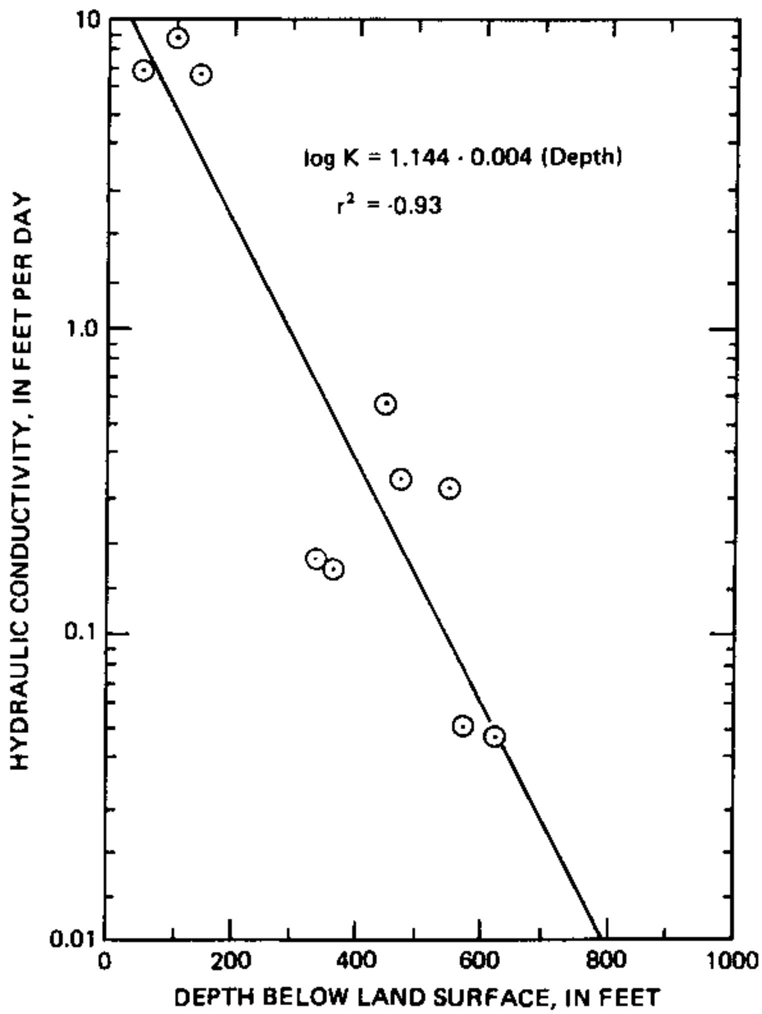


Figure 3.4-1. — Variation of hydraulic conductivity with depth.
Depth is plotted as the mid-point of the open-hole zone.
(From Duigon and Smigaj,1985, fig. 28.)

3.0 HYDROLOGIC SETTING

3.5 GROUND-WATER LEVELS

WATER LEVELS IN WELLS REFLECT VARIATIONS OF GROUND-WATER FLOW BELOW LAND SURFACE

Some wells flowed, while the water level in others was several hundred feet below land surface

Water levels in observation wells were measured periodically, beginning in 1978. At three sites, 13 test wells were equipped with instruments in 1980 to record hydraulic-head changes in different zones. Figure 3.5-1 shows the open-hole zones of each of these test wells in cross-section view; the zones are numbered from deepest to shallowest. Water levels, at every well, rose higher than the top of the zone to which the well was open.

In March 1980, water was observed seeping from a small terrace eroded into the hillside at site 3, at a rate of about 0.1 ft^3/s. The soil of this site is mapped as the Cookport loam (20). This soil has a fragipan, which impedes vertical drainage, and creates a perched water condition. Some other soils in the area are also characterized by perched water.

Figure 3.5-2 shows hydrographs for each of the wells of the three clusters for the period May 1980 through September 1981. At site 1, the heads, from highest to lowest, are in the order of zone 4-zone 3-zone 2, whereas at sites 2 and 3, the heads are in the order of zone 2-zone 3-zone 4. The head of zone 1, which is below the Upper Freeport coal, is out of order at each site, indicating that this zone is a part of a separate regional flow system. At all sites, before March 1981, the water level in zone 1 declined at a fairly constant rate. The sharp water-level declines at site 1 and in several zones after March 1981 to a lesser degree at site 3 were due to the approach of a side heading of the mine.

Ground water was discharged to the surface at three additional sites FA 35, GA 3, and GA 6 (fig. 3.3-1). The first site drains the abandoned mine in the Lower Bakerstown coal, and the other two sites drain the abandoned mine in the Upper Freeport coal.

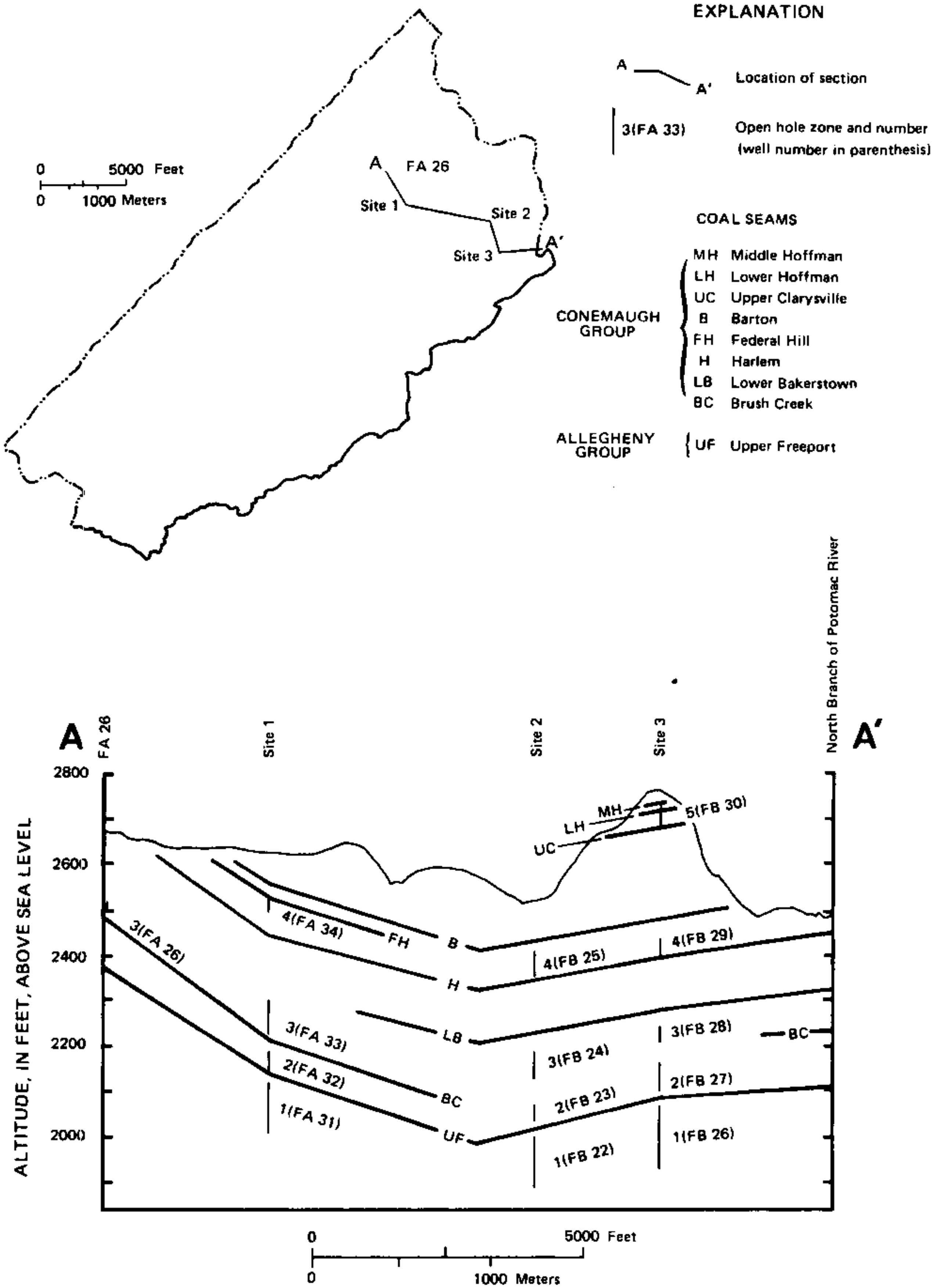


Figure 3.5-1.— Open-hole zones in relation to coal seams.
(From Duigon and Smigaj, 1985, fig. 22.)

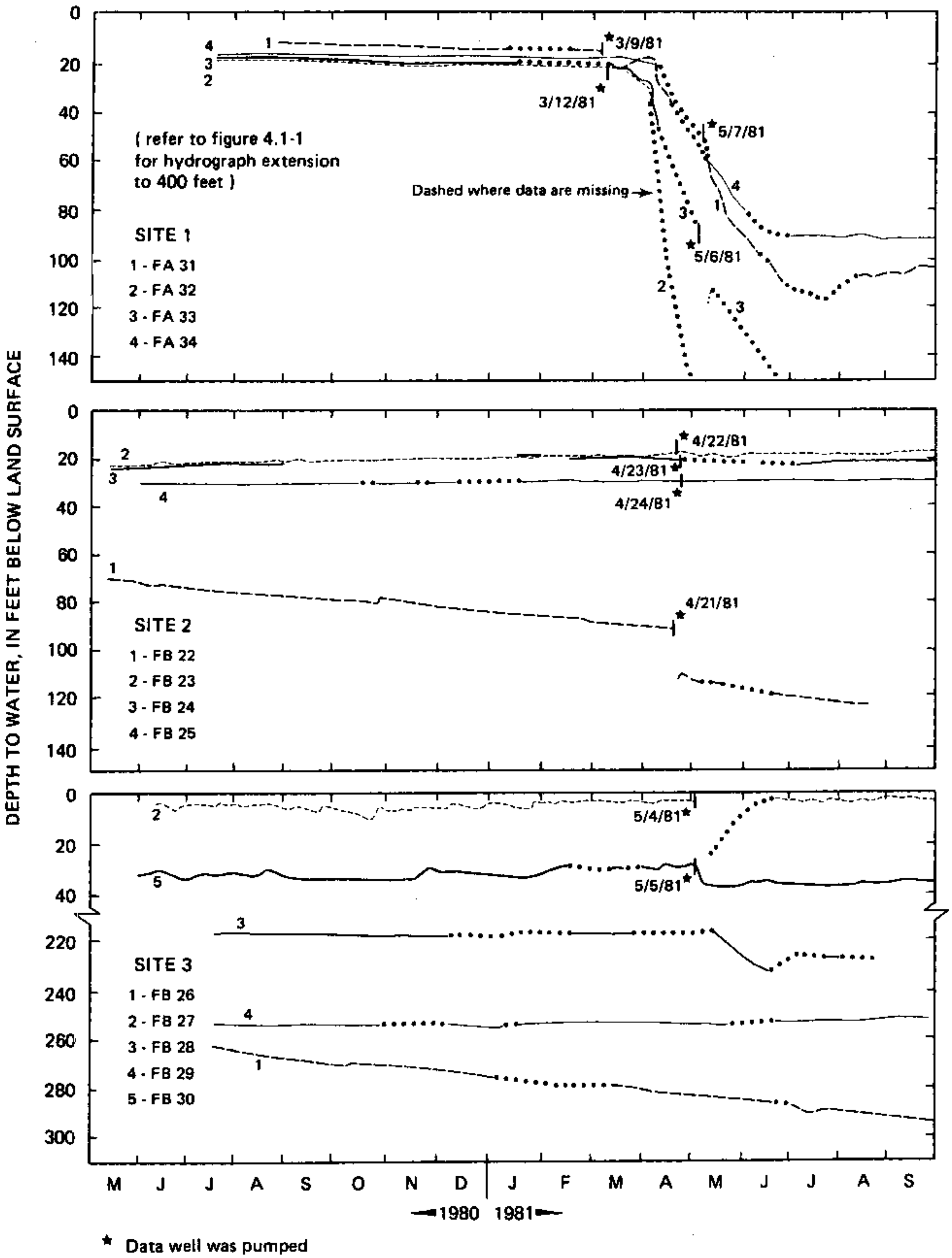


Figure 3.5-2.— Water-level variations at the observation wells at sites 1, 2, and 3. (From Duigon and Smigaj, 1985, fig. 24.)

3.6 GROUND-WATER QUALITY

SHALLOW FRESHWATER-FLOW SYSTEMS OVERLIE A DEEP, SALTY-WATER ZONE

Water-quality samples from streams, springs and wells indicates ground-water quality is different from surface-water quality.

The chemical quality of ground water, which was determined from laboratory analyses of samples collected from eight wells, three underground-mine discharge sites, three springs, and one site within the mine, is presented in table 3.6-1. The small yields of the deeper wells precluded pumping enough water to ensure that the samples represented formation water. Values of pH as large as 11.6, in some samples from deeper wells, are greater than the usual pH limits of near-surface environments (11) and indicate that the water may have reacted with the cement grout at the bottom of the casing. Consequently, some of the analyses in table 3.6-1 may not be representative of formation water. The pH of water in wells FA 31 and FA 32 was 10.4 and 11.6, respectively. However, a sample from a wall seep inside the mine near the wells and at about the same depth had a pH of 7.6, which seems reasonable for aquifers when compared with similar data from the area. The marked difference in pH of the well water and the mine-seep water further supports the conclusion that some of the well samples are not representative. Therefore, considerable care and judgment are needed in evaluating the chemical quality of ground water in relation to mining.

The potassium concentrations of several of the wells are nearly as large as, or larger than the sodium concentrations; this may be due to abundant potassium bearing minerals, such as potash-feldspar, muscovite, or illite in the rocks. Numerous stylolites in rock cores indicate that mineral solution has been extensive. Most of the sandstones are well cemented with silica, indicating that much precipitation has also taken place.

Well FA 31 was sampled from a depth of 1,131 feet, while it was flowing. The large sodium and chloride concentrations of 1,800 and 2,900 mg/L, respectively, show that the saltwater zone had been entered. Because the well was flowing, there must have been some mixing with water from other zones in the borehole.

The trilinear diagram (fig. 3.6-1) compares ground-water and surface-water samples according to relative concentrations of major ions. The well samples are distinct from the stream samples, although water from a shallow well, FB 25, appears to show mixing with water from the South Fork Sand Run. A sample collected inside the active mine resembles the sample from FB 25. The three abandoned-mine drainage samples (FA 35, draining the Buffalo Coal Company Mine in the Lower Bakerstown seam; GA 3 and GA 6, draining the Kempton Mine in the Upper Freeport seam) had much larger sulfate concentrations than the well samples and figure 3.6-1 indicates that the stream chemistry is strongly affected by these discharges.

Spring samples (GA 1, GA A, and GA 5) had smaller specific conductances than water from the wells (table 3.6-1), indicating the spring water is less mineralized. This condition may reflect shorter flow paths and residence times of water in these systems.

Table 3.6-1.– Chemical analyses of ground water.
[ft, feet; mg/L, milligrams per liter; ug/L, micrograms per liter; Site code: A-active mine wall; D-abandoned mine drainage; S- spring; W-well]

Site number	Type of site	Geologic group	Date of sample	Depth to top of sample interval (ft)	Depth to bottom of sample interval (ft)	Specific conductance, field (micromhos)	Specific conductance, lab (micromhos)	Field pH (units)	Laboratory pH (units)	Temperature, water (°C)	Hardness (mg/L as $CaCO_3$)	Hardness noncarbonate (mg/L $CaCO_3$)	Acidity total heated (mg/L as H)	Acidity (mg/L as $CaCO_3$)	Calcium dissolved (mg/L as Ca)	Magnesium dissolved (mg/L as Mg)	Sodium dissolved (mg/L as Na)	Potassium dissolved (mg/L as K)
FA 20	W	Conemaugh	78-08-03	22	78	25	—	6.8	—	—	12	3	—	—	3.3	0.8	0.3	0.5
FA 31	W	Pottsville	80-02-11	488	2/1,131	—	9,470	—	8.0	—	300	99	—	—	90	18	1,800	4.7
		Allegheny	80-02-11	488	3/1,131	380	—	—	7.9	—	34	10	—	—	11	1.6	95	.7
		1/	81-03-10	470	606	420	286	10.4	11.0	9.8	64	0	—	—	24	1.0	10	7.9
FA 32	W	1/	81-03-12	430	473	2,600	2,910	11.6	11.8	10.0	710	—	—	—	280	1.7	13	41
FA 34	W	Conemaugh	81-05-07	96	115	141	161	7.0	7.6	14.8	82	8	—	—	24	5.4	.7	1.1
FA 35	D	Conemaugh	81-05-15	—	—	3,280	3,210	4.9	3.0	11.3	1,700	1,700	—	—	470	120	5.5	12
		do.	81-06-30	—	—	—	3,110	—	4.0	—	1,600	1,600	9.0	447	440	110	6.5	13
FB 22	W	1/	81-04-21	517	640	480	363	10.6	10.8	11.6	33	0	—	—	13	.2	.20	43
FB 23	W	Conemaugh	81-04-22	460	495	195	216	7.0	7.8	12.0	110	19	—	—	34	5.7	1.1	1.0
FB 25	W	do.	81-04-24	120	180	438	443	7.3	8.2	9.4	210	87	—	—	60	14	11	3.7
FB 30	W	do.	81-05-05	82	85	193	202	6.4	7.2	12.3	110	7	—	—	31	6.7	.4	1.6
GA 1	S	Conemaugh	81-10-29	—	—	86	—	6.9	—	11.0	—	—	—	—	—	—	—	—
GA 3	D	Allegheny	----	—	—	803	897	3.2	3.0	10.5	190	—	4.8	—	47	18	4.5	2.8
GA 4	S	Conemaugh	81-10-29	—	—	21	—	5.1	—	9.1	—	—	—	—	—	—	—	—
GA 5	S	do.	81-10-29	—	—	26	—	6.3	—	10.0	—	—	—	—	—	—	—	—
GA 6	D	Allegheny	70-08-25	—	—	1,020	1,690	3.4	2.6	10.3	—	599	—	—	90	32	56	3.5
Mine drip	A	do.	81-12-18	—	—	330	332	—	7.6	8.0	160	62	—	—	48	9.6	2.7	2.2

Site number	Alkalinity (mg/L as $CaCO_3$)	Sulfate dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Nitrogen, NO_2+NO_3 total (mg/L as N)	Nitrogen, NO_2+NO_3 dissolved (mg/L as N)	Phosphorus, total (mg/L as P)	Silica, dissolved (mg/L as SiO_2)	Iron, suspended recoverable (ug/L as Fe)	Iron, total (ug/L as Fe)	Iron dissolved (ug/L as Fe)	Manganese, suspended recoverable (ug/L as Mn)	Manganese, total (ug/L as Mn)	Manganese, dissolved (ug/L as Mn)	Solids, residue at 180°C dissolved (mg/L)	Solids, sum of constituents, dissolved (mg/L)	Solids volatile, dissolved (mg/L)
FA 20	8	1.5	0.1	0.0	—	—	0.00	4.6	—	80	—	—	10	—	25	17	—
FA 31	200	.6	2,900	—	.03	—	.050	10	2,000	4,200	2,200	20	130	110	—	4,950	—
	24	.1	150	—	—	—	—	7.5	320	450	130	0	10	20	—	280	—
	79	8.4	2.1	.3	—	.11	—	8.4	—	—	780	—	—	5	106	111	—
FA 32	740	29	1.6	<.1	—	.01	—	9.5	—	—	170	—	—	10	1,360	821	—
FA 34	74	4.0	.5	.1	—	<.01	—	7.5	0	1,400	1,400	0	90	100	102	89	—
FA 35	0	2,100	2.5	.1	—	.04	—	31	60,000	290,000	230,000	0	5,700	6,000	3,360	2,980	—
	0	2,100	2.4	.2	—	.03	—	22	—	—	130,000	—	—	5,800	3,430	2,840	507
FB 22	98	12	1.3	.2	—	<.01	—	10	—	—	2,300	—	—	30	163	161	—
FB 23	89	14	1.0	.2	—	.01	—	6.3	—	—	40	—	—	120	120	117	—
FB 25	120	99	.6	.2	—	<.01	—	7.8	—	—	290	—	—	60	275	269	—
FB 30	98	7.2	1.1	.2	—	.02	—	7.8	0	3,600	3,800	0	260	290	121	119	
GA 1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
GA 3	—	440	2.6	.4	—	<.01	—	33	2,000	52,000	50,000	100	1,800	1,700	—	—	—
GA 4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
GA 5	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
GA 6	—	—	2.2	.8	—	—	—	43	—	85,000	—	—	2,500	—	1,000	—	—
Mine drip	97	68	0.9	.2	.41	—	<.01	6.8	1,600	2,300	750	0	120	120	222	198	—

1/ probably affected by grout and not representative of formation water. 2/ sampled at a depth of 1,100 feet. 3/ sampled at a depth of 870 feet.

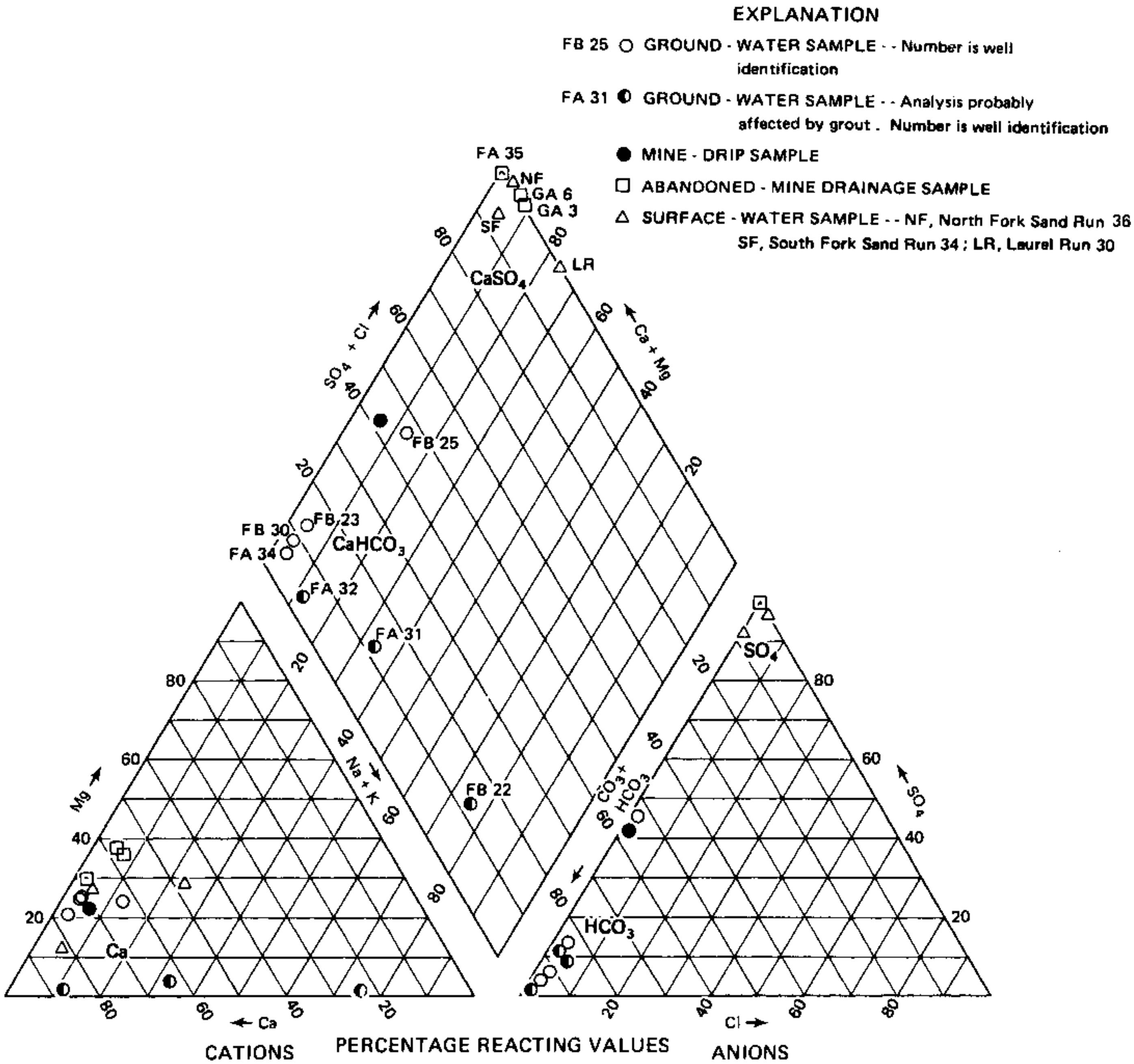


Figure 3.6-1.— Comparison of the chemical quality of ground and surface water in the general area..
(From Duigon and Smigaj, 1985, fig. 32.)

3.0 HYDROLOGIC SETTING

3.7 STREAMFLOW

QUANTITY OF STREAMFLOW IS AFFECTED BY PAST AND PRESENT MINING ACTIVITIES

Streamflows in the general area are from precipitation, abandoned and current mine drainage. Some streamflow is from treated mine pumpage and sewage from mine facilities.

Streamflows in Laurel Run, North Fork Sand Run, and South Fork Sand Run have been affected by abandoned mines and by current mining. Laurel Run, the largest of the streams, consistently receives drainage from the abandoned Kempton Mine (fig. 2.1-1). This drainage has been measured at sites GA 3 and GA 6. A tributary of Laurel Run, Chestnut Ridge Run, receives pumpage from the C mine (fig. 3.3-2), which is treated and discharged along with treated sewage from the mining facilities.

The North Fork Sand Run receives drainage from the abandoned Buffalo Coal Company mine in the Lower Bakerstown seam (fig. 2.1-1). This drainage has been measured at site FA 35. The flow at this site is much smaller than that from the Kempton Mine and ceases during dry periods.

The South Fork Sand Run receives treated pumpage from both the A and B mines (fig. 3.3-2), plus treated sewage from the mine facilities. Water is withdrawn for a coal-treatment facility from a pond about 1,200 feet downstream from this discharge point.

Figure 3.7-1 shows the hydrographs of daily flow, precipitation, and mine pumpage for May 1, 1980, to September 30, 1981. Table 3.7-1 summarizes steam-flow at the three gaging stations for the 1981 water year.

Table 3.7 1.– Summary of streamflow for water year 1981 (October 1, 1980 to September 30, 1981)
[ft^3/s, cubic feet per second; (ft3/s)/mi^2; cubic feet per second per square mile]

Station	Highest daily mean		Lowest daily mean		Annual mean		Annual runoff (inches)
	ft^3/s,	(ft^3/s)/mi^2	ft^3/s	(ft^3/s)/mi^2	ft^3/s	(ft^3/s)/mi^2	
North Fork Sand Run	47	24.6	0.32	0.168	4.79	2.51	33.7
South Fork Sand Run	52	33.5	.02	.013	3.7	2.4	[1]/ 33
Laurel Run	260	31.6	3.4	.413	26.4	3.21	43.1

[1]/ estimated—record incomplete

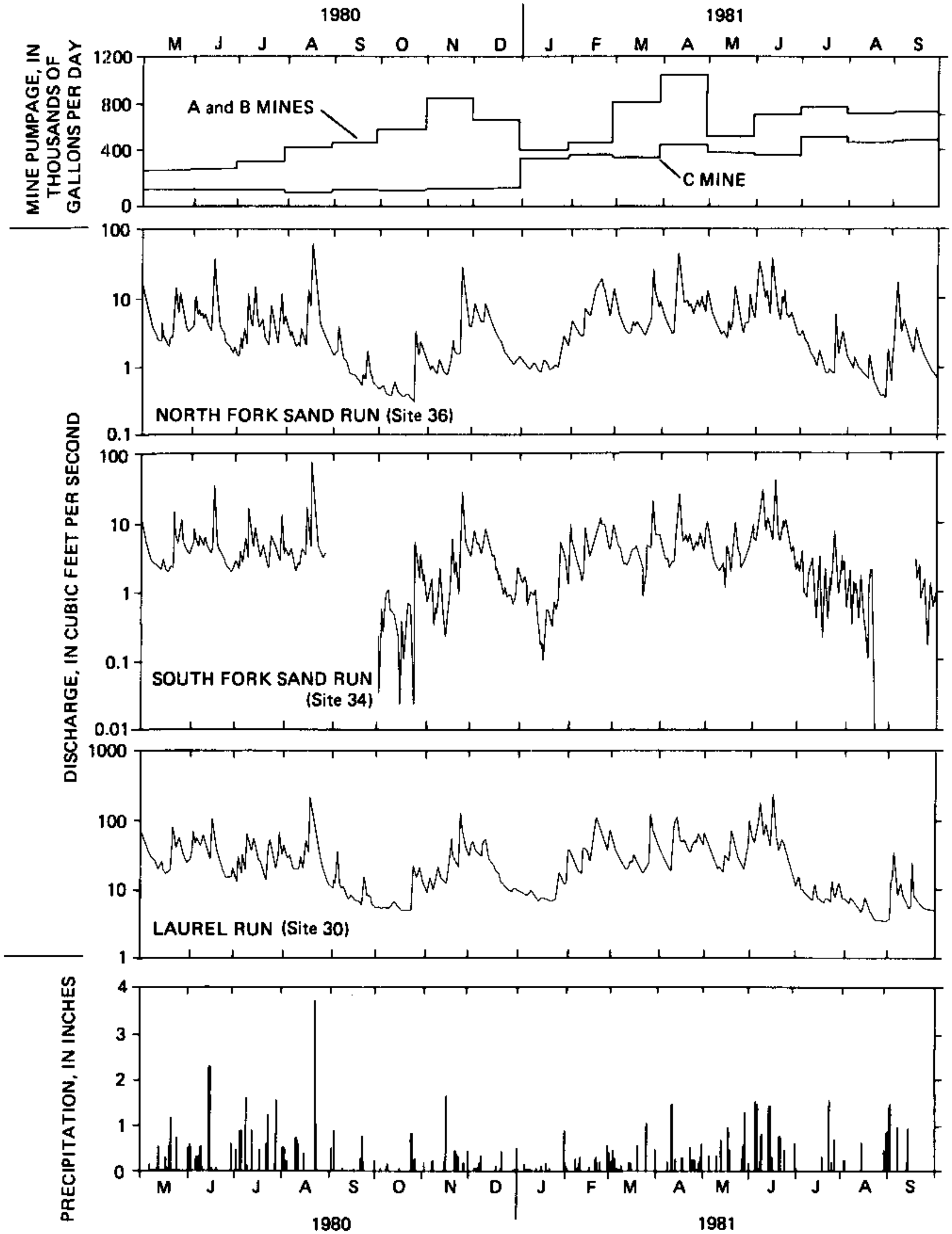


Figure 3.7-1— Mine pumpage, stream discharge, and precipitation for the period May 1, 1980, to September 30, 1981.
(From Duigon and Smigaj, 1985, fig. 14.)

3.0 HYDROLOGIC SETTING

3.8 SURFACE-WATER QUALITY

QUALITY OF STREAMFLOW IS AFFECTED BY PAST AND PRESENT MINING ACTIVITIES

Abandoned-mine drainage and effluent from mine-drainage treatment plants affect surface-water quality.

Field measurements were made and samples were collected periodically for a laboratory analysis at several stream sites (fig. 3.3-1). Ranges and median values for some of the physical and chemical characteristics are given in table 3.8-1. Temperature/specific conductance monitors provided hourly measurements at the three gaging stations. Specific conductance provides an approximation of the dissolved-solids concentration.

Figure 3.8-1 shows the variation of pH, specific conductance, and sulfate concentrations with discharge for three sites. The small pH (4.2) of the South Fork Sand Run was measured on a day that the acid mine-drainage treatment plant was not operating. The narrow ranges in pH of the South Fork Sand Run and Laurel Run may reflect the effects of the mine-drainage treatment plant and abandoned-mine drainage (site GA 3), respectively. These conditions also contribute to the large specific conductance of these two streams. The rate of change in specific conductance with discharge in the North Fork Sand Run is smaller than that of the other two streams, possibly because the mine-drainage contribution is relatively small. The sulfate-discharge relationships resemble the specific conductance-discharge relationships, for similar reasons.

Stream waters above points of abandoned mine discharges are less acidic than downstream and have small dissolved-solids concentrations. Some of them support fish.

Table 3.8-1. – Summary of chemical quality of selected surface-watersites
(From Duigon and Smigaj, 1985, table 7)
[mg/L, milligrams per liter; mg/L, micrograms per liter]

	pH (units)	Specific conductance (micromhos)	Alkalinity (mg/L as CO_3)	Acidity (mg/L as CO_3)	Solids sum of constituents dissolved (mg/L)	Turbidity (MTU)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Ca)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Iron, dissolved (mg/L as Fe)	Aluminum, dissolved (mg/L as Al)	Manganese, dissolved (mg/L as Mn)	Sulfate dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Oxygen, dissolved (mg/L) (mg/L)	Silica, dissolved (mg/L as SiO_2)	Nitrogen NO_2+NO_3 dissolved (mg/L as N)
Station	Laurel Run near Red Oak (Site 23)																	
Number of samples	6	6	0	5	6	1	6	6	6	6	6	0	6	6	6	3	6	6
Maxim an	3.1	915	–	159	397	6	41	17	5	2.6	12	–	1.6	290	2	23	25	1.1
Minimum	2.6	297	–	74	139	6	14	5.9	1.4	1.1	7.2	–	0.57	91	0.8	8.8	11	0.04
Median	3.1	200	–	104	285	6	29	11.5	3.1	1.9	10.5	–	1.2	200	1.8	10.3	19	0.22
Station	Chestnut Ridge Run near Red Oak (Site 26)																	
Number of samples	7	6	1	6	6	1	6	6	6	6	6	0	6	6	6	4	6	6
Maximum	6.9	540	8	10	364	8.1	73	15	7.3	3.6	0.22	–	1.4	250	3.5	12	6.9	1.3
Minimum	4.0	78	8	5	53	8.1	8.5	2.6	0.8	0.8	0.09	–	0.31	26	1.3	7.6	4.2	0.3
Median	5.7	163	8	5	101	8.1	18.5	4.5	2.2	1.3	0.16	–	0.48	56.5	2	10.6	4.9	0.6
Station	Dutch Run at Red Oak (Site 29)																	
Number of samples	6	5	0	4	4	0	5	5	5	5	5	0	5	5	5	5	5	5
Maximum	6.4	165	–	10	102	–	18	4.8	1.5	1.7	1.3		1.3	165	2.4	10.3	5.2	0.9
Minimum	4.5	98		5	67		9.4	2.9	0.7	0.8	0.26	–	0.89	98	1.4	5.4	4.5	0.1
Median	5.1	120	–	5	73	–	13	3.8	0.9	0.9	0.85	–	1.2	120	1.4	6	4.8	0.3
Station	Laurel Run at Dobbin Road near Wilson (Site 30)																	
Number of samples	21	20	9	18	16	11	18	18	18	18	19	5	20	20	17	16	18	14
Maximum	3.8	745	16	149	357	19	42	14	14	2.5	11	6.9	1.4	250	3.8	12.3	20	1.1
Minimum	2.4	143	0	10	69	0.4	9.8	3	0.8	0.8	1.6	1.7	0.47	42	0.9	4.9	5.3	0.16
Median	3	433	1	70	208.5	4.9	24	8.4	2.2	1.6	5	5.1	0.97	195	1.6	9.9	13	0.32
Station	North Branch Potomac River at Wilson (Site 31)																	
Number of samples	7	7	5	6	1	0	1	1	1	1	7	0	7	7	1	7	1	1
Maximum	4.8	2,000	2	41	110	–	28	3	1.1	.9	2	–	0.86	800	.9	12.5	4.1	.47
Minimum	3.5	189	0	5	110	–	28	3	1.1	.9	0.18	–	.24	68	0.9	7.7	4.1	.47
Median	4.4	588	0	23.1	110	–	28	3	1.1	.9	0.87	–	.50	240	.9	9.1	4.1	0.47
Station	South Fork Sand Run at Moon Ridge (Site 32)																	
Number of samples	5	4	0	2	4	0	4	4	4	4	4	0	4	4	4	3	4	4
Maximum	7	678	–	5	457	–	71	14	48	3	.18	–	1.7	300	2.2	9.7	7.4	.59
Minimum	6.3	183	–	0	111	–	21	4	3.1	1.1	0.06	–	0.12	56	1.1	8.4	3.7	.34
Median	6.8	261	–	2.5	158	–	28.5	4.9	17.1	1.7	.11	–	0.16	82.5	1.7	9.5	4.4	.47
Station	South Fork Sand Run near Wilson (Site 34)																	
Number of samples	17	6	8	12	15	10	15	15	15	15	17	5	17	17	5	13	15	11
Maximum	7.1	959	28	20	683	45	170	20	25	4.2	0.70	1.0	2.4	470	4.9	12.7	7.5	.92
Minimum	4.2	125	0	0	65	0.6	13	2.1	0.5	0.9	0	0	0.04	40	1.2	7.9	3.1	.20
Median	6.5	452.5	170	5	373	2	81	9.5	4.6	2.4	0.03	0.05	0.62	250	2.6	9.5	4.5	.39
Station	North Fork Sand Run at Moon Ridge (Site 35)																	
Number of samples	5	5	0	3	4	0	4	4	4	4	5	0	5	6	5	3	4	5
Maximum	6.8	122	–	25	72	–	9.4	3.1	.9	1.4	.16	–	1.3	280	2.6	11	5.6	.98
Minimum	3.4	46	–	15	39	–	6.4	1.9	.4	0.5	0	–	0.48	21	0.7	7	4.1	.11
Median	3.9	83	–	15	55	–	7	2.3	.5	0.8	.53	–	0.64	34.5	1	9.2	4.7	.31
Station	North Fork Sand Run near Wilson (Site 36)																	
Number of samples	18	7	3	4	15	10	5	5	5	5	17	5	7	7	5	12	15	13
5Maximum	6.9	547	31	60	332	8.6	68	15	1.4	2.1	12	.75	1.6	220	3.7	12.6	7.9	.97
Minimum	3.8	53	1	0	37	0.8	5.4	0.8	0.6	0.6	0.11	0.03	0.28	20	0.7	7.9	3.6	.2
Median	5.1	139	21	5	83	3.1	17	3.8	0.9	0.9	0.36	0.05	0.46	54	1.3	9.5	4.7	.45
Station	Sand Run at Wilson (Site 42)																	
Number of samples	7	7	3	4	7	0	7	7	7	7	7	0	7	7	7	6	7	6
Maximum	7.8	535	6	30	372	–	89	12	17	2.7	.49	–	.59	240	2.8	11.6	5.7	.58
Minimum	4.2	140	0	5	74	–	13	2.6	.6	0.8	0.01	–	0.32	45	1.2	7.3	3.7	.23
Median	6.3	345	1	10	213	–	46	7.3	4.5	1.7	.14	–	.46	130	1.5	9.3	4.6	.45

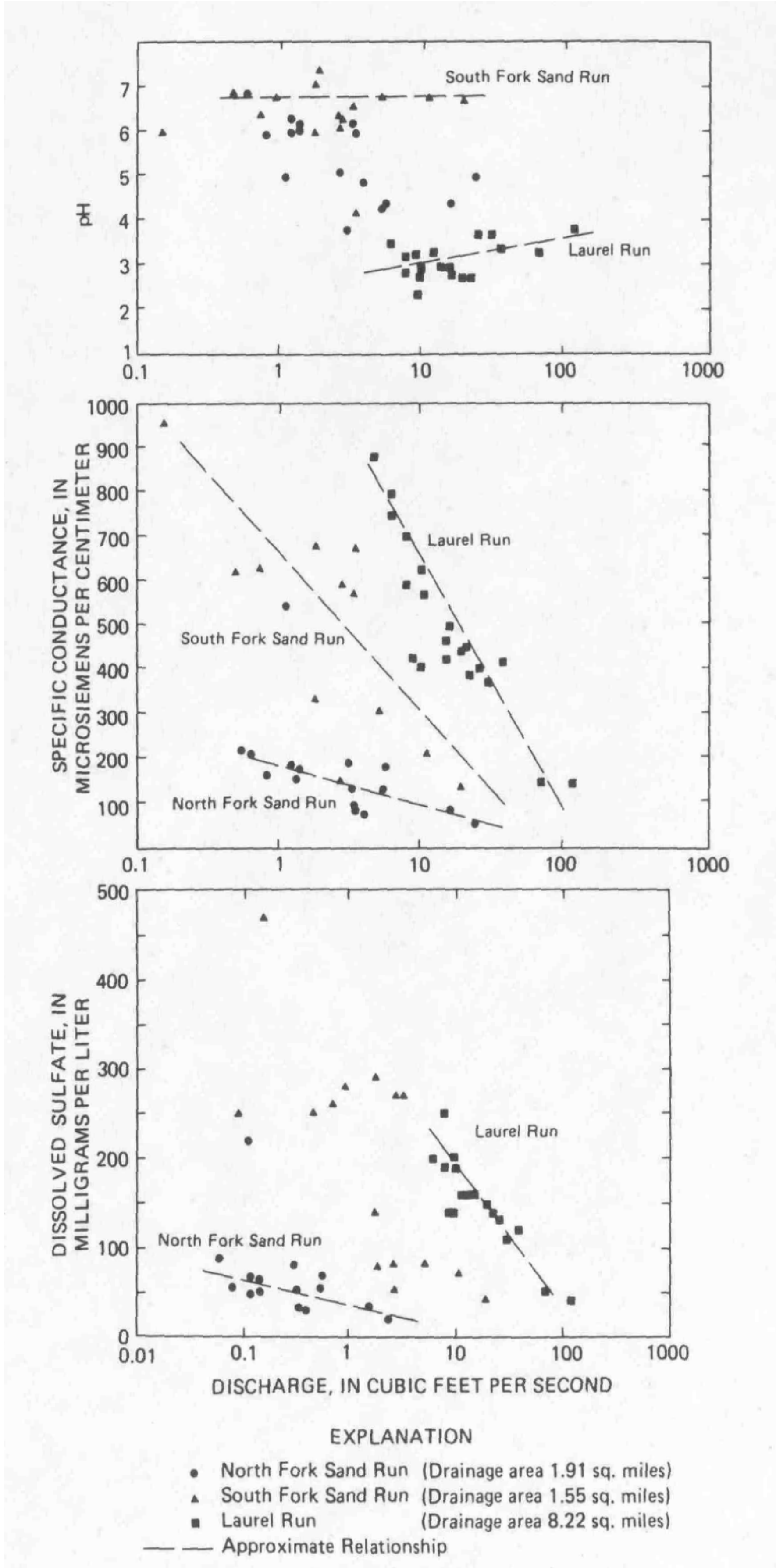


Figure 3.8-1.— Relationship of discharge to Ph, specific conductance, and sulfate.

4.0 HYDROLOGIC CONSEQUENCES DURING AND AFTER MINING

4.1 HYDROLOGIC BUDGET

BUDGET ANALYSES FOR BASINS REVEALED STORAGE LOSSES RESTRICTED TO AREAS IN THE VICINITY OF MINE WORKINGS

The change in storage for the three-basin area is related to the mine dewatering after a hydrologic budget analysis.

Large quantities of water must be pumped to allow underground-mining operations. The hydrologic properties of the overlying rocks are such that, although ground-water levels may be lowered significantly by the pumping, the entire overlying mass is not dewatered. In dewatered areas, flow may divert toward the mine. Aquifers may be recharged by leakage of water through streambeds where the water levels have dropped. Some springs and shallow wells may become dry as a result of lowered water tables.

As an example of how mining can affect water levels, a side heading in a northerly direction in the A mine extending from the main heading was begun in January 1981 (fig. 4.1-1), to provide drainage sumps for the mine. At the end of March 1981, water levels in all four wells at site 1 declined substantially (fig. 4.1-1). By July 1, when the side heading had approached to within about 300 feet of site 1, progress had been suspended. The water levels ceased to decline steeply by the end of July, and the water levels in two wells even rose.

The water level of the well completed in the zone above the Upper Freeport coal (FA 32) was most affected. The well completed in the zone below the coal (FA 31) was much less affected, owing to the effectiveness of the underclay as a confining bed. Excluding this zone, the declines appear to be inversely proportional to the logarithm of the distance of the zone above the coal (fig. 4.1-2).

Mining impacts on streams include changes in flow rates by discharge into or withdrawal from surface waters, and alterations of water chemistry. The South Fork Sand Run receives treated mine pumpage from the A and B mines. Pumpage from the C mine is discharged into Chestnut Ridge Run, a tributary of Laurel Run. Interbasin transfers may have decreased the flow of Laurel Run and increased the flow of the South Fork.

The withdrawal of water from South Fork Sand Run for use in the coal-treatment facility causes periods of very low flow. The withdrawals from, and discharges into, the South Fork greatly affect its streamflow. Discharge of treated water into Laurel Run represents a small fraction of that stream's flow, and withdrawals from it are not significant, so its pattern of flow is less affected by current mining. North Fork Sand Run has no significant additions or withdrawals, so its flow regimen may be representative of nonmining conditions.

Flooding of underground mine workings is prevented by pumping the water out of the mine, which lowers ground-water levels; this lowering, in turn, results in leakage of water through streambeds where the streams cross at or near undermined areas and, consequently, lowers stream flows. The streams are not likely to become completely dry, however, because the abundant precipitation maintains saturated zones, perched near land surface, that maintain streamflow. Average annual flows, however, may be expected to decline as longer stream reaches are undermined and leakage through streambeds increases.

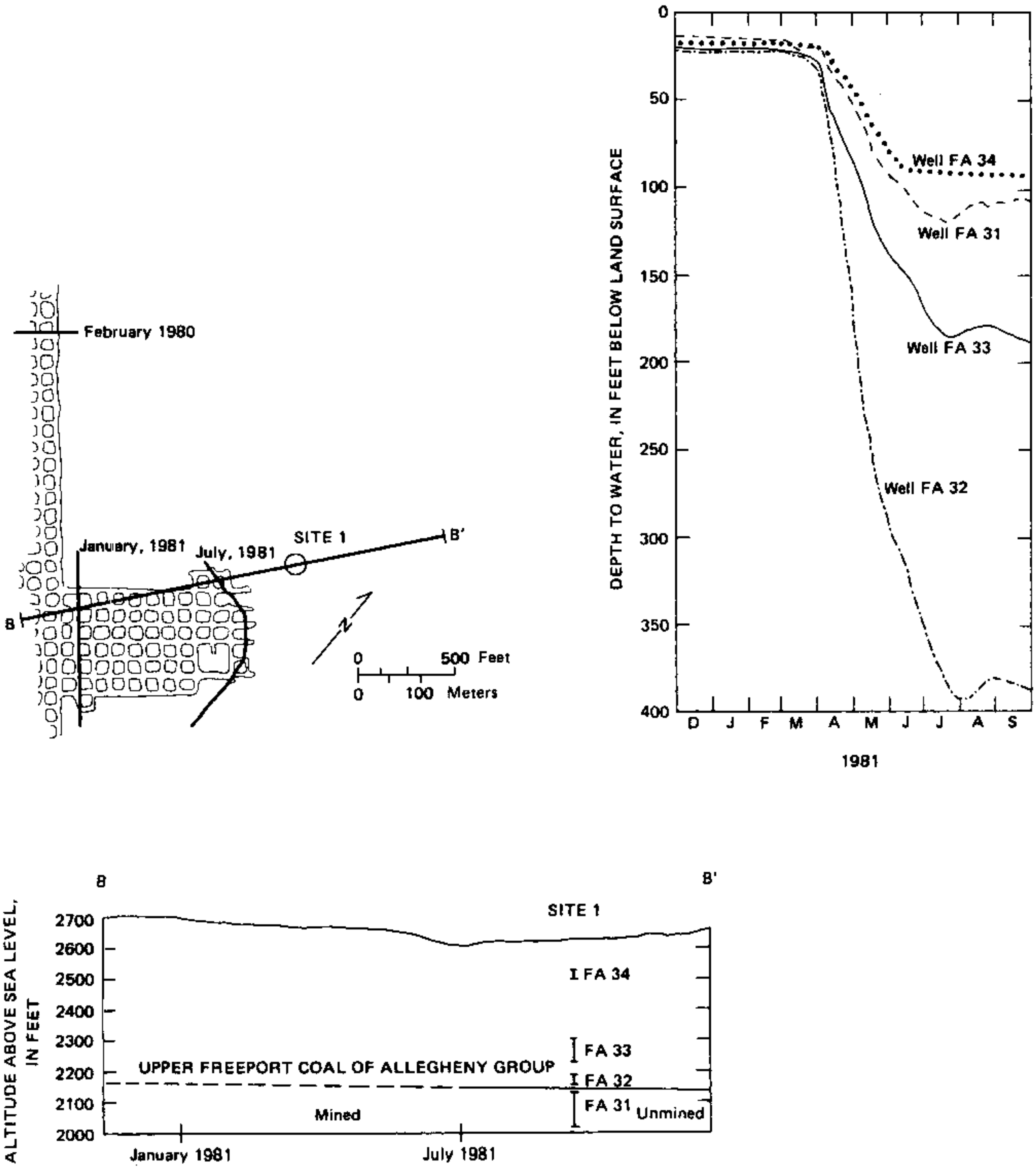


Figure 4.1-1.— Mine-map and cross section for site 1 with mining progress and associated water-level declines, as a consequence of mine dewatering. (Modified from Duigon and Smigaj, 1985, fig. 25.)

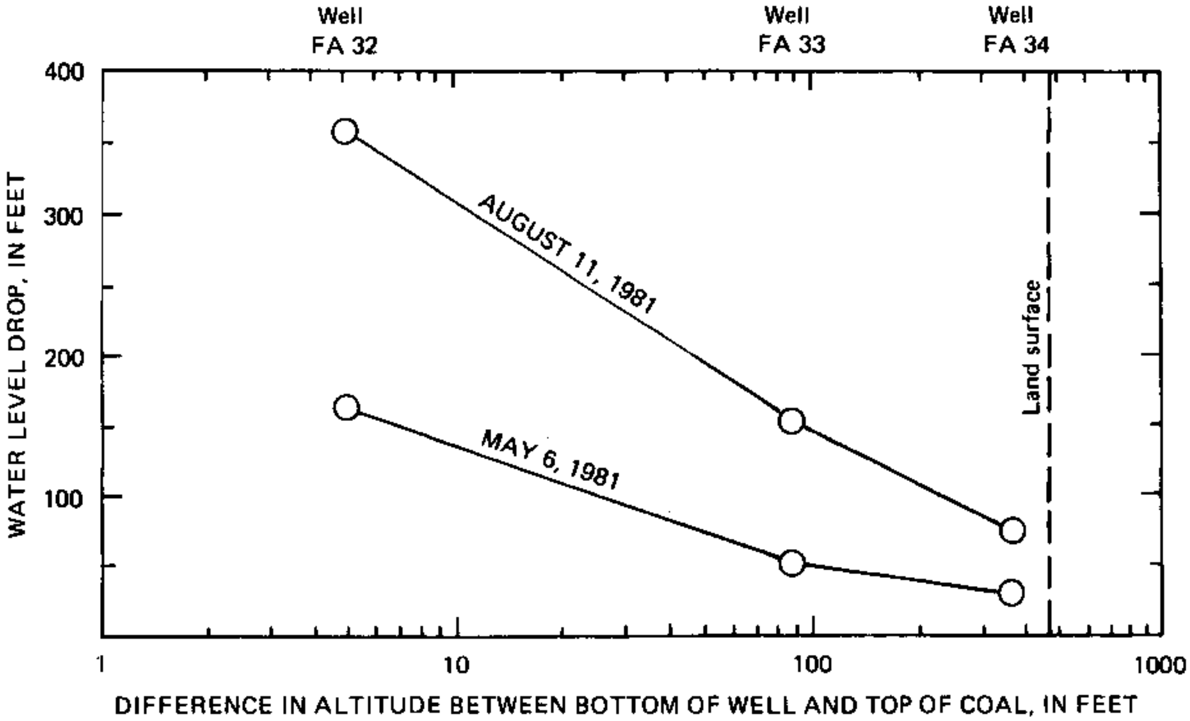


Figure 4.1-2. — Relationship between the water-level decline at site 1 and the difference in altitude between the well bottom and the Upper Freeport coal of the Allegheny Group.
(From Duigon and Smigaj, 1985, fig. 26.)

The general equation of the water balance, in simple terms, is:

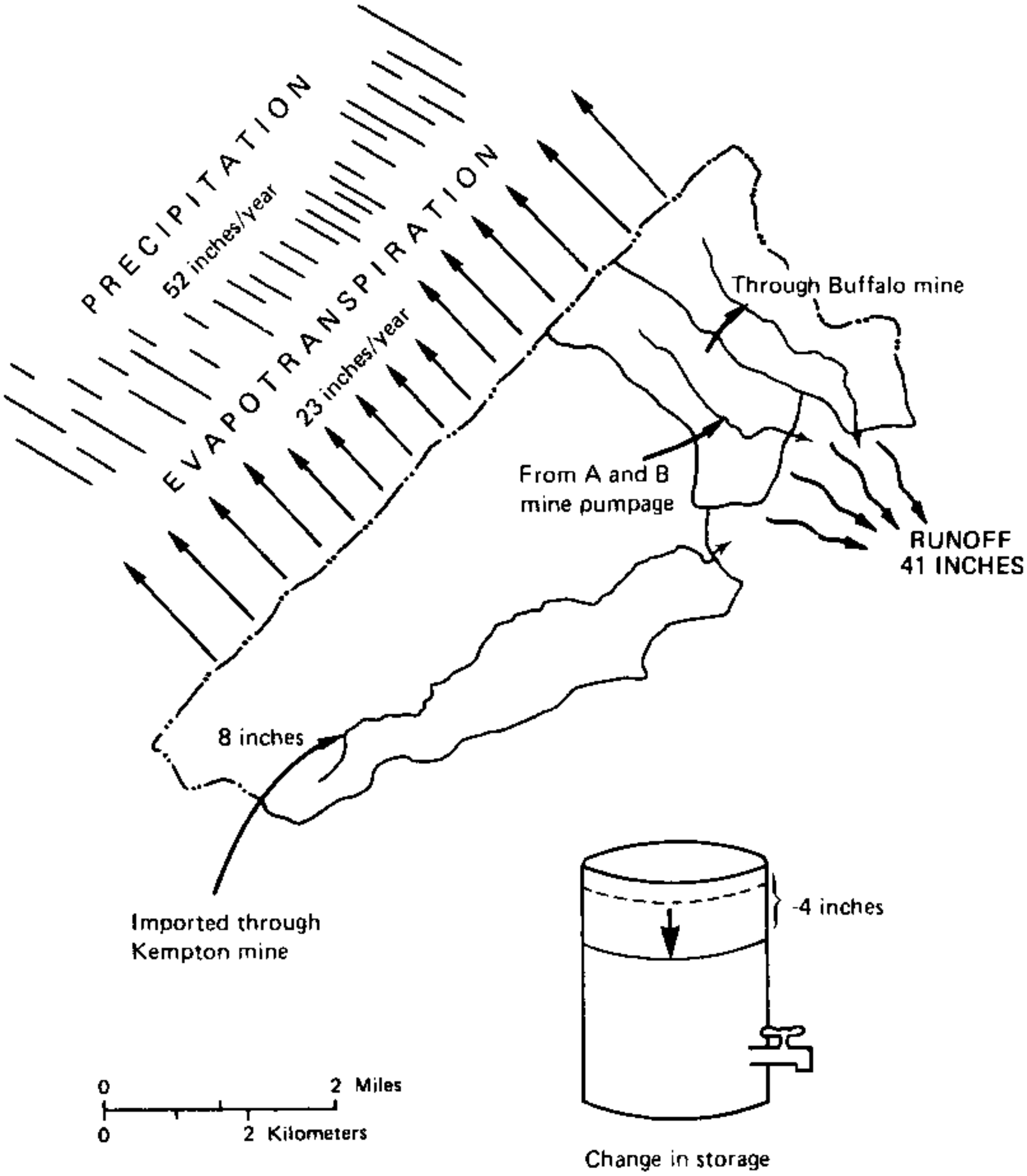
$$\text{INPUT} = \text{OUTPUT}, \quad \text{or} \quad P + I = R + ET + E + \Delta S$$

where P = precipitation,
I = water imported into the basin,
R = total runoff (discharge past the gage),
ET = evapotranspiration,
E = water exported outside the basin, and
ΔS = change in basin storage.

For the three basins, an estimation of the hydrologic budget is (all units in inches):

52 in. + 8 in. = 41 in. + 23 in. + 0 in. - 4 in.

Precipitation and total runoff were measured for water year 1981. Water imported by way of the abandoned Kempton Mine was measured at site GA 3 and was estimated for site GA 6. Other interbasin transfers were not quantified. Evapotranspiration was estimated by the method described in (21). Change in basin storage can be calculated as the residual term in the equation. Because the change was due to mine dewatering, it can also be estimated from the mine-pumpage data, and, in fact, the results are in agreement. For the area as a whole, the import term is important because of the contribution coming from the Kempton Mine. At present (1982), no water is exported from the area. If the individual basins are considered separately, then both imports and exports need to be evaluated because of the amount of interbasin transfers of mine pumpage and the extent of underground mines.

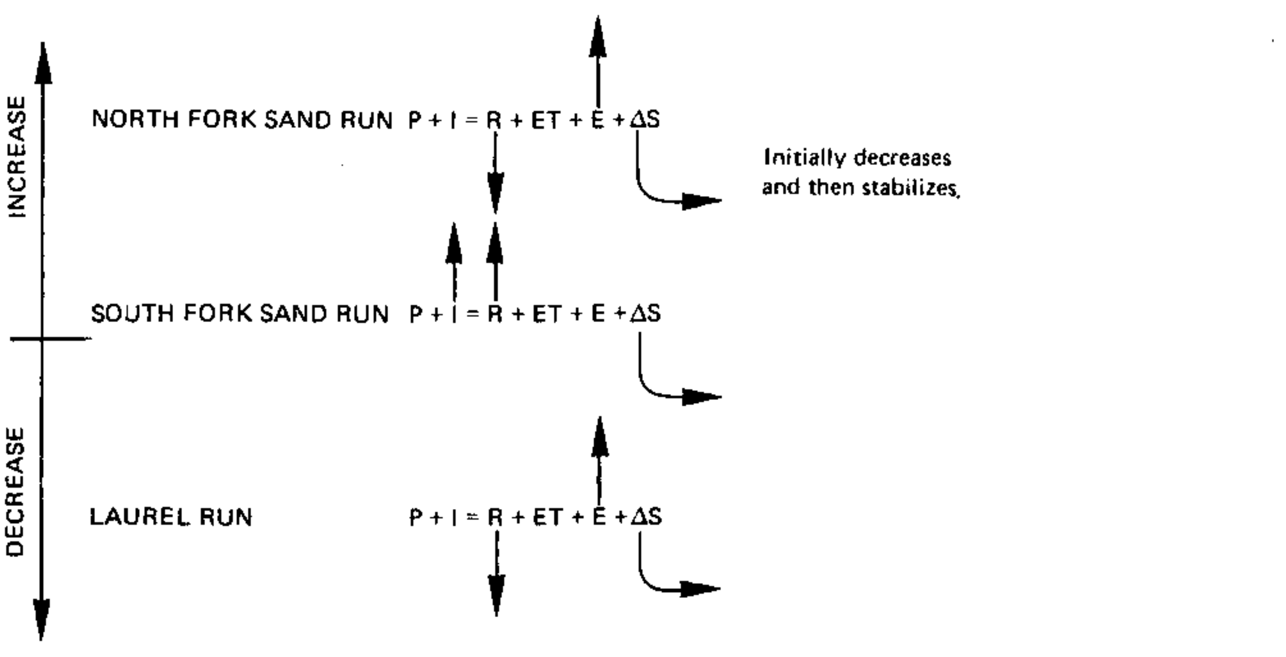


$P + I = R + ET + E\,\underline{1}/ + \Delta S$; $\underline{1}/\ E = 0$; no water is exported from the basin.

Figure 4.1-3.— Approximate hydrologic budget for water year 1981. (October 1980-September 1981). Dashed arrows indicate inter-basin transfers through abandoned mines or active mining operations. (From Duigon and Smigaj, 1985, fig. 33.)

Figure 4.1-3 shows the relationships of the terms of the budget. Precipitation and evapotranspiration are assumed to be uniform throughout the area. For the three-basin area, about 4 inches has been lost from storage for the 1-year period. This loss represents water pumped out of active mines. Water-level declines did not spread very far from the undermined area; storage losses were concentrated near mine workings. Ground-water storage will decline as dewatering continues. Figure 4.1-4 indicates the type of changes that might occur in the hydrologic budget.

The most immediately noticeable impact on water quality is the discharge of treated mine pumpage and wastewaters. The wastewater consists primarily of conventionally treated sewage—about 4,000 to 5,000 gal/d from each mine. In addition, dewatering of each mine produces about 670,000 gal/d. One facility treats water from the A and B mines and discharges into the South Fork Sand Run. Another facility treats water from the C mine, and discharges into Chestnut Ridge Run. Mine waters are neutralized by reaction with lime, a process which decreases the acidity but increases the dissolved-solids content. This has had a greater impact on South Fork Sand Run than on Laurel Run, because South Fork Sand Run receives more treated mine drainage, which constitutes a greater fraction of the stream's total flow.



where P = Precipitation

I = Water imported into the basin

R = Total runoff (discharge past the gage)

ET = Evapotransporation

E = Water exported outside the basin

ΔS = Change in basin storage

Figure 4.1-4.— Relationship of hydrologic budgets during mining to hydrologic conditions before current mining began.

4.2 SUBSIDENCE, FRACTURES, AND ACID MINE DRAINAGE

POST-MINING SUBSIDENCE FRACTURES AFFECT GROUND WATER AND SURFACE WATER

Post-mining subsidence fractures may cause increased base flows and some acid input to streams. Collapse into mine voids will allow greater rates of vertical movement of ground water.

After cessation of mine dewatering, water levels will rise, and recharge from streams may diminish, although infiltration may generally be increased throughout the area. Fracturing, caused by mining and post-mining subsidence, will change the hydrologic properties of the rocks, resulting in new equilibria which may be characterized by a hydraulic-head distribution different from the pre-mining distribution. As a possible consequence, water levels may not recover fully under hilltops, and gradients will flatten.

Fractures created by subsidence into mine voids may cause hydraulic conductivity to increase. The rocks in the area may have very small initial permeability, and increases in secondary permeability, due to subsidence, will probably be significant. Because sections of the rock mass will become hydraulically linked, transmissivity over the area will increase. The rock mass will be able to store greater quantities of water as a result of the increase in fracture volume.

Flow paths may be altered as a result of fracturing. As flow-impeding layers are breached, perched zones may leak downward more readily. This condition may diminish lateral flow components, at least locally, and affect the flow of springs emanating from outcrops of perched zones. The mined coal seam will be a very permeable zone, despite collapse of overburden, and its configuration will exert a significant control on flow directions; this condition may increase the movement of ground water between surface-water basins. Because flow velocities may increase as a result of increased secondary permeability, ground water may move more rapidly to discharge zones along streams. The flow systems above the coal seam will be affected the most. The deeper flow system will be much less affected, owing to less fracturing and the sealing effect of the underclay.

Alteration of ground-water flow paths can effect changes in water quality, owing to the mixing of waters with different chemistries, exposure of zones of different mineralogies to increased solution, and changes resulting from the water's contact with atmospheric oxygen and carbon dioxide. One consequence of coal mining has been the discharge of acid waters from mines no longer in operation. Two such mines in the study area have been described in previous sections. These confirm that acid mine drainage is a potential problem in this environment. Much emphasis in the literature has been given to minimizing contact of water seeping into mines with air because of the acid-producing oxidation of pyrite and other sulfide minerals. However, pyrite can oxidize in mine waters essentially devoid of oxygen (1,2). The sealing of mine entrances and dewatering wells upon completion of mining will decrease the input of oxygenated water to the mine voids and the number of concentrated discharge points. Subsidence fractures, if sufficiently developed, could allow upward movement of mineralized water from the mined seam. Barrier pillars between the mines may retard the flow along the direction of synclinal plunge. The water filling the mine voids will become mineralized and acidic, and some of it will emerge at the surface.

Figure 4.2-1 indicates the types of consequences on streamflow that may be expected after the cessation of mining. The post-mining hydrologic budget of the three basins will show some differences from pre-mining conditions, primarily in response to the creation of numerous fractures. Near-surface fractures will allow greater amounts of ground-water recharge.

Base flows may increase (8) and the magnitudes of high flows may decrease because of increased infiltration. Total runoff may increase or decrease, depending on the amounts of water transferred into or out of the individual basin by way of the mined coal seam. Figure 4.2-2 summarizes the expected alterations in the hydrologic budget of the three sub-basins after mining ceases.

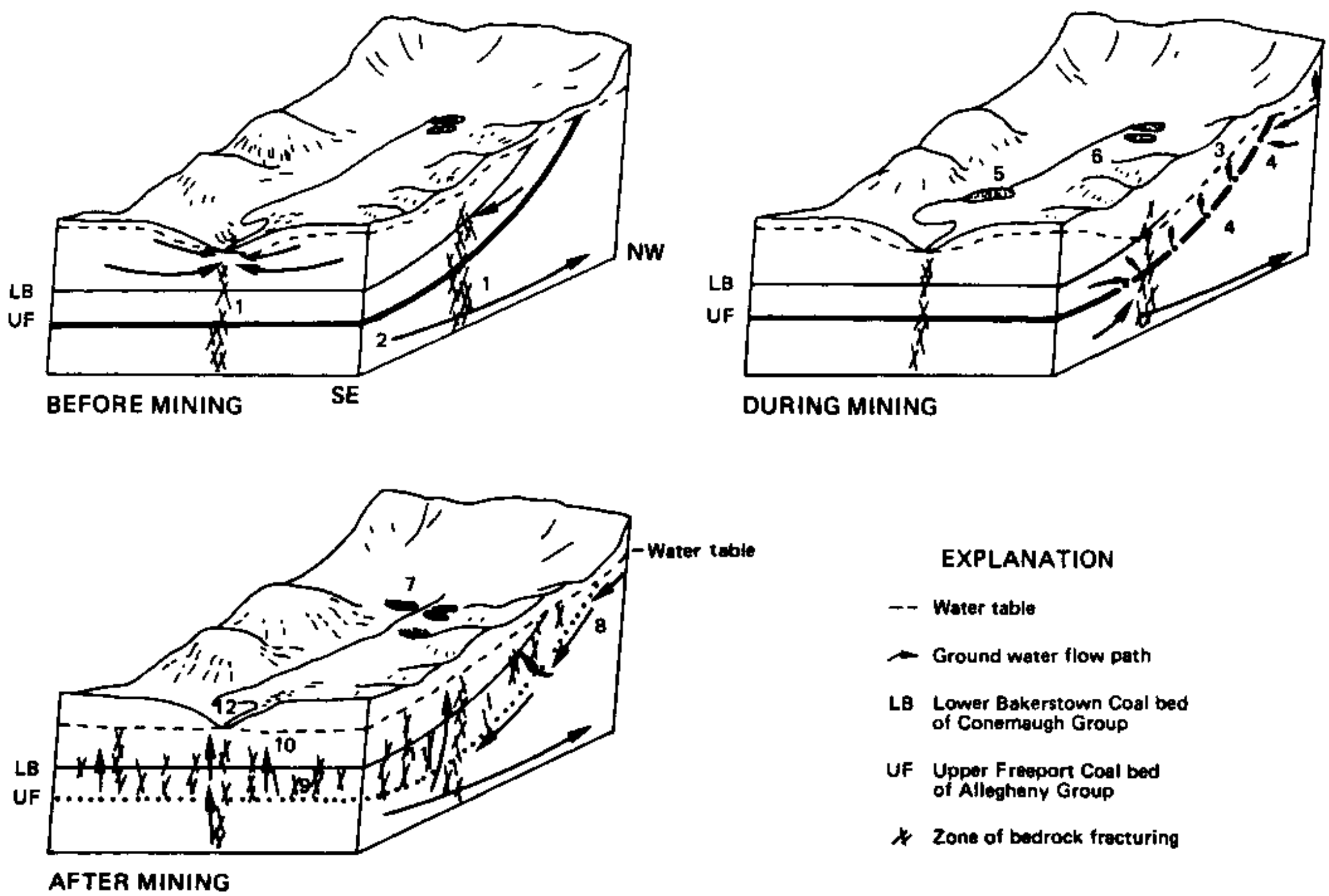
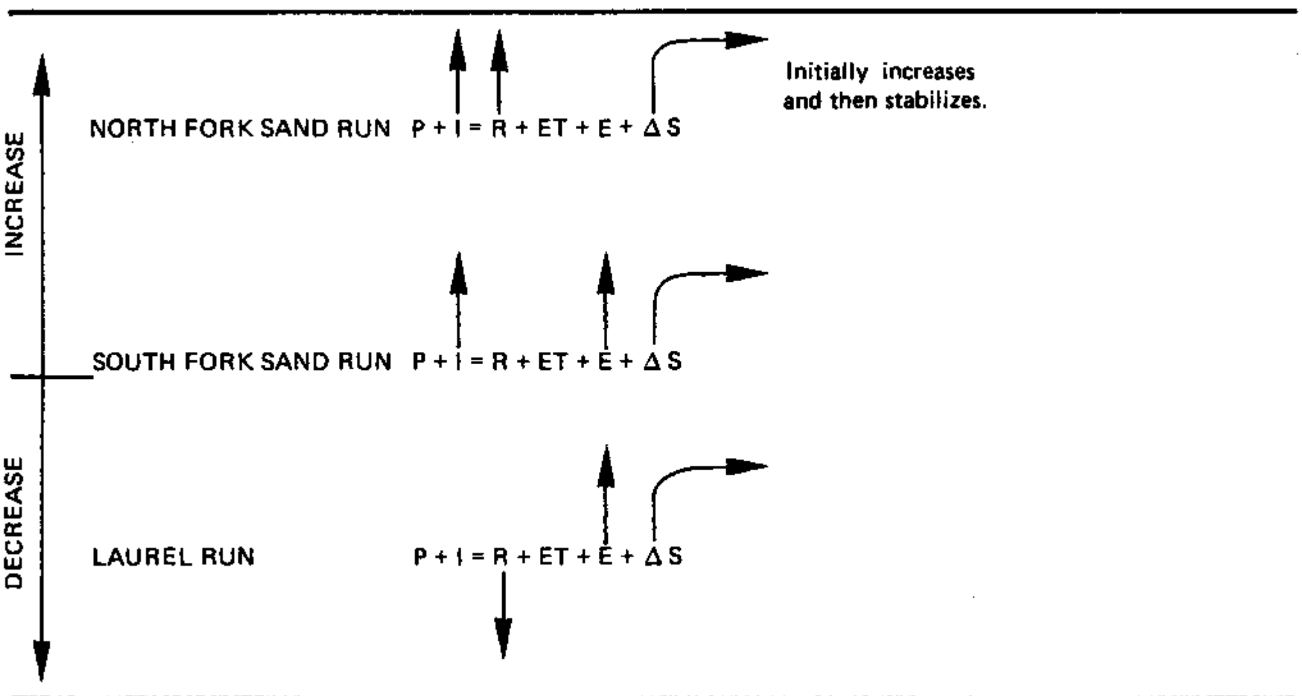


Figure 4.2-1.— Possible consequences of underground mining on the hydrologic system. The block corresponds approximately to the basin of the South Fork of Sand Run. (From Duigon and Smigaj, 1985, fig. 34.)



where P	=	Precipitation
I	=	Water imported into the basin
R	=	Total runoff (discharge past the gage)
ET	=	Evapotransporation
E	=	Water exported outside the basin
ΔS	=	Change in basin storage

Figure 4.2-2.— Postulated relationship of post-mining hydrologic budgets to hydrologic conditions before current mining began.

5.0 POST-MINING HYDROLOGIC MONITORING

POST-MINING HYDROLOGIC MONITORING DETERMINES LONG-TERM HYDROLOGIC IMPACTS

Most of existing hydrologic monitoring plan can be included in the post-mining plan, although fewer recording instruments need to be maintained.

Post-mining hydrologic monitoring will be needed to determine lasting impacts. Most of the existing data-collection network can be utilized. The streamflow-gaging stations would continue to record stream stage, temperature, and specific conductance. Flows at the non-instrumented stations may also be measured, and the relationship compared to earlier relationships.

Although wells deeper than the Upper Freeport coal will be destroyed as mining passes through them, measurement can be made in the others. The integrity of the wells will need to be checked after the area is mined out to determine if casing or grout seals become damaged by subsidence.

At this time, field measurements of temperature, pH, specific conductance, dissolved oxygen, alkalinity, and acidity can be made periodically at the same sites previously measured, including wells. It would also be desirable to collect samples at the three gaging stations and the wells for laboratory analyses of major ions, aluminum, iron, manganese, and residue on evaporation; selected samples would also be analyzed for dissolved trace metals.

The frequency of measurements and sample collection and the duration of post-mining monitoring can be determined as the post-mining data are analyzed. An evaluation of climatic conditions is needed to determine whether stream flows and water levels are representative of average conditions.

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GROUND-WATER STUDY 3

by

G. C. Mayer and A. C. Razem

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1.0 ABSTRACT

Geology and the Occurrence of Coal

The coal-producing sedimentary rocks of the mine permit area are of Pennsylvanian and Permian age. These relatively horizontal strata consist of interbedded sandstone, siltstone, shale, limestone, and thin beds of coal. The area is part of the unglaciated Allegheny Plateau physiographic province.

Hydrology of the Study Watersheds

Ground water in the study watershed is found in two local perched aquifers and a deeper regional aquifer. The aquifers typically yield less than 1 gallon per minute to wells. The storage and flow of ground water are controlled by primary and secondary porosity and permeability. Most of the area is forest and agricultural land; withdrawal demands on the aquifer systems are not significant.

Aquifer testing has usually been limited to 2 hours, even for pumping rates as small as 2 gallons per minute. Computer simulation has been used to improve the understanding of the ground-water flow system. Pre-mining hydro-geological interpretation was based on core holes, gaged springs, and observation wells.

Ground-water quality varies widely within and between aquifers throughout the area. Dissolved-solids concentrations of natural ground water in parts of the middle and deep aquifers exceed the limit for drinking water established by the U.S. Environmental Protection Agency.

Base flow of the streams is largely from the middle-aquifer system. Other discharge from the middle aquifer is leakage downward through the underclay into the deeper regional-flow system.

Hydrologic Consequences of Surface Mining and Hydrologic Monitoring Network

Ground-water levels in the perched aquifers were affected by surface mining. Water levels declined as much as 20 feet within 5 months. Water levels beneath the mined coal seams did not change significantly during and after mining.

Ground water and stream water during base flow are expected to have larger concentrations of dissolved solids and sulfate after mining than before mining. The ground-water quality in the top aquifer is expected to change from a calcium bicarbonate type to a calcium sulfate type.

The post-mining hydrologic monitoring network includes wells completed in the spoils and in the underlying deep aquifers. Periodic water samples will be analyzed from wells and from a stream site.

The watersheds described in this report range in size from 29 to 52 acres. Site 1 was not mined and served as a control watershed. Sites 2 and 4 were mined and reclaimed from November 1976 to August 1978 and January 1977 to August 1978, respectively. Site 3 was mined during the summer of 1980 and was reclaimed by spring 1982.

2.0 GENERAL FEATURES

THE MINE PERMIT AREA IS CHARACTERISTIC OF THE UNGLACIATED ALLEGHENY PLATEAU

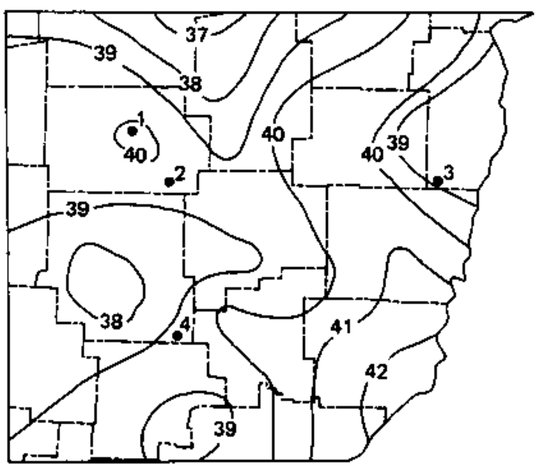
The area has a continental climate and low relief.

The mine permit area for this ground-water study consists of four separate watersheds which are called sites. These sites have a continental climate and a mean annual precipitation ranging from 37 inches in the northern part to 42 inches in the southeastern part (fig. 2.0-1). Spring is the wettest season and April, the wettest month; autumn is the driest season and October, the driest month (7).

Nearly all the area is within the unglaciated Allegheny Plateau (fig. 2.0-2), which rises very slightly to the east. The area is characterized by flat, narrow valley floors, rounded ridgetops, and hilly to steep ridge slopes. Local relief ranges from 100 to several hundred feet (2).

Soils in most of the area developed from shale and sandstone (fig. 2.0-3). Generally, these soils are moderately deep, have little natural fertility, have relatively small proportions of organic matter, and are acidic. Other soils in the area are formed on glacial drift and vary in natural fertility and proportion of organic matter (6).

The extent of mining in the area is shown in figure 2.0-4. Most of the mined areas were forested or used for agriculture before mining.



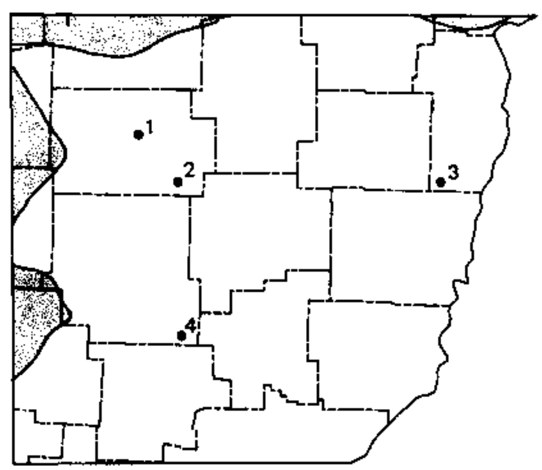


Figure 2.0-1. Precipitation

Figure 2.0-2. Physiography

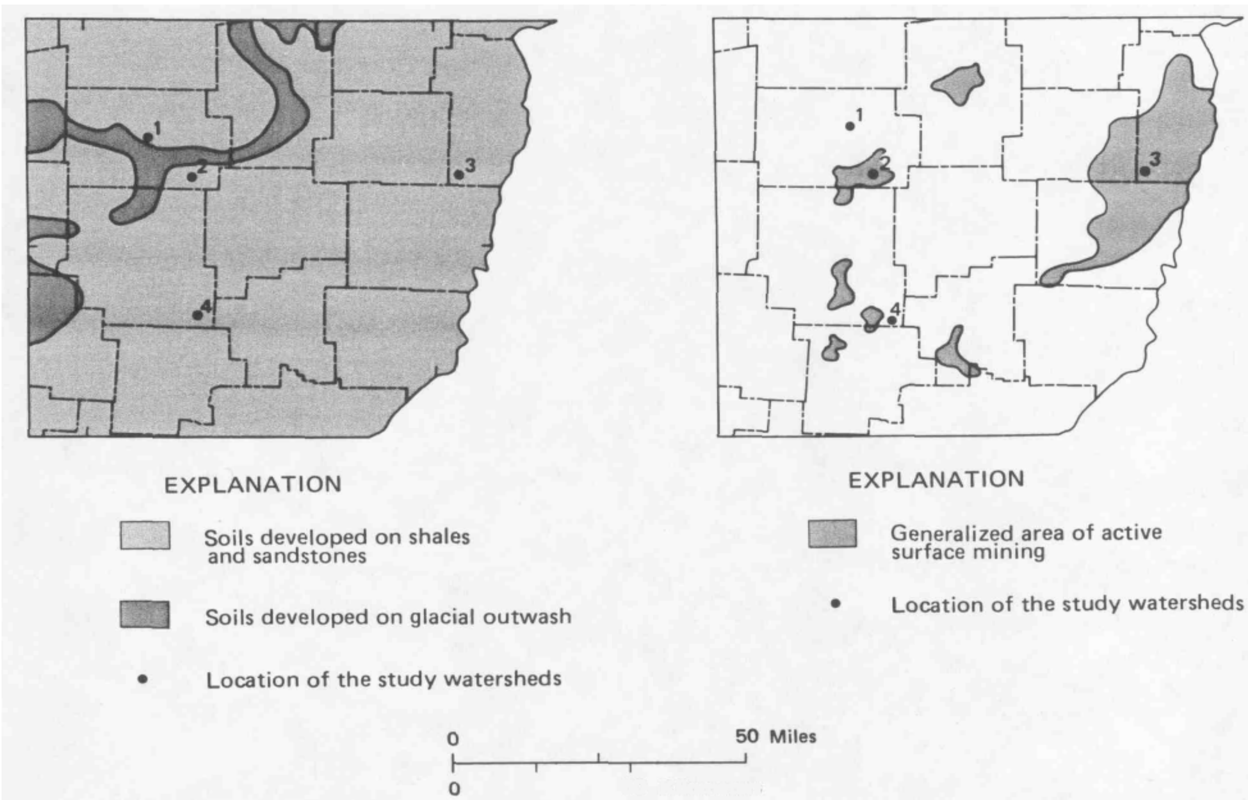


Figure 2.0-3.— Soils

Figure 2.0-4.— Areas of active mining

3.0 GEOLOGIC SETTING

ROCKS OF THREE GEOLOGIC SYSTEMS ARE EXPOSED

The strata exposed represent the Mississippian, Pennsylvanian, and Permian Systems.

The Mississippian System is represented by the Cuyahoga and Logan Formations, which crop out in the northwestern part of the area. These formations consist of massive sandstone, siltstone, and shale; they do not contain coal.

The Permian System is represented by the upper part of the Dunkard Group, which crops out in the southeastern part of the area. This group consists of sandstone, shale, and thin seams of coal.

Most of the area, including the four watersheds, is underlain by rocks of Pennsylvanian age (fig. 3.0-1), including the Pottsville, Allegheny, Conemaugh, and Monongahela Formations and the lower part of the Dunkard Group. These rocks, which unconformably overlie the Mississippian System, consist of sandstone, shale, bituminous coal, and limestone, which crop out in northeast-to-southwest trending belts. The rocks dip gently to the southeast at about 30 ft/mi (5).

The coal mined at site 2 was the Middle Kittanning No. 6, which is in the Allegheny Formation. At site 3, the coal mined was the Waynesburg No. 11; and at site 4, the Meigs Creek No. 9. These latter two coals are in the Monongahela Formation (fig. 3.0-1).

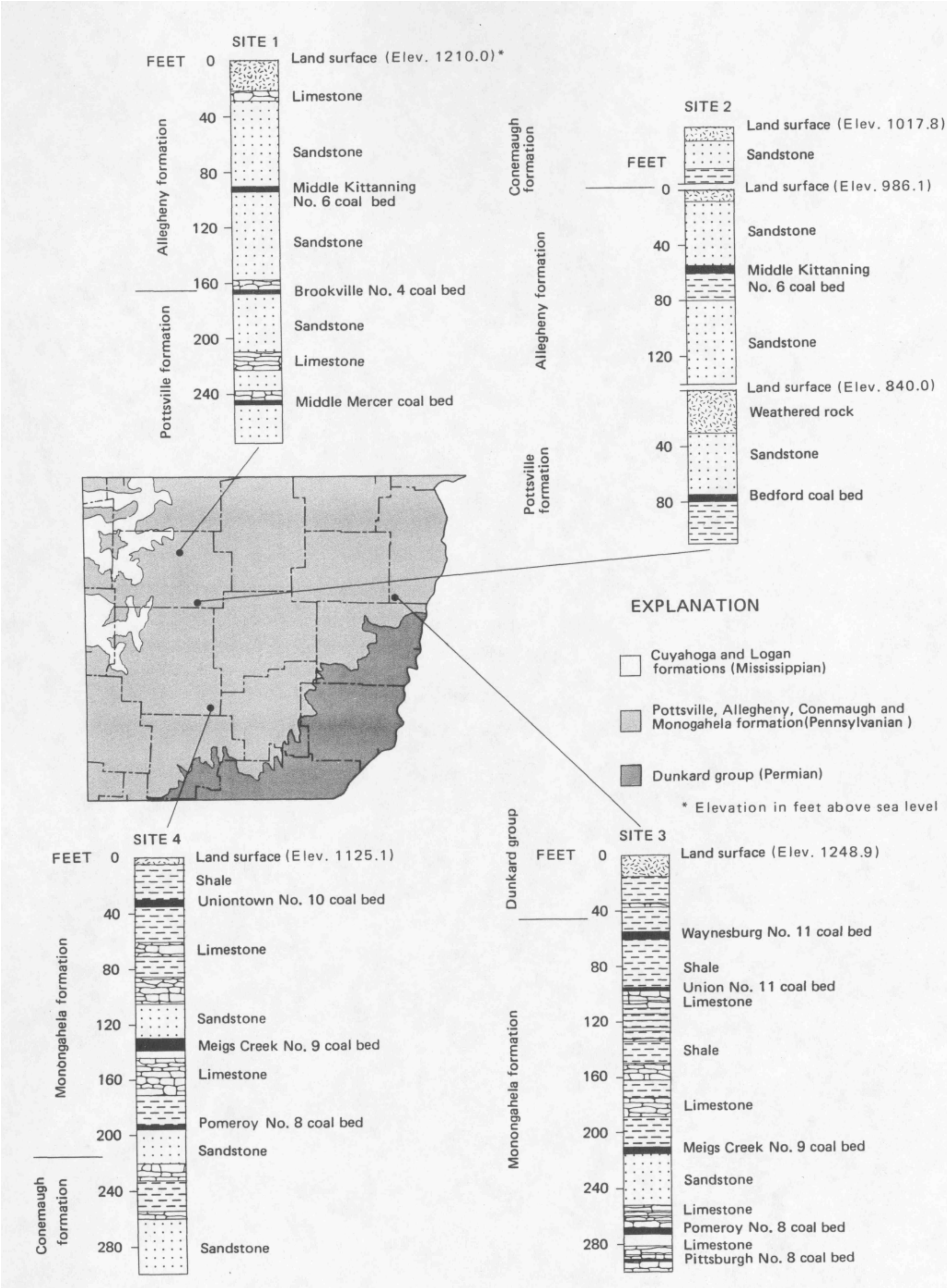


Figure 3.0-1.— Stratigraphic sections of the four watersheds.

4.0 GROUND-WATER HYDROLOGY

4.1 OCCURRENCE, MOVEMENT, AND HYDRAULIC PROPERTIES

GROUND-WATER SYSTEMS OF THE STUDY WATERSHEDS WERE SIMILAR BEFORE MINING

Each of the four watersheds studied had two local perched aquifers and a deeper regional aquifer.

Ground water is stored and transmitted within intergranular pore space, or fractures and bedding-plane openings. Observation wells (table 4.1-1) were completed in each aquifer in each watershed. Water levels in the wells indicate that two perched zones occur within the upper 250 feet in each watershed. Figures 4.1-1 and 4.1-2 show the ground-water movement in these two zones. Relatively impermeable clay or shale beds underlying the coal seams were sufficiently continuous to form bases for these perched aquifers. A cross section of these zones is shown in figure 4.1-3. The major saturated zones are referred to as "aquifers" for convenience, even though they typically yield less than 1 gal/min to wells.

Precipitation was the source of recharge to the top aquifer as indicated by the close correlation between rainfall and changes in water levels (fig. 4.1-4). However, water was lost to spring and seep discharge and evapotranspiration along the edge of the aquifer (outcrop of the top coal), and to subsurface discharge as leakage through the underclay that formed the base of the aquifer. In some places, water moved as underflow across watershed boundaries (fig. 4.1-2).

The middle aquifer was recharged by leakage through the overlying clay bed and by precipitation where the clay bed was absent. Springs discharging from the top aquifer probably provided a small amount of recharge in some places. The slope of the potentiometric surface in the middle aquifer (fig. 4.1-2) indicates that water was discharged as stream base flow. Additional water was discharged as evapotranspiration near the stream, as leakage downward through the underclay, and as underflow across watershed boundaries.

At site 4, the top aquifer was above the clay underlying the Meigs Creek No. 9 coal bed (fig. 4.1-3). The middle aquifer was above the clay underlying the Pittsburgh No. 8 coal bed. Water in the top aquifer (fig. 4.1-1) flowed toward the outcrop. Water in the middle aquifer (fig. 4.1-2) generally flowed toward the stream, but some flowed across the northern boundary of the watershed.

Hydraulic properties of the rocks before mining were estimated by field tests and by computer modeling. Transmissivities were estimated from data obtained from single-well aquifer tests by a method described in (1). Average hydraulic conductivities were obtained by dividing the computed transmissivities by the appropriate saturated thickness. The very small yields of the aquifers usually limited the tests to 2 hours, even for pumping rates as small as 0.5 gal/min. Two-dimensional computer simulation of selected aquifer tests produced results in agreement with the analytical results (11).

Table 4.1-1.– Hydraulic data pertaining to observation wells (From U.S. Bureau of Mines, 1978b.)

Study site	Well [1]/ number	Land-surface altitude in feet above sea level	Total depth, in feet	Casing [2]/ depth, in feet	Approximate depth to water, in feet (July1976 except as indicated)
Site 1	W 1-1	1,207.84	90	19	84
	W 2-2	1,207.29	169	99	157
	W 3-1	1,206.26	75	18	67
	W 4-2	1,206.07	170	* 170 (slotted)	93 (Nov 1976)
	W 5-1	1,136.82	10	9	Dry
	W 6-2	1,136.32	98	19	27
	W 7-1	1,138.28	12	10	5
	W 8-2	1,138.64	101	19	30
	W 9-3	1,138.35	183	* 183 (slotted)	111 (Nov 1976)
	W10-3	1,011.87	66	17	11
	W11-2	1,092.35	56	18	16
	[3]/ W157	1,115.45	14	—	9
Site 2	W 1-1	1,051.46	132	22	84
	W 2-2	1,051.59	245	140	186
	W 3-1	945.54	29	20	20
	W 4-2	914.28	100	100 (slotted)	50 (Oct 1976)
	W 5-1	1,019.18	109	24	100
	W 6-1	952.70	41	21	36
	W 7-2	952.42	140	50	93
	W 8-3	953.69	200	147	193
	W 9-2	877.82	60	19	25
	W10-3	820.47	62	19	12
Site 3	W 1-1	1,259.50	62	18	54
	W 2-2	1,259.41	211	65	85
	W 3-1	1,235.20	38	19	35
	W 4-1	1,251.37	60	19	53
	W 5-3	1,251.74	280	218	Dry
	W 6-1	1,238.36	46	18	39
	W 7-2	1,237.25	192	54	65
	W 8-2	1,156.67	105	20	36
	W 9-3	1,154.60	198	120	Dry
Site 4	W 1-1	1,097.83	90	19	62
	W 2-2	1,097.97	181	95	91
	W 3-1	1,039.93	31	12	15
	W 4-3	1,020.57	260	102	234
	W 5-2	973.03	49	17	21
	W 6-1	1,123.07	130	20	50
	W 7-2	1,122.90	213	134	186
	W 8-1	1,053.59	55	21	48
	W 9-2	1,053.69	140	58	67
	W10-3	941.51	190	190 (slotted)	36 (Oct 1976)
	W11-2	1,020.65	100	20	14
	Dug	1,001.97	20	—	11

[1]/ Last digit of well number refers to aquifer the well was completed in:
1 = top, 2 = middle, 3 = deep.

[2]/ Casing diameter is 6 inches except for those marked with asterisk, which are 4 inches.

[3]/ Dug well.

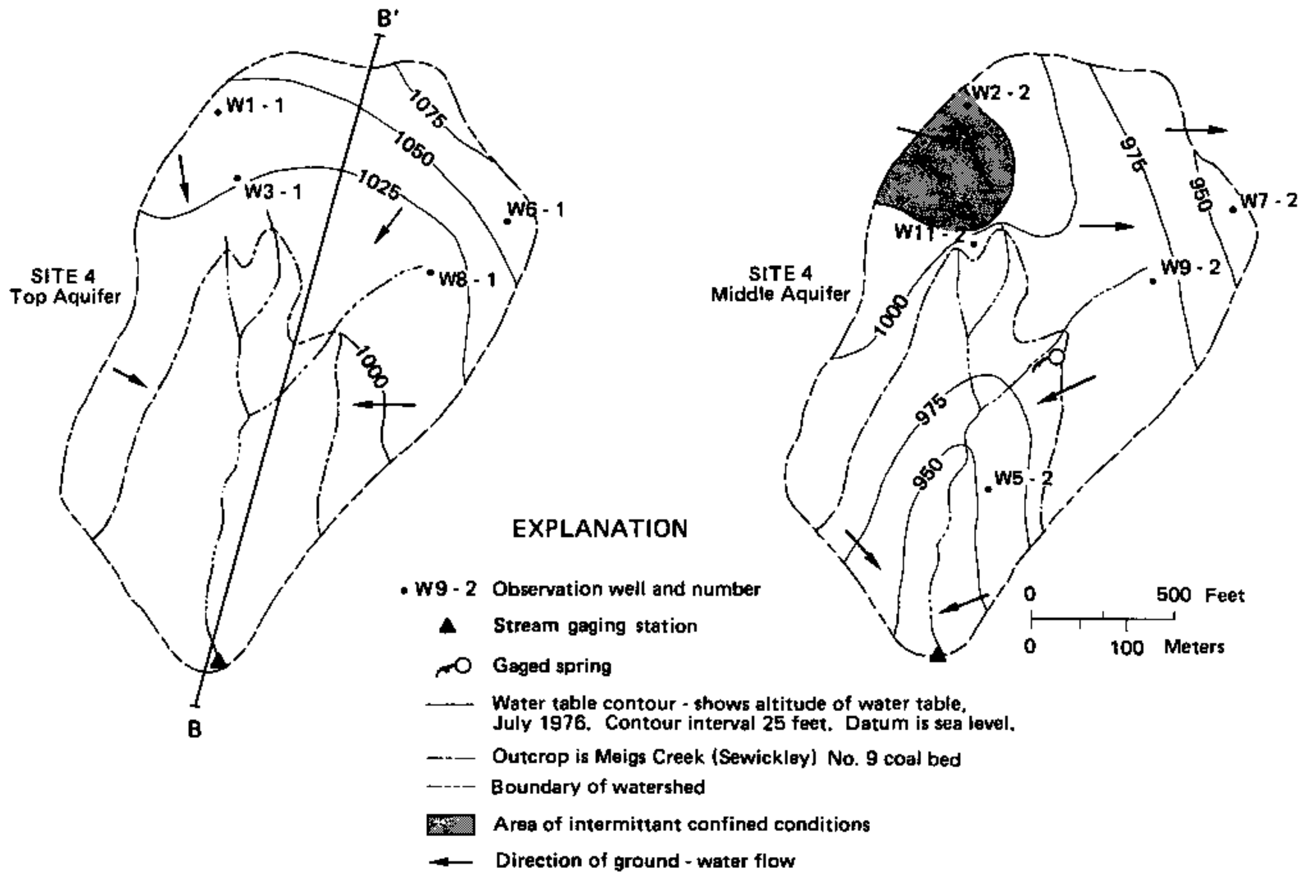


Figure 4.1-1.— Ground-water movement in the top aquifer. (From U.S. Bureau Mines, 1983, fig. 14.)

Figure 4.1-2.— Ground-water movement in the middle aquifer. (From U.S. Bureau Mines. 1983, fig. 15.)

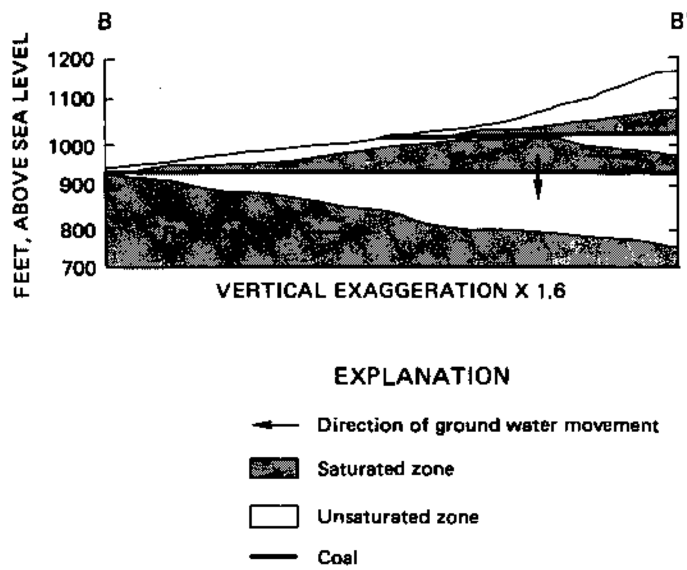


Figure 4.1-3.— Pre-mining cross section showing ground-water occurrence and movement. (From U.S. Bureau of Mines, 1983, fig. 12.)

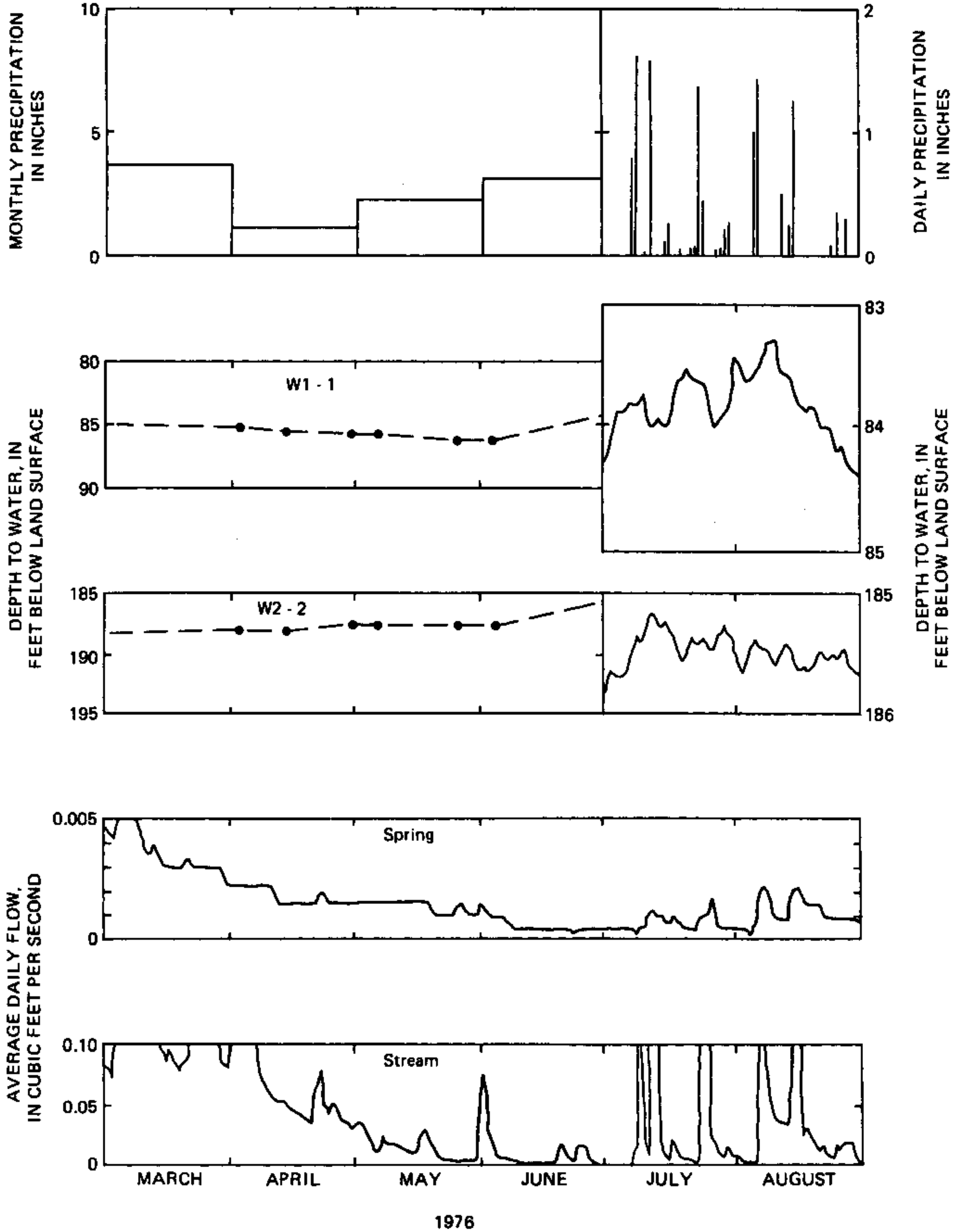


Figure 4.1-4.— Graphs of precipitation, ground-water levels, spring flow, and streamflow at site 2 for part of 1976. (From U.S. Bureau of Mines, 1978b.)

Aquifer-test results are given in table 4.1-2. Hydraulic conductivity of the rocks was generally in the range of 10^{-8} to 10^{-5}ft/s and specific yield was on the order of 0.1. Underclay leakance (vertical hydraulic conductivity divided by thickness of the confining bed) was on the order of 10^{-10}/s as determined from model calibration.

Table 4.1-2. — Hydraulic properties of aquifers at sites 1 and 4.
[ft/s, feet per second]

		Horizontal hydraulic conductivity ($x10^{-7}$ft/s)			Specific yield	
Site number	Well number	Aquifer test (type curve)	Aquifer test (computer simulation)	Slug test	Type curve	Computer simulation
1	W 1-1*	1.8	1.0	1.8	0.28	0.12
	W 4-2	.81	–	–	.26	–
	W 6-2	–	–	3.2	–	–
	W 8-2	.58	.80	–	–	.17
	W10-2	–	–	.81	–	–
	W11-2	3.0	–	14	–	–
4	W 1-1	–	–	110	–	–
	W 3-1	–	–	220	–	–
	W 5-2	3.1	1.0	–	.25	.12
	W10-3	–	–	3.6	–	–
	W11-2	–	–	6.2	–	–

* last digit of well number refers to aquifer the well was completed in: l=top, 2=middle, 3=deep.

4.0 GROUND-WATER HYDROLOGY

4.2 GROUND-WATER QUALITY

GROUND-WATER QUALITY VARIED CONSIDERABLY BETWEEN STUDY WATERSHEDS

The uppermost aquifers generally contained calcium-bicarbonate-type water, whereas the deeper aquifers contained mixed types with increasingly larger total dissolved solids with depth.

Chemical analyses of water from wells and springs for sites 1-4 displayed considerable variations between sites, between aquifers, and within most aquifers. Results of water analyses from the same well also varied with time.

In figure 4.2-1, a representative analysis from each aquifer at sites 2 and 4 is graphically shown by a Stiff diagram (8). Concentrations of major ions in water samples from wells show general patterns in relation to the aquifers. Major ions in the top aquifer were commonly calcium and bicarbonate. The waters from the deeper aquifers varied in major ions and generally had larger concentrations of dissolved solids, as measured by specific conductance (tables 4.2-1 and 4.2-2). (Dissolved solids in milligrams per liter varies from one to one-half of the specific conductance. (14)

Dissolved-solids concentrations of natural water in parts of the middle and deep aquifers in both watersheds exceeded the established limit (500 mg/L) for drinking water (13). Large concentrations of sodium and chloride were present in parts of the middle and deep aquifers in watershed 4 (fig. 4.2-1). Limits for dissolved iron (0.30 mg/L) and dissolved manganese (0.05 mg/L) (13) were commonly exceeded in water from each aquifer in each watershed. The diversity of the deeper waters is probably the result of: (1) variable lithology, from which the water acquires its chemical characteristics, and (2) variable hydraulic conductivity, which controls the length of contact time with the rocks.

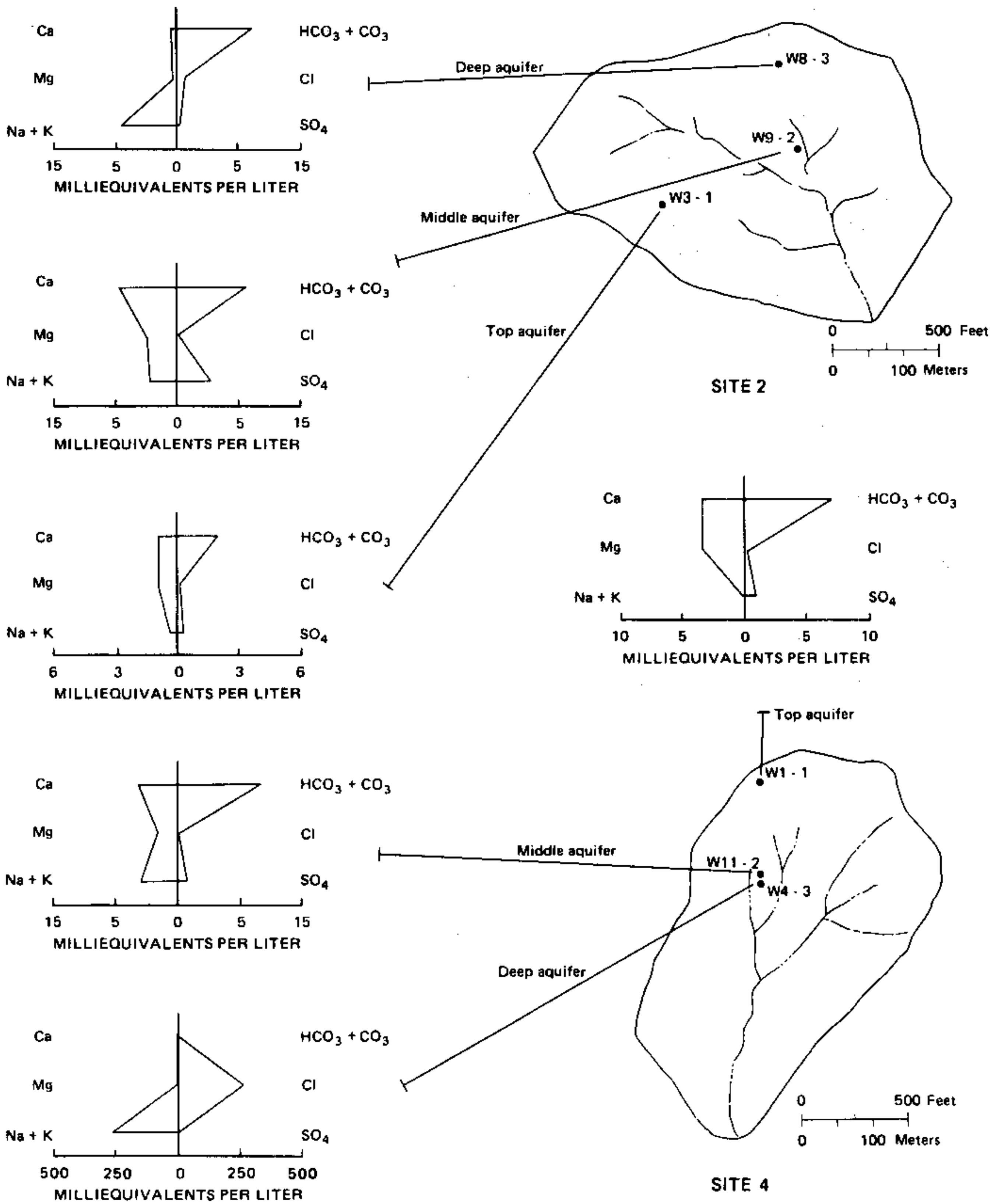


Figure 4.2-1.— Stiff diagrams showing premining water quality at sites 2 and 4.

Table 4.2-1.– Chemical analyses of ground water from site 2, during the period November 1975 to October 1976. (From U.S. Bureau of Mines, 1978b.)
[cm, centimeter; ˚C, degrees Celsius; mg/L, milligrams per liter; ug/L, micrograms per liter]

		Concentration or value					
		Top aquifer		Middle aquifer		Deep aquifer	
		Range of values	Median value	Range of values	Median value	Range of values	Median value
Alkalinity as $CaCO_3$	mg/L	21-135	92	125-284	222	97-351	108
Aluminum total	ug/L	60-5,000	920	20-5,600	2,100	50-9,100	1,000
Antimony total	ug/L	0-2	0	0-1	0	0-5	1
Arsenic total	ug/L	0-43	3	0-5	1	0-23	5
Barium total	ug/L	0-1, 100	100	0-300	100	0-200	200
Bicarbonate	mg/L	25-164	112	152-346	271	118-428	132
Calcium total	ug/L	0-62	5	1-34	7	2-14	4
Calcium dissolved	mg/L	3.1-53	26	3.2-90	38	3.0-28	25
Carbon dioxide	mg/L	1.7-154	35	13-122	35	4.7-49	17
Carbon total organic	mg/L	1.3-27	4.1	0.2-8.6	3.0	0.1-45	2.3
Carbonate	mg/L	0-0	0	0-0	0	0-0	
Chloride dissolved	mg/L	1.0-91	2.3	1.1-9.0	3.9	1.2-70	3.8
Chromium total	ug/L	0-110	<10	<10-60	<10	<10-30	10
Color	Pt/Co	1-46	3	1-8	1	1-170	3
Copper total	ug/L	0-950	10	0-110	10	0-190	10
Cyanide	mg/L	0.00-0.01	0.00	0.00-0.00	0.00	0.00-1.0	
Fluoride dissolved	mg/L	0.1-1.6	0.2	0.3-0.9	0.3	0.2-1.7	0.3
Hardness noncarbonate	mg/L	0-65	32	0-72	36	0-31	16
Hardness total	mg/L	11-170	115	14-330	190	12-130	120
Hydrogen sulfide	mg/L	0.0-0.3	0.0	0.0-0.2	0.0	0.0-0.2	0.0
Iron dissolved	ug/L	10-2,300	130	40-2,000	930	10-630	50
Iron total	ug/L	120-170,000	5,400	1,200-27,000	7,600	1,700-32,000	6,600
Lead total	ug/L	0-400	22	2-44	15	3-120	13
Magnesium dissolved	mg/L	0.8-15	0.9	1.4-26	16	1.2-15	14
Manganese dissolved	ug/L	0-930	140	20-710	270	20-110	60
Manganese suspended	ug/L	0-70,000	360	0-210	120	10-500	120
Manganese total	ug/L	0-70,000	690	40-840	270	70-540	140
Mercury total	ug/L	<0.5-<0.5	<0.5	<0. 5-2.0	<0.5	<0.5-1.1	<0.5
Nickel total	ug/L	2-550	19	1-20	13	2-100	15
Nitrogen NH_4 as N total	mg/L	0.00-1.3	0.04	0.00-0.53	0.31	0.00-0.43	0.01
NO_2+NO_3 as N	mg/L	0.02-0.73	0.07	0.01-0.39	0.04	0.05-0.10	0.07
pH (field)	units	6.0-8.2	6.8	6.3-7.6	7.2	6.6-8.1	7.1
Phenols	ug/L	0-8	0	0-4	0	0-7	0
Phosphorous total as P	mg/L	0.08-3.8	0.10	0.03-0.12	0.06	0.02-0.54	0.08
Phosphorous total PO_4	mg/L	0.06-12	0.32	0.09-0.37	0.18	0.06-1.7	0.25
Potassium dissolved	mg/L	1.0-4.9	1.6	1.7-4.8	3.3	0.4-7.4	0.9
Sodium adsorption ratio		0.1-29	0.2	0.3-14	0.8	0.1-31	0.1
Selenium total	ug/L	0-6	0	0-0	0	0-29	0
Silver total	ug/L	0-1	0	0-2	0	0-3	0
Sodium dissolved	mg/L	1.0-220	6.4	7.7-120	21	3.3-250	3.8
Sodium	percent	3-97	11	11-94	21	5-97	6
Specific conductance (field)	micromhos/cm	120-520	288	280-905	600	258-1,110	278
Strontium total	ug/L	30-240	90	100-920	280	50-140	70
Sulfate dissolved	mg/L	11-80	36	2.9-160	48	8.2-80	20
Water temperature	˚C	7.0-18	13	11. 0-14.0	12.5	12.0-17.0	12.5
Zinc total	ug/L	10-800	90	20-1,500	220	20-310	90

Table 4.2-2.– Chemical analyses of ground water from site 4, during the period April to November 1976. (From U.S. Bureau of Mines, 1978b.)
[cm, centimeter; ˚C, degrees Celsius; mg/L, milligrams per liter; ug/L, micrograms per liter]

		Concentration or value					
		Top aquifer		Middle aquifer		Deep aquifer	
		Range of values	Median value	Range of values	Median value	Range of values	Median value
Alkalinity as $CaCO_3$	mg/L	167-373	314	234-499	373	222-559	432
Aluminum total	ug/L	10-8,300	2,000	50-58,000	3,100	3,400-60,000	13,000
Antimony total	ug/L	0-2	0	0-3	0	0-1	0
Arsenic total	ug/L	0-64	4	0-130	9	11-45	25
Barium total	ug/L	200-1,800	200	100-12,000	300	100-3,000	200
Bicarbonate	mg/L	204-455	399	94-608	455	246-602	444
Calcium total	ug/L	1-20	6	0-13	4	5-14	11
Calcium dissolved	mg/L	58-81	70	4.1-92	40	3.2-230	4.9
Carbon dioxide	mg/L	6.2-119	18	0.1-66	8.2	0.7-1.4	1.3
Carbon total organic	mg/L	0.5-40	2.4	0.5-6.5	3.2	5.6-30	12.2
Carbonate	mg/L	0-0	0	0-0	0	0-0	
Chloride dissolved	mg/L	1.5-5.6	3.0	1.3-4,100	8.4	530-9,900	590
Chromium total	ug/L	<10-130	<10	<10-160	10	10-150	50
Color	Pt/Co	1-3	2	1-40	2	2-370	160
Copper total	ug/L	0-30	10	10-60	10	10-50	20
Cyanide	mg/L	0.00-0.00	0.00	0.00-2.0	0.00	0.01-2.0	1.0
Fluoride dissolved	mg/L	0.2-0.3	0.2	0.2-2.9	1.3	3.6-5.5	3.6
Hardness noncarbonate	mg/L	0-72	14	0-46	0	0-600	0
Hardness total	mg/L	210-450	315	18-350	100	12-820	17
Hydrogen sulfide	mg/L	0.0-5.8	0.0	0.0-0.3	0.0	0.0-0.0	0.0
Iron dissolved	ug/L	0-170	40	10-470	40	40-90	60
Iron total	ug/L	90-160,000	4,200	120-140,000	5,400	7,100-89,000	19,000
Lead total	ug/L	0-300	18	2-160	17	27-280	41
Magnesium dissolved	mg/L	15-59	33	1.4-39	8.6	0.9-59	1.1
Manganese dissolved	ug/L	0-290	20	0-240	20	10-80	10
Manganese suspended	ug/L	0-1,400	110	0-1,700	40	40-1,100	160
Manganese total	ug/L	20-1,400	140	20-1,700	100	50-1,200	170
Mercury total	ug/L	<0.5-<0.5	<0.5	<0.5-0.9	<0.5	<0.5-0.9	<0.5
Nickel total	ug/L	1-240	10	2-340	12	13-350	53.38
Nitrogen NH_4 as N total	mg/L	0.00-0.04	0.01	0.00-1.2	0.20	0.14-3.6	0
NO_2+NO_3 as N	mg/L	0.01-0.63	0.12	0.00-0.36	0.03	0.03-0.48	0.03
pH (field)	units	6.5-7.8	7.6	7.0-9.7	7.8	8.8-8.9	8.8
Phenols	ug/L	0-120	2	0-68	4	0-5	0
Phosphorous total as P	mg/L	0.02-0.59	0.06	0.03-0.93	0.04	0.11-15	0.38
Phosphorous total PO_4	mg/L	0.06-1.8	0.20	0.09-2.9	0.14	0.34-46	1.2
Potassium dissolved	mg/L	0.5-2.7	1.6	0.8-10	1.6	1.5-24	1.8
Residue dissolved (calculated sum)	mg/L	267-402	367	329-1,700	431	1,400-1,400	1,400
Residue dissolved	tons/acre-ft					46-46	46
Sodium adsorption ratio		0.1-0.7	0.2	0.2-92	9.9	49-71	66
Selenium total	ug/L	0-23	2	0-4	2	0-78	8
Silica dissolved	ug/L	9.8-19	11	6.8-17	13	2,9-2.9	2.9
Silver total	ug/L	0-0	0	0-1	0	0-0	0
Sodium dissolved	mg/L	4.0-28	5.4	9.3-2,900	120	560-3,200	620
Sodium	percent	2-16	5	6-97	88	89-99	99
Specific conductance (field)	micromhos/cm	430-890	545	560-12,400	796	1,750-26,800	2,700
Strontium total	ug/L	250-2,600	720	330-7,600	690	190-25,000	360
Sulfate dissolved	mg/L	30-122	40	9.0-94	36	31-180	36
Water temperature	˚C	10.5-16.0	13.5	12.0-14.5	13.0	11.5-15.0	13.0
Zinc total	ug/L	10-160	80	20-310	70	20-80	30

4.0 GROUND-WATER HYDROLOGY

4.3 GROUND-WATER MODELING

A GROUND-WATER FLOW MODEL WAS USED TO DESCRIBE GROUND-WATER SYSTEMS

A quasi-three-dimensional finite-difference model was adapted to simulate pre-mining ground-water flow systems between three aquifers.

The study area was divided into a set of rectangular blocks (known as a grid) so that the average physical characteristics, such as transmissivity, storage, and recharge, of each block could be described mathematically. These characteristic variables were then used in the computer model to solve flow equations at each node (center point) of each block. The model grid (fig. 4.3-1) has 24 columns and 18 rows, forming evenly spaced squares 100 feet on a side.

The model consists of three layers that represent the top, middle, and deep aquifers. Horizontal flow is simulated only within layers and vertical flow only between layers. The site 2 model is described here. The approach, input, and results were similar for the site 4 model; sites 3 and 1 were not modeled.

The model is illustrated schematically in figure 4.3-2. The top aquifer is represented by nodes between the watershed divide and the coal outcrop, whereas the middle and deep aquifers are represented by nodes across the entire watershed. The deep layer consists entirely of constant-head nodes that function as sinks for downward leakage.

In the top layer, springs and seeps at the outcrop of the underclay are simulated by a line of nodes in the model grid. The simulated discharge rate at these nodes is controlled by a leakage coefficient, by the altitude of the clay bed, and by the calculated hydraulic head. In the middle layer, discharge at stream nodes is determined by the head difference between stream surface and aquifer and by leakance of the streambed. Vertical leakage through underclays is determined by the head gradient across the clay and the underclay leakance.

Sensitivity analysis showed that model results (simulated heads and budget) are most sensitive to recharge from precipitation and to underclay leakance. A 100-percent change in precipitation recharge resulted in head changes of 18 to 39 feet in the top aquifer, except at spring nodes, where head changes ranged from 1 to 4 feet. A 100-percent change in underclay leakance in both layers resulted in head changes of 6 to 19 feet, except at spring nodes, where head changes were less than 1 foot.

Best steady-state pre-mining simulation results were obtained with the following input data:

1.87×10^{-8} ft/s (at each node)	Recharge rate (7 inches per year)
2.0×10^{-7} ft/s	Aquifer hydraulic conductivity
5.5×10^{-10}/s	Underclay leakance
1×10^{-8} ft/s	Spring leakage coefficient
1×10^{-7} ft/s	Streambed leakage coefficient

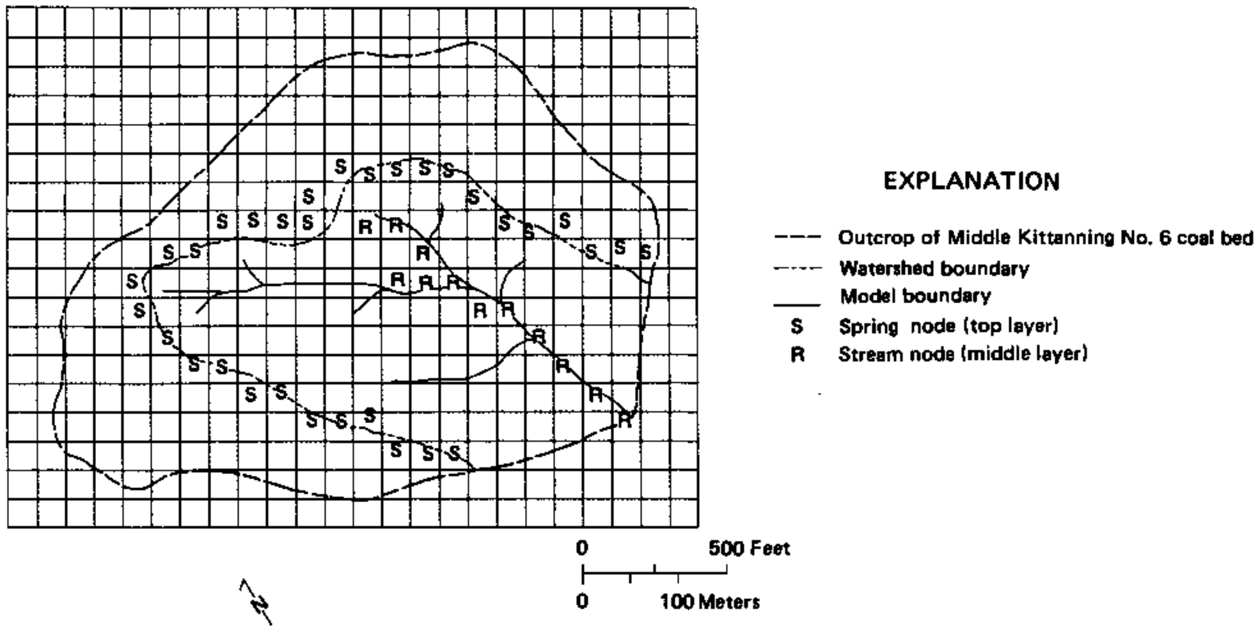


Figure 4.3-1— Ground-water-flow model grid for site 2.

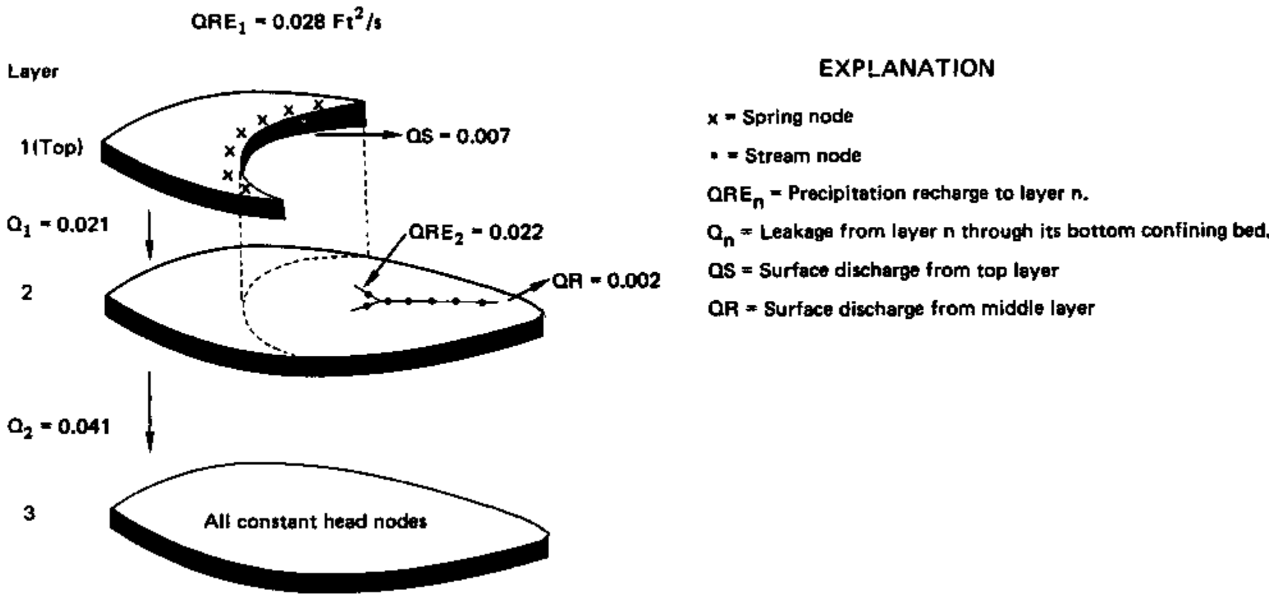


Figure 4.3-2.— Schematic diagram of components of ground-water flow model for site 2.

Simulated top- and middle-aquifer lateral-discharge rates are comparable to springflow and streamflow data collected in 1976. Agreement between observed and simulated potentiometric surfaces of the top and middle aquifers was considered fair; simulated heads ranged from 25 feet too high to 26 feet too low at locations of observation wells. Data were not sufficient to justify varying hydraulic properties within and between layers, even though approximate simulations could be achieved.

5.0 PROBABLE HYDROLOGIC CONSEQUENCES OF MINING

5.1 EFFECTS ON TOPOGRAPHY AND GEOLOGY

EACH MINED WATERSHED UNDERWENT CHANGES IN THE LOCAL OUTCROP PATTERN, TOPOGRAPHY, DRAINAGE, AND GEOLOGY.

Mining entailed removal of the top coal bed.

After topsoil was removed, mining began along the coal outcrop and excavated overburden was placed downslope (fig. 5.1-1). As coal was mined and the position of the highwall moved toward the watershed divide, additional ridges of overburden material were formed. Underclay was left essentially undisturbed. Reclamation included grading of the spoils, replacement of topsoil, and seeding for revegetation.

Reclaimed watersheds are substantially smaller than before mining, owing to changes in location of drainage divides. At site 4 (fig. 5.1-2), the topographic relief was much gentler than before mining.

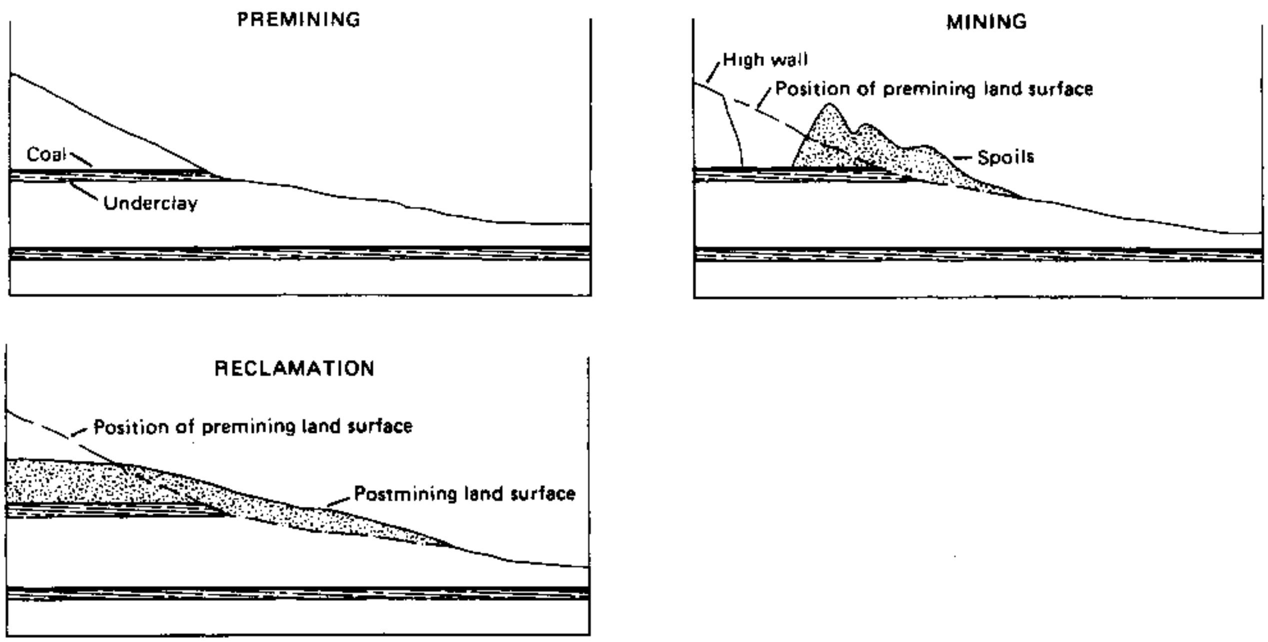


Figure 5.1-1.— Schematic sections illustrating surface-mining process. (From Helgesen and Razem, 1981, fig. 2.)

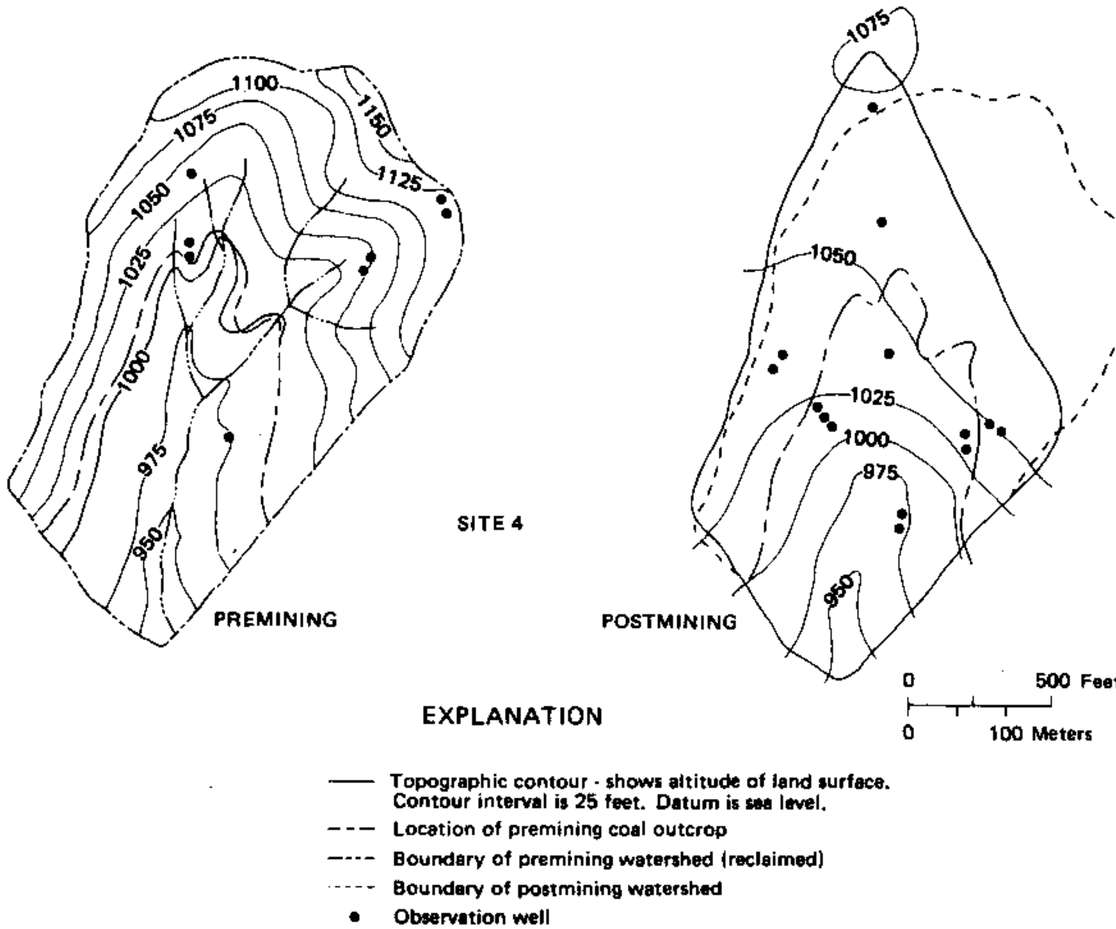


Figure 5.1-2.— Effects of mining on topography and drainage.
(From U.S. Bureau of Mines, 1983, figs. 2 and 24.)

5.0 PROBABLE HYDROLOGIC CONSEQUENCES OF MINING

5.2 EFFECTS ON GROUND-WATER OCCURRENCE AND MOVEMENT

AFTER MINING, SPOILS OF THE UPPERMOST AQUIFER DISPLAYED A VERY SLOW RESATURATION RATE

Flow systems of the lower aquifers were not significantly affected.

Mining in adjacent watersheds affected ground-water levels several months before mining started at two of the sites. Mining of the No. 6 coal in the watershed west of site 2 caused water levels in the top aquifer to decline during the autumn of 1976. The decline was caused by drainage from the aquifer to the mine pit. At site 4, water-level declines of as much as 20 feet within 5 months (fig. 5.2-1) were observed in the top aquifer as nearby mining operations moved progressively closer. Springflow also ceased shortly before or after mining began at the watersheds.

Initial data from observation wells installed in August and September 1978, shortly after reclamation, indicated that little of the mine spoils was saturated. Two of three wells at site 4 were initially dry (fig. 5.2-2). Initial saturated zones were in areas where the spoils covered the pre-mining land surfaces rather than where spoils covered the underclay. Water-level hydrographs (fig. 5.2-2) reflect a slow, unsteady resaturation of spoils.

Water levels (fig. 5.2-2) beneath the mined coals did not change significantly during and after mining. Data were available only from wells not destroyed by mining—one well in the deep aquifer at site 2 and one well each in the middle (W5-2) and deep (W10-3) aquifers at site 4. However, a water-level rise in the middle-aquifer well (W5-2) at site 4 at the end of April 1977 (fig. 5.2-2) seems larger than might be expected from the amount of rainfall during this period. The rise may be related to mining, although no logical explanation can be given.

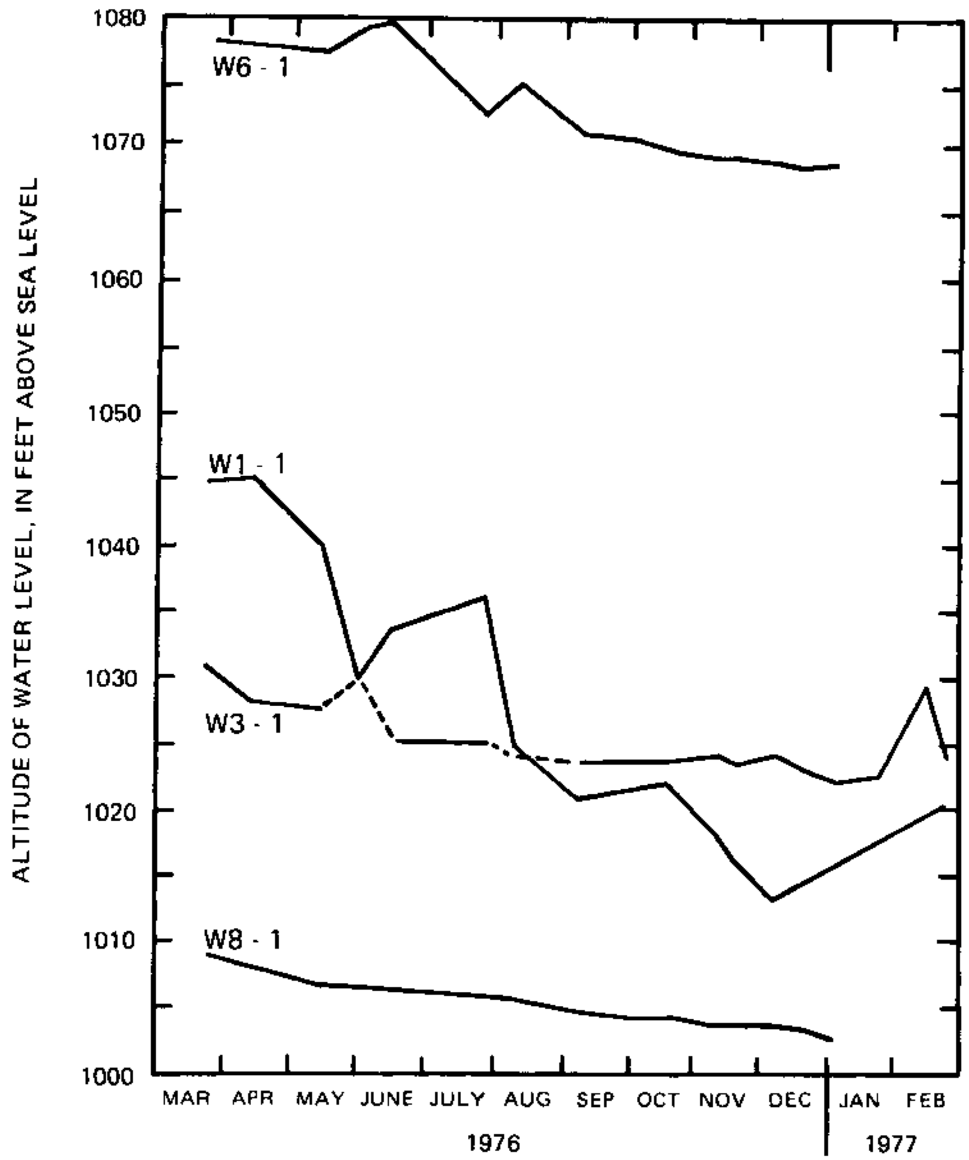


Figure 5.2-1.— Hydrographs for observation wells completed in the top aquifer at site 4.

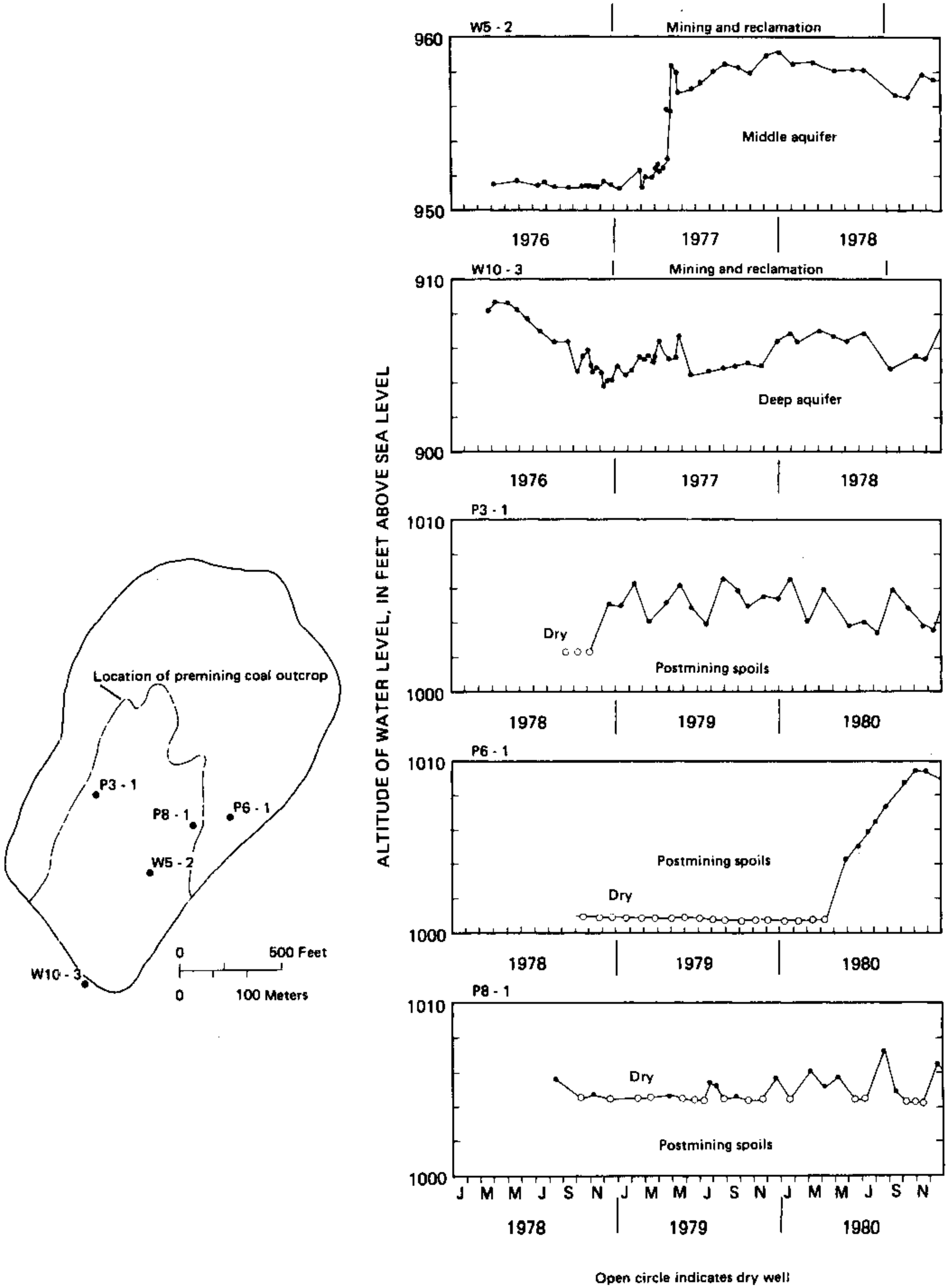


Figure 5.2-2.— Hydrographs of observation wells at site 4.
(From U.S. Bureau of Mines, 1983, fig. 47.)

5.3 EFFECTS ON GROUND-WATER QUALITY

MINERALIZATION OF WATER IN THE UPPERMOST AQUIFER INCREASED SIGNIFICANTLY AFTER MINING

Increased surface area in the mine spoils caused increased solubility and dissolved solids in water.

Initial post-mining sampling of water in spoils was not possible, owing to a lack of water in the wells. However, enough water was present in some wells for specific-conductance measurements, which showed larger values than in the pre-mining top aquifer. This increase is likely a result of blasting and handling of overburden, which exposed more surface area of the rock and increased its susceptibility to solution.

Figure 5.3-1 shows pre-mining and post-mining specific conductances from site 4. Based upon these data and the rock type, water accumulating within the spoils is expected to have increased concentrations of dissolved solids and sulfate. The water quality in the top aquifer, generally a calcium-bicarbonate-type water before mining, is expected to be a calcium-sulfate-type water after mining. Water quality in the middle and lower aquifers remained relatively unchanged.

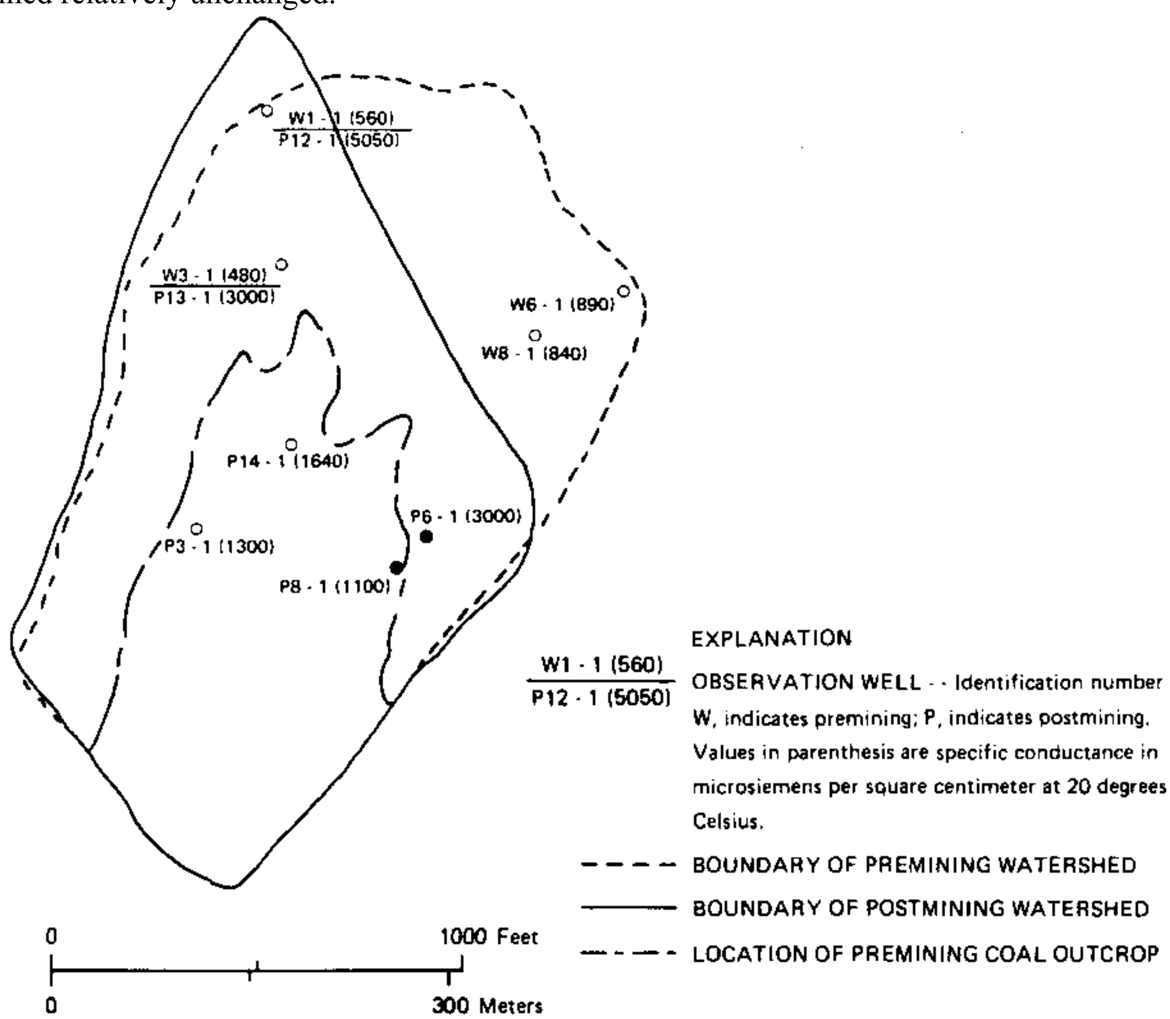


Figure 5.3-1.— Pre-mining and post-mining specific conductance values from site 4.

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GROUND-WATER STUDY 4

by

Jeffrey D. Stoner

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1.0 ABSTRACT

Geology and Occurrence of Coal

Greene County lies within the Appalachian Plateau physiographic province. As part of the Appalachian coal basin (Eastern Coal Province), the area contains much of the Nation's high-volatile, high BTU and metallurgical grade, bituminous coal reserves. The coal-bearing rocks of the basin are nearly flat-lying and consist of interbedded coal, sandstone, siltstone, shale, and limestone of Pennsylvania and Permian age. The oldest exposed rocks include the upper 60 feet of the Conemaugh Group.

The principal seams that have been developed for coal mining are the Pittsburgh, Sewickley, and Waynesburg coals of the Monongahela and lower Dunkard Groups. A large thickness of overburden has made it impractical to mine coal seams of the Allegheny Group. The upper Dunkard Group contains a few coal seams less than 3 feet thick, which have been mined locally by surface-mining methods.

Hydrology

Greene County has a temperate climate and its average annual precipitation that ranges from 38 to 41 inches. Large topographic relief (200 to 600 feet) and the interlayering of permeable and relatively impermeable rocks enhances horizontal ground-water movement and the occurrence of hillside springs. Bedrock permeability is small and attributed mostly to fracture openings along joints and bedding planes.

Unconsolidated valley-fill deposits of probable Recent age commonly are less than 25 feet thick and consist mostly of clay and silt but also contain some fine gravel. Pleistocene deposits, which are generally less than 40 feet thick and are difficult to distinguish from locally derived valley fill, have been mapped in benches along the major valleys of the study area. The saturated zone of these deposits is usually thin, but contributes significant quantities of water locally. Natural water quality of shallow aquifers is generally suitable for most uses. Mineralization of the water tends to increase with depth.

Mining Method

The Pittsburgh coal seam has a consistent average thickness exceeding 6 feet, and constitutes the major coal to be developed by subsurface methods in the area. Depth to this coal ranges from 0 feet at its outcrop to about 1,400 feet in the west-central part of the county. The eastern one-third of the Pittsburgh coal reserve has been largely removed by underground mining. In contrast, the Sewickley and Waynesburg coal seams are less persistent and thinner and have been mined mostly by small-scale surface mines.

Probable Hydrologic Consequences

Water-level declines in wells overlying underground mining operations depend on the thickness of bedrock between the mine and the well bottom and the amount of secondary permeability induced by coal excavation. Drawdown gradients are steep near the mine opening and decrease rapidly with distance away from the mine according to cross-sectional flow model results. Observation wells located in shallow aquifers above the mines and downgradient from waste refuse piles can be used to detect changes in ground-water storage and chemistry attributed to mining.

2.0 GEOLOGIC SETTING

2.1 ROCK TYPES AND CONTINUITY OF STRATA

BEDROCK IS COMPOSED OF SANDSTONE, SILTSTONE, SHALE, LIMESTONE, AND COAL INTERBEDDED IN COMPLEX SEQUENCES

Sedimentary strata vary in thickness, shape, and lateral extent. Bedrock in Greene County consists of interbedded sandstone, siltstone, shale (or mudstone), limestone, and coal. Sandstone and limestone are the thickest lithologic units, exceeding 90 feet in some areas (fig. 2.1-1). However, sandstones and limestones where they are interbedded with thin shales and siltstones are commonly less than 20 and 3 feet thick, respectively. Coal beds are typically less than 10 feet thick and contain one or more claystone partings.

The lower and upper limits of each bedrock formation are either marked by persistent limestones or by easily correlatable coal beds (fig. 2.1-1). In most areas, contacts with overlying formations are conformable. The predominant rock type of the Glenshaw and Casselman Formations is mudstone, interbedded with some sandstone and limestone. The Pittsburgh Formation is composed mostly of limestone and contains persistent coal seams. The basal unit of the Lower Member is the Pittsburgh coal, which is the most valuable coal unit in the county. The Uniontown Formation consists of a dominantly shale member overlying a limestone member. Both members contain siltstone, sandstone and coal. The Waynesburg Formation usually contains one or more massive channel sandstones, and the Washington and Greene Formations have numerous lenses of siltstone or calcareous mudstone and some sandstone.

The unconsolidated Carmichaels Formation, which unconformably overlies many of the bedrock formations exposed in Greene County, is composed of mostly clay and iron-stained sand. The Carmichaels is usually less than 40 feet thick and is difficult to distinguish from locally derived valley fill. Unconsolidated valley-fill deposits, which consist mostly of clay and silt and also some fine gravel, commonly are less than 25 feet thick.

With the exception of certain coal seams, the geometry of individual lithologic units is variable and complex. The cycle of deposition (cyclothem) (fig. 2.1-2) is representative of the geology just north of the study area (1) and, although idealized, is believed to be representative of the lithologic associations found in Greene County. A relatively persistent coal seam, at the base of the cycle, is overlain directly by a sandstone or mudstone. The next overlying lithologic units may be any one of the four general associations: (1) channel deposits of cross-bedded sandstone; (2) sheet-like deposits of interbedded sandstone, siltstone, and mudstone; (3) lenticular or sheetlike deposits of mudstone, limestone, and siltstone; and (4) lenticular or tabular deposits of limestone and mudstone. The sequence, whichever is present, is topped with a claystone or underclay to a coal, which may begin the next cycle of deposition. Hence, individual units are discontinuous, with lithologic variation greatest in the direction perpendicular to bedding.

Sandstones are mostly fine grained, contain 60-75 percent quartz, and have a siliceous cement. The texture in channel-type deposits is coarse grained. Siltstones commonly are mixed with mudstone. Shales (mudstones) are fissile to plastic and consist of the clays illite, chlorite, and kaolinite (1). Limestones (marlstones) are microcrystalline with a calcite matrix, less than 8 percent dolomite, and contain more than 10 percent clay minerals. Coal beds are bituminous and contain claystone partings and pyrite locally.

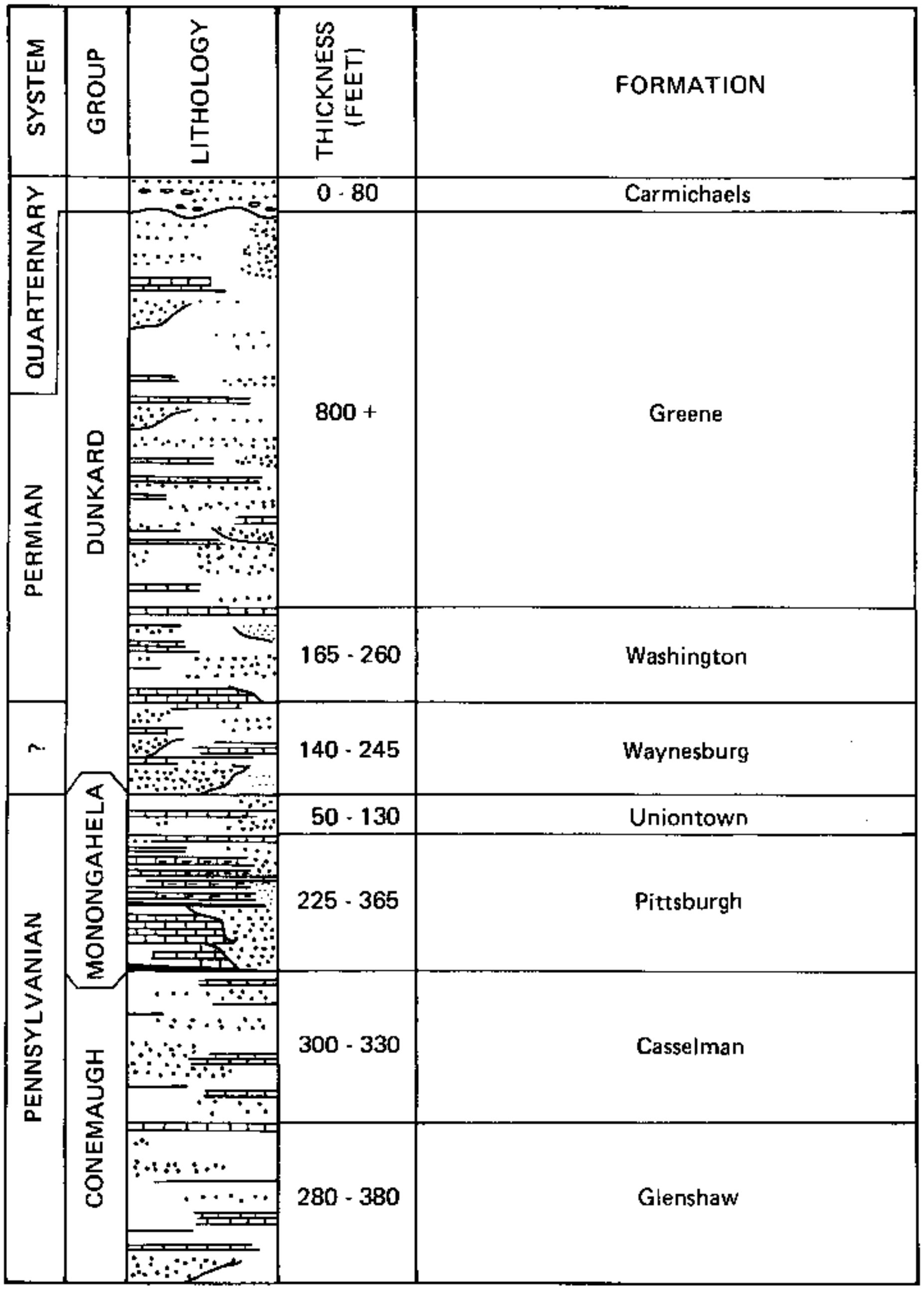


Figure 2.1-1.—Generalized geologic column for Green County.

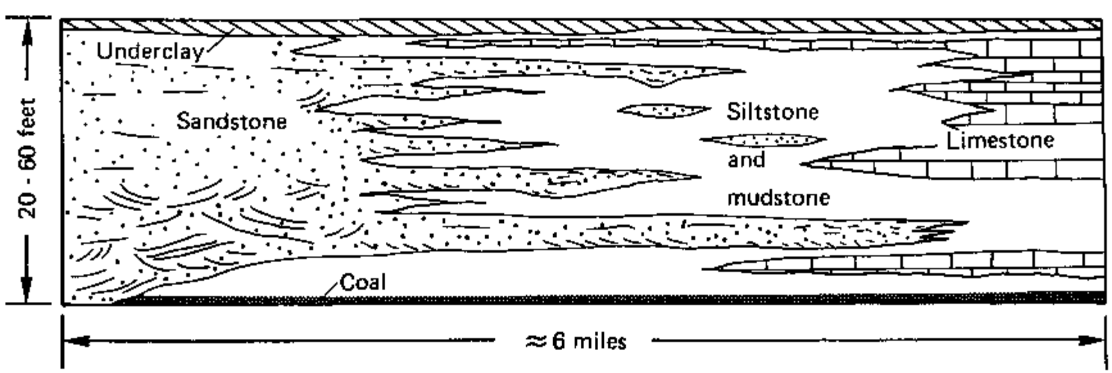


Figure 2.1-2.— Idealized section of lithologic associations.
(Modified from Berryhill and others, 1971)

2.0 GEOLOGIC SETTING

2.2 STRUCTURAL GEOLOGY

BEDROCK HAS BEEN GENTLY FOLDED TO FORM SUBPARALLEL ANTICLINES AND SYNCLINES

The bedrock dips at angles of less than 3˚; orientation of the folds generally correlates with local joint directions.

The dip of strata, jointing, and faulting can affect ground-water flow patterns in the county area. The effect is especially true for natural flow of the shallow ground-water system and flow to and from surface mines. Vertical fracture zones might interconnect deep subsurface mines and shallow aquifers. Therefore, a brief discussion of structural geology of the study area is important.

Bedrock has been gently folded to form a series of subparallel anticlines and synclines trending north to northeast (fig. 2.2-1). Dips of the rocks generally are less than 3˚. The bases of coal seams, such as the Pittsburgh seam, probably were nearly horizontal prior to folding, are easily identifiable in test holes, and are relatively continuous between test borings. For these reasons, the bases of coal seams are useful in identifying local and regional attitudes of strata in the Pennsylvanian and Lower Permian rocks of the region. The altitude of the base of the Pittsburgh coal seam as determined from drill-hole data was used to prepare the structure-contour map (fig. 2.2-1).

Fractures and joints occur in most of the rocks. Systematic joint sets in coal, termed cleat, tend to follow the regional structure. Face cleat, the predominant joint set, trends N. 70˚ W. in the Pittsburgh seam or perpendicular to regional folding in Greene County. Butt cleat, or secondary jointing, is generally parallel to folding (fig. 2.2-1).

Joints in surface outcrops of sandstone and limestone also tend to follow the regional structure (fig. 2.2-2). The Roman numerals indicate the relative order of dominance, with 'I' being the greatest. Photolinear features such as straight river courses, stream valleys, and abrupt right-angle bends of streams as determined from infrared aerial photographs (fig. 2.2-3) may be useful in identifying regional jointing trends. The most dominant photo-lineaments (Roman numeral I) correlate closely to the Pittsburgh coal cleat. Photolineaments may also be indicative of major fracture zones. The reader is referred to the Reports of Investigation series by the U.S. Bureau of Mines for further information on methods of data analysis for jointing in this coal region.

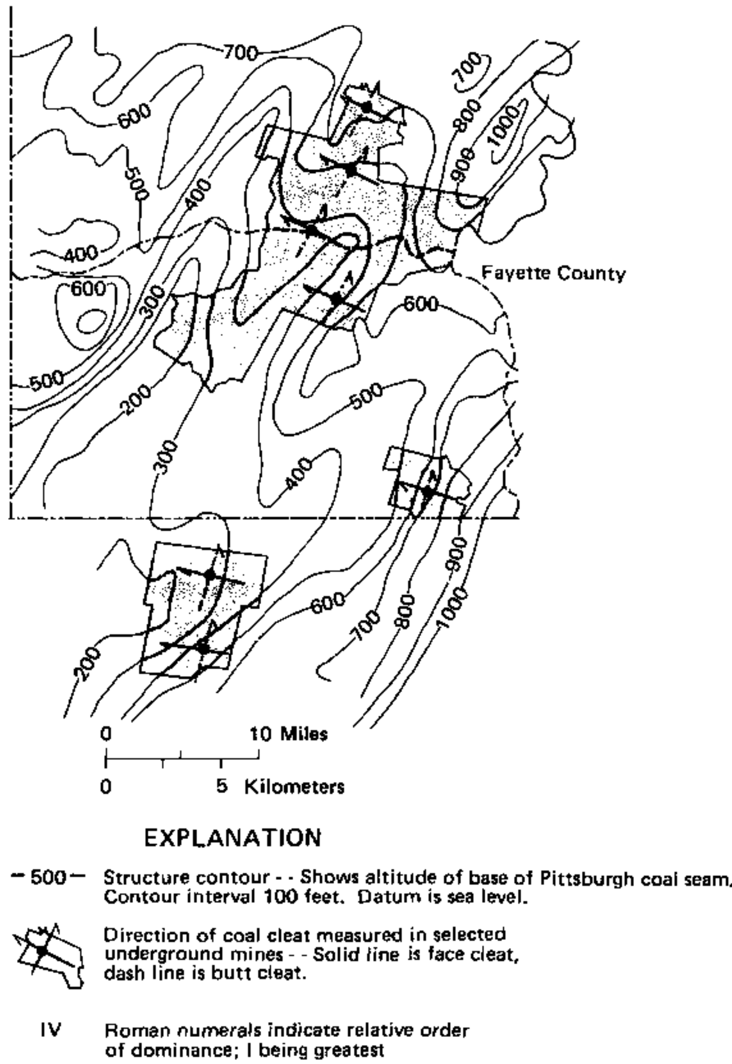


Figure 2.2-1.— General structure and cleat direction of Pittsburgh coal seam in and near Greene County. (Modified from McCulloch and others, 1976)

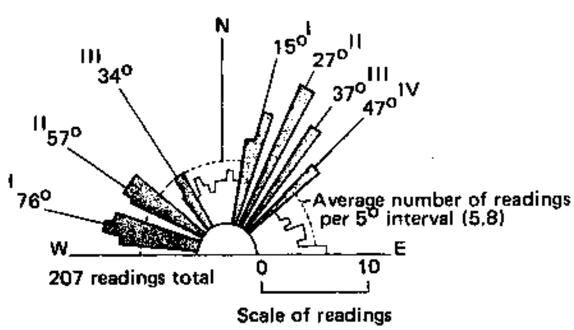


Figure 2.2-2.— Composite rose diagram of principal surface joint trends. (From Diamond and others, 1967)

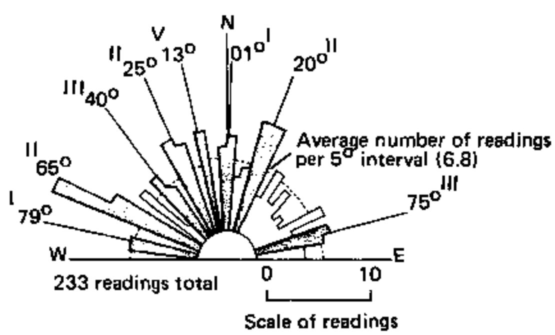


Figure 2.2-3.— Composite rose diagram of principal infrared photograph photolinears. (From Diamond and others, 1967)

3.0 GROUND-WATER HYDROLOGY

3.1 RECHARGE, OCCURRENCE, AND MOVEMENT

AN ACTIVE, SHALLOW FLOW SYSTEM OVERLIES A DEEPER, STAGNANT FLOW SYSTEM

Ground water is stored in all rock types but moves most readily through joints and fracture openings at shallow depths.

The source of ground water is precipitation. The mean annual precipitation ranges from 38 to 41 inches across Greene County. Part of the precipitation returns to the atmosphere via evaporation and transpiration, part flows overland into streams, and part seeps downward through soils and rock to the saturated zone. Within the saturated zone, movement continues downward and laterally toward discharge locations such as springs and streams and upward toward major stream valleys (fig. 3.1-1). Analysis of streamflow hydrograph separation (into base-flow and direct-runoff components) indicates that, on the average, 22 to 25 percent of annual precipitation circulates through the aquifer system of Greene County. Shallow local aquifers, exposed in the area, receive direct recharge from rain or snowmelt. The deeper, regional aquifer system is recharged by leakage from the overlying aquifers or from streams in upland valleys.

Water occurs in fracture openings and intergranular pore spaces in all rock types below the water table. The size and interconnection of the fracture openings and pores control the permeability of the bedrock, which constitutes the larger part of the bedrock permeability. Fracture openings tend to diminish in width and number as overburden thickness increases; thus, bedrock permeability is reduced with depth.

Most ground-water circulation is within the shallow, more permeable bedrock aquifers. Downward movement beneath hills is retarded by relatively impermeable confining layers such as shales, mudstones, and unfractured limestones. At shallow depths below the water table, such confining layers can cause perching of ground water and lateral flow to hillsides where the water discharges at springs or seeps. At greater depths, the hydraulic head is commonly great enough to force vertical leakage through confining layers into the underlying confined aquifer units (fig. 3.1-1). Vertical head loss is reflected by decreasing water levels as well depths increase in such recharge areas. The water level indicated by each well (fig. 3.1-2) represents average annual head of the interval open to the well. Water levels at well sites A, and B show a vertical head loss with depth.

Movement in the deeper regional aquifer system is predominantly lateral toward major valleys and relatively stagnant in comparison to the more permeable shallow flow system. Vertical leakage through confining layers beneath major valleys is usually upward. Wells drilled in such discharge areas flow or their water levels become higher as well depth increases, as shown by well site C of figure 3.1-2. The deeper bedrock aquifers contain brackish to salty (saline) water that has not been flushed by fresher shallow water circulation (fig. 3.1-1). The salty (saline) brine, which is about 1,700 feet below average land surface in Greene County, marks the base of the regional fresh water aquifer system.

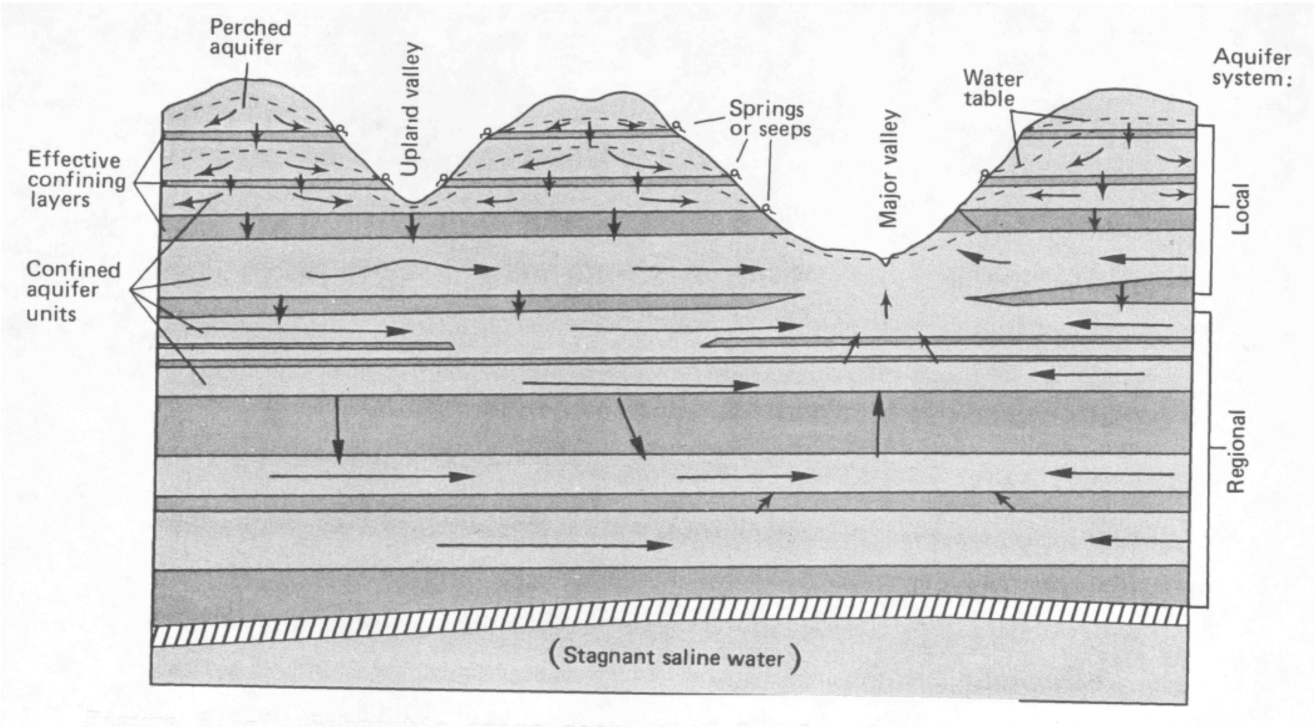


Figure 3.1-1.— Schematic cross section of local and regional ground-water movement. (Length and number of arrows are generally proportional to relative flow rate.

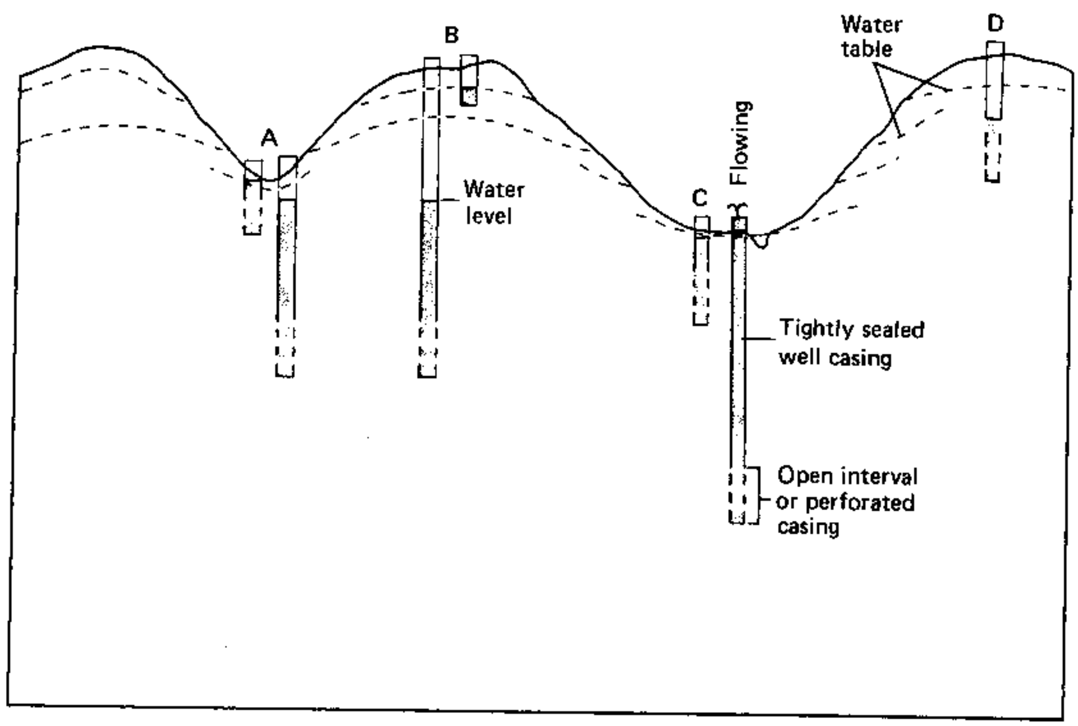


Figure 3.1-2.— Relationship of water levels in wells to well depth and topographic position.

3.0 GROUND-WATER HYDROLOGY

3.2 WATER-LEVEL FLUCTUATIONS

WATER-LEVEL CHANGES IN DIFFERENT WELLS REFLECT VARIABLE RECHARGE

Aquifer storage capacity, permeability, and potential recharge are principal hydrologic conditions that affect water-level fluctuations in wells.

Water-level hydrographs from four different wells in Greene County show the relationship between water-level changes and rainfall (fig. 3.2-1). The relative depths and topographic positions of the wells are indicated in figure 3.2-2. Daily water-level changes range from about 0.2 foot in deep confined aquifers to about 5 feet in shallow bedrock aquifers. Of the bedrock wells (numbers 602, 118, and 803), the hilltop well (602) shows the greatest water-level fluctuations and the valley well (803) shows the least change. Well 804, which is completed in unconsolidated alluvium, also responds readily to rainfall.

The observed results are related primarily to differences in potential for recharge, aquifer-storage capacity, permeability, and location with respect to the ground-water flow system. Wells 602, 118, and 804 are essentially completed in water-table aquifers that receive recharge directly from percolation. Potential recharge to the water table is affected by precipitation intensity and duration, land slope, vegetation, and soil-moisture conditions. Recharge potential is probably smallest at the forested hillside site (well 118) and largest at the flat, grassed, valley site (well 804) where surface runoff tends to collect.

Recharge potential at the sparsely forested hilltop site (well 602) is probably in between that of the hillside and valley sites. Recharge is also proportional to soil-moisture content. Water-table levels respond more readily to rain during moist soil conditions, such as in June (fig. 3.2-1), than during dry soil conditions, such as in mid-July.

Specific yields of the bedrock water table aquifers penetrated by wells 602 and 118 probably are similar, and the differences in water-level response to recharge may be due to differences in infiltration. However, alluvial aquifers generally have larger apparent specific yield than shallow bedrock aquifers in Greene County. This could explain why water-level rises are larger in bedrock well 602 than in alluvial well 804, even though recharge from the same rainfall event may be larger at well 804.

Well 803 is completed in a confined aquifer about 100 feet below the water table. Daily water-level fluctuations are small in comparison to the other three hydrographs and correlation to rainfall is not readily apparent. Confined aquifers have storage coefficients that are usually several orders of magnitude smaller than the specific yield of water-table aquifers. Given the same recharge, water-level rises are expected to be much greater in a confined aquifer. However, recharge to confined aquifers is generally much slower and smaller than that received by the overlying water-table aquifer. Water-level rises observed in well 803 represent small pressure changes and slow leakage applied through the confined layers.

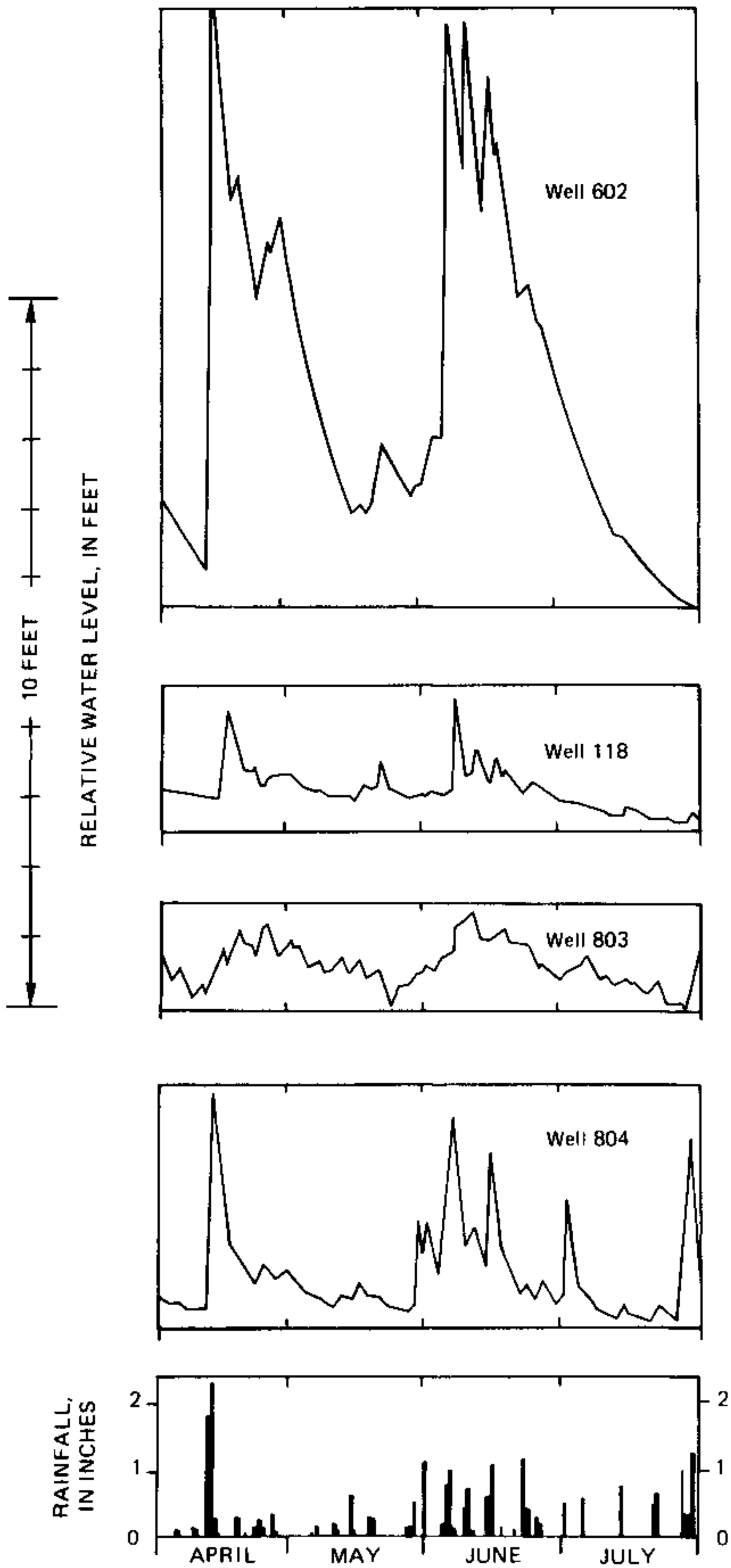


Figure 3.2-1.— Comparison between water-levels in wells and daily rainfall.

The number and type of aquifers tapped by a well must be defined before aquifer-storage changes due to natural or mining-related conditions can be accurately evaluated. Bedrock wells, with large open-hole intervals, effectively tap and interconnect a number of aquifer units. Such an open-hole well, located along a hilltop, functions like a leaky cistern, in which the well bore receives recharge water rapidly from the shallow aquifers and loses the water more slowly to deeper, less permeable aquifer zones. The hydrograph of well 602 may show this cistern effect to a certain extent. The water level in another hilltop well (not shown), which is 165-feet deep and has only 21 feet of casing, rises as much as 45 feet in less than a day and takes more than a month to return to the original level. Such a well may poorly represent storage changes within all aquifer units open to well. Many existing domestic and stock wells in Greene County are constructed by the open-hole method to provide greater yield and well storage.

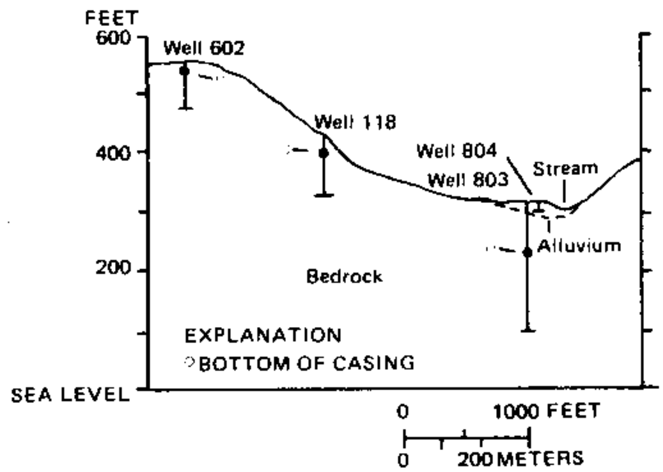


Figure 3.2-2.— Representative topographic setting of observation wells.

3.0 GROUND-WATER HYDROLOGY

3.3 AQUIFER IDENTIFICATION

FRACTURE PERMEABILITY COMMONLY ASSOCIATED WITH SANDSTONES AND COALS

Well and spring inventory, test wells and borehole geophysical logs are used to locate water-bearing zones in bedrock.

Bedrock in the study area normally yields water to wells and springs through discrete fractures such as joints and bedding-plane openings. Waterbearing zones are most common in fractured sandstone and coal but also occur at changes in lithology. Shale, mudstone, and dense limestone are usually confining layers. Therefore, lithology can be used to correlate aquifer units across an area.

Well and spring inventory is a relatively inexpensive and rapid method of identifying aquifers. The types of data obtained and presented in the U.S. Geological Survey water-resources reports is shown in table 3.3-1. Other sources of such data include water-well completion reports, U.S. Department of Agriculture Soil Conservation Service spring records, and field inventory. The types of data provided by each of these sources are indicated in table 3.3-1. Complete inventory coverage is rarely achieved from any single source. Current information on water levels, discharge rates, use status, and ownership are best obtained by field checking. Locations are plotted on 7½-minute topographic quadrangle maps and latitude, longitude, and altitude of land-surface elevation are determined.

Springs and shallow wells can be used to locate water-table or perched water-table aquifers. Springs and seeps that occur at the same altitudes along a hillside are usually the result of local perched aquifers. Generally, the water table ranges from 25 to 70 feet below the surface along hilltops and is less than 10 feet below the surface in valleys. Most aquifers below the water-table aquifer are confined by underlying and overlying less permeable beds.

Test wells provide a more reliable method of identifying aquifers, particularly in areas where wells are few or nonexistent. An example of the pertinent hydrogeologic and well-construction information for confined sandstone aquifer units is indicated in figure 3.3-1. The descriptions of drill cuttings and geophysical logs were used to construct the detailed columnar section. The most useful geophysical logs for ground-water study in Greene County included gamma, density, electric, temperature, and caliper. Application of these and other logs to ground-water work is described in (7). Columnar sections from several wells may be used to draw a cross section, which helps to describe the location of a particular aquifer unit and its relative continuity with respect to a minable coal seam.

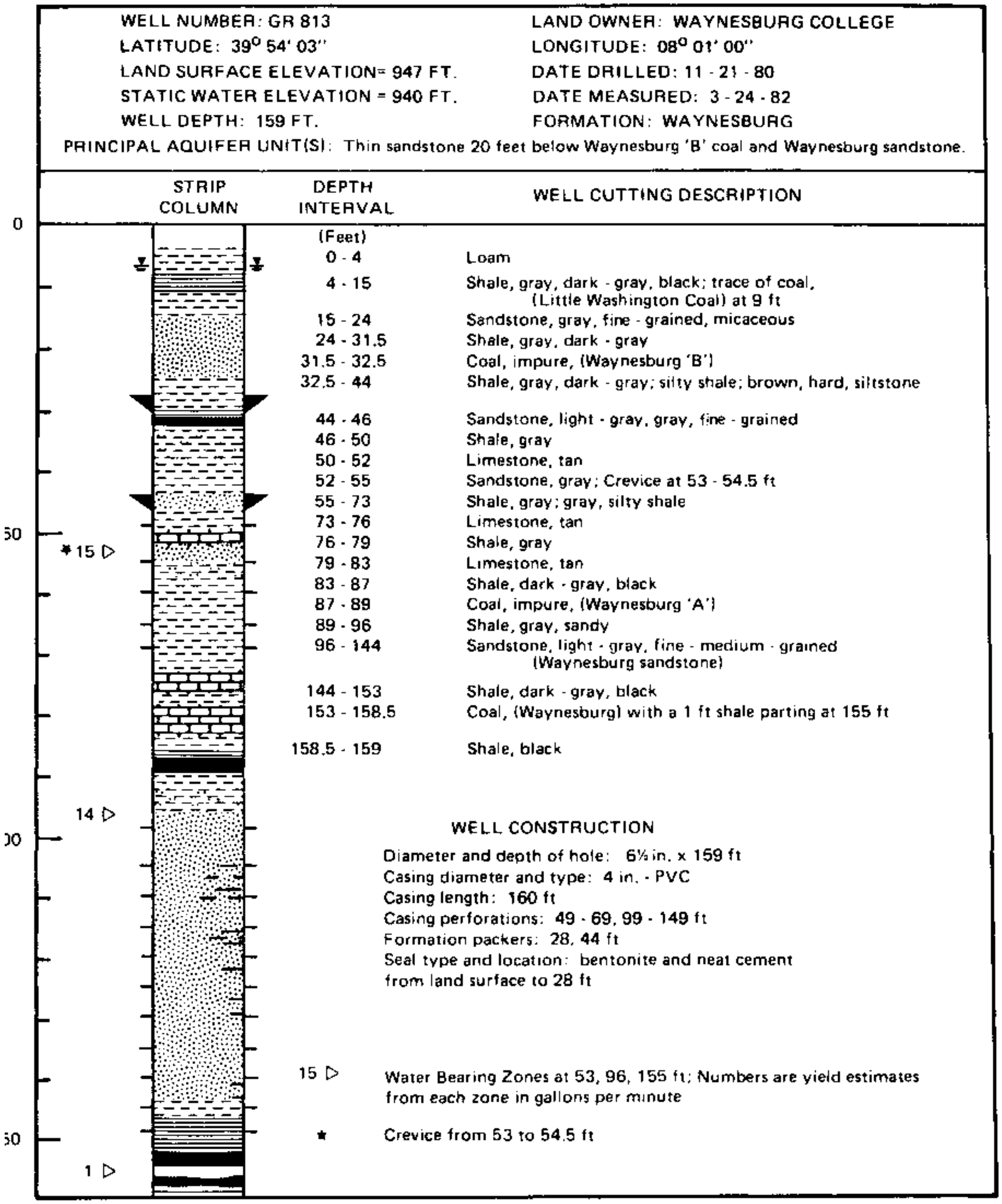


Figure 3.3-1.— Lithology and well-construction information for test well GR 813 in Franklin Township.

Table 3.3-1. – Record of selected wells and springs from the Greene County study.
[gal/min, gallons per minute; gal/min/ft, gallons per minute per foot of drawdown;
Data source: D, driller's water-well completion report; F, field visit and property owner interview; S, Soil Conservation Service spring records]

Well number (Well location)	Latitude (Well location)	Longitude (Well location)	7½ minute quadrangle map name (Well location)	Owner	Driller	Year completed	Use	Altitude of land surface above sea level (feet)	Topographic setting	Aquifer	Aquifer lithology
Data Source			F	D,F	D,F	D,F	F	F	F	F	
116	395257	802700	Wind Ridge	Ryerson State Park	Pa. Drilling Co.	1962	P	999	V	Wbrg	sandstone
322	395543	802352	Wind Ridge	Ross, David	E. Byron Braddock	1977	H	1,154	S	Wsng	sandstone
365	395617	802258	Wind Ridge	Minton, Robert	E. Byron Braddock	1977	U	1,136	V	Gren	sandstone and shale
402	395132	801158	Oak Forest	Orndoff, Charles	—	—	S	973	V	Pbrg	limestone, sandstone and shale
510	395243	802313	Wind Ridge	Robinson, Barbara	Allen Burns	1976	H	1,210	S	Gren	limestone
516	395456	802916	Wind Ridge	Parley, Frank	E. Byron Braddock	1977	H	912	V	Wbrg	sandstone
519	395439	802614	Wind Ridge	Staggers, Anna	E. Byron Braddock	1969	H	1,380	S	Gren	shale
533	395309	802933	Wind Ridge	Weekly, Roger	E. Byron Braddock	1978	H	1,340	H	Gren	shale
654	395538	802226	Rodgersville	Miller, D.	Steve Harman	1978	U	1,070	V	Gren	shale
727	395510	802928	Wind Ridge	Barnhart, Harold	E. Byron Braddock	1977	H	920	S	Unnn	limestone, sandstone and shale
801	395259	802706	Wind Ridge	USGS	Stockert Drilling Co.	1980	O	1,011	H	Wbrg	sandstone and shale
802	395812	802649	Wind Ridge	USGS	Stockert Drilling Co.	1980	O	946	V	Wbrg	sandstone and shale
804	395807	802652	Wind Ridge	USGS	Stockert Drilling Co.	1980	O	939	V	Alvm	sand, gravel and clay

Well number	Well depth below land surface (feet)	Casing: Depth (feet)	Casing: Diameter (inches)	Depth to water-bearing zones (feet)	Static Water Level: Depth below land surface (feet)	Static Water Level: Date measured	Yield (gal/min)	Specific Capacity (gal/min/ft)	Specific Conductance (micromhos at 25˚ C)	PH (units)
Data Source	D,F	D		D	F		D,F	D	F	F
116	138	19	12	95; 115	36	10/69	6	0.40	2,190	8.6
322	80	17	8	40	30	9/79	1	—	435	—
365	76	23	8	30; 50	30	9/77	4	—		—
402	600	7	3.5	—	F	9/81	1	—	780	7.5
510	74	25	8	35; 51	—	—	2	—	580	—
516	53	18	10	32	18	10/79	6	—	360	6.4
519	40	—	8	26	10	3/69	20	.80	1,680	—
533	184	22	8	85	54	2/80	2	.08	425	7.5
654	60	1	4	—	0.3	5/80	6	1.2	690	9.1
727	79	—	5	—	63	7/80	1	—	330	7.2
801	163	10	6.5	—	47	10/80	1	.02	1,750	8.6
802	218	18	6.5	98; 118	10	12/81	45	2.2	11,000	7.6
804	19	4	6.5	—	5	12/81	4	1.6	725	7.4

Remarks:
Owner: USGS, U.S. Geological Survey
Use: H, domestic; P public; S, stock; O, observation; U, unused
Topographic setting: H, hilltop or ridge; S, hillside; V, valley.
Aquifer: Formation names:
Pbrg, Pittsburgh;
Unnn, Uniontown;
Wbrg, Waynesburg;
Wsng, Washington;
Gren, Greene;
Alvm, alluvium.
Static water level: F, flowing.

Spring number (Spring location)	Latitude (Spring location)	Longitude (Spring location)	7½ minute quadrangle map name (Spring location)	Owner	Use	Altitude of land surface (feet)	Aquifer	Permanence	Improvements	Date yield measured (M) or estimated (E)	Yield (gal/ min)	Date quality parameters measured	Specific conductance (micromhos at 25 ˚C)	PH (units)
Data Source:	S,F			S,F	S,F	F	F	F	F	S,F	F	F	F	F
1303	395112	801520	Holbrook	Greenlee, Dr. P.	S	1,360	Gren	Perennial	Trough	E 10/25/79	1.5	10/25/79	750	7.6
1304	395105	801645	Hol brook	Shriver, Ephriam	H	1,100	Gren	Intermittent	Trough	M 10/25/79	.1	10/25/79	520	7.2
1701	395619	802430	Wind Ridge	Whipkey, Reed	H	1,180	Wsng	Perennial	Other	M 11/21/80	2.0	11/21/80	390	7.7
1702	395624	802425	Wind Ridge	Whipkey, Reed	U	1,200	Wsng	Intermittent	None	M 11/21/80	.0	11/21/80	220	7.0
1798	395239	802303	Wind Ridge	Richardson, Lester	U	1,160	Gren	Perenial	Spring House	E 8/28/81	.1	8/28/81	450	7.3
2000	394527	801931	Holbrook	George, Norman	H	1,080	Gren	Perenial	Spring House	M 9/ 1/81	1.0	9/ 1/81	235	7.5
2305	394659	802925	New Freeport	Yoss , Elmer	H	1,440	Gren	Perenial	Trough	M 8/27/81	.1	8/27/81	325	8.2

3.0 GROUND-WATER HYDROLOGY

3.4 ESTIMATION OF AQUIFER PROPERTIES

AQUIFER TEST METHODS USED TO ESTIMATE TRANSMISSIVITY AND STORAGE COEFFICIENTS

Time-drawdown, specific capacity, recovery, and slug tests provide estimates of aquifer characteristics. Borehole storage, well development, and impermeable boundaries are common test considerations.

Quantitative evaluation of ground-water flow requires a knowledge of hydraulic coefficients, such as transmissivity (T), storage (S), and apparent specific yield (S_{ya}). Several controlled well tests were used to estimate these characteristics in Greene County. The following examples illustrate methods and analysis found to be most useful in the bedrock aquifers.

A two-well aquifer test was designed to determine the continuity and to estimate hydraulic coefficients of the Waynesburg Sandstone Member of the Washington Formation near Ryerson Station State Park, western Greene County. The pumped well was an existing Park water-supply well (116) that is open to the lower Waynesburg Formation containing 45 feet of Waynesburg Sandstone. An observation well (801) was drilled 435 feet distant (fig. 3.4-1) to a depth of 159 feet and completed in the same stratigraphic unit. Before drilling the observation well, a procedure outlined in (10), was used to estimate the time rate of expansion of the cone of depression to help determine an appropriate distance between the pumping well and the observation well for the aquifer test. Values of transmissivity between 0.1 and 20 ft^2/d and storage coefficient between 10^{-5} and 10^{-4} (for confined aquifers), and a pumping rate of 7 gal/min were used in the analysis.

The Waynesburg Sandstone Member is mostly silty to sandy shale at well 801, which differs markedly from the medium- to coarse-grained sandstone tapped by well 116. Well development of well 801 indicated a yield of less than 1 gal/min or 10 times less than the reported yield of well 116. At such a small low yield potential, well 801 obviously could not be used as the pumping well for the aquifer test. Well 801, nevertheless, was suitable as an observation well for pumping well 116, as the drawdown rate in well 801 was expected to be small.

Tests were first conducted on well 801 for later comparison to the two-well test. In addition to surging with air by the driller, the well was overpumped a number of times to ensure full development. A slug-test method, adapted from (3) and outlined in (8), was conducted by quickly injecting a weighted pipe capped at both ends that had a volume of 0.200 ft. The timed water-level response and sample calculation of transmissivity and storage are shown in figure 3.4-2. This test method explicitly considers well-bore storage and was found to work well in small-yielding aquifers where the water-level response occurred entirely within tightly sealed casing. However, slug tests in which the water level fluctuated in the open hole (below the bottom of casing) or in poorly sealed casing generally did not plot on any of the theoretical type curves. Under such conditions, the measured response may not represent the intent of the method.

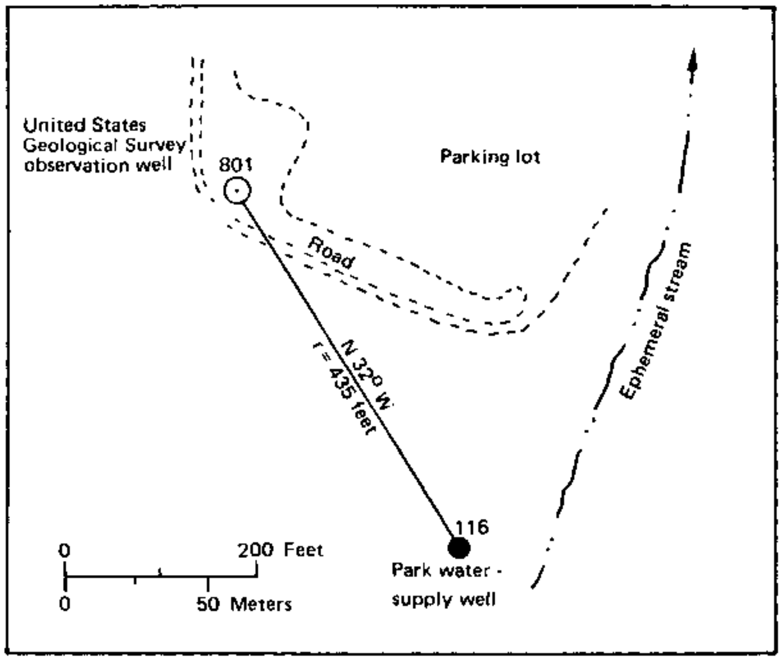


Figure 3.4-1.— Location of aquifer test site at Ryerson Station State Park.

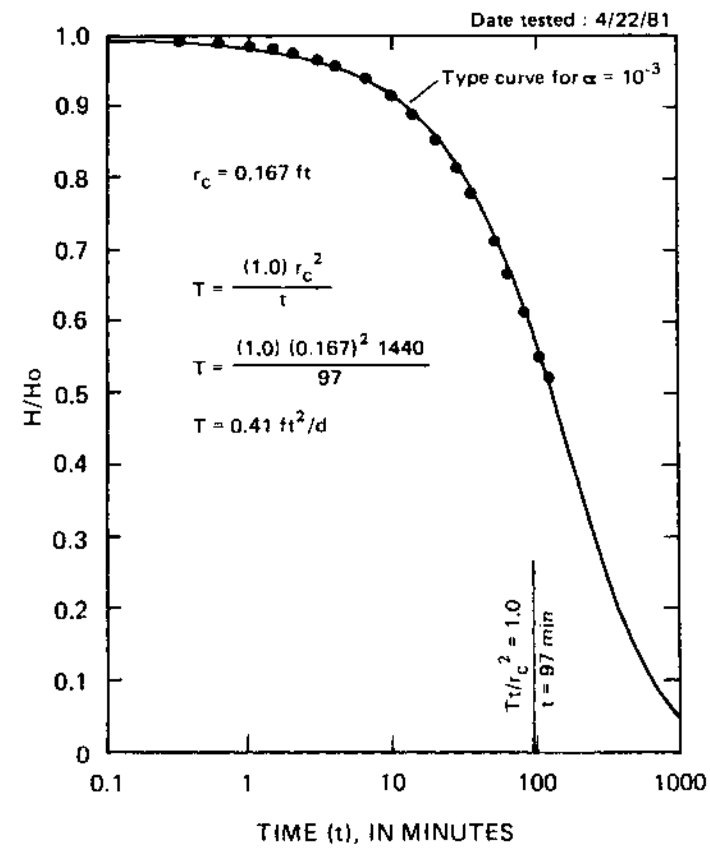


Figure 3.4-2.— Slug-test plot from well 801.

Antecedent water-level trends determined for several hours prior to a slug test were useful for correcting the slug-test water-level response. The slug test has limitations in that it provides hydraulic properties of an aquifer only very close to the well borehole. Furthermore, the determination of storage coefficient is quite sensitive to personal judgment in curve matching (3). Nevertheless, the slug-test method is simple, gives reasonable results in properly developed wells, and can add corroborative support to other tests.

Specific-capacity and recovery tests were also tried at well 801. Borehole storage contributed much of the water during the drawdown pumping. Drawdown data after 40 minutes of pumping gave results similar to the slug test. The recovery test resulted in a value one order of magnitude less than the transmissivity determined by the slug-test results. The transmissivity of the lower Waynesburg Member aquifer, which is 44 feet thick near well 801, is probably between 0.04 and 0.4 ft^2/d.

Periodic pumping with normal use of the Park supply well results in a drawdown response at well 801 about 2 hours after pumping starts. From this information and development-test data of well 116, a reasonable pumping rate was estimated which would provide sufficient time-drawdown data at well 801 without dewatering the pumping well 116. The Park supply well was taken offline 1½ days before the aquifer test to allow some recovery of the aquifer system from that use. Figure 3.4-3 shows the time-drawdown response of both wells as a result of pumping well 116 at a constant rate of 9.8 gal/min for 780 minutes.

With the exception of the first two measurements, the drawdown data from the observation well match the Theis type curve. However, the early time data from the pumping well match poorly to the Theis curve. Discharge was controlled to within 2 percent of 9.8 gal/min during the test except during the first minute of pumping when it was much larger. Furthermore, the water level dropped below the bottom of the casing of the pumping well early in the test. Both conditions provide a plausible explanation of the poor early time fit with the Theis curve. Use of the delayed yield from storage type-curve procedure (2, 8) or matching the Theis curve to late-time data gives a transmissivity estimate larger but in the same order of magnitude as that determined from the observation-well data.

The Jacob analysis method (10) was also applied to the same aquifer-test data (fig. 3.4-4). The value of transmissivity obtained from the pumping well is practically the same as that determined by the Theis method for the same well. However, the value of transmissivity on the observation-well data as determined from the Jacob method (false T in fig. 3.4-4) is more than twice the value. Recall that one restriction of the Jacob method (10) is that:

$$\frac{r^2}{4at} < 0.01$$

where $a = \frac{T}{S}$ for confined aquifers,

and $a = \frac{T}{S_{ya}}$ for unconfined aquifers

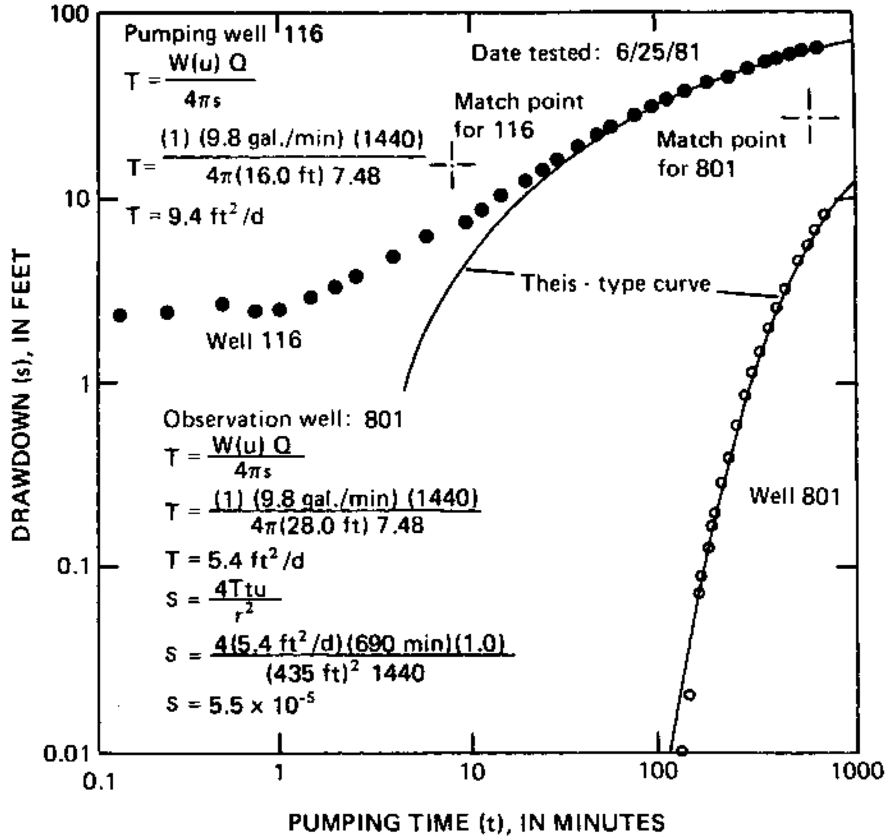


Figure 3.4-3.— Drawdown plots of pumping well 116 and observation well 801.

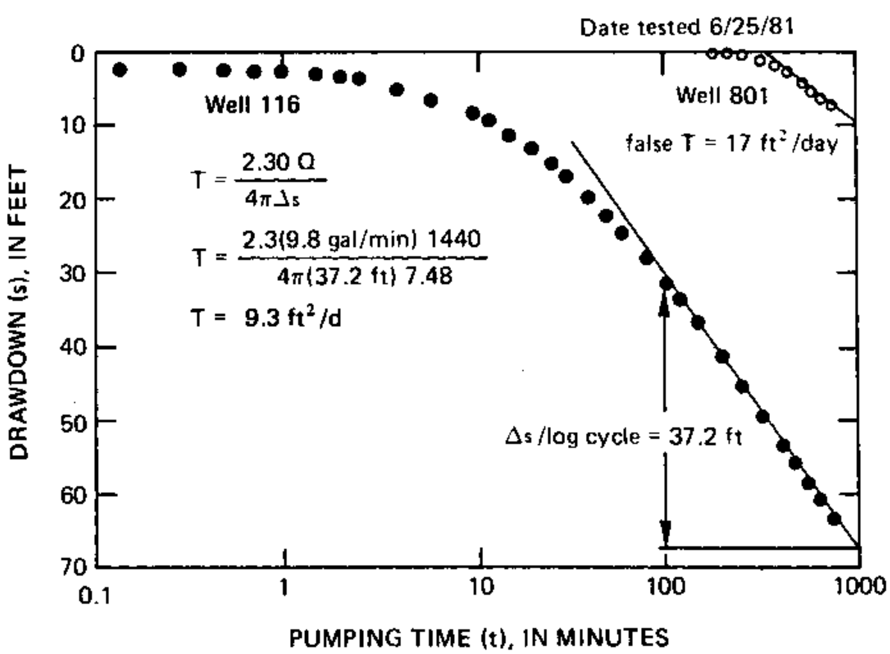


Figure 3.4-4.— Jacob method of analysis for the Ryerson Station State Park aquifer test.

Assuming $T = 17 ft^2/d$, $S = 4.9x10^{-5}$ and r = 435 feet, the minimum test duration time for the Jacob method to be applicable, theoretically, would be 19,700 minutes or 13.7 days.

Recovery data were measured at a different well, which is completed in the Waynesburg Sandstone Member on a hillside. Well 811 was pumped at a constant rate of 1.2 gal/min for 720 minutes. The drawdown data did not plot in a smooth curve so recovery data were collected to corroborate the specific-capacity results. The Theis recovery method (10) was used on the late-time data (fig. 3.4-5). Theoretically, the data will fall on a line passing through the point where s= 0 and $\frac{t}{(t-t_2)} = 1$

where t = time since pumping began, and
t_2 = time when pump was turned off and water level started recovering. Deviations from this, as indicated in figure 3.4-5, may be explained by storage changes during pumping (6).

Specific capacity after 1 hour of pumping was compared to transmissivity estimated for the same well at several sites in Greene County (fig. 3.4-6). The theoretical relationships described in (14) and (15) are also shown. To minimize the effects of borehole storage, most of the transmissivity values are derived from pumping longer than 1 hour or from recovery data. The 1-hour specific capacities have not been corrected for borehole storage, which probably explains the lack of fit of the data to the theoretical relationship. The effects of borehole storage decrease with pumping time, and a consistent method of correcting the effects is difficult to determine. Transmissivity estimated by the specific-capacity method may be as much as two orders of magnitude too large if well-bore storage is not considered. The specific-capacity method, nevertheless, can provide rough estimates of transmissivity.

The hydraulic characteristics determined from well 801 data in response to controlled pumping of well 116 are the most representative results of the well methods presented. Such multiple-well tests give the best average results over the largest volume of the aquifer tested. In addition, the effects of well-bore storage are practically negligible and overall aquifer homogeneity, isotropy and continuity can be evaluated. Two-well aquifer tests performed in valley settings commonly produce a time-drawdown response that plot nearly as straight lines on log-log paper. Such a response is probably due to the drawdown cone intercepting lesser permeability aquifer zones beneath the hills adjacent to the valley. Such test results are difficult to analyze for hydraulic coefficients by the usual documented methods.

With regard to overall method application and accuracy of results, the order of preference among the single-well tests presented are: (1) Theis recovery, (2) specific capacity or Theis and Jacob drawdown, and (3) slug. A combination of single-well methods, such as specific capacity and recovery, provided added data for comparison at small additional cost. Thus, for well 801, $T = 5.4 ft^2/d$ determined from the Theis method is preferred over $T = 0.41 ft^2/d$ determined from the slug test (figs. 3.4-2 and 3.4-3).

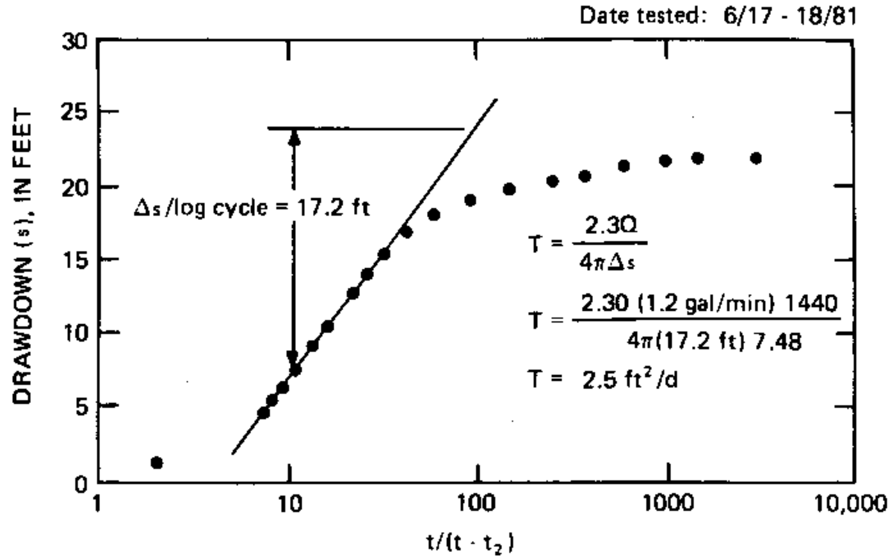


Figure 3.4-5.— Theis recovery method of analysis on well 811 test.

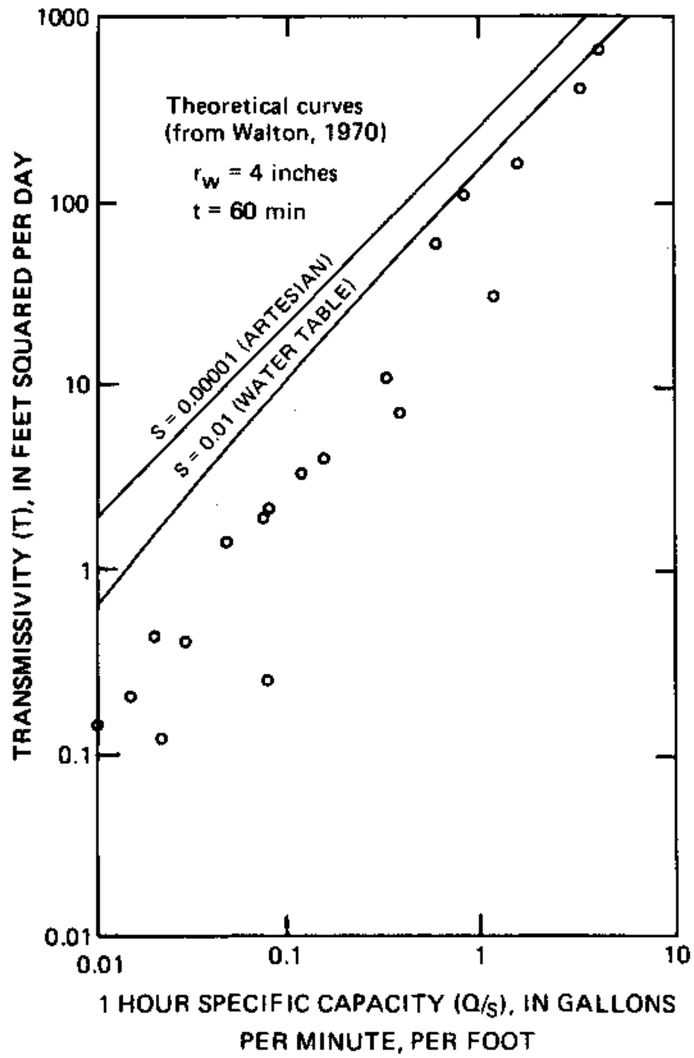


Figure 3.4-6.— Comparison of transmissivity to one-hour specific capacity determined by pumping tests in Greene County.

3.0 GROUND-WATER HYDROLOGY

3.5 CHEMICAL QUALITY OF GROUND WATER

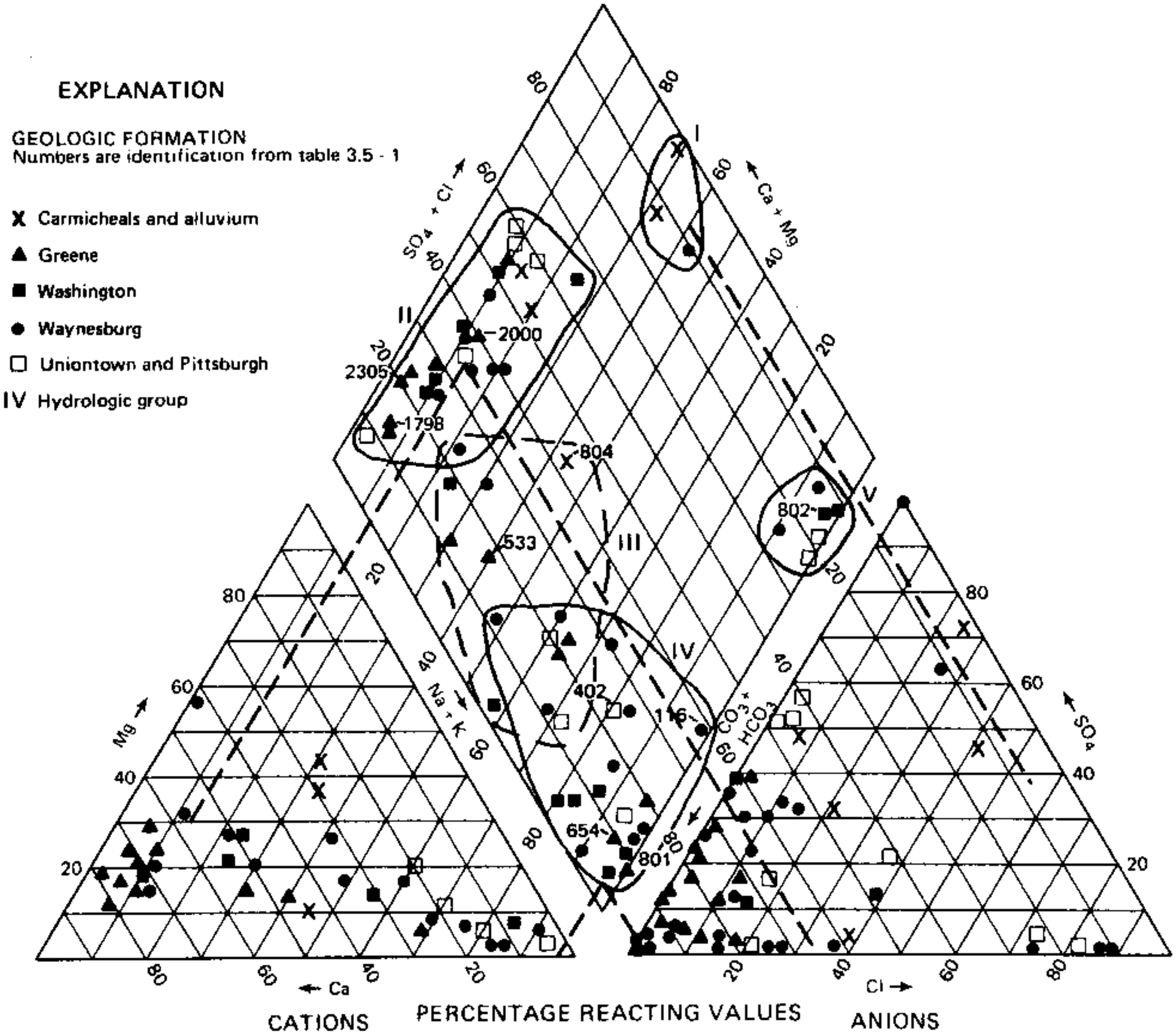
CHEMICAL CHARACTER VARIES ALONG FLOW PATH

The percentages of calcium, magnesium, and sulfate decrease, whereas sodium, bicarbonate, and chloride increase with time and distance from areas of recharge. Dissolved solids and pH generally increase with residence time.

Chemical data pertaining to ground water in Greene County were collected to determine natural variation and to establish general baseline conditions from which the changes attributed to future mining could be determined. Table 3.5-1 shows the analyses and associated pertinent information for representative samples collected from wells and springs. Other data relevant to ground-water sampling include the site latitude and longitude, land-surface altitude, well depth and diameter, and the open or perforated interval of the well. This information was included in the well and spring inventory tables of section 3.3.

All the well samples were collected after at least two times the volume of well-bore storage was removed in order to obtain representative aquifer water. For small-capacity wells, the well was allowed to recover before repumping it to collect the sample. Domestic wells, which receive daily use, were pumped until plumbing was flushed. Storage tanks were bypassed when possible, and samples were not collected if the water had been treated by softening or filtering. Standard U.S. Geological Survey methods were used for field determinations, sample preparation, and laboratory analysis, (12, 16).

The results of 61 analyses were plotted on a trilinear diagram (5) and (11) to evaluate possible chemical trends in natural ground water. The basic water types appear to be independent of the individual geologic formations sampled (fig. 3.5-1). Coal aquifers commonly yield sulfate water and limestone aquifers commonly contain large concentrations of bicarbonate. Evaluation of the data shows a general trend along the ground-water-flow path. Moving from recharge (Group I) through intermediate residence time (Group III) to regional discharge (Group V), the principal ions change from mostly calcium, magnesium, and sulfate to sodium, bicarbonate, and chloride. Furthermore, dissolved solids and pH generally increase with residence time (fig. 3.5-1).



-------> INCREASING RESIDENCE TIME---------> ------->

	HYDROLOGIC SETTING				
	Recharge	Intermediate			Discharge
Group	I	II	III	IV	V
Topographic Setting	Terrace Hilltop	Hilltop	Hillside Upland Valley	Valley	Valley
Relative Depth of Sample (feet)	0 - 50	25 - 175	10 - 150	10 -	100 -
Group Means of dissolved solids (milligrams per liter)	120	280	425	527	5450
Field pH (units)	5.6	6.7	7.5	8.3	7.7

Figure 3.5-1.— Trilinear plot and characterization of natural ground-water quality sampled in Greene County.

Table 3.5-1– Chemical quality of ground water from selected springs and wells in Greene County, [ft, feet; gal/min, gallons per minute; mg/L, milligrams per liter]

General Data						Field Determinations						
Site type	Local number	Date	Time	Aquifer	Lithology	Static water level (ft below land surface]	Discharge (gal/min)	Temperature (˚C)	Total alkalinity (mg/L)	Total acidity (mg/L)	Specific conductance (micromhos)	PH (units)
Spring	1798	8-28-81	1230	Wsng	Lssdshl	—	0.1	18.0	200	14	450	7.3
Spring	2000	9-01-81	1000	Gren	Sdshl	—	1.0	16.0	66	8.0	235	7.5
Spring	2305	8-27-81	1330	Gren	Sdshl	—	.1	19.0	120	0	325	8.2
Well	116	6-25-81	1500	Wbrg	Snds	36.50	9.8	13.5	640	0	2,190	8.6
Well	402	8-26-81	1300	Pbrg	Lssdshl	F	1.1	20.5	310	9.0	735	7.9
Well	533	3-05-80	1430	Gren	Shale	54.21	2.0	12.0	87	10	425	7.5
Well	654	5-15-80	1340	Gren	Shale	.28	6.7	13.0	320	0	690	9.1
Well	801	7-10-80	1015	Wbrg	Sdshl	50.70	1.1	13.5	770	0	1,750	8.6
Well	802	10-02-80	1330	Wbrg	Sdshl	9.70	11	12.0	790	50	11,000	7.6
Well	804	9-29-80	1545	Alum	Sgvc	4.67	4.4	13.5	200	1.0	725	7.4

Remarks:
Aquifer formation names: Wsng, Washington; Gren, Greene; Pbrg, Pittsburgh; Wbrg, Waynesburg; Alvm, alluvium.
Lithology: Snds, sandstone; Sdshl, sandstone and shale; Lssdshl, limestone, sandstone, and shale; Sgvc, sand, gravel, and clay.
Static water level: F, flowing.
* ion used in trilinear plot.
< less than.

General Data			Laboratory Determinations													
Local number	Date	Time	Specific conductance (micromhos)	PH (units)	Dissolved iron (mg/L as Fe)	Total iron (mg/L as Fe)	Dissolved manganese (mg/L as Mn)	Total manganese (mg/L as Mn)	Calcium* (mg/L as Ca)	Magnesium* (mg/L as Mg)	Sodium* (mg/L as Na)	Chloride* (mg/L as Cl)	Bicarbonate* (mg/L as HCO_3)	Sulfate* (mg/L as SO_4)	Hardness as $CaCO_3$	Dissolved solids (mg/L)
1798	8-28-81	1230	408	8.1	0.02	0.15	0.01	0.01	71	13	6.6	1.0	250	30	230	254
2000	9-01-81	1000	226	8.0	.02	.13	<.01	<.01	34	38	5.2	1.4	81	42	100	148
2305	8-27-81	1330	284	8.4	.03	.35	.05	.11	46	5.4	3.0	2.8	150	29	140	196
116	6-25-81	1500	2,060	8.4	.06	.08	.01	.01	2.5	0.9	500	290	760	7.0	10	1,240
402	8-26-81	1300	720	8.1	.25	.34	.02	.01	23	3.9	140	64	380	.9	74	433
533	3-05-80	1430	448	8.3	.07	1.2	<.01	.05	50	7.6	47	1.2	260	35	160	281
654	5-15-80	1340	693	8.8	.18	7.5	.01	.23	2.3	0.3	160	29	380	6.8	7	412
801	7-10-80	1015	2,920	8.3	.01	1.5	.01	.02	1.0	0.5	430	98	910	5.2	5	1,060
802	10-02-80	1330	12,000	7.6	.41	.15	.04	.05	24	15	2,700	3,700	960	19	130	6,670
804	9-29-80	1545	696	7.5	.02	2.7	.13	.23	65	8.6	45	94	250	15	200	364

4.0 PROBABLE HYDROLOGIC CONSEQUENCES

4.1 ACTIVE MINING

GROUND-WATER FLOW INTO UNDERGROUND MINES IS COMPLEX

Mining related water level declines in wells above mines depend on the thickness of bedrock between the mine and the well bottom and the amount of secondary permeability induced by coal excavation. Mining can cause increases in water acidity and mineralization.

Ground-water levels have been recorded in wells over three active underground mines in Greene County. The type of mining and the distance between the well bottom and the mined coal seam differ at each site (fig. 4.1-1). Generally, the magnitude of water-level decline is expected to be inversely proportional to the thickness of bedrock between the mine and the well bottom, as indicated by the hydrographs of wells GR 253 and GR 543. In addition, the retreat (pillar removal) and long-wall method of mining may induce fracturing above the coal seam, thus hydraulically connecting shallow aquifers to the deep mine. Such conditions may explain why no decline is seen in well GR 118, which is 240 feet above room and pillar mining, and a 10-foot decline is seen in well GR 543, which is 608 feet above long-wall mining. The 5- to 8-foot declines (labeled D in fig. 4.1-1) on the well GR-118 hydrograph are caused by summer droughts. During the time of the 1981 drought, the closest long-wall mining activity was about 620 feet distant from the vertical projection of well GR 543. The close correlation of the water-level response to the well GR 118 hydrograph indicates that the drought was the dominant cause of the water-level decline, however.

The decline and recovery observed in January 1982 at well GR 543 correlate closely with test drilling that penetrated the same formations 845 feet away. A large quantity of formation water was reportedly removed during drilling before the test hole was cased.

The third decline and recovery (March and April, 1982) correlate closely to long-wall mining directly beneath well GR 543 (fig. 4.1-1). The rapid decline probably is related to increased vertical permeability caused by mining-induced fracturing. The water level, however, recovered 8 feet in less than a day. At that time, mining had advanced beyond the vertical projection of well GR 543 by about 100 feet. The rate and appearance the recovery might be explained by (1) reduction of vertical permeability of strata overlying the mine coupled with complex interflow between various aquifers of the open-hole well, or (2) small land subsidence. Both explanations are plausible at well GR 543, although surface subsidence had not been verified.

Ground-water-quality changes caused by coal mining in Greene County usually are related to the oxidation of pyrite and subsequent increase in acidity. Greater acidity leads to increased dissolved solids including dissolution of heavy metals such as iron and manganese. Natural ground water near potential surface mines will likely have small concentrations of dissolved solids and large changes in chemistry, owing to the common acidity problem caused by mining. Table 4.1-1 is an example of post-mining water chemistry from a spring below mine spoils. The spring flows from a hillside near the altitude of the underclay to the mined coal. Underground mines, on the other hand, are near ground water of naturally large alkalinity that neutralizes the acid. Disposal of mine inflow having large natural dissolved-solids concentration and leaching of waste refuse piles at land surface are the usual ground-water quality problems associated with subsurface mining.

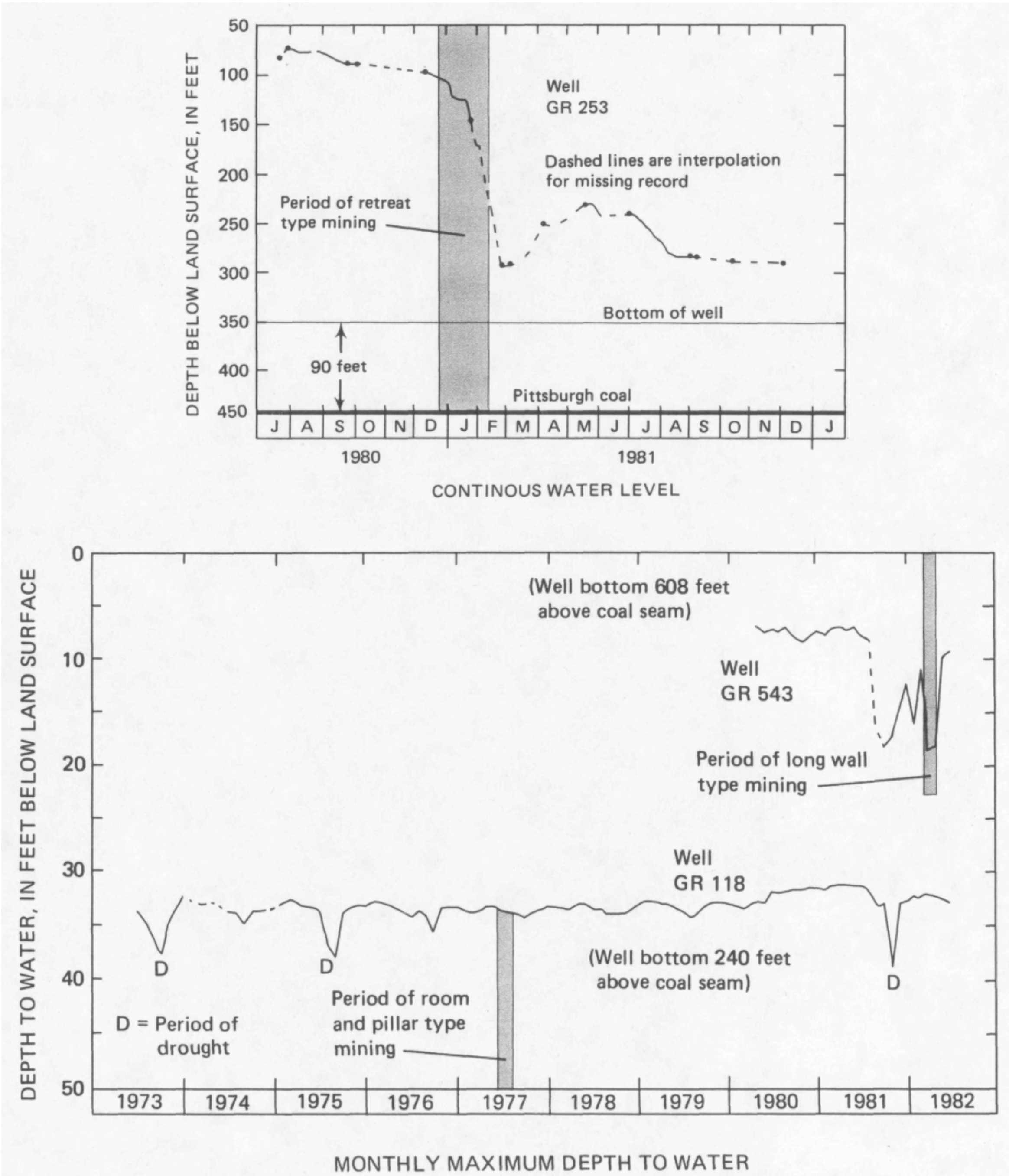


Figure 4.1-1.— Water-level changes above subsurface mining.

Table 4.1-1.– Chemical quality of spring discharge below subsurface mine spoils in Greene County
(concentrations in milligrams per liter except where indicated)
[gal/min, gallons per minute; ˚C, degrees Celcius]

GENERAL DATA	
Local number	599
Date	8-27-81
Time	0830
FIELD DETERMINATION	
Discharge (gal/min)	4.5
Temperature (˚C)	16.0
Total alkalinity	0.0
Total acidity	1,860
Specific conductance (micromhos at 25 ˚C)	7,000
pH (units)	2.8
LABORATORY DETERMINATIONS	
Specific conductance (micromhos at 25 ˚C)	5,940
pH (units)	2.6
Dissolved iron (Fe)	.27
Total iron (Fe)	.26
Dissolved manganese (Mn)	.26
Total manganese (Mn)	
Calcium (Ca)	390.29
Magnesium (Mg)	370
Sodium (Na)	11
Chloride (CD	9.1
Bicarbonate (HCO_3)	0.0
Sulfate (S04)	5,800
Hardness (as $CaCO_3$)	2,500
Dissolved soilds	9,630

4.0 PROBABLE HYDROLOGIC CONSEQUENCES

4.2 FUTURE UNDERGROUND MINING

HYDROLOGIC EFFECTS CAN BE ESTIMATED WITH A CROSS-SECTIONAL FLOW MODEL

Drawdown gradients are steep near the mine opening and decrease rapidly with distance away from the mine. Vertical fracture zones could accelerate drawdowns locally.

A two-dimensional cross-section digital model was used to test general ground-water flow concepts and to estimate hydrologic effects of a hypothetical subsurface mine. The digital finite-difference program used for the model is documented in (13). Partial results and discussion from the Greene County study are presented herein to illustrate the use of a two-dimensional model for simulating ground-water flow near subsurface coal mining.

The cross section was designed to generalize the geometry and hydro-geology of western and central Greene County where future mining is expected. Boundary conditions and input data used to build the steady-state model are illustrated by figure 4.2-1. A primary assumption of this type of model is that all flow is in the plane of the section. The cross-section trace was made along the expected flow path of the shallow aquifer system, which follows the general topographic expression from hilltop to adjacent valley. The direction of flow in the regional aquifer system is probably more perpendicular to the plane of the cross section. Regional flow rates are slow relative to the local flow rates and the orientation of the cross-section is therefore most critical with the shallow-flow direction.

The errors contributed by the misalignment of regional flow direction to the model cross-section are expected to be insignificant for steady-state conditions. However, the model results for nonsteady-flow problems may significantly misrepresent actual conditions.

The water table is represented by constant head nodes located roughly along land-surface altitude. Values of head assigned to these nodes are from water-level data collected at shallow water wells located at various topographic settings. The basal and end boundaries of the model are no flow. The bottom is about 1,700 feet below average land-surface altitude, which is the average depth of the fresh water aquifer system according to oil and gas drilling data. The total width of the cross section is 16,500 feet. Coarser grids were tested, but could not be used to represent the flow system adequately near the undulating water-table surface.

The finite-difference grid indicated along the perimeter of the active flow model in figure 4.2-1 is oriented along stratigraphic bedding (flat-lying strata assumed). Grid spacing is uniform in the x-direction at 500 feet. Spacing in the z-direction increases with depth, ranging from 50 to 220 feet.

When a two-dimensional digital-model program is turned on its side to run a cross-sectional problem such as this one, the aquifer is confined and usually assigned a thickness of unity (1 foot in this example). Therefore, average hydraulic conductivity is used in place of transmissivity for the model input. Data from aquifer tests were used to set the initial framework

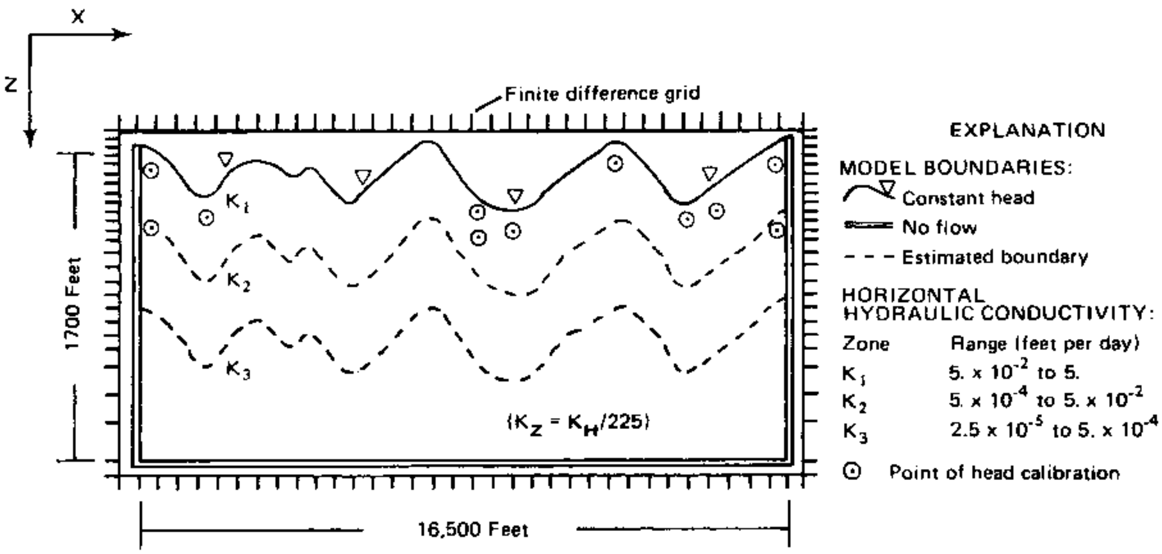


Figure 4.2-1— Input design and boundary conditions of two dimensional cross-section model.

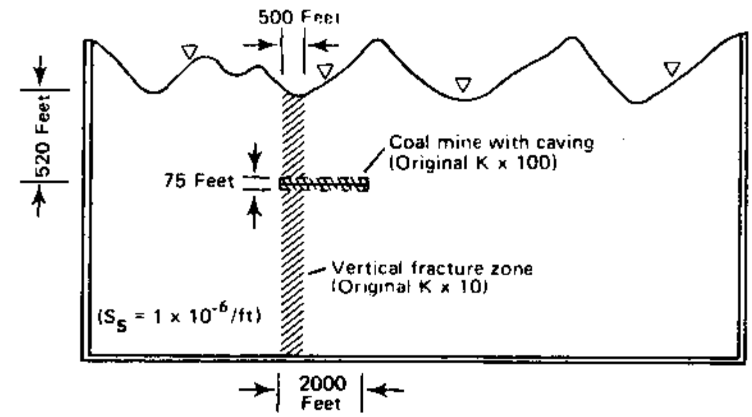


Figure 4.2-2.— Model features used to simulate subsurface mining and a vertical fracture zone.

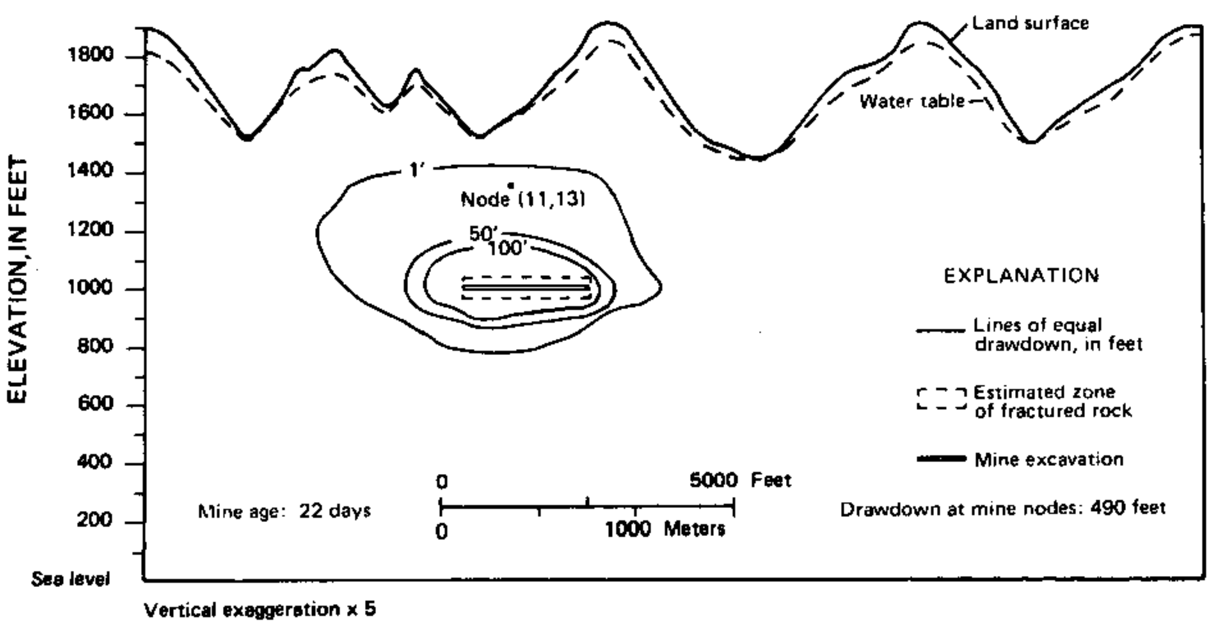


Figure 4.2-3.— Drawdown configuration 22 days after mining.

of the hydraulic-conductivity distribution throughout the cross section. These tests indicated that permeability decreased with depth below land surface and was relatively independent of geologic formation. In addition, horizontal hydraulic conductivity was allowed to be greater than vertical hydraulic conductivity in an attempt to represent the effects of multiple confining layers present in the aquifer system.

The combination of hydraulic-conductivity distribution and anisotropy shown in figure 4.2-1 gave the best overall calibration within $\pm$ 15 feet in the steady-state case and subsequent mine simulations. Steady-state calibration was accomplished by varying the average hydraulic-conductivity distribution and horizontal- to vertical-permeability ratio (anisotropy) until heads matched at the points indicated in figure 4.2-1 and discharge to hillsides and valleys matched mean annual base flow. The points of head calibration represent the average observation depth of cased wells located in similar topographic settings of Greene County. Average potentiometric heads with respect to local drainage level and land surface near the observation wells are assigned to the points shown in figure 4.2-1 for calibration. The greatest restrictions to the adjustment of hydraulic conductivity were near the water table of the model where most of the aquifer-test information was available. Hydraulic conductivity of the deep aquifers is relatively unknown and values used in the model were set closer to the higher range of expected values to provide a worst-case situation in terms of mining effects. The model is most sensitive to the anisotropy property. Although not based on field data, the ratio of 1 to 225 is within acceptable limits according to analytical models based on typical differences of hydraulic conductivity and thickness of aquifers and confining layers.

The relative position and dimensions of a hypothetical subsurface coal mine are shown in figure 4.2-2. The mine is simulated by constant head nodes with values set to the altitude of the mine nodes. This could effectively represent a typical set of entries driven in a direction perpendicular to the cross-section plane. The coal-seam thickness is not actually specified in the model, but is located near the center of a 75-foot thick zone that is assigned a horizontal and vertical hydraulic conductivity 100 times the pre-existing value. In this way, the model may better describe typical caving conditions associated with retreat or long-wall type mining.

A subsequent simulation was made to reflect the effects of a mine which intercepts a vertical fracture zone. The zone is represented in the model by assigning values of hydraulic conductivity 10 times larger than the preexisting values along a 500-foot wide column of finite difference blocks. Such a representation could be equivalent to a much narrower zone that has larger permeability. A specific storage (S_s) of $1x10^{-6}$ per foot was used for both mine simulations.

Drawdown results from the mine simulations are shown in figures 4.2-3 and 4.2-4 for mine ages of 22 days and 4 years, respectively. The drawdown is steep near the mine and gradients decrease rapidly away from the mine even after 4 years. Figure 4.2-5 shows the drawdown of the same mine that has intercepted a vertical fracture zone. Drawdown is effectively increased locally near the fracture zone and is expanded within the shallow aquifers above the mine.

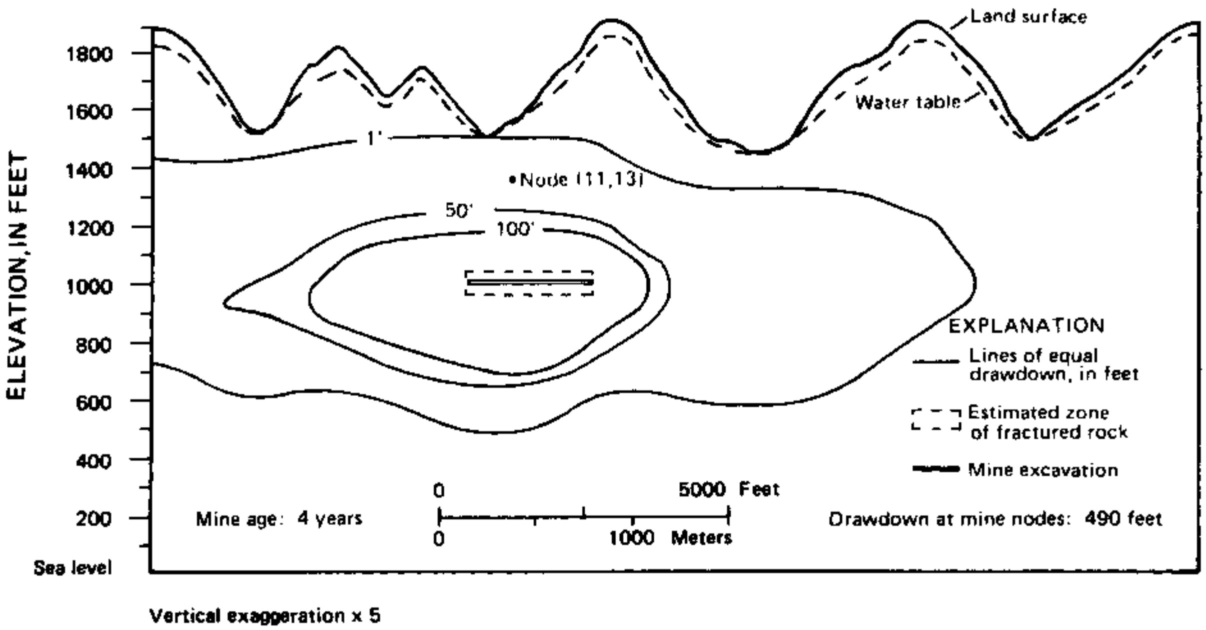


Figure 4.2-4.— Drawdown configuration 4 years after mining.

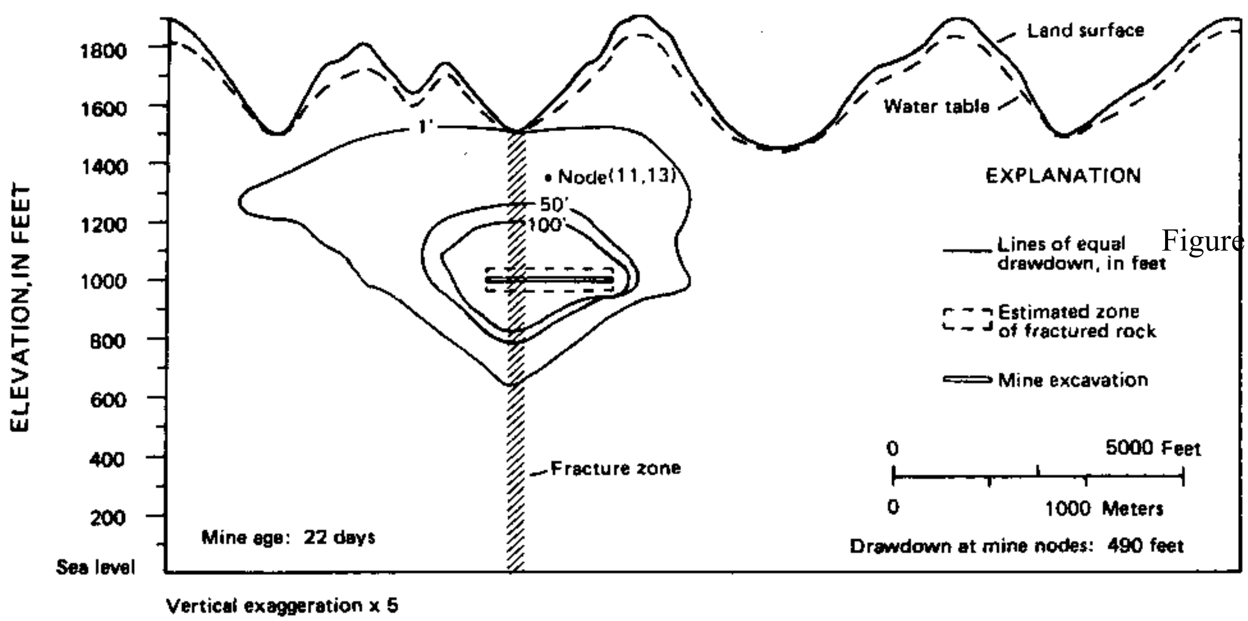


Figure 4.2-5.— Drawdown configuration 22 days after mining near a vertical fracture zone.

Drawdown at a point between the mine and land surface is plotted against time for both conditions in figure 4.2-6. As might be expected, the drawdown rate is much faster for the fracture zone condition. In both conditions, drawdown has essentially stabilized after 1 year of mine age.

Specific mine inflow has also been plotted with mine age (fig. 4.2-6). The fracture zone interconnects the mine to the shallow, more permeable aquifers, resulting in more than a two-fold increase of inflow to the mine.

Given the features described by figures 4.2-1 and 4.2-2, the cross-section-flow model indicates the following probable hydrologic effects:

1. Water levels could decline as much as 15 feet in 150-foot deep wells located along undermined valleys. The maximum effects of water-level decline would occur within 1 year of mining.

2. Springs and shallow wells above basin drainage level probably will not be affected.

3. Streamflow may be reduced by 0.6 $(ft^3/s)/mi^2$ about 1 year after undermining completion. Larger reductions could occur with vertical fracture zones of greater permeability.

4. The presence of vertical fracture zones could magnify and accelerate the drawdown effects and mine inflow.

The mine problem described above might be better handled with a three-dimensional flow model and more representative boundary conditions. However, the ground-water system is obviously complex and the accuracy gained may not justify the additional expense of data collection needed to develop the more elaborate model.

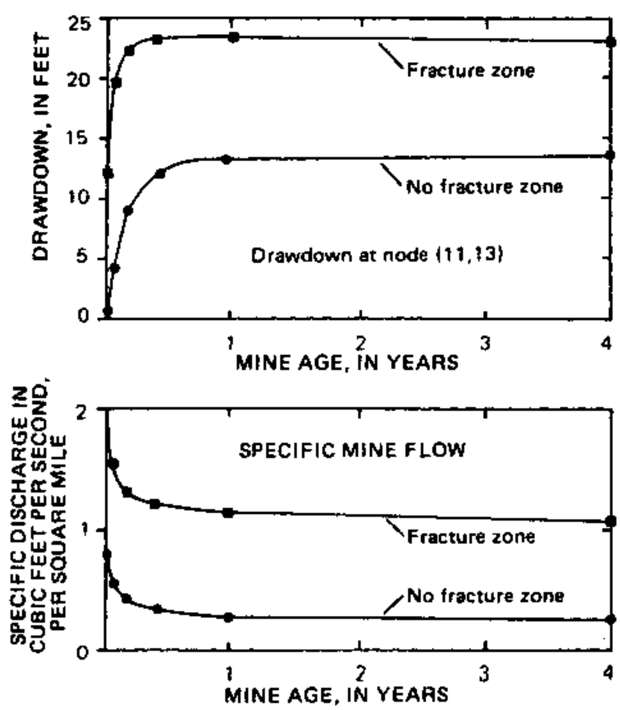


Figure 4.2-6.— Drawdown and mine inflow changes with time.

5.0 GROUND-WATER MONITORING

OBSERVATION WELLS NEEDED TO MEASURE GROUND-WATER CHANGES CAUSED BY SUBSURFACE MINING

Wells are necessary to observe the extent of drawdowns near subsurface mining and water-quality changes near waste-rock refuse sites.

A network of wells could be used to observe changes in ground-water storage and quality near a hypothetical mine plan (fig. 5.0-1), which is similar to the conditions modeled in the section 4.2. Sites M1 through M7 include wells completed in the water-table aquifer along hills and valleys and confined aquifer units above the minable coal seam. All the observation wells are located where they will not be affected by pumping of existing water wells. Altitude of land surface and reference points, from which water-levels are measured, are usually referenced to a standard vertical datum within 0.01 foot accuracy. A suitable benchmark reference is selected in an area that is not expected to subside from underground mining.

Aquifer units located more than 300 feet below land surface have not been proven and may be of marginal use in Greene County. Based on the current usefulness of deep bedrock aquifers, observation wells probably need not be completed in formations beneath the mine, which is located, on the average, 500 feet below stream altitude.

Wells designed to tap the deepest confined aquifers (fig. 5.0-1) need to be properly cased and sealed with grout or expandable clay. A poorly sealed observation well could short-circuit ground-water flow between deep and shallow aquifers, giving false indications of storage changes related to mining.

Hydrogeologic information could be collected from coal-resource exploration drilling and used to locate persistent aquifer units. For many of the deeper aquifer units, these holes could be plugged back, developed, and cased as observation wells. Mud infiltrating from deep exploration drilling tends to seal the borehole from shallow aquifer zones. Construction of shallow observation wells from such drill holes would require very thorough well development or reaming.

Unused or abandoned wells may serve as observation wells, especially in the shallow aquifer zones. Complete inventory of the well construction and water-bearing zones, in addition to well development, is needed to establish usefulness of the site for observation.

Water levels would be measured monthly in all wells located within one-half mile of mine openings (sites M1, M2, M3, and M4 for initial mining) and in wells completed in the deep aquifers. Other well sites could be measured quarterly. Annual pumping of all observation wells is needed to ensure adequate communication between the well-bore and the aquifers. A water sample could be collected at that time. More frequent sampling may be needed if water-level declines occur in the well as a result of mining.

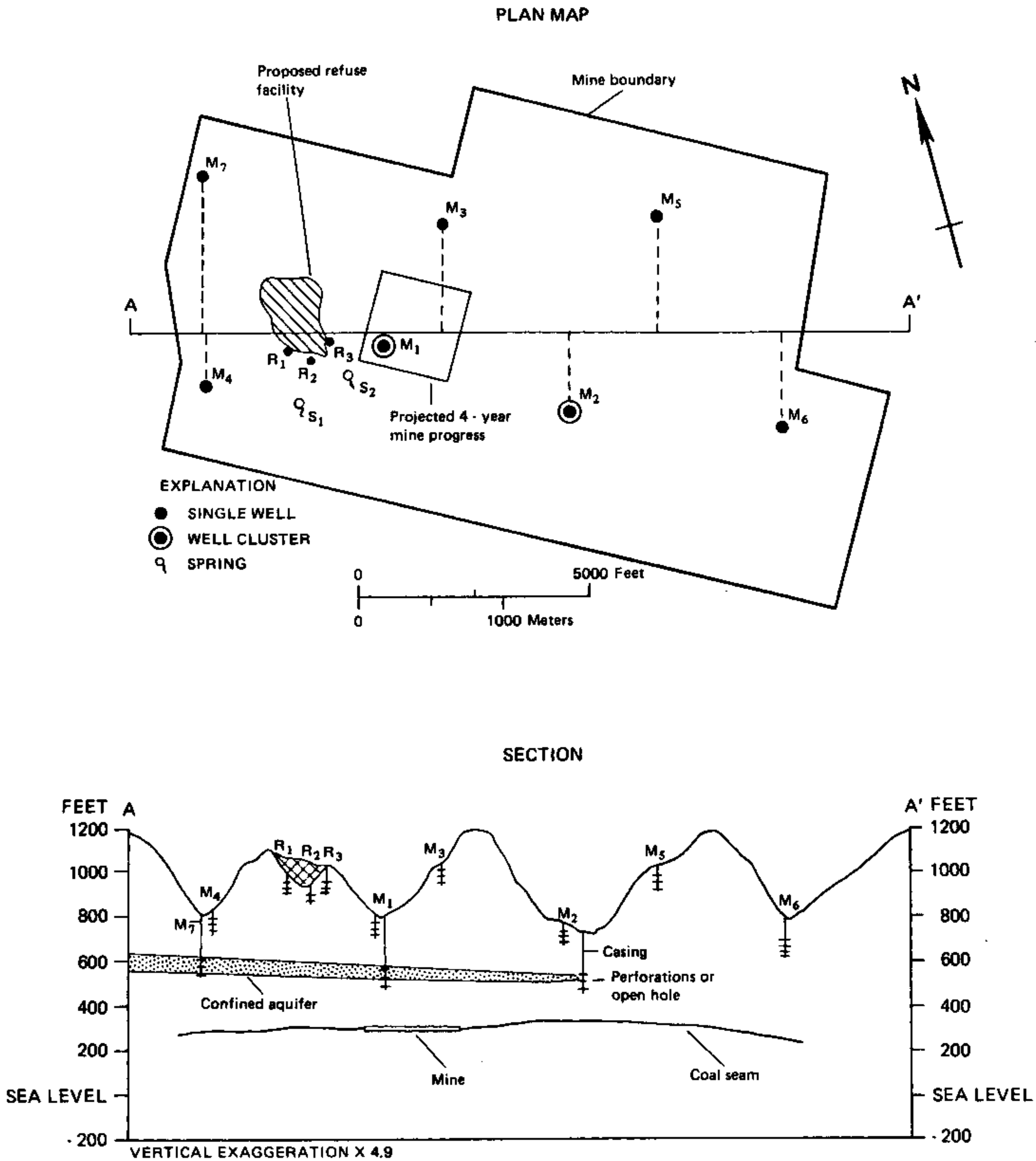


Figure 5.0-1.— Observation well network for a hypothetical subsurface mine.

Changes in ground-water chemistry resulting from the waste-rock refuse facility could be measured from well sites R1, R2, and R3 shown in figure 5.0-1. Each of these wells would penetrate the water-table aquifer downgradient from the storage pile where any changes might be expected to occur first. Additional wells could be added around the perimeter and farther from the pile if leachate infiltration into the ground-water system is determined to be extensive. Existing springs (S1 and S2 in fig. 5.0-1) downgradient from the refuse pile could also be sampled.

Samples would be collected quarterly to screen the water quality during changes in seasonal recharge rates to the aquifer. More frequent sampling may be needed if significant changes in concentrations of sulfate, iron, manganese, acidity, and dissolved solids are determined in the quarterly samples.

The common water-quality constituents analyzed for a monitoring program are shown in table 3.5-1. Trace metals determined in initial sampling, could be used as a guide to subsequent sampling.

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GROUND-WATER STUDY 5

by

William A. Hobba, Jr.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Figure | Page

LIST OF TABLES

Table Page

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.

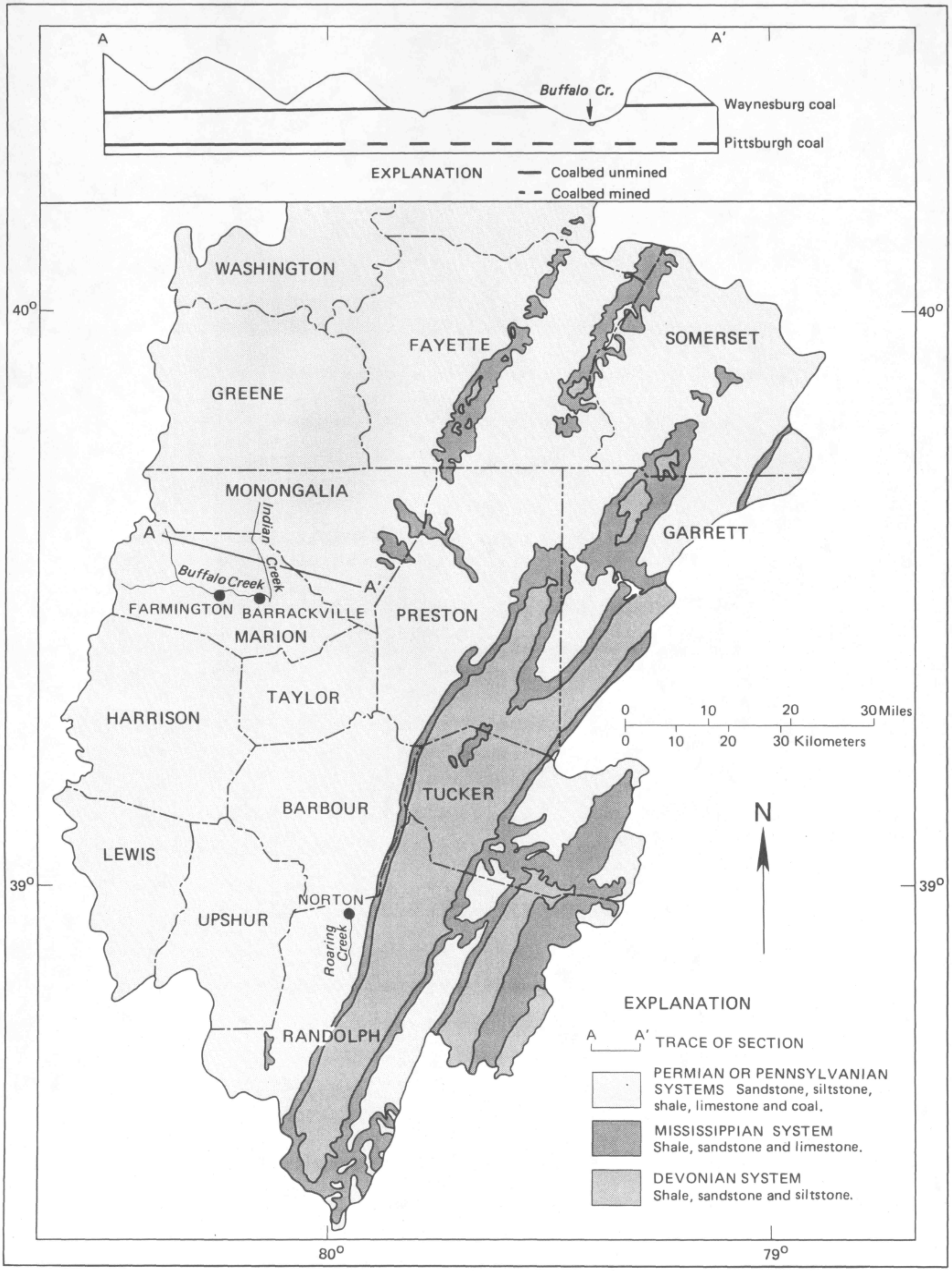


Figure 2.0-1— Surface geology and cross section. (Modified from Herb and others, 1981, fig. 4.1-1.)

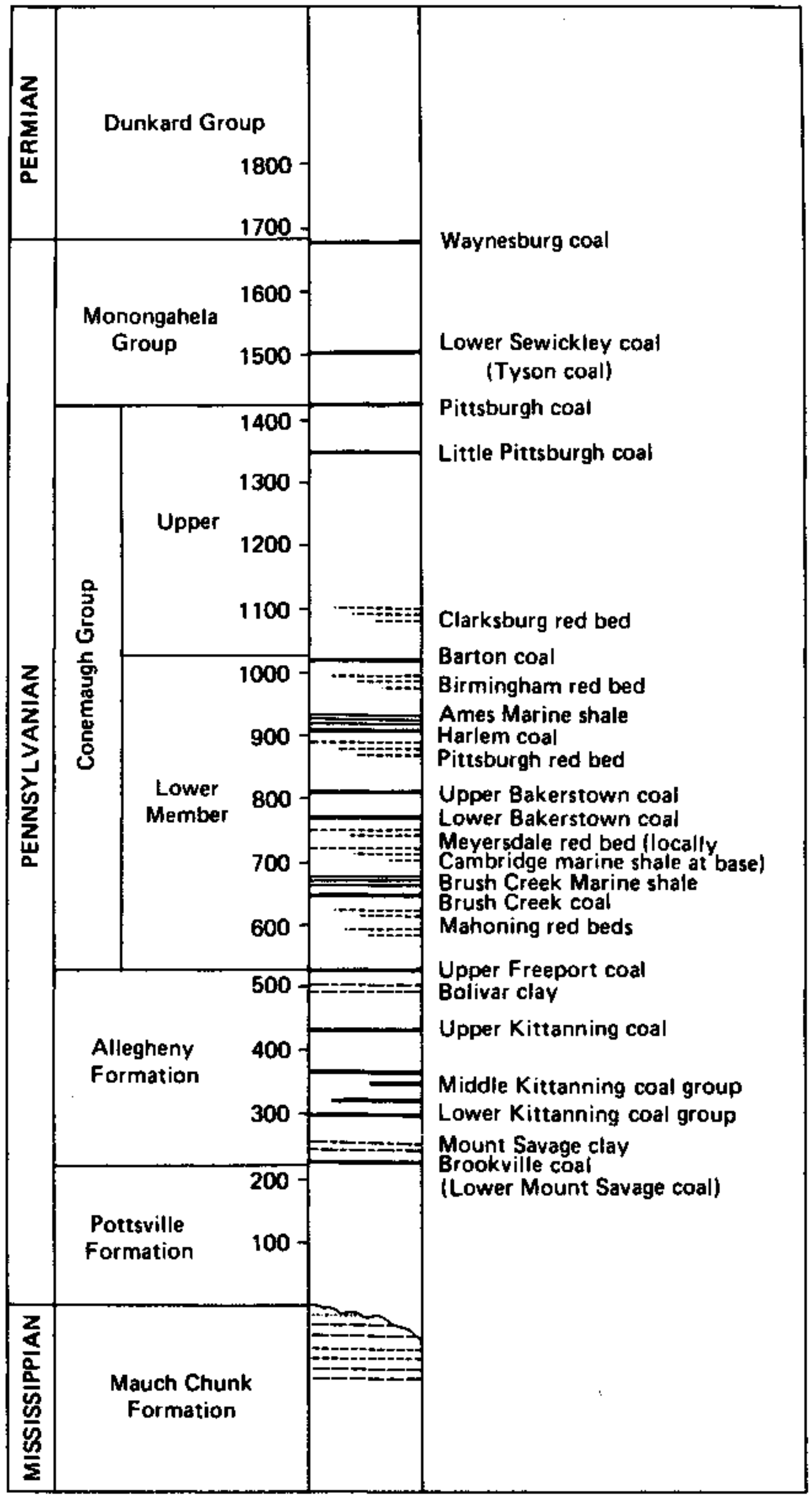


Figure 2.0-2.— Generalized geologic section of the Pennsylvanian-age strata. (From Amsden and others, 1954, p. 48)

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.

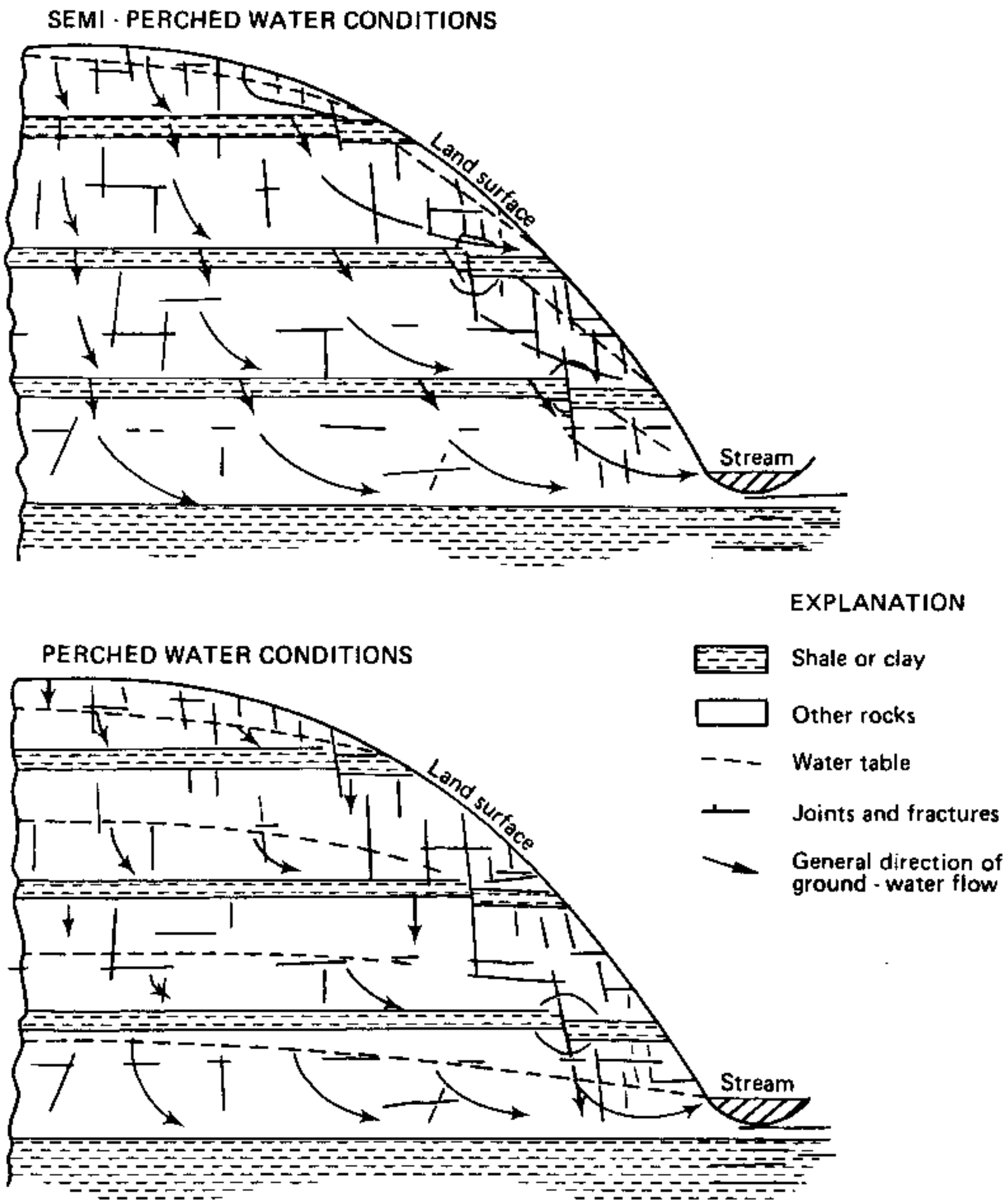


Figure 3.2-1.— Diagrams showing idealized semiperched and perched water conditions in the Monongahela River basin.
(Modified from Ward and Wilmoth, 1968, p. 11)

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.

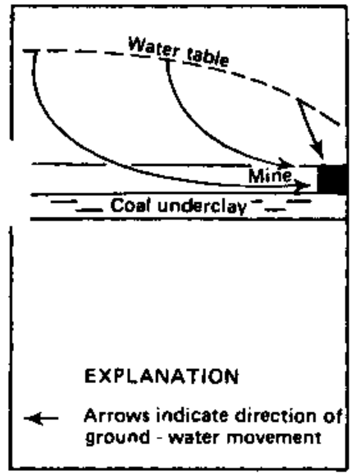


Figure 3.2-2.— Diagram showing general ground-water flow to a mine drift. (From Ward and Wilmoth, 1968, p. 17)

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	Dunkard Group	39	0 – 1,610	16	0 – 16	2	5 – 720	112	6.0 – 8.5	7.5
Upper	Monongahela Group	42	0 – 105	6	0 – 18	.2	0.5 – 1,212	124	5.8 – 8.8	7.1
Pennsylvanian	Conemaugh Group	161	0 – 1,700	5	0 – 24	.1	0 – 1,479	102	4.8 – 9.0	7.0
Middles-Lower	Allegheny Formation	38	0 – 237	4	0 – 12	1.0	1 – 1,650	81	5.0 – 8.4	6.7
Pennsylvanian	Pottsville Group	49	0 – 688	4	0 – 20	1.5	5 – 242	46	4.3 – 8.1	6.6
Pre-	Mauch Chunk Group	3	3 – 4	3.5	0	.01	70 – 136	77	5.0 – 6.8	5.9
Pennsylvanian	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

3.0 HYDROLOGY

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.

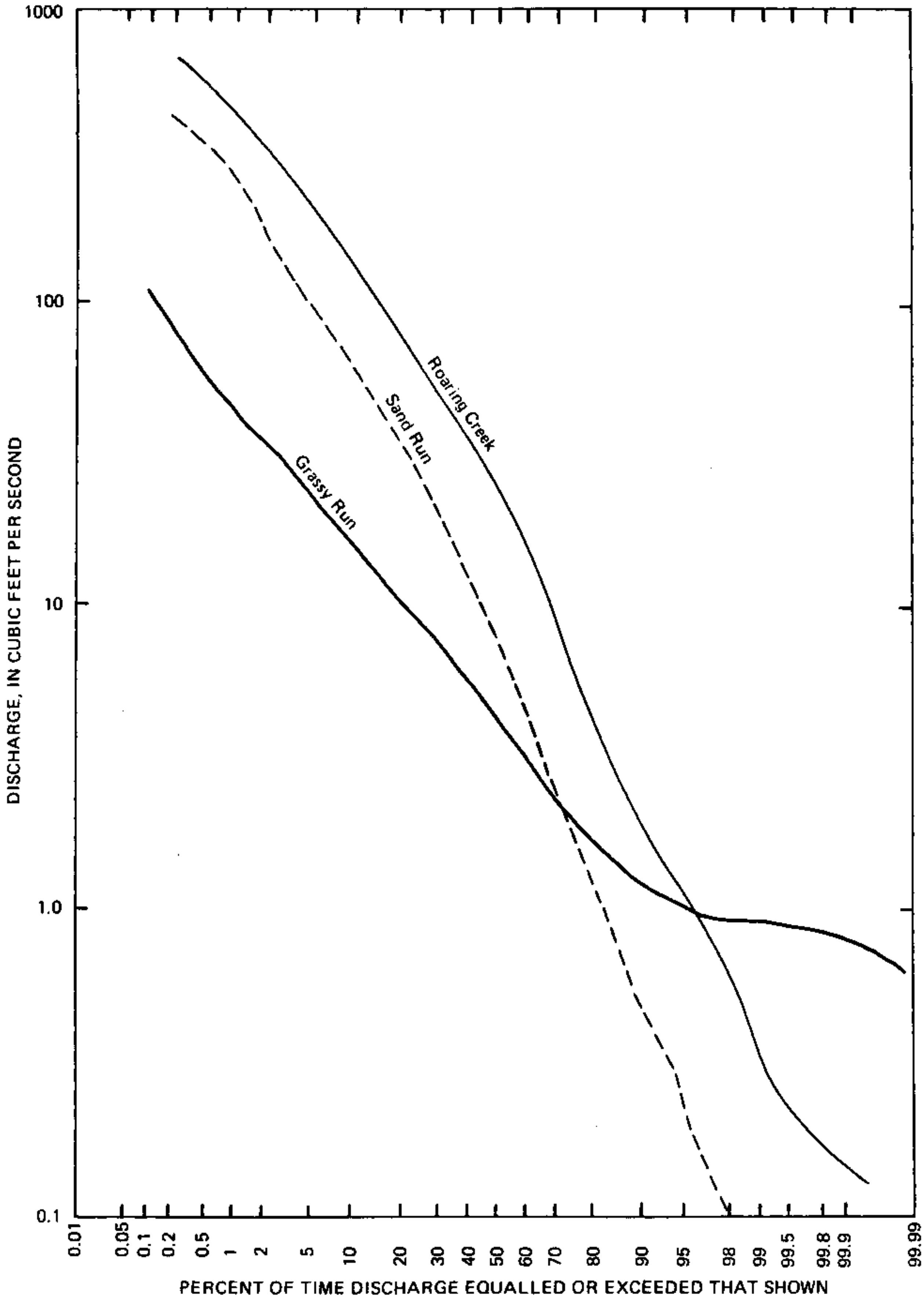


Figure 3.3-1.— Flow-duration curves of Roaring Creek, Grassy Run, and Sand Run. (From Hobba, 1981, fig. 2.2.2-B.)

4.0 AQUIFER CHARACTERISTICS

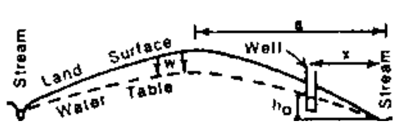
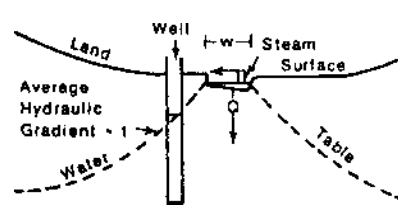
4.1 AREAL AQUIFER ANALYSIS

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 (f^{t2}/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

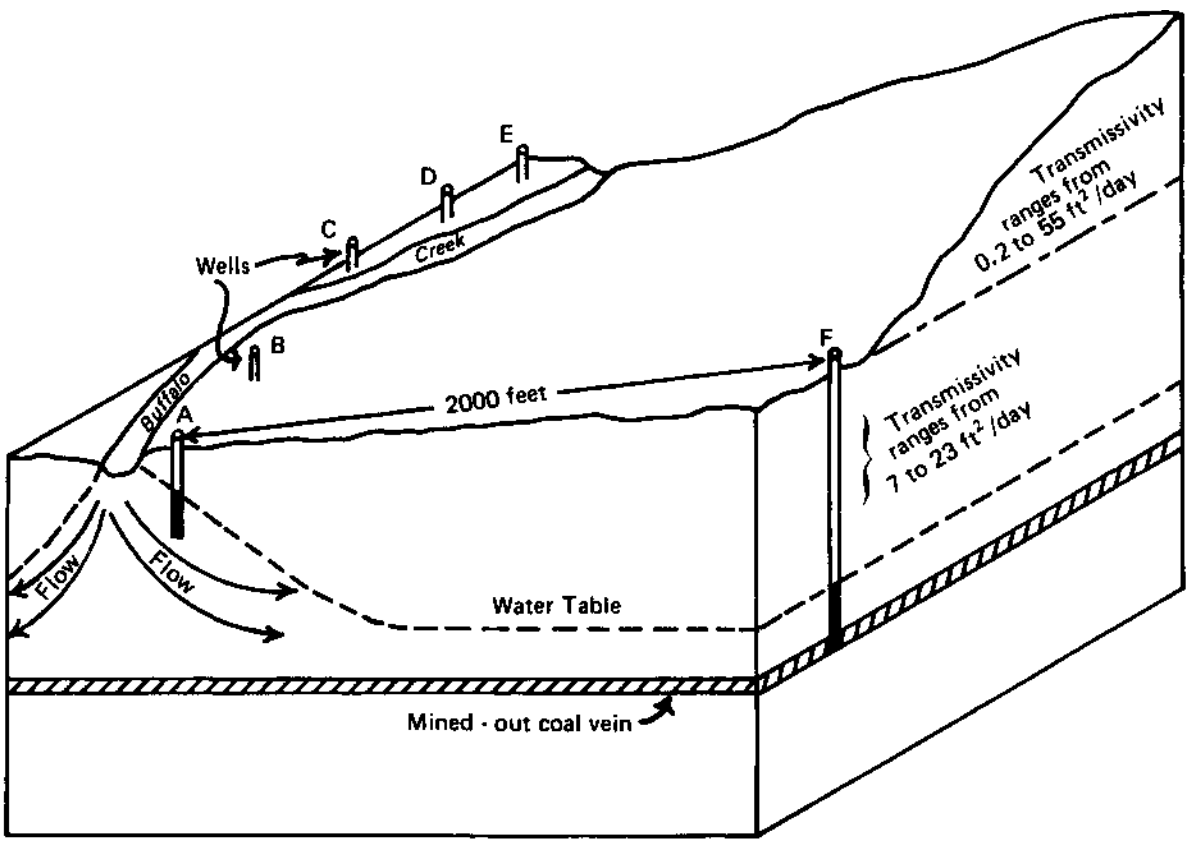


Figure 4.1-1.— Block diagram showing wells, water table, and computed ranges of transmissivity at Farmington where Buffalo Creek was losing about 1.4 cubic feet per second per mile. (From Hobba, 1981, fig. 3.5.1-B.)

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.

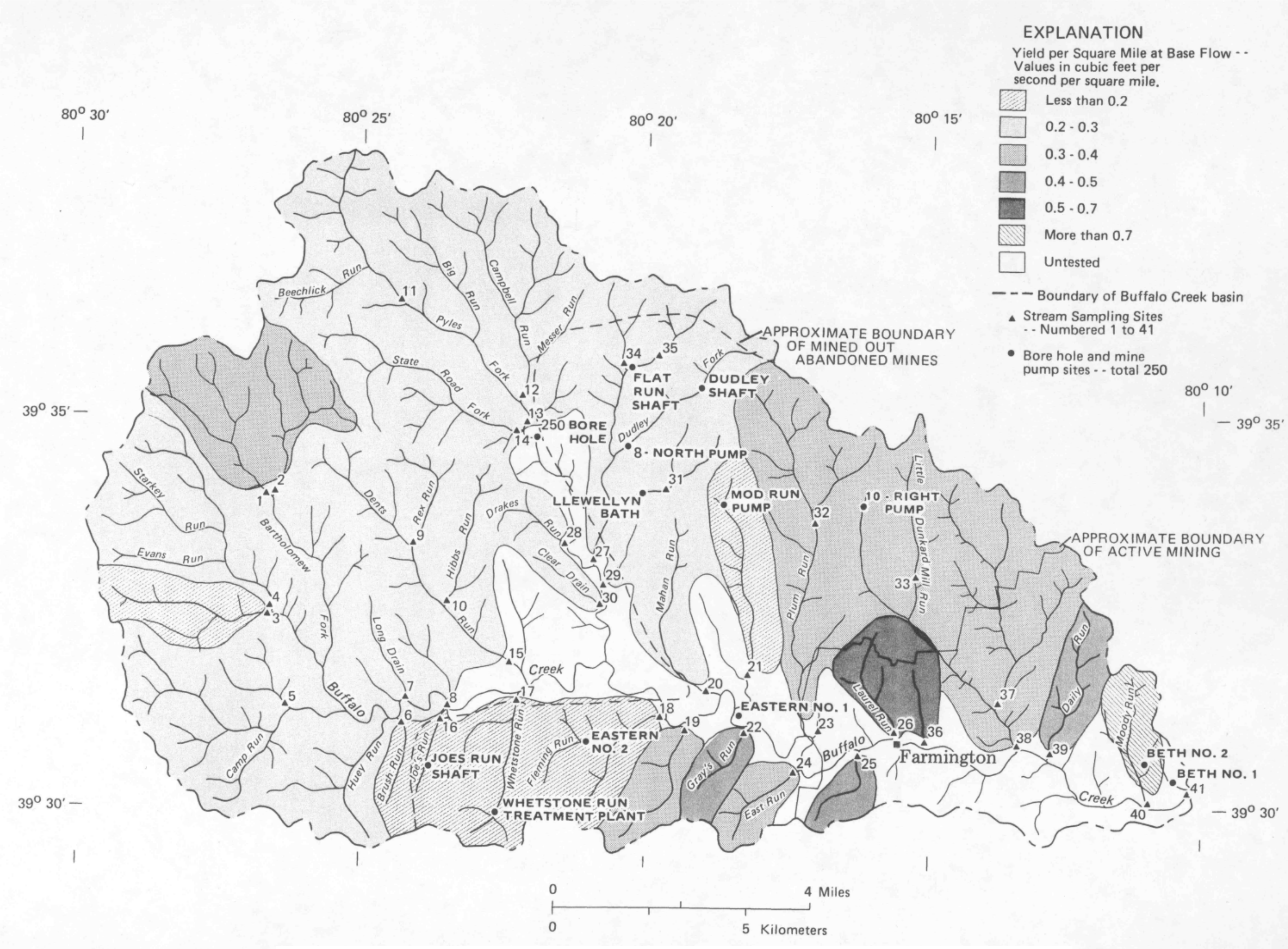


Figure 5.1-1.— Yield per square mile at base flow, Buffalo Creek, October 1977. (From Hobba, 1981, fig. 3.2.1-A.)

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.

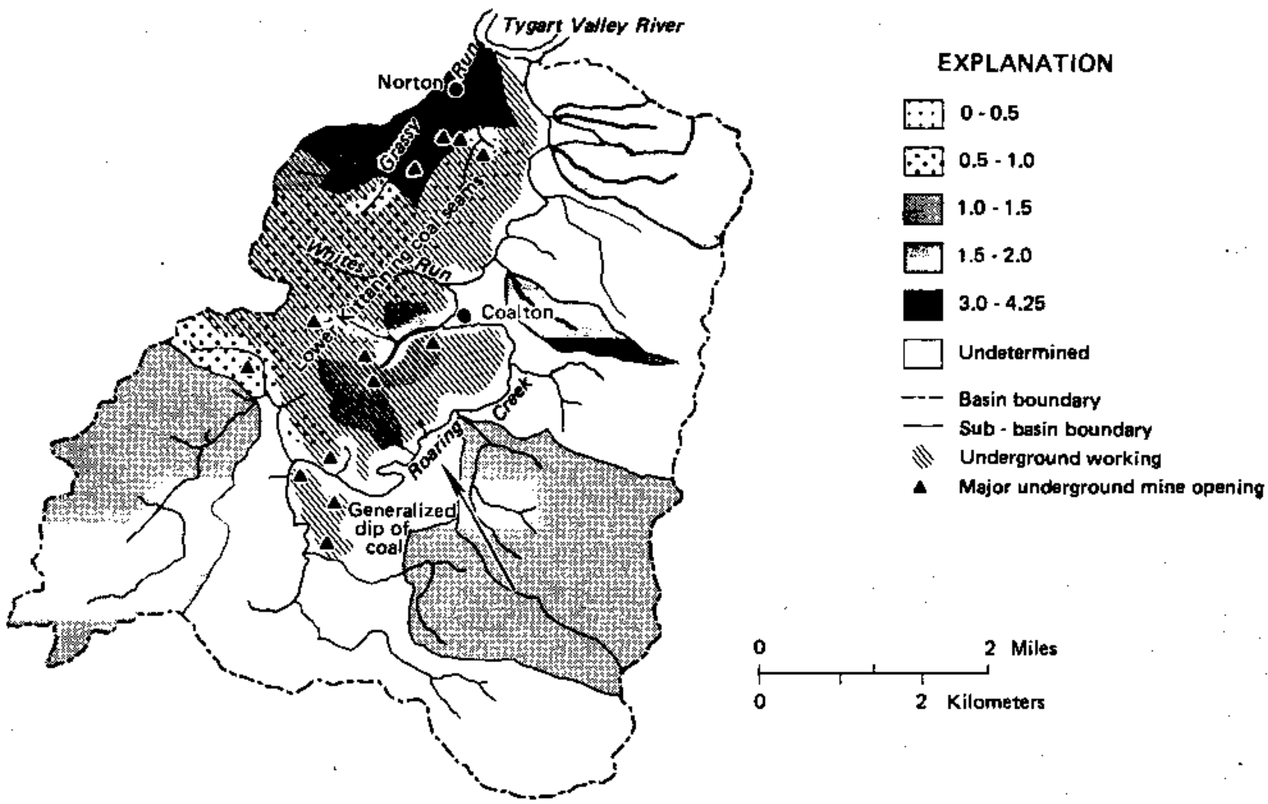


Figure 5.1-2.— Yield per square mile of small drainage basins, April 1979. (From Hobba, 1981, fig. 2.2.1-A.)

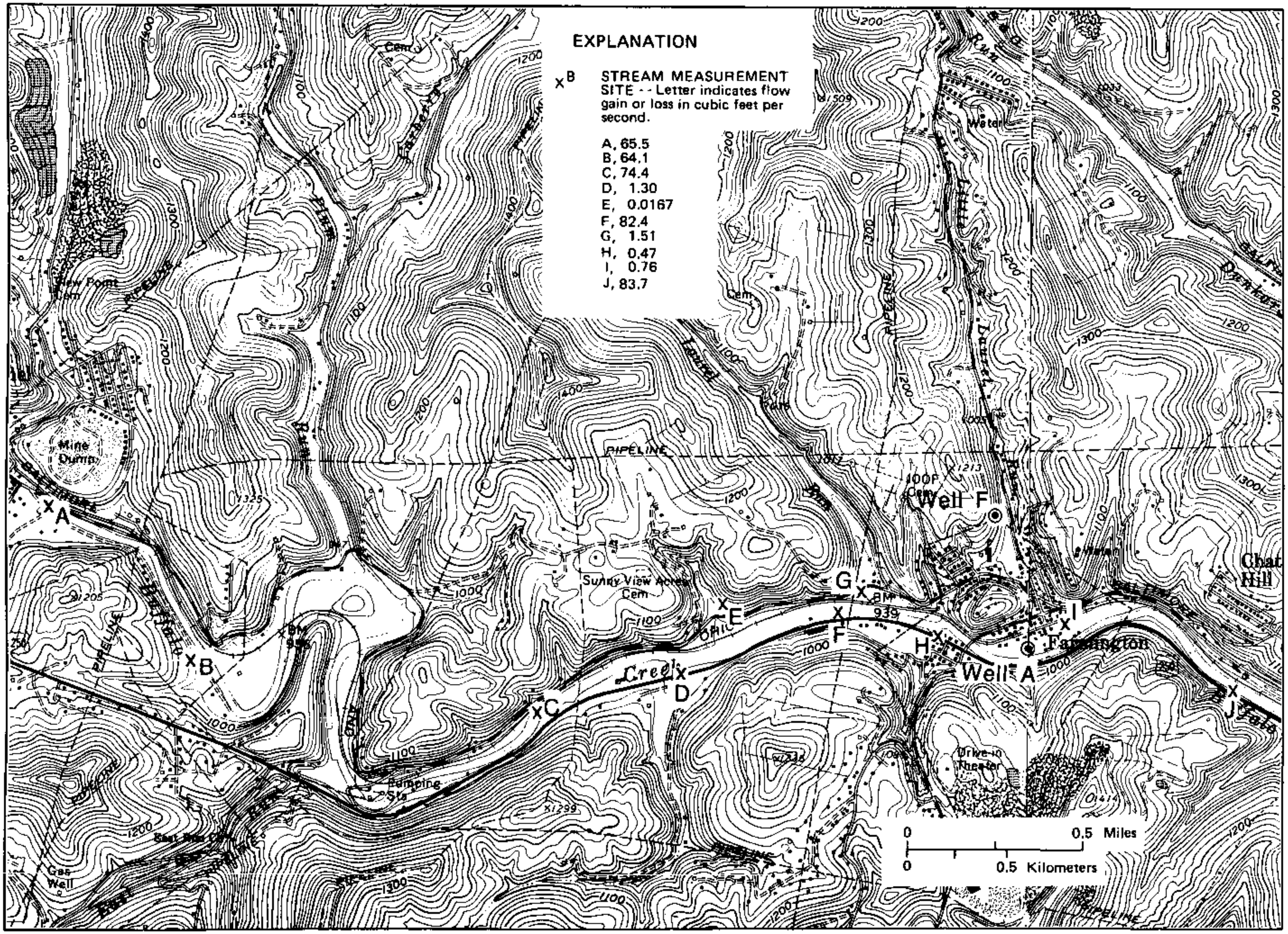


Figure 5.1-3.— Stream sites measured to determine flow gain or loss in Buffalo Creek near Farmington.
(From Hobba, 1981, fig. 3.2.3-A.)

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.

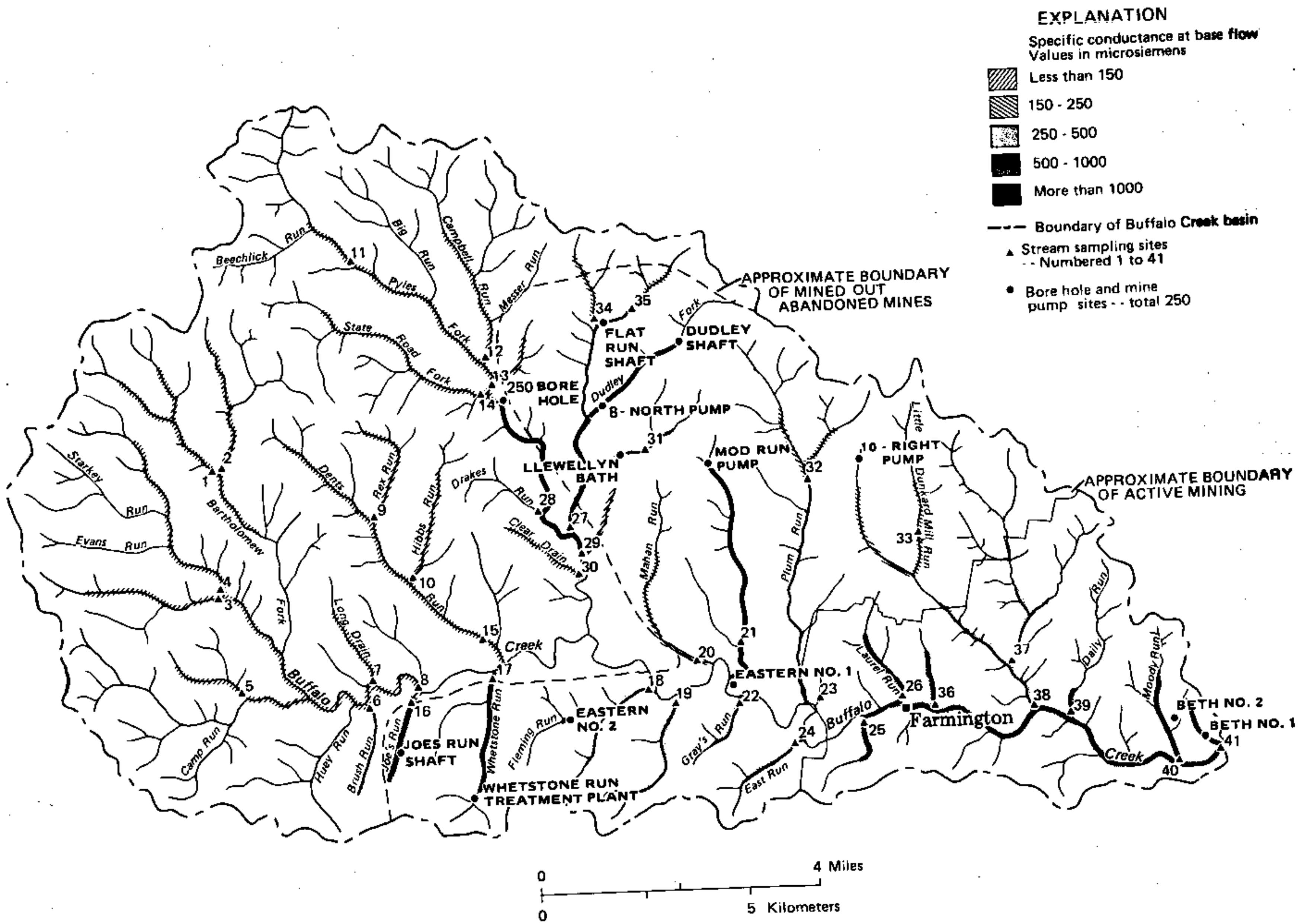


Figure 5.2-1— Specific conductance at base flow, Buffalo Creek, October 1977. (From Hobba, 1981, fig- 3.3.1-A.)

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.

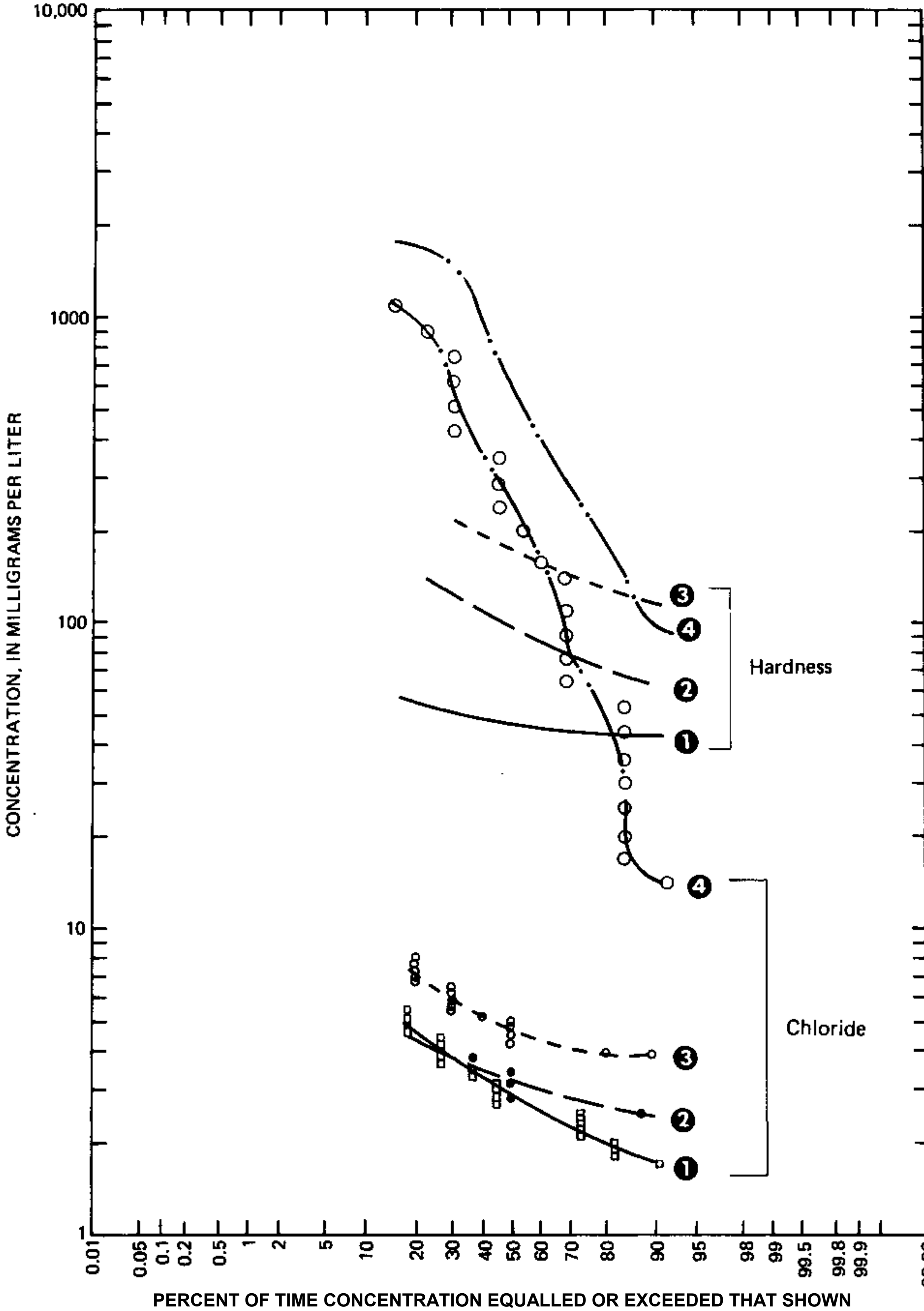


Figure 5.2-2.— Duration curves for hardness and chloride for streams in (1) unmined basins, (2) mined basins with low water yield, (3) mined basins with high water yield and (4) for treated and untreated mine water. (From Hobba, 1981, fig. 3.3.3-B.)

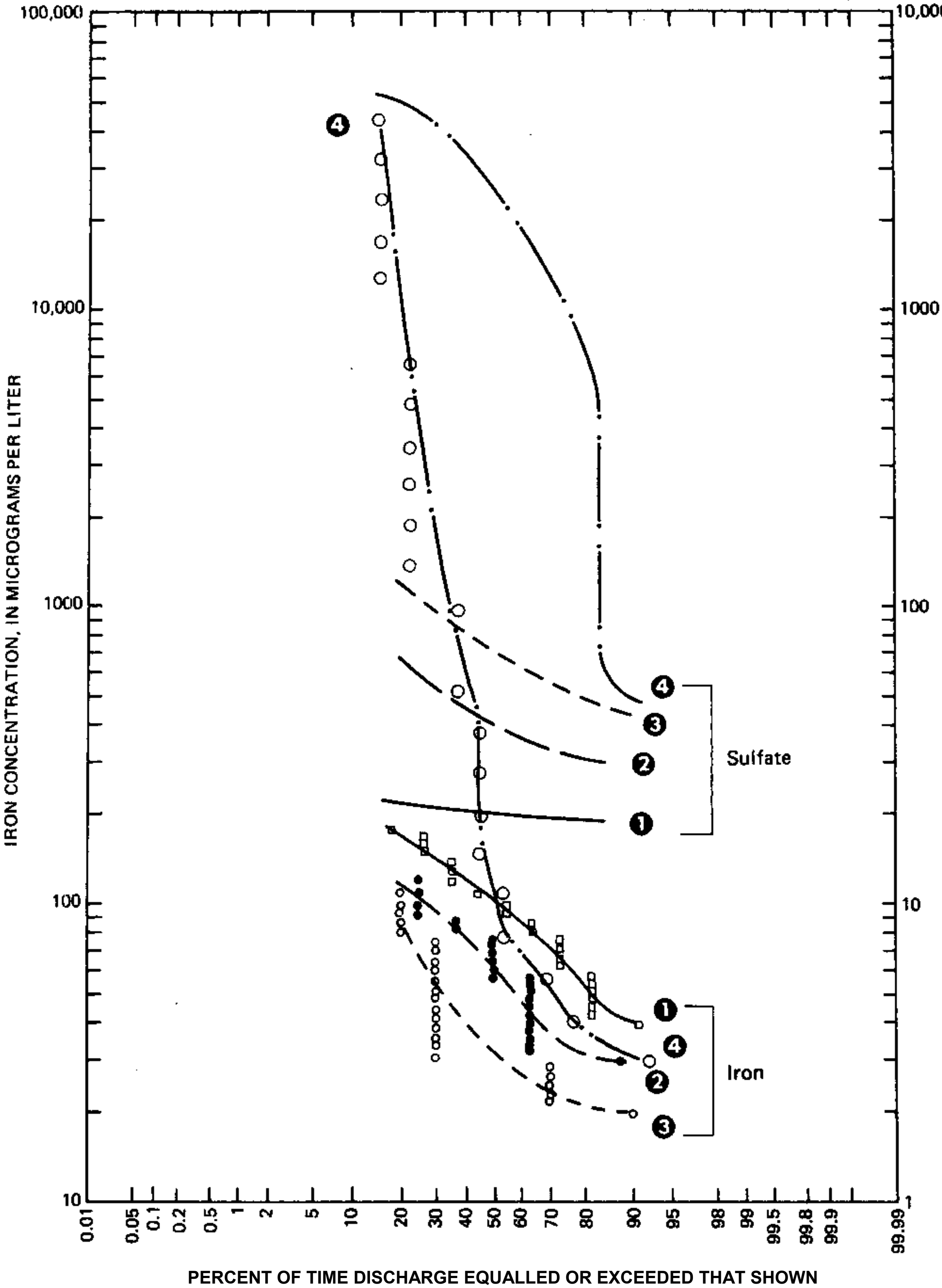


Figure 5.2-3.— Duration curves for sulfate and iron content for streams in (1) unmined basins, (2) mined basins with low water yield, (3) mined basins with high water yield, and (4) for treated and untreated mine water. (From Hobba, 1981, fig. 3.3.3-A.)

5.3 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.

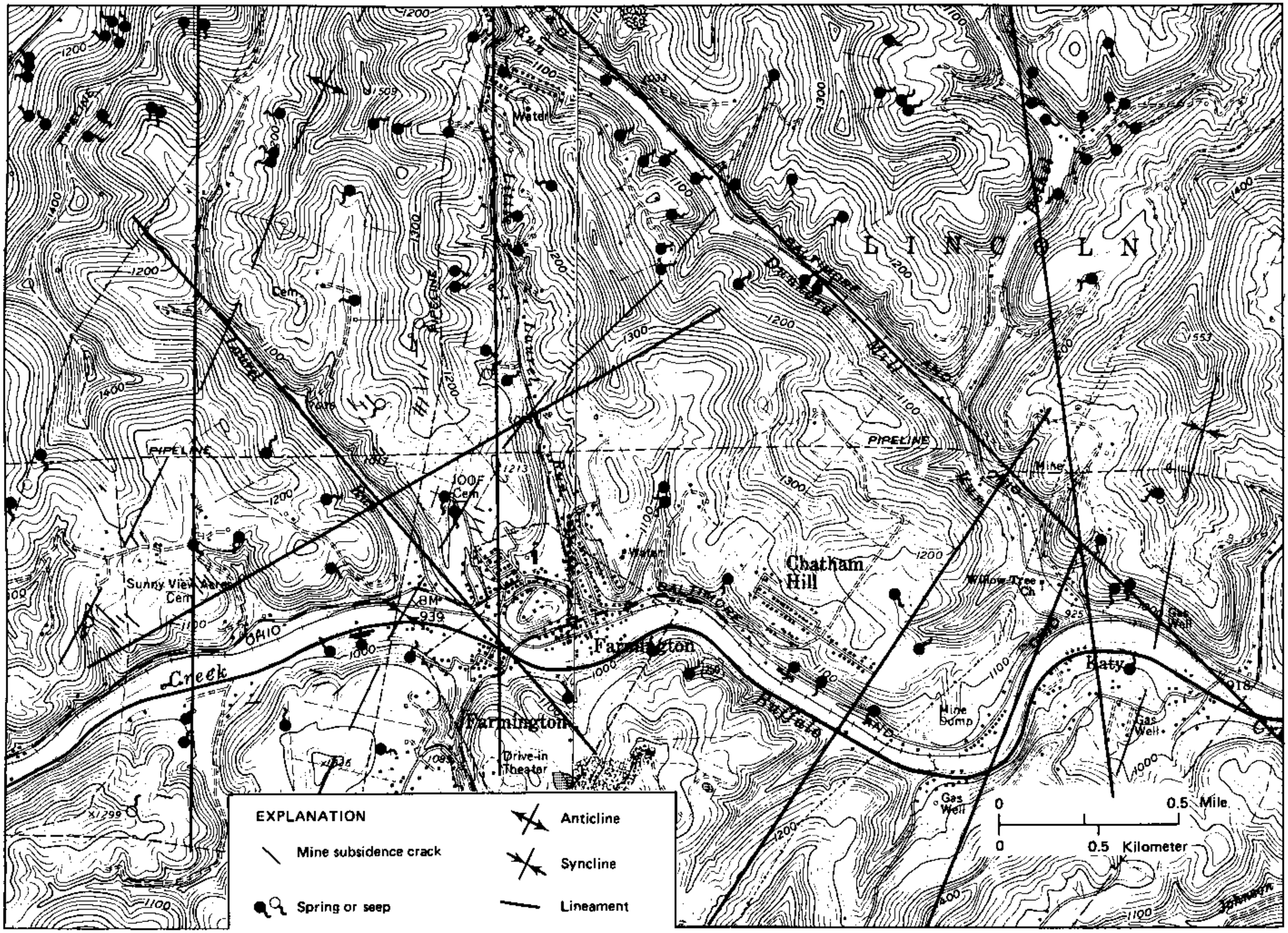


Figure 5.3-1.— Map showing mine-subsidence cracks, wet and dry springs, geologic structure, and lineaments. (From Hobba, 1981, fig. 3.1.3-A.)

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.

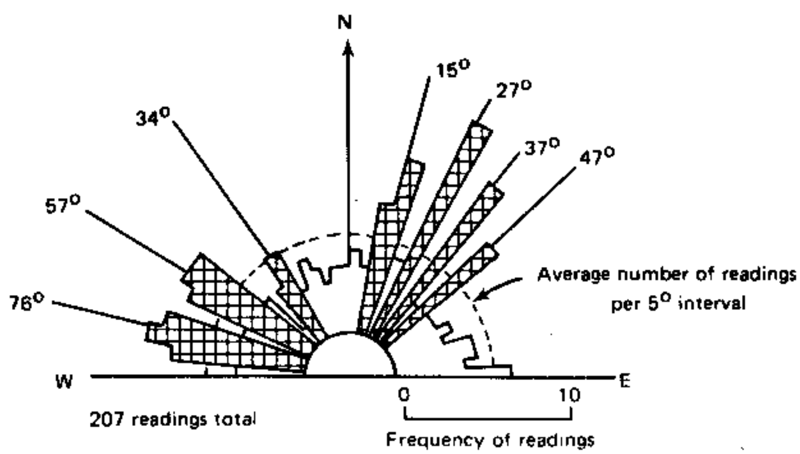


Figure 5.3-2.— Composite rose diagram of principal bedrock joint trends. (Modified from Bench and others, 1977, p. 19.)

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.

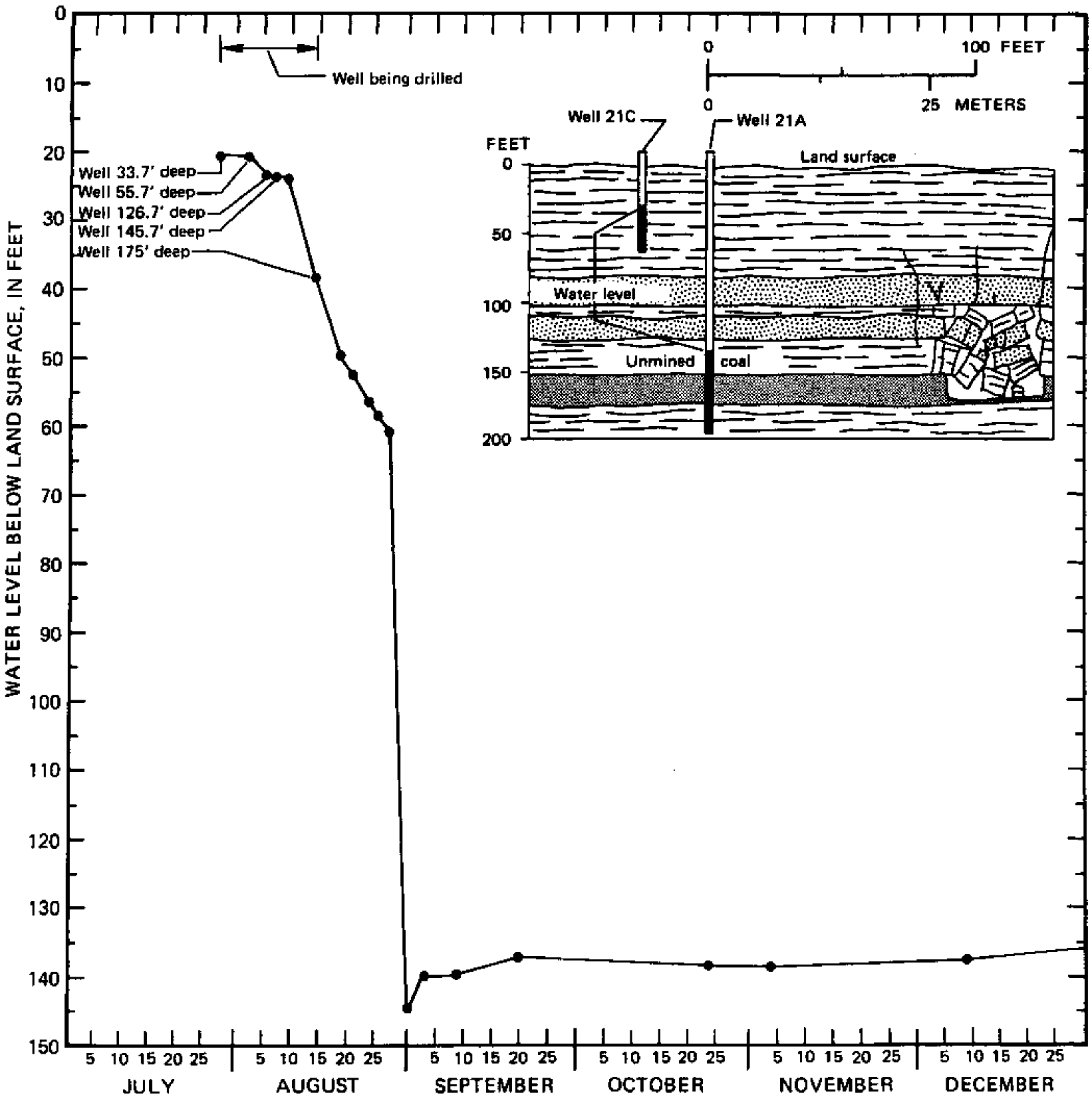


Figure 5.4-1.— Hydrograph of well 18-3-21A as it was being drilled, and for the following four months; and approximate physical setting at wells 21A and 21C. (On August 29, 1964, well 21A was bailed and muck removed from bottom; packer set at 155 feet.)
(From Hobba, 1981, fig. 2.4.2-A.)

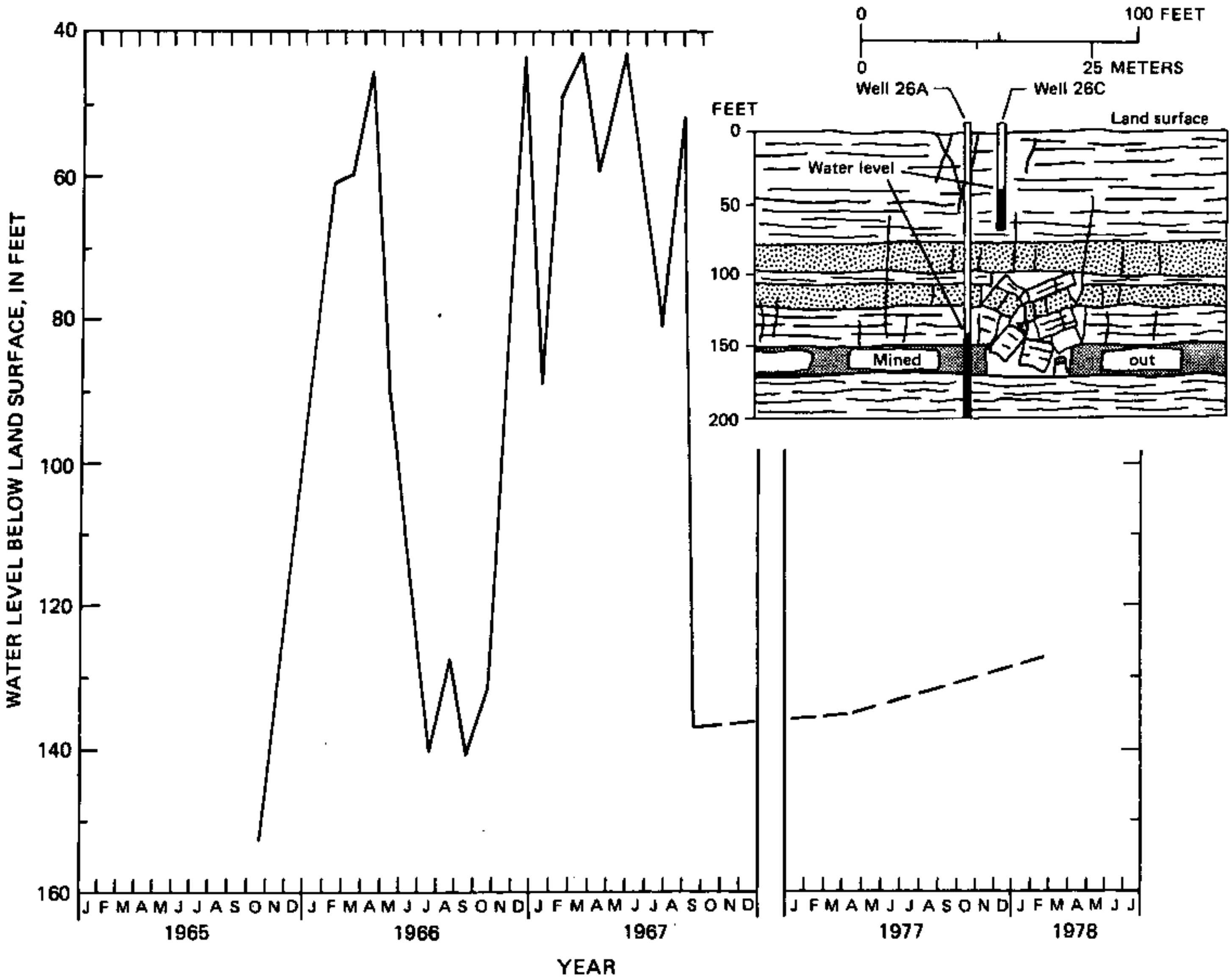


Figure 5.4-2. — Hydrograph of well 18-3-26A and approximate physical setting at wells 18-3-26A and 26C.
(From Hobba, 1981, fig. 2.4.2-B.)

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.

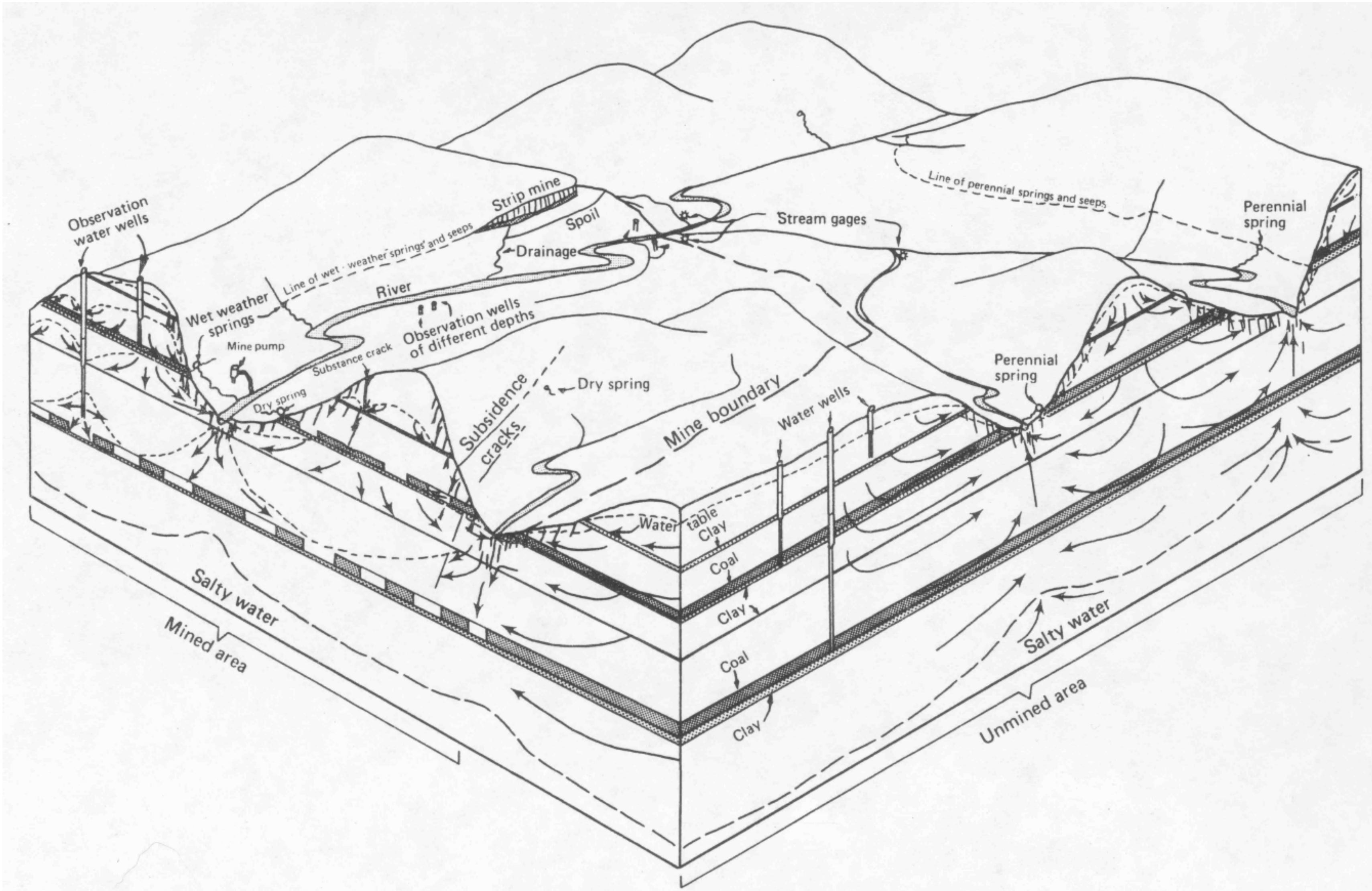


Figure 6.0-1.— Block diagram of hypothetical area showing hydrology of both mined and unmined areas, and possible well- and stream-monitoring sites.
(Modified from Hobba, 1981, fig. 4.0-B.)

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GROUND-WATER STUDY 6

by

Devin L. Galloway

and

James B. Foster

CONTENTS

LIST OF FIGURES

1.0 ABSTRACT

Geology and the Occurrence of Coal

Glacial deposits as much as 200 feet thick overlie bedrock of Pennsylvanian age. The composition of glacial deposits ranges from sand and gravel to clay. Sand and gravel occur in buried bedrock valleys and in alluvial deposits along stream channels.

The bedrock geology consists of flat-lying Pennsylvanian sedimentary rocks composed of shale and clay, some sandstone, and a little limestone and coal. Minable coal beds include the Herrin (No. 6) and Harrisburg-Springfield (No. 5).

Hydrology and Hydrologic Monitoring

The water-bearing capability of the glacial deposits is variable, depending upon the grain and pore sizes within the materials. The sand aquifer overlying the proposed mine site has measured hydraulic conductivity values of 60 to 125 ft/yr. Specific yield values range from 0.15 to 0.32. Wells in the sand and gravel yield as much as 500 gal/min.

Hydrologic boundaries of the sand aquifer at the mine site include the overlying clayey-silt alluvium, the underlying fireclay and shale bedrock, the unreclaimed mine spoils to the east, and the Possum River to the west. Hydraulic conductivity of the mine spoil ranges from 2 to 300 ft/yr.

The sandstone and limestone bedrock units, above and below the coal units, are water-bearing. The productivity of these aquifers is variable, depending on the development of secondary permeability from fracturing, parting along bedding planes, or solution cavities in limestone. The yield of bedrock aquifers to wells ranges from 20 to 100 gal/min.

Mining Method and Potential Stresses on Aquifer

The surface mine will start near the stream and advance toward the abandoned mine spoils. The first cut will require drains, sump drains, and pumps to remove inflow from the aquifer. Inflow to subsequent cuts will be decreased by covering the river side of the first cut with fireclay (underclay) and covering the clay with spoils material.

The alluvial sand and gravel aquifer is used for domestic, municipal, industrial, and small commercial water supplies. The bedrock aquifers are used in areas where the alluvial aquifers are absent or of limited productivity. By mining part of these aquifers, the surface mine will create a potential water-supply problem for users of these resources.

Probable Hydrologic Impact and Proposed Hydrologic Monitoring Network

During the post-mining period, the concentrations of dissolved solids in the ground water may increase, owing to the presence of iron sulfides in the spoils. The ground water may have a lower pH, depending on the buffering capacity of the mine spoils. Because ground water may flow from the mine spoils toward the river, acidic mineralized water may flow to the municipal well field and contaminate the supply. Dilution by upstream river water will minimize the effect of spoils water on river quality.

During mining, dewatering of the open pit will decrease ground-water flow to nearby wells to some extent. The flow of river water infiltrating through the alluvial aquifer material into the pit will reach a steady rate of 155 gal/d per linear foot of excavation in about 60 days. The ground-water inflow to the pit from the abandoned mine to the east will be 35 gal/d per foot of excavation in 400 days. Use of the underclay to seal the wall on the river side of the cut becomes more significant in reducing ground-water inflow with increasing time.

The post-mining ground-water monitoring program will include wells in the mine spoils and a river-sampling point downstream. Water levels will be measured to determine the rate of recovery and the direction of flow. Ground-water quality will be monitored, in the spoils area, to determine the concentrations of selected chemical constituents moving toward the river and toward the municipal well field.

2.0 GEOLOGIC SETTING

2.1 QUATERNARY SYSTEM

UNCONSOLIDATED DEPOSITS OVERLIE THE COAL-BEARING BEDROCK

Unconsolidated deposits of the Pleistocene Series overlie the Pennsylvanian sedimentary bedrock which contains the coal seams.

Unconsolidated deposits, which overlie the coal-bearing Pennsylvanian bedrock, occur throughout the general area. These deposits consist of glacial till (also called ground moraine and glacial drift), lake (or lacustrine) deposits, and alluvium. The till is variably in composition and thickness, and is poorly sorted. The till deposits are commonly sandy, with lenses of silt, sand, and gravel. Lake deposits are well-bedded and include layers of silt, clay, and sand. Alluvial deposits consist of sand and gravel, which have been transported and deposited by streams. These Unconsolidated deposits can vary in thickness from 0 to 200 feet. In the proposed mine-permit area, the thickness is about 30 feet.

Figure 2.1-1 shows the general area containing the proposed mine permit site, which is overlain by alluvium. These deposits are bounded on the west by the silty clay terrace deposits, and on the east by the unreclaimed mine spoils from a previous mining operation. Figure 2.1-2 is a generalized cross section of these deposits overlying the coal-bearing bedrock.

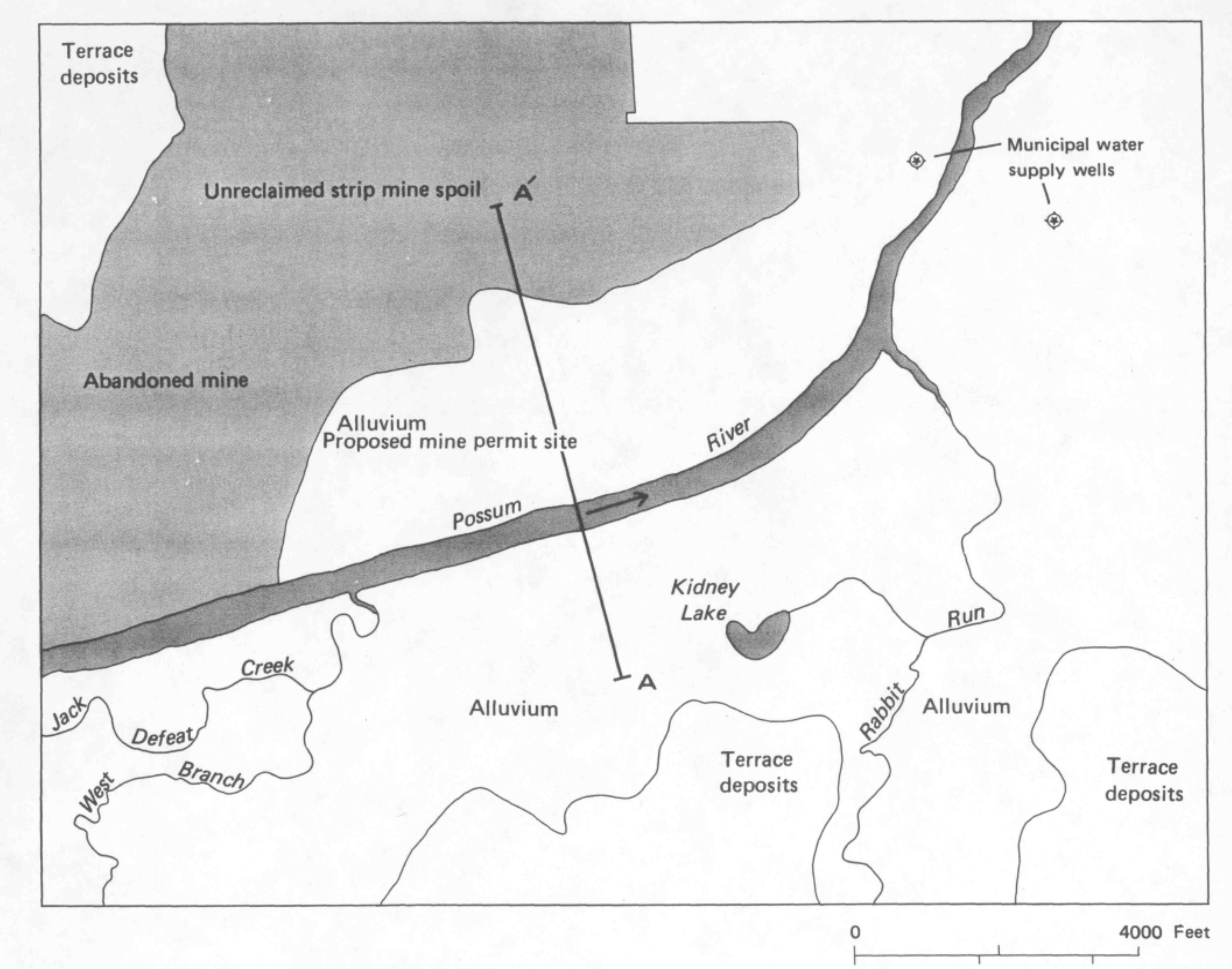

Figure 2.1-1.— Mine setting in Possum River flood plain northwest of Iona, Illinois.

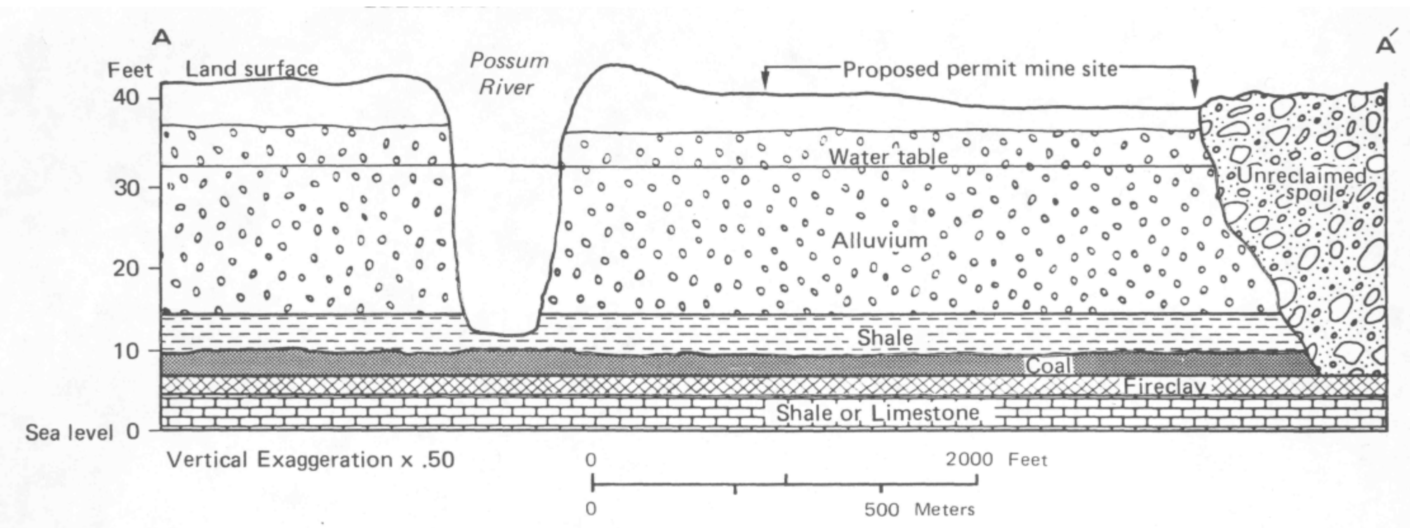

Figure 2.1-2.— Cross-section through proposed mine area and Possum River showing hydrogeologic setting.

2.0 GEOLOGIC SETTING

2.2 PENNSYLVANIA SYSTEM

CARBONDALE FORMATION CONTAINS MOST OF THE COAL MINED

In the Carbondale Formation, the Herrin and Harrisburg-springfield coal members are the coal seams mined most in the area.

The general mine area is underlain by the sedimentary bedrock of the Pennsylvanian System (fig. 2.2-1). This bedrock consists of sandstone, siltstone, limestone, shale, clay, and coal. The proposed mine-permit area is on the southern edge of a basin, where the sedimentary layers dip gently to the north at a low angle. The bedrock is underlain by Mississippian rocks, which are primarily limestone (20). The Kewanee Group consists of two formations–the Carbondale Formation overlying the Spoon Formation (figs. 2.2-1 and 2.2-2)–and contains most of the coal seams (17). In the mine area, most of the coal mined is Herrin (No. 6) coal and Harrisburg-springfield (No. 5) coal of the Carbondale Formation. The average thickness of the Herrin coal is 5.5 feet; 56 percent of the mapped reserves have a thickness of 6 feet or more (15). The average thickness of the Harrisburg-Springfield coal is 4.5 feet; 47 percent of the mapped reserves have a thickness of 5 feet or more (15).

Figure 2.2-1— Bedrock geology of the general area. (From Willman and others, 1967.)

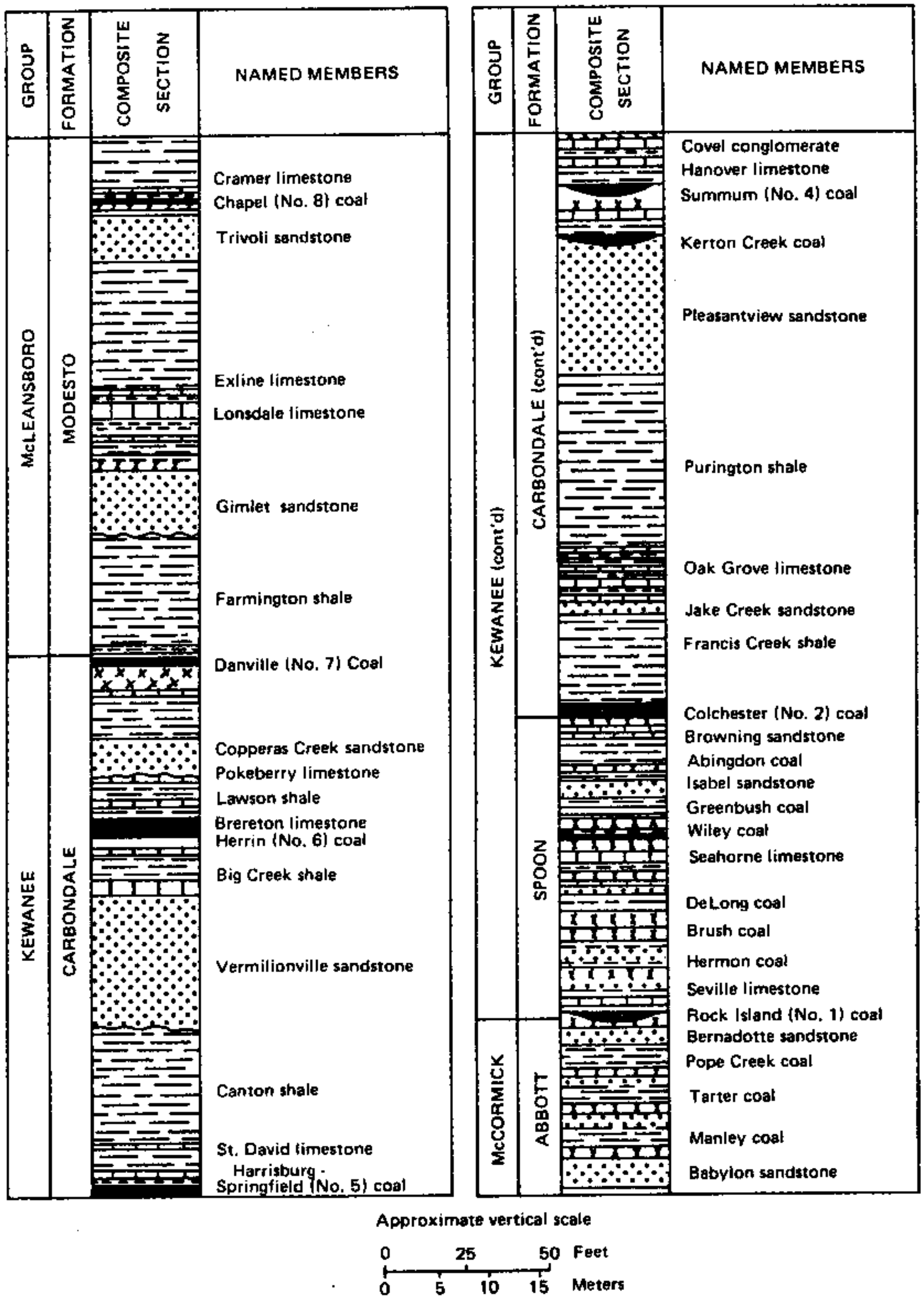

Figure 2.2-2.— Composite section of the Pennsylvanian-age strata in the general area. (After Smith and Berggren, 1963.)

3.0 HYDROLOGIC SETTING

3.1 PHYSIOGRAPHY AND CLIMATE

MINE AREA IS IN A HUMID CLIMATE AND THE TOPOGRAPHY IS FLAT

Average annual precipitation is 44 inches, most of which is from rainstorms during the warm season.

The general mine area lies within the glaciated Central Lowland physiographic province. The area is a prairie plain with generally level to gently undulating topography. The average altitude of the land surface is 600 feet and the local relief is generally less than 200 feet.

The climate is of the humid continental type. The average annual temperature is 57˚F. The average annual precipitation is 44 inches (11). Rainstorms account for more than 70 percent of the warm-season precipitation (20). The mean annual snowfall varies from 10 to 15 inches (20).

3.0 HYDROLOGIC SETTING

3.2 GROUND-WATER SYSTEM

GROUND-WATER AVAILABILITY IS GREATEST IN THE ALLUVIAL AQUIFERS

Sand and gravel aquifers occur as alluvium in stream valleys and as outwash deposited in pre-glacial bedrock valleys. Bedrock aquifers may occur above or below minable coal seams.

Saturated alluvial deposits of sand and gravel occur in stream valleys and as buried pre-glacial outwash channels overlying the bedrock. Ground water in the alluvial deposits flows toward and into the river, and is hydraulically connected with the river. Water-table contours based on measurements in observation wells indicate the direction of ground-water flow (fig. 3.2-1).

Recharge to the sand and gravel aquifers is largely from the infiltration of precipitation and from leakage of streamflow during floods. These aquifers are used for domestic and small commercial water supplies, and are capable of producing as much as 500 gal/min to wells for municipal and industrial supplies. The hydraulic conductivities of alluvial aquifers range from 100 to 1,000 times the conductivity values of the bedrock aquifers.

Bedrock aquifers are composed of sandstones and limestones and are present both above and below the coal seams in the mine-permit area. Ground-water availability in the aquifers is variable and depends on the development of secondary permeability from fracturing or from solution cavities in the limestone.

Water in the shallow bedrock aquifers is generally derived from circulation of shallow ground-water flow systems. Precipitation infiltrates the ground in the upland areas, percolates downward, and enters the bedrock formations through joints and fractures (5).

Shallow bedrock aquifers discharge primarily to major streams. These aquifers are used for water supplies in areas where sand and gravel aquifers are either absent or of limited productivity. The yield of bedrock aquifers to wells ranges from 20 to 100 gal/min.

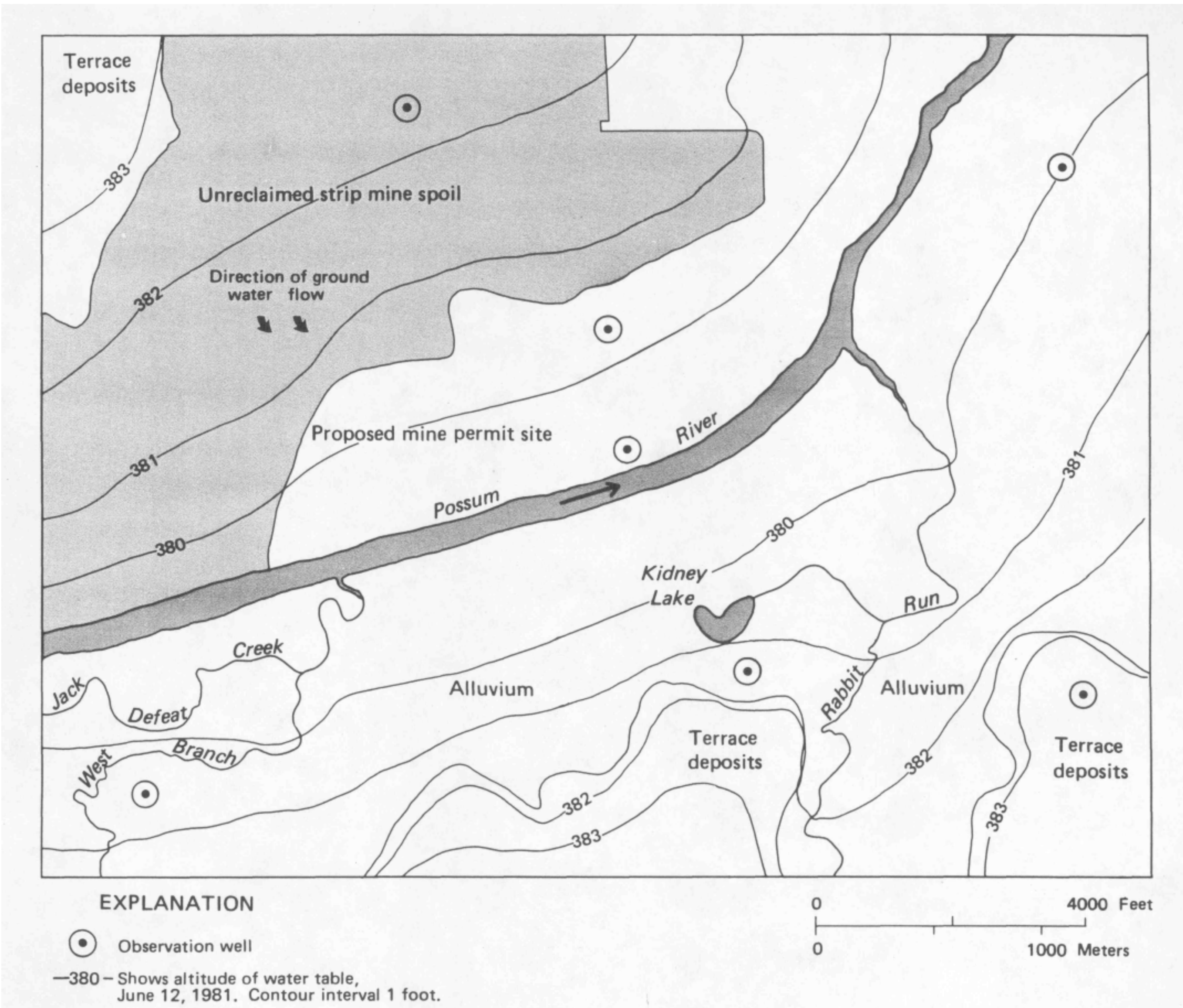

Figure 3.2-1.— Proposed mine area and adjacent area showing water-table contours.

3.0 HYDROLOGIC SETTING

3.3 HYDRAULIC PROPERTIES OF THE ALLUVIAL AQUIFER

HYDRAULIC-CONDUCTIVITY AND SPECIFIC-YIELD VALUES ARE TYPICAL FOR ALLUVIAL AQUIFERS

The alluvial aquifer has an average hydraulic conductivity of about 90 feet per year and an average specific yield of about 0.20.

Average hydraulic-conductivity (K) values for the aquifer ranged from 60 to 254 ft/yr, and averaged 90 ft/yr. Average specific yield values ranged from 0.15 to 0.32, and averaged about 0.20. Data obtained from slug tests on 10 wells distributed across the proposed min£ site were used to compute hydraulic conductivities. The areal distribution of aquifer properties is shown in figure 3.3-1.

The 'Bouwer and Rice' slug-test method (4), a single-well recovery test, was chosen because the method can be applied to completely or partially penetrating wells for a wide range of well geometries in unconfined aquifers. The method can also be applied, in some instances, to confined aquifers. The equation for calculating K by this method is

$$K = r_c^2 \frac{\ln(R_e/r_w)}{2L} \frac{1}{t} \ln(y_o/y_t)$$

where L = length of screen open to aquifer,
r_c = radius of the casing,
r_w = radial distance between the undisturbed aquifer and the well center (includes sand or gravel envelopes),
$\underline{R_e}$ = effective well radius,
R_e/r_w = determined as a fraction by equation 3.3-2,
t = time after the start of the aquifer test,
y_o = drawdown at $t = 0$ (and y_t is taken as drawdown at some time greater than zero).

$$\ln(R_e/r_w) = \left[\frac{1.1}{\ln(h/r_w)} + \frac{A + B\ln((D-h)/r_w)^{-1}}{(l/r_w)}\right]$$

with an upper limit of ln((D-H)/rw) = 6, and if D = H then

$$\ln(R_e/r_w) = \left[\frac{1.1}{\ln(h/r_w)} + \frac{A + B\ln((D-h)/r_w)^{-1}}{(l/r_w)}\right]$$

where values for A, B, and C are obtained from figure 3.3-2.

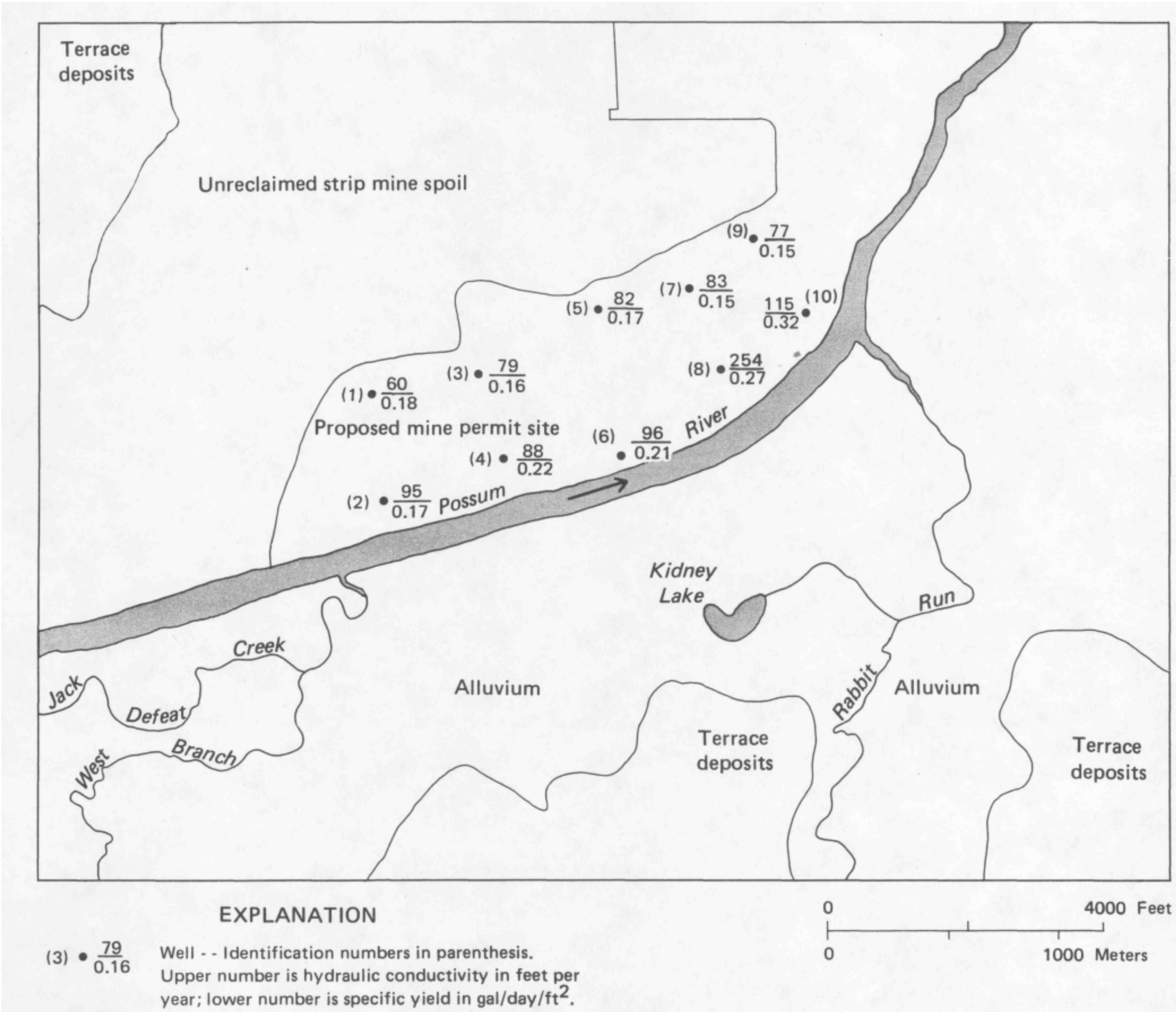

Figure 3.3-1.— Proposed mine area showing areal distribution of hydraulic conductivity and specific yield of alluvial aquifer overlying coal seam.

Figure 3.3-3 shows a vertical cross section of well 8 at some time after a slug of water has been removed. Values for the parameters necessary to calculate K are given. In addition, R_e is equivalent to the radial distance over which the head loss y is dissipated, and depends on the geometry of the flow system.

The drawdown curve for a slug test on well 8 is shown in figure 3.3-4. A bailer, with a volume capacity equivalent to a 3.0-foot change in water level in the well, was used to remove a slug of water. Subsequent water-level measurements yielded the drawdown curve. The straight-line section of the curve is used to compute hydraulic conductivity and transmissivity, as shown in figure 3.3-5.

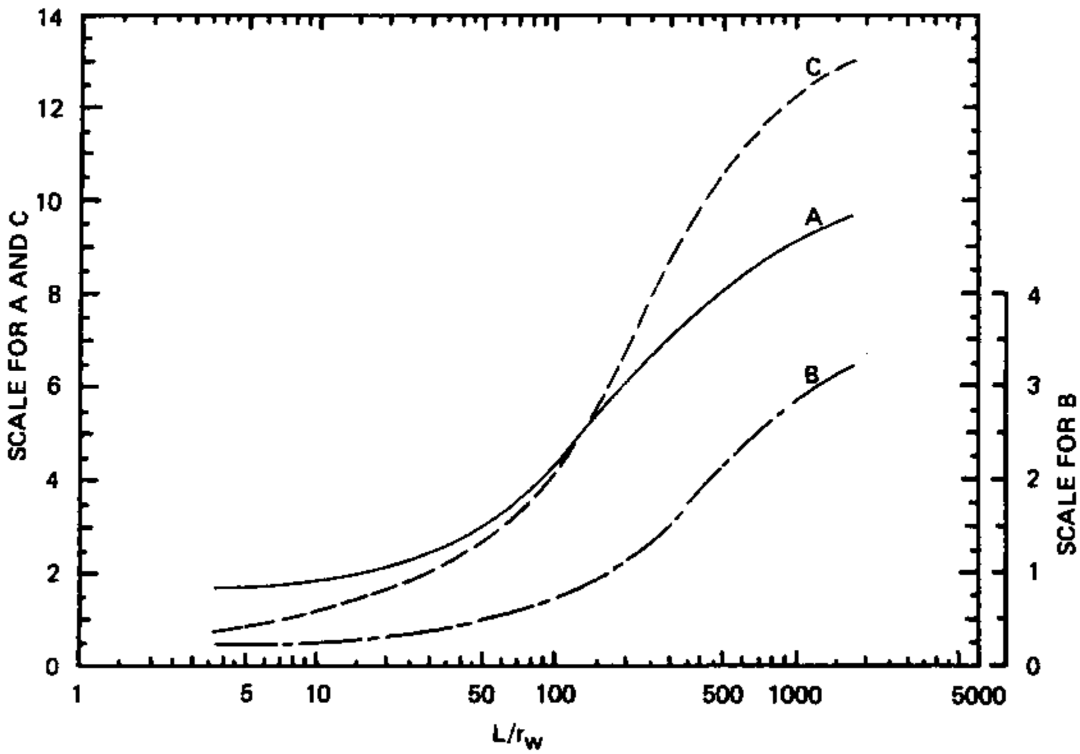

Figure 3.3-2.— Curves relating coefficients A, B, and C to L/r_w .
(From Bouwer and Rice, 1976, fig. 3.)

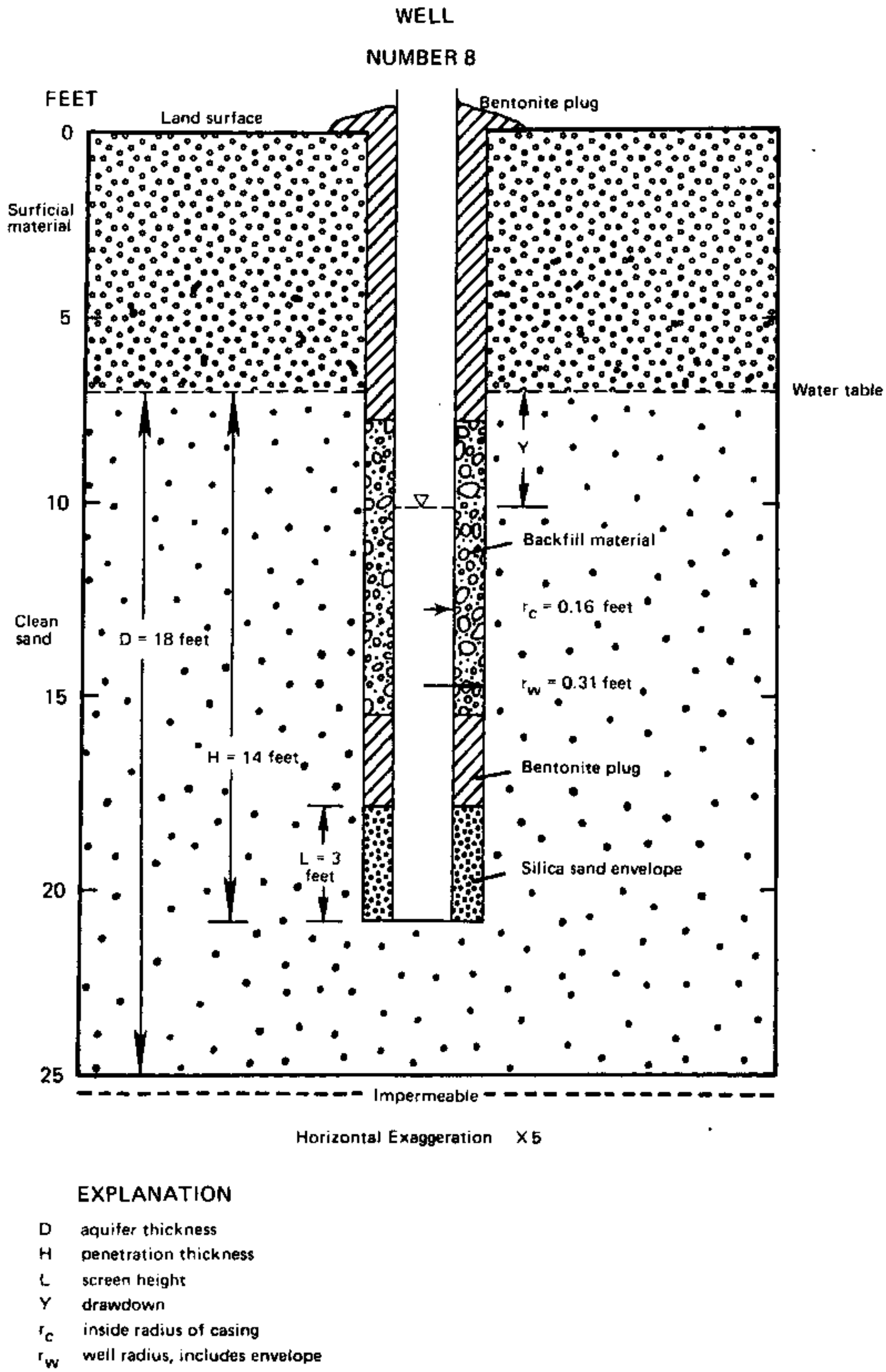

Figure 3.3-3.— Geometry of well number 8 and symbols used in slug test. (From Bouwer and Rice, 1976.)

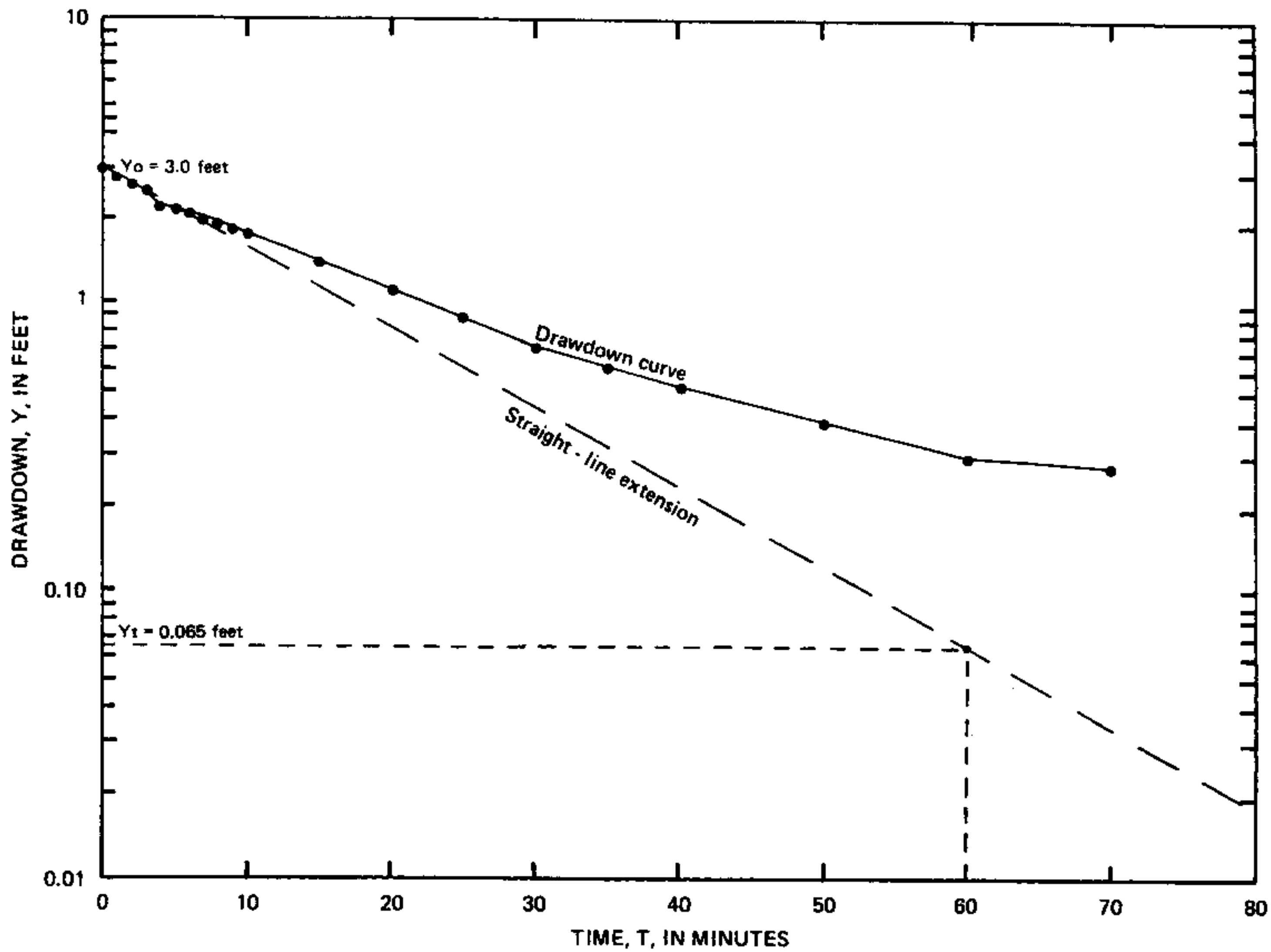

Figure 3.3-4. —Drawdown curve for slug test on well number 8.

Given: from figure 3.3-3

$r_c = 0.16$ foot

$r_w = 0.31$ foot

$L = 3$ feet

$H = 14$ feet

$D = 18$ feet

from figure 3.3-4

$y_o = 3.0$ feet

$y_t = 0.065$ foot

Find: hydraulic conductivity (K) and transmissivity (T) for well no. 8

$$K = \frac{(r_c)^2 \ln(R_e/r_w)}{2L} \frac{1}{t} \ln(y_o/y_t) \quad \text{and} \quad T = KD$$

$$\ln(R_e/r_w) = \left| \frac{1.1}{\ln(H/r_w)} + \frac{A + B\ln((D - H)/r_w)}{(L/r_w)} \right|^{-1}$$

with $L/r_w = 3/0.31 = 9.68$, then $A = 1.9$ and $B = 0.3$, from figure 3.3-2.

$$\ln(R_e/r_w) = \left| \frac{1.1}{\ln(14/0.31)} + \frac{1.9 + 0.3\ln((18-14)/0.31)}{9.68} \right|^{-1} = \frac{1}{0.2887 + 0.2755}$$

$$= 1.77$$

$$K = \frac{(0.16)^2 \times 1.77}{2 \times 3} \frac{1}{60} \ln(3.0/0.065) = 0.000483 \text{ foot per minute}$$

$$= 254 \text{ feet per year}$$

$$T = K D = 254 \times 18 = 4570 \text{ feet squared per year}$$

Figure 3.3-5.— Calculation of transmissivity for well no. 8 using Bouwer and Rice method.
(From Bouwer and Rice 1976.)

3.0 HYDROLOGIC SETTING

3.4 SURFACE-WATER GROUND-WATER INTERRELATIONSHIP

GROUND-WATER LEVELS AT THE PROPOSED MINE PERMIT SITE FLUCTUATE WITH CHANGING RIVER STAGE

Hydraulic conductivity of the alluvial aquifer permits ground-water levels adjacent to the streambank to fluctuate in response to changes in river stage.

The Possum River is hydraulically connected with the alluvial sand aquifer, which is continuous over the proposed mine site. Water moves into or out of the aquifer depending on the river stage (figs. 3.4-1 and 3.4-2). When the river stage is lower than the water level in the aquifer, which is normally the situation, a hydraulic gradient is established that allows water to flow from the aquifer to the river. Similarly, when the river stage rises above the water level in the aquifer, such as during a flood, water flows from the river into the aquifer. The extent of infiltration depends on the length of time of the flood stage and the hydraulic conductivity of the stream-aquifer interface and the alluvial material.

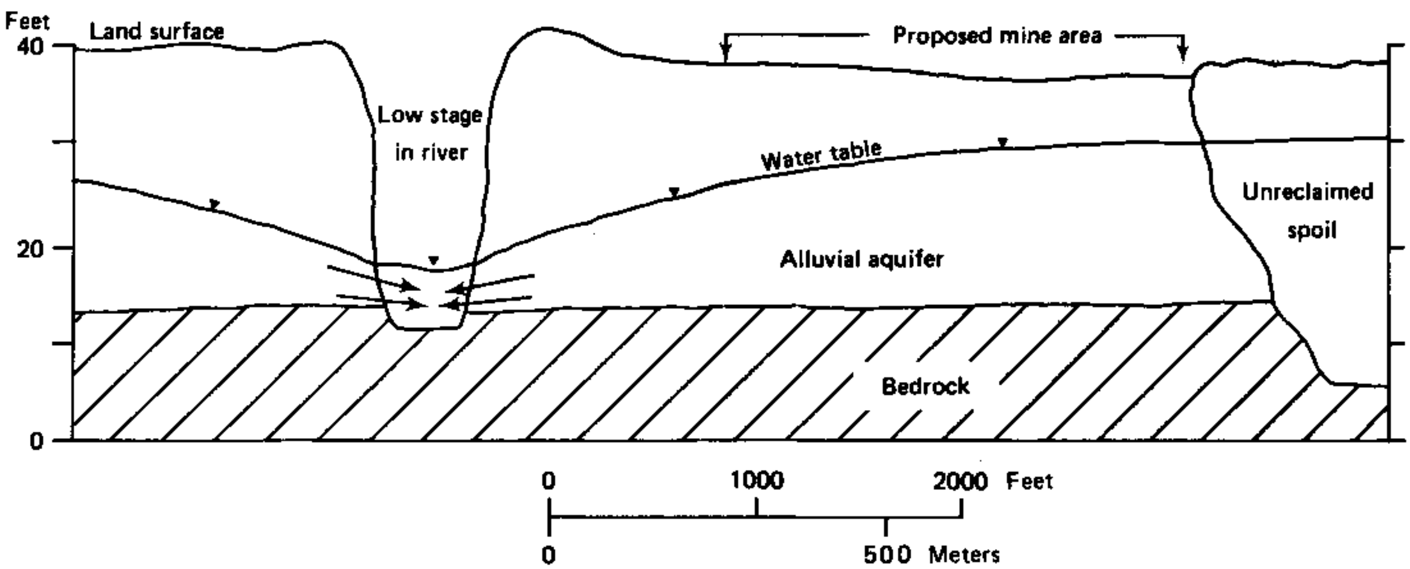

Figure 3.4-1.— Cross-section showing flow from the alluvial aquifer to the river during low-flow stage.

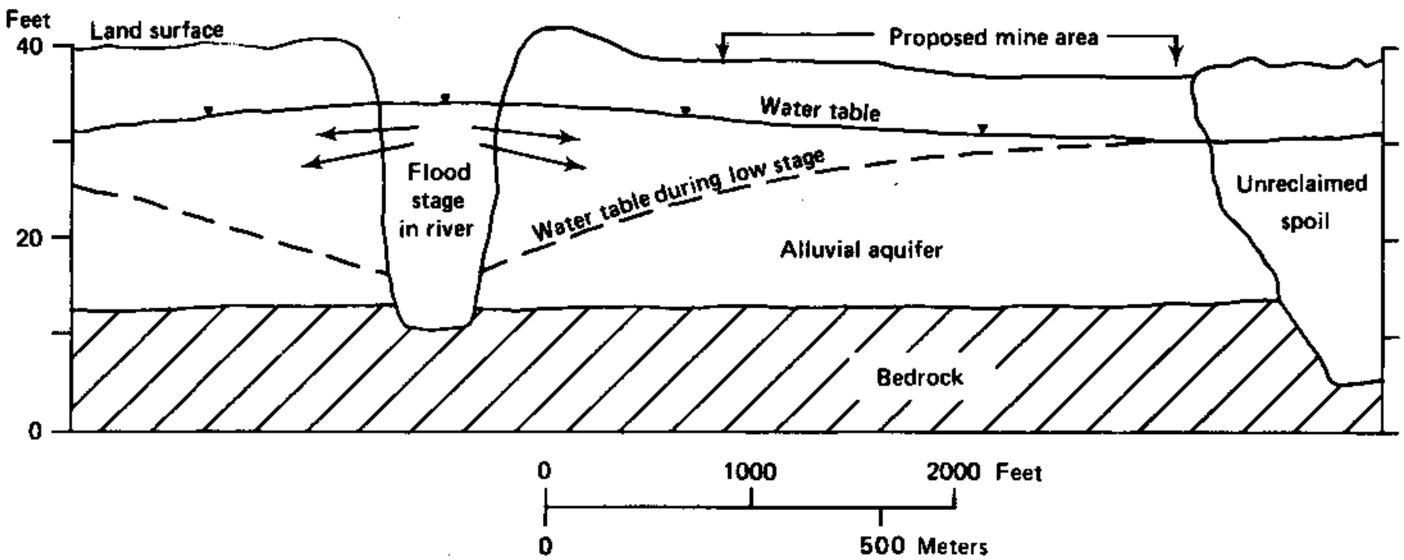

Figure 3.4-2.— Cross-section showing flow from the river to the aquifer during flood stage.

4.0 PROBABLE HYDROLOGIC IMPACTS OF MINING

4.1 GROUND-WATER DISCHARGE INTO EXCAVATION

GROUND-WATER INFLOW TO A MINE EXCAVATION THAT INTERCEPTS THE WATER TABLE NEEDS TO BE ESTIMATED PRIOR TO EXCAVATION

Ground water will discharge into a mine excavation that intercepts the water table of an aquifer. A seepage face will develop on the walls of the excavation. Fireclay will be graded onto the river side face of the excavation in an attempt to reduce ground-water inflow.

The size, shape, location, rate of excavating and hydrogeologic properties of the soil or rock are factors which affect the rate of ground-water inflow. The mine will be excavated through alluvium and shale bedrock to the Herrin No. 6 coal seam. The alluvium is a sand with a median grain size of 0.25-0.30 millimeters; the unit ranges in thickness from 10 to 22 feet. The depth to coal ranges from 20 to 45 feet and averages 30 feet.

The coal will be surface mined by a box-cutting operation. The first cut will be excavated from 'L1' to 'M1' (fig. 4.1-1); this cut will be 6,000 feet long, 800 feet from the river, and about 2,000 feet west of the mine boundary. Subsequent cuts will reverse the direction of excavating from the preceding cut, as the open pit will advance eastward. The pit dimensions of the first cut are 6,000 feet long, 30 feet deep, and 60 feet wide at the base with 1:1 slopes. The calculated mining rate is 1,500 linear feet per month, or 4 months to open the first cut.

Water in the alluvial aquifer is under water-table conditions when the river is at the mean annual stage. Figure 3.2-1 shows the water-table contours in and adjacent to the site on June 12, 1981. As the first cut is made, hydraulic gradients will begin to slope toward the excavation, inducing inflow toward the excavation. A seepage face will develop on both sides of the excavation.

The excavated face is depicted as being vertical (fig. 4.1-2) to simplify the conceptual hydraulic model. In figure 4.1-2, FC may be specified as a constant head boundary; DC and HI are impermeable boundaries. The water table EF meets the outflow boundary GD at E. The assumption is made that flow through the unsaturated part of the system, the area between EF and HI, is negligible.

Control of ground-water flow to the excavation will be necessary to minimize the pumping required to dewater the pit. Dewatering the excavation will lower ground-water levels in the aquifer near the pit, reducing pore pressures on the walls and thus improving slope stability. Dewatering can be accomplished with drains, drainage trenches, or pumping wells.

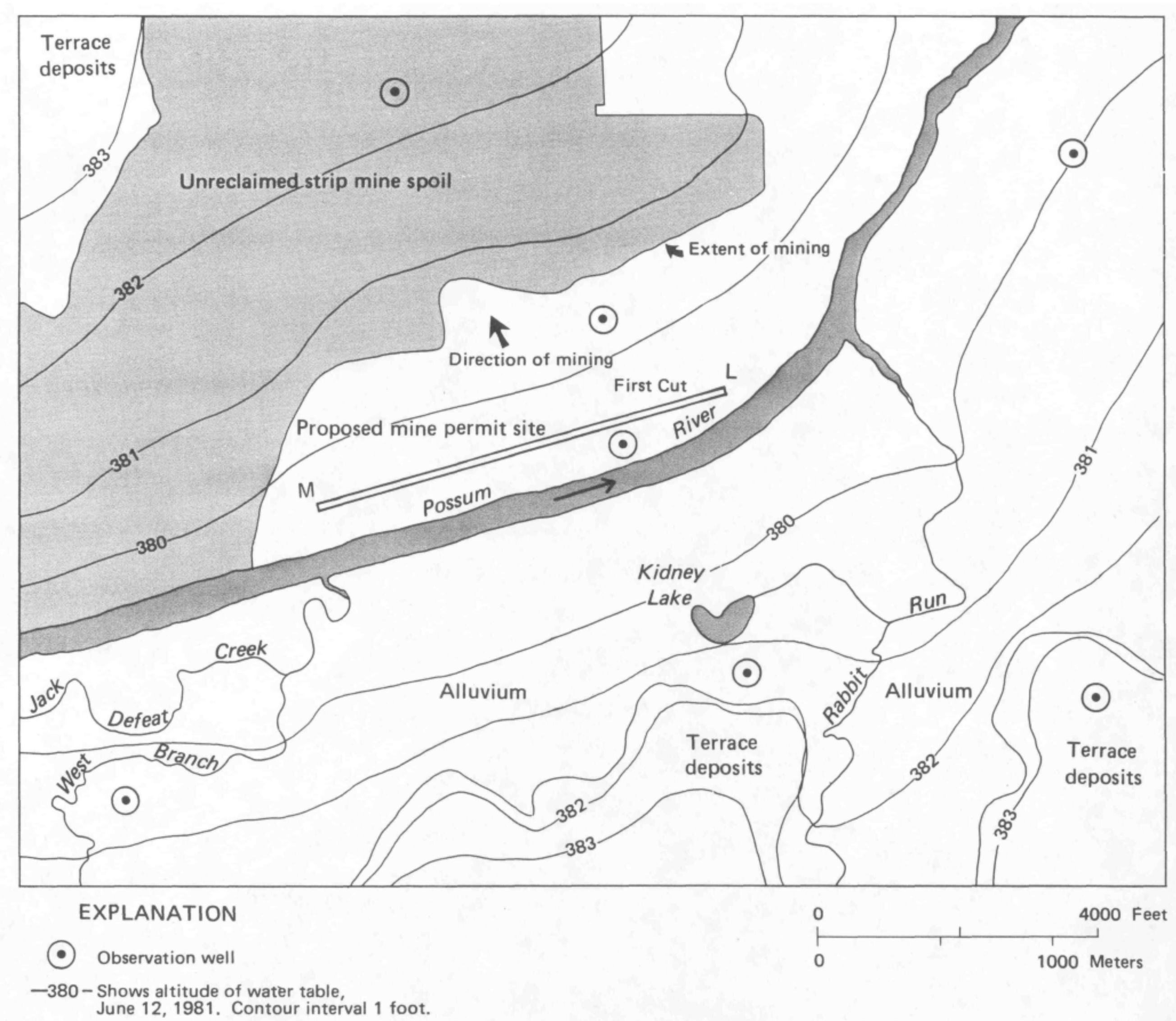

Figure 4.1-1.— Proposed mine and adjacent area showing location of first mine cut, direction of mining, and water-table contours.

A different method to reduce inflow is being considered for this mine. Some of the fireclay would be excavated in the first section of the cut and graded onto the excavation face nearest the river. As the clay is laid down, it would be covered with spoils material to provide additional support for the clay barrier against hydraulic pressures resulting from rising ground-water levels behind the barrier (fig. 4.1-3).

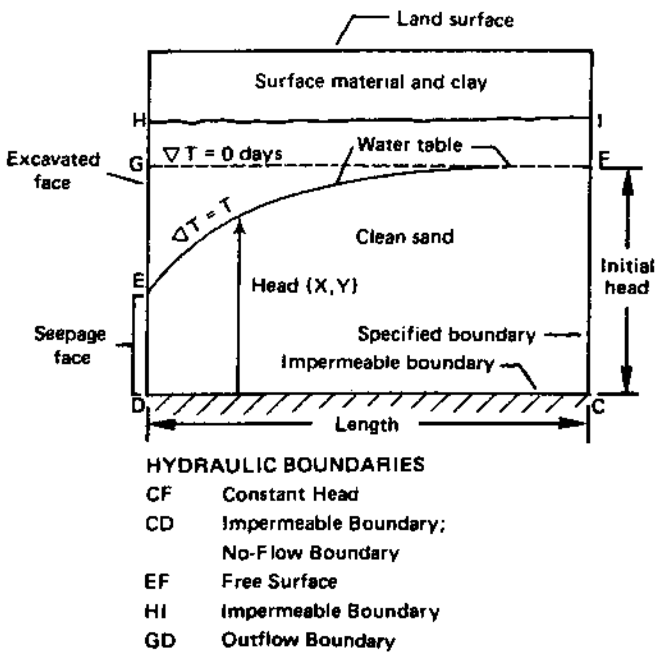

Figure 4.1-2.— Cross section of pit showing drainage to seepage face.

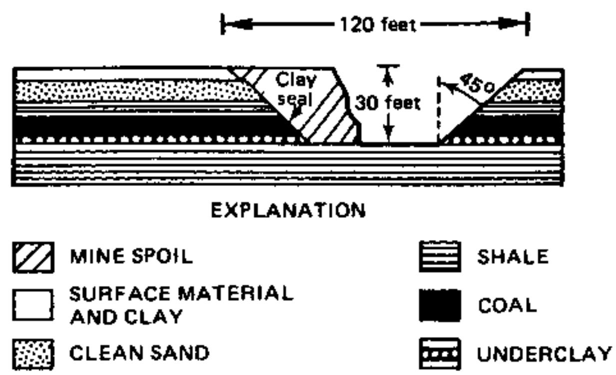

Figure 4.1-3.— Cross section through first cut showing clay seal supported by layer of mine spoil

4.0 PROBABLE HYDROLOGIC IMPACTS

4.2 PREDICTIVE ANALYSIS OF GROUND-WATER INFLOWS INTO EXCAVATION

GROUND-WATER INFLOW RATES CAN BE ESTIMATED FROM ANALYSES OF PREVIOUS INVESTIGATIONS

Ground-water discharge depends on the hydraulic boundaries. The ground-water discharge, on the river side of the excavation, reaches steady state in about 30 days. The ground-water discharge from the abandoned mine side approaches zero after more than a year.

The geohydrologic cross section from figures 2.1-1 and 2.1-2 is presented in figure 4.2-1(a). To calculate the ground-water discharge into the excavation for this setting, the following simplifying analytical assumptions (8) are made:

1. The river fully penetrates the sand unit and is not separated from it by a confining layer.
2. The sand unit is horizontal and of uniform thickness.
3. Water in the aquifer is unconfined. (For the analysis, the initial saturated thickness of the aquifer and the river stage is 20 feet. Stream-gaging records for Possum River at Iona show that the mean daily river stage exceeds 20 feet less than 4 percent of the time.)
4. Drainage to the excavation will be at right angles to the length of the cut.
5. Recharge to the aquifer from infiltration or leakage through 'surface material or clay ' is negligible.
6. The hydraulic boundaries of the aquifer are a constant line source on the river side and an impermeable boundary on the other.
7. The alluvial aquifer is considered to be homogeneous, isotropic, and of infinite extent in a direction parallel to the river.

These assumptions provide a larger than expected value of ground-water flow into the excavation.

Following the solution for transient drainage of ground-water flow from a constant-head boundary (Possum River) to an outflow reservoir (the floor of the excavation) (16), the water-table profiles between the River and the excavation are shown in figure 4.2-2. The altitude of the water table between the excavation and the River approaches steady state after about 30 days.

Ground-water inflow from the river side of the excavation initially is greater than 1000 gal/d per linear foot of length of excavation. However, the discharge declines to a steady-state value of 155 (gal/d)/ft at 60 days after coal excavation begins (fig. 4.2-3).

The water-table profiles between the mine-floor excavation and the abandoned mine are shown in figure 4.2-4. The ground-water inflow from the abandoned-mine side of the excavation is initially greater than 300 (gal/d)/ft and gradually decreases with time, as shown in figure 4.2-5. After 400 days of surface mine excavation, the transient discharge is about 34 (gal/d)/ft.

The total ground-water inflow is the sum of discharges from figures 4.2-3 and 4.2-5 for the respective times. Ground-water profiles in the alluvial aquifer after 90 and 400 days are shown in figures 4.2-1b and 1c.

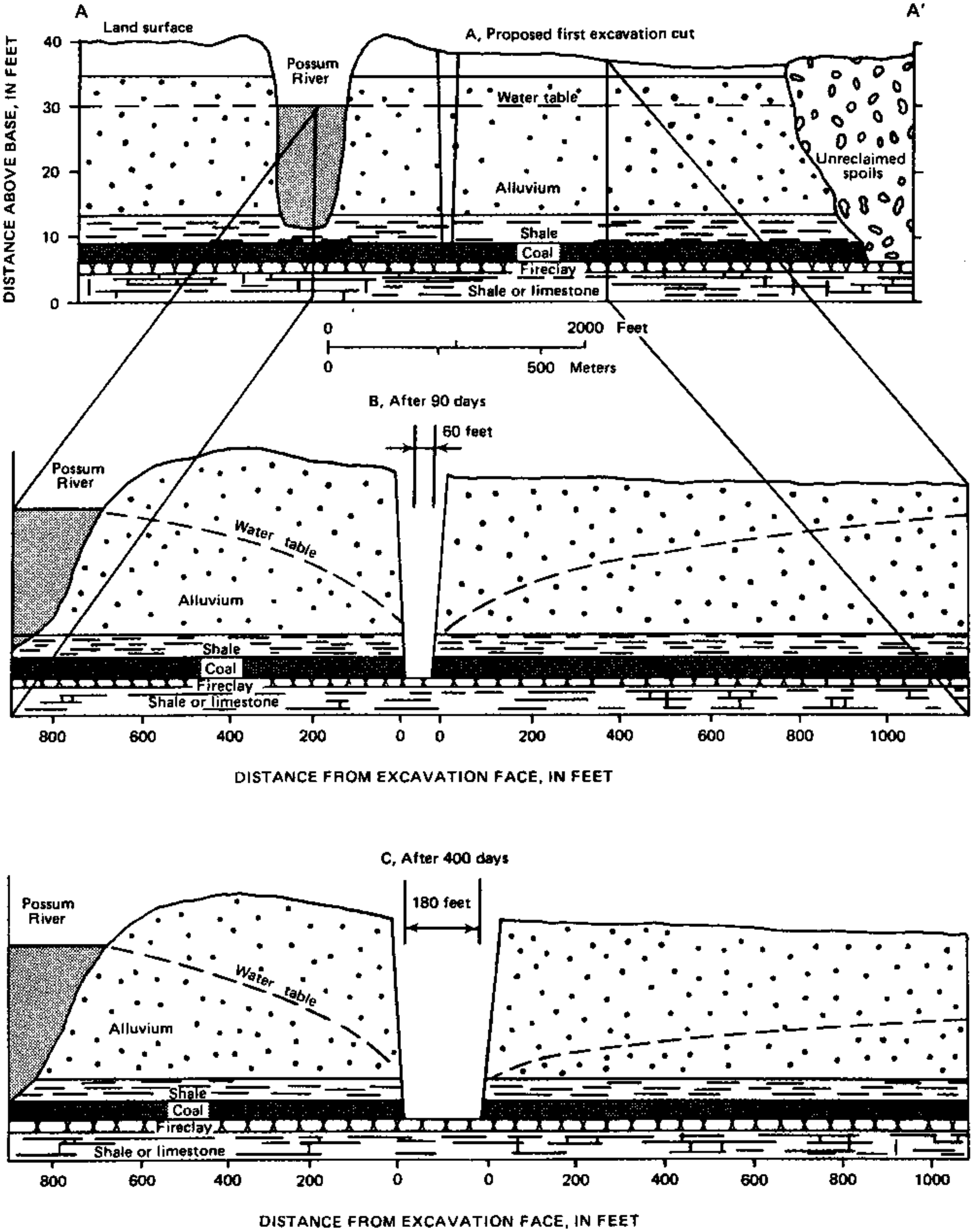

Figure 4.2-1.— Water profiles in alluvial aquifer after 90 and 400 days from the start of surface mining operations.

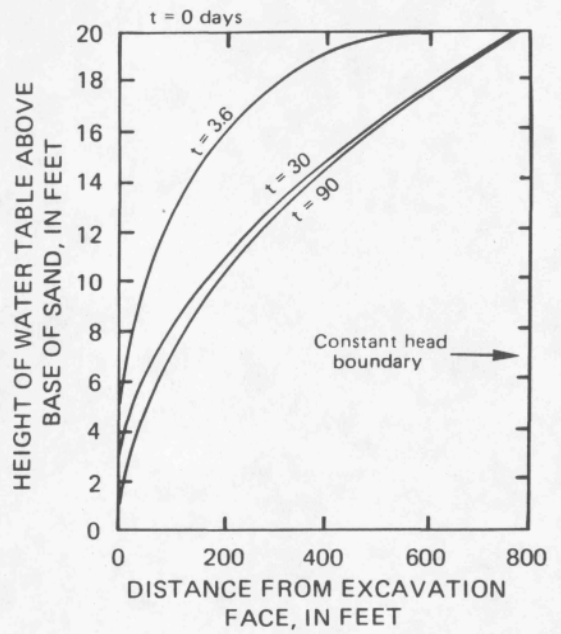

Figure 4.2-2.— Response or water table between mine pit and Possum River.

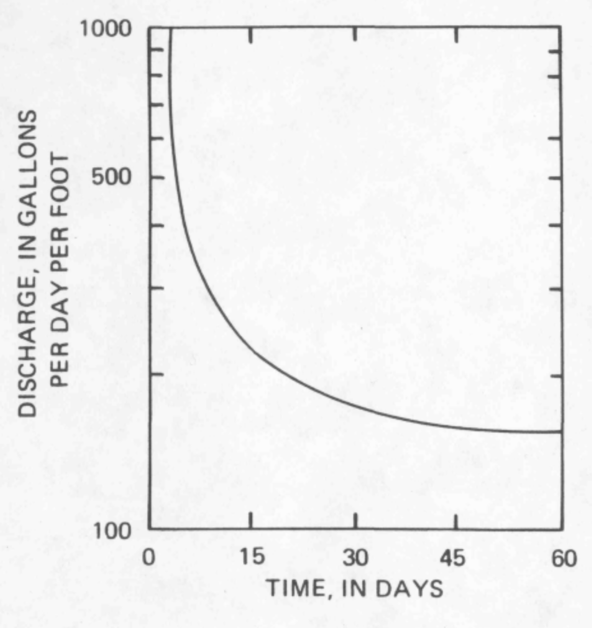

Figure 4.2-3.— Ground-water inflow hydrograph for river side of pit.

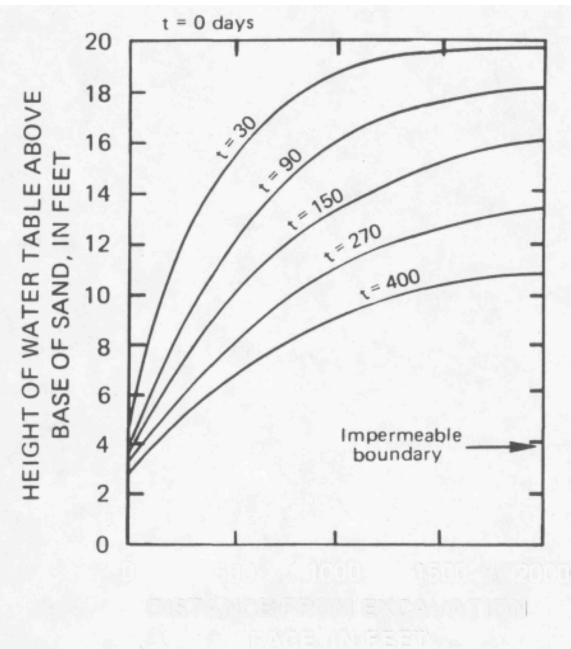

Figure 4.2-4.— Response of water table between mine pit and abandoned mine.

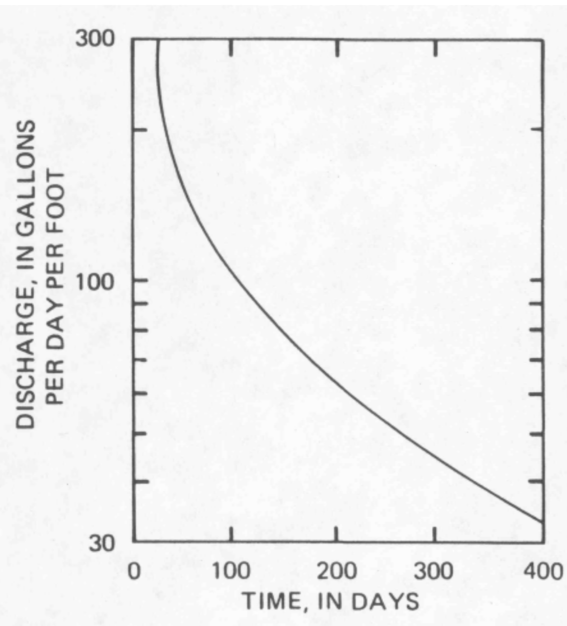

Figure 4.2-5.— Ground-water inflow hydrograph for abandoned mine side of pit.

4.0 PROBABLE HYDROLOGIC IMPACTS

4.3 HYDRAULIC ANALYSIS OF GROUND-WATER INFLOW TO FIRST CUT

GROUND-WATER INFLOW FROM EITHER SIDE OF FIRST CUT MAY BE USED TO ESTIMATE THE DRAINAGE DURING EXCAVATION

Ground-water inflow to the excavation reaches a maximum as the first cut is completed. The effect of sealing the river side of the first cut to reduce ground-water inflow becomes more significant later during opening of the excavation.

The maximum inflow of ground water will occur when the first cut is completed. Although the excavation rate will be 1,500 linear feet per month, it is assumed in the analysis that four sections, each 1,500 feet in length, will be opened instantaneously at 1-month intervals. Each 1,500-foot section allows an equivalent length and height of aquifer to drain from both the river and abandoned-mine side of the cut. Excavation of the second cut begins at the end of the fourth month. Simulation of ground-water flow to the second cut is not made.

The rates of inflow through both faces have been evaluated at monthly intervals for each open 1,500-foot section (fig. 4.3-1). Inflow increases as the length of the open pit is increased. The decreasing slope of the hydrograph with time results primarily from the slowing rate of inflow from the abandoned-mine side of the cut.

The analysis considers ground-water inflow into the excavation with sealing of the seepage face on the river side of the cut. It is assumed that the seal is applied instantaneously over each 1,500-foot section, 1 month after the section is completed. Sealing the seepage face at this frequency leaves only 1,500 feet of open face to drain on the river side of the excavation at any time. Based upon hydrologic analyses the sealing of the river side seepage face causes (1) a 20-percent reduction of ground-water discharge at the end of the second month of excavation, (2) about 40-percent reduction at the end of the third month, and (3) about 60-percent reduction at the end of the fourth month.

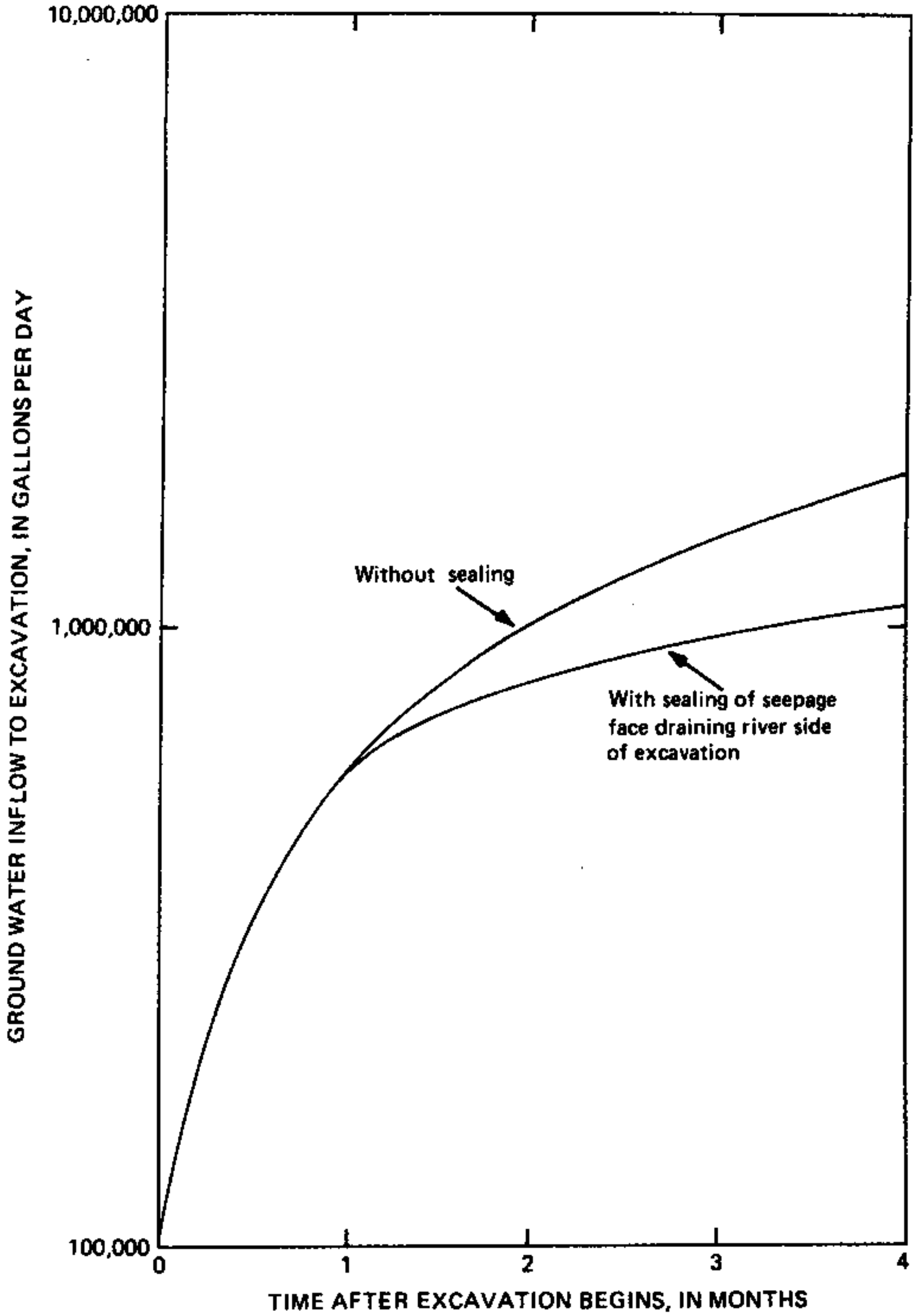

Figure 4.3-1.— Ground-water inflow hydrographs for first cut, with and without clay barrier.

4.0 PROBABLE HYDROLOGIC IMPACTS

4.4 GROUND-WATER-QUALITY CONSIDERATIONS

WATER IN ALLUVIAL AQUIFER MAY BE IN CONTACT WITH POTENTIALLY ACIDIC AND VERY MINERALIZED WATER

Lack of adequate buffering capacity in the spoils to neutralize acid water produced from oxidation of pyrite and marcasite in the spoils may result in acidic and very mineralized ground water. Water in the spoils will eventually discharge to the river, where dilution by river water will minimize the effects on river water quality.

The major effect of mining on the ground-water quality will result from the mine spoils being in contact with the alluvial aquifer. The spoils will consist of silty clay, clean sand, and shale. There will be two to three times, by volume, more sand than either clay or shale. The silty clay, derived from the more recent alluvial deposits above the sand unit, has been subjected to leaching by infiltrating water over many years, and consequently, would not contribute significantly to the mineralization of the water in the spoils. The shale associated with the coal seam has an abundance of pyrite and marcasite, which are likely to be sources of acid production in the spoils. Buffering capacity of the spoils material is small. The potential exists for the formation of an acidic and very mineralized water in the spoils.

Following the recovery of water levels in the alluvial aquifer and spoils, ground-water flow will most likely be from the mine spoils toward the river. However, the direction of flow will depend on the river stage. Discharge of the acidic, mineralized spoils water will probably have a minimal effect on the river water quality because of dilution by the river water. A less likely but possible alternative would be for the ground water to flow from the spoils through the alluvial aquifer toward the river in a downstream direction. Water from the spoils then might flow toward a municipal well field and contaminate that water supply.

5.0 GROUND-WATER MONITORING NETWORK

PRE-, DURING, AND POST-MINING GROUND-WATER MONITORING CAN BE USED TO EVALUATE IMPACTS OF MINING

Wells or borings completed during the permitting process may be used for monitoring. Other wells will have to be installed to complete the monitoring system.

A monitoring system needs to provide sampling points for monitoring surface-water and ground-water quality and for determining the rate of ground-water drawdown and recovery in and adjacent to the mined area. The number of sampling points required to adequately monitor the effects of mining on an alluvial aquifer will depend on the distribution of hydraulic gradients and complexity of the hydrogeology. Wells for water sampling and measurement of water levels need to be installed both within, and adjacent to, the mine site.

Records of premining ground-water and surface-water quality are necessary as background data in a monitoring program (fig. 5.0-1). Historical data are needed to determine if changes take place during mining. The monitoring system is designed to account for contamination by sources outside of the site. If not accounted for, these contaminants might inadvertently be attributed to the mining.

Geologic and hydrologic data gathered as a part of the permitting process will provide a basis for the design of a monitoring program. Monitor wells can be located between the pit and river and between the abandoned mine and the pit to monitor changes in water levels as mining progresses (fig. 5.0-2). The quality of the water collecting in the pit during mining will be monitored prior to discharge to the river.

Once mining has been completed, ground-water levels will recover to near the premining level. Water levels need to be measured periodically to determine rate of recovery and direction of flow in the spoils. After mining, water that infiltrates the surface and enters the ground water may leach minerals from the spoils. Monitoring the ground-water quality on the river side of the mined area will be necessary to determine whether or not the quality has been altered (fig. 5.0-3).

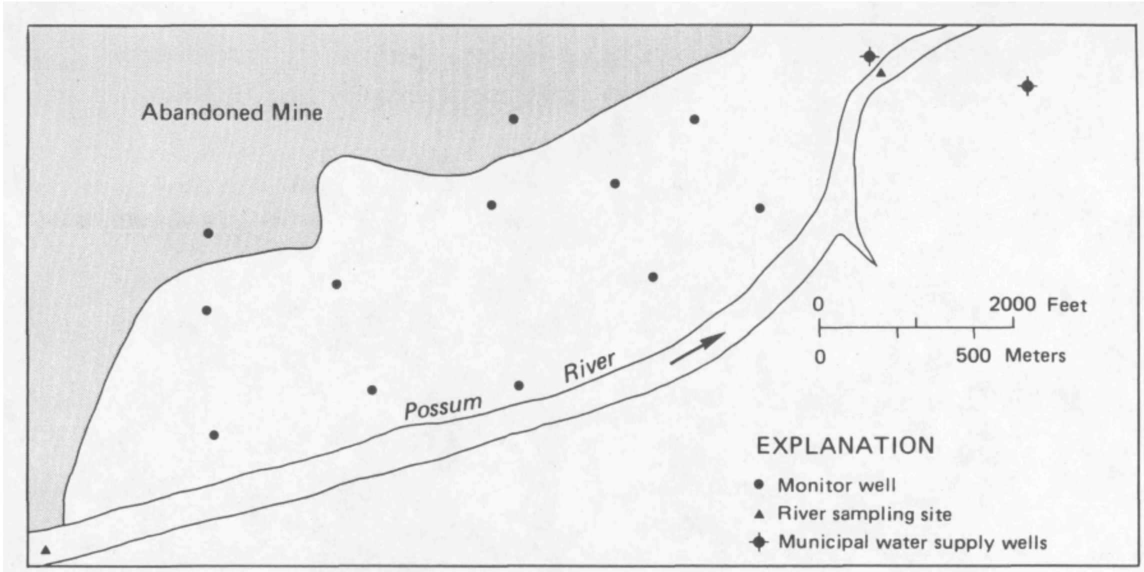

Figure 5.0-1— Distribution of pre-mining monitoring wells and river-quality sampling sites.

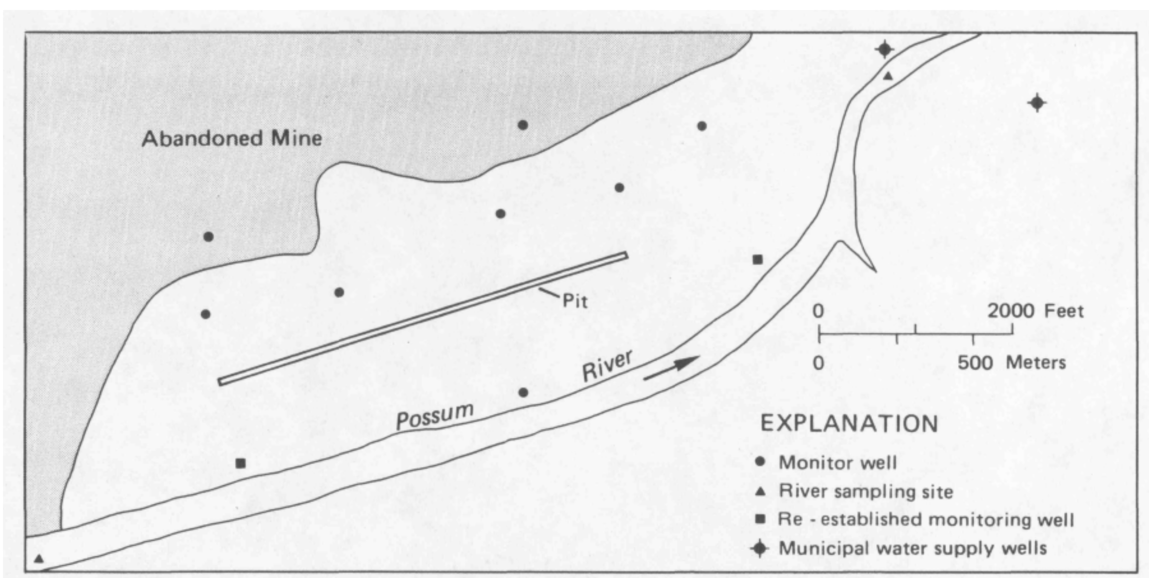

Figure 5.0-2.— Distribution of monitoring wells and river quality sampling sites during mining.

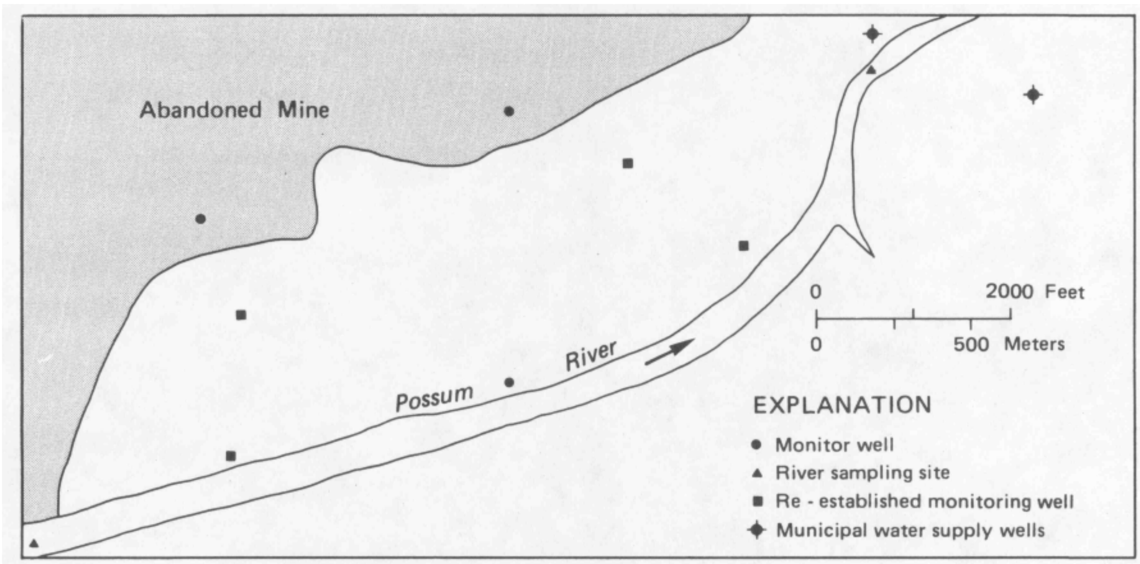

Figure 5.0-3.— Distribution of post-mining monitoring wells and river-quality sampling sites.

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GROUND-WATER STUDY 7

by

Hugh E. Bevans

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1.0 ABSTRACT

Geology and Occurrence of Coal

The mine area is in the Osage Plains division of the Central Lowlands physiographic province. The bedrock is of Pennsylvanian age and consists of alternating beds of shale, siltstone, limestone, sandstone, coal, and underclay. These rocks dip to the northwest at about 20 feet per mile. Unconsolidated deposits of silt, clay, sand, and gravel of Quaternary age occur in stream valleys incised into the older Pennsylvanian bedrock.

Hydrogeology

The area has a humid-continental climate and receives average annual precipitation of about 40 inches, almost all in the form of rain. Topographic relief is low, but the predominantly shale bedrock and soils having slow infiltration rates cause most of the precipitation to move as runoff into streams. Base streamflow is poorly sustained because few aquifers are capable of providing sufficient water to maintain it.

Unconsolidated valley-fill deposits and shallow bedrock aquifers sometimes yield water of adequate quantity and quality to meet domestic needs. The quality of ground water usually depends on the geochemistry of the rock unit that yields it. Limestone rocks yield calcium bicarbonate type water, shales yield water with large concentrations of sulfate, and sandstones yield water with relatively small concentrations of dissolved solids. Wells completed in alluvial terrace deposits yield water that reflects the geochemistry of upstream and adjacent rock outcrops. Shallow aquifers are susceptible to contamination, mining disturbance, and drought. Deeper aquifers near the base of the Pennsylvanian System and in the Mississippian System yield water that is too mineralized to meet any water-use requirement.

Mining Method

The area has yielded about 300 million tons of bituminous coal, primarily from underground mines in the Weir-Pittsburg coal bed. An estimated 640 million tons of coal reserves remain for surface mining, primarily in the Mineral, Bevier, Weir-Pittsburg, Rowe, and Croweburg coal beds. Surface mining has been the only method used to recover coal in the area since 1964 and will continue to be the predominant method of mining. Great thicknesses of overburden (as much as 100 feet) must be removed to mine the relatively thin coal seams (less than 4 feet) and large areas are disturbed during surface mining.

Probable Hydrogeologic Impacts

The probable hydrogeologic impacts of coal mining differ with hydrogeologic conditions and the method of mining. Few aquifers in this area that are used for water supply could be impaired by coal mining. Occasionally, valley-fill or shallow bedrock aquifers are used for domestic or stock-watering supplies. If these shallow aquifers or their recharge areas are disturbed by surface mining, both the quantity and quality of water yielded will probably decrease. Underground mining could dewater shallow aquifers or contribute acid mine discharge to them.

In this area mine spoils function as recharge areas and as aquifers that discharge to the

adjacent streams. The principal impact of coal mining here would be increased base flow and impaired quality of streamflow as a result of recharge received from the spoils.

Hydrologic Monitoring

Wells, seeps, and base streamflow were sampled in both mined and unmined areas for water-quality and -quantity analyses. Low-flow data were collected because discharges from abandoned coal mines may be a significant part of low flow in streams. Relationships were developed between the percentage of a drainage basin surface mined and concentrations of sulfate and dissolved solids in base streamflow. These relationships are adequate for estimating the effects of surface mining on the quality of base streamflow. Potentiometric surfaces were developed using lake, stream, and well water-level altitudes in combination with topographic maps.

2.0 GEOLOGIC SETTING

2.1 SURFACE GEOLOGY

Bedrock that crops out in the study area is of Pennsylvanian age and contains the commercially important coal beds. Unconsolidated Quaternary deposits overlie bedrock along stream valleys.

The surficial geology of the study area (fig. 2.1-1) consists mostly of shale, limestone, and sandstone beds of Pennsylvanian age and unconsolidated deposits of silt, clay, sand, and gravel of Quaternary age. The consolidated Pennsylvanian rocks dip to the northwest at about 20 ft/mi, exposing progressively older rocks from northwest to southeast. Pennsylvanian rock units exposed in the study area are, from oldest to youngest: Krebs Formation, Cabaniss Formation, Fort Scott Limestone, Labette Shale, and Pawnee Limestone. Generalized lithologic description of these bedrock units is presented in table 2.1-1. The Krebs and Cabaniss Formations contain coal beds. However, the commercially important coal beds, including the Weir-Pittsburg, Mineral, and Bevier coals, are in the Cabaniss Formation. The coal outcrop lines shown in figure 2.1-1 represent only the major coal beds at the surface in the study area. The outcrop lines do not represent the limit of good quality coal, as erosion has removed some coal and weathering has rendered some unusable.

Unconsolidated deposits of silt, clay, sand, and gravel of Quaternary age occur in stream valleys. The valleys are incised into the older Pennsylvanian bedrock.

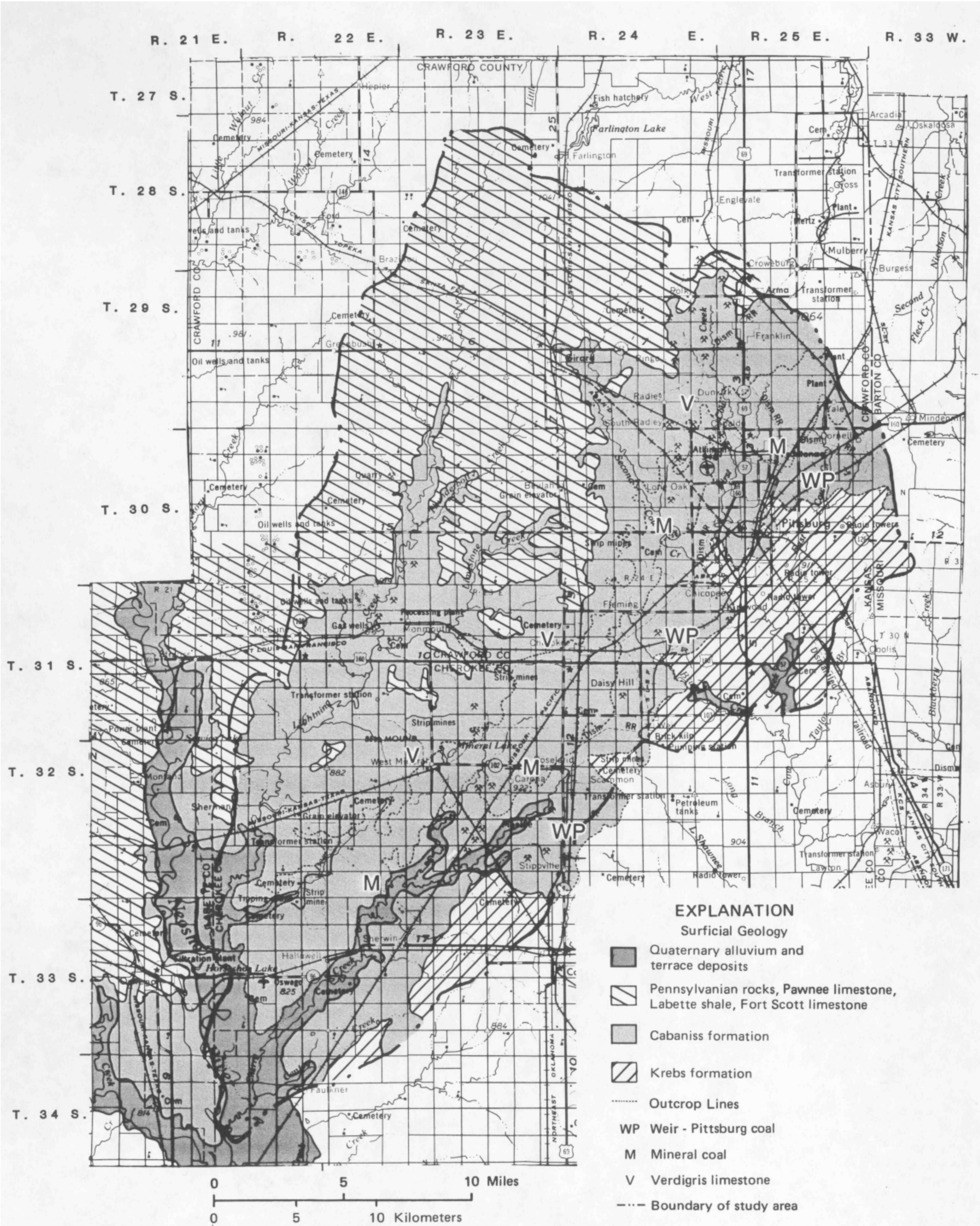


Figure 2.1-1.— Surface geology and coal outcrops. (From Pierce and Courtier, 1937.)

Table 2.1-1– Description of the surface rocks.
(From Seevers. 1975, and Howe, 1956.)

System	Geologic unit	Average thickness (feet)	Description
Quaternary	Alluvium	30	Silt, and silty sand, gray to grayish-brown, limonite stained in part; contains some sand and median to coarse gravel at base.
	Terrace deposits	25	
Pennsylvanian	Pawnee Limestone	20	Limestone, light-gray to white, fine crystalline, cherty, massive.
	Labette Shale	60	Shale, gray to greenish-gray to black; contains fine-grained sandstone and thin local limestone and coal bed.
	Fort Scott Limestone	20	Limestone, light-gray to brownish-gray, and black to light-gray shale, light-gray shale.
	Cabaniss Formation	225	Shale, light- to dark-gray; contains siltstone, limestone, sandstone, and coal. Commercially most important coal beds occur in this formation.
	Krebs Formation	225	Shale, light- to dark-gray, and fine-to median-grained sandstone; contains coal, under clay, siltstone, and some limestone locally.

2.0 GEOLOGIC SETTING

2.2 STRATIGRAPHY OF BEDROCK CONTAINING COAL BEDS

Coal beds of economic importance in the coal field occur as part of cyclothems.

The stratigraphy of the commercially important coal-containing Krebs and Cabaniss Formations is shown in figure 2.2-1. The Krebs and Cabaniss Formations exhibit typical cyclic successions (cyclothems) from the top of a given coal bed to the top of the next higher coal bed. These successions are commonly composed of five lithologic units occurring from the base upward:

(1) Dark shale or dark irregular limestone. The Krebs Formation commonly has clay-ironstone, with iron-sulfide minerals such as pyrite and marcasite associated with the dark shale; whereas, the Cabaniss Formation has phosphatic nodules in platy black fissile shale associated with the limestone.

(2) Unfossiliferous, evenly bedded gray shale. This is commonly the thickest unit in the lithologic succession.

(3) Either sandstone or impure nodular limestone. Sandstone ranges from massive to shaley or thin-bedded; most of it is fine grained, lenticular, and grades laterally into impure sandy limestone, called underlimestone.

(4) Underclay. This unit is least variable in lithology, is relatively uniform in thickness, and is commonly silty and slightly calcareous.

(5) Coal. This is the most economically important rock in the succession. Lateral extent, thickness, and quality are variable; however, many beds in the area are remarkably persistent.

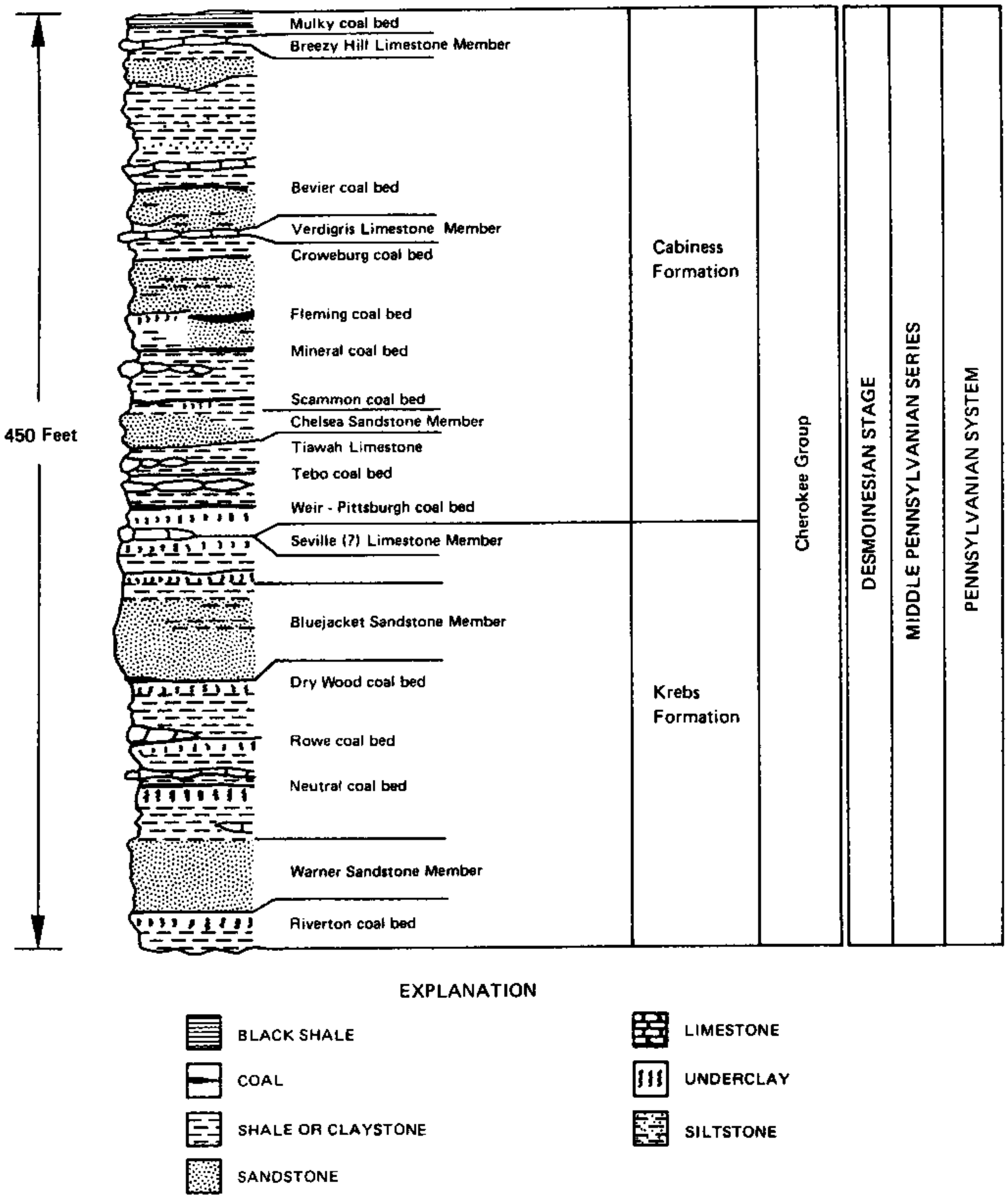


Figure 2.2-1.— Generalized stratigraphic column of the Krebs and Cabaniss Formations. (From Zeller, 1968.)

3.0 HYDROLOGIC SETTING

3.1 PHYSIOGRAPHY AND CLIMATE

The mine site is in a humid-continental climate and within flat rolling plains. Annual precipitation exceeds 40 inches, most occurring as rainfall from spring through summer.

The climate is humid-continental and is characterized by abundant precipitation, warm to hot summers, mild winters, moderate to high humidity, light to moderate winds, and little annual snowfall. The average annual precipitation exceeds 40 inches; about 75 percent of this occurs as rain from April through October. However, gentle rains of longer duration occur during the spring and fall.

The permit area is in the Osage Plains division of the Central Lowlands physiographic province. The natural topography is gently undulating with maximum relief less than 200 feet. In areas where shales crop out, the terrain is nearly flat and the stream valleys have broad flood plains. Areas where limestones crop out have more relief and narrower stream valleys.

3.0 HYDROLOGIC SETTING

3.2 HYDROLOGIC-MONITORING NETWORK

The hydrologic-monitoring network consists of 20 stream data-collection stations and 25 well and seep data-collection stations.

Hydrologic data were obtained at data-collection stations and sites shown in figure 3.2-1. Stream data were collected from April 1976 through March 1980. Most well data were collected from 1963 through 1965. Well 4 was sampled in 1947 and 1954. Wells 15, 21, and 22 were drilled and sampled in 1972. Wells 24 and 25, which are actually discharges from air shafts of abandoned underground mines, were sampled in March 1980.

Stream stations were used primarily to monitor base flow during periods of no overland runoff. This discharge is from shallow aquifers, which are providing the base flow. Sampling the base flow provides information on the water quality of shallow aquifers in the area drained.

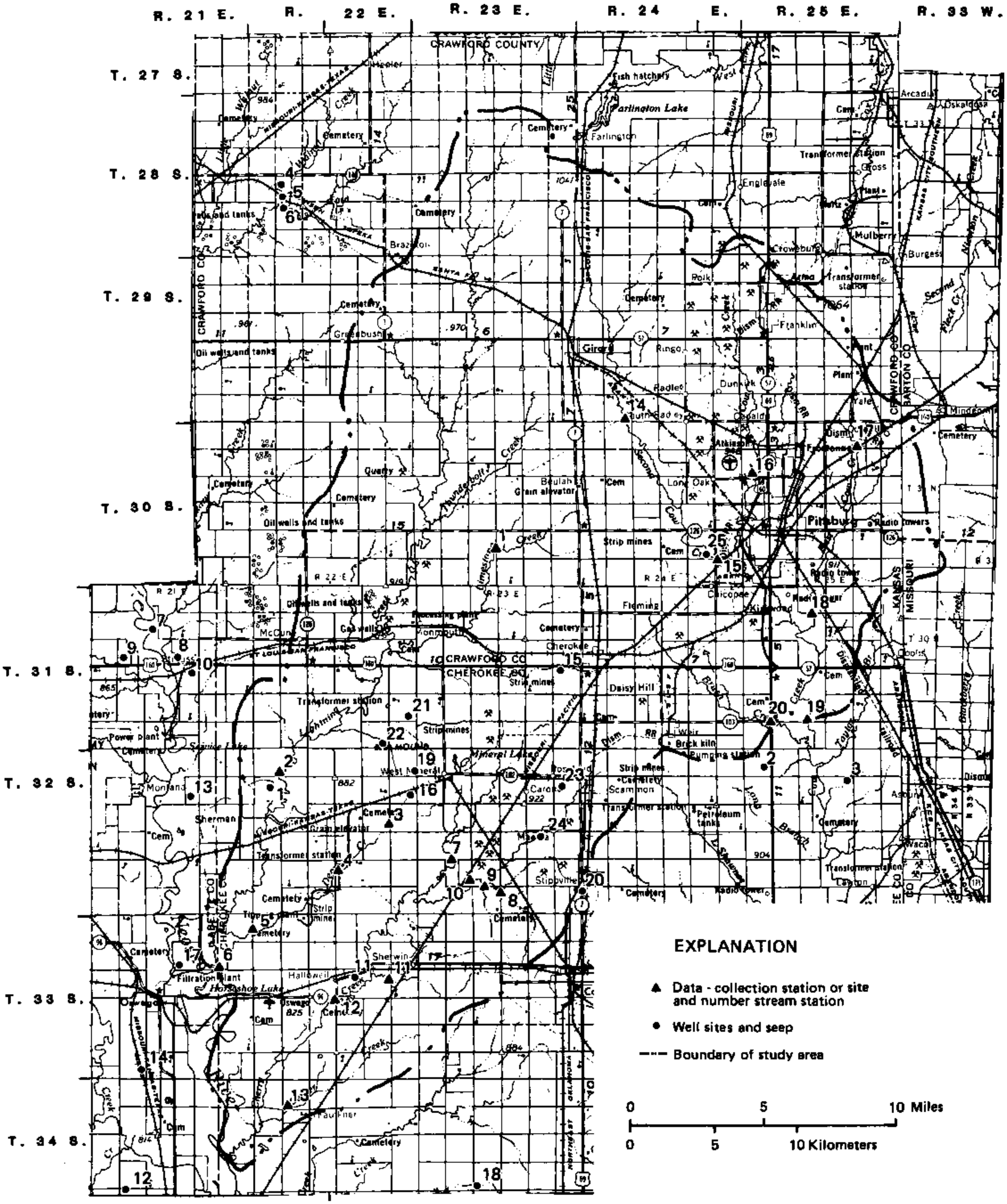


Figure 3.2-1.— Hydrologic-monitoring network.

3.0 HYDROLOGIC SETTING

3.3 GROUND-WATER OCCURRENCE AND AVAILABILITY AT PRE-MINING

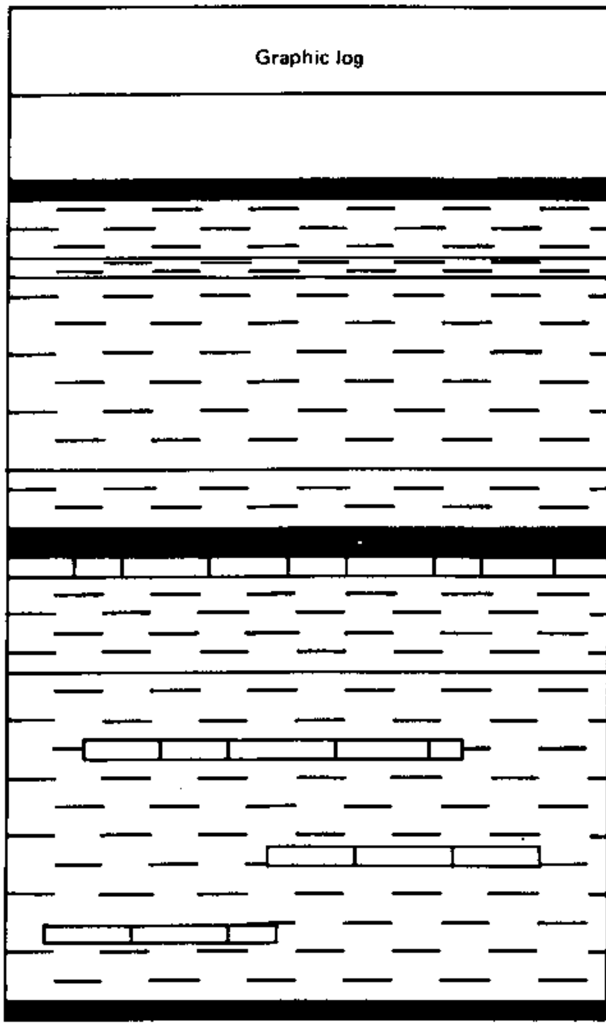
Aquifers capable of yielding quantities of water sufficient to satisfy water-use requirements are generally absent in the area.

The Krebs and Cabannis Formations of Pennsylvanian age have combined thicknesses ranging from about 200 feet in the south to 500 feet in the northwest. These formations contain relatively few aquifers capable of satisfying any water-use requirements. The rocks are mostly fine-grained marine shales and siltstones, which are poor aquifers. Continuous underclay beneath many of the coal beds impedes the vertical movement of ground water. Well 15 (T. 31 S., R. 23 E., sec. 24 on fig. 3.2-1) in the hydrologic-monitoring network, is 43-feet deep, is completed in the Cabaniss Formation, and yields only about 2 gal/min. The geologic log for this well is presented in figure 3.3-1. The well is open throughout its depth, but the principal water-producing zone is the sandy shale at 8.5 to 17.5 feet below land surface. Limestones and thin discontinuous sandstones can also produce small quantities of water. Typically, shallow bedrock wells yield less than 5 gal/min. Bedrock wells completed in the Warner Sandstone Member or Blue Jacket Sandstone Member of the Krebs Formation may yield as much as 50 gal/min, but the quality of the water is suitable for domestic use only near their outcrops.

Except during periods of drought, quantities of water suitable for domestic uses are yielded by wells completed in unconsolidated terrace and alluvial deposits of Quaternary age. Wells tapping these deposits can yield as much as 100 gal/min.

Ground-water recharge in the area varies with climate, topography, and rock and soil textures. Recharge occurs mainly during the spring when rainfall is plentiful and evapotranspiration loss is small. Recharge is greatest on alluvium developed on valley fill and terrace deposits where slopes are gentle and the soils are most permeable. Gently sloping surfaces developed on northeast- to southwest-trending outcrops of thick limestone units collect moderate amounts of recharge water. Very little recharge takes place on steep slopes or where the land surface is underlain by claypan or impermeable shale.

Water movement in alluvial and terrace deposits is towards the streams. Water in confined and unconfined bedrock aquifers moves downgradient. Water movement in unconfined bedrock aquifers is affected by the topography. Ground-water movement in perched aquifers is lateral toward the outcrop of the underlying impermeable bed. Estimates of the rate of ground-water movement in this general area range from 0.34 ft/d in unconsolidated alluvial and terrace deposits to 0.03 ft/d in upland bedrock aquifers (12).



Depth (feet)	Thickness (feet)	Lithologic description
0.0 - 4.0	4.0	Silty clay loam
4.0 - 4.5	0.5	Weathered Fleming coal bed
4.5 - 7.5	3.0	Gray, mottled - brown shale
7.5 - 8.5	1.0	Brown clayey shale
8.5 - 17.5	9.0	Gray shale, sandy and clayey (principal aquifer)
17.5 - 20.0	2.5	Dark - gray shale
20.0 - 21.0	1.0	Mineral coal bed
21.0 - 22.0	1.0	Hard, gray limestone
22.0 - 27.0	5.0	Gray shale
27.0 - 42.5	15.5	Dark - gray shale with 2 to 6 inch limestone streaks
42.5 - 43.0	0.5	Scammon coal bed

Figure 3.3-1.— Geologic log for well 15 of the hydrologic monitoring network.

3.0 HYDROLOGIC SETTING

3.4 PRE-MINING GROUND-WATER-QUALITY CONDITIONS

The quality of ground water in the study area is variable; calcium, magnesium, bicarbonate, and sulfate are the major ions in solution.

The chemical composition of ground water in the area depends on the geochemical composition of the aquifer that is the source of the ground water. Water quality in alluvial aquifers commonly reflects the chemical composition of upstream adjacent rock outcrops. Wells 1, 2, and 3, are completed in alluvium adjacent to outcrop areas of coal and black shale containing iron sulfides. Water from these wells has large concentrations of sulfate ion relative to bicarbonate ion (table 3.4-1).Wells 4,5, and 6, are completed in alluvium adjacent to limestone outcrop areas. Water from these wells has large concentrations of bicarbonate relative to sulfate.

Wells completed in terrace deposits also reflect the geochemistry of the adjacent bedrock. Wells 10, 11, and 12 are completed in terrace deposits adjacent to outcrops of coal and black shale and also in areas of mines. Water from these wells has relatively large sulfate concentrations. Wells 7, 8, and 9 are completed in terrace deposits adjacent to limestone outcrop areas. Water from these wells has relatively large bicarbonate concentrations.

Wells 13-17, completed in the Cabaniss Formation, and wells 18-20, in the Krebs Formation, contain waters whose chemical types are dependent on the geochemistry of the aquifers. However, in most wells the particular rock unit that yields water is not known. Wells 14, 15, and 20 probably produce water from shale units based on the relatively large concentrations of sulfate ion. Wells 13, 16, and 19 probably produce water from limestone based on the relatively large concentrations of bicarbonate ion. Well 17 probably produces water from both shale and limestone units because the concentrations of sulfate ion and bicarbonate ion are roughly equal. Water from well 18, which is finished in the Bluejacket Sandstone Member of the Krebs Formation, has very small concentrations of both sulfate ion and bicarbonate ion.

Examination of dissolved-solids data indicates that large concentrations of dissolved solids are commonly associated with large concentrations of sulfate ion. However, large concentrations of dissolved solids may also be associated with large concentrations of bicarbonate ions. The pH values in table 3.4-1 are all in the neutral range. This condition indicates that sufficient amounts of carbonate rocks are present to buffer the acidity resulting from dissolution of iron-sulfide minerals associated with black shales and coal beds. Iron and manganese concentrations cannot be related to geologic source, perhaps because pH values are not low enough to keep the iron and manganese in solution.

Table 3.4-1.— Water-quality data fran wells in unmined areas
[ft, feet; mg/L, milligrams per liter; ug/L, micrograms per liter; < less than]

Well number	Land-line location (township-range-section)	Depth (ft)	Geologic source	Specific conductance (micromhos per centimeter at 25˚C)	PH (units)	Bicar-bonate (mg/L)	Sulfate (mg/L)	Dissolved solids (mg/L)	Total iron (ug/L)	Dissolved mangan-ese (ug/L)
1	32S-22E- 7	12	Alluvium	2,170	—	224	1,050	1,660	—	—
2	32S-25E- 6	25	do.	1,650	—	59	816	1,250	—	8,600
3	32S-25E-10	29	do.	2,500	—	212	898	2,020	40	600
4	28S-22E-20	35	do.	—	7.1	454	26	451	—	220
	28S-22E-20	35	do.	—	7.1	446	37	470	800	210
5	28S-22E-20	50	do.	—	7.2	454	40	496	600	260
6	28S-22E-20	23	do.	—	7.2	588	51	630	2,200	<10
7	31S-21E- 9	28	Terrace deposits	680	—	478	20	439	9,200	1,000
8	31S-21E-15	18	do.	620	—	256	116	406	7,200	200
9	31S-21E-17	30	do.	970	7.4	226	118	650	70	<10
10	31S-21E-22	33	do	2,210	—	393	922	1,710	30	220
11	32S-21E-10	23	do.	1,420	7.0	528	201	905	30	1,100
12	33S-22E-16	64	do.	1,480	7.9	146	715	1,160	590	<10
13	32S-21E-10	52	Cabaniss Formation	850	7.7	422	.0	504	490	<10
14	33S-21E-32	35	do.	1,090	—	105	458	835	2,000	<10
15	31S-23E-24	43	do.	1,750	8.0	256	872	1,470	2,700	330
16	32S-22E-12	100	do	1,440	—	791	80	874	320	<10
17	34S-21E-29	102	do.	2,490	7.9	608	665	1,670	3,400	150
18	34S-23E-24	26	Krebs Formation	85	—	27	.0	68	70	<10
19	32S-22E- 1	400	do.	2,130	—	939	9.8	1,220	7,100	150
20	32S-23E-36	201	do.	3,470	7.2	861	1,020	2,350	<10	<10

3.0 HYDROLOGIC SETTING

3.5 PRE-MINING BASE FLOW

Base flow is poorly sustained in the area.

The interaction of surface water and ground water can be interpreted by examining the base-flow parts of the flow-duration curves, which indicate the percentage of time streamflow was equaled or exceeded. The flow-duration curves shown in figure 3.5-1 represent low- and base-flow duration at three nearby continuous-record streamflow stations: (a) Big Hill Creek near Cherryvale, 40 miles west of the general area with a drainage area of 37 mi^2 ; (b) Little Osage River at Fulton, 55 miles to the north with a drainage area of 295 mi^2; and (c) Marmaton River near Marmaton, 40 miles to the north with a drainage area of 292 mi^2. The period of record covered by the flow-duration curves is October 1976 through September 1980. The three stations are considered close to the general area and are representative of undisturbed streams within the area.

To compensate for differences in drainage-area size, unit discharge was calculated for each station. Unit discharge is the streamflow divided by the drainage area. Even though the drainage area ranged from 37 mi^2 to 295 mi^2, the flow-duration curves are similar for the three stations. Base flow at 90-percent flow duration is 0.0005 $(ft^3/s)/mi^2$ for the Marmaton River near Marmaton, and 0.00056 $(ft^3/s)/mi^2$ for the Little Osage River at Fulton. The steep slopes of the curves indicate little base flow and the streams mainly respond to storm runoff. Flow-duration curves for the two larger streams indicate higher unit discharge base flows, which are related to the greater percentage of alluvial deposits within their drainage areas.

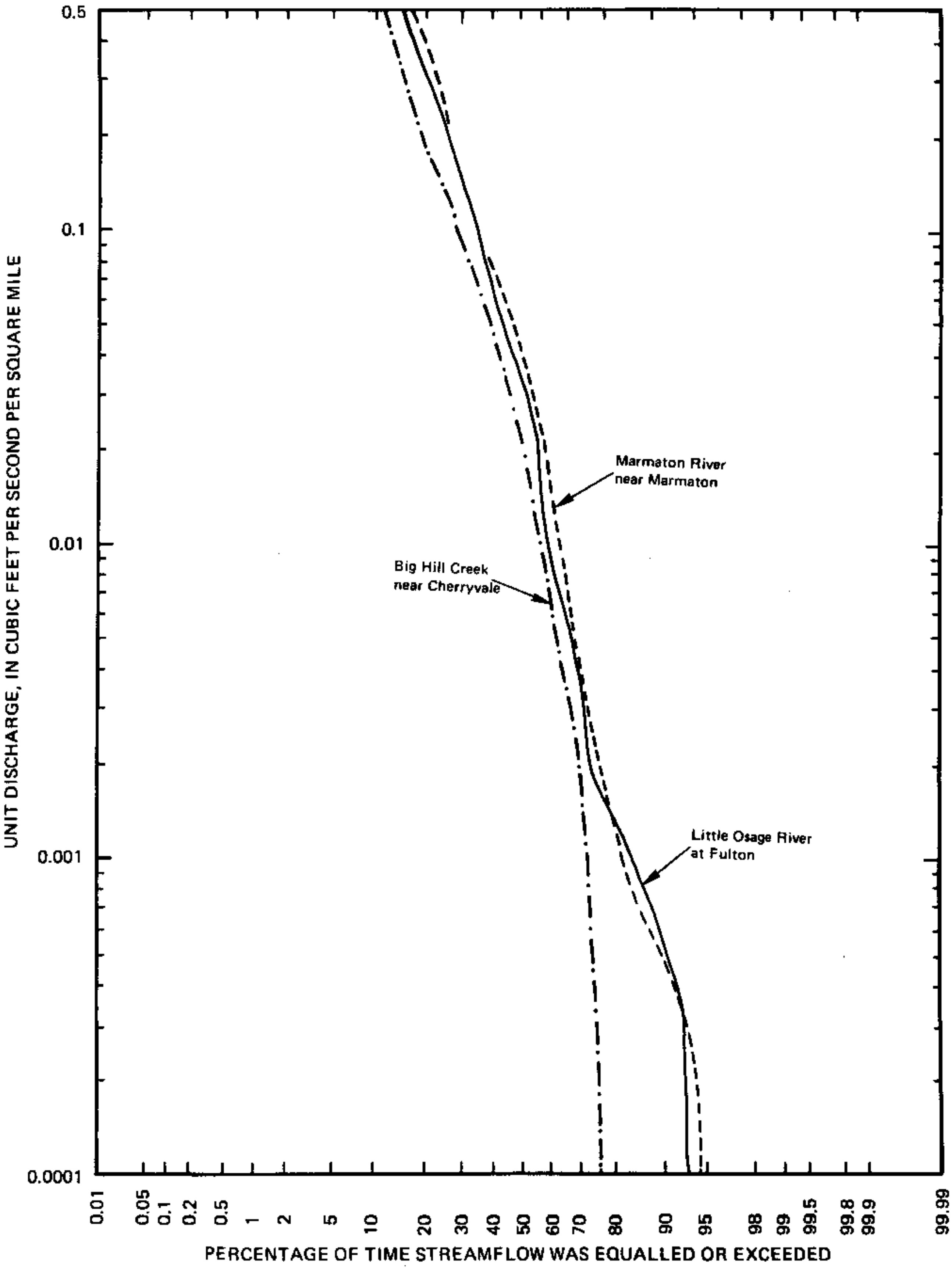


Figure 3.5-1.— Flow-duration curves for selected streams draining unmined areas.

3.0 HYDROLOGIC SETTING

3.6 BASE-FLOW QUALITY

Quality of base flow of streams draining unmined areas indicates the pre-mining water quality of the shallow aquifers.

Streams draining unmined areas where limestone crops out contain water with large concentrations of bicarbonate relative to sulfate during base-flow periods. Base-flow water-quality data presented in table 4.6-1 show that station 1 (Limestone Creek near Beulah) and station 14 (Second Cow Creek near Girard) contain water with large concentrations of bicarbonate ion relative to sulfate ion. These two streams are examples of streams that drain areas of limestone outcrops.

Streams that drain unmined areas where black shales, coal beds, and associated iron sulfide minerals crop out contain water with large concentrations of sulfate relative to bicarbonate during base-flow periods. Water-quality data in table 3.6-1 show that station 8 (Little Cherry Creek tributary 1), station 9 (Little Cherry Creek tributary 2), station 11 (Denny Branch Creek near Hallowell), and station 13 (Center Creek near Faulkner), contain water with large concentrations of sulfate ion relative to bicarbonate ion during base-flow periods. These streams are examples of streams that drain areas of black shale and coal outcrops.

Table 3.6-1.– Water-quality data from streams draining unmined areas during base-flow periods [ft^3/s, cubic feet per second; mg/L, milligrams per liter; ug/L, micrograms per liter]

Station Number	Station name	Stream -flow (ft^3/s)	Specific conductance (micromhos per centimeter at 25˚C)	pH (units)	Bicar- bonate (mg/L)	Sul- fate (mg/L)	Dis- solved solids (mg/L)	Total iron (ug/L)	Total mangan- ese (ug/L)
1	Limestone Creek near Beaulah	0.11	519	7.5	230	97	335	290	130
8	Little Cherry Creek tributary 1	.08	428	7.7	73	130	245	480	170
9	Little Cherry Creek tributary 2	.02	403	7.1	66	120	232	1,100	700
11	Denny Branch Creek near Hallowell	.12	542	7.4	90	170	318	960	700
13	Center Creek near Faulkner	.09	330	6.8	61	95	205	2,700	320
14	Second Cow Creek near Girard	.13	580	7.3	220	110	380	230	160

4.0 HYDROLOGIC IMPACTS OF COAL MINING

4.1 GROUND-WATER OCCURRENCE AND AVAILABILITY

Coal-mining activities in the area may increase or decrease the occurrence and availability of ground water.

Usable ground water is naturally scarce in most of the area. However, there are some reasonably good aquifers, principally alluvial aquifers and the Warner and Bluejacket Sandstone Members of the Krebs Formation. If these aquifers are disturbed during mining operations by (1) disrupting their continuity, (2) decreasing their recharge capabilities, or (3) dewatering them, the occurrence and availability of ground water may diminish locally.

In most of the area, the shallow shale aquifers yield little water. The fracturing of the bedrock that may occur during mining operations can increase the permeability and transmissivity, and consequently can increase the local occurrence and availability of ground water.

Wells 15, 21, and 22 of the hydrologic-monitoring network were drilled in an attempt to determine the differences in yields from undisturbed bedrock aquifers and unreclaimed strip-mined land. Well 15 was drilled into the undisturbed geologic interval between the Verdigris Limestone Member of the Cabanis Formation and the Mineral coal bed. This well had an estimated yield of about 2 gal/min. Wells 21 and 22 were drilled into unreclaimed spoils. The estimated yield of these wells was 10 to 50 gal/min.

Some of the effects of surface-mined areas on the aquifer systems are illustrated in figure 4.1-1. Illustrated in cross section A-A' are (1) the mine spoils with the 'ridge and furrow' topography, (2) the surface-mine pit lakes which provide increased surface-water storage, and (3) the disturbance of the sandstone aquifer. Illustrated in cross section B-B' are (1) the coal mine aquifers formed by the voids after abandoning of underground mining activities, and (2) the draining of the sandstone aquifers into the underground mine workings by the collapse of abandoned shaft openings, and coal-test drill holes. Illustrated in cross section C-C ' are (1) the disturbed spoils area and surface-mine pit lakes which recharge the sandstone, and (2) the disturbance of the sand and gravel alluvial aquifer, and stream base flow.

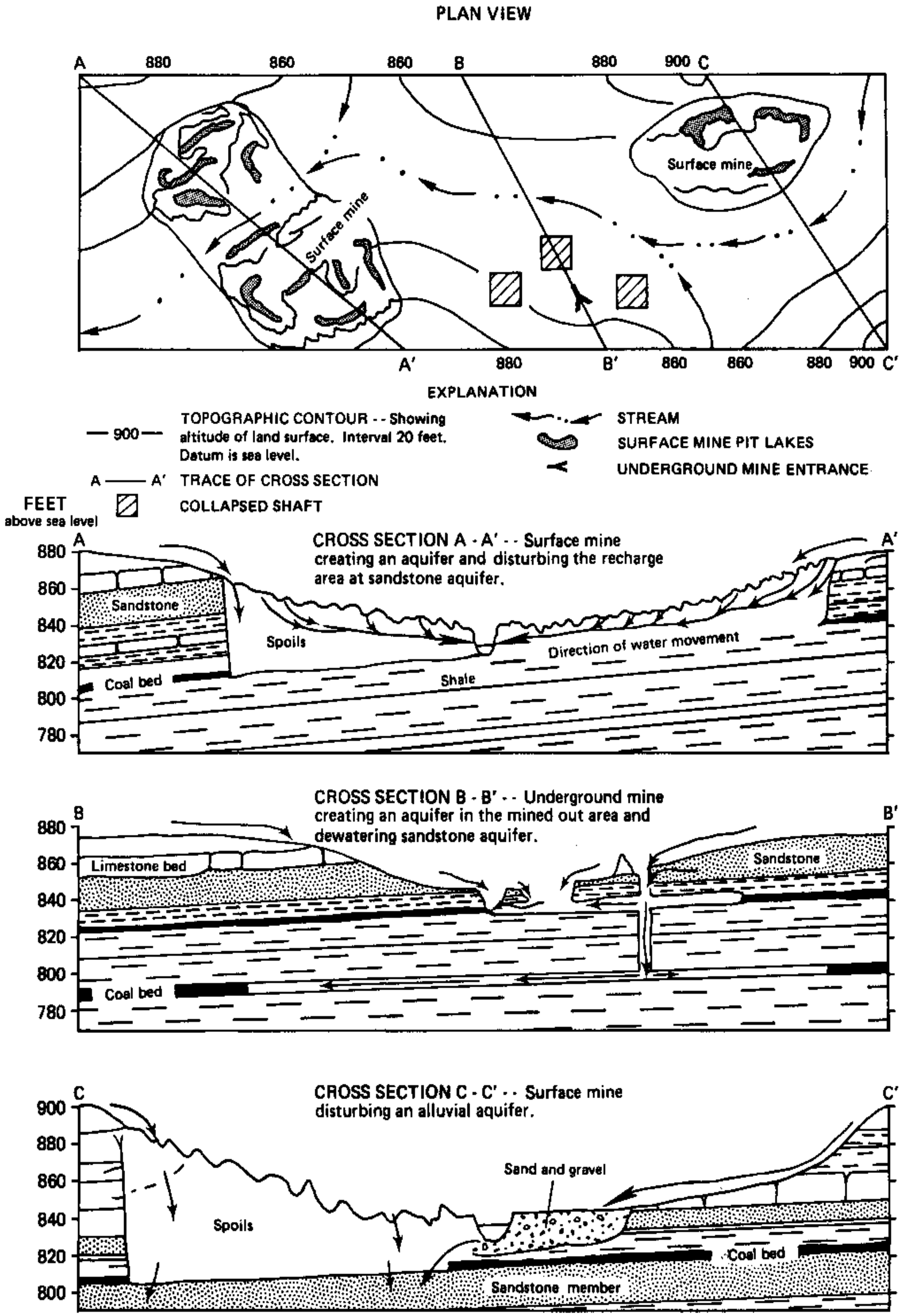


Figure 4.1-1.— Typical examples of coal mining creating or impairing aquifers in the area.

4.2 GROUND-WATER QUALITY

Ground water in coal-mined areas generally has large concentrations of sulfate ion and consequently large concentrations of dissolved solids.

The quality of ground water in coal-mined areas is illustrated by data presented in table 4.2-1. Wells 21 and 22 are completed in unreclaimed mine spoils. These wells yield water with large sulfate concentrations, and large concentrations of dissolved solids. The pH values of 7.4 and 8.1 and the concentrations of bicarbonate ion of 590 and 634 mg/L repsectively, for waters from the two wells indicate the presence of enough limestone fragments in the spoils to neutralize the acid produced by the weathering of iron-sulfide minerals.

Well 23 is completed in strata that have been both underground mined for Weir-Pittsburg coal and surface mined for Mineral coal. Water from this well has large concentrations of sulfate and dissolved solids. The relatively small bicarbonate concentration indicates that the pH, which was not recorded, was probably acidic and that the well could be receiving underground-mine discharge.

Samples 24 and 25 are ground water seeping from underground mines. Waters from these underground mines have large concentrations of sulfate and dissolved solids. The pH values are acidic, allowing more iron to be in solution and indicating, along with the smaller bicarbonate concentrations, that underground-mine discharge usually does not come into contact with enough limestone to neutralize the acid formed by weathering of iron-sulfide minerals.

Table 4.2-1.— Water-quality data from wells in coal-mined areas
[ft, feet; mg/L, milligrams per liter; ug/L, micrograms per liter]

Well number	Land-line location (township-range-section)	Depth (ft)	Source	Specific conductance micromhos per centimeter at 25˚C	pH (units)	Bicar-bonate (mg/L)	Sulfate (mg/L)	Dis-solved solids (mg/L)	Total iron (ug/L)	Dis-solved manga-nese (ug/L)
21	31S-22E-25	33	Surface -mined area	3,400	7.4	590	1,760	2,930	1,700	5,200
22	31S-22B-35	33	Surface -mined area	5,030	8.1	634	2,740	4,340	460	4,100
3	32S-23E-14	40	Shaft- and surface- mined area	3,470	—	71	1,950	2,960	620	540
24	32S-23E-23	Sur-face	Shaft-mine seep	1,640	4.0	0	970	1,370	6,900	7,500
25	30S-24E-26	Sur-face	Shaft-mine seep	—	6.1	320	1,200	2,100	49,000	1,800

4.0 HYDROLOGIC IMPACTS OF COAL MINING

4.3 BASE-FLOW QUANTITY

Base flow may be increased by coal mining.

Abandoned coal mines in the area usually function as aquifers that discharge to adjacent streams. The flow-duration curves (fig. 4.3-1) present streamflow, for the period October 1976 through September 1980, of drainage basins that have been affected by surface or underground mining. Lightning Creek near McCune (station 2 in the hydrologic monitoring network) has been slightly affected by surface mining; only 2.5 percent of its drainage area is disturbed. Cherry Creek near Hallowell (station 12 in the network) and Cow Creek near Weir (station 19 in the network) have been more affected by coal mining; 11 and 12 percent of their respective drainage areas are disturbed by surface mining. Cherry Creek and Cow Creek are also affected by abandoned underground mines.

The flow-duration curve for Lightning Creek is similar to those of undisturbed streams presented in figure 3.5-1, indicating that the small amount of surface mining has had little effect on the quantity of base-flow. The 90-percent flow-duration value for Cherry Creek is 0.003 $(ft^3/s)/mi^2$, and for Cow Creek is 0.006 $(ft^3/s)/mi^2$, which are an order of magnitude greater than the unit discharge values of the undisturbed basins. Curves representing Cherry Creek and Cow Creek also indicate longer duration base-flow periods. The increased base flow probably results from coal mining creating new recharge areas and aquifers that discharge water into adjacent streams. An example of a surface-mine aquifer discharging into an adjacent stream is presented in figure 4.3-2.

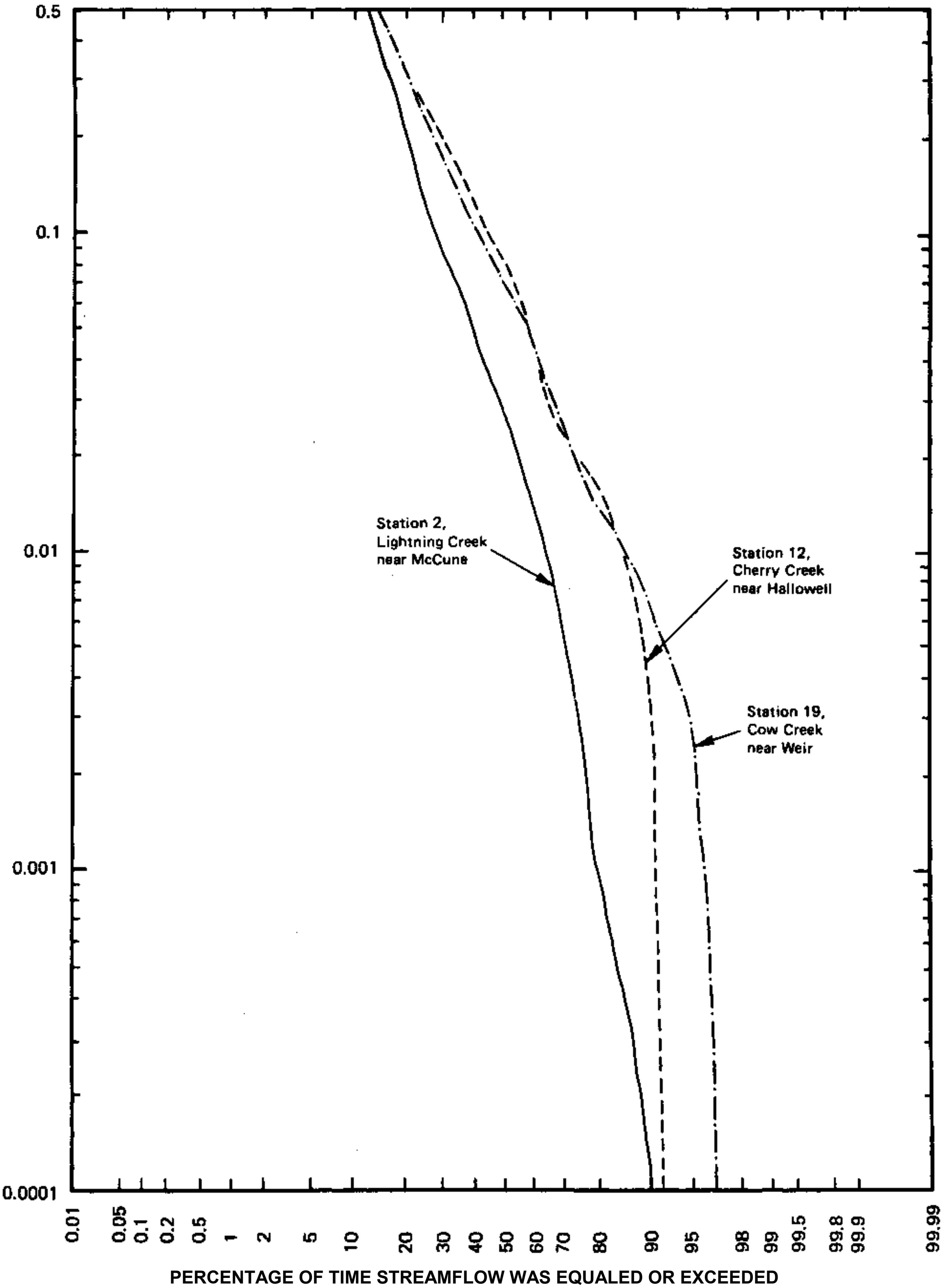


Figure 4.3-1.— Modified flow-duration curves for selected streams draining coal-mined area.

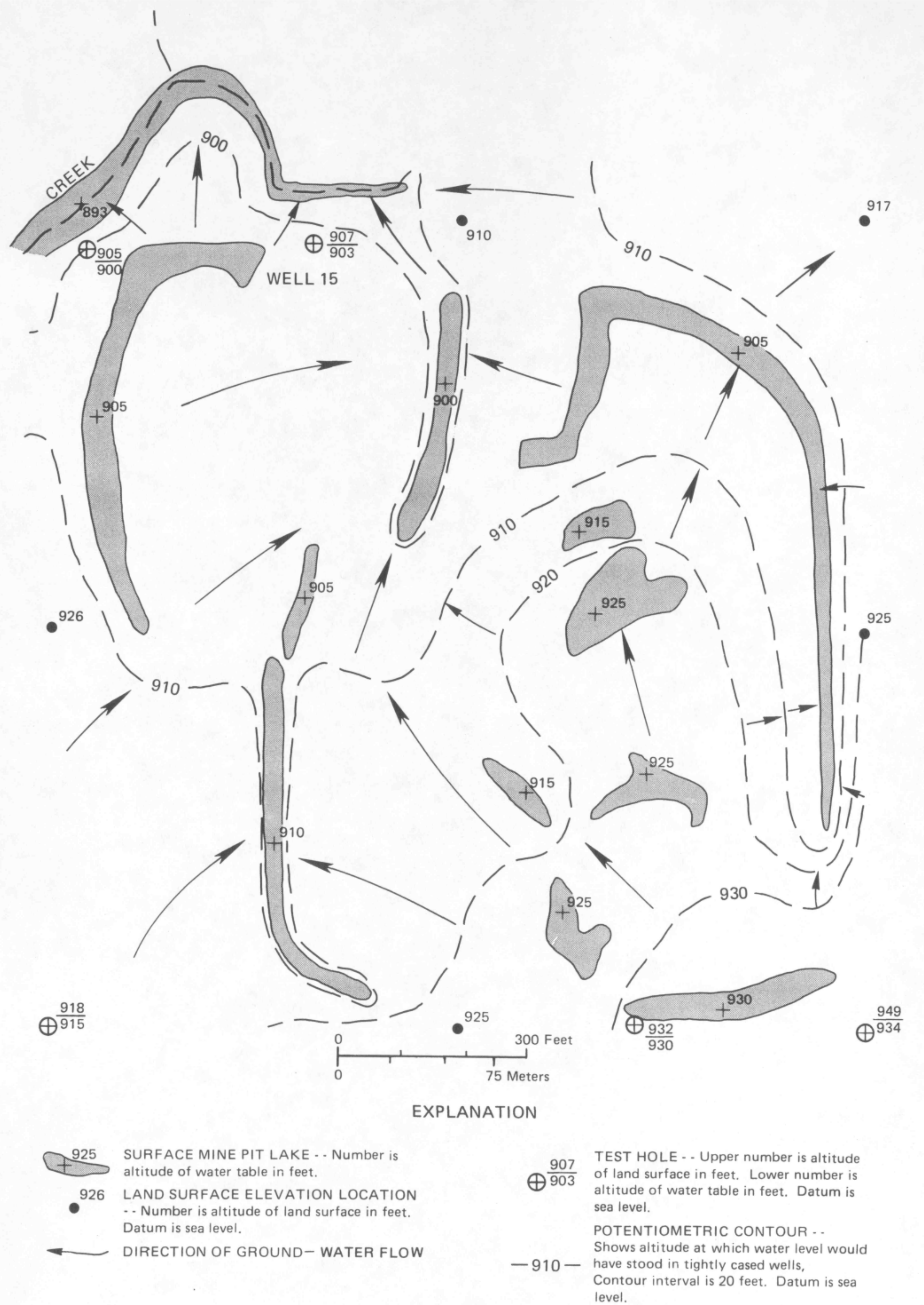


Figure 4.3-2.— Surface-mine aquifer discharging into an adjacent stream.

4.4 BASE-FLOW QUALITY

Coal mining in the area has increased concentrations of sulfate and dissolved solids in streams during base-flow conditions.

Base-flow water-quality data collected from October 1976 through September 1980 at 14 streams draining coal-mined areas were analyzed statistically (4,5). Mean values of selected parameters and constituents are presented in table 4.4-1. General conclusions about the base-flow water-quality characteristics of streams affected by coal-mining activities, are:

(1) Mean concentrations of dissolved solids, principally sulfate and bicarbonate, are significantly larger in streams draining mined areas than in streams draining unmined areas.

(2) Mean sulfate concentrations exceed mean bicarbonate concentrations for all stations in mined areas.

(3) Mean pH values are in the neutral range for all stations affected only by surface mining.

(4) Stream reaches receiving underground-mine discharge generally have acidic pH and contain small concentrations of bicarbonate and high concentrations of iron and manganese relative to streams draining surface-mined areas.

(5) Large variations in mean concentrations of dissolved solids and sulfate throughout the area appear to be related to the extent of mining.

Table 4.4-1.– Mean values of selected-quality parameters and constituents sampled in streams draining coal-mined areas during base-flow conditions, 1976-80
[ft^3/s, cubic feet per second; mg/L, milligrams per liter; ug/L, micrograns per liter]

Station Name	Lightning Creek near McCune	Deer Creek near West Mineral	Deer Creek near Hallowell	Deer Creek near Oswego	Lightning Creek near Oswego	Cherry Creek near West Mineral	Little Cherry Creek near West Mineral	Cherry Creel near Hallowell	Second Cow Creek at Pittsburg	First Cow Creek at Frontenac	East Cow Creek at Fronenac	East Cow Creek at Pittsburg	Cow Creek at Weir	Brush Creek near Weir
Hydrologic monitoring network map-index number	2	3	4	5	6	7	10	12	15	16	17	18	19	20
Streamflow, in ft^3/sec	3.7	0.49	1.2	1.7	5.0	1.2	3.2	5.2	1.8	1.7	0.87	3.7	15	1.1
Specific conductance, in micromhos per centimeter	912	3,960	3,540	3,260	1,740	2,250	1,590	1,560	1,850	1,860	2,440	1,820	1,300	1,290
pH, in standard units	7.3	7.9	7.8	7.5	7.8	7.5	3.6	6.4	7.6	7.5	7.8	6.6	7.3	3.6
Dissolved solids, in mg/L	592	3,310	3,130	2,830	1,330	2,260	1,300	1,210	1,400	1,370	1,970	1,450	875	930
Bicarbonate as HCO_3, in mg/L	220	310	230	210	200	220	0	42	220	230	250	35	120	0
Sulfate as SO_4, in mg/L	280	2,300	2,200	2,000	890	1,600	930	860	950	820	1,360	1,110	510	650
Total iron, in ug/L	1,100	360	440	620	320	400	2,000	490	820	380	390	890	790	5,000
Total manganese, in ug/L	1,400	990	540	630	390	990	7,600	4,800	980	710	730	14,400	3,800	5,000
Percentage of drainage area surface mined	2.5	42	57	55	7.7	21	11	11	7.7	16	38	22	12	12

The quality of base flow in mined areas is generally more affected by surface mining than by underground mining. Most underground mined areas are below the bedrock formations into which the streams are incised. Streams are affected by underground-mine drainage only in areas where the hydraulic gradient is from the mine to the stream and (1) the stream is incised deeply enough to intersect the mined formation or (2) air shafts or exploratory holes penetrate the underground-mined area and discharge mine drainage into the stream. In surface-mined parts of the area, the bedrock has been disturbed from the surface down to the coal bed and haphazardly piled back into the surface pits. Black shales and associated iron sulfide minerals, their surface areas multiplied many times by being broken into small fragments, are exposed to water at all depths, including the surface. The greater permeability of the spoils allows shallow ground water in these surface-mined areas to flow laterally into adjacent streams, especially in areas where the streambed itself was mined.

The relationships between the percentage of a stream's drainage area that has been surface mined and mean values of specific conductance, concentration of dissolved solids, and concentration of sulfate ion during low-flow conditions, are shown in figure 4.4-1. Results of correlation and regression analyses of these relationships are given in table 4.4-2. The regression equations are arithmetic linear equations of the form:

$$Y = mX + b$$

where Y = predicted value of the dependent variable,
m = slope of the regression line,
X = known value of the independent variable, and
b = Y-intercept value of the dependent variable.

The standard error of the estimate ($\sigma_{y/x}$), which is equivalent to the standard deviation of the dependent variable about the regression line, was computed for each relationship.

The significant coefficient of determination ($r^2 = 0.81$) associated with these relationships and the reasonable standard error of estimates, that would be expected when applying them, show that there is a strong direct relationship between surface mining an area and increased concentrations of sulfate and dissolved solids in the base flow of streams draining that area. These relationships provide a technique for estimating the effects of surface mining on the quality of base flow in streams of comparable geology and climate within the Western Interior Coal Basin.

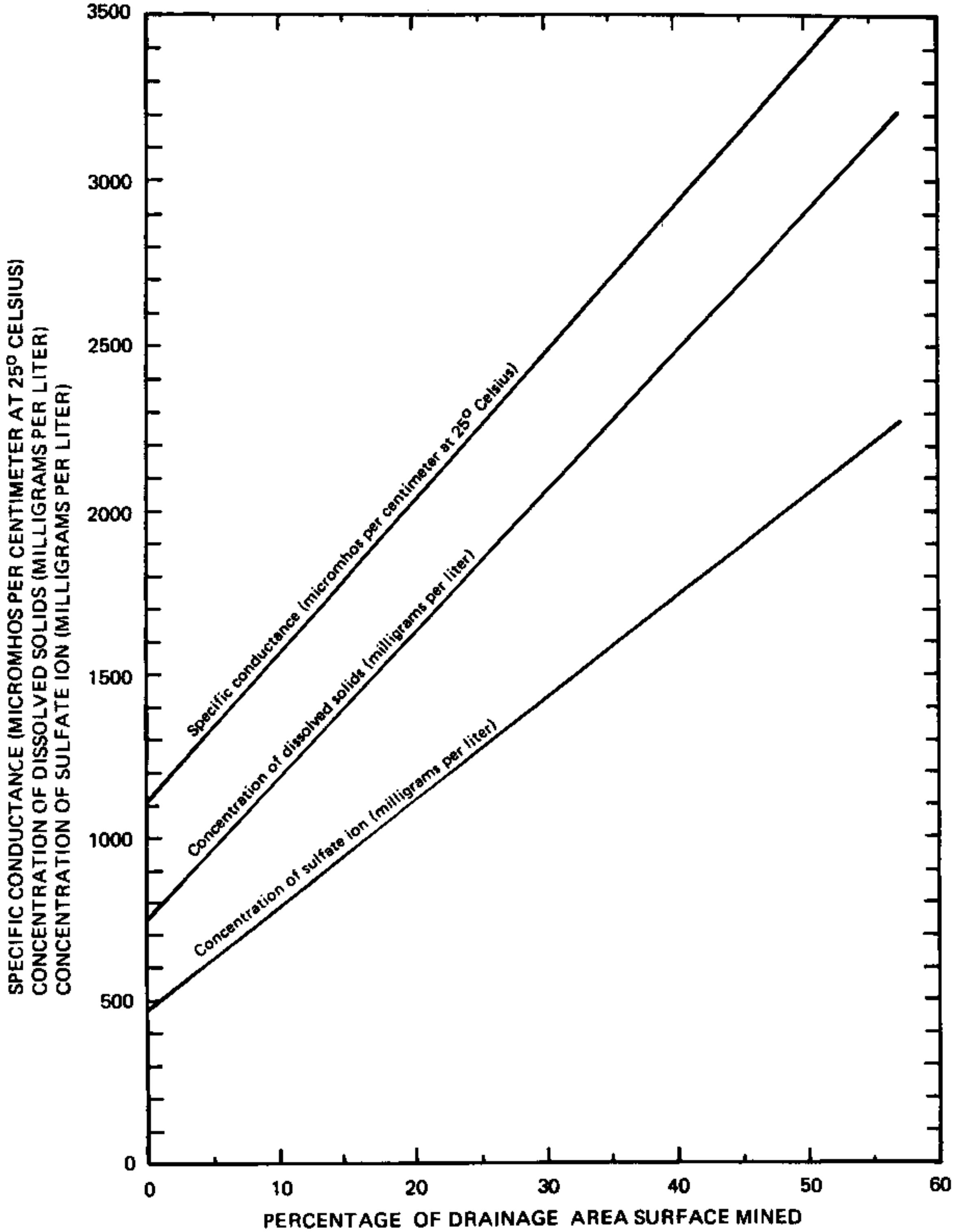


Figure 4.4-1.— Relationship of percentage of drainage area surface mined to (1) mean specific conductance, (2) mean concentration of sulfate ion, and, (3) mean concentration of dissolved solids during base-flow periods.

Table 4.4-2.– Results of correlation and regression anlyses (Y = mX+b) relating the percentage of drainage area surface mined to (1) mean specific conductance; (2) mean concentration of sulfate ion, and (3) mean concentration of dissolved solids during base-flew conditions.

Dependent variable (Y)	Slope (m)	Independent variable (X)	Y-intercept (b)	Correlation Coefficient (r)	Standard error of estimate (σy/x)
Specific conductance (micromhos per centimeter at 25˚ Celsius)	45.28	Percentage of drainage area surface mined	1,000	0.90	415
Concentration of sulfate ion (milligrams per liter)	31.42	Percentage of drainage area surface mined	470	.90	260
Concentration of dissolved solids (milligrams per liter)	43.01	Percentage of drainage area surface mined	744	.90	383

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GROUND-WATER STUDY 8

by

Joe A. Moreland

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1.0 ABSTRACT

Geology and the Occurrence of Coal

The area is underlain by nearly horizontal sedimentary rocks of Tertiary age consisting of shales interbedded with sandstones, siltstones, and subbituminous coal beds. The coal beds, which occur in the Tongue River Member of the Fort Union Formation and in the Wasatch Formation, are extensive and variable in thickness. In the mine area, the Anderson, Dietz-1, and Dietz-2 coal beds coalesce to form a single bed 80 feet thick. The geologic structure of the area is broadly synclinal and is traversed locally by several normal faults. A large part of the area is underlain by clinker deposits, which were produced by the burning of coal beds near their outcrops.

Hydrology and Hydrologic Monitoring

In the area, the coal beds are the principal sources of good quality ground water for domestic and stock wells. Most wells completed in these beds yield less than 10 gallons per minute. The sandstones are aquifers, but their yields vary considerably. Wells in the alluvial aquifers commonly yield 10 gallons per minute or more. Variations in primary and secondary hydraulic conductivity cause an order of magnitude difference in transmissivity. Clinker deposits are very permeable and allow precipitation to recharge the underlying aquifers. The sandstone beds, underlying the coal beds, are alternate water sources for municipal and industrial uses. Ground-water data for the area were obtained from existing springs and wells, and from specially drilled and constructed observation wells. Ground-water quality is variable between aquifers and within aquifers in different areas. The quality of water from the sandstone overlying the uppermost coal generally does not meet U.S. Environmental Protection Agency standards for domestic use, owing to excessive concentrations of dissolved solids. Natural ground-water flow patterns generally parallel the land-surface profile in the unconfined alluvial and clinker aquifers. The area of natural ground-water discharge is along the Tongue River valley.

Mining Method and Other Stresses on Aquifer System

The coal is removed only by surface mining. The total ground-water use does not exceed 30,000 gallons per day (21 gallons per minute). Nevertheless, ground water from the wells and springs is critical to the economy and population of the area.

Probable Hydrologic Consequences and Proposed Hydrologic Monitoring Network

The principal shallow aquifers (coal and sandstone) will be disrupted by surface mining. The natural shallow ground-water flow has been changed by mining and by dewatering of the mine pit. From 1972 to 1975, water levels in wells completed in the Dietz-1 coal bed declined as much as 40 feet near the mine pit.

Ground-water model results illustrate the relationship between coal mining and aquifer dewatering. The results include water-level declines in space and time, with variable aquifer properties and with different hydrologic-boundary conditions. Wells completed in the coal beds several miles from the mines might undergo water-level declines, but the water-level declines would probably cause only a very small loss of yields.

Ground water from the mine spoils contains larger concentrations of dissolved constituents than water from natural aquifers. Calcium, magnesium, and sulfate concentrations also were substantially larger in mine-spoils waters.

A proposed hydrologic monitoring scheme includes wells outside of the mine-permit area. Water from these wells will also be analyzed periodically to determine any variations in ground-water quality. The Tongue River, upstream from the Tongue River Reservoir, will also be routinely sampled.

2.0 GEOLOGY

2.1 STRATIGRAPHY OF GEOLOGIC UNITS

NEAR-SURFACE CRETACEOUS AND TERTIARY BEDROCK COMPOSED OF SANDSTONE, SILTSTONE, CLAYSTONE, SHALE, AND COAL

Geologic units important to coal mining include the Fort Union Formation and the Wasatch Formation.

The area is underlain by several thousand feet of sedimentary rocks that range in age from Cambrian to Holocene. The continental deposits of the Upper Cretaceous Hell Creek Formation and the Tertiary Fort Union and Wasatch Formations overlie the marine deposits of the Upper Cretaceous Bearpaw Shale and Fox Hills Sandstone (fig. 2.1-1).

The Bearpaw Shale is a massive bentonitic shale and sandy shale that contains a few thin beds of silty sandstones and siltstones. The Fox Hills Sandstone is predominantly sandstone that contains thin beds of sandy shale. The lower part of the Hell Creek Formation consists of interbedded shale, siltstone, and sandstone and the upper part consists of massive shale with lenticular sandstone and siltstone with traces of coal and coaly shale.

The Fort Union Formation contains the Tullock, Lebo Shale, and Tongue River Members. The Tullock Member is composed of sandstone, sandy and silty shale, and thin coal beds. The Lebo Shale Member is predominantly shale, mudstone, and claystone with interbeds of siltstone and thin coal beds. The Tongue River Member contains alternating layers of sandstone, siltstone, and shale interlain with thick and extensive coal beds (fig. 2.2-1).

The Wasatch Formation contains lenticular sandstones interbedded with shale and coals. The coal beds are as extensive as those in the underlying Fort Union Formation. Clinker or baked sedimentary rocks formed by burning coal beds crop out throughout the area.

System	Series	Formation and member		Thickness in feet	
Quaternary	Holocene and Pleistocene	Alluvium (flood plain and terraces)		0 - 100 ±	
Tertiary	Eocene	Wasatch Formation		0 - 400 ±	
	Paleocene	Fort Union Formation	Tongue River Member	1600 ±	Shallow aquifers
			Lebo Shale Member	500 ±	Confining bed
			Tullock Member	500 ±	
Cretaceous	Upper Cretaceous	Hell Creek Formation		300 ±	Deep aquifers
		Fox Hills - Lower Hell Creek		600 ±	
		Bearpaw Shale		300 ±	Confining bed

Figure 2.1-1.— Generalized geologic column of the major aquifers in the mine area.

2.0 GEOLOGY

2.2 COAL BEDS IN THE MINE AREA

ANDERSON, DIETZ 1, DIETZ 2, AND CANYON COAL BEDS SUITABLE FOR SURFACE MINING IN AREA

The Andersen and Dietz 1 coal beds coalesce to form a single bed 52 feet thick.

At least nine persistent beds 5 to 35 feet thick and numerous thinner beds are contained in the Tongue River Member of the Fort Union Formation. Most of the thick beds have been mapped over hundreds of square miles and are the target coal beds in other mines in the region.

The coal beds mined in the area include the Anderson, Dietz 1, Dietz 2, and Canyon beds. In parts of the area, the Anderson and the Dietz 1 coal beds coalesce to form a single unit 52 feet thick. West of the mine area, the combined Anderson-Dietz 1 bed coalesces with the underlying Dietz 2 to form an 80-foot bed of coal.

Because of the coalescing nature, coal beds are difficult to correlate from one area to another. Correlation problems have resulted in wide use of local names for individual coal beds.

The relative position and approximate thickness of the coal beds underlying proposed mines in the area are shown in figure 2.2-1. The cross section illustrates the variable thickness of strata between the major coal beds. Also evident is the widespread occurrence of altered rocks formed by burning of coal beds. Such rocks, which are locally termed, "clinker," occur near the Anderson and Dietz 1 coal beds.

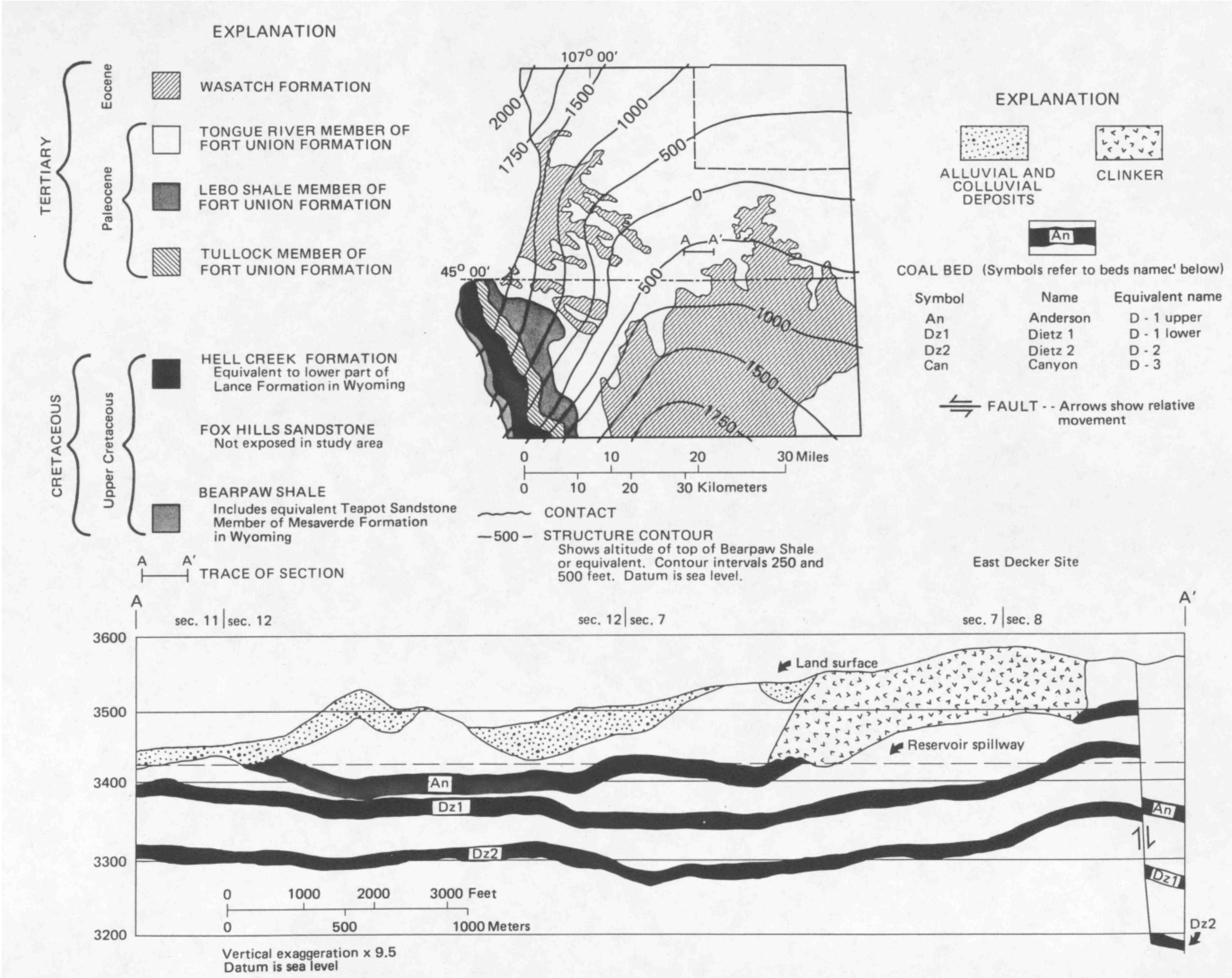


Figure 2.2-1.— Map and cross sections showing generalized geology and major coal beds in the mine area.

3.0 HYDROLOGY

3.1 CLIMATE

MINE AREA CHARACTERIZED BY SEMIARID CLIMATE

The mine area has cold winters, warm summers, and large variations in annual and seasonal precipitation and temperature.

The semiarid climate in the mine area is the continental steppe type characteristic of the Northern Great Plains. Cold winters, warm summers, and large annual and seasonal variations in precipitation and temperatures are common. Microclimate varies appreciably over the area as a result of local differences in relief, slope, exposure, and plant cover.

Precipitation records have been collected continuously by the National Weather Service since 1931 at a site about 25 miles southwest of the mine area. Daily precipitation records have been collected almost continuously since 1949 at a site in the mine area.

Annual precipitation at the area weather station has ranged from 6.5 inches in 1960 to 17.6 inches in 1968 (fig. 3.1-1). Average annual precipitation for the period of record is 11.8 inches. Nearly one-half of the mean annual precipitation falls from April through June. Much of the remainder (30 percent) falls as snow from October through March. Summer rain storms commonly accompanied by strong winds and hail account for the remaining 20 percent of annual precipitation.

Temperature variations are extreme for both seasonal and daily periods. Daily variations of 30˚F to 35˚F are common because of low humidity and strong solar radiation. Temperatures recorded at a site 25 miles southwest of the mine area ranged from -30˚F to 103˚F. At a weather station 20 miles northeast of the mine area temperatures have ranged from -45˚F to 107˚F. The growing season usually lasts 100 to 130 days.

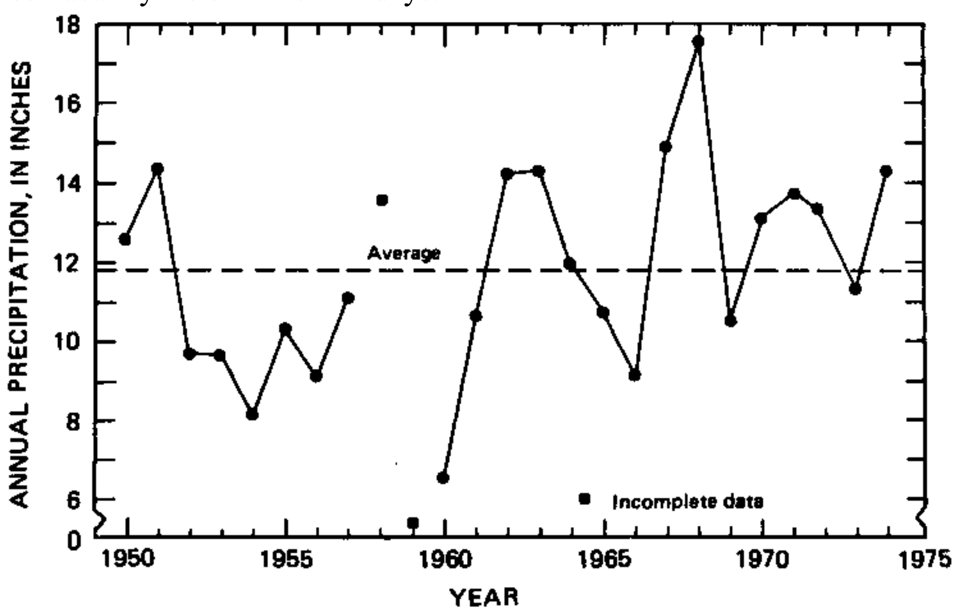


Figure 3.1-1.— Range of annual precipitation 1949-75 at Decker Post Office. (From U.S. Geological Survey and Montana Department of State Lands, 1977, p. 103.)

3.0 HYDROLOGY

3.2 GROUND WATER

3.2.1 AQUIFERS OVERLYING THE LEBO SHALE MEMBER

COAL BEDS, ALLUVIUM, AND SANDSTONE PROVIDE WATER TO WELLS IN MINE AREA

Coal beds are the most reliable sources of ground water in the mine area owing to their widespread occurrence and continuity.

The coal beds underlying the mine area are the principal source of ground water for domestic and stock wells. Although coal is virtually impermeable and has no appreciable primary porosity, the beds are usually fractured sufficiently to allow storage and transmission of water. Coal-bed aquifers are laterally extensive and continuous under the entire area and, therefore, are a reliable source of ground water. Most wells produce less than 10 gal/min but larger yields have been obtained locally. Ground-water use locations, namely wells and springs, for water supply are shown in figure 3.2.1-1. Some of the well-inventory information is presented in table 3.2.1-1.

Sandstone aquifers occur above and between coal beds in the Tongue River Member of the Fort Union Formation. Generally, the sandstones are lenticular bodies of fine sand, which were deposited in channels, and are surrounded by layers of less permeable siltstone and shale. The sandstones differ considerably in their ability to yield water to wells. The yields depend upon the amount of fine-grained material in the rock, the degree of fracturing, and the extent of the unit. Yields greater than 10 gal/min have been reported for wells completed in the sandstones.

Alluvial aquifers are limited to the unconsolidated deposits in the Tongue River valley and tributary streams. Because of the limited areal extent of the alluvial aquifers, only a few wells obtain water from them.

Clinker is an extremely permeable rock type in the mine area and is a significant aquifer where saturated. However, the clinker is generally located in topographically high areas above the saturated zone. Some ground water may occur near the base of clinker units as a perched water body and may contribute to spring flows along hill slopes or valley sides. Few wells penetrate the clinker because it is difficult to penetrate by drilling.

Aquifer-test results are given in table 3.2.1-2. They provide an indication of the aquifer properties of the various coal beds, sandstones, and alluvium in the mine area. Several types of aquifer-test analyses were used to determine aquifer transmissivity, hydraulic conductivity, and storage coefficient for various aquifer units.

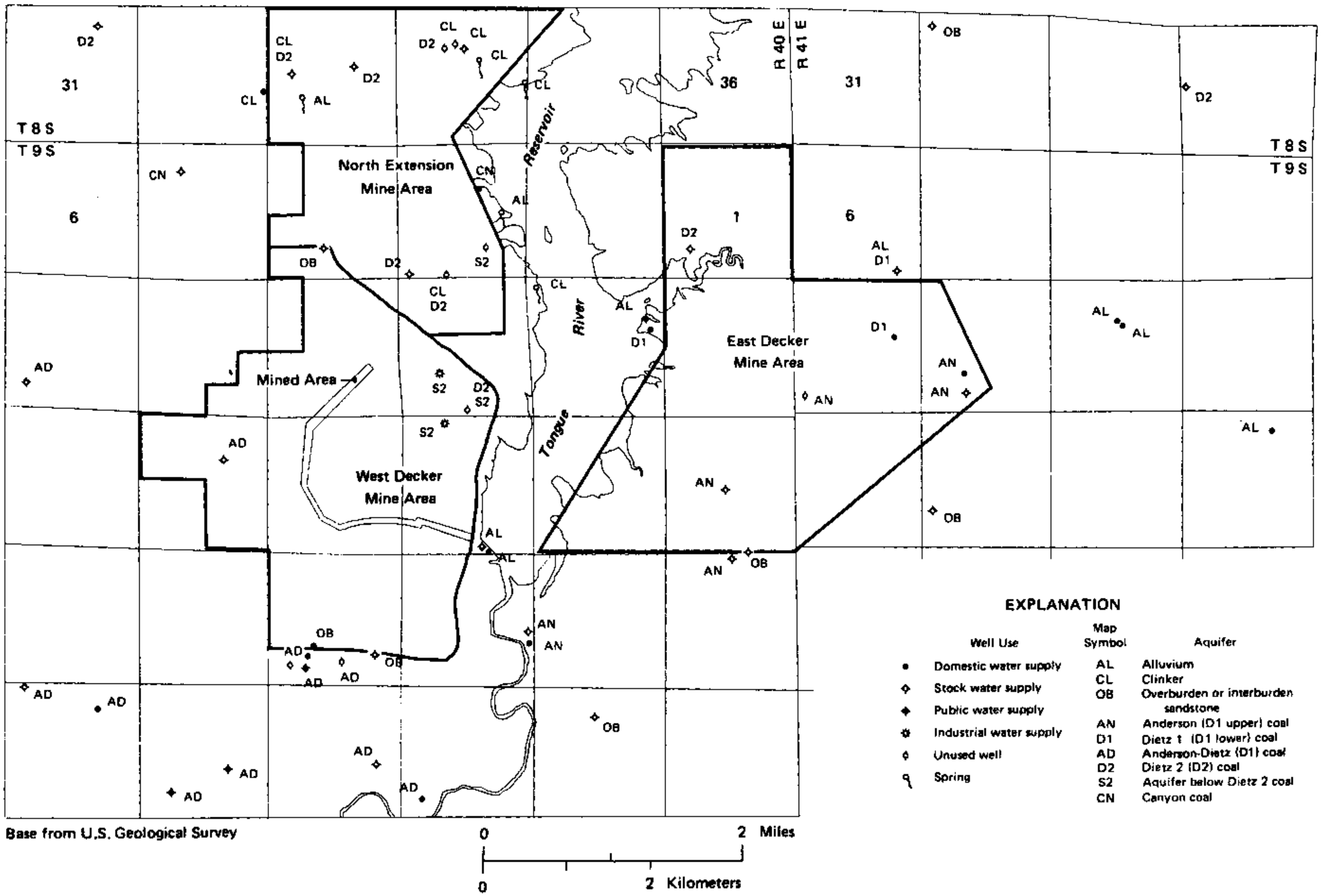


Figure 3.2.1-1 — Locations of wells and springs used for water supply in the general area. (From U.S. Geological Survey and Montana Department of State Lands, 1977.)

Table 3.2.1-1. – Example of water-well data for the mine area.
(From VanVoast and Hedges, 1975, p. 11)

[Location: Township, Range, Section with quarter-quarter-quarter subdivision.
(refer to referenced report for well location details)
Altitude: Land surface elevation at well estimated from U.S.G.S. 7½-minute quadrangle topographic maps, accurate to 10 ft.
Aquifer: Interpretations by Montana Bureau of Mines and Geology. Coded sources D-l
C1 = D-1 Clinker; Sub D-2 = unspecified aquifers below mineable coal beds.
Depth to water: Depths to nearest 0.1 foot measured; depths to nearest 1.0 foot reported; + indicates flowing well.
Discharge: gal/min, gallons per minute to nearest 0.1 measured; gal/min to nearest 1.0 reported.
Drawdown: Drawdown (at indicated discharge) to nearest 0.1 foot, measured; drawdown to nearest 1.0 foot, reported.
Specific Conductance: Field electrical conductance of water, in micromhos per centimeter at 25˚ C; L indicates laboratory conductance.
Data source: MBMG, Montana Bureau of Mines and Geology; USGS, U.S. Geological Survey. Water analyses: refer to water quality table in referenced report.]

Location	Water use	Altitude (feet)	Well Depth (feet)	Aquifer	Depth to water (feet)	Dis-charge (gal/min)	Draw-down (feet)	Specific conduc-tance (umhos/cm)	Data source	Water analysis
9S 39E 14DCBB	Unused	3,647	391	Sub D-2	160.9	—	—	4,000	USGS	
9S 39E 24DCDC	Unused	3,610	244	D-1& D-2 Coal	106	10	—	—	MBMG	
9S 39E 24ACDA	Unused	3,590	235	D-l & D-2 Coal	88	10	—	—	MBMG	
9S 39E 25DDC	Stock	—	150	D-l Overburden	—	10	—	—	USGS	
9S 40E 010CA	Stock	3,445	125	D-2 Coal	26.4	—	—	1,900	USGS	
9S 40E 03ACAB	Stock	3,424	200	Sub D-2	+	33	—	1,380	MBMG	yes
9S 40E 03DCA	Stock	3,440	462	Sub D-2	3	4	44	—	USGS	
9S 40E 04CDAB	Stock	3,542	—	D-2 Goal	95	10	—	3,980	MBMG	
9S 40E 05BACC	Stock	3,580	260	Sub D-2	70	6	—	2,000	MBMG	
9S 40E 070CAB	Stock	3,720	274	D-l Coal & Overburden	138	50	—	—	MBMG	
9S 40E 10CDDD	Industrial.	3,465	498	Sub D-2	29	60	88.5	—	MBMG	
9S 40E 10DDBA	Industrial.	3,452	160	D-2 Coal & Sub D-2	23	20	6	1,714L	MBMG	yes
9S 40E 11ADA	Stock	3,430	32	D-l Lower Coal	17.5	—	—	1,750	MBMG	
9S 40E 13CAAA	Stock	3,500	108	D-l Upper Coal	63.4	—	—	2,400	USGS	
9S 40E 13DCCD	Stock	3,520	75	D-l Overburden	31.2	—	—	925	USGS	
9S 40E 21CACD	Domestic	3,554	110	D-l Overburden	—	—	—	5,010	MBMG	yes
9S 40E 210CDB	Unused	3,642	200	D-l Overburden	131.6	—	—	—	MBMG	
9S 40E 21CDAC	Unused	3,565	280	D-l Coal	123	—	—	2,700	MBMG	
9S 40E 21CDBB	Domestic	3,578	—	Unknown	—	—	—	—	MBMG	
9S 40E 21CDBD	Commercial	3,574	227	D-l Coal	117	5	73	1,570	MBMG	yes
9S 40E 21DDBA	Stock	3,502	171	Sandstone	26	20	39	4,500	MBMG	
9S 40E 22DAAD	Stock	3,455	269	D-l Coal	40.7	5	—	2,500	USGS	yes
9S 40E 22DADA	Domestic	3,460	170	D-l Coal	41	—	—	2,340	MBMG	yes
9S 40E 24ABBB	Stock	3,520	140	D-l Upper Coal	82	5	48	—	USGS	
9S 40E 26BADD	Stock	3,490	40	Above mineable beds	15	36	15	2,200	MBMG	

Table 3.2.1-2— Aquifer-test results for observation wells in the Squirrel Creek area.
[ft, feet; ft^2/d, square feet per day; ft^3/min, cubic feet per minute]

Pumped well location	Pumped well number	Test date	Observation well	Test analysis	Pumping rate (ft^3/min)	Pumping duration (minutes)	Transmissivity (ft^2/d)	Hydraulic conductivity* (ft/d)	Storage coefficient
ALLUVIUM ALONG SQUIRREL CREEK									
9S. 39E. 14DDBD	WR-58	03/12/80	WR-58A	Jacob (1940) drawdown	3.0	480	3,050	76	0.05
14DDCC	WR-58D	03/13/80	WR-58E	Boulton (1963) delayed-yield	2.1	500	3,000	75	.02
14DDCD	WR-58B	03/11/80	pumped well	Jacob drawdown	3.6	480	2,700	82	–
"	"	03/11/80	WR-58C	Theis (1935) drawdown	3.6	480	2,750	83	.34
9S. 40E. 19CBCC	WR-56	10/24/79	pumped well	Jacob drawdown	2.4	225	1,600	32	–
29CACB	WR-52B	10/26/79	"	"	8.0	180	9,150	352	–
"	"	"	WR-52F	Boulton delayed-yield	8.0	180	9,150	352	.0004
"	"	"	WR-52A	"	8.0	180	6,800	262	.0002
"	"	"	WR-52C	"	8.0	180	11,400	438	.0013
29CBDA	WR-52A	10/23/79	pumped well	Jacob drawdown	10.7	290	3,750	101	–
"	"	"	WR-52B	Boulton delayed-yield	10.7	290	4,100	158	.0018
"	"	"	WR-52F	"	10.7	290	2,450	94	.0023
29CBDC	WR-52F	10/25/79	pumped well	Jacob drawdown	7.2	385	1,600	59	–
"	"	"	WR-52A	Boulton delayed-yield	7.2	385	1,350	50	.0034
"	"	"	WR-52E	"	7.2	385	1,750	65	.0021
FORT UNION CLASTICS (ANDERSON OVERBURDEN)									
9S. 39E. 23DACC2	WR-18A	10/07/79	pumped well	Skibitzke (1958) bailer recovery			0.2	0.005	–
9S. 40E 19CBBD2	WR-55A	10/07/79	"	Cooper, et al (1967) slug recovery	–	–	.008	.0006	.000004
29BBAC3	WR-17B	10/04/79	"	Skibitzke bailer recovery	0.12	60	46	1.5	–
29BDCB2	WR-51A	10/02/79	"	Theis recovery			6.3	.7	–
SPOILS AT THE DECKER MINE (DISTURBED ANDERSON OVERBURDEN)									
9S. 40E 09DCAB2	DS-5B	04/15/77	pumped well	Skibitzke bailer recovery	0.07	15	0.2	0.002	
15CACD	DS-3	04/12/77	"	"	.13	20	87	3.5	.00002**
15CBDA	DS-4	04/11/77	"	"	.07	17	.3	.025	.00003**
15CDBC	DS-1A	03/24/76	"	Jacob recovery	.27	170	130	8.4	–
15CDBC2	DS-1B	04/13/76	"	"	.67	250	83	5.2	–
15DBCC2	DS-2B	04/12/76	"	Skibitzke bailer recovery	.13	20	.02	.001	–
CLINKER									
9S. 39E. 32ACAA	WR-33	10/18/77	pumped well	Theis (1963) specific capacity	4.7	120	3,350	48	–
ANDERSON COAL BED									
9S. 39E. 16AABA2	WR-20	10/09/79	pumped well	Jacob drawdown	.36	300	120	3.9	–
28CCAD2	WR-37	11/04/77	"	"	.42	50	12	.5	–
29ABAA	MR-26	03/10/76	"	"	.53	50	3.2	.1	–
9S. 40E. 13DCCD	WRE-11	02/25/75	"	Theis specific capacity	.24	80	26	1.0	–
23BCCD	WRE-12	02/26/75	"	Sicibitzke bailer recovery	–	–	42	1.6	–
DIETZ 1 COAL BED									
9S. 40E. 13DCCB	WRE-10	02/25/75	pumped well	Theis specific capacity	.43	35	16	1.0	–
23BCCD2	WRE-13	04/04/75	"	Jacob drawdown	1.8	220	150	8.1	.00006**
DIETZ 2 COAL BED									
9S. 40E. 09AADD	WRN-15	04/30/75	pumped well	Jacob drawdown	.27	103	20	1.5	–
09DCAB2	DS-5A	04/13/77	"	"	.43	360	138	7.2	–
11CBCC	WRN-17	04/15/77	"	"	.86	150	441	29	.00007**
13DCBC	WRE-9	02/20/75	"	Theis recovery	.44	20	6.5	.5	–
16ABCD2	WR-7	07/15/71	"	Jacob drawdown	1.1	480	65	4.1	.00001**
23CBBA	WRE-14	02/26/75	"	Theis specific capacity	.67	150	7.5	.5	–
COMBINED ANDERSON AND DIETZ 1 COAL BEDS									
9S. 40E. 16ABCD	WR-6	07/13/71	pumped well	Jacob drawdown	.90	300	190	3.8	.00002**
29BDCB	WR-51	10/05/79	"	"	.59	330	240	4.2	–
COMBINED ANDERSON, DIETZ 1 AND DIETZ 2 COAL BEDS									
9S. 39E. 33DBBD	WR-27	03/23/76	pumped well	Jacob Drawdown	.67	240	17	.2	–
35BADB	WR-28	02/18/81	"	Cooper, et al slug injection	–	–	96	1.1	–
9S. 40E. 19CBBD	WR-55	10/06/79	"	Jacob drawdown	.83	360	120	1.5	–
COMBINED DIETZ 1 AND DIETZ 2 COAL BEDS									
8S. 39E. 32DBBC	WR-21	03/23/76	pumped well	Jacob drawdown	.80	180	58	1.2	–
9S. 38E. 01AADC	WR-23	03/19/76	"	"	1.6	130	44	.8	–
9S. 39E. 16AABA	WR-19	10/08/79	"	"	1.5	320	84	1.6	–
28CCAD	WR-36	11/05/77	"	Theis recovery	.44	60	52	1.0	–
CANYON COAL BED									
9S. 39E. 29BBDD	WR-24	03/09/76	pumped well	Jacob drawdown	1.2	165	48	3.2	–

* Hydraulic conductivity values based upon aquifer thicknesses at pumped wells.
**Designated storage-coefficient values calculated from barometric efficiencies (Jacob, 1940, p. 583).

3.0 HYDROLOGY

3.2 GROUND WATER

3.2.2 AQUIFERS UNDERLYING THE LEBO SHALE MEMBER

ALTERNATIVE WATER SUPPLIES AVAILABLE FROM AQUIFERS UNDERLYING THE LEBO SHALE MEMBER

Several aquifers underlie the Lebo Shale Member of the Fort Union Formation. The deep aquifers are not likely to be disrupted by surface-mining activities.

Surface mining is expected to disrupt or remove only the upper 100 to 200 feet of overburden in the mine area. The Tongue River Member of the Fort Union Formation, which is composed of about 50 percent sandstone, may extend to about 2,100 feet below land surface in this area (fig. 2.1-1). Wells could be drilled into the deeper sandstones as alternative supplies to replace shallower wells lost to mining. Yields are expected to be similar to yields of shallower sandstone wells.

The Lebo Shale Member underlies the Tongue River Member throughout the mine area. Geophysical logs of deep test holes indicate that the Lebo consists of about 500 feet of siltstone and shale containing less than 10 percent sand. Vertical movement of water through this massive, relatively impermeable unit would be limited even under large vertical gradients. Therefore, hydrologic impacts due to mining are not likely to extend below the Lebo Shale Member.

The Tullock Member of the Fort Union Formation, which underlies the Lebo Shale Member is composed of 60 to 70 percent sand and is about 500 feet thick. Although no wells have been completed in this aquifer in the mine area, the unit yields as much as 40 gal/min in nearby areas.

The Fox Hills-lower Hell Creek aquifer lies about 3,000 feet below land surface in the mine area. This widely used aquifer is about 600 feet thick and could provide significant quantities of water for municipal or industrial use. Wells drilled to the Fox Hills-lower Hell Creek aquifer in nearby areas yield as much as 200 gal/min.

3.0 HYDROLOGY

3.2 GROUND WATER

3.2.3 GROUND-WATER FLOW

GROUND-WATER FLOW PATTERNS ARE AFFECTED BY TOPOGRAPHY, STRUCTURE, AND AQUIFER PROPERTIES

Recharge to shallow aquifers occurs in topographically high areas and discharge occurs in topographically low areas. The pattern of ground-water flow between the two areas is affected by faults and aquifer permeability.

Clinker outcrops in the higher areas surrounding the mine site are the major recharge areas for shallow aquifers. Ground water flows from the recharge areas toward the discharge points in the valley of the Tongue River and its tributaries. Because the recharge areas roughly coincide with topographic highs and discharge areas with topographic lows, the water table or potentiometric surface approximates the general slope of the land surface.

Ground-water flow patterns most closely approximate the land surface profile in the water-table alluvial and clinker aquifers. The potentiometric surface for the Dietz 1 (D-l) coal aquifer is unconfined (water table) and is shown in figure 3.2.3-1. The flow patterns in the confined coal and sandstone aquifer and are less likely to approximate the slope of the land surface.

Faults, like the ones in figures 2.2-1 and 3.2.3-1 that have offset the coal and sandstone aquifers, appear to form barriers to ground-water flow. Displacement or offset of permeable zones interrupts ground-water flow paths. Also, fault gouge along the fault zone may be relatively impermeable.

Faults can also increase aquifer permeability, particularly in coal beds. The stresses on coal beds near fault zones can significantly increase the number of fractures and joints that are the major avenues of flow through coal-bed aquifers. Increases in fracture permeability in coals also occur along major structural features such as synclines or folds.

EXPLANATION

- DIRECTION OF LATERAL GROUND - WATER FLOW
- —3440— POTENTIOMETRIC CONTOUR - - Shows altitude at which water level would have stood in tightly cased wells, April 1975. Contour interval 20 feet. Datum is sea level.
- D - 1 AND D - 2 AQUIFER INFORMATION COMBINED
- BOUNDARY OF PROPOSED MINE AREA
- ● WR 3 DECKER - OBSERVATION WELL
- ○ WATER - USE WELL
- FAULT - - U, Upthrown side; D, Downthrown side
- LIMIT OF CLINKER DEPOSITS

Scale: 0, 1, 2 Miles; 0, 1, 2 Kilometers

Decker Observation Wells Completed in D - 1 Coal

Well location (all are in 9S 40E) Section	Decker number	Land - surface altitude (feet)	Well depth (feet)	Water - level altitude April 1975 (feet)
08 DCAA	WR 3	3612	215	3431
09 BDDA$_1$	14	3598	192	3419
16 ABCA	1	3498	104	3404
16 ABCD$_1$	6	3499	135	3406
17 DACB	4	3585	220	3428
17 DACC	12	3486	230	3427
18 ABAD	16*	3640	237	3451
19 BAC	15*	3685	390	3445
21 ACCA$_1$	8	3537	165	3426
21 BCAC	11	3575	210	3429
21 CADA	10	3537	169	3426
29 BBAC	17*	3570	300	3455

*Aquifers D - 1 and D - 2 combined.

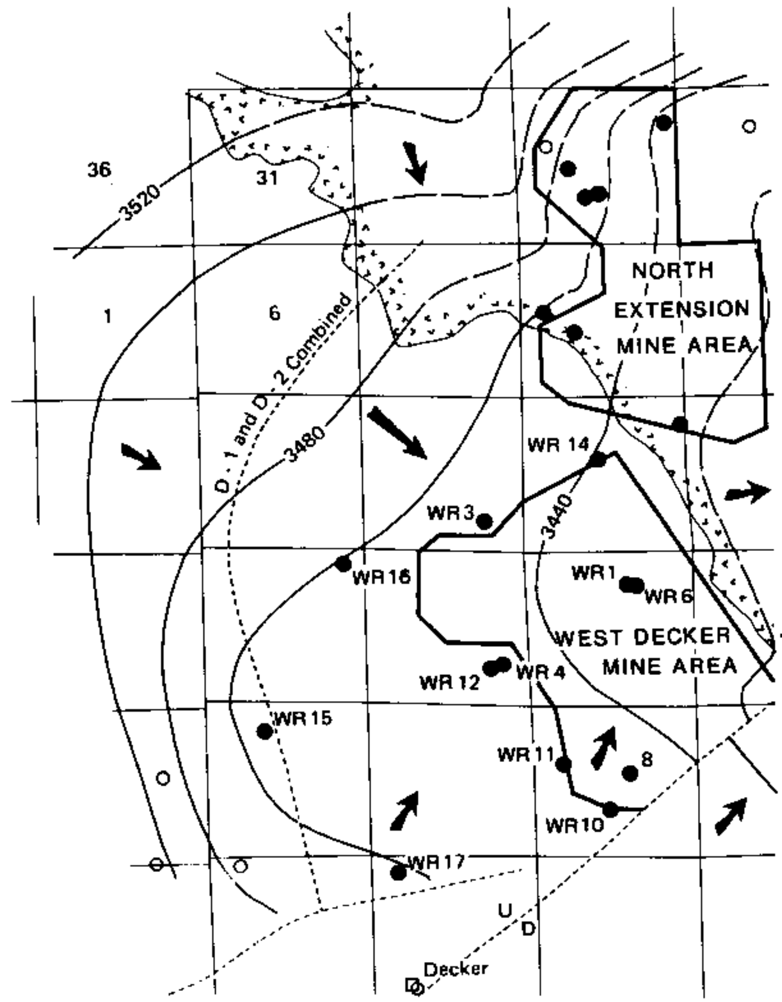


Figure 3.2.3-1.— Potentiometric surface of Dietz 1 coal aquifer before mining began near Decker. (From Van Voast ands Hedges, 1975, pl. 4.)

3.0 HYDROLOGY

3.2 GROUND WATER

3.2.4 QUALITY OF GROUND WATER

GROUND-WATER QUALITY VARIES BETWEEN AQUIFERS AND BETWEEN AREAS

Ground-water quality is extremely variable...not only between aquifers but within aquifers over different areas.

Water from coal beds in the Decker area is characteristically a sodium bicarbonate type, with very large sodium concentrations. Concentrations of dissolved solids range from about 675 to 3,400 mg/L and average about 1,600 mg/L. The coal beds on the east side of the Tongue River contain water with larger concentrations of dissolved solids than coal beds west of the river (fig. 3.2.4-1). Water from coal beds is used extensively for domestic and stock use in the area, but is of limited use for irrigation because of large sodium concentrations and salinity hazard.

Water from sandstone overburden and interburden generally contains larger concentrations of dissolved solids than water from coal beds. The sandstone waters generally contain sodium as the dominate cation and sulfate and bicarbonate as the dominant anions. Because of the large concentrations of dissolved solids, the waters are generally considered to be unfit for domestic use. Dissolved-solids concentrations range from about 2,100 to 7,200 mg/L and average more than 5,000 mg/L.

Water from alluvium and clinker is extremely variable in quality depending upon the source of recharge. In uplands near recharge areas, water from clinker zones may have dissolved-solids concentrations of less than 1,000 mg/L, and be a magnesium-calcium bicarbonate type water. In valley areas near discharge points, water from the alluvium may have dissolved-solids concentrations in excess of 6,000 mg/L and be a calcium-magnesium sulfate type water. In general, water from alluvium is used for irrigation because of its small sodium concentrations, but it is not used for domestic or stock supplies if deeper, more suitable sources are available.

As a general indication of variability of water quality between aquifers and between areas, specific conductances of samples from numerous wells and springs in the mine area are shown in figure 3.2.4-1. Specific conductance is a rough indication of dissolved-solids concentration.

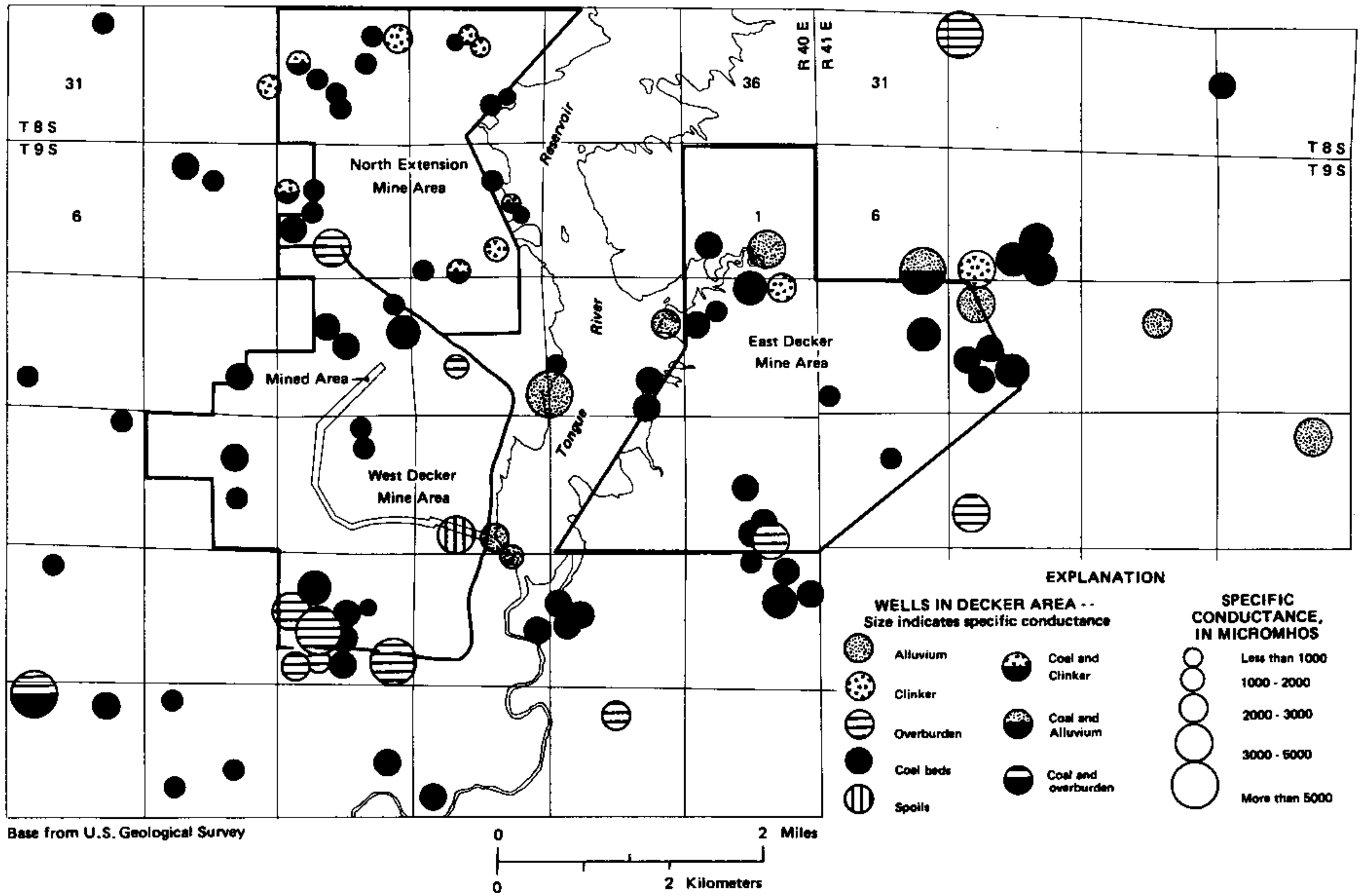


Figure 3.2.4-1.— Specific conductance of water wells completed in various aquifers in the general area. (From U.S. Geological Survey and Montana Department of State Lands, 1977.)

3.0 HYDROLOGY

3.2 GROUND WATER

3.2.5 EVOLUTION OF GROUND-WATER QUALITY

AQUIFER MINERALOGY AND GROUND-WATER FLOW PATHS CONTROL QUALITY

The quality of ground water depends upon the geochemistry of the rocks through which it flows.

When water first enters the ground-water system in recharge areas, it typically contains small concentrations of dissolved solids and is generally dominated by magnesium, calcium, and bicarbonate (fig. 3.2.5-1). Because the water has recently been in contact with the atmosphere, it may contain relatively large levels of dissolved oxygen and be undersaturated with respect to many soluble minerals contained in the aquifer.

This extremely reactive water tends to dissolve many of the minerals, such as gypsum, calcite, dolomite, nahcolite, and albite, present in the aquifers. The dissolution of these and other minerals results in increasing concentrations of the dissolved constituents in the water.

As the ground water moves away from the recharge area and into a more stable environment, the dissolution process commonly becomes less important in controlling ground-water chemistry. Instead, cation exchange or "natural softening" becomes the dominant geochemical process. The calcium and magnesium ions in solution are replaced by sodium ions as the water percolates through the sodic clays abundant in the Fort Union Formation. This process results in the development of water containing large concentrations of dissolved solids with cations dominated by sodium.

Simultaneous with cation exchange, sulfate reduction occurs as sulfate-reducing bacteria convert sulfate ions and simple organic compounds (coal) to water, bicarbonate, sulfide, and carbon dioxide. The presence of carbon dioxide and sulfide gases in water from coal beds affirms the sulfate-reduction process.

The end result of these processes is the formation of ground water containing large concentrations of sodium and bicarbonate (fig. 3.2.5-1). Because recharge and mixing occur over most of the area, intermediate water-quality types can be almost anywhere in the flow system.

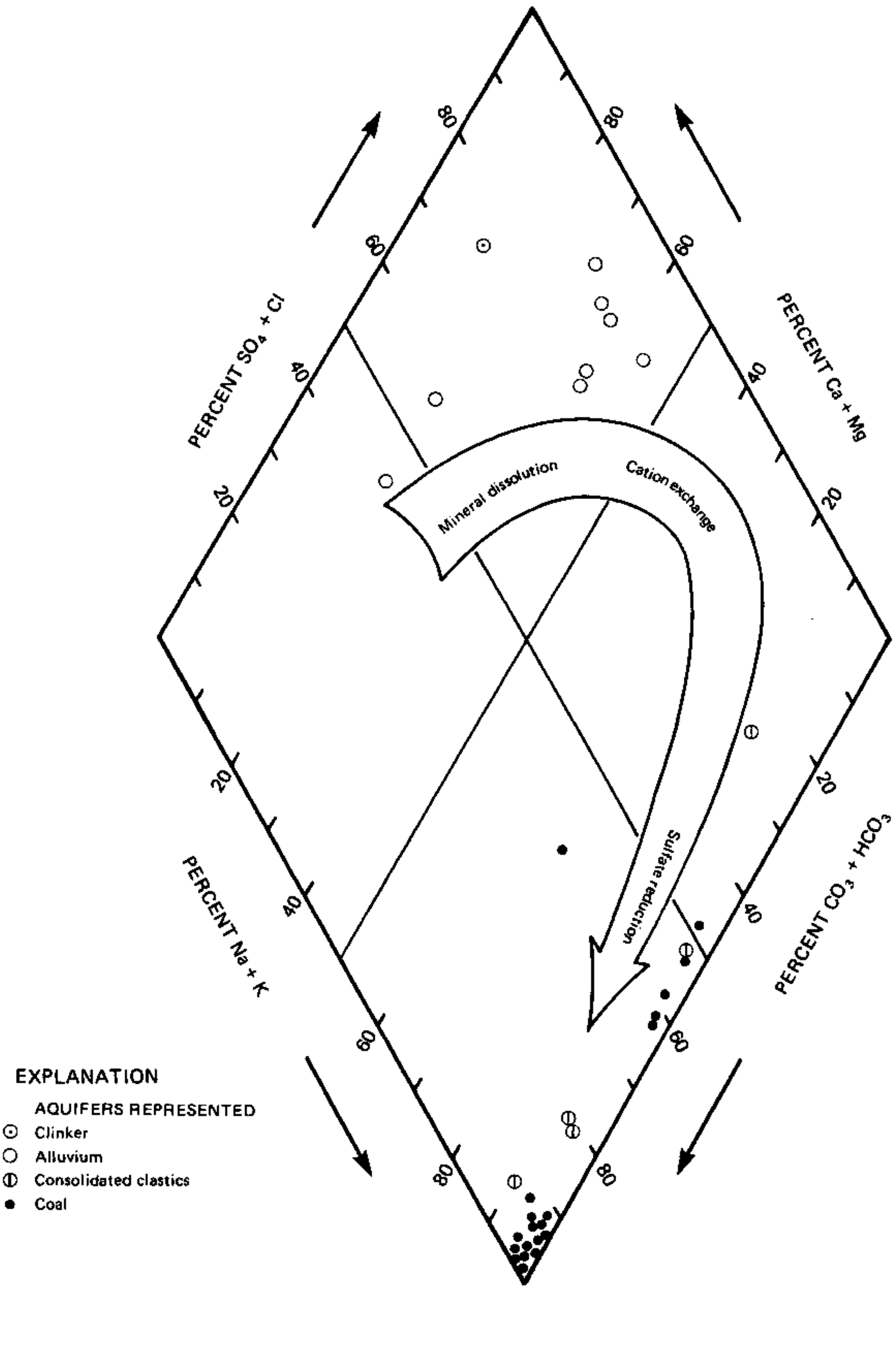


Figure 3.2.5-1.— Evolution of ground-water quality along flow path. (From Thompson and Van Voast, 1981, p. 34.)

3.0 HYDROLOGY

3.2 GROUND WATER

3.2.6 GROUND-WATER/SURFACE-WATER RELATIONS

REACHES OF SOME STREAMS HAVE ALMOST CONTINUOUS FLOW AS A RESULT OF GROUND-WATER DISCHARGE

The Tongue River Reservoir is the major discharge area for the shallow ground-water system but many of the tributary streams drain alluvial aquifers in their valleys.

The operation of the Tongue River Reservoir significantly affects the rate of ground-water discharge in the mine area. When the reservoir stage is low, the ground-water gradient is steep and the ground-water discharge is large. When the reservoir stage is high, the gradient is flattened and may even be reversed in some areas. The long-term average gradient is toward the reservoir, and ground-water discharge has been estimated to be 4 to 6 ft^3/s.

Of the major streams traversing the mine area, Deer Creek, Spring Creek, and South Fork Spring Creek commonly flow in their upper reaches until early summer. During unusually wet years, the streams may flow along most of their reaches well into summer.

Evapotranspiration from phreatophytes occurs in the stream bottoms. Evapotranspiration probably uses most of the ground-water discharge in the area.

Recharge to the alluvial aquifers during snowmelt and spring rains raises water levels in the valley aquifers and increases the water in storage. After the recharge season, the alluvial aquifers drain to the streams; the seasonal discharge varies according to the amount and timing of the earlier recharge.

Low flow of the streams cannot be defined because of lack of data. However, the direct relationship between streamflow and ground-water levels is illustrated in fig. 3.2.6-1.

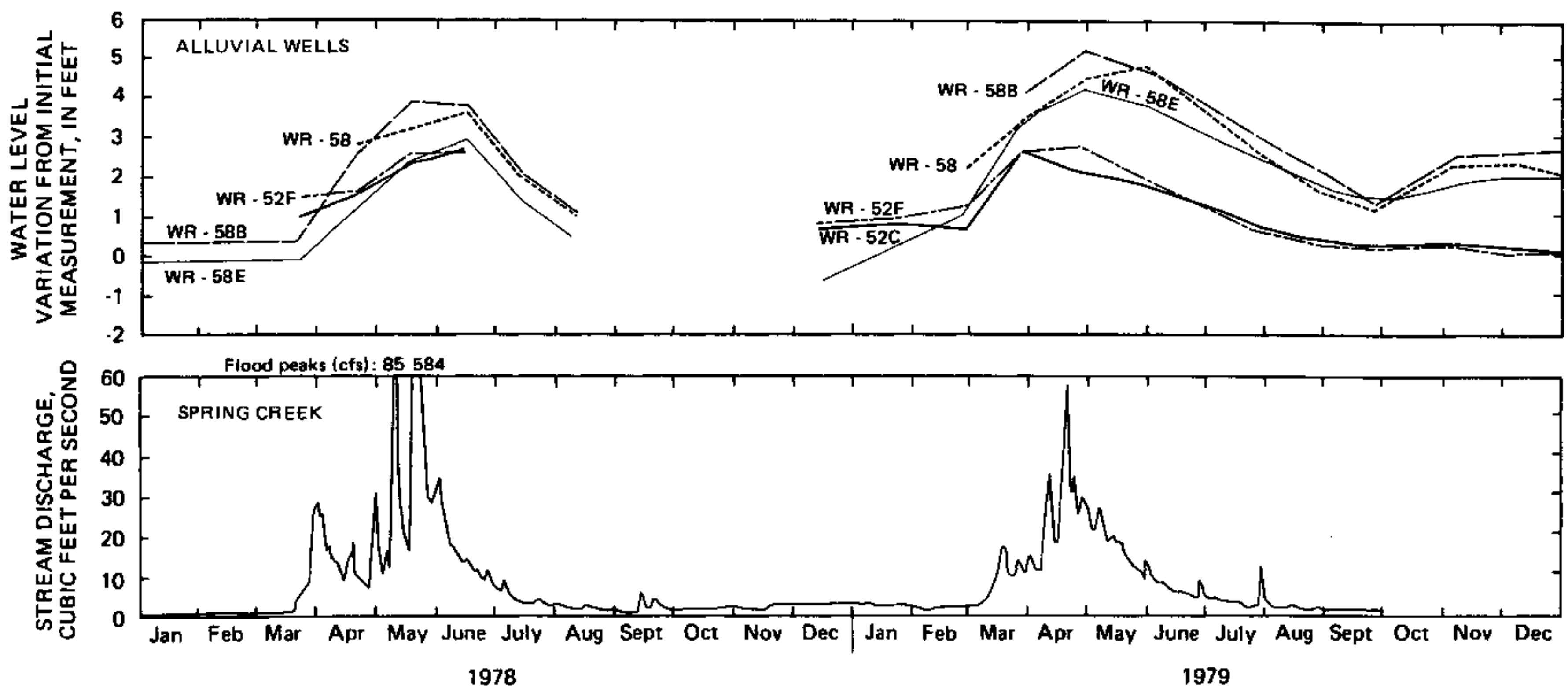


Figure 3.2.6-1.— Stream discharge in Spring Creek and water levels in alluvial wells. (From Thompson and Van Voast, 1981, p. 25.)

3.0 HYDROLOGY

3.3 GROUND-WATER MONITORING

OBSERVATION WELLS DRILLED BEFORE AND AFTER MINING PROVIDE DATA ON AQUIFER CHARACTERISTICS, WATER-LEVEL FLUCTUATIONS, AND GROUND-WATER QUALITY

Sixty-four wells in the mine area monitor hydrologic conditions before and after mining.

Observation wells have been installed throughout the area to be mined (fig. 3.3-1). Some wells have been installed as far as 1.5 miles from the maximum anticipated mined area to monitor water-level declines in coal beds.

The locations of observation wells were selected on the basis of geologic and hydrologic conditions to obtain as much information on pre- and post-mining conditions as possible in areas where water-level or ground-water quality changes might occur. Wells were installed to observe water levels near the Tongue River Reservoir, across faults suspected of forming barriers to ground-water flow, and both upgradient and downgradient from the proposed mine areas.

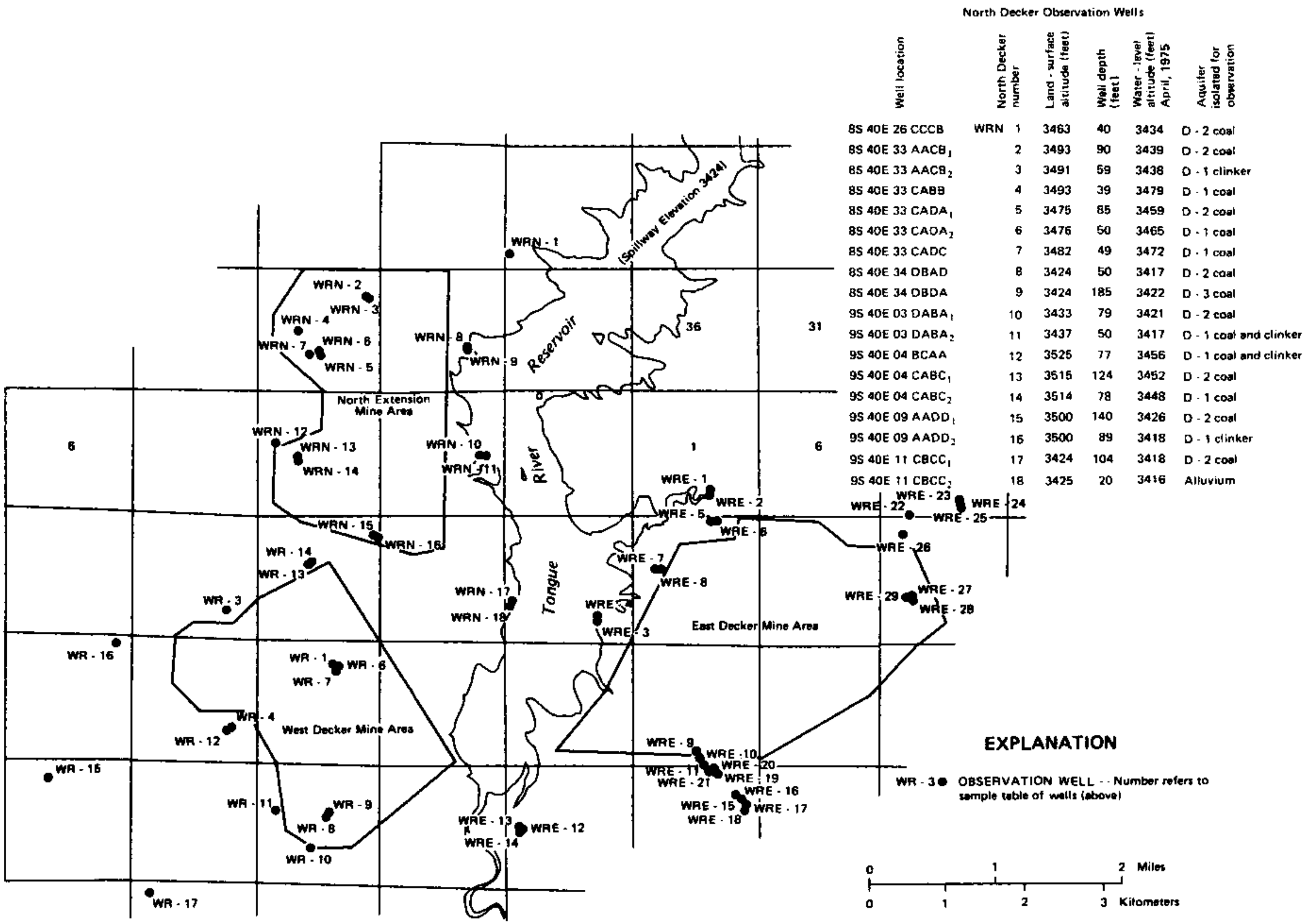
Each observation well was installed to monitor conditions in a single aquifer unit. Where more than one aquifer was identified at a location, several wells were installed with each well perforated in an individual aquifer.

During drilling, each well was logged to record the materials penetrated. Thus, the first information obtained from the wells was an accurate description of the geology. This information was useful in defining vertical and areal extent of each major water-bearing zone in the area.

After observation wells were installed, pumping tests were made to determine the hydraulic characteristics of the major aquifers. Where multiple observation wells were installed, the effectiveness of confining layers was evaluated from the pumping tests and water-level differences.

Samples collected during the pumping tests provided information on ground-water quality between aquifers and over the total area. Samples collected later provided information on water-quality changes caused by natural recharge or mining.

Water levels are monitored regularly at all sites to determine water-level changes due to natural or manmade causes. Continuous recorders were installed on selected wells where rapid water-level changes were anticipated. The frequency of measurements in other wells ranged from monthly to annually depending upon location and anticipated water-level changes.



Well location	North Decker number	Land - surface altitude (feet)	Well depth (feet)	Water - level altitude (feet) April, 1975	Aquifer isolated for observation
8S 40E 26 CCCB	WRN 1	3463	40	3434	D - 2 coal
8S 40E 33 $AACB_1$	2	3493	90	3439	D - 2 coal
8S 40E 33 $AACB_2$	3	3491	59	3438	D - 1 clinker
8S 40E 33 CABB	4	3493	39	3479	D - 1 coal
8S 40E 33 $CADA_1$	5	3475	85	3459	D - 2 coal
8S 40E 33 $CADA_2$	6	3476	50	3465	D - 1 coal
8S 40E 33 CADC	7	3482	49	3472	D - 1 coal
8S 40E 34 DBAD	8	3424	50	3417	D - 2 coal
8S 40E 34 DBDA	9	3424	185	3422	D - 3 coal
9S 40E 03 $DABA_1$	10	3433	79	3421	D - 2 coal
9S 40E 03 $DABA_2$	11	3437	50	3417	D - 1 coal and clinker
9S 40E 04 BCAA	12	3525	77	3456	D - 1 coal and clinker
9S 40E 04 $CABC_1$	13	3515	124	3452	D - 2 coal
9S 40E 04 $CABC_2$	14	3514	78	3448	D - 1 coal
9S 40E 09 $AADD_1$	15	3500	140	3426	D - 2 coal
9S 40E 09 $AADD_2$	16	3500	89	3418	D - 1 clinker
9S 40E 11 $CBCC_1$	17	3424	104	3418	D - 2 coal
9S 40E 11 $CBCC_2$	18	3425	20	3416	Alluvium

Figure 3.3-1.— Network of observation wells used to monitor effects of mining. (From Van Voast and Hedges, 1975, pl. 3.)

4.0 PROBABLE HYDROLOGIC CONSEQUENCES

4.1 OBSERVED WATER-LEVEL DECLINES

DEWATERING MINE PITS CAUSES GROUND-WATER LEVELS TO DECLINE

Water levels in wells perforated in the Dietz 1 coal bed declined as much as 40 feet during the first 3 years of mining.

In the mine area, the pattern of ground-water flow toward the natural discharge area along the Tongue River valley has been modified by mine excavation. Removal of the aquifers and concurrent dewatering of the mine pit has produced a depression in the potentiometric surface about 50 feet lower than, and about a mile upgradient from, the natural discharge point. Consequently, ground-water gradients have steepened toward the mine cuts upgradient from the mine and have reversed direction downgradient from the mine. Between the Tongue River and the mine cut, ground water now flows from the river toward the mine.

Mining of the Dietz 1 coal bed began at the mine early in 1972. During the mining operation, water levels in observation wells declined according to their relative distances from the mined area and according to the changing geometry of the mine cut. The potentiometric surface for the Dietz 1 coal, based on water-level measurements in January 1975, showed large hydraulic gradients toward the mined area along its entire length, as shown in figure 4.1-1. The mine cut penetrates and receives water from the entire thickness of the aquifer, thereby creating a depression lower than the surrounding potentiometric surface and the nearby water table along the Tongue River.

Water levels in wells in the Dietz 2 coal also declined, even though the aquifer was not being mined. The water-level declines in these wells are a result of increased vertical leakage upward to the Dietz 1 coal.

Degree and extent of water-level declines presumably caused by the first 3 years of mining are shown in figure 4.1-2. Northwest of the mined area, water levels in the Dietz 1 coal had declined 10 feet or more within a distance of about 1.5 miles. Southwest of the mine, water-level declines were 10 feet or more within a distance of 1.75 miles. The area in which water levels declined 20 feet or more did not extend more than about 0.75 mile in any direction from the mine. East of the mine, water-level declines were much less extensive because of recharge induced from the Tongue River Reservoir and nearby alluvium and clinker.

Until early 1974, water levels declined at constant or increasing rates. These rates reflected the effect of increasing stress on the flow system as the mine area expanded. In early 1974, the rates of decline in all observation wells began to diminish. The moderation of decline rates indicated that, after 2 years of mining, the system had begun to approach a new equilibrium; however, the ground-water system will not fully attain equilibrium while the mine is in operation.

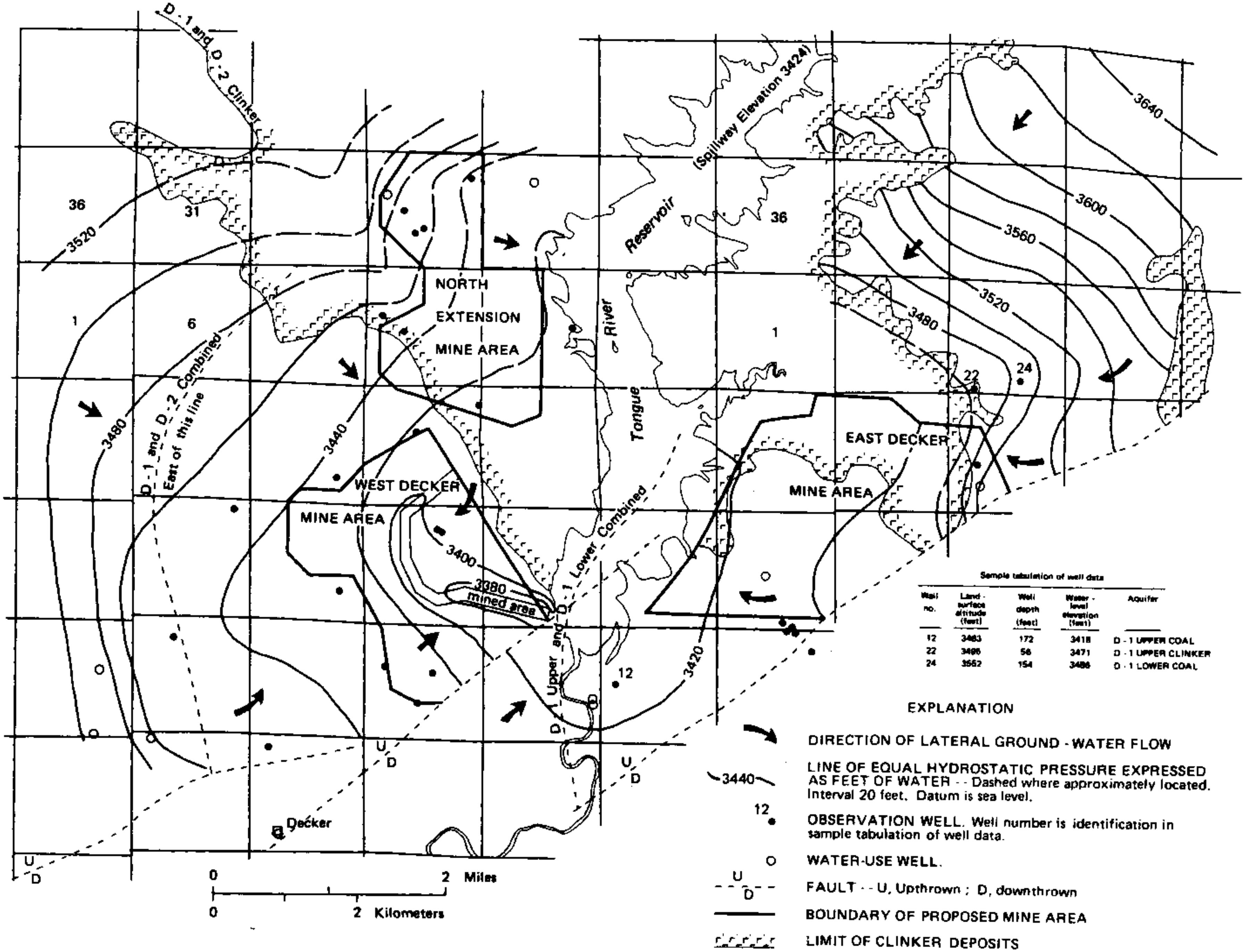


Figure 4.1-1.— Potentiometric surface of water in the Dietz coal aquifer (D-l), January 1975. (From Van Voast and Hedges, 1975, pl. 7.)

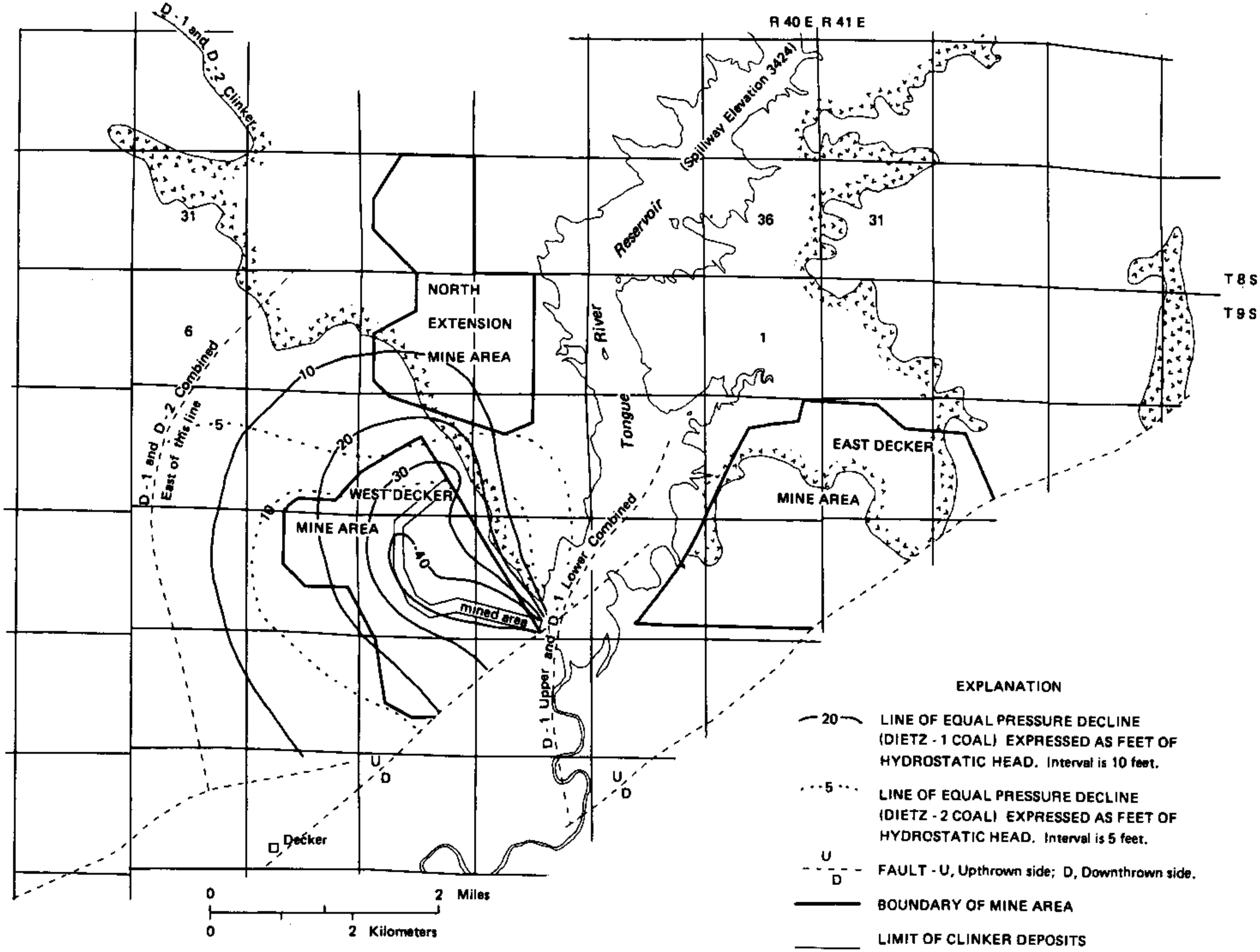


Figure 4.1-2.— Drawdown of water level in the Dietz coal aquifers after 3 years of mining. (From Van Voast and Hedges, 1975, pl. 9.)

Water levels in one of the wells farthest from the mined area (WR-15 fig. 3.2.3-1) illustrate that the potential area of hydrologic effect of mining extends beyond the existing observation-well network. In this well, constructed in mid-1974, the water level declined almost 3 feet in the first year of measurement. The well is more than 2 miles from the mined area. Similar water-level declines have been recorded in other wells similar distances from the mine (WR-16 and WR-17).

4.0 PROBABLE HYDROLOGIC CONSEQUENCES

4.2 PREDICTING WATER-LEVEL DECLINES

GROUND-WATER MODELS PREDICT WATER-LEVEL DECLINES UNDER VARIOUS CONDITIONS

Ground-water models can predict water-level declines using various aquifer characteristics, mining plans, or boundary conditions.

Digital models can be used to simulate the effects of various mining conditions on ground-water systems having various aquifer materials and boundary conditions. A model (17) was used to simulate the water-level response in various aquifers under different mining conditions.

Dewatering of the excavation was simulated as an instantaneous removal of water to the bottom of mine cut. Except where noted, boundaries for each simulation were set at a sufficient distance to minimize boundary effects on water levels. The models produce a worst-case simulation of water-level declines because of the instantaneous removal of water. The models do not account for recharge by surface infiltration of rainfall, snowmelt, or stream loss.

The premise is to illustrate the effects of changes in head, hydraulic conductivity, storage coefficient, and mine-cut size, and the effects of hydrologic boundaries. Effects of changes in these parameters are illustrated by comparison with a base model, which depicts a homogeneous, isotropic, infinite aquifer, 10 feet thick and having a hydraulic conductivity of 0.5 ft/d and a storage coefficient of 1×10^{-4}. The initial potentiometric surface is placed 10 feet above the top of the aquifer. The aquifer simulated in the model represents the coal bed to be mined or the overburden above the target coal bed.

In reality, the aquifer system is probably anisotropic such that horizontal hydraulic conductivity is much larger than vertical hydraulic conductivity. Furthermore, the aquifer would become unconfined near the open pit and a storage coefficient larger than 1×10^{-4} would better represent the problem in the unconfined area. Both of these factors are possible sources of error to the model results. Incorporation of these assumptions into the model would probably result in drawdowns smaller than those indicated by this experiment.

The results of the models are illustrated in map and graphic forms. After 1 year of mining, water-level declines of more than 1 foot extend about 2 miles from the mine cut; after 20 years, the water-level declines of more than 1 foot extend about 8 miles from the mine cut (fig. 4.2-1).

The effects of changes in hydraulic conductivity, storage coefficient, aquifer thickness, depth of mine below the initial potentiometric surface, size of excavation, and aquifer thickness are illustrated in figure 4.2-2. Each curve illustrates the effect of modifying one parameter in the base model. The effect of each change can be determined by comparing each curve with curve 1. Curve 2 was developed by changing the hydraulic conductivity from 0.5 to 5 ft/d, curve 3 by changing the storage coefficient from 1×10^{-4} to 1×10^{-3}, curve 4 by placing the top of the

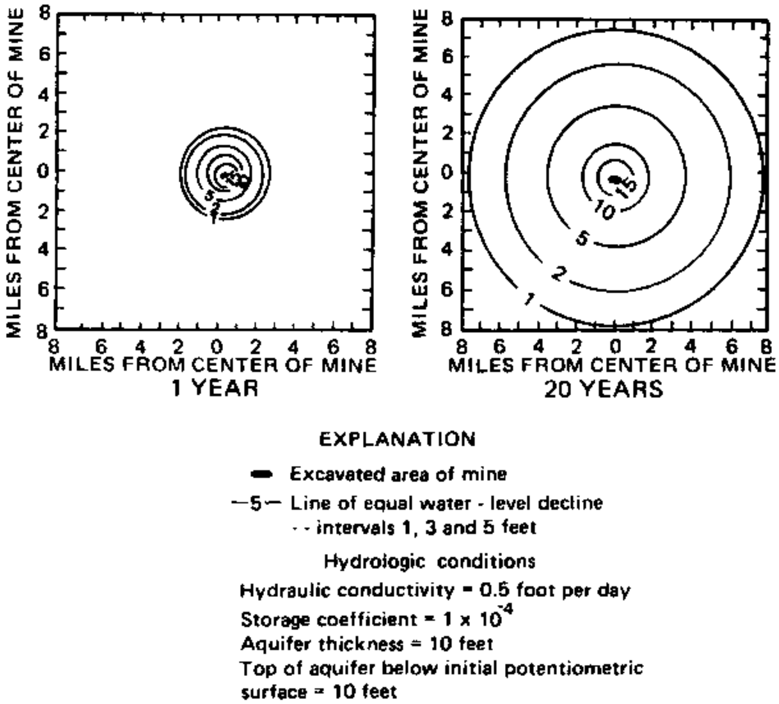
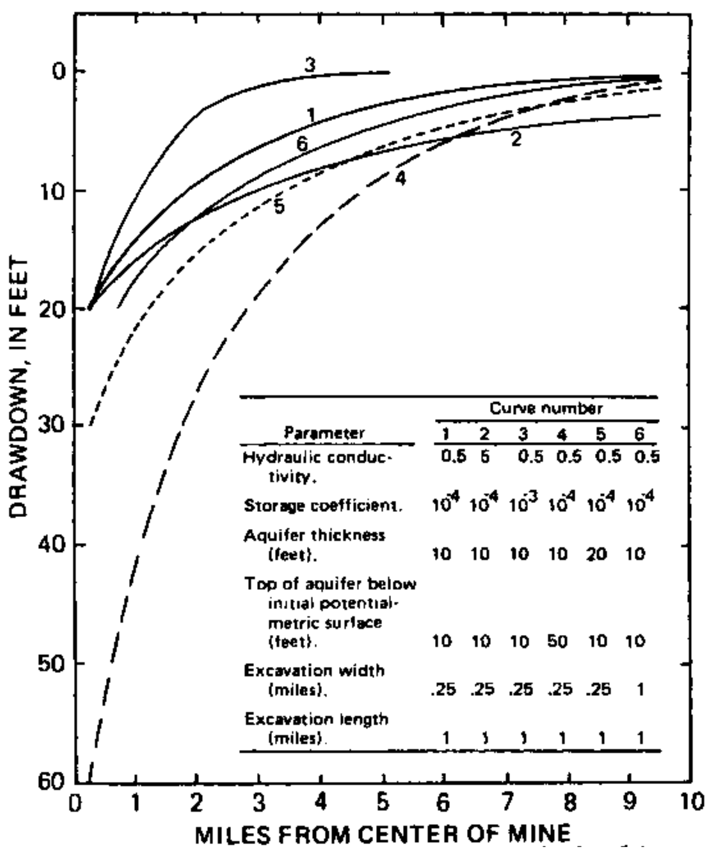


Figure 4.2-1.— Simulated water-level declines after 1 year and 20 years of mine dewatering.
(From Slagle and others, 1985, fig. 8.)



Parameter	Curve number 1	2	3	4	5	6
Hydraulic conductivity.	0.5	5	0.5	0.5	0.5	0.5
Storage coefficient.	10^{-4}	10^{-4}	10^{-3}	10^{-4}	10^{-4}	10^{-4}
Aquifer thickness (feet).	10	10	10	10	20	10
Top of aquifer below initial potentiometric surface (feet).	10	10	10	50	10	10
Excavation width (miles).	.25	.25	.25	.25	.25	1
Excavation length (miles).	1	1	1	1	1	1

Figure 4.2-2.— Simulated water-level declines with various aquifer characteristics.
(From Slagle and others, 1985, fig. 9.)

aquifer 50 feet below the initial potentiometric surface (instead of 10 feet), curve 5 by increasing the aquifer thickness from 10 to 20 feet, and curve 6 by increasing the excavation width from one-fourth to 1 mile.

The effects of a nearby surface-water body on water-level declines are depicted in figure 4.2-3. In this simulation, water levels along the boundary are maintained constant, allowing recharge from a lake or stream to limit water-level declines.

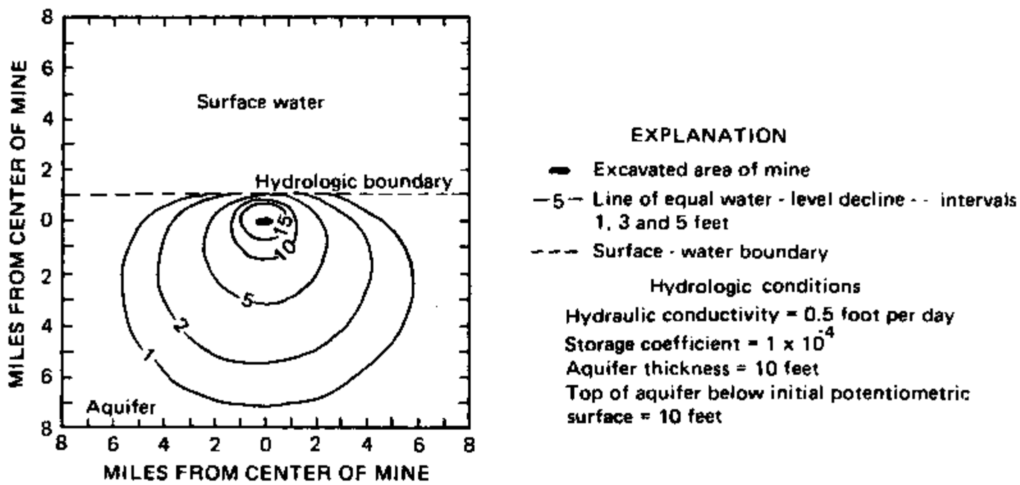


Figure 4.2-3.— Simulated water-level declines in an aquifer adjacent to a surface-water boundary. (From Slagle and others, 1985, fig. 11.)

4.0 PROBABLE HYDROLOGIC CONSEQUENCES

4.3 IMPACTS OF WATER-LEVEL DECLINES

WATER-LEVEL DECLINES MAY AFFECT SPRINGS AND WELLS

About 50 wells and springs in the mine area could be affected by water-level declines.

Water-level declines can significantly affect the yield of wells and springs. In the worst case, if water levels declined below the bottom of the well, the well would become dry. Similarly, if the water table dropped below the discharge point of a spring, the spring would stop flowing. Under water-table conditions, a water-level decline would result in decreasing well yields (specific capacity), because the saturated thickness available to contribute water to the well would be less. Under confined conditions water-level declines would effectively increase pumping lifts and maximum well yield would be less.

In the mine area, about 50 wells and springs supply water for wildlife, agriculture, stock, domestic, industry, and public supply. Although total ground-water use probably does not exceed 30,000 gal/d, the wells and springs are vital to the economy and population of the area.

Springs in the area are used exclusively by livestock and wildlife. The springs shown in figure 3.2.1-1 are those identified as dependable sources of supply and do not include ephemeral springs that flow in response to seasonal high water levels in alluvium or clinker deposits. Because springs are a surface expression of the water table, even small water-level declines could affect them.

About two-thirds of the wells are used for watering stock. Generally, these wells are drilled to the shallowest source of ground water. These wells would be readily susceptible to impacts from mining.

Wells drilled for domestic, industrial, or public supplies generally are completed in coal aquifers to obtain good quality water. If the wells are in a coal bed to be mined, they are likely to be affected to some degree. Most of the coal beds contain water under confined conditions so only those wells near the mines where the coal beds would be dewatered would be significantly affected. Coal-bed wells a few miles from the mines might undergo water-level declines but their yield probably would not significantly decrease.

4.0 PROBABLE HYDROLOGIC CONSEQUENCES

4.4 WATER QUALITY IN MINE SPOILS

SPOILS WATER CONTAINS MORE DISSOLVED CONSTITUENTS THAN NATIVE GROUND WATER

Dissolved constituents in water from resaturated mine spoils are more concentrated than those found in water from overburden sandstone aquifers.

When mine spoils are returned to the mine pit, the original structured system of aquifers is replaced with a heterogeneous mixture of rubble composed of waste coal, siltstone, sandstone, clinker, alluvium, soil, or any other material that was removed from the pit. Materials that had originally resided in the saturated zone where the potential for oxidation was slight now may lie in the unsaturated zone where oxidation can release soluble salts. The disruption of the natural system would result in significant differences in quality between water from the original aquifers and water from the mine spoils.

Observation wells drilled into resaturated mine spoils at the mine site have clearly shown changes in ground-water quality. Calcium, magnesium, and sulfate concentrations were substantially larger in mine-spoils waters than in water from coal aquifers (fig. 4.4-1). However, the mine-spoils water quality is similar to the water quality from sandstone aquifers in the overburden.

Water quality in wells drilled in mine spoils was extremely variable during the early period of resaturation. In 1975 and 1976, for example, dissolved-solids concentrations in one well fluctuated between 6,400 and 3,800 mg/L. Although data are not conclusive, the quality apparently has stabilized at the smaller concentration since the mine spoils have become saturated. Data indicate that during the early phase of resaturation, the first flush of water through the system may have leached much of the soluble minerals from the spoils.

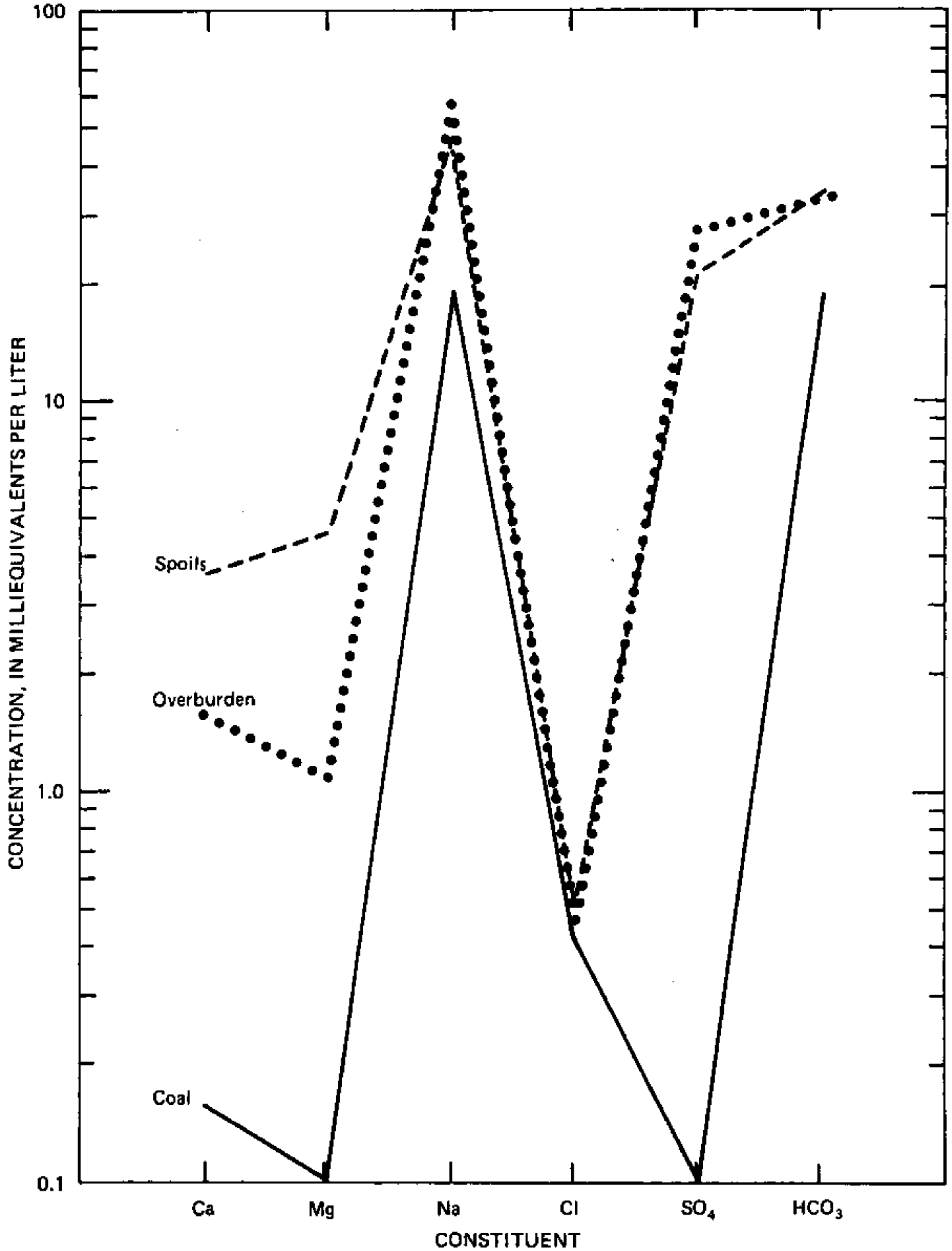


Figure 4.4-1.— Comparison of water quality in spoils and pre-mining aquifers. (From Van Voast, Hedges, and McDermott, 1978),

4.5 PREDICTING OFF-SITE GROUND-WATER QUALITY

AFTER GROUND-WATER FLOW PATTERNS RE-ESTABLISH, MINE-SPOILS WATER WILL MIGRATE DOWNGRADIENT

Predicting the ultimate ground-water-quality conditions in the vicinity of a reclaimed mine requires considerable speculation and simplifying assumptions.

During mining, ground-water flow patterns will generally be toward the mine cut as dewatering operations draw the water level down to the base of the mine (fig. 4.5-1). As the mine cut proceeds through the area, spoils replaced in earlier cuts will become saturated with ground water and the pattern of flow would continue to be toward the mine cut. Ultimately, after all mining has ceased and mine spoils have been resaturated, the original pattern of ground-water flow likely will be re-established. However, some variations will occur owing to differences in aquifer characteristics between mine spoils and the original aquifers and in the infiltration characteristics between the reclaimed surface and the original land surface.

The return of the original flow patterns will result in movement of mine-spoils water downgradient toward natural discharge areas. Any wells located downgradient from the reclaimed mine area and perforated in the shallow aquifers in contact with the spoils eventually will be affected by the mine-spoils water.

No data collected to date indicate what geochemical changes might occur as mine-spoils water enters natural aquifers. However, a prudent assumption is that mine-spoils waters would retain most of their dissolved solids after leaving the spoils. By using that assumption, the areas to be affected by migrating mine-spoils water can be predicted by outlining the downgradient path of ground water from the pre-mining water-level data. A rough estimate of travel time could also be made by calculating the volume rate exchange of water through the aquifer.

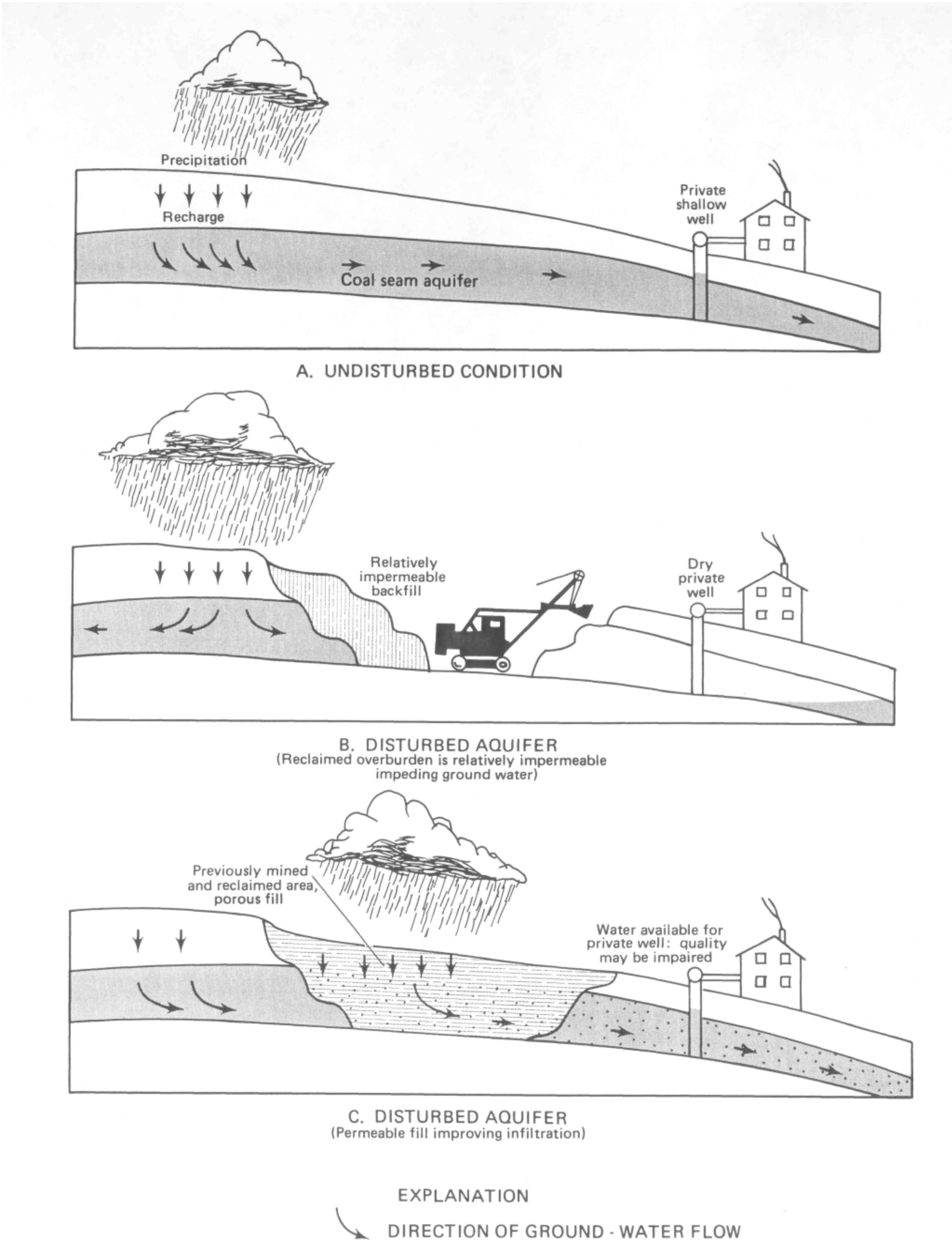


Figure 4.5-1.— Hypothetical migration of mine spoils water after reclamation.

4.0 PROBABLE HYDROLOGIC CONSEQUENCES

4.6 MONITORING POST-MINING HYDROLOGIC CONDITIONS

AFTER MINING AND RECLAMATION HYDROLOGIC MONITORING WOULD SHOW CHANGES IN THE HYDROLOGIC SYSTEMS

Post-mining monitoring of ground-water levels, ground-water quality, and aquifer characteristics not only would show the ultimate affects of mining on hydrologic systems but also would serve as an aid in predicting hydrologic impacts in other areas to be mined.

A network of observation wells could be used to monitor changes in ground-water storage, quality, and flow patterns. Although mining is planned to continue in the area for at least 20 years, monitoring of hydrologic conditions during and following each phase of the operation would provide information useful in evaluating effects of mining and reclamation. Because of the long-term nature of the mining activity in the mine area, concurrent monitoring could provide data needed to evaluate the effectiveness of improved mining methods, various reclamation techniques, or other mitigating measures. The monitoring would also assist in predicting hydrologic impacts in other areas to be mined.

The network of wells shown in figure 4.6-1 could provide information on water-level changes in the various aquifer units in and near the mine areas. Additional wells outside the proposed mine boundaries as mining expands would be useful in showing water-level changes due to mine dewatering or mine spoil saturation. The frequency of water-level measurements would depend upon the status of mining and reclamation. As mine pits move through the proposed mining areas, frequency of monitoring could be increased in nearby wells and decreased in wells in which water levels have stabilized or have approached equilibrium.

As mine areas are reclaimed, replacement observation wells could be installed in mine spoils to monitor resaturation of the spoils material. Placement, density, and depth of the wells would depend upon the progression of mining and reclamation. Wells could be installed after surface reclamation activities have been completed and danger of damage to well casing and equipment has passed.

As mine spoils become resaturated, frequency of monitoring could be monthly or more frequently depending upon the rate of change in water levels. In some wells continuous recorders could be used to document the water-level rises. After the mine spoils have become saturated and water levels have stabilized, frequency could be reduced to quarterly.

Water samples could be collected from the observation wells installed in mine spoils to document water quality in the spoils. A few of the wells would need to be sampled monthly during the period of resaturation but most wells could be sampled annually to provide data on long-term variations in mine-spoils water.

Sample Table of Wells
West Decker Observation Wells

Well location	Decker number	Land surface altitude (feet)	Well depth (feet)	Water - level altitude (feet) April, 1975	Aquifer isolated for observation
9S 40E 08 DCAA	WR 3	3612	215	3431	D - 1 coal
9S 40E 09 BDDA$_1$	14	3598	192	3419	D - 1 coal
9S 40E 09 BDDA$_2$	2	3595	192	-	D - 1 coal discont. 12/20/72 - silt
9S 40E 09 BDDB	13	3592	247	3436	D - 2 coal
9S 40E 16 ABCA	1	3498	104	3404	D - 1 coal
9S 40E 16 ABCD$_1$	6	3499	135	3406	D - 1 coal
9S 40E 16 ABCD$_2$	7	3498	207	3445	D - 2 coal
9S 40E 17 DACB	4	3585	220	3428	D - 1 coal
9S 40E 17 DACC	12	3486	230	3427	D - 1 coal
9S 40E 18 ABAD	16	3640	237	3451	D - 1 & 2 coal combined
9S 40E 19 BAC	15	3685	390	3445	D - 1 & 2 coal combined
9S 40E 21 ACCA$_1$	8	3537	165	3426	D - 1 coal
9S 40E 21 ACCA$_2$	9	3537	256	3458	D - 2 coal
9S 40E 21 BCAC	11	3575	210	3429	D - 1 coal
9S 40E 21 BCAD	5	3574	200	-	D - 1 coal discont. 9/15/73 - silt
9S 40E 21 CADA	10	3537	169	3426	D - 1 coal
9S 40E 29 BBAC	17	3570	300	3455	D - 1 & 2 coal combined

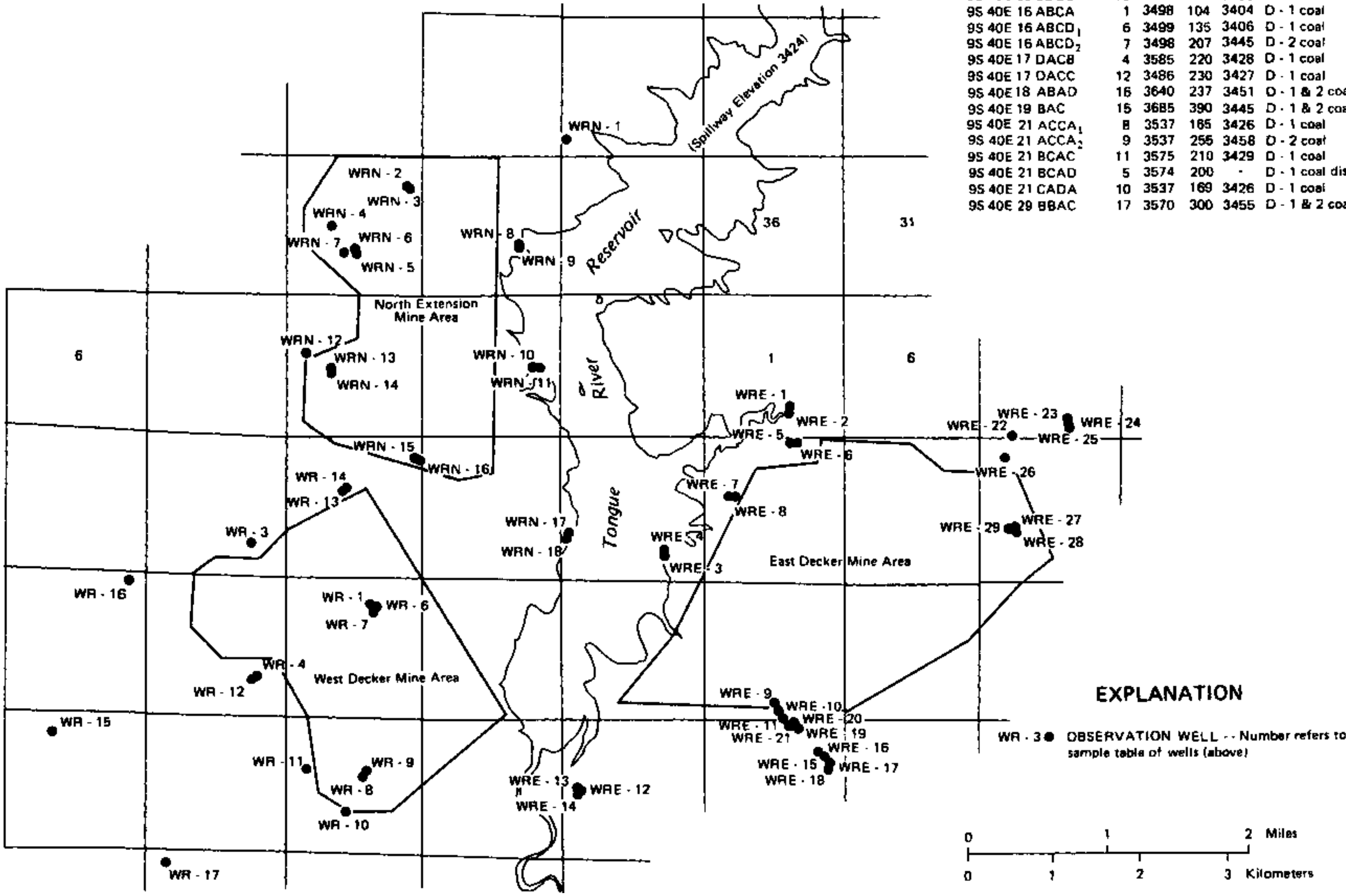


Figure 4.6-1.— Post-mining network of observation wells which could be used for long-term monitoring. (From Van Voast and Hedges, 1975, pl. 3.)

Off-site effects of mining could be monitored by observation wells down-gradient from the mine areas. Although ground-water flow would be toward pits during the mining operation, the original flow pattern probably would be reestablished after mining had ceased. Ground-water samples collected from the downgradient wells would provide data on migration of mine-spoils water into and through the undisturbed aquifers.

Selected observation wells in reclaimed spoils could provide information on aquifer characteristics of the spoils material. When water samples are collected, observations of drawdown and recovery of water levels in the pumped well and any nearby observation wells could provide information on aquifer properties including transmissivity and storage coefficient. Any changes in these properties over time as a result of compaction, piping, or readjustment of compaction , piping, or readjustment of spoil material would be observed from periodic repetition of the aquifer tests.

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GROUND-WATER STUDY 9

by

Robert L. Boughton

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1.0 ABSTRACT

Geology and the Occurrence of Coal

The sedimentary rocks of the Paleocene Fort Union Group consist of sandstone interbedded with siltstone, claystone, and lignite, which dip gently north into the Williston basin. The Bullion Creek and Sentinel Butte Formations of the Fort Union Group contain the only lignite coal reserves suitable for surface mining. The most important lignite seam is the 30-foot Harmon bed, which is separated by underclay from sandstone and siltstone in the lower unit of the Bullion Creek Formation. The rock units are jointed and further fractured by mine operations.

Hydrology

The principal aquifers are the Harmon lignite and the underlying sandstones of the Slope and lower Bullion Creek Formations. The lignite and sandstone aquifers provide base flow to tributaries of Buffalo Creek and are locally important sources of domestic and livestock water. Where present, the Harmon lignite is the surficial aquifer; the sandstone aquifer is confined by the underclay of the Harmon. Where the Harmon lignite is absent, the sandstone aquifer is unconfined. The occurrence and flow of ground water is complex, owing to (l) dendritic channel sands in the strata overlying the Harmon lignite and in the lower unit of the Bullion Creek Formation, and (2) natural fracturing in the lignite beds and additional fracturing caused by mine blasting. The hydraulic conductivity in both aquifers commonly varies by several orders of magnitude within short distances. The mining operations causes additional secondary permeability and porosity.

The hydrologic data-collection network in the 42 square mile area consisted of 546 test holes, 15 core holes, and 44 unsaturated-zone lysimeters; 114 test holes were completed as wells. The wells penetrated both aquifers and were used to determine ground-water flow, hydraulic properties, and water quality. Sodium-adsorption ratios and sulfate and dissolved-solids concentrations proved most useful in detecting water-quality changes caused by mining.

The regional ground-water flow is northeast toward the center of the Williston basin; however, local flow is southwest toward Buffalo Creek. The nature of this flow reversal in the aquifer system is not well understood. The large cones of depression in both aquifers, produced by mine dewatering, have limited shallow ground-water availability. The most important underlying regional aquifer is the Fox Hills-lower Hell Creek aquifer system.

The type of water in the lignite and sandstone aquifers ranges from sodium sulfate to sodium bicarbonate. It is controlled principally by chemical reactions in the unsaturated zone.

Mining Method and Other Stresses on the Aquifer System

Surface mining of lignite from the 30-foot Harmon bed began in 1946 on a small scale. Annual production was increased in 1951 to about 100,000 tons and in 1974 was increased again by a factor of 30.

The aquifer system does not have any significant withdrawals other than those from active coal mines and their dewatering wells. However, domestic and livestock wells yielding small quantities of water are common.

Probable Hydrologic Consequences and Proposed Hydrologic-Monitoring Network

Only aquifers of the Slope-Bullion Creek aquifer system are being directly disrupted by surface-mining activities. In 1981, decline of the potentiometric surface of the sandstone aquifer due to mine dewatering may have been as much as 65 feet and extended as far as 3 miles beyond the mine perimeter. Pumpage to dewater the lignite exceeds 1,000 gallons per minute.

Water levels recover rapidly by lateral flow when dewatering ceases. However, the decreased hydraulic conductivities of mine spoils relative to undisturbed overburden imply long-lasting consequences for water levels in these shallow aquifers.

Oxidation of iron sulfide minerals exposed during mining and the resultant sulfates may significantly degrade post-mining ground waters. Additional sulfate concentrations may result if the replaced overburden is below the water table.

Low-flow water quality in tributaries draining the mine will deteriorate roughly proportional to the amount of basin drainage disturbed by mining. However, the quality deterioration of the principal creek will be smaller than in tributaries because of dilution.

A post-mining hydrologic monitoring network includes (1) about 30 observation wells completed in both major aquifers to monitor the enlarging cone of depression, (2) two streamflow-gaging stations to monitor the effect on stream base flow, and (3) routine water-quality sampling of observation wells and low-flow stream sites.

2.0 GENERAL DESCRIPTION OF AREA

2.1 DESCRIPTION OF GASCOYNE AREA

THE AREA IS IN THE LIGNITE PART OF THE NORTHERN GREAT PLAINS COAL REGION

The climate of the area is semiarid and the lignite seams are important aquifers supplying water for livestock and domestic uses.

The Gascoyne study area (fig. 2.1-1) is in the lignite part of the Northern Great Plains coal region and includes about 45 mi^2 surrounding the Gascoyne Mine in Bowman County. The area lies within the unglaciated part of the Missouri Plateau physiographic province (10). Maximum relief is about 250 feet. The climate is semiarid with mean annual precipitation being about 15 inches (30).

The shallow, flat-lying lignite seams of the Gascoyne area and other surrounding coal areas commonly are important aquifers that supply water for livestock and domestic use. Surface mining of lignite aquifers has prompted concern about the effect of mining on the quantity and quality of shallow ground water in this area. In 1973, the U.S. Geological Survey began hydro-geochemical investigations in the vicinity of the Gascoyne (Peerless) Mine.

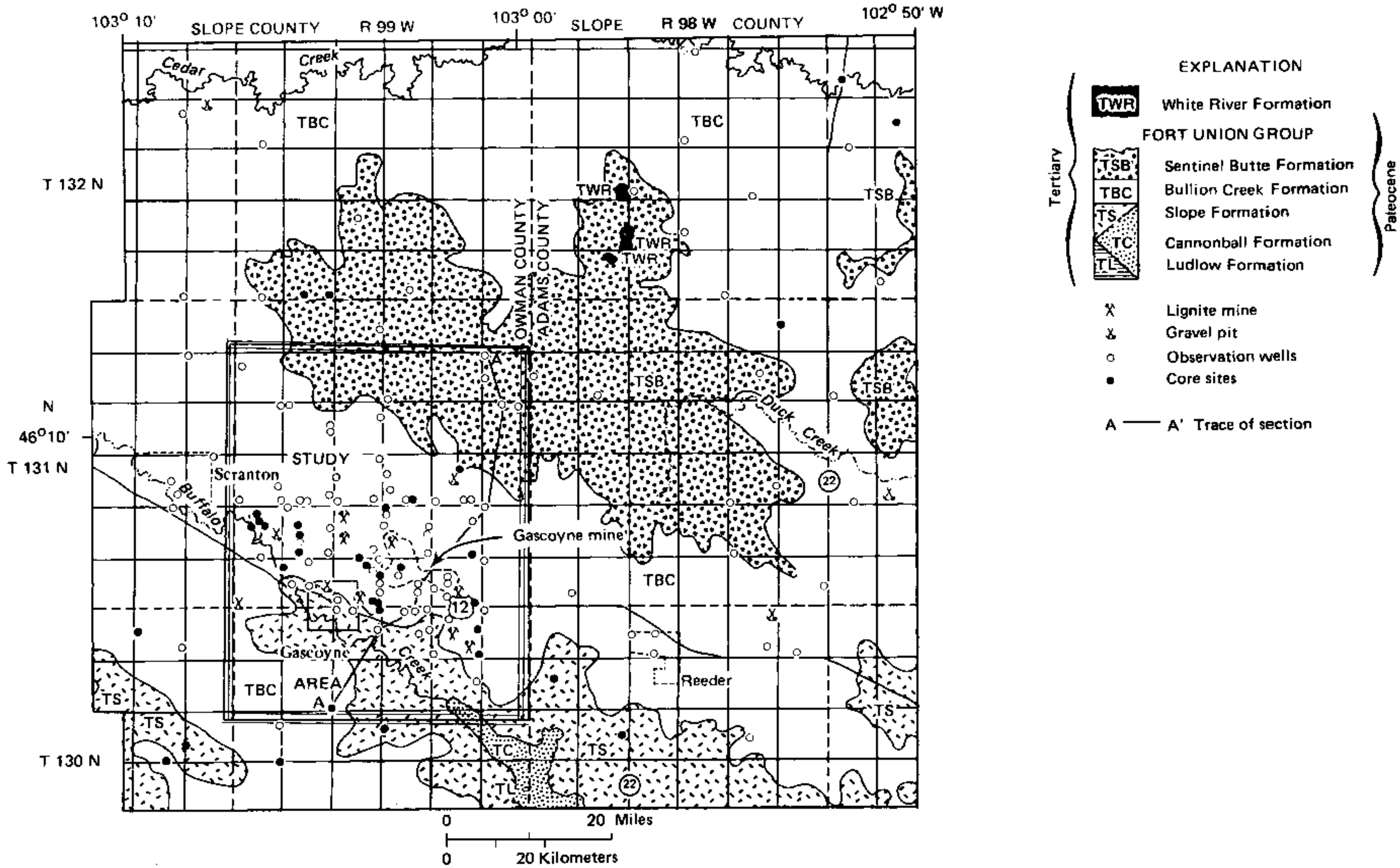

Figure 2.1-1. — Location of the Gascoyne study and the hydrology of the area. (Geology modified from Carlson, 1979.) (From Houghton and others, 1984, fig. 2.)

2.0 GENERAL DESCRIPTION OF AREA

2.2 GEOLOGY, OCCURRENCE, AND MINING OF COAL

THE BULLION CREEK AND SENTINEL BUTTE FORMATIONS CONTAIN THE ONLY LIGNITE RESERVES SUITABLE FOR SURFACE MINING

The geology of sedimentary bedrock containing the lignite beds is complicated due to periods of erosion and of marine and nonmarine deposition causing interfingering of sandstone, siltstones, shales, and lignite beds.

The Fort Union Group is the oldest geologic unit exposed in the area (fig. 2.1-1). The group consists of about 700 feet of sandstone interbedded with siltstone, claystone, and lignite, which dip gently north at about 20 to 30 ft/mi. The Fort Union Group has been divided, in ascending order, into the Ludlow and its lateral marine equivalent the Cannonball, Slope, Bullion Creek, and Sentinel Butte Formations (4). In the general area, the Ludlow, Cannon-ball, and Slope Formations are exposed only in the valley of Buffalo Creek (fig. 2.1-1). The Bullion Creek Formation crops out in most of the Gascoyne area, but is overlain by the Sentinel Butte Formation in the northeastern part.

In the Gascoyne area the stratigraphic sequence is complicated by inter-tonguing of the Ludlow and Cannonball Formations (fig. 2.2-1). In Buffalo Creek valley, carbonaceous sandstones and shales of the Ludlow Formation interfinger with marine shales of the Cannonball Formation. Where the Cannonball is absent, the Ludlow is unconformably overlain by the T-Cross lignite at the base of the Slope Formation. Interfingering of the Ludlow and Slope Formations in parts of Bowman County was considered likely (4), but they cannot be differentiated in the Gascoyne area because their lithologies are similar.

The Bullion Creek and Sentinel Butte Formations contain the only lignite reserves suitable for surface mining in the study area. The weakly consolidated Bullion Creek Formation consists of alternating sequences of sandstone, siltstone, claystone, and lignite beds (fig. 2.2-2). Different lithologies grade laterally into one another within short distances thus reflecting cyclical changes in depositional environment (15, 16, 17). The most important lignite occurs as three seams in the 30-foot Harmon bed (18), about 60 feet above the base of the Bullion Creek Formation and separated from the lower Bullion Creek sandstones and siltstones by underclay as much as 48 feet thick. The silty sandstones of the Sentinel Butte Formation are extensively interbedded with thin beds of lignite, which are only locally thick enough to be economically important.

The Bullion Creek and Sentinel Butte sandstones and siltstones consist principally of grains of quartz and some limestone, dolomite, and metamorphic rock fragments. Expandable sodic smectites and mixed-layer clay minerals compose as much as 60 percent of the clay fraction. Gypsum, mirabilite, and other sulfate minerals are commonly present in the unsaturated zone. In undisturbed rocks, iron sulfide minerals are absent above the water table but constitute as much as 3 percent of the overburden below the water table. Limonite pseudomorphs of pyrite and concentrations of sulfate minerals in the unsaturated overburden indicate the former presence of sulfide throughout both formations.

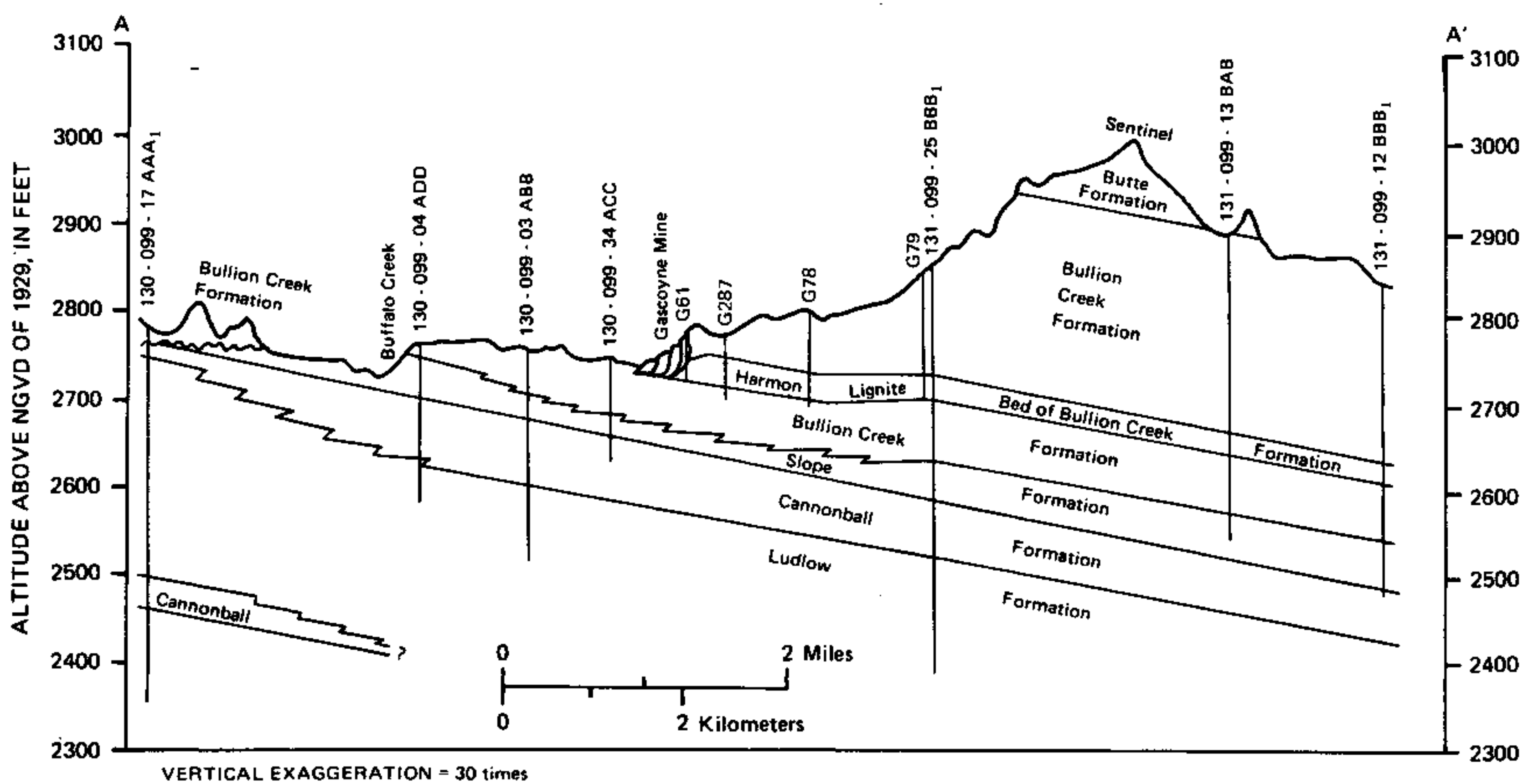

Figure 2.2-1. — Geologic Section A-A′.
(From Houghton and others, 1984, fig. 5.)

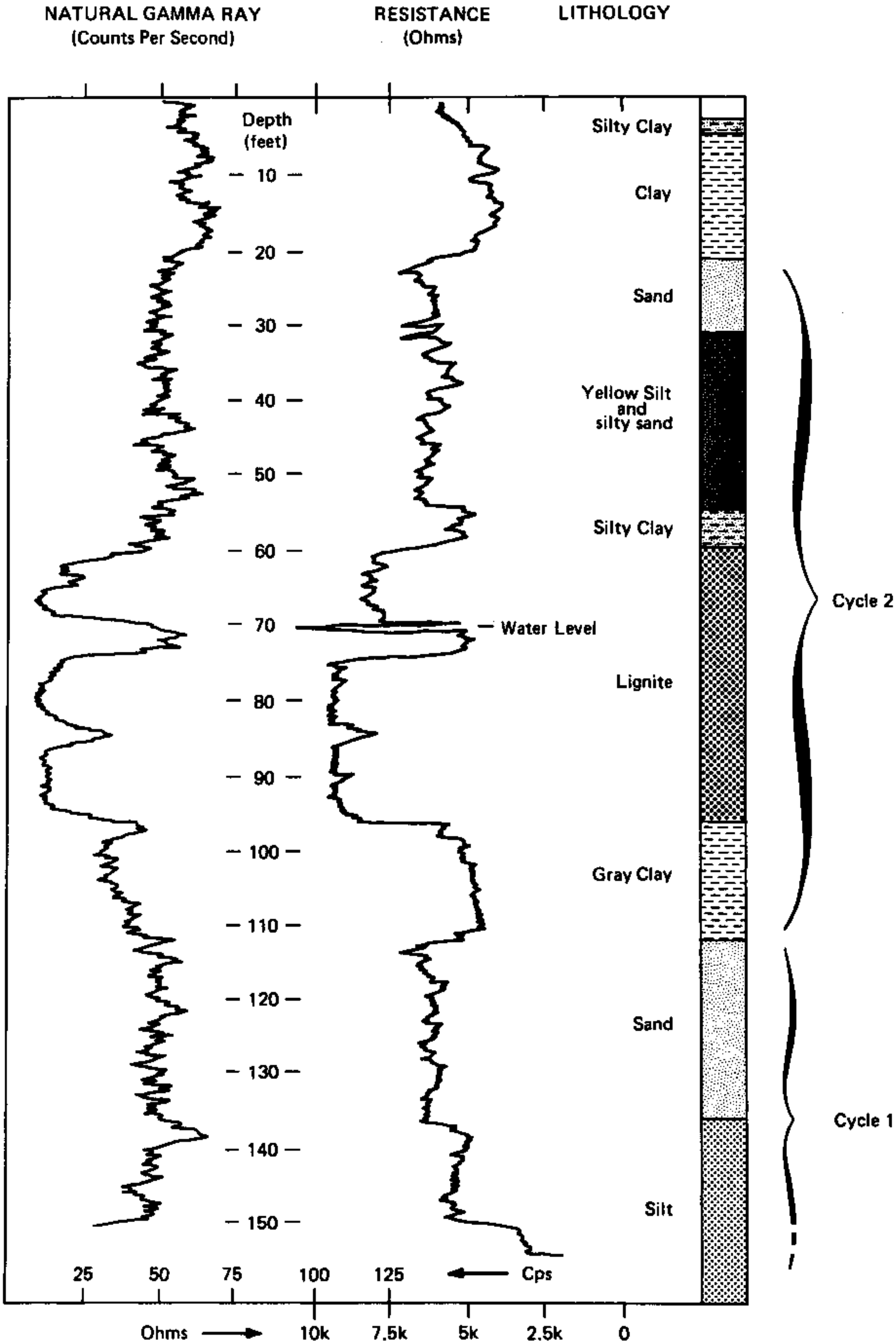

Figure 2.2-2. — Cyclical lithologic sequence of the Bullion Creek Formation in well 131-099-29BBB.
(From Houghton and others, 1984, fig. 12)

2.0 GENERAL DESCRIPTION OF AREA

2.3 THE GASCOYNE MINE

THE GASCOYNE MINE OPENED IN 1946

The definition of overburden by exploratory methods is essential in the determination of reclamation potential and probable hydrologic consequences of mining.

Surface mining of lignite from the 30-foot Harmon bed in the Gascoyne Mine began in 1946. Production was expanded 30-fold in 1975 to its current level of 3 million tons per year. The Gascoyne Mine operates with a surface coal thickness/overburden thickness ratio greater than 0.8. The three lignite seams of the Harmon bed (Alpha, Beta, and Gamma) are mined in four pits. The lignite in each pit has a different sodium content. At the electric power-generating facilities, the lignites are mixed to arrive at an optimum composition for burning. The least sodium content occurs in lignite deposited adjacent to sand channels of the Paleocene fluvial system (fig. 2.3-1). These channels are mappable using geophysical logs and lithologic data collected by the mining company during routine development drilling.

Particle size, chemical characteristics (electrical conductivity, pH, sodium-adsorption ratio, cation-exchange capacity), and hydraulic properties of overburden determined by the mining company from drill cuttings and core material are essential to assessing overburden reclamation potential (11,19) and the probable hydrologic consequences of mine activities. Overburden is removed by standard key cut, cyclical dragline operations (2). Reclamation is proceeding selectively by strike-off grading (8) of individual "reclamation units" as identified in (22) to produce the desired post-mining topographic surface.

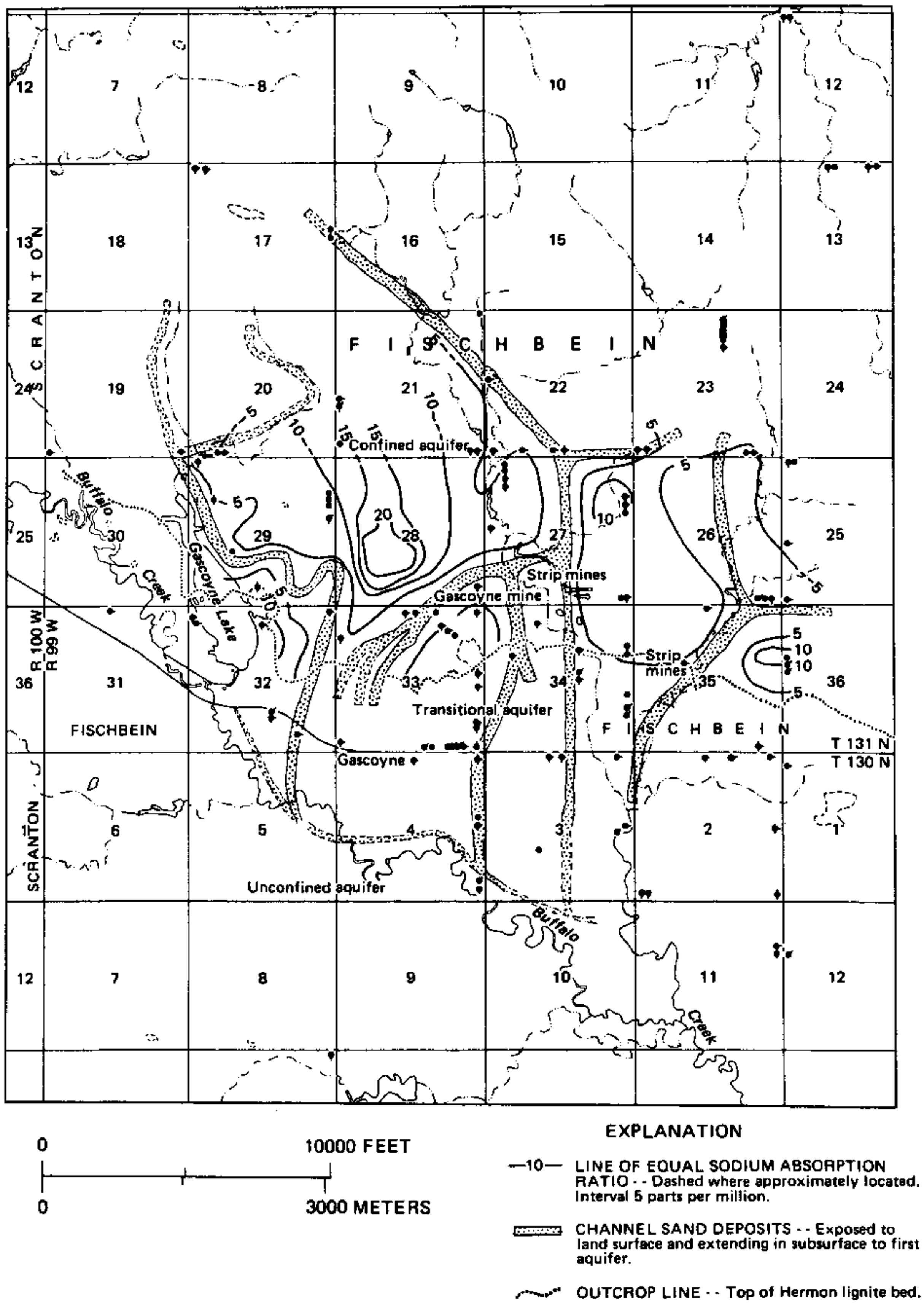

Figure 2.3-1. — Relationship of the sodium adsorption ratio (SAR) of the Harmon lignite to the position of channel sands in the overlying Bullion Creek strata. (From Houghton and others, 1984, fig. 16.)

3.0 GROUND-WATER HYDROLOGY

3.1 HYDROLOGIC REGIME

FIVE REGIONAL AQUIFERS IDENTIFIED

The principal shallow local aquifers in the Gascoyne area are the Harmon lignite and the underlying Slope-lower Bullion Creek sandstone.

Five regional aquifers were identified by (7) in Bowman and Adams Counties. Only aquifers of the Slope-Bullion Creek aquifer system are being directly disrupted by surface-mine activities. Correlation of aquifers to geologic formations is shown in figure 3.1-1. In the Gascoyne area, the Slope-Bullion Creek aquifer system consists of the Harmon lignite aquifer and the underlying Slope-lower Bullion Creek sandstone aquifer. Well data indicate that the claystone below the Harmon lignite is a confining layer over the Slope-lower Bullion Creek sandstone aquifer in the northern one-half of the Gascoyne area. However, the same aquifer is unconfined in the southern one-half of the area (fig. 3.1-1). Along the lignite outcrop line, water levels in wells completed in the Slope-lower Bullion Creek sandstone aquifer are both above and below the claystone confining layer. Both aquifers are locally important sources for domestic and livestock wells yielding small quantities of water. The only large-yield wells in the aquifers in the Gascoyne area were installed by the mine for dewatering purposes.

The lignite aquifer is recharged principally by local precipitation. Potential evaporation demand exceeds precipitation during most of the year and most infiltration from precipitation is lost within the root zone. Only the precipitation from major events percolates below the root zone, and even then percolating water may take 10 to 30 years to reach the water table. Accordingly, most recharge is confined to a few zones with relatively large hydraulic conductivities, such as the sandstones of the Sentinel Butte Formation north of the mine, channel sands within the Bullion Creek Formation that are exposed to the surface, lignite exposed during mining operations, and scoria zones (baked sediment formed by burning of underlying lignite). Outcrops of lignite are commonly encrusted with secondary sulfate minerals generated from the oxidation of iron-sulfide minerals. Recharge through these outcrops is mineralized by dissolution of the salts and is retarded owing to pore closure by the salts. Results from infiltrometer tests, observation-well water-level analysis, and flow modeling indicate that average annual recharge ranges from 0.04 to 0.4 inch. The lignite aquifer discharges through fractures in its underclay mainly to the underlying Slope-lower Bullion Creek sandstone aquifer and to tributaries of Buffalo Creek.

The Slope-lower Bullion Creek sandstone aquifer is about 450 feet thick and includes many lignite and silty clay seams. Where unconfined, the sandstone aquifer is recharged directly by precipitation; where confined, it is recharged by leakage from the overlying lignite. Average annual recharge is estimated to range from 0.15 inches where the aquifer is confined to 2 inches in unconfined zones of large hydraulic conductivity. The base of the sandstone aquifer generally is defined by claystone seams in the upper Slope Formation. Locally, the Slope-lower Bullion Creek sandstone aquifer discharges principally to Buffalo Creek and its tributaries south of the mine according to potentiometric-head data. However, regional discharge is primarily to the northeast by leakage to underlying aquifers.

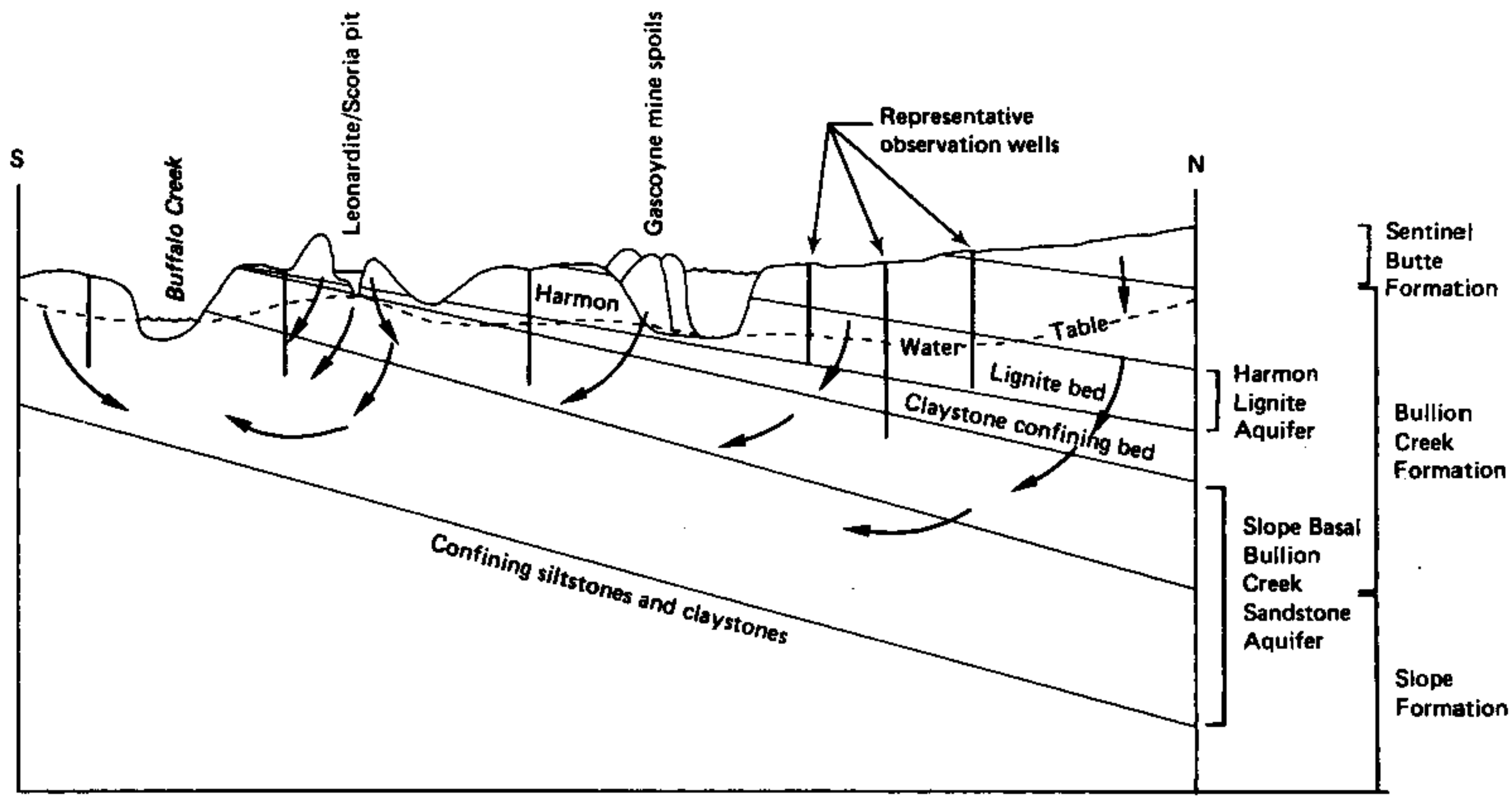

Figure 3.1-1.— Generalized hydrogeologic section showing correlation of aquifers with geologic formations. Arrows show general directions of ground-water flow. (From Houghton and others, 1984, fig. 7.)

3.0 GROUND-WATER HYDROLOGY

3.2 HYDROLOGIC-DATA NETWORK

GROUND WATER OF PRIMARY CONCERN

The hydrologic-data network consisted of wells for water-level measurements and of streamflow-gaging stations for base-flow discharge, and water-quality analyses for both ground water and surface water.

An extensive hydrologic-data network was necessary to permit data collection and development of hydrologic-flow and solute-transport models near the Gascoyne mine. The data network included: 546 test holes and core holes that were geophysically logged to determine lithologic and geochemical variations in overburden and aquifer materials, 44 lysimeters to sample overburden pore waters, and 4 clusters of gas probes to sample free gases in the unsaturated overburden (fig. 3.2-1). Observation wells were completed in 114 of the test and core holes. Only finely screened (less than 0.008-inch slot) wells packed with 9-12 mesh silica sand and sealed at a relatively confining bed with low-sodium cement or plastic packers (fig. 3.2-2) were found to produce water in the finer grained materials and yield relatively unaltered samples for water-quality determinations. All water-quality samples were obtained with teflon or polyethylene air-squeeze or gas-reciprocating pumps to minimize sample contamination and were preserved in the field as prescribed in (3,29) to limit sample alteration prior to analysis.

From this network of wells, the mining company selected about 30 wells in which to measure water levels and to collect semiannual water samples for the life of the mine. Well sites were chosen so that their geographic distribution would permit preparation of reliable potentiometric-surface maps. Most sites have dual wells, one in the lignite aquifer and one in the sandstone aquifer. Wells in the network which were destroyed by mining were reinstalled in or beneath the mine spoils at the same location.

Ground-water contributions to tributaries of Buffalo Creek are measured at two streamflow-gaging stations located upstream and downstream from the mine (fig. 3.2-1). Water quality at these sites is determined every 6 weeks during periods of flow.

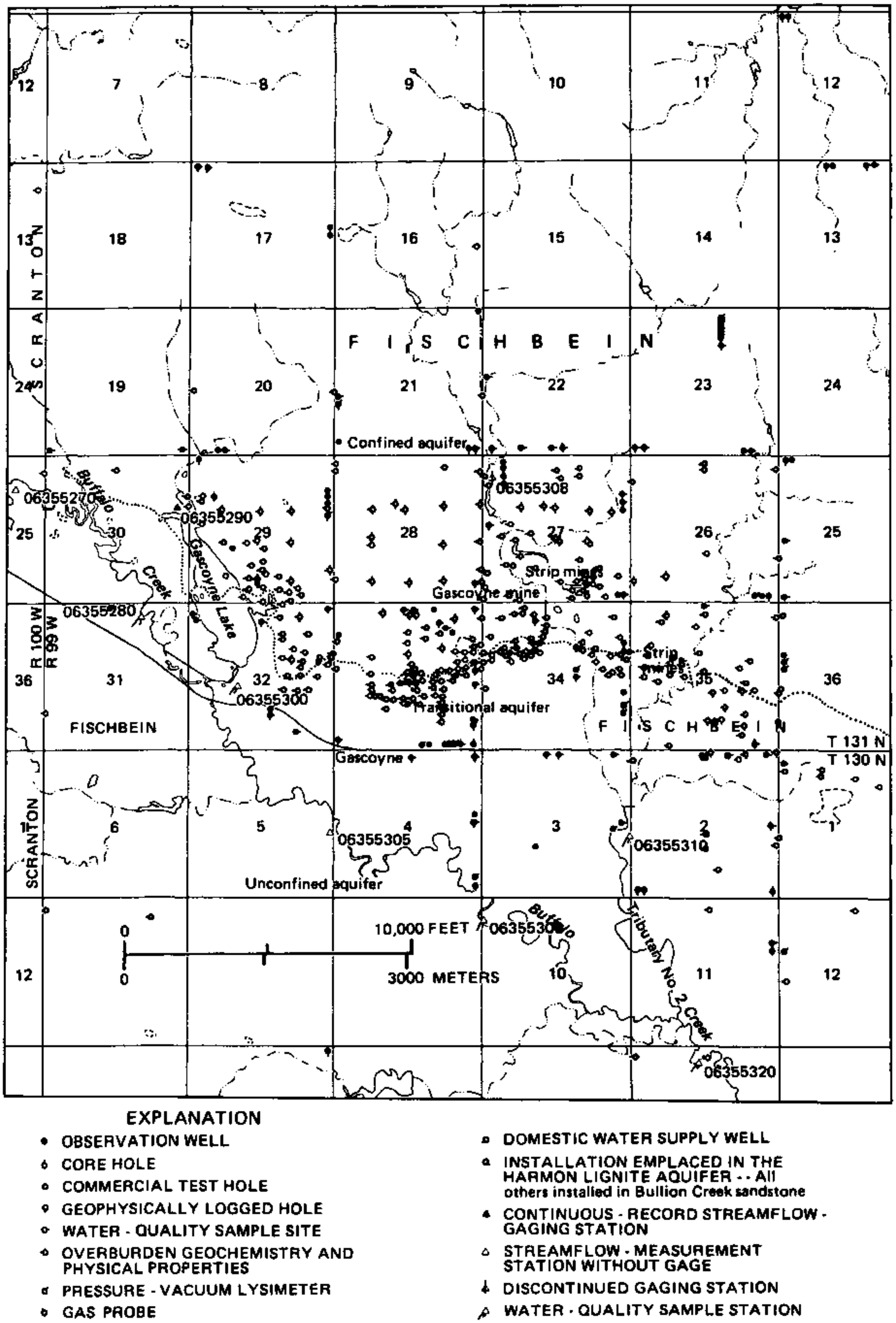

Figure 3.2-1.— Hydrologic data network.
(In part from Boughton and others, 1984, fig. 27.)

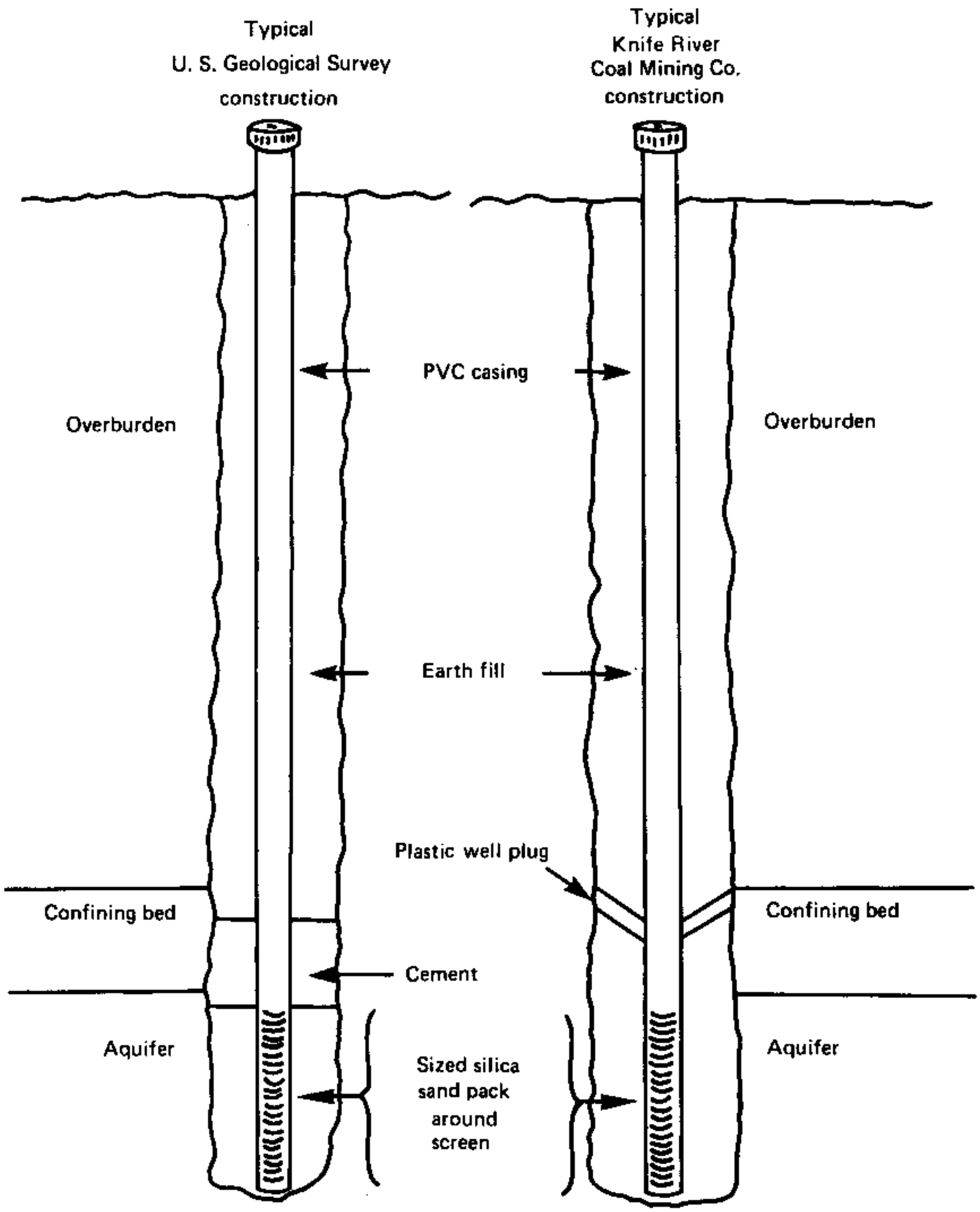

Figure 3.2-2.— Water-quality well designs used in area.

3.0 GROUND-WATER HYDROLOGY

3.3 HYDRAULIC PROPERTIES

HYDRAULIC PROPERTIES NEEDED TO ASSESS PROBABLE HYDROLOGIC CONSEQUENCES OF MINING LIGNITE

The hydraulic properties of each aquifer reflect depositional environment and mine activities.

The hydraulic conductivity, storage coefficient, and transmissivity of the lignite and sandstone aquifers and the confining claystone and siltstone must be known to determine ground-water flow patterns and rates and to evaluate the probable hydrologic consequences of surface mining on ground-water systems. Hydraulic properties for each of these materials in the Northern Great Plains differ widely, because local ground-water flow is controlled by joints and fractures. However, all three hydraulic properties may be determined by specifically designed aquifer tests. Mine production wells and observation wells have usually been adequate for this purpose.

In the Gascoyne area, aquifer tests were conducted at two wells completed in silty sandstones of the Slope-lower Bullion Creek sandstone aquifer. The tests indicated that hydraulic conductivities range from 2.5 to 10 ft/d, storage coefficients are 0.0004 where the aquifer was confined and 0.2 where unconfined, specific capacities range from 0.1 to 0.7 (gal/min)/ft, and computed transmissivities range from 260 to 2,100 gal/d/ft. (35 to 280 ft^2/d). Average hydraulic conductivities of the sandstone aquifer calculated from electric-log curves (6) ranged from 2 to 8 ft/d; these values indicate that geophysical logs collected during mine test drilling may be used to extend the data obtained by other methods and to minimize the necessity for expensive aquifer tests. Results from laboratory tests and field slug tests (5) of hydraulic conductivity, however, indicate that these properties are more variable than determined by the electric-log method. Figure 3.3-1 shows a complex hydraulic conductivity distribution that was used to calibrate a two-dimensional steady-state flow model (31) of the sandstone aquifer. The distribution is based on laboratory determinations. Hydraulic conductivity in the sandstone aquifer ranges from 1.5 to 390 ft/d according to the model results, and the largest hydraulic conductivities form a dendritic pattern corresponding to channel-sand deposits. Smaller hydraulic conductivities characterize levee and overbank siltstones. Hydraulic conductivities calculated from electric logs are in general agreement with this pattern.

Hydraulic-conductivity distributions of the lignite aquifer also indicate a dendritic pattern, which probably reflects fracturing of the lignite beneath saturated sandstones in the overburden. Hydraulic conductivity in the lignite ranges from 1 to about 250 ft/d; an anisotropy is clustered around fracture orientations of about N. 45˚W and N. 58˚E. Additional areas of large conductivity that radiate from active mine pits indicate fracturing of the lignite by mine blasting. The decrease of hydraulic conductivities in both aquifers with depth indicate decreasing fracturing.

Field measurement of the hydraulic conductivity of the claystone confining the sandstone aquifer has not been feasible. Laboratory estimates range from 10^{-6} to 10^{-8} ft/d. Estimates of recharge to the confined sandstone aquifer suggest that larger mean hydraulic-conductivity values for the claystone are the result of fracturing.

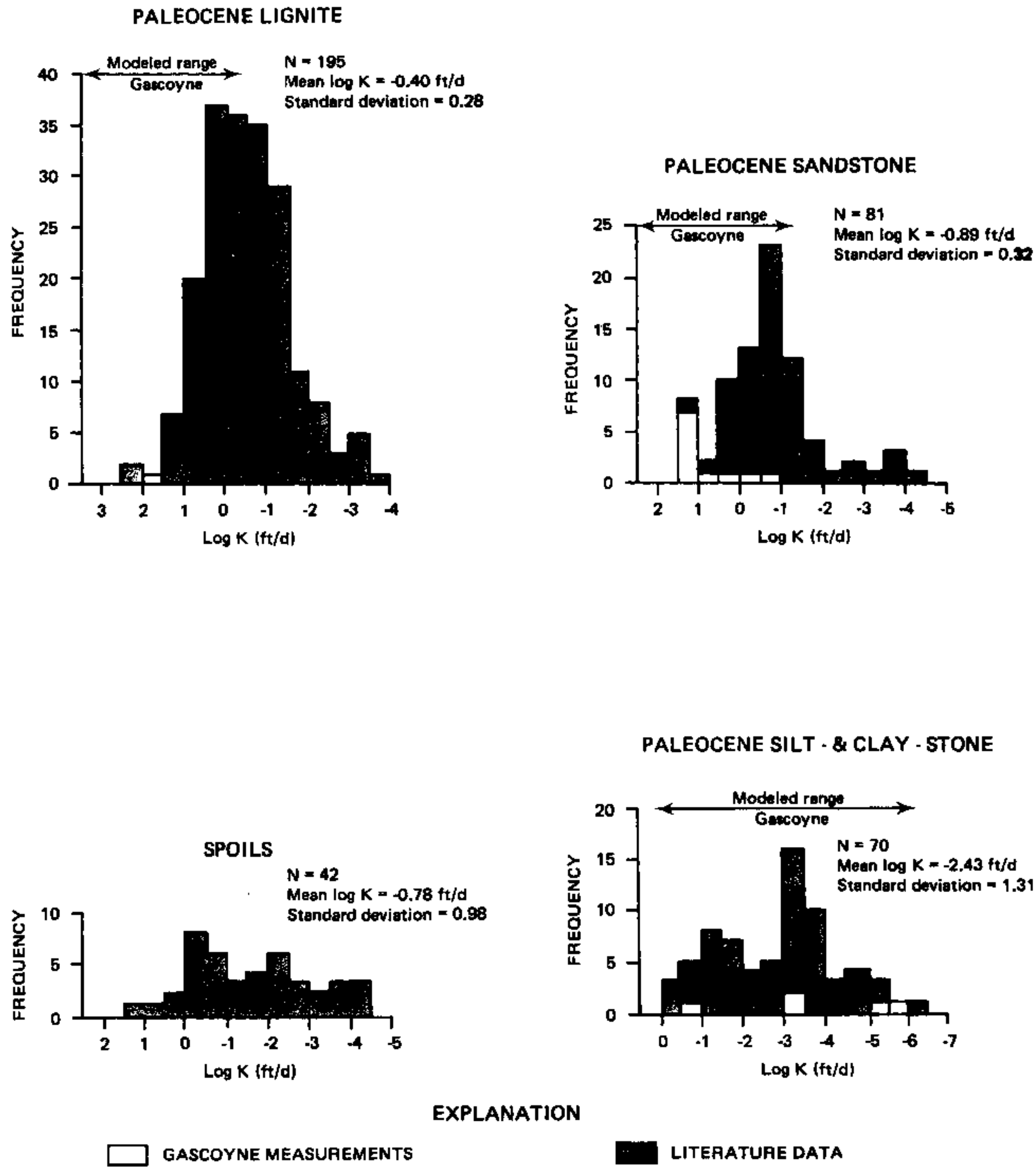

Figure 3.3-1.— Histograms of laboratory determined hydraulic conductivity (K) from the Northern Great Plains.
(Modified after Rehm and others, 1980.)

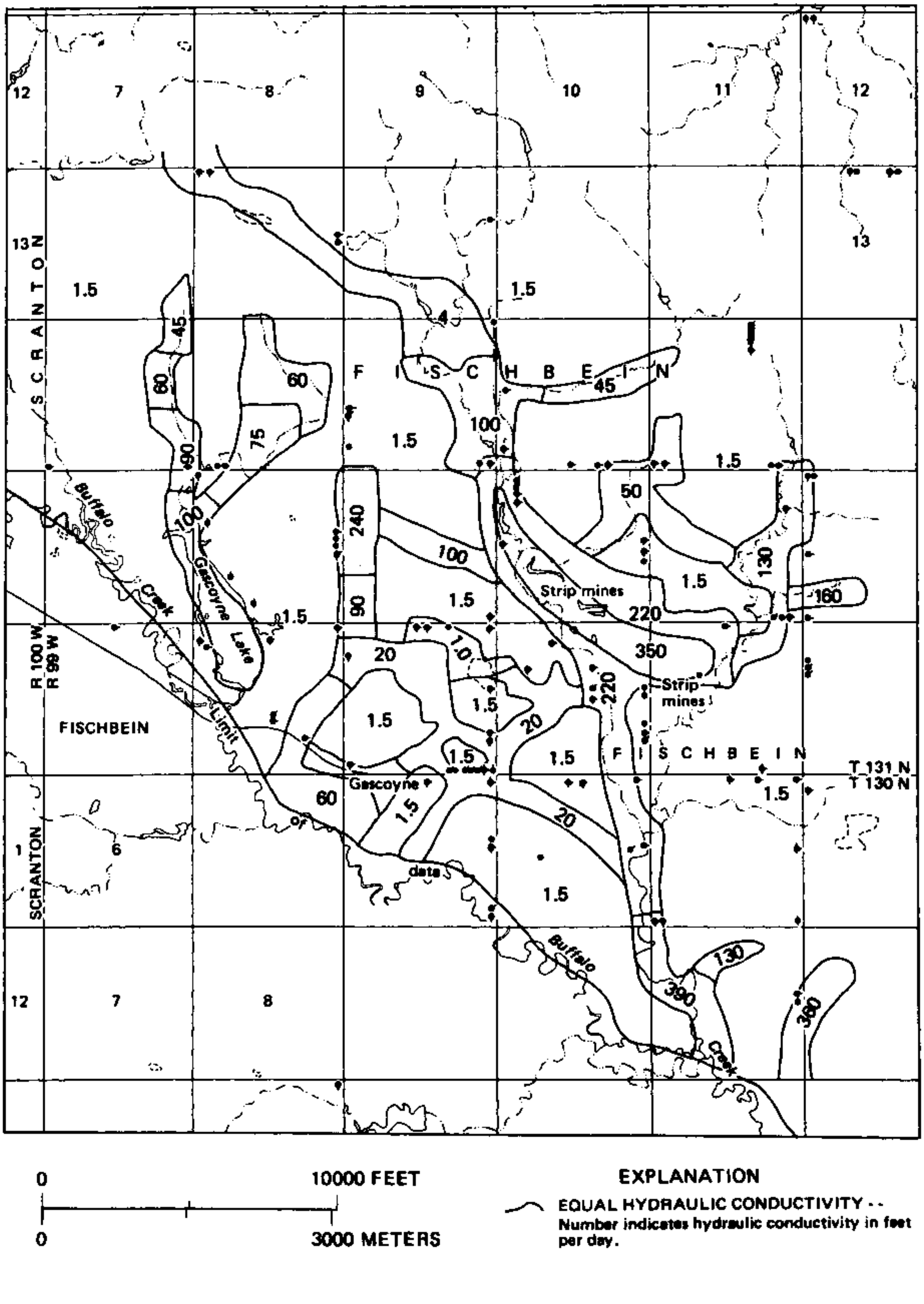

Figure 3.3-2.— Areal distribution of hydraulic conductivity of the basal sandstone of the Bullion Creek Formation.
(From Houghton and others, 1984, fig. 24.)

3.0 GROUND-WATER HYDROLOGY

3.4 POTENTIOMETRIC SURFACES

DEPRESSION OF POTENTIOMETRIC SURFACES BENEATH MINE CAUSED BY DEWATERING.

The potentiometric surfaces of the aquifers reflects variations in lithology and the location of surface-water discharges. Mine dewatering has locally caused ground-water flow reversals where the sandstone aquifer recharges the overlying lignite aquifer in the center of the potentiometric cone of depression.

The potentiometric surface of the Harmon lignite aquifer slopes south toward Buffalo Creek (fig. 3.4-1). Three major southeast-trending lobes persist in the potentiometric surface along the northern border of the mine. Because the potentiometric ridges may be related to sand-channel trends in the overlying Bullion Creek strata, recharge in these areas may be greater. Troughs in the potentiometric surface reflect the generally smaller hydraulic conductivities of interchannel silts and clays as well as seepage from the Harmon to tributaries of Buffalo Creek, The general pattern of the potentiometric surface changed little during the 8 years of the investigation. Water levels fluctuated no more than 3 feet seasonally in response to variations in annual precipitation. The dampened response of water levels to precipitation indicates that infiltrating water may require considerable time to reach the water table.

The potentiometric surface of the Slope-lower Bullion Creek sandstone aquifer is shown in figure 3.4-2. The effects of mine dewatering on recharge of the sandstone aquifer are reflected in a troughlike depression in the potentiometric surface beneath and downgradient from the mine. Deflections of the potentiometric surface from the generally northeasterly regional trend reflect local topography and variations in surface permeabilities that affect the amount of recharge.

In unmined parts of the Gascoyne area, potentiometric heads in the lignite are higher than those in the underlying sandstone aquifer, and the lignite aquifer recharges the sandstone. However, near the mine, the potentiometric head in the sandstone locally may be higher than that in the lignite, reversing the direction of leakage. Two large troughs in the potentiometric surface of the sandstone aquifer have developed beneath the two most active mine pits, where discharge from the sandstone aquifer to the pit is being pumped into surface holding ponds. As pre-mining hydrologic conditions at Gascoyne are not well known, the total effect of mine dewatering activities on the potentiometric surfaces of these aquifers cannot be assessed precisely. However, extension of the regional potentiometric surface for the Slope-lower Bullion Creek Sandstone aquifer through the Gascoyne area indicates that the present cone of depression in the potentiometric surface of the sandstone aquifer due to mine dewatering and aquifer disruption locally may be as much as 65 feet and extend as far as 3 miles beyond the mine perimeter.

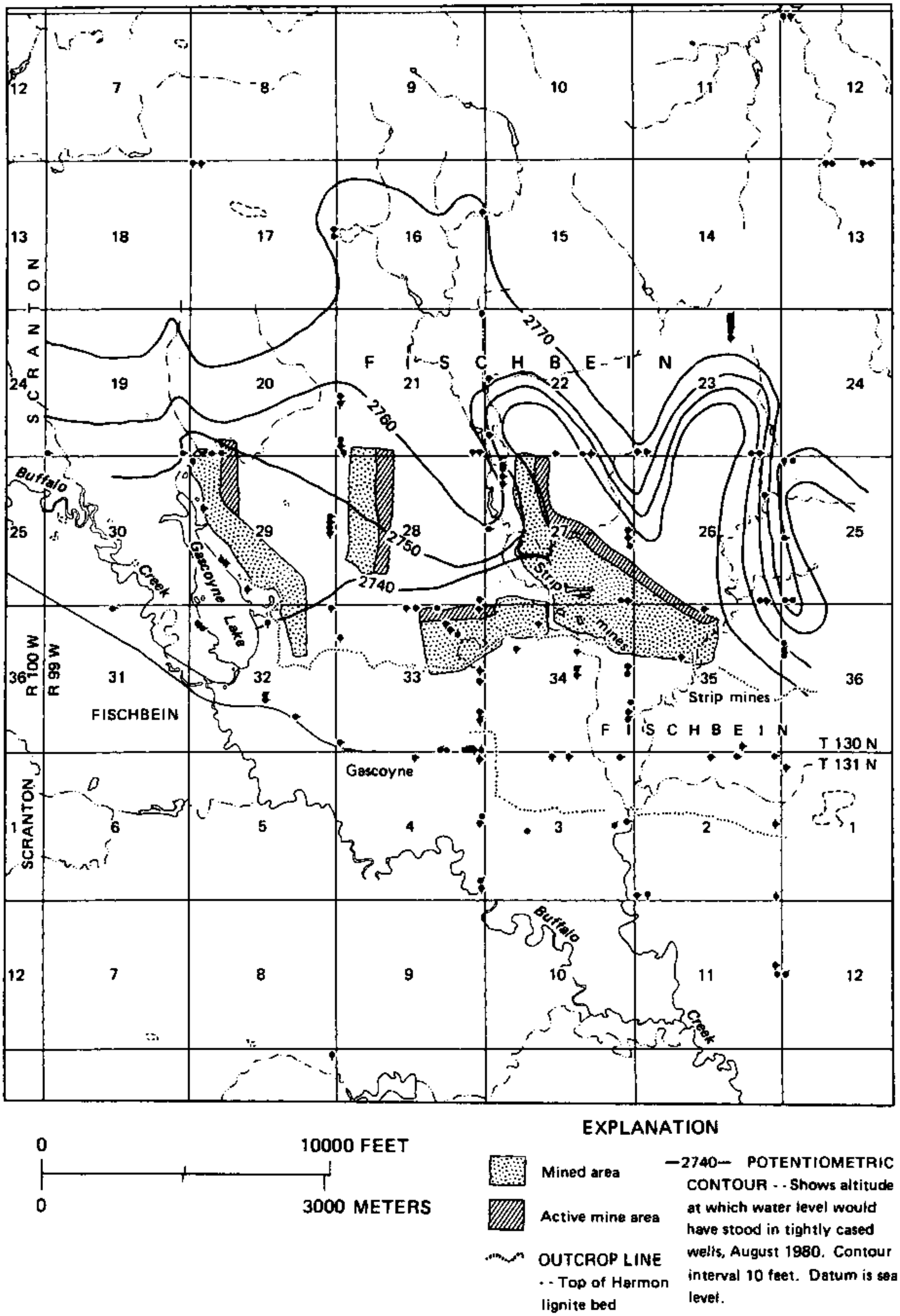

Figure 3.4-1.— Potentiometric map of the Harmon lignite aquifer. (From Houghton and others, 1984, fig. 18.)

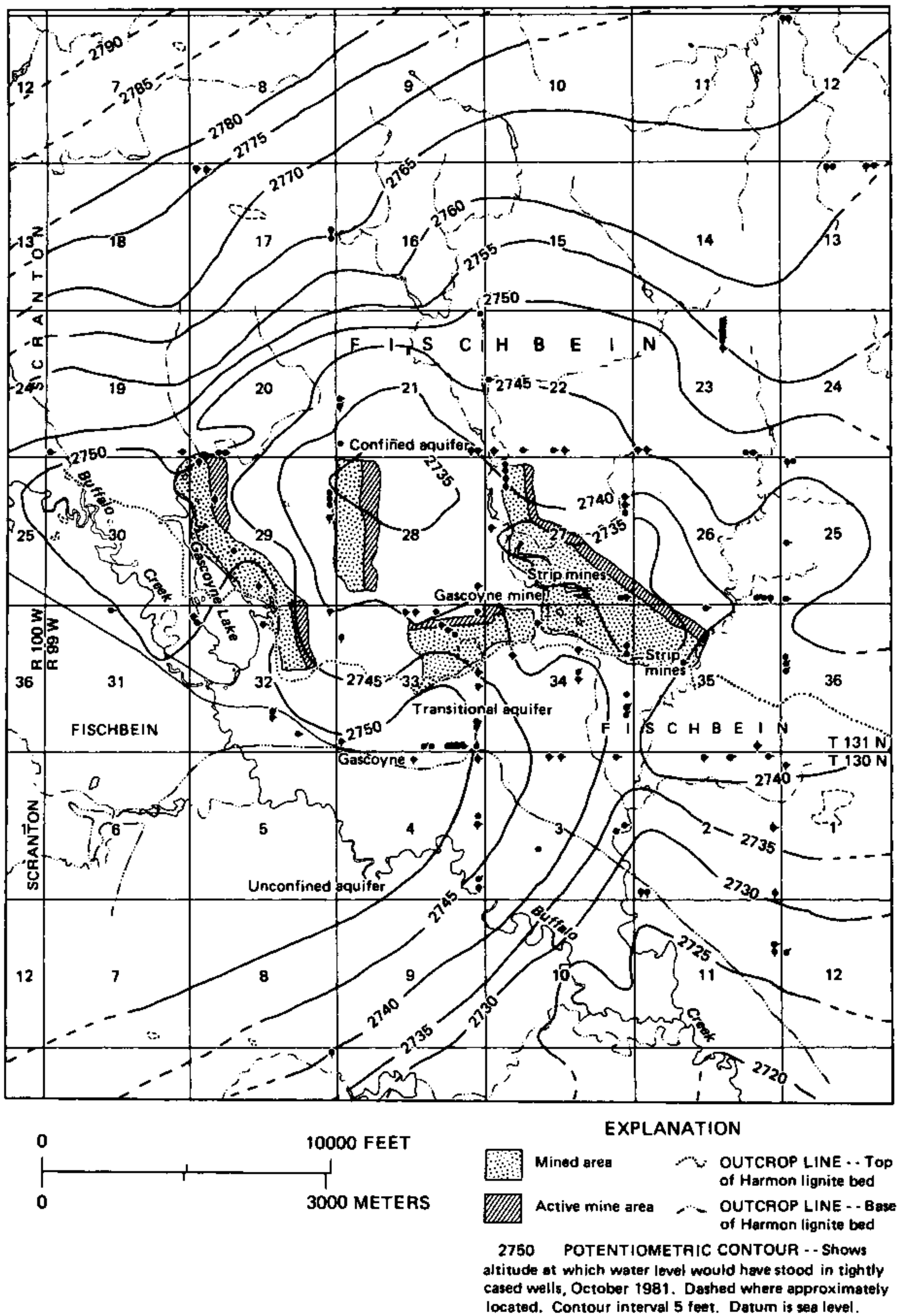

Figure 3.4-2.— Potentiometric map of the Slope-basal Bullion Creek sandstone aquifer. (From Houghton and others, 1984, fig. 25.)

3.0 GROUND-WATER HYDROLOGY

3.5 GROUND-WATER QUALITY

THE LARGEST CHEMICAL CHANGES TO GROUND WATER OCCUR DURING INFILTRATION OF RAIN OR SNOWMELT

Principal ions in water in the lignite and sandstone aquifers are sodium, sulfate, and bicarbonate. Chemical reactions in the unsaturated zone cause the largest changes along the natural ground-water flow path.

Water in the lignite and sandstone aquifers is predominantly a sodium sulfate or sodium sulfate-bicarbonate type (fig. 3.5-1). In general, the sandstone aquifer has larger dissolved-solids concentrations than the lignite aquifer. However, the waters having the largest dissolved solids occur in the lignite aquifer in a narrow band adjacent to its outcrop line. Dissolved-solids concentrations in both aquifers are smallest beneath outcrops of channel sandstones. All the waters analyzed were nontoxic except those within the channel sandstones. Dissolved-sulfide concentrations were small and no methane was detected. Waters in both aquifers generally are slightly saturated with respect to quartz and slightly undersaturated with respect to calcite, dolomite, and gypsum. Waters in the sandstone aquifer are commonly highly colored with organic compounds derived from the lignite. Locally, major seasonal and year-to-year changes in ground-water composition may reflect changes in the quantity and path of percolating water.

As precipitation is the principal source of recharge to the shallow aquifers in the Gascoyne area, the largest chemical changes to ground water occur during infiltration of rain or snowmelt and percolation through the unsaturated zone. Subsequent alteration of water quality within the saturated zone is relatively minor. Laboratory experiments, field observations, and geochemical modeling indicate shallow ground-water quality in the area is controlled mainly by the nine processes detailed in figure 3.5-2. Reaction-path (24) and mass-balance modeling supported by isotopic data indicate organic compounds locally may affect some of the reduction-oxidation reactions. Sulfate concentrations are controlled principally by dissolution of gypsum. In equilibrium, gypsum dissolution should generate sulfate concentrations of no more than about 1,240 mg/L. However, if a sink for calcium is present, such as clay minerals or organic materials having large cation exchange/adsorption capacity, larger sulfate concentrations may occur. Exposure of lignitic compounds, clay minerals, and gypsum, produced by oxidation of iron sulfide minerals, to infiltrating solutions along the lignite outcrop line permits sulfate concentrations in the shallow aquifers to approach 8,000 mg/L locally. Exchange of calcium and magnesium for sodium on sodic clay minerals and lignites generates the observed sodium-sulfate type water. The amount of gypsum present in and just below the root zone exceeds that which would be generated from the available sulfur sources in the Bullion Creek strata. This gypsum accumulated over geologic time as erosion of overlying strata exposed sulfur sources, such as iron sulfide minerals, to the oxidizing environment.

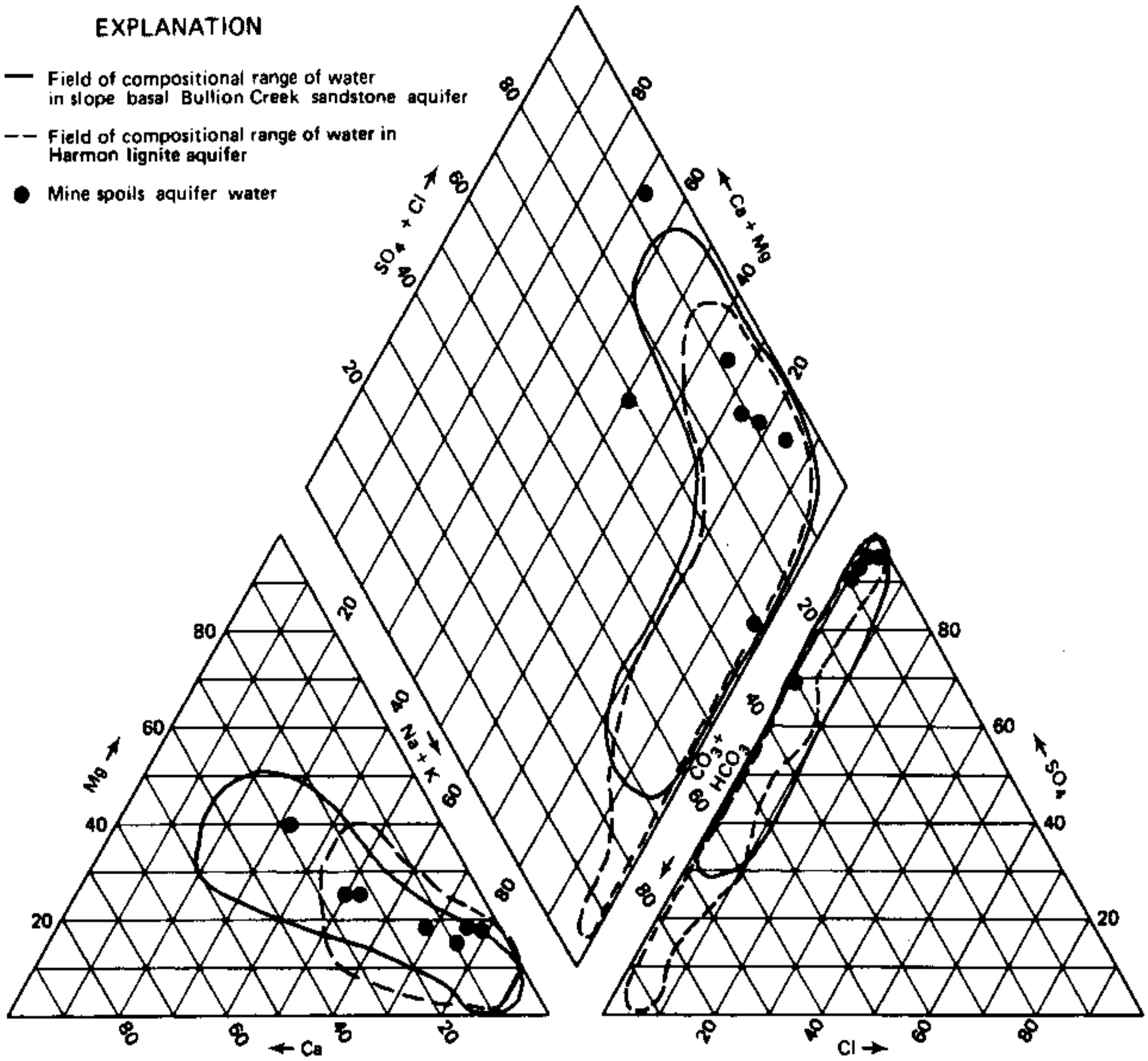

Figure 3.5-1.— Piper diagram of the relationship of major constituents in the mine spoils to the shallow aquifers of the Gascoyne area. (From Houghton and others, 1984, fig. 45.)

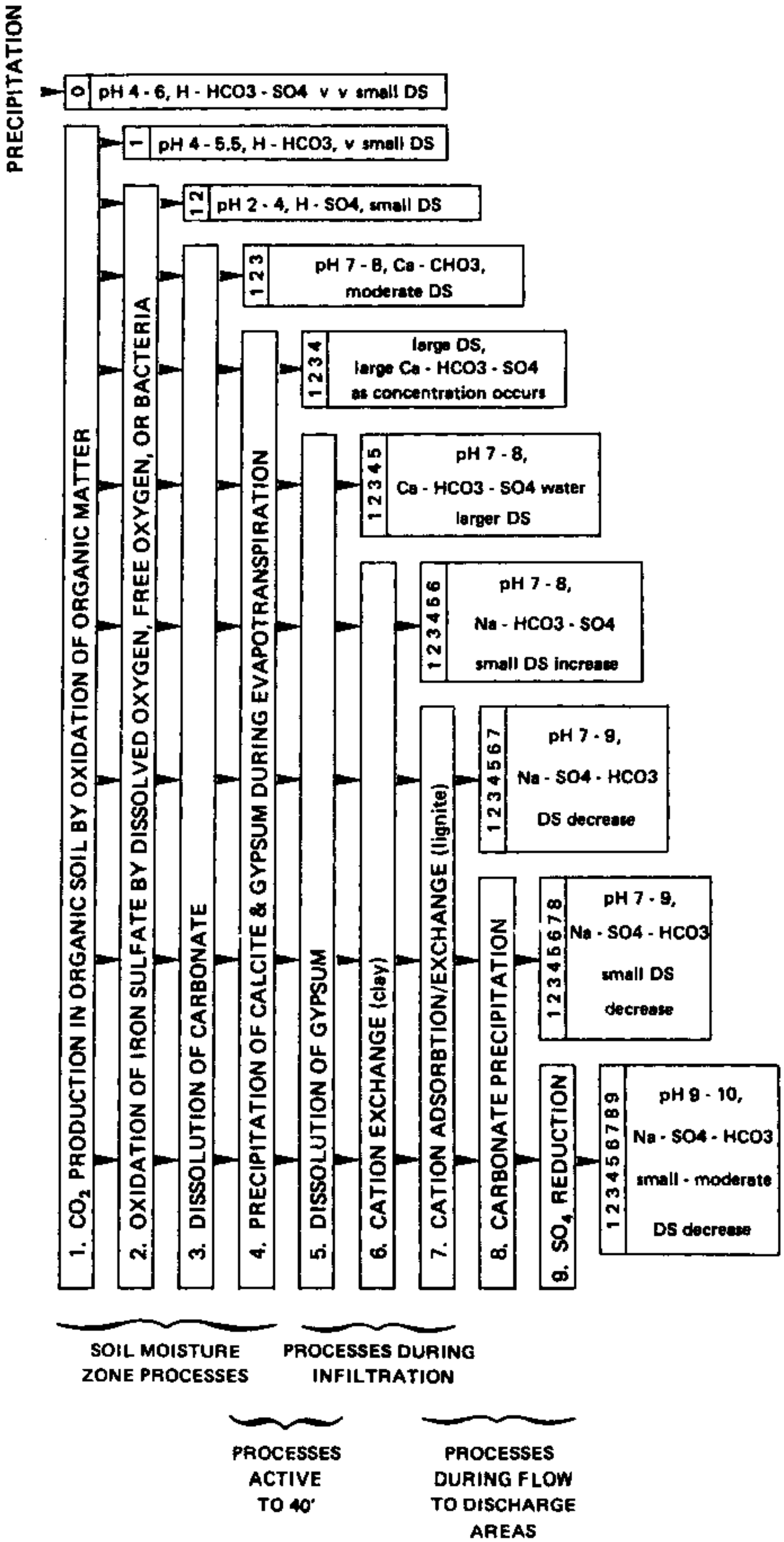

Figure 3.5-2.— Relationships between major geochemical processes and water chemistry in the Gascoyne area.
(Modified from Moran, Groenewold, and Cherry, 1978.)

4.0 HYDROLOGIC CONSEQUENCES

4.1 QUANTITY AND AVAILABILITY OF POST-MINING SHALLOW GROUND WATER

MINE DEWATERING HAS PRODUCED A LARGE CONE OF DEPRESSION WHICH WILL PROBABLY RECOVER 1 TO 3 YEARS AFTER RECLAMATION

As mining in the Gascoyne area disrupts the aquifer recharge area, a decrease in the infiltration potential of surficial materials may be expected to cause post-mining water levels to decline both locally and farther downgradient.

Mine dewatering has lowered water levels continuously in the lignite and sandstone aquifers, thereby producing large potentiometric cones of depression below the mine. Although water levels rebound rapidly when dewatering ceases, the decreased hydraulic conductivities of mine spoils relative to undisturbed overburden imply that mining of this recharge zone may have long-lasting consequences for water levels in these shallow aquifers.

Between 1976 and 1980, water levels in the Harmon lignite in the vicinity of the mine (such as that in well 131-099-19DDD) declined about 2 ft/yr (fig. 4.1-1); however, since 1980 water levels in the lignite appear to have stabilized. Water levels in wells more than 3 miles from active mine pits seemed to be nearly unchanged between 1976 and 1980. Pumping to dewater the lignite at the mine currently exceeds 1,000 gal/min and is believed to be the principal cause of observed water-level decline. Temporary cessation of pumping by mine sumps (point A, fig. 4.1-1) locally resulted in a 1-month 25-foot rise in the water level in the lignite. Water levels in the Slope-lower Bullion Creek sandstone aquifer (such as in wells 131-099-22CCB and 131-099-29BBB) have declined about 1.5 ft/yr since 1978, a rate which may continue for the life of the mine.

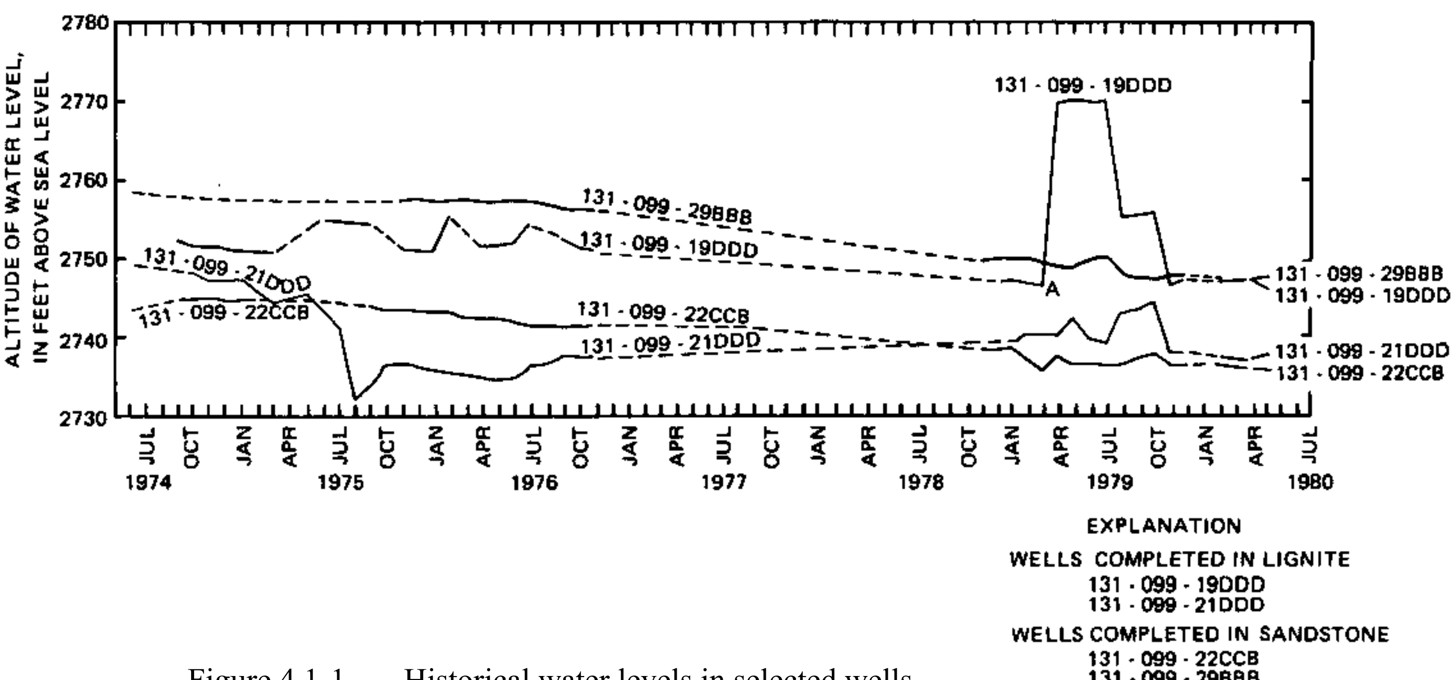

Figure 4.1-1.— Historical water levels in selected wells. (From Houghton and others, 1984, fig. 21.)

Rubble zones at the base of the recontoured spoils are resaturated by lateral flow from the unmined lignite aquifer. Within 3 years, water levels probably will return to pre-mining levels. However, gradual compaction of the spoils may reduce its water-bearing capacity with time (13). The mining process by homogenizing much of the stripped overburden eliminates former zones of larger higher hydraulic conductivity, such as channel sandstones, by mixing them with sediments of lesser hydraulic conductivity, such as overbank siltstones. Young mine spoils from a single site generally have hydraulic conductivities ranging about one order of magnitude. Compaction of the spoils with time may reduce this range even further. Infiltrometer measurements in spoils replacing channel fill differ little from those in spoils replacing overbank silts (fig. 4.1-2). Infiltration rates change rapidly during the first year after reclamation owing to

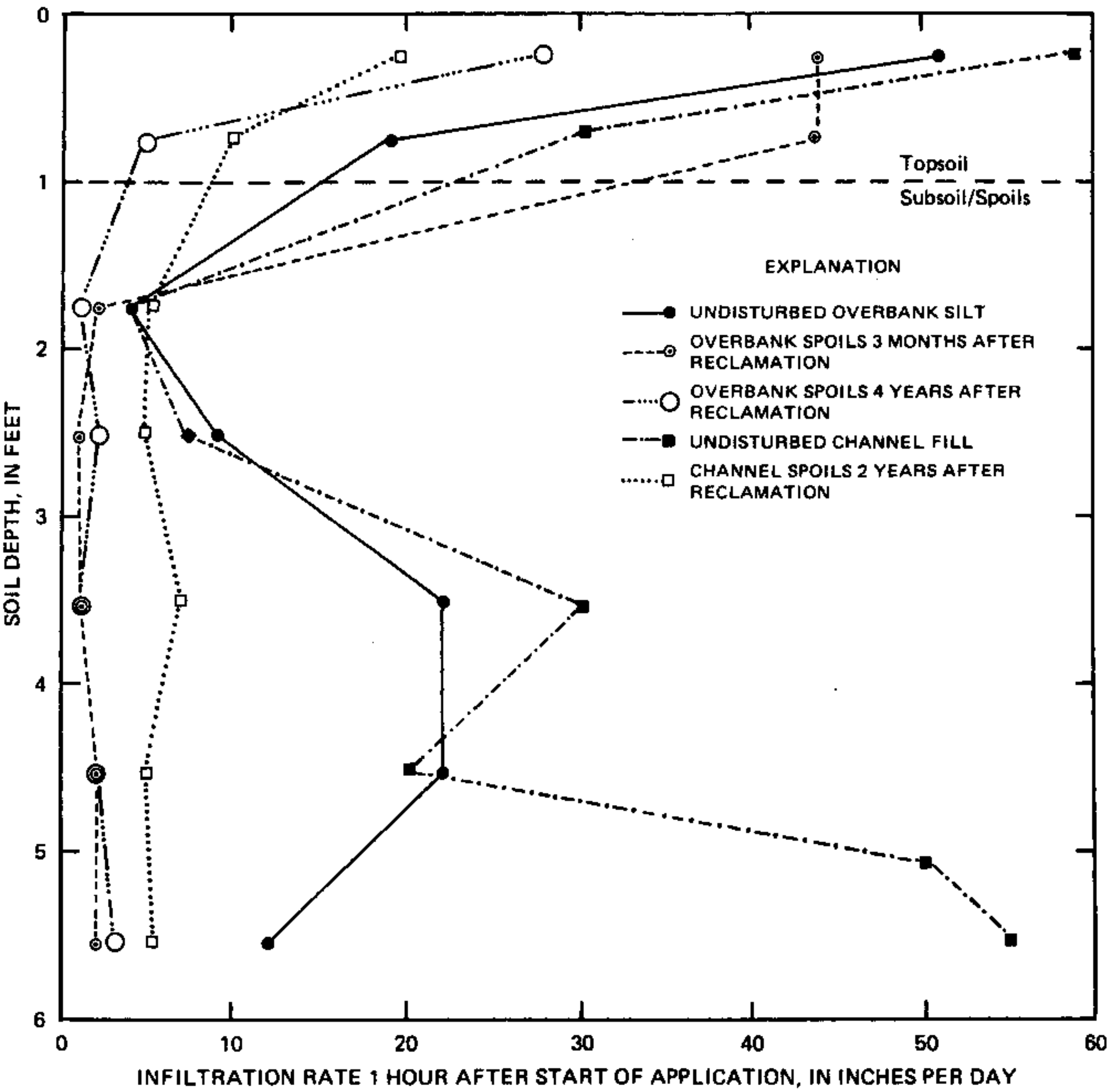

Figure 4.1-2.— Infiltration rate measured by infiltrometer on soil and mine spoils in relation to depth in soil system.

compaction, but the change is slower thereafter. As mining in the Gascoyne area disrupts the aquifer recharge area, reduction in the infiltration potential of surficial materials may be expected to cause post-mining water levels to decline both locally and farther downgradient.

As the spoils aquifer will have significantly less storage and permeability than the lignite aquifer it replaces, alternative water supplies may have to be developed for local domestic and livestock use. The Slope-lower Bullion Creek aquifer generally will be adequate for a limited need, but wells will cost more because this aquifer is deeper than the lignite aquifer. If larger volumes of water are required, the Fox Hills-lower Hell Creek aquifer contains abundant water below the Fort Union strata. However, this deep water commonly contains fluoride concentrations in excess of the drinking-water standard established by the U.S. Environmental Protection Agency (32).

Because water is used to replenish ground-water levels, base flow to Buffalo Creek tributaries has slightly decreased. However, these tributaries have no current use downstream from the mine, so this impact is considered noncritical.

4.0 HYDROLOGIC CONSEQUENCES

4.2 QUALITY OF POST-MINING SHALLOW GROUND WATER

SELECTIVE PLACEMENT OF SPOILS MATERIAL CRITICAL TO MINIMIZING POTENTIAL WATER-QUALITY PROBLEMS

Selective placement of organic- and clay-rich material below the water table and mineral rich, near-surface overburden above the water table may limit significant degradation of post-mining shallow ground-water quality.

Oxidation of iron sulfide minerals exposed during mining and dissolution of resultant sulfate minerals may significantly degrade post-mining ground water. Additional sulfate concentrations may result if near-surface, mineral rich overburden is placed below the water table. Dissolved-solids concentrations in the Harmon lignite aquifer re-established in the rubble zone at the base of the spoils may increase if any of the geochemical processes outlined in figure 3.5-2 are accelerated during mining or reclamation activities. Oxidation of iron sulfide minerals (usually framboidal and micro-crystalline forms of pyrite and marcasite) to sulfate minerals or compounds proceeds to completion during overburden removal and before reclamation begins. Dissolution of these sulfide minerals is the principal source of solutes to the spoils aquifer and significantly enriches the sulfate content adjacent to some mine pits (fig. 4.2-1). However, as natural waters percolating below the root zone are already near saturation with respect to gypsum, increased ground-water solute concentrations in mine waters can result only where sulfate solubilities are increased by complementary reactions removing calcium. Where spoils material is devoid of relict lignite or carbonaceous clays, which remove calcium by cation exchange and adsorption, sulfate concentrations in mine ground waters are not significantly enriched. Larger solute concentrations can result if near-surface overburden enriched in sulfate minerals through geologic time is emplaced below the water table during mining.

Leakage from the spoils/lignite aquifer through the remaining underclay to the sandstone aquifer results in deterioration of water quality in the sandstone aquifer. Selective placement of organic- and clay-rich materials below the water table and mineral-rich, near-surface overburden above the water table may limit significant degradation of post-mining shallow ground-water quality. Increased overburden handling could be accomplished with minimal delays for about 1.1 to 1.5 times normal operating costs (9). If organic-rich material is emplaced in the oxidizing zone (generally the upper 2 to 5 feet at Gascoyne), infiltrating waters are also enriched in trace metals like boron, lithium, lead, and zinc, similar to waters along the lignite outcrop line.

Cation-exchange reactions have depleted sodium in near-surface overburden relative to the rocks at depth. Surface spoils tend to be enriched in sodium by a factor of 2 to 3 over undisturbed rocks, indicating an increased exchange potential. Waters infiltrating surficial spoils are enriched in sodium by exchange. Cycling of the unsaturated spoils waters through the overlying top-soils by evapotranspiration and capillary attraction increases the sodium-adsorption ratio of mine soil waters (fig.4.2-2), which would significantly limit use of the land for some

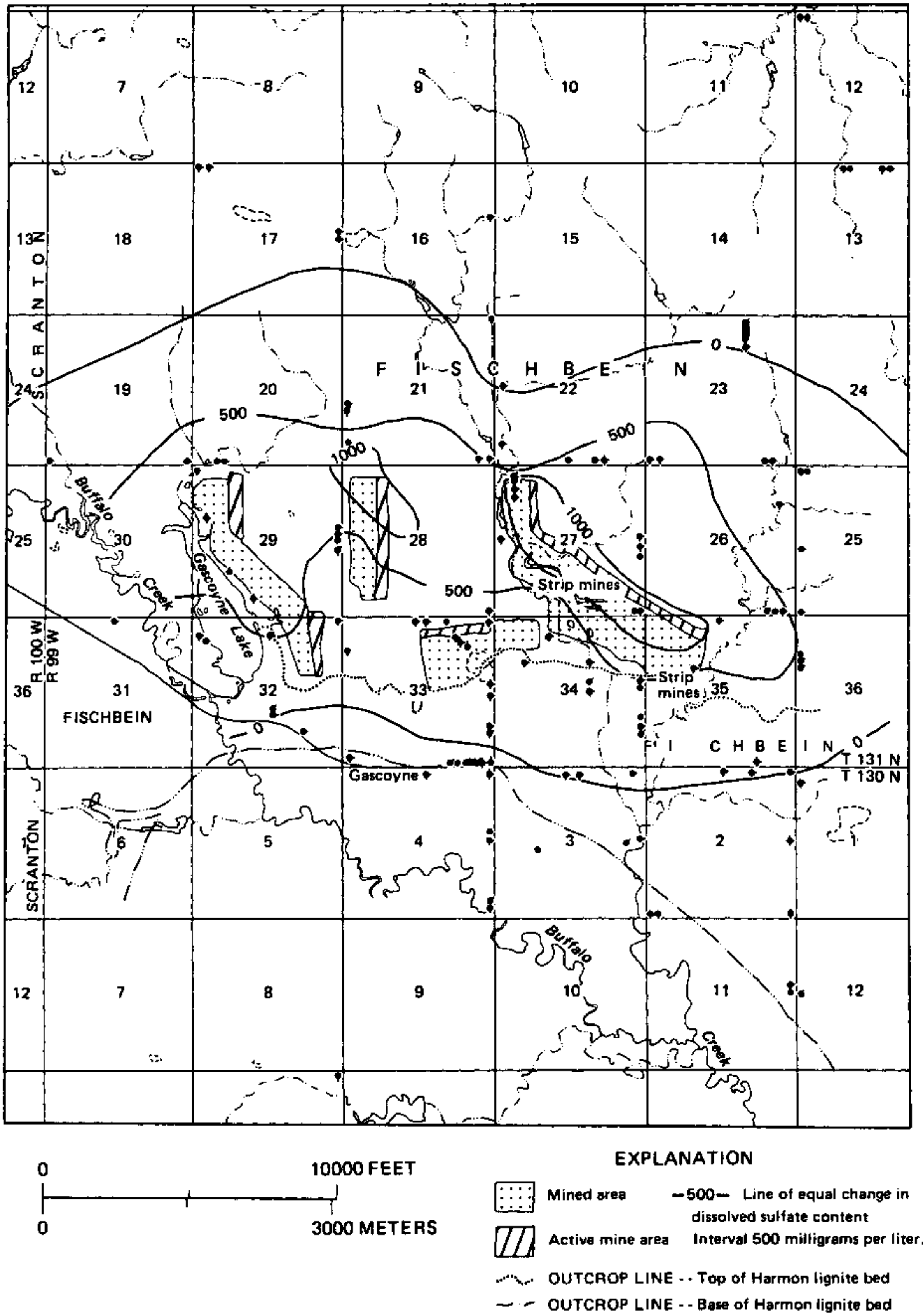

Figure 4.2-1.— Change in dissolved-sulfate concentrations in the Harmon lignite/spoils aquifer, 1976-81.
(Modified from Houghton and others, 1984, fig. 41.)

types of agriculture (19). Standard reclamation methods to reduce the sodium-adsorption ratio in soil water involve application of calcic salts. However, this application only enriches the total sodium-adsorption ratio of water percolating to the water table by making more divalent cations available for exchange with sodium adsorbed on clay minerals and organic materials.

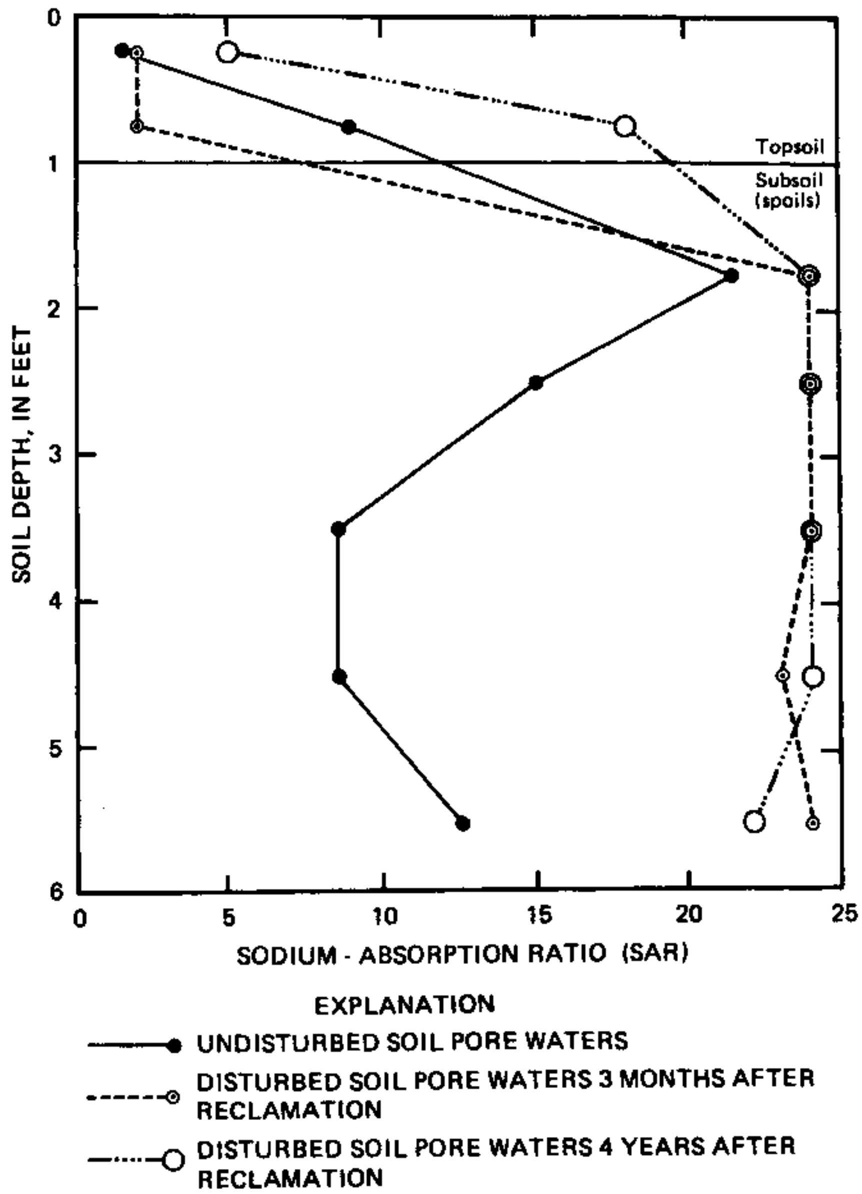

Figure 4.2-2.— Sodium-adsorption ratio of soil waters before and after mine disturbance.

4.0 HYDROLOGIC CONSEQUENCES

4.3 QUALITY OF POST-MINING SURFACE-WATER BASE FLOW

MINE INDUCED DEGRADATION OF GROUND-WATER QUALITY MAY BE REFLECTED IN STREAMS DURING PERIODS OF LOW FLOW.

The chemical quality of low flows in tributaries draining the mine will deteriorate roughly proportional to the amount of basin drainage disturbed by mining, but the chemical quality of Buffalo Creek will be essentially unaffected.

Water in the lignite and sandstone aquifers discharges to Buffalo Creek and its tributaries; therefore, any mine-induced degradation in ground-water quality should be reflected in surface-water quality during periods of low flow. In the Gascoyne area, the dissolved-solids concentrations of natural ground water average about 1,605 mg/L, whereas for mine waters the average is 6,330 mg/L. A plot of dissolved-solids concentrations of base flow of a tributary to Buffalo Creek downstream from the mine (station 06355310 in fig. 3.2-1) versus the fraction of drainage basin occupied by mine spoils from 1974 to 1981 closely approximates the line drawn between natural ground water and mine spoils water in figure 4.3-1. This linear relationship is based on data analyzed for a broad range of areas disturbed by mining in nearby basins (21). Assuming all leased land is mined, 32 percent of the basin of Buffalo Creek would be disturbed and the dissolved-solids concentration of base-flow discharge to the tributary can be expected to increase to about 3,000 mg/L. However, any direct discharge of mine waters to the main stem of Buffalo Creek will be diluted substantially.

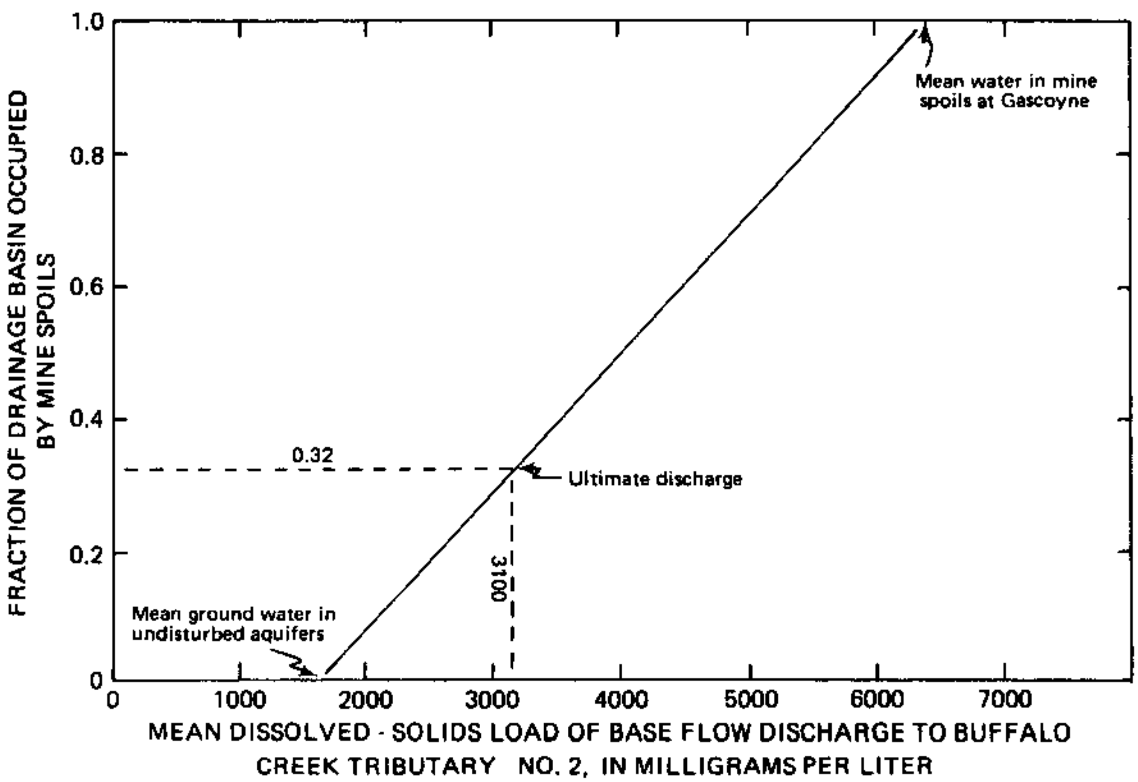

Figure 4.3-1.— Nomograph for determining dissolved solids concentrations of the base flow component of streamflow given the proportion of the drainage basin occupied by mine spoils and the dissolved-solids loads of natural ground water and water in spoils.

5.0 ADDITIONAL LITERATURE RESOURCES

NUMEROUS STUDIES HAVE BEEN MADE OF IMPACTS OF MINING LIGNITE

Procedures employed during this investigation are detailed in technical manuals and are recommended as a means of acquiring the hydrologic data required to meet mining and reclamation regulations.

Details of hydrogeochemical investigations at Gascoyne summarized here are presented in (15). Similar investigations (12, 22, 23) were made around nearby mines in the Sentinel Butte Formation. Procedures utilized for hydrologic aspects of the investigation are summarized in (1). Procedures for geochemical characterization of overburden, spoils, and their waters are described in (28). Methods for successful reclamation of mined land in the Northern Great Plains are summarized in (25, 27). The methods detailed in these technical reports and utilized in this investigation are judged to be appropriate for the acquisition of data to meet mining and reclamation regulations currently established by State and Federal regulatory authorities.

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GROUND-WATER STUDY 10

by

Robert S. Williams, Jr. and Nancy E. Driver

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1.0 ABSTRACT

Geology and the Occurrence of Coal

The Denver Formation, in the Denver basin, contains lignitic coal seams, which are 20 to 60 feet thick. The seams, which are relatively flat, are thickest in the eastern part of the basin.

Hydrology and Hydrologic-Data Collection

The Denver aquifer, part of the Denver Formation, will be affected by the surface mining of the lignite. The transmissivity of the aquifer system ranges from about 50 to 150 ft^2/d. Estimates of the storage coefficient range from 0.014 to 0.088, Dissolved-solids concentrations in the ground water increase to the north and east as the potentiometric head decreases.

Probable Hydrologic Impacts

Distance-drawdown curves are used to show the extent of drawdown near the proposed surface mine. After reclamation, the spoils will cause increased concentrations of dissolved solids in the ground water. This increase could affect streams, springs, alluvial aquifers, and ground-water use.

Proposed Monitoring

Additional data on hydraulic characteristics of the aquifer, ground-water levels, streamflow, and chemical quality of ground and stream waters are needed to estimate the impact of mining more accurately. Ideally, the wells will be placed both upgradient and downgradient from the mine site in locations where the maximum hydrologic information can be obtained. The pH, specific conductance and temperature of the mine discharge, and a nearby creek, need to be monitored continuously and samples of water collected periodically for chemical analysis.

2.0 GEOLOGIC SETTING

2.1 DENVER FORMATION AND LIGNITIC COAL RESERVES

THE DENVER FORMATION CONTAINS THE LIGNITIC COAL

The Denver Formation contains lignitic coal seams which are 20 to 60 feet thick and extend from the land surface to a depth of 500 feet in the study area.

The oval-shaped Denver basin is about 120 miles long and 60 miles wide (fig. 2.1-1). The upper formations within the basin are, from shallowest to deepest: Dawson Arkose, Denver Formation, Arapahoe Formation, Laramie Formation, and Fox Hills Sandstone (fig. 2.1-2). The formations on the southern, eastern, and northern margins of the basin dip gently toward the center. However, along the Front Range on the western margin of the basin, the rocks generally dip steeply 40˚ to 45˚ to the east (2).

The Denver Formation ranges in age from Late Cretaceous to early Paleocene. This formation consists primarily of 600 to 1,600 feet of medium-yellow, olive to greenish-gray claystone, siltstone, shale, very fine to fine grained sandstone, and andesitic conglomerate. The formation which was deposited in a continental environment, includes all the surface mineable lignite in the basin (fig. 2.1-2). Thick lignite beds, fossilized plant remains, and carbonaceous shales occur in the upper 300 to 500 feet of the formation and are thickest and most prevalent in the eastern part of the basin.

The lignite zone consists of three to eight lignite seams interbedded with carbonaceous shale, claystone, siltstone, and sandstone. The total thickness of the lignite beds in the surface mineable areas ranges from 20 to 60 feet (2). Near the proposed mine site six major seams of lignite are present (fig. 2.1-3). The total thickness of these seams ranges from 20 to 40 feet.

An abandoned kaolinite mine is within 1 mile of the proposed mine site. Kaolin, a kaolinite-rich rock, is the primary parting in the lignite. In some areas kaolinite beds 2 to 5 feet thick overlie individual lignite seams. The kaolinite contains alumina (Al_2O_3), which is a potential source of aluminum (2). If the process for extracting aluminum from kaolinite becomes economically feasible, the Denver Formation may have a dual resource. Therefore, mining of the low-quality lignite may economically benefit from mining of the kaolinite.

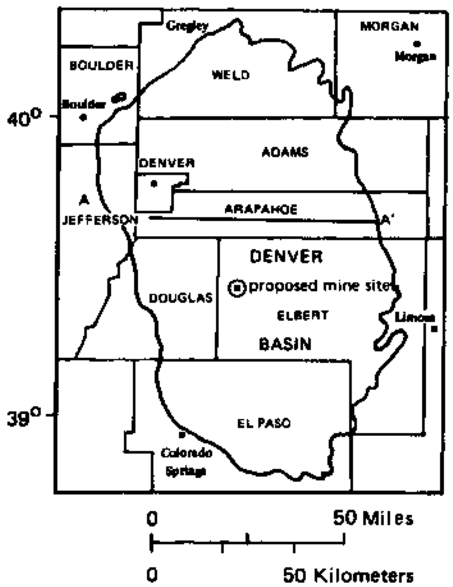


Figure 2.1-1— Location of the Denver basin, proposed mine site

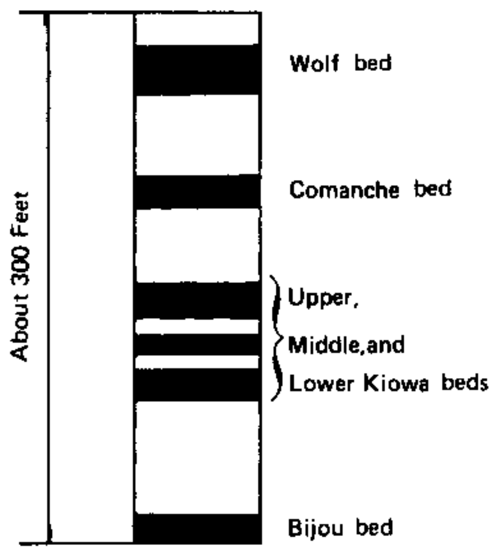


Figure 2.1-2— Generalized geologic section of the Denver basin showing coal

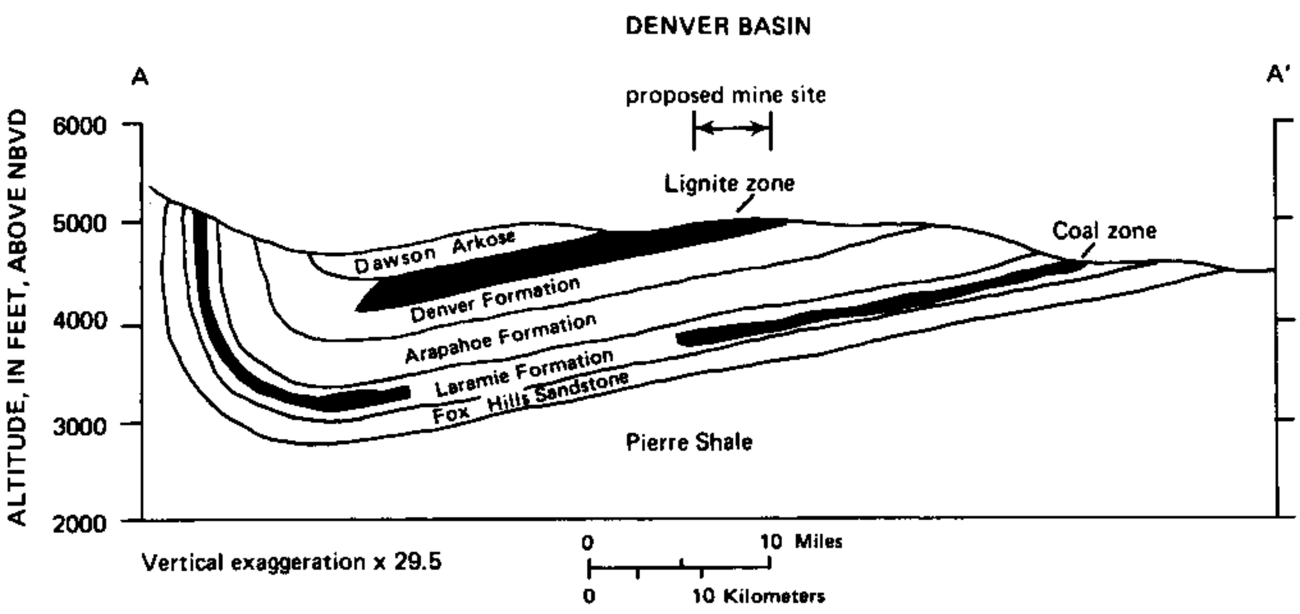


Figure 2.1-3— Generalized section showing location of the lignite beds in the Denver Formation near the proposed mine.

3.0 HYDROLOGIC SETTING

3.1 PHYSIOGRAPHY, VEGETATION, AND CLIMATE OF THE STUDY AREA

AREA HAS LOW RELIEF AND SEMIARID CLIMATE

The area is in gently rolling plains, covered by grasses and small cacti, that receive 13 to 17 inches of annual rainfall.

The proposed mine-permit area lies in gently rolling plains with local relief that averages 300 to 500 feet. Altitudes range from 5,500 feet in the north to 6,700 feet in the south. Grasses and small cacti are the primary vegetation. Groves of pine trees grow on some hilltops. Hay and wheat are grown on dryland farms on the plains. The land is used primarily for cattle grazing.

The average annual rainfall in the area ranges from 13 to 17 inches, indicating a semiarid climate. Most of the precipitation falls as rain, primarily in the spring, but 2 to 6 feet of snowfall in the winter is common. Little humidity and strong winds are characteristic of these plains. The mean temperature is 59˚F, the normal seasonal temperature fluctuations are from 150 to 75˚F, and extremes in temperature range from -38˚ to about 100˚F (1).

3.0 HYDROLOGIC SETTING

3.2 GROUND-WATER SYSTEM

DENVER AQUIFER IS THE ONLY MAJOR AQUIFER AFFECTED BY PROPOSED LIGNITE SURFACE-MINING

The Denver aquifer is the principal source of domestic and stock water near the proposed surface-mine site.

The Denver Formation is a major aquifer in the mine area. Regionally, the Denver aquifer is overlain by the Dawson aquifer and underlain by the Arapahoe aquifer. The Denver aquifer receives recharge from precipitation at the outcrop, from some stream reaches, and from the Dawson aquifer. Water in the Denver aquifer discharges to streams and to the Arapahoe aquifer, as shown in figure 3.2-1. Streamflow in the outcrop area is not significantly increased by the ground-water discharge because most of the gained ground water is lost by evapotranspiration.

The Denver aquifer is the principal source of domestic and stock water in the mine area. Little or no water is withdrawn from this aquifer to irrigate commercial crops (5).

The Denver aquifer consists of a series of lenticular water-bearing sandstone and siltstone units interbedded with lenses of claystone and shale. Because the few drill holes in the area are irregularly spaced, the extent and thickness of the sandstone-siltstone units are difficult to determine. However, the available data indicate that the water-bearing sandstone-siltstone units are lenticular. Intergranular pore space provides the permeability in the aquifer. In the upper 200 feet of the area, the sandstone-siltstone lenses probably range in thickness from several feet to 20 feet; locally, isolated lenses are as much as 40 feet thick.

The lower part of the Denver aquifer is primarily confined, whereas the upper part of the aquifer is generally unconfined (4). Because the lignite beds are in the upper part, the hydrologic setting of the mine area is primarily an unconfined or water-table condition.

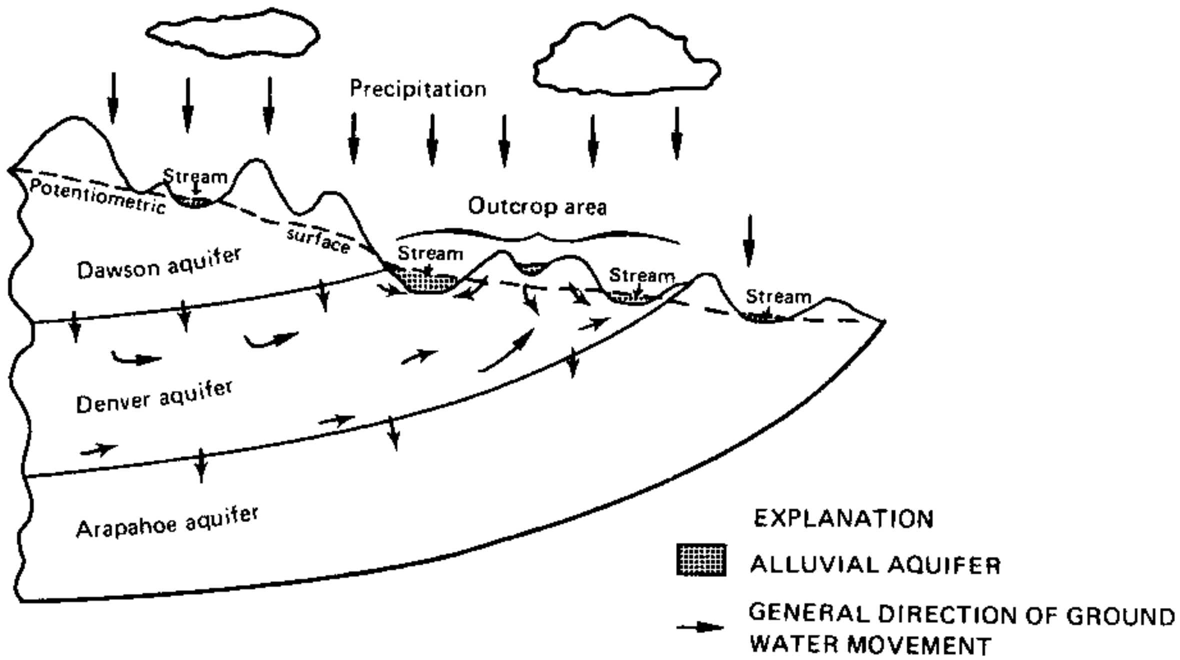


Figure 3.2-1.— Generalized west-to-east cross section showing the hydrologic setting of the Denver aquifer.
(Modified from Robson and Romero, 1981.)

3.3 HYDRAULIC CHARACTERISTICS

TRANSMISSIVITY AND STORAGE COEFFICIENT DETERMINED FOR AREA

The transmissivity of the Denver aquifer, as determined from specific-capacity tests ranges from about 50 to more than 200 ft^2/d. Storage coefficients were determined from specific-yield information.

Transmissivity values for the Denver aquifer were based on specific-capacity tests (6) of wells inventoried near and within the proposed mine permit area. They ranged from about 50 to more than 200 ft^2/d. In addition, values for hydraulic conductivity, porosity, specific retention, and specific yield from undisturbed samples of permeable bedrock, which were obtained from the results of laboratory tests (4), are listed in table 3.3-1.

Transmissivity values were also calculated as the product of hydraulic conductivity and saturated thickness. Saturated-thickness values were taken from published maps (5) of the thickness of sandstone and siltstone, which are the water-bearing beds of the Denver aquifer. Figure 3.3-1 illustrates the variation of transmissivity within the proposed mine-permit area.

Storage coefficients of the unconfined systems vary widely. Estimates of the storage coefficient range from 0.014 to 0.088. Therefore, a representative mean value for an unconfined aquifer in the area was used. The storage coefficient of the unconfined aquifer was determined by multiplying the average specific yield of the aquifer by the percent of permeable material in the aquifer–30 percent (4).

Table 3.3-1– Physical properties of sampled water yielding materials in the Denver Formation (4)
[ft/d, feet per day]

Well identifier	Specific yield (percent)	Specific retention (percent)	Porosity (percent)	Hydraulic Conductivity (ft/d)
SC00306328DD	23.9*	20.5	44.4	8.5*
SC00306419DC	18.5*	11.9	30.4	—
SC00406333CC	4.7	10.1	14.8	.006*
SC00506328CC	29.4*	9.2	38.6	.9*
SC00806111AA	24.6	13.8	38.4	4.0*
SC01006214AA	—	—	35.4	—

* Calculated Value

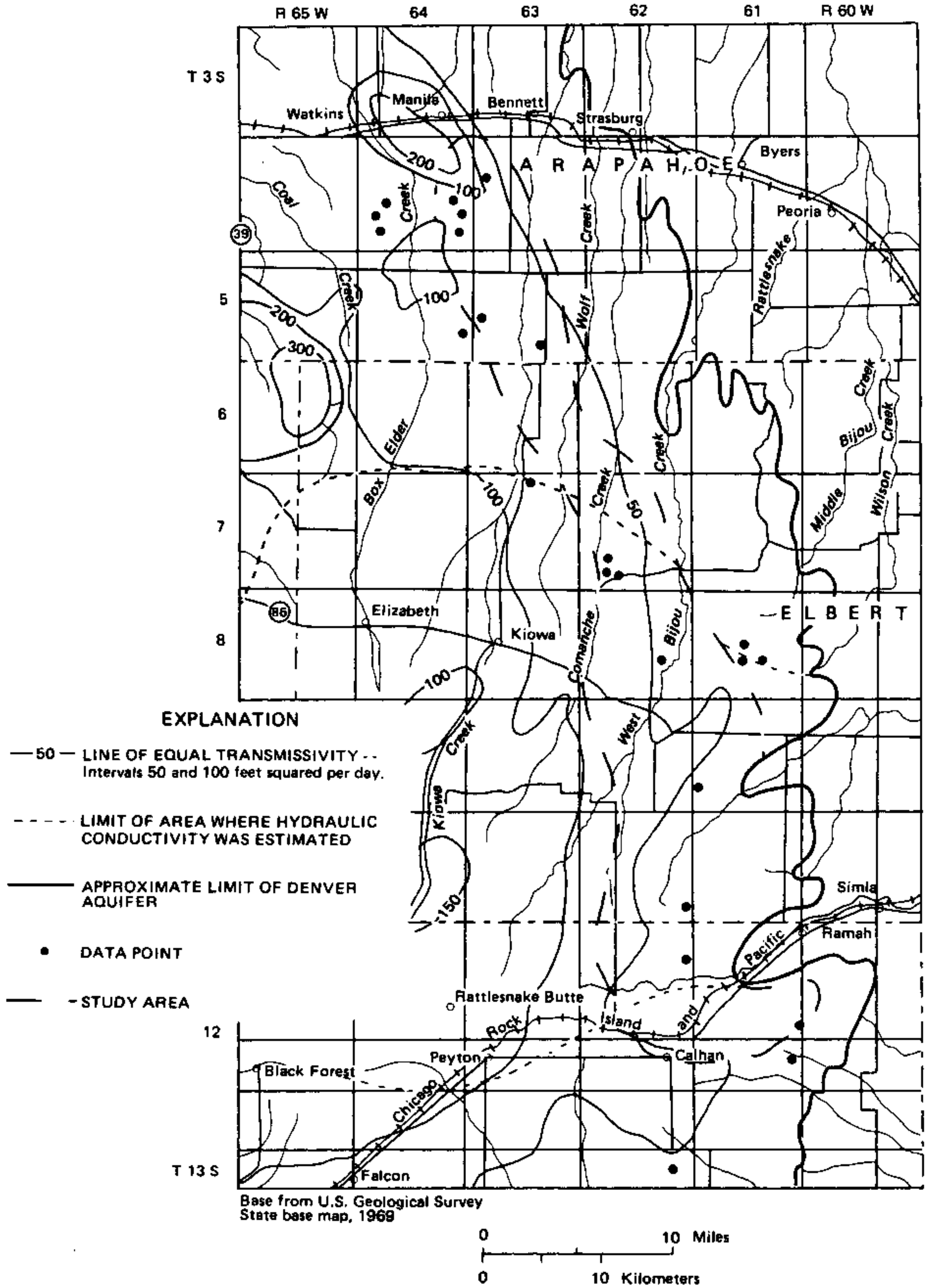


Figure 3.3-1.— Transmissivity of the Denver aquifer.
(Modified from Robson, 1983.)

3.0 HYDROLOGIC SETTING

3.4 POTENTIOMETRIC SURFACE

POTENTIOMETRIC HEAD DECREASES TO THE NORTH AND EAST

Potentiometric-surface map of the Denver aquifer indicates ground water flows toward the north and east.

The potentiometric-surface map (fig. 3.4-1) depicts the altitude of static water levels in part of the Denver aquifer in 1978. The altitude of the potentiometric surface is highest in the south and lowest in the north and east. Water in the aquifer moves from points of high water-level altitude to areas of lower altitude along lines at right angles to the potentiometric contours shown in figure 3.4-1. Therefore, the potentiometric head in the Denver aquifer underlying the study area decreases from the south to the north and east. In the outcrop area of the Denver aquifer, lateral movement of water is determined primarily by the location and altitude of sources of recharge and discharge. At the proposed mine area, water moves through the aquifer from the subsurface-recharge areas in the west and south to the area of discharge into Bijou Creek, which flows to the north.

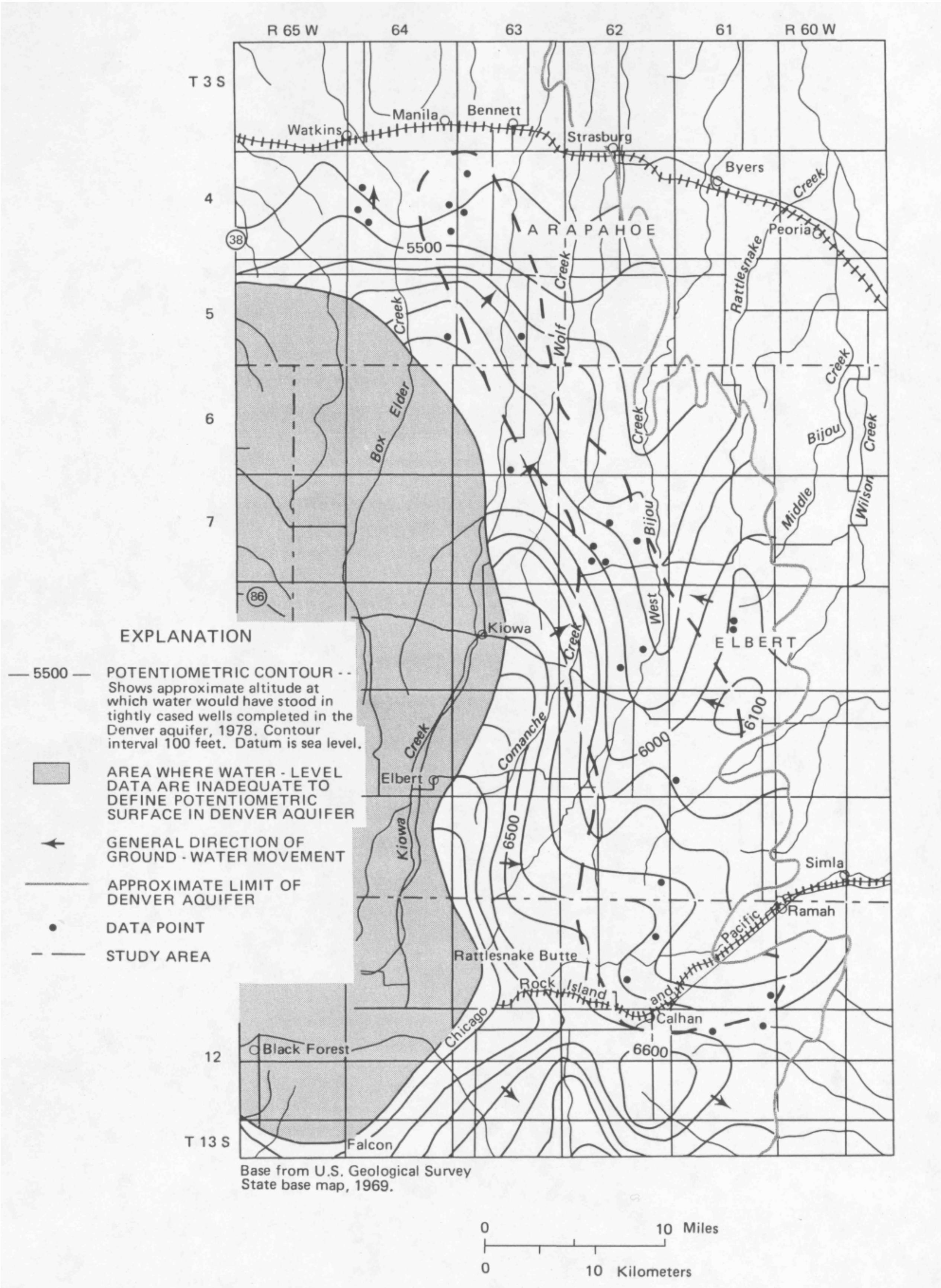


Figure 3.4-1. — Potentiometric surface of the Denver aquifer.
(Modified from Robson and Romero, 1981.)

3.0 HYDROLOGIC SETTING

3.5 CHEMICAL QUALITY OF GROUND WATER

PRE-MINING WATER-QUALITY INFORMATION IS NEEDED

Pre-mining water quality can be used to determine the natural flow path, to determine changes in ground-water quality along the flow path, and to predict where water-quality impacts will occur.

The pre-mining flow path and the quality of the ground water are needed to determine the impacts of surface mining on ground-water quality. The flow path shows the direction in which the potential solutes from mining probably would travel. Under normal conditions, these solutes would form certain patterns along the flow path. For example, the dissolved-solids concentrations would be expected to increase downgradient from the mine area.

Twenty domestic and stock wells were sampled near and within the study area (fig. 3.5-1 and table 3.5-1). These wells were selected because they were either in or near the study area, because they were completed solely in the Denver aquifer, or because thorough drilling and completion information was available. Specific conductance, pH, and temperature were measured at the time of sample collection. Samples were analyzed for major and minor dissolved constituents and trace metals. Data on specific conductance, pH, dissolved solids, and major dissolved constituents are given in table 3.5-2, and data on temperature, alkalinity, hardness, and minor dissolved constituents are given in table 3.5-3.

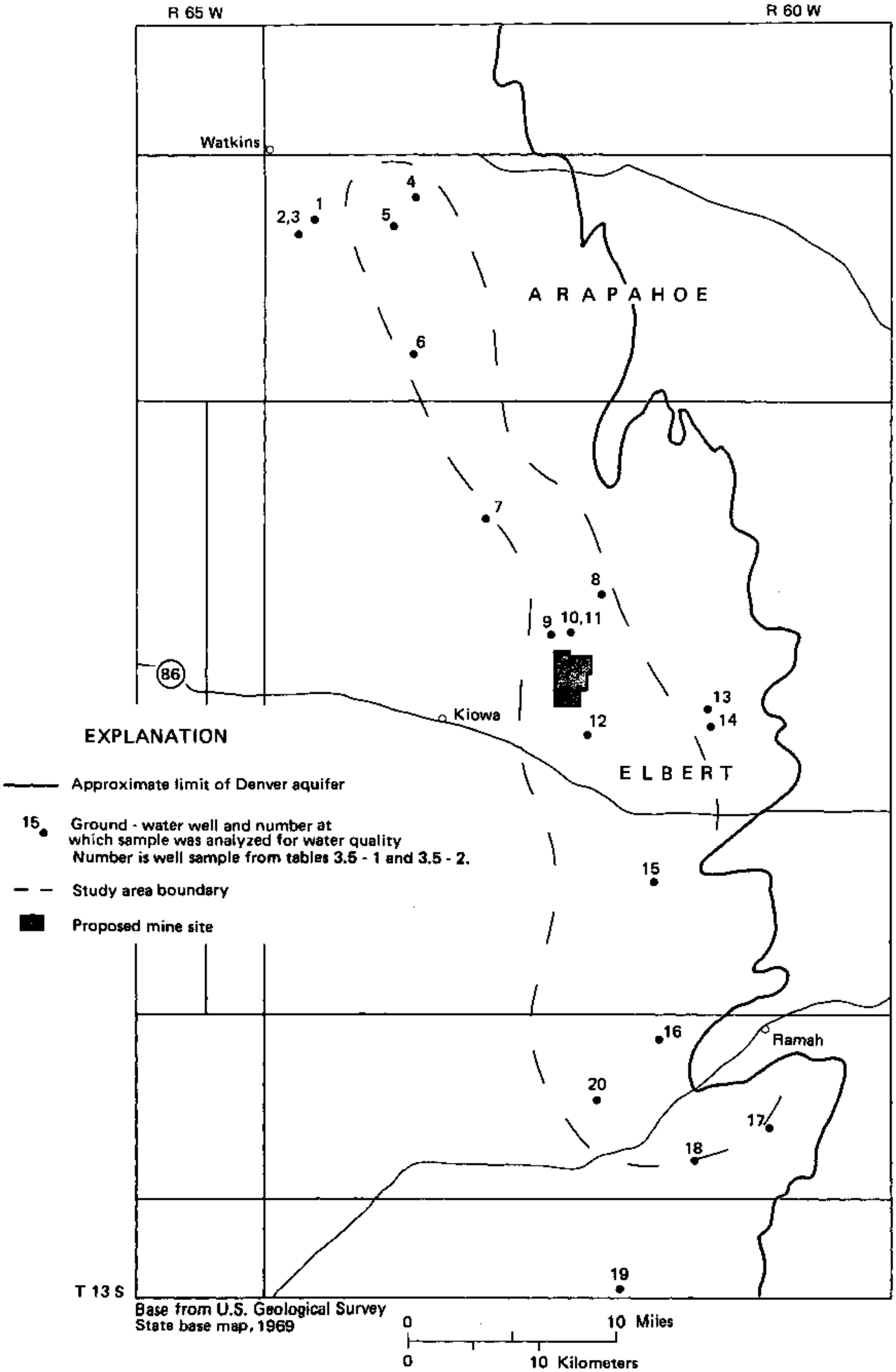


Figure 3.5-1.— Location of wells sampled for water-quality analysis.

Table 3.5-1 – General information on the wells sampled for water-quality analysis.

Map* and sample number	Well identifier	Lithology	Altitude above sea level (feet)	Depth drilled below land surface (feet)	Depth to first opening in well (feet)	Water level below land surface (feet)
1	SC00406416CDD1	Sandy clay	5735	731	468	330
2,3	SC00406420CDB1	Sandstone	5752	575	340	240
4	SC00406307CCB1	Sandstone	5717	515	415	191
5	SC00406413CCA1	Sandstone	5754	755	555	414
6	SC00506424BDA1	Sandy shale	6000	156	114	112
7	SC00606334CAB1	Sandy shale	6067	155	111	120
8	SC00706214BDB1	Sandstone	5770	189	75	64
9	SC00706227BCB1	Sandy shale	5910	307	79	137
10,11	SC00706229ADA1	Sandstone	6150	479	299	399
12	SC00806222AAB1	Sandstone & shale	5960	275	200	156
13	9C00806122ACB1	Sandstone	6110	174	111	125
14	SC00806127BDB1	Sandstone	6224	200	160	178
15	SC01006130ABC1	Sandstone & shale	6325	227	165	12
16	SC01106106DBD1	Sandstone	6360	231	91	145
17	SC01106031AAA1	Sandstone	6535	190	70	178
18	SC01206104CCB1	Sandstone	6660	290	200	144
19	SC01306201CCB1	Sandstone	6673	225	165	171
20	SC01106234DCA1	Sandy clay	6512	195	58	41

* see fig. 3.5-1

Table 3.5-2 – Specific conductance, pH, dissolved solids, and major dissolved constituents in ground-water samples

[mg/L, milligrams per liter]

Map* and sample number	Local identifier	Date of sample	Specific conduct-ance (micro-mhos)	PH lab (units)	Solids sum of constituents, dissolved (mg/L)	Bicar-bonate (mg/L as HCO_3)	Calcium dissolve d (mg/L as Ca)	Sodium dissolved (mg/L as Na)	Sulfate dissolved (mg/L as SO_4)
1	SC00406416CDD1	82-05-12	340	8.6	224	195	11	77	17
2	SC00406420CDB1	78-09-19	450	7.8	309	290	24	98	15
3	SC00406420CDB1	82-05-12	460	8.3	286	293	21	90	<5.0
4	9C00406307CCB1	82-05-12	350	8.6	274	256	22	91	5.0
5	SC00406413CCA1	82-05-12	410	8.5	269	268	15	89	<5.0
6	SC00506424BDA1	82-05-12	1,000	7.6	817	195	130	97	430
7	9C00606334CAB1	78-09-19	845	7.8	600	170	110	70	280
8	9C00706214BDB1	82-05-18	1,400	7.9	964	256	89	200	510
9	SC00706227BCB1	82-05-18	780	7.6	544	317	46	140	170
10	SC00706229ADA1	78-10-09	470	8.1	316	320	12	110	12
11	SC00706229ADA1	82-05-18	500	8.1	369	317	35	140	10
12	SC00806222AAB1	82-05-18	930	8.3	602	293	22	160	250
13	SC00806122ACB1	82-05-18	350	7.0	301	96	63	49	100
14	SC00806127BDB1	82-05-18	890	7.1	659	183	100	100	330
15	SC01006130ABC1	82-05-17	1,100	8.4	676	268	18	210	290
16	SC01106106DBD1	78-09-21	1,480	8.0	972	460	28	320	370
17	9C01106031AAA1	78-10-04	561	8.0	337	210	45	54	59
18	SC01206104CCB1	82-05-17	370	6.7	242	43	68	28	68
19	SC01306201CCB1	78-10-02	232	8.8	145	110	3.3	49	24
20	SC01106234DCA1	82-05-17	600	7.4	446	134	59	70	210

Table 3.5-3 —— Temperature, alkalinity, hardness, and minor dissolved constituents in ground-water samples.

[mg/L, milligrams per liter; ug/L, micrograms per liter]

Map* and sample number	Date of sample	Tem-pera-ture (˚C)	Alka-linity field (mg/L as $CaCO_3$)	Hard-ness (mg/L as $CaCO_3$)	Magne sium, dis-solved (ug/L as Mg)	Nitrogen, NO_2+NO_3 dis-solved (mg/L as N)	Phos-phorous, dis-solved (mg/L as P)	Potas-sium, dis-solved (mg/L as K)	Chlo-ride, dis-solved (mg/L as Cl)	Fluo-ride, dis-solved (mg/L as F)	Silica, dis-solved (mg/L as SiO_2)	Boron, dis-solved (ug/L as B)	Iron, dis-solved (ug/L as Fe)	Lead, dis-solved (ug/L as Pb)	Manga-nese, dis-solved (ug/L as Mn)	Zinc, dis-solved (ug/L as Zn)	Sele-nium, dis-solved (ug/L as Se)
1	82-05-12	15.6	160	31	0.9	0.02	0.050	2.5	6.0	2.3	11	60	34	<1	8	13	<1
2	78-09-19	21.0	240	67	1.8	.04	—	3.4	11	1.1	11	—	30	—	20	—	—
3	82-05-12	15.0	240	59	1.5	.03	.060	3.4	9.7	1.3	10	50	39	<1	15	15	<1
4	82-05-12	13.0	210	64	2.3	.03	.070	3.4	8.5	2.6	13	60	95	<1	27	35	<1
5	82-05-12	12.0	220	42	1.2	.18	.060	2.7	9.3	1.7	13	60	73	<1	21	13	<1
6	82-05-12	11.5	160	380	13	.13	.080	10	24	1.1	14	50	440	<1	180	220	1
7	78-09-19	13.0	140	300	6.3	.32	—	9.5	15	.6	23	—	40	—	20	—	—
8	82-05-18	21.0	210	260	8.7	.89	<.010	5.1	9.6	.8	10	60	37	<1	110	120	<1
9	82-05-18	21.5	260	140	7.2	.18	.020	3.2	8.7	1.5	10	60	49	<2	67	110	<1
10	78-10-09	17.0	260	35	1.3	.02	.010	3.1	7.7	1.9	9.9	—	140	—	20	—	—
11	82-05-18	18.5	260	100	3.2	.09	.020	3.8	7.6	1.9	11	60	75	<5	44	25	<1
12	82-05-18	25.0	240	63	2.0	.02	.040	3.2	6.8	.9	13	50	27	<2	57	31	<1
13	82-05-18	25.0	79	100	5.9	.17	<.010	6.0	1.8	1.0	26	40	88	<2	160	280	<1
14	82-05-18	25.0	150	280	8.1	.17	.030	7.4	6.1	.5	15	70	21	<2	110	530	<1
15	82-05-17	18.0	220	53	1.9	.17	.030	2.5	10	1.9	9.4	40	21	5	26	13	1
16	78-09-21	14.0	380	81	2.8	.71	.030	2.8	8.5	1.1	9.1	—	20	—	60	—	—
17	78-10-04	11.5	170	150	10	5.2	.010	4.2	22	.6	15	—	130	—	20	—	—
18	82-05-17	18.0	35	210	10	<50	.030	6.5	17	.1	23	20	100	<5	240	180	10
19	78-10-02	16.0	90	9	.20	.10	.030	.7	2.3	.6	10	—	20	—	<10	—	—
20	82-05-17	19.5	110	170	5.0	.23	<.010	3.1	5.3	.4	26	30	13	<5	5	42	<1

3.0 HYDROLOGIC SETTING

3.6 DISSOLVED SOLIDS

DISSOLVED SOLIDS INCREASE DOWNGRADIENT TO THE NORTH AND EAST

Dissolved-solids concentrations increase naturally to the north and east as the head decreases along the ground-water flow line.

In general, the dissolved-solids concentration in the Denver aquifer increases as the ground water moves downgradient. This increase is due to the solution of minerals by undersaturated water. The dissolved-solids concentration of ground water in the study area ranges from 150 to 1,000 mg/L and increases downgradient perpendicular to the contour lines of the potentiometric surface, as shown in figure 3.6-1. The potentiometric-surface map shows that the flow is generally to the north and east, the directions in which the dissolved-solids concentrations primarily increase.

In the Denver aquifer, the dissolved-solids concentrations in the water gradually increase as the water travels from areas of recharge to areas of discharge. The direction of increase in dissolved-solids concentration helps delineate the flow path of the water. The dissolved-solids concentrations are small where the Dawson aquifer overlies the Denver aquifer (5). The Dawson aquifer, consisting primarily of sandstone, contributes water to the Denver aquifer that is less mineralized than the Denver aquifer generally contains. The large concentrations in the Denver aquifer are due to the fact that the Denver aquifer is part of a formation consisting primarily of shale. As water in the Denver aquifer moves to areas of discharge from its outcrop, the water dissolves additional dissolved minerals carried into the aquifer from near-surface sources, increasing the dissolved-solids concentration.

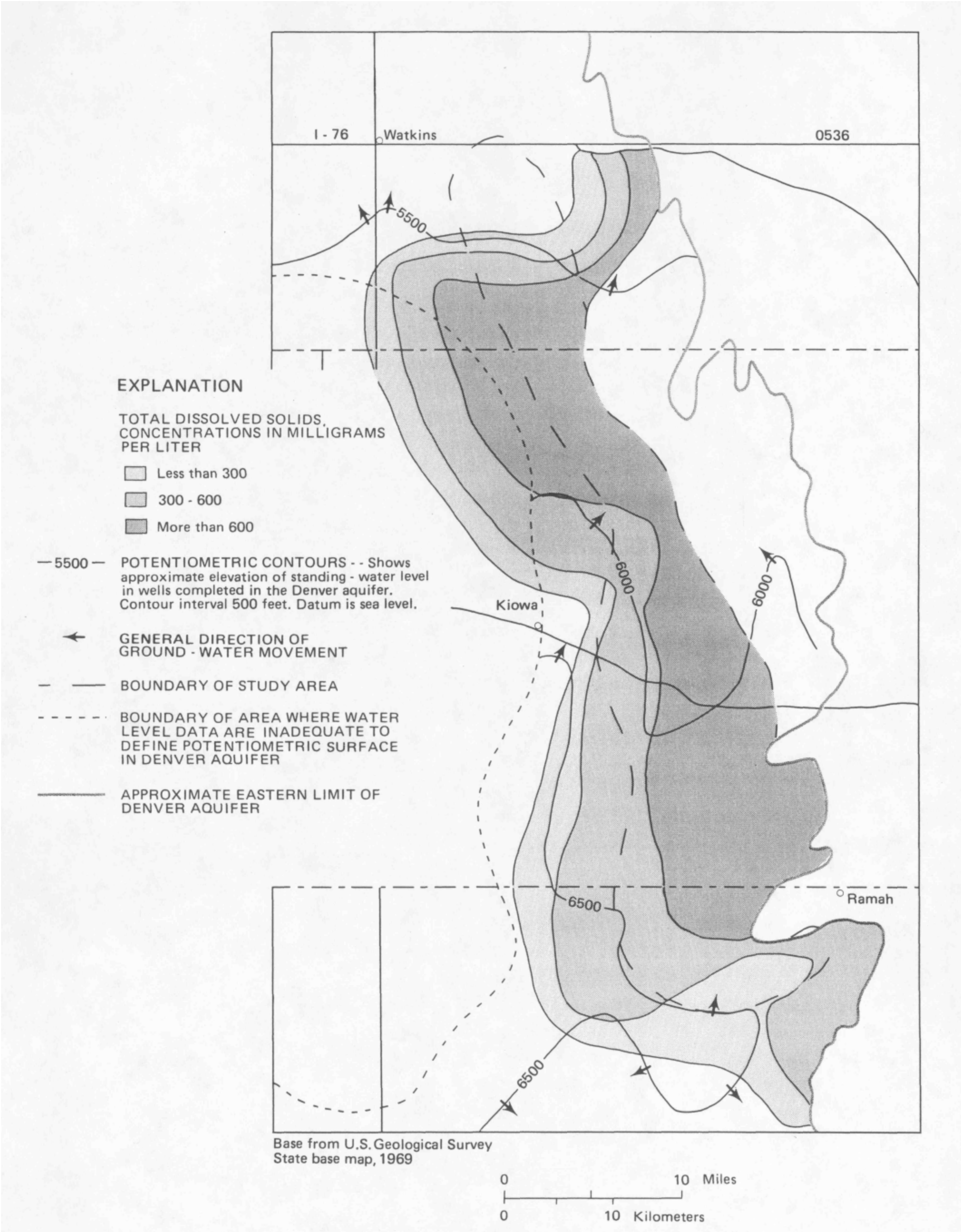


Figure 3.6-1.— Dissolved-solids concentration and flow path in the Denver aquifer.

4.0 PROBABLE HYDROLOGIC IMPACTS

4.1 GEOLOGIC AND HYDROLOGIC CONDITIONS BEFORE AND DURING MINING

DEFINING THE PRE-MINING GEOLOGIC AND HYDROLOGIC CONDITIONS IS NEEDED TO EVALUATE THE CHANGES DURING MINING

Knowledge of the hydrologic conditions before mining can be used to help minimize the impact the active mine will have on the surrounding area.

A variety of geologic and hydrologic conditions can exist in an area to be mined. One simple set of pre-mining conditions has been selected to illustrate the impacts of mining on an aquifer system. These conditions are:

1. A sandstone and siltstone unit directly overlies a lignite unit; no intervening confining layers are present.

2. The sandstone-siltstone and lignite units comprise a single, continuous aquifer.

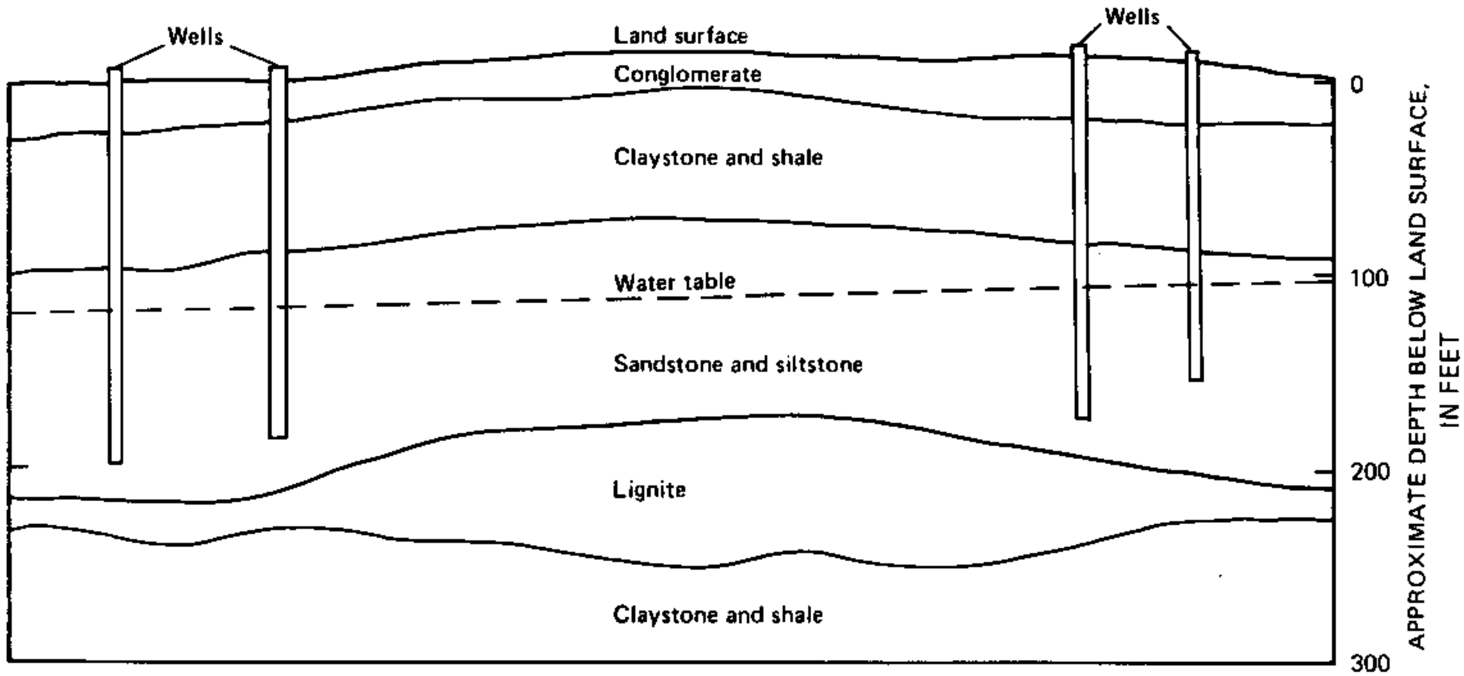
3. The aquifer is unconfined.

4. The aquifer discharges into a stream downgradient from the area to be mined.

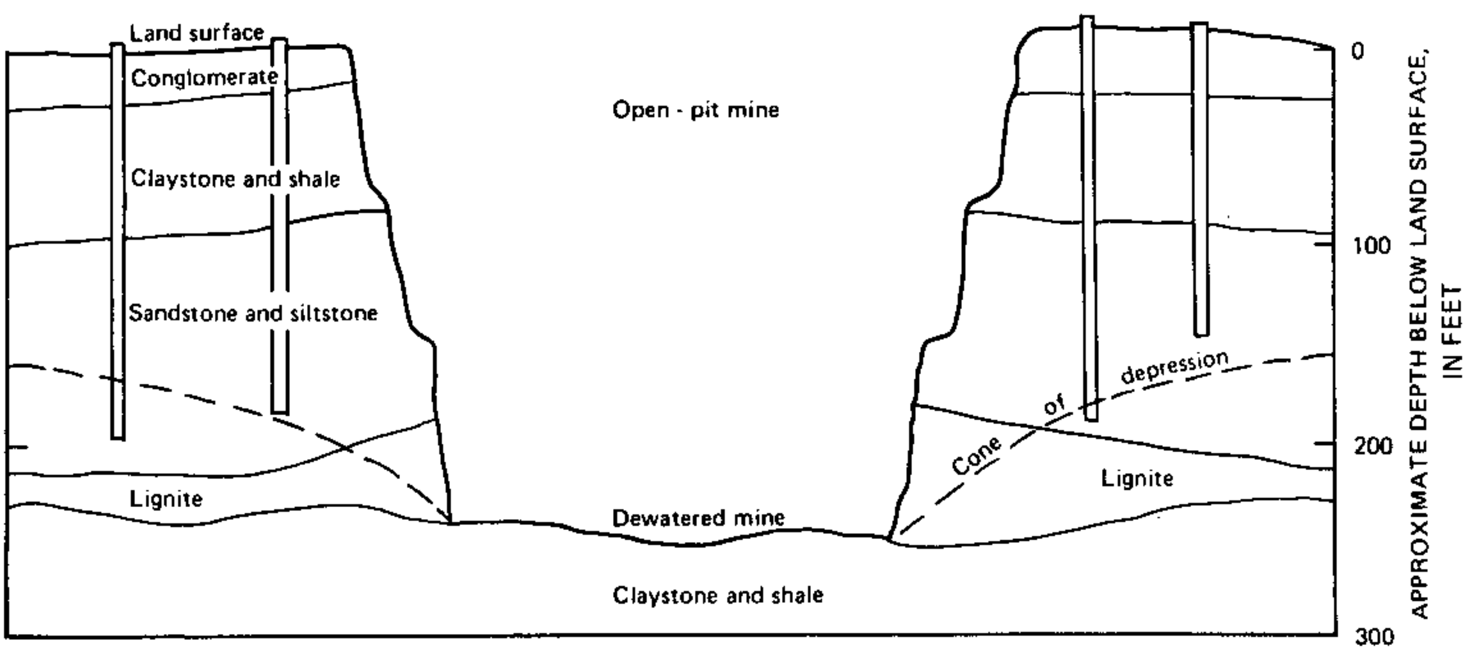
Pre-mining conditions 1, 2, and 3 are depicted in figure 4.1-1A; they can be used to assess the impacts of mining on the hydrologic system in the proposed mine area.

During surface mining, the quantity and flow paths of ground water can be affected significantly, in the vicinity of the mine, by aquifer disruption and disturbance of the recharge areas. Aquifers penetrated by a surface mine will drain into the open pit. Dewatering of the mine further reduces the quantity of water within and surrounding the mine area (fig. 4.1-1B). The conditions before mining are generally: (1) lignite seams are variable in thickness from 20 to 60 feet and are about 500 feet below land surface, (2) the average well depth is about 325 feet (from table 3.4-1), and, (3) the average depth of water level below land surface is 190 feet (from table 3.4-1). The conditions during mining would be an excavation 500 feet deep and a drawdown at the mine floor of about 110 feet for an unconfined aquifer having a transmissivity of 50 ft^2/d and a storage coefficient of 0.058 (fig. 4.1-2). The distance-drawdown curves of figure 4.1-2 approximate the long-term and short-term effects of dewatering the excavation in wells near and distant from the mined area. These head-loss curves were calculated using the Theis nonequilibrium formula (3).

The probable outcome of the dewatering would be that domestic and stock wells within the cone of depression either would become completely dry or would contain less water, as shown in figure 4.1-1B. This reduction in water supply would necessitate drilling deeper wells or finding alternative supplies of surface water. A second possible effect from dewatering might be that water levels would decline in streams and alluvial aquifers supplied by the bedrock aquifer within the cone of depression. Although water levels might decline during the mining operation, the water quality of the aquifer would not change significantly until spoils material is replaced in the mine pit.



A. Conditions before mining



B. Conditions during mining

Figure 4.1-1.— Idealized sections showing the effect of mining on the Denver aquifer.

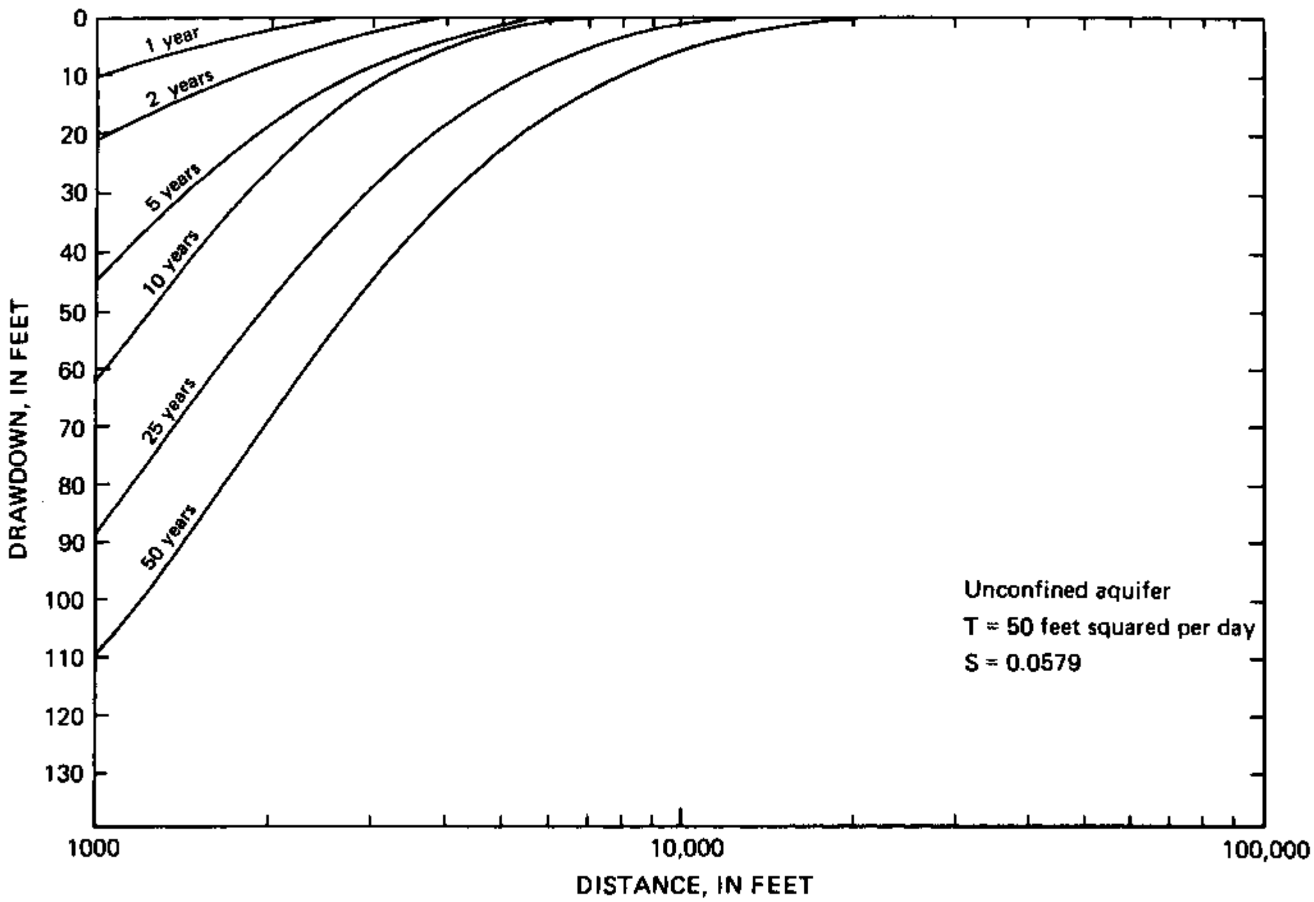


Figure 4.1-2. — Distance-drawdown curves with time for a pumping rate of 100 gallons per minute in unconfined aquifers having a transmissivity of 50 feet squared per day and a storage coefficient of 0.058.

4.0 PROBABLE HYDROLOGIC IMPACTS

4.2 CONDITIONS AFTER MINING

AFTER RECLAMATION THE MINE SPOILS MAY BE A LONG-TERM SOURCE OF INCREASED DISSOLVED SOLIDS

After reclamation the spoils will continue to increase the dissolved-solids concentrations of water in the Denver aquifer. This increase could affect streams, springs, alluvial aquifers, and domestic users.

As mining progresses, the mine spoils are replaced in the mine pit and recontoured to approximate pre-mining conditions. The characteristics of spoils depend upon reclamation techniques and the local spoils. The spoils are assumed to be a heterogeneous mixture of siltstone, sandstone, claystone, and shale, which allows water to percolate easily through the system (fig. 4.2-1). The spoils may locally increase infiltration and deep percolation, thereby altering the hydrostatic conditions. The increased infiltration through the spoils causes recharge and leaching of ions to increase and surface flow to decrease.

During mining, the natural flow path in the aquifer is disrupted. However, when permeable spoils are replaced in the mine, water in the aquifer eventually will return to approximately its pre-mining level.

As the spoils material is replaced, the ground-water quality can be significantly affected by ions leached from replaced overburden. During mining the overburden is scraped, hauled, or dragged outside of the mine pit. The overburden is broken and mixed during this process. While on the surface, some of the overburden is exposed to weathering. When the overburden is replaced in the mine pit during reclamation, further breakage and mixing occur. Therefore, these newly exposed or slightly weathered rock surfaces of the rubble in the pit are readily susceptible to leaching of their ions when in contact with water. As water from rain and overland flow moves over and around these newly exposed surfaces in the permeable spoils, minerals from the overburden are dissolved in the water, which then joins the water from the aquifer. The dissolved-solids concentration of the water in the spoils may be as much as four times the natural concentration.

Because water in the undisturbed aquifer flows from the south to the north, the concentration of dissolved solids from the spoils probably will form a plume that moves northward. The extent of the plume would depend on the boundaries of the aquifer, fractures in the formation, permeability of the bedrock material, kinds of minerals and their solubility equilibrium in the undisturbed aquifer, and area of discharge.

The area of aquifer discharge is within the boundaries of the dissolved-solids plume; therefore, streams and alluvial aquifers in the discharge area might be affected. The dissolved-solids loads would increase in the gaining stream and alluvial aquifer. The concentrations of dissolved solids and the quantity and quality of water in the stream and alluvial aquifer would determine the effects of water from the discharging bedrock aquifer on the alluvial system. Because streams in the area are intermittent, the diluting effect of the stream may be minimal.

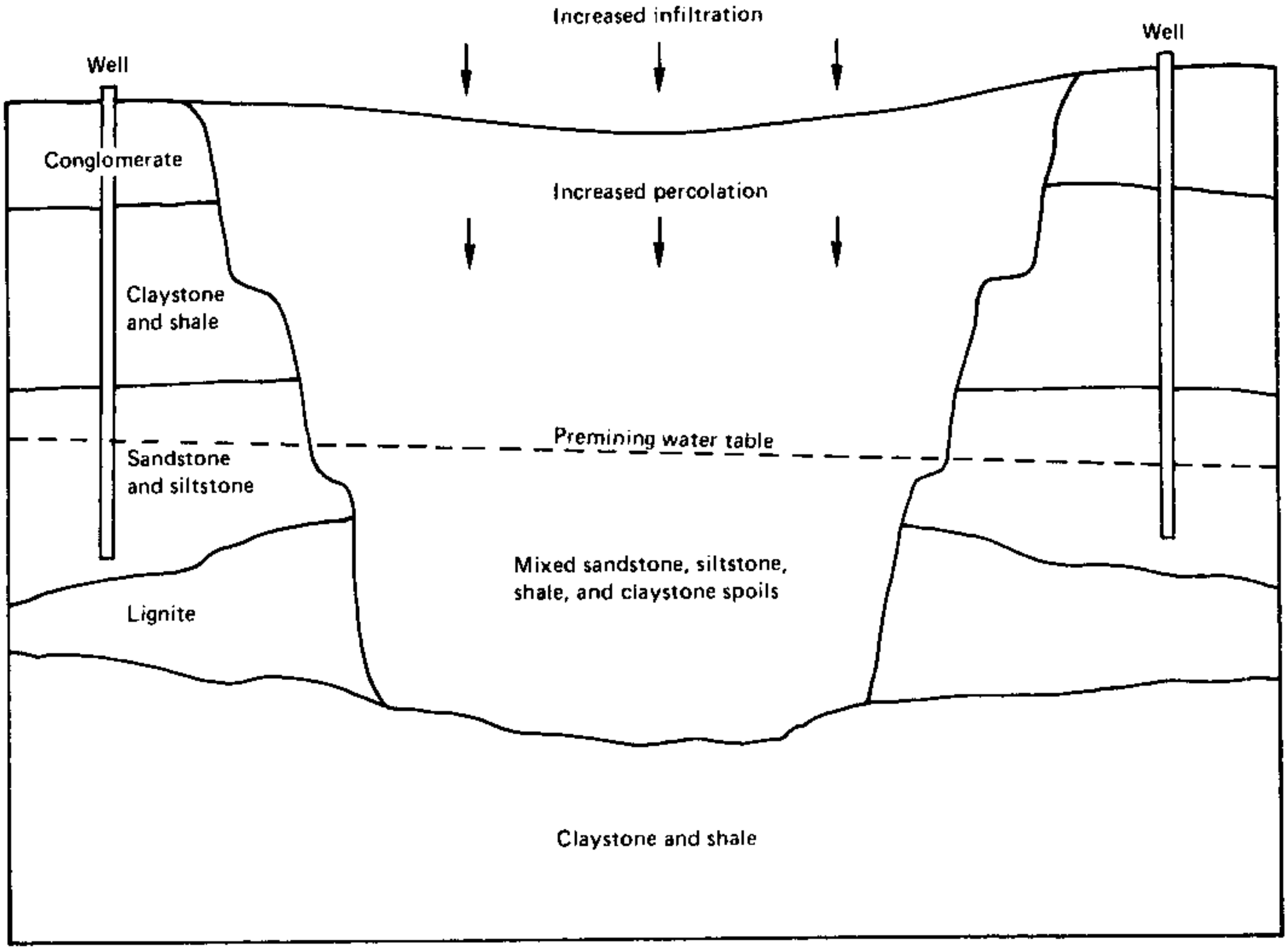


Figure 4.2-1.— Idealized section of a permeable spoils pile showing associated ground-water conditions.

5.0 GROUND-WATER AND SURFACE-WATER MONITORING

OBSERVATION WELLS AND SURFACE-WATER MONITORING SITES ARE NEEDED

Additional data on hydraulic characteristics of the aquifer, ground-water levels, streamflow, and chemical quality of ground and stream waters are needed to estimate the impact of mining more accurately.

To assess the impacts of the proposed surface mine accurately, additional data on pre-mining conditions are needed. The existing wells in the area are insufficient to provide adequate ground-water information near the mine; therefore, observation wells need to be drilled upgradient and downgradient from the mine. Possible locations for these wells are shown in figure 5.0-1. The location of the wells would be chosen to obtain the maximum hydrologic information. These wells would be test pumped to determine the hydraulic properties of the aquifer near the mine. During and after mining, these wells would be monitored periodically for changes in water level and for changes in water chemistry.

Discharge from the mine needs to be monitored continuously, and water samples for chemical analysis of the discharge taken periodically. The analysis would determine the concentration of major ions, trace metals, and other constituents required by State and Federal regulations. An automatic monitor would provide continuous records of pH, specific conductance, and temperature in relation to mine discharge.

A streamflow-gaging and sampling station installed on West Bijou Creek would monitor the impact, if any, that mining may have on this stream. Because West Bijou Creek is an ephemeral stream, a sampler that is activated once the stream rises to a specific stage seems to be the most feasible.

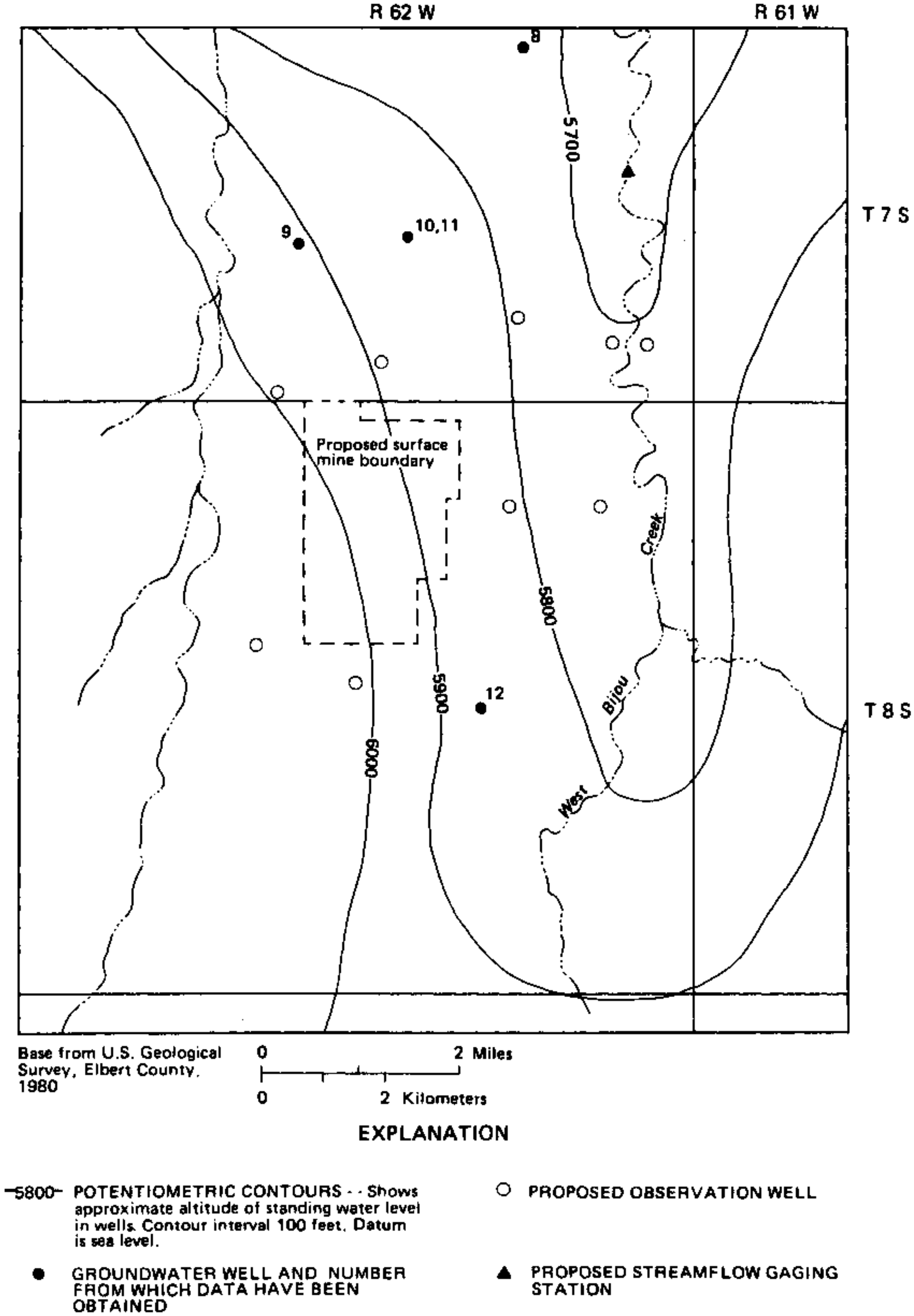


Figure 5.0-1.— Hypothetical network of observation wells and a streamflow-gaging station used to monitor water levels and water quality near the proposed surface mine.

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GROUND-WATER STUDY 11

by

Gregory C. Lines

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1.0 ABSTRACT

Geologic Setting

The coal in the Emery coal field occurs in a number of beds in the Ferron Sandstone Member of the Mancos Shale of Cretaceous age. The I-coal bed, which is the most important economically, has a maximum thickness of about 30 feet. The Ferron crops out in a series of prominent cliffs along the eastern edge of the Emery coal field and dips 2 to 10˚ to the northeast beneath the land surface. The Ferron consists of a variety of sandstones and siltstone, shale, mudstone, and coal. The Ferron ranges in thickness from about 300 to 850 feet. Traditionally, coal has been mined with underground techniques from the I-coal bed. However, a surface mine has been proposed for the Emery field.

The Ground-Water System

The complete thickness of the coal-bearing Ferron Sandstone Member usually is saturated with water a short distance downdip from the outcrop area. Recharge to the Ferron sandstone aquifer is mainly subsurface inflow from the west. The aquifer receives small amounts of recharge from the 8 inches of average annual precipitation on the outcrop area and from leakage from underlying and overlying rocks. Water is discharged from the Ferron by dewatering of an underground mine, by wells, by leakage to underlying and overlying rocks, by leakage along streams, by springs and seeps, and by phreatophytes.

Downdip from the outcrop area, transmissivity of the Ferron ranges from about 200 to 700 square feet per day. Water in the Ferron is confined in most areas, and the storage coefficient ranges from about 3×10^{-6} to 2×10^{-3}.

There are significant hydraulic-head differences in the Ferron Sandstone aquifer. Downdip from the outcrop area, head in the Ferron usually increases with depth and usually is higher than the water table in overlying rocks.

The concentration of dissolved solids in the Ferron ranges from about 750 to 8,000 milligrams per liter. Deterioration of water quality usually is due to increased concentrations of dissolved sodium and sulfate.

Probable Hydrologic Consequences of Mining

Identified changes in the ground-water system caused by dewatering of an underground mine include dewatering of much of the Ferron sandstone aquifer near the mine and both improvement and deterioration of water quality in the aquifer. Dewatering of a proposed surface mine would have the same effects on the aquifer and, in addition, the base flow and water quality in a stream would be changed. A computer model of the ground-water system was used to make semiquantitative predictions of hydrologic effects of the surface mine.

Ground-Water Monitoring

A network of observation wells would be needed near mines to monitor changes in potentiometric surfaces and water quality in the Ferron Sandstone aquifer. In addition, the quantity and the quality of water discharged from mines would need to be monitored.

2.0 GEOLOGIC SETTING

2.1 OCCURRENCE OF COAL

COAL IN THE EMERY FIELD OCCURS IN SEVERAL BEDS

Coal in the Ferron Sandstone Member of the Mancos Shale can be recovered by both underground and surface mining.

The total coal resource in the Emery coal field (fig. 2.1-1) is estimated to be 2.06 billion tons (2). The coal occurs in several beds in the Ferron Sandstone Member of the Mancos Shale of Cretaceous age. As shown in figure 2.1-2, five major beds of coal occur in the Ferron; thin, localized beds of coal are not shown. The coal beds are labeled alphabetically, in ascending stratigraphic order, according to the scheme proposed by Lupton (7). The I-coal bed, which is the most important economically, has a maximum thickness of about 30 feet.

Traditionally, coal has been mined by underground methods in the Emery field. The first recorded mining was of the I-coal bed at the Emery Mine (formerly the Browning Mine) in 1881. Activity at the Emery Mine was irregular until 1937 but has been steady since (2). Coal from the I bed also has been mined at the Dog Valley Mine since 1930. About 99 million tons of coal in the Emery field are recoverable by surface mining (1), and a surface mine has been proposed near the Emery Mine.

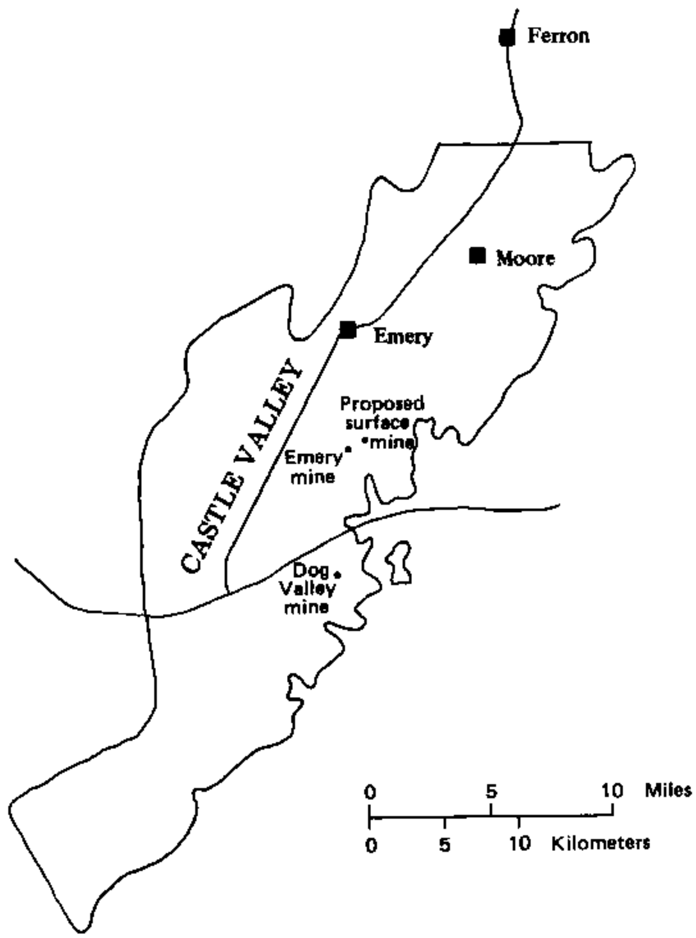

Figure 2.1-1.— Outline of Emery coal field.
(Modified from Ryer, 1981, fig. 1.)

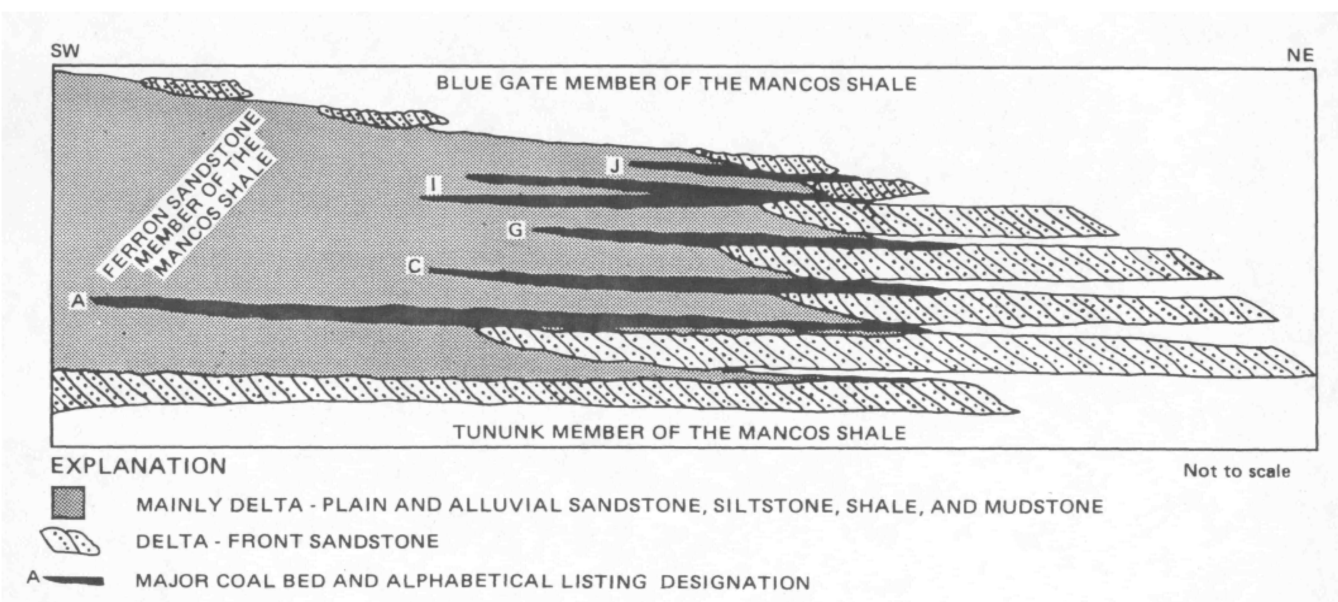

Figure 2.1-2.— Diagrammatic cross section of the Ferron Sandstone Member of the Mancos Shale.
(Modified from Ryer, 1981, fig. 13.)

2.0 GEOLOGIC SETTING

2.2 EXTENT AND THICKNESS OF THE FERRON SANDSTONE MEMBER

OUTCROP AREAS OF GEOLOGIC UNITS ARE MAPPED

The coal-bearing Ferron Sandstone Member ranges in thickness from about 300 to 850 feet in the Emery coal field.

Outcrop areas of the coal-bearing Ferron Sandstone Member and other geologic units in the Emery area are shown in figure 2.2-1. The Ferron crops out in a series of prominent cliffs along the eastern edge of the Emery coal field and dips 2 to 10˚ to the northwest beneath the land surface. Along the outcrop, the Ferron ranges in thickness from about 300 feet in the northern part of the Emery field to about 850 feet in the southern part (5). The Ferron also generally thickens in the subsurface downdip from the outcrop.

The Ferron Sandstone Member consists of massive beds of very fine to medium-grained, delta-front sandstone and a variety of delta-plain and alluvial rock types, mainly very fine grained sandstone, siltstone, shale, mudstone, and coal. The Ferron lies between and intertongues with marine shales in the Tununk and Blue Gate Members of the Mancos Shale. The Tununk and Blue Gate each are several hundred feet thick.

The continuity of the Ferron is broken in the subsurface by the Paradise Valley-Joes Valley fault system. The fault system extends about 60 miles north of the area shown in figure 2.2-1 and about 20 miles south (3). The faults form a graben, and vertical displacement is as much as 3,000 feet in the Emery field (7).

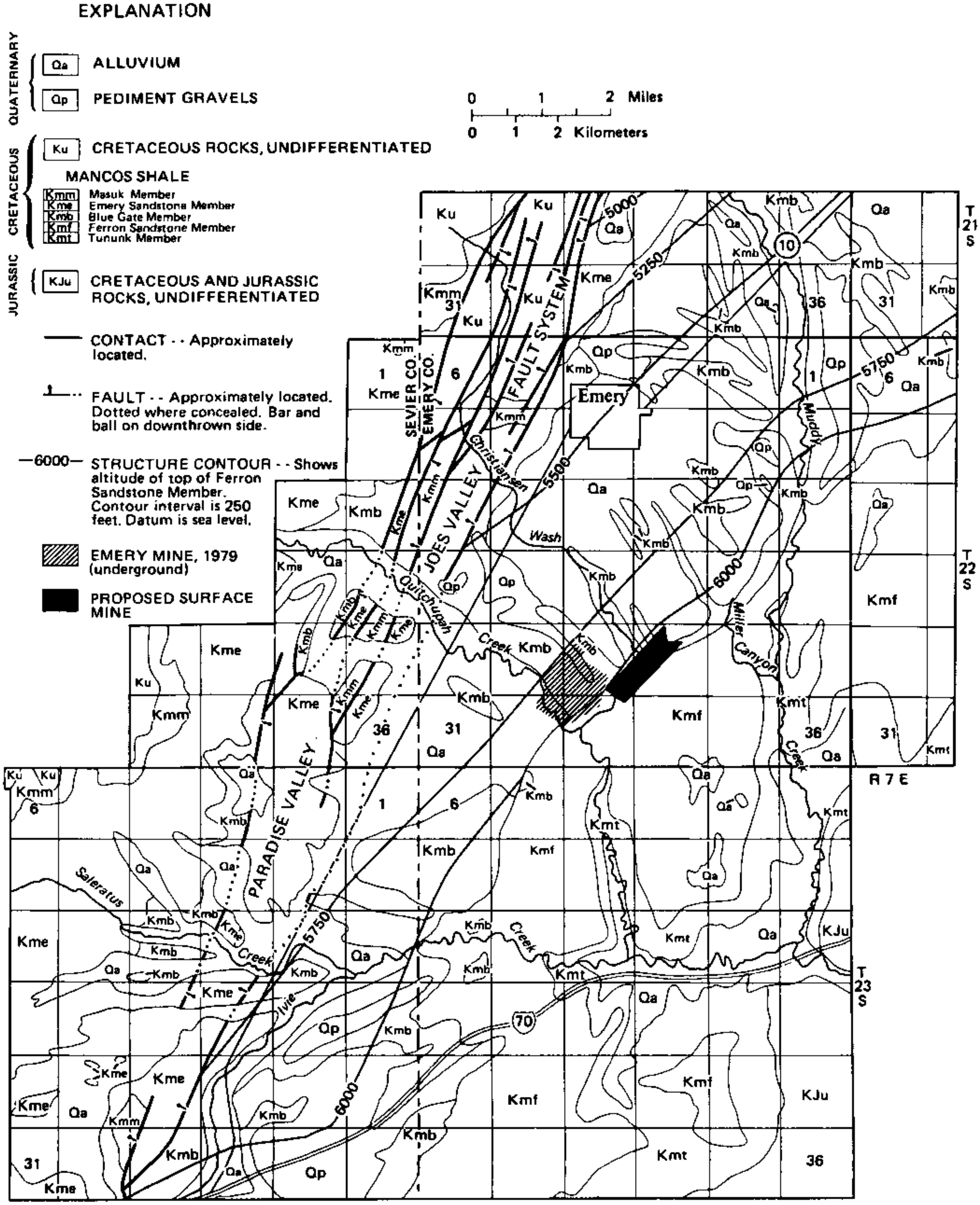

Figure 2.2-1.— Geology of the Emery area.
(Geology from Williams and Hackman, 1971; modified by Lines, 1980; structure contours from Lines and Morrissey, 1981, fig.5.)

3.0 THE GROUND-WATER SYSTEM

3.1 OCCURRENCE, RECHARGE, AND DISCHARGE

THE COAL-BEARING FERRON SANDSTONE MEMBER IS AN AQUIFER

Dewatering of the underground Emery Mine was the largest manmade discharge from the Ferron Sandstone aquifer during 1979.

Records from wells and test holes indicate that the complete thickness of the coal-bearing Ferron Sandstone Member usually is saturated with water within a short distance from the outcrop area. Not all the Ferron is saturated in the outcrop area; much of it is unsaturated at higher altitudes along the outcrop. The Ferron Sandstone Member yields water to wells and the underground Emery Mine, and the unit comprises the Ferron sandstone aquifer.

The Tununk and Blue Gate Members also contain water. Although the shales in these units are relatively impermeable compared with the Ferron Sandstone aquifer, they transmit water and are in hydraulic connection with the Ferron.

Sources of recharge to and discharge from the Ferron Sandstone aquifer in the Emery area are shown in the generalized block diagram (fig. 3.1-1). A complete description of the methods used to measure or estimate rates of recharge and discharge is given in (5). By far the largest source of recharge to the Ferron is subsurface inflow from the west, mainly along the Paradise Valley-Joes Valley fault system. The aquifer also receives small amounts of recharge from precipitation, which averages 8 inches annually on the Ferron outcrop, and from leakage from the Tununk and Blue Gate Members.

Water is discharged from the Ferron Sandstone aquifer by wells, by dewatering of the Emery Mine, by leakage to the Tununk and Blue Gate, by leakage along streams, by springs and seeps, and by transpiration of phreatophytes. By far the largest manmade discharge from the Ferron is the dewatering of the underground Emery Mine, which averaged 0.7 ft^3/s during 1979. Wells that tap the Ferron provide water for the public-water supply at the town of Emery, for coal washing, for stock watering and domestic supplies at ranches, and for a small amount of irrigation.

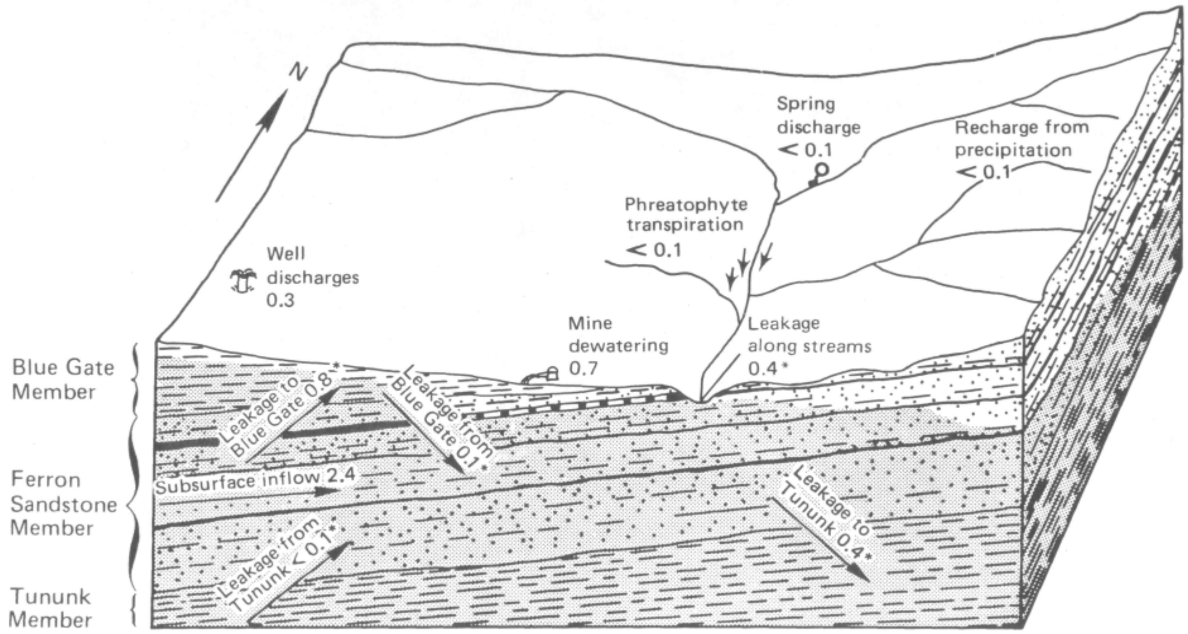

Figure 3.1-1.— Generalized diagram showing sources of recharge to and discharge from the Ferron Sandstone aquifer in the Emery area, 1979. Recharge and discharge rates are in cubic feet per second; an asterisk indicates that rate was calculated by steady-state model simulation. The saturated zone is indicated by the shaded area.
(From Morrissey and others, 1980, fig. 2.)

3.0 THE GROUND-WATER SYSTEM

3.2 AQUIFER TESTS

LABORATORY AND FIELD TESTS CONDUCTED

Porosity and hydraulic conductivity of rocks in the Ferron Sandstone aquifer vary markedly.

Results of laboratory tests of porosity and hydraulic conductivity of cores from the Ferron Sandstone aquifer are summarized in table 3.2-1. The large variation in the porosity and hydraulic conductivity of the sandstone cores probably is due to differences in cementation and compaction. Similar unconsolidated sand would have a porosity of about 40 percent (4), as compared to the average of 16 percent for sandstone in the Ferron. In all sandstone cores from the Ferron, the difference between horizontal and vertical hydraulic conductivities was less than one order of magnitude. Hydraulic conductivities of shale and siltstone cores were much less than those of most sandstones.

Aquifer tests of the Ferron Sandstone aquifer are summarized in table 3.2-2. All tests were conducted where the aquifer was confined. Considering the thickness and lithology of that part of the aquifer tapped by each test well, some calculated transmissivity values agree fairly well with what would be expected from hydraulic conductivities determined in the laboratory. At sites near the Paradise Valley-Joes Valley fault system, the calculated transmissivities of several hundred feet squared per day are larger than would be expected from the laboratory data. This is due to secondary permeability in the aquifer in the form of fractures.

None of the tested wells fully penetrated the Ferron. However, where the Ferron is extensively fractured, thus increasing hydraulic connection in the aquifer, the computed transmissivities fairly accurately represent the transmissivity of the full thickness of the aquifer. Computed transmissivities from most tests that were conducted more than about 2 miles from the Paradise Valley-Joes Valley fault system represent the transmissivity of only part of the aquifer.

Table 3.2-1– Laboratory determination of porosity and hydraulic conductivity of core samples from the Ferron Sandstone aquifer in the Emery coal field. (From Lines and Morrissey, 1983, table 1.)

Location of test hole	Lithology	Depth (feet below land surface)	Porosity (percent)	Hydraulic Conductivity (feet per day)	
				Horizontal	Vertical
SE¼ SE¼ SW¼ sec. 22 ,	S	182	19	8.0×10^{-2}	1.1×10^{-1}
T. 22S., R. 6E.	S	202	18	9.8×10^{-2}	9.5×10^{-2}
SW¼ NE¼ SW¼ sec. 34 ,	S	84	17	2.5×10^{-1}	2.1×10^{-1}
T. 22S., R. 6E.	S	125	18	4.9×10^{-3}	$5.1 \times l0^{-3}$
	S	169	10	2.4×10^{-3}	2.3×10^{-3}
	S	181	13	5.6×10^{-2}	4.1×10^{-2}
	Sh	200	—	———	5.5×10^{-6}
SW¼ SE¼ SE¼ sec. 3,	S	9	20	7.7×10^{-1}	3.2×10^{-1}
T. 23S., R. 6E.	S	34	18	1.1×10^{-2}	2.9×10^{-3}
	S	54	14	7.3×10^{-4}	———
	S	164	17	2.7×10^{-2}	6.8×10^{-3}
	S	224	12	7.3×10^{-4}	2.9×10^{-3}
	S	283	20	3.2×10^{-1}	2.6×10^{-1}
NW¼ W¼ NE¼ sec. 5,	S	42	20	8.8×10^{-2}	1.6×10^{-1}
T. 24S., R. 6E.	Slt	92	11	3.2×10^{-5}	2.9×10^{-6}
	Slt	151	16	7.3×10^{-4}	$3,2 \times 10^{-5}$
	S	342	15	9.8×10^{-3}	4.6×10^{-3}

Table 3.2-2.– Summary of aquifer tests of the Perron sandstone aquifer 1978-79. (Modified from Lines and Morrissey, 1981, table 2.)

[Method of test analysis: C, constant drawdown (Lohman, 1972, p. 23-26); L, Hantush modified method for leaky confined aquifer (Lohman, 1972, p. 32-34.); R, straight-line recovery method (Lohman, 1972, p. 26 and 27.)]

Location of discharging well	Time-weighted average discharge (gallons per minute)	Duration of test (minutes)	Depth of well below land surface (feet)	Depth to first opening in well (feet)	Distance to observation well from discharging well (feet) and direction	Transmissivity (feet squared per day)	Storage coefficient	Method of test analysis	Remarks
NW ¼ NE ¼ SW ¼ sec. 4, T. 22 S., R. 6E.	51	150	1,614	1,586	——	800 600	(1) ——	C R	Open hole below 1,586 feet in basal section of Ferron Sandstone aquifer
SW¼ W¼ NE¼ sec. 17, T. 22S., R. 6E.	176	310	1,543	1,386	——	400 600	(1) ——	C R	Taps basal section of Ferron Sandstone aquifer
Do.	3	120	1,100	1,040	——	30	——	R	Expandable packer set at 1,040 feet; open hole below in upper section of Ferron Sandstone aquifer
SE ¼ SE¼ SW¼ sec. 22, T. 22S., R. 6E.	10	1,500	275 270	100 230	—— 375, northwest	10 20	—— 2×10^{-3}	R L	Both wells tap upper section of Ferron sandstone aquifer
NW¼ NW¼ NW¼ sec. 26, T. 22S., R. 6E.	8	1,500	349 300	40 30	—— 174, south	— — 100	—— 7×10^{-4}	— L	Both wells tap entire upper section and part of basal section of Ferron sandstone aquifer
NW¼ W¼ SW¼ sec. 27, T. 22S., R. 6E.	4	40	380	310	——	100	——	R	Open hole below 310 feet in basal section of Ferron Sandstone aquifer
Do.	3	1,500	158 150	118 75	—— 206, north	40 100	—— 8×10^{-4}	R L	Both wells tap upper section of Ferron sandstone aquifer
NW¼ NE ¼ SE ¼ sec. 31, T. 22S., R. 6E.	13	3,065	406	360	——	200	——	R	Taps upper section of Ferron Sandstone aquifer
NW ¼ NW ¼ NW ¼ sec. 32, T. 22S., R. 6E.	16	1	280 280 282 240 245	225 —— 160 200 205	—— 480, north 695, northwest 480, southwest 890, southwest	100 50 400 90 60	—— 1×10^{-5} 1×10^{-5} 3×10^{-6} 3×10^{-5}	R L L L L	All wells tap basal section of Ferron sandstone aquifer

(1) Storage coefficient could not be determined because the effective well radius was unknown, due to fracturing.

3.0 THE GROUND-WATER SYSTEM

3.3 TRANSMISSIVITY AND STORAGE COEFFICIENT

TRANSMISSIVITY AND STORAGE IN THE FERRON ARE DEFINED

Transmissivity of the Ferron Sandstone aquifer downdip from the outcrop area ranges from about 200 to 700 ft^2/d; storage coefficient ranges from about 3×10^{-6} to 2×10^{-3} where the aquifer is confined.

Transmissivity of the Ferron Sandstone aquifer in the Emery area is shown in figure 3.3-1. The transmissivity map was constructed on information from aquifer tests, lithology, hydraulic conductivity and estimates of saturated thickness. Because of secondary permeability (fractures) and the nonhomogeneous nature of the aquifer, the lines of equal transmissivity are considered to be approximate. Calibration of a three-dimensional digital-computer model of the aquifer indicated that the aquifer was simulated most accurately when transmissivity north of about the line of 200 ft^2/d, in figure 3.3-1, was reduced by 10 to 30 percent (5).

Downdip from the outcrop area, transmissivity of the Ferron ranges from about 200 to 700 ft^2/d and increases towards the Paradise Valley-Joes Valley fault system. Transmissivity is generally less than 200 ft^2/d in the outcrop area, with the decrease mainly due to the decrease in saturated thickness of the aquifer.

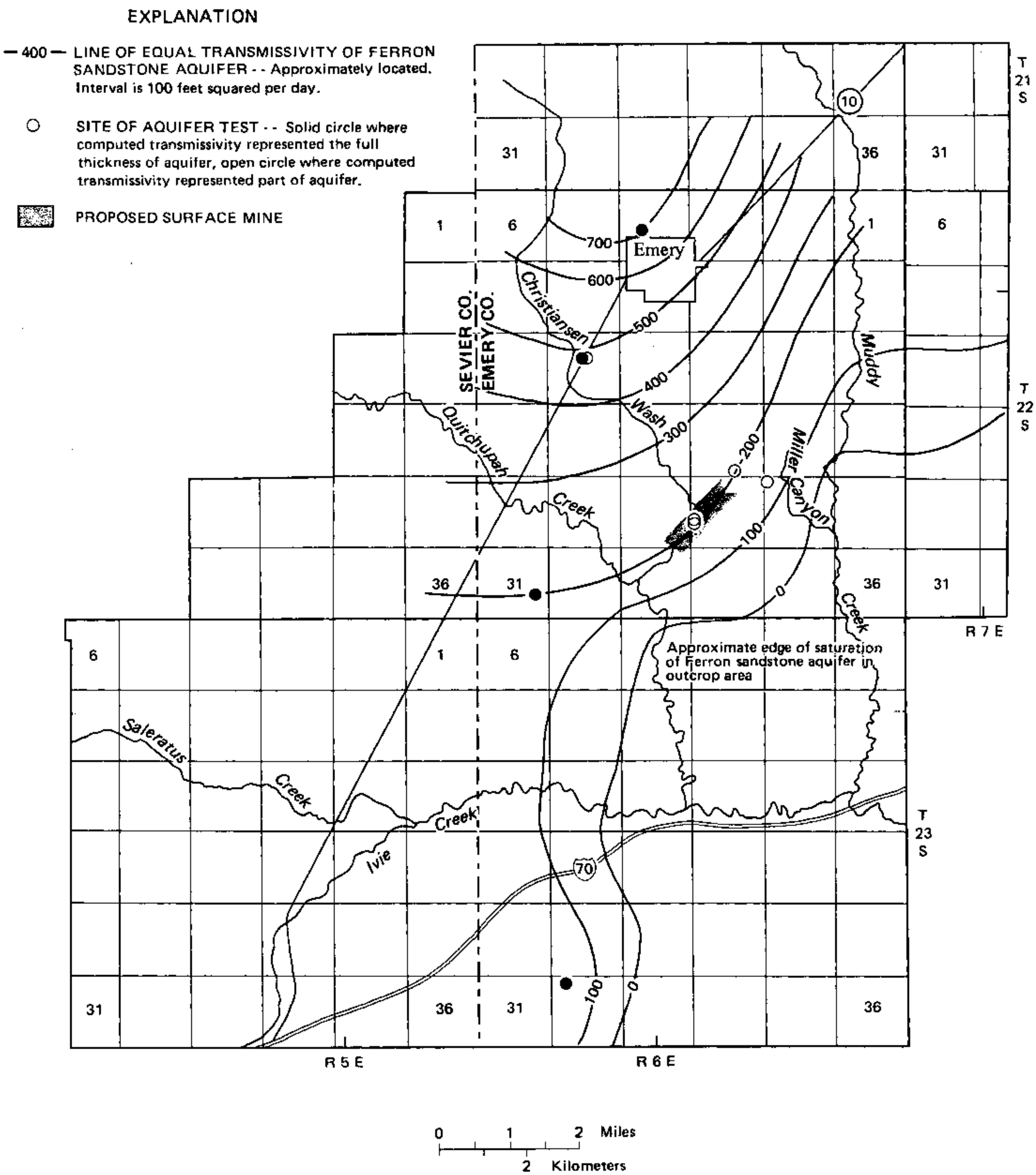

Figure 3.3-1.— Transmissivity of the Ferron Sandstone aquifer in the Emery area. (From Lines and Morrissey, 1983, fig. 7.)

3.0 THE GROUND-WATER SYSTEM

3.4 POTENTIOMETRIC SURFACES OF FERRON SANDSTONEAQUIFER

HYDRAULIC HEAD IN THE FERRON VARIES AREALLY AND WITH DEPTH

Downdip from the Ferron outcrop, head in the aquifer usually increases with depth; in the outcrop area, head decreases with depth.

Potentiometric surfaces of the basal section of the Ferron Sandstone aquifer (below the A-coal bed) and of the upper section of the aquifer (above the base of the I-coal bed) are shown in figures 3.4-1 and 3.4-2. The potentiometric surface varies appreciably with depth in the aquifer. Downdip from the Ferron outcrop, hydraulic head in the aquifer generally increases with depth and usually is higher than the water table in the Blue Gate Member; thus, water from the Ferron leaks into the Blue Gate. In the Ferron outcrop area where water from the Ferron leaks downward into the underlying Tununk Member, and where a small amount of recharge is received from precipitation, head in the aquifer decreases with depth.

In addition to vertical movement of water through the aquifer, water moves laterally at approximately right angles to the potentiometric contours. On a regional scale, the strike and dip of beds in the aquifer have little effect on the movement of water. Movement of water is governed instead by the location and altitude of areas of recharge and discharge. In the Emery area, water moves through the aquifer from areas of subsurface recharge in the west and northwest toward areas of manmade discharge and toward areas of natural discharge mainly along the Ferron outcrop.

The potentiometric contours in figures 3.4-1 and 3.4-2 are based on measurements of different accuracy. The potentiometric surface was determined most accurately in tightly cased wells completed only in a part of the aquifer and in uncased test holes where an expandable packer was used to isolate different sections of the aquifer. However, less accurate data from uncased test holes where an expandable packer was not used also were considered in drawing potentiometric contours.

The altitude of the I-coal bed in the underground Emery Mine also was considered in drawing potentiometric contours for the upper section of the aquifer. Observations in the mine indicate that much of the aquifer has been dewatered above the I-coal bed. Water in the mine during 1979 was mostly in those areas farthest downdip, and much of the older mine workings were dry.

The Ferron Sandstone aquifer has yielded hydrogen sulfide, methane, and carbon dioxide gases to some wells in the Emery coal field. When the wells flowed water at the land surface, shut-in water pressures could not be determined accurately because of the gases.

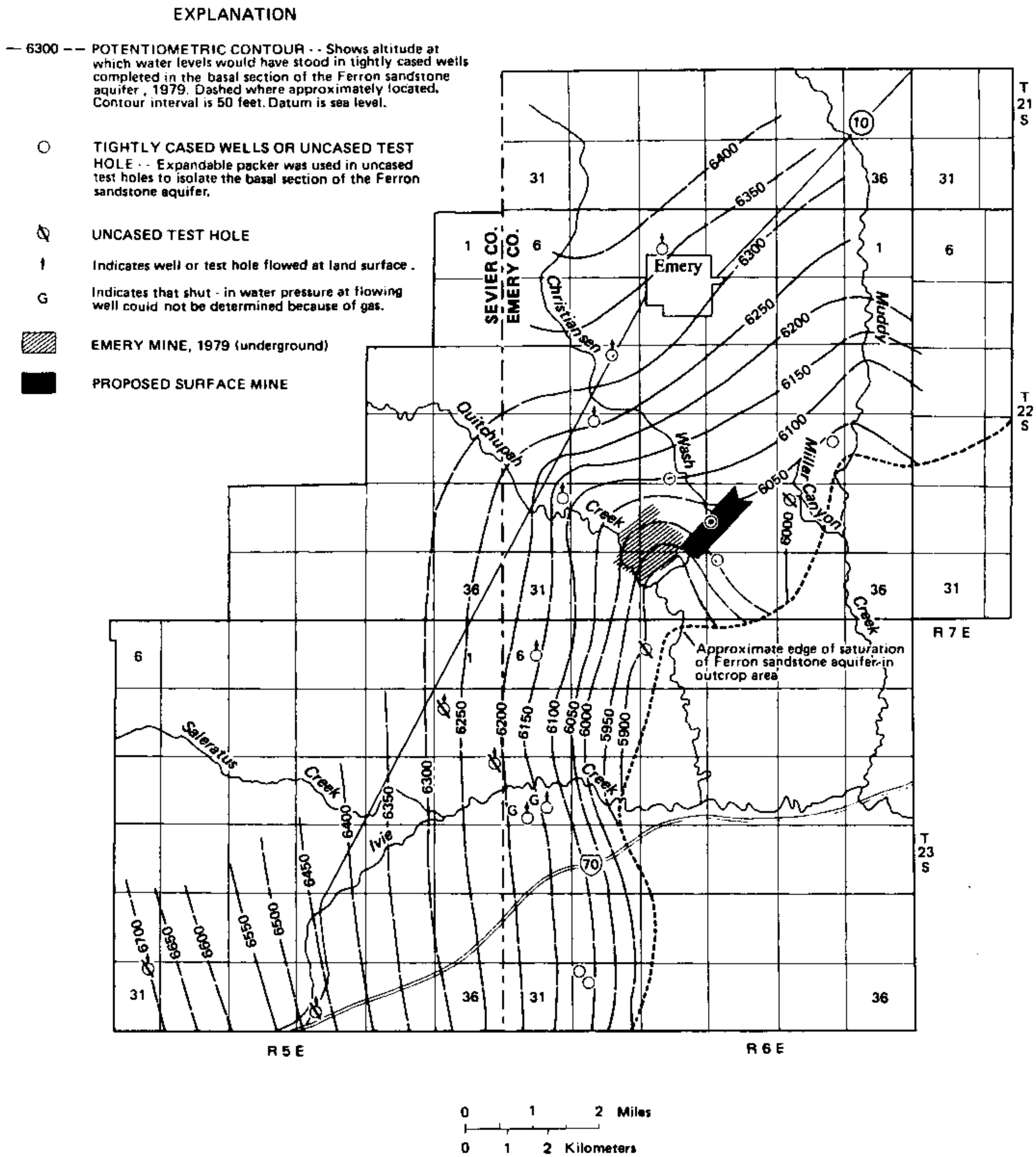

Figure 3.4-1.— Potentiometric surface of the basal section of the Ferron Sandstone aquifer.
(From Lines and Morrissey, 1983, fig. 8.)

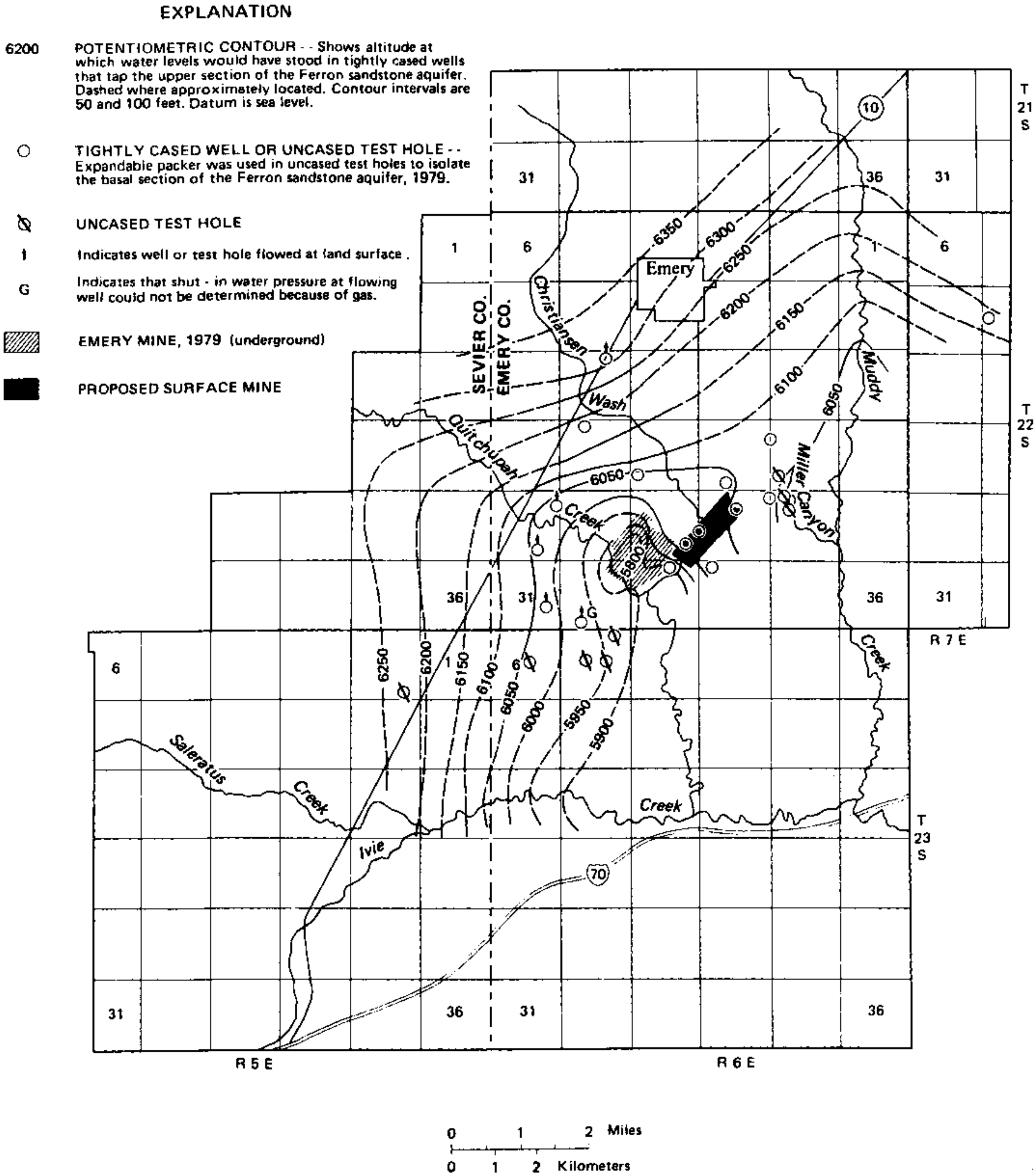

Figure 3.4-2.— Potentiometric surface of the upper section of the Ferron Sandstone aquifer.
(From Lines and Morrissey, 1983, fig. 9.)

3.5 WATER TABLE IN ROCKS OVERLYING THE FERRON

CONFIGURATION OF THE WATER TABLE DEFINED

In most areas, the water table in the Blue Gate and pediment gravels is lower than the potentiometric surface of the upper section of the Ferron Sandstone aquifer.

The approximate configuration of the water table (the level at which pressure is atmospheric) in rocks that overlie the Ferron Sandstone aquifer is shown in figure 3.5-1. During the summer of 1979, the water table in many areas was in the Blue Gate Member; but on the benches north of Quitchupah Creek, the water table was commonly in pediment gravels and alluvium.

Data to define the water table were available from 11 wells and test holes. Along perennial streams and irrigation canals and at springs that issue from the Blue Gate and pediment gravels, the water table was assumed to be at the altitude of the land surface. Along ephemeral streams, the water-table contours were drawn at an altitude below land surface. The water table was assumed to be within 50 feet of the land surface in areas of phreatophytes.

The water table in the Blue Gate and pediment gravels is lower than the potentiometric surface of the upper section of the Ferron Sandstone aquifer in most areas. This is not the condition, however, near the Emery Mine where the Ferron is being dewatered and where water from the Blue Gate leaks into the aquifer.

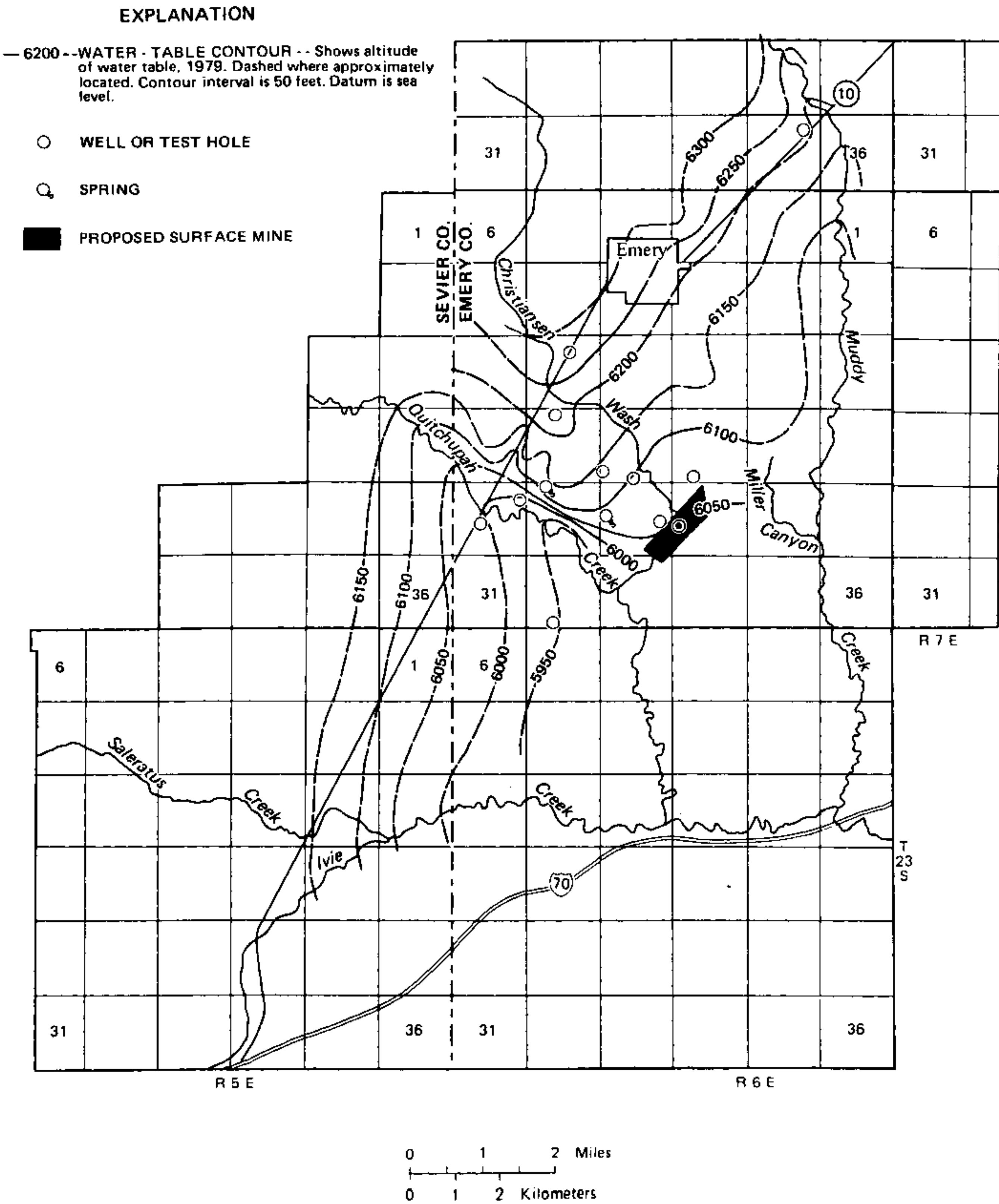

Figure 3.5-1.— Configuration of the water table in rocks that overlie the Ferron Sandstone aquifer.
(From Lines and Morrissey, 1983, fig. 10.)

3.0 THE GROUND-WATER SYSTEM

3.6 CHEMICAL QUALITY OF GROUND WATER

DISSOLVED-SOLIDS CONCENTRATIONS VARY MARKEDLY

Dewatering of the Emery Mine has changed water quality in the Ferron Sandstone aquifer.

Selected chemical analyses of ground water are listed in table 3.6-1. As shown in figures 3.6-1 and 3.6-2, dissolved-solids concentrations in the lower section of the Ferron Sandstone aquifer increase from the Paradise Valley-Joes Valley fault system toward the Ferron outcrop. Dissolved-solids concentrations also increase upward in the aquifer in most areas. Deterioration of water quality usually is due to increased concentrations of dissolved sodium and sulfate.

The configuration of lines of equal dissolved-solids concentration in figure 3.6-2 indicates that dewatering of the Emery Mine has improved water quality in the upper section of the Ferron between the mine and the fault system to the west. In this area, the increased movement of less saline water toward the mine from the west and from the lower part of the aquifer has more than offset any deterioration of water quality that may have been caused by downward leakage from the Blue Gate.

The largest observed dissolved-solids concentrations in the upper section of the Ferron east of the fault system were in an area near the proposed surface mine (fig. 3.6-2). Water in the Blue Gate Member, which contained about 20,000 mg/L of dissolved solids, was leaking into the Ferron in this area. The downward leakage of saline water from the Blue Gate was induced, at least in part, by dewatering of the Emery Mine.

Water quality in the Ferron deteriorates, at least in some areas, west of the Paradise Valley-Joes Valley fault system. This condition is consistent with the hypothesis that most of the water that recharges the Ferron from the west is transmitted along an extremely permeable zone created by the faulting.

Table 3.6-1— Selected chemical analysis of water from wells, test holes, springs, and the Emery Mine.

Water-bearing zone: Hub, Blue Gate Member of the Mancos Shale; Kmf, Ferron Sandstone Member of the Mancos Shale.

Method of Collection: A, air line used to lift water to surface; B, bailed; D, Sample collected while drilling with air; D6, sample recovered from drill-stem test; F, natural flow; p, pumped.

pH: Field determination except L, determined in laboratory.

Dissolved solids: Calculated from sum of constituents.

Specific conductance: Field determination except L, determined in laboratory; reported in micromhos per centimeter at 25˚ Celsius.

								Milligrams per Liter														
Location		Water-bearing zone	Interval sampled below land surface (feet)	Method of collection	Date of collection	Temperature (degree Celcius)	PH (units]	Dissolved Calcium (Ca)	Dissolved Magnesium (Mg)	Dissolved Sodium (Na)	Dissolved Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Dissolved Sulfate (SO_4)	Dissolved Chloride (Cl)	Dissolved Bromide (Br)	Dissolved Boron (B)	Dissolved Silica (SiO_2)	Hardness as $CaCO_3$	Noncarbonate Hardness as $CaCO_3$	Dissolved solids	Specific Conductance (micromhos at 25 ˚C)
T. 22S., R. 5E.																						
NE¼ SW¼ NE¼	sec. 23	Kmf	1,305-1,319	F	1-19-53	–	–	109	32	[1] 2,317	–	395	–	4,143	575	–	–	–	–	–	7,370	–
ditto.		Kmf	1,520-1,530	DS	1-28-53	–	–	222	62	[1] 2,077	–	855	–	3,465	707	–	–	–	–	–	6,954	–
T. 22S., R. 6E.																						
W¼ NE¼ NE¼	sec. 4	Kmf	1,586-1,614	F	2- 5-79	26.0	7.9	31	19	180	4.1	280	0	350	20	0.1	0.22	15	160	0	757	1,100
SW¼ NW¼ NE¼	sec. 17	Kmf	1,368-1,543	F	7-10-79	25.0	7.6L	29	19	200	4.4	300	–	300	32	.2	.23	16	150	0	749	1,150L
ditto.		Kmf	1,040-1,100	F	12-14-78	15.5	8.1	19	14	290	5.1	310	0	440	30	.2	.29	16	110	0	967	1,480
NW¼ SW¼ SW¼	sec. 21	Kmf	600- 725	A	11-30-78	10.5	9.0	19	16	460	4.4	570	5	590	31	.2	.61	12	110	0	1,420	2,100
SE¼ SE¼ SW¼	sec. 22	Kmf	100- 275	P	4-19-79	13.0	7.1	300	290	880	12.	640	0	3,200	120	.5	.62	19	1,900	1,400	5,140	6,100
NE¼ SE¼ SE¼	sec. 23	Kmf	Spring	F	4-04-78	10.0	7.5L	130	110	660	5.3	690	–	1,500	110	.5	.47	12	780	210	2,870	3,850L
NE¼ NW¼ NW¼	sec. 26	Kmf	At 29	B	5-31-78	12.5	–	510	370	240	8.3	6	–	3,000	45	.3	2.6	18	2,800	2,800	4,200	4,500
NW ¼ NW¼ NW¼	sec. 26	Kmf	40- 349	P	6-21-79	12.5	3.6L	110	930	940	10.	0	0	5,900	140	1.0	.77	36	4,100	4,100	8,070	10,700
NE¼ NW¼ SW¼	sec. 27	Kmf	75- 150	A	11-17-78	8.5	7.4L	140	220	760	48.	330	–	2,500	20	.5	.43	21	1,300	980	3,870	5,000
ditto.		Kmb	51- 71	B	5-31-79	11.0	7.9L	170	1,100	4,000	46.	300	–	12,000	230	.8	1.1	6.9	5,000	4,700	17,700	20,000
NE¼ SW¼ NW¼	sec. 28	Kmf	In Mine	F	3-29-79	13.0	8.7	9.3	9.2	380	2.6	590	0	390	28	.2	.59	12	61	0	1,120	1,620
NE¼ NW¼ SW¼	sec. 28	Kmf	In Mine	F	9-01-78	13.5	8.4	24	29	420	2.6	[2] 630	–	520	28	.3	.58	13	180	0	1,350	2,040L
SW¼ NE¼ NE¼	sec. 30	Kmf	838- 884	F	10-15-79	19.0	8.0	12	6.9	220	4.4	[2] 400	0	180	16	.1	.35	14	58	0	652	1,100
SE¼ NW¼ NW¼	sec. 34	Kmf	At 160	D	12-12-78	10.5	8.9	10	6.3	260	6.3	430	–	230	23	.1	.36	11	51	0	759	1,100
		Kmf	273- 360	A	12-04-78	9.0	9.1	14	7.4	300	5.2	700	17	140	21	.2	.47	3.9	65	0	854	
T. 23S., R. 6E.																						
SW¼ SW¼ NE¼	sec. 6	Kmf	At 385	D	11-21-78	12.5	8.2	35	19	370	4.1	280	0	660	49	.4	.30	15	170	0	1,290	1,980
ditto.		Kmf	665- 720	A	11-28-78	13.5	8.9	13	4.3	290	3.2	370	13	330	30	.2	.35	11	50	0	877	1,400
NE¼ NW¼ SE¼	sec. 17	Kmf	Spring	F	11-08-78	13.0	7.4 L	210	190	470	8.1	360	–	1,800	150	.6	.56	16	1,300	1,000	3,020	3,720L
NW¼ SE¼ SE¼	sec. 18	Kmf	160- 484	F	10-26-78	17.0	7.8	34	18	170	4.2	280	0	290	16	.2	.19	15	160	0	686	980
NW¼ NW¼ NW¼	sec. 32	Kmf	225- 280	P	9-20-78	13.5	8.7L	6.0	2.1	370	1.8	420	–	450	16	.4	.33	8.1	24	0	1,060	1,650

[1] Sodium plus potassium

[2] Estimated from total laboratory alkalinity

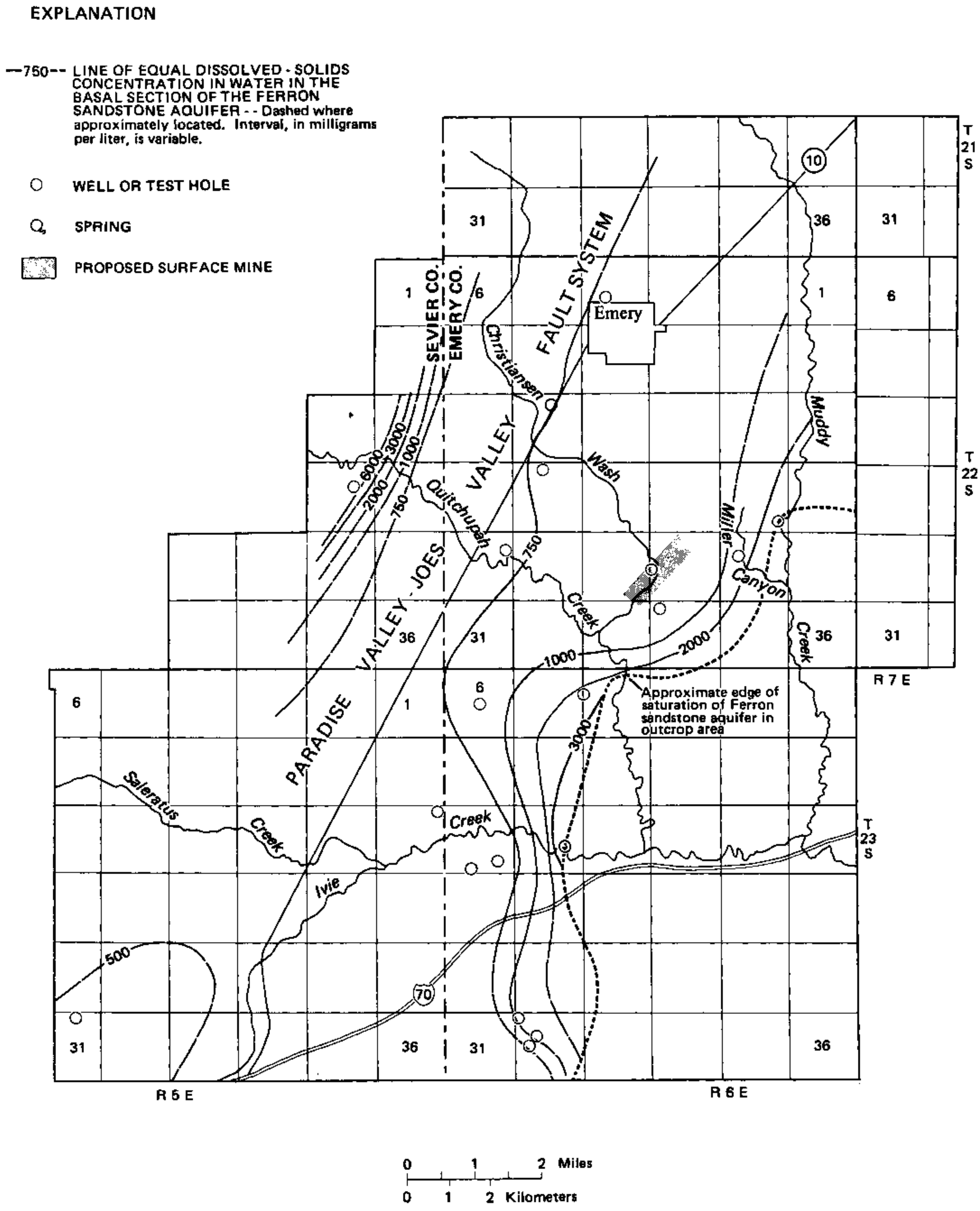

Figure 3.6-1.— Concentration of dissolved solids in water in the basal section of the Ferron Sandstone aquifer.
(From Lines and Morrissey, 1983, fig. 14.)

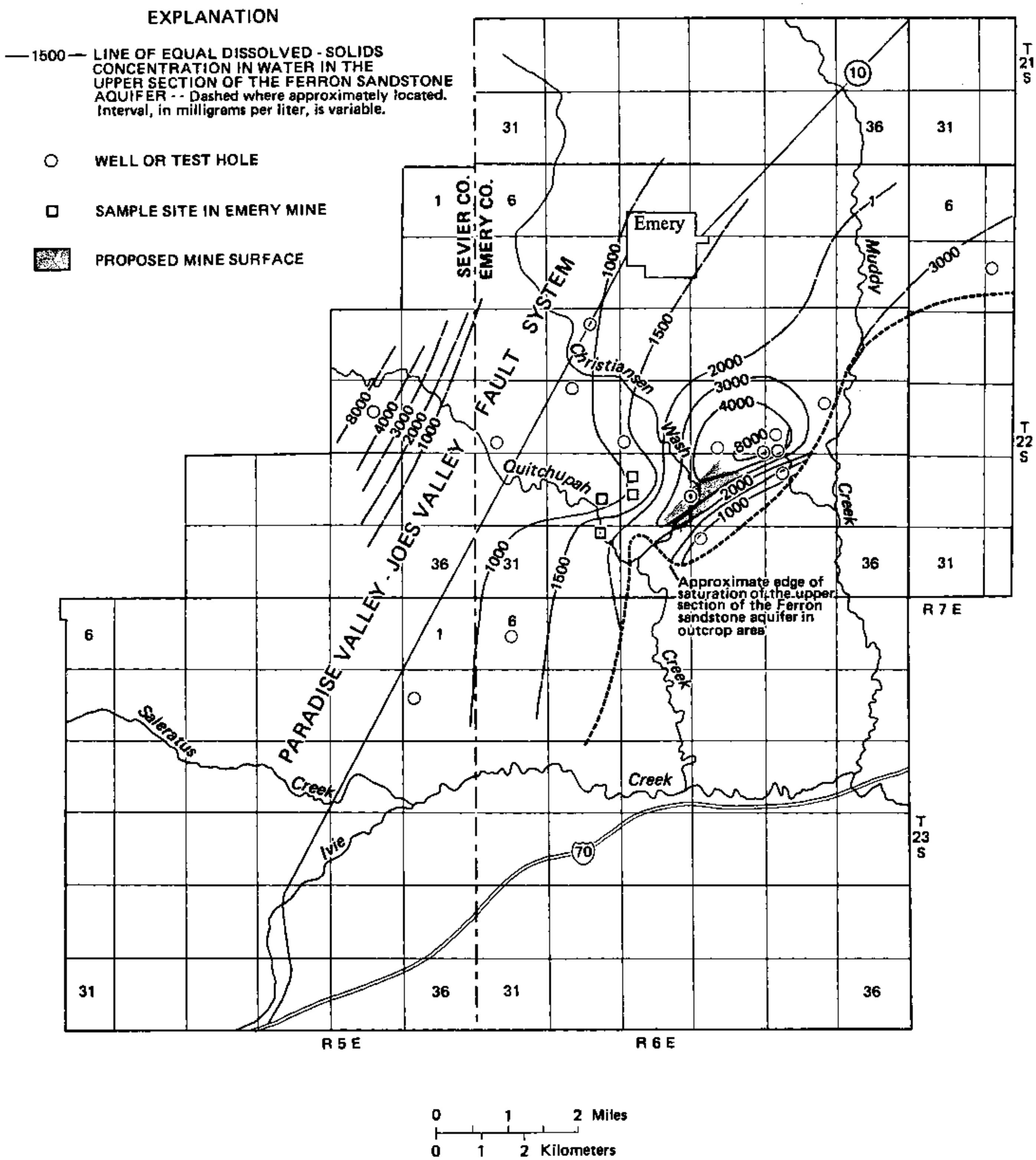

Figure 3.6-2.— Concentration of dissolved solids in water in the upper section of the Ferron Sandstone aquifer.
(From Lines and Morrissey, 1983, fig. 15.)

4.0 PROBABLE HYDROLOGIC CONSEQUENCES

4.1 UNDERGROUND MINING

PATTERN OF GROUND-WATER FLOW CHANGED BY MINE DEWATERING

Water levels in wells have declined due to dewatering of the Emery Mine.

Dewatering of the Emery Mine has changed the pattern of ground-water flow near the mine, and part of the upper section of the Ferron Sandstone aquifer has been dewatered. Changes in the flow pattern near the mine are illustrated in figure 4.1-1. Prior to mining, the vertical component of flow was upward from the Ferron into the Blue Gate Member. As mining progressed, ground-water flow was directed toward the mine workings, and much of the aquifer and other rocks above the mined coal bed were dewatered. The steady-state pattern of flow shown in figure 4.1-1 probably would not develop unless mining ceased and dewatering of the mine continued for several years.

Discharge from the mine averaged 0.7 ft^3/s during 1979, and the discharge will probably increase as the mine progresses farther downdip and into areas of larger aquifer transmissivity.

Water levels in four representative wells completed in the Ferron Sandstone aquifer in the Emery coal field are shown in figure 4.1-2. Water-level declines in the wells are due to manmade withdrawals of water from the aquifer, mainly dewatering of the Emery Mine. The two hydrographs (fig. 4.1-2) that have the smallest and greatest water-level declines are for wells in the NW¼NW¼SW¼ sec. 27, T. 22 S., R. 6 E. The water level in the well completed in the Blue Gate and most of the Ferron Sandstone aquifer has changed very little in comparison to the water level in the well completed in the upper section of the Ferron. The different water-level responses indicate the importance of constructing observation wells completed in only a small interval of an aquifer, particularly near dewatered mine shafts where head differences with depth can be great.

As discussed earlier, dewatering of the Emery Mine has improved water quality in the upper section of the aquifer in some areas, particularly west of the mine. However, water quality in the upper section of the Ferron has deteriorated northeast of the mine as a result of induced leakage of saline water from the Blue Gate.

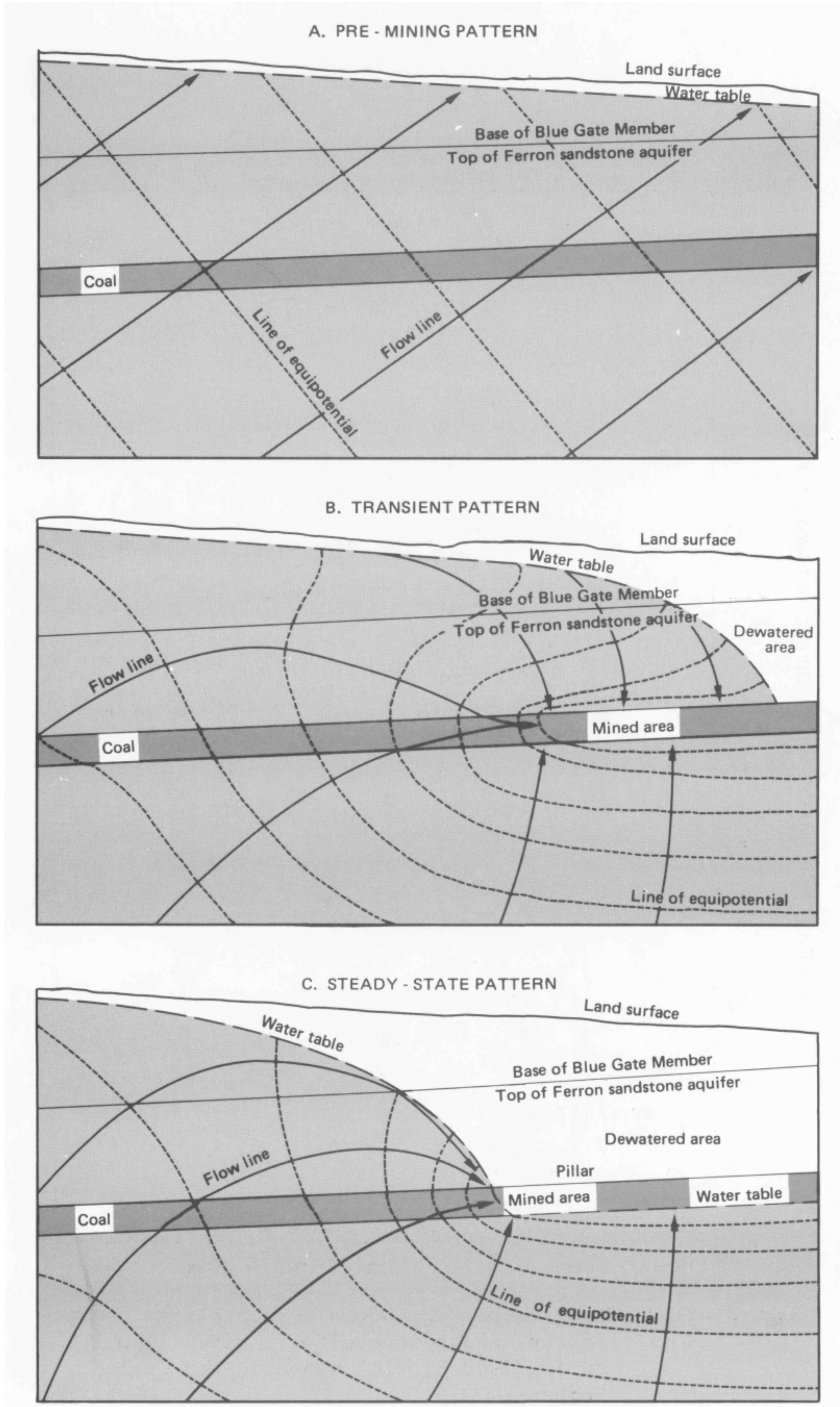

Figure 4.1-1.— Cross sections showing the approximate pre-mining, transient, and steady-state portions of ground-water flow around the Emery Mine.

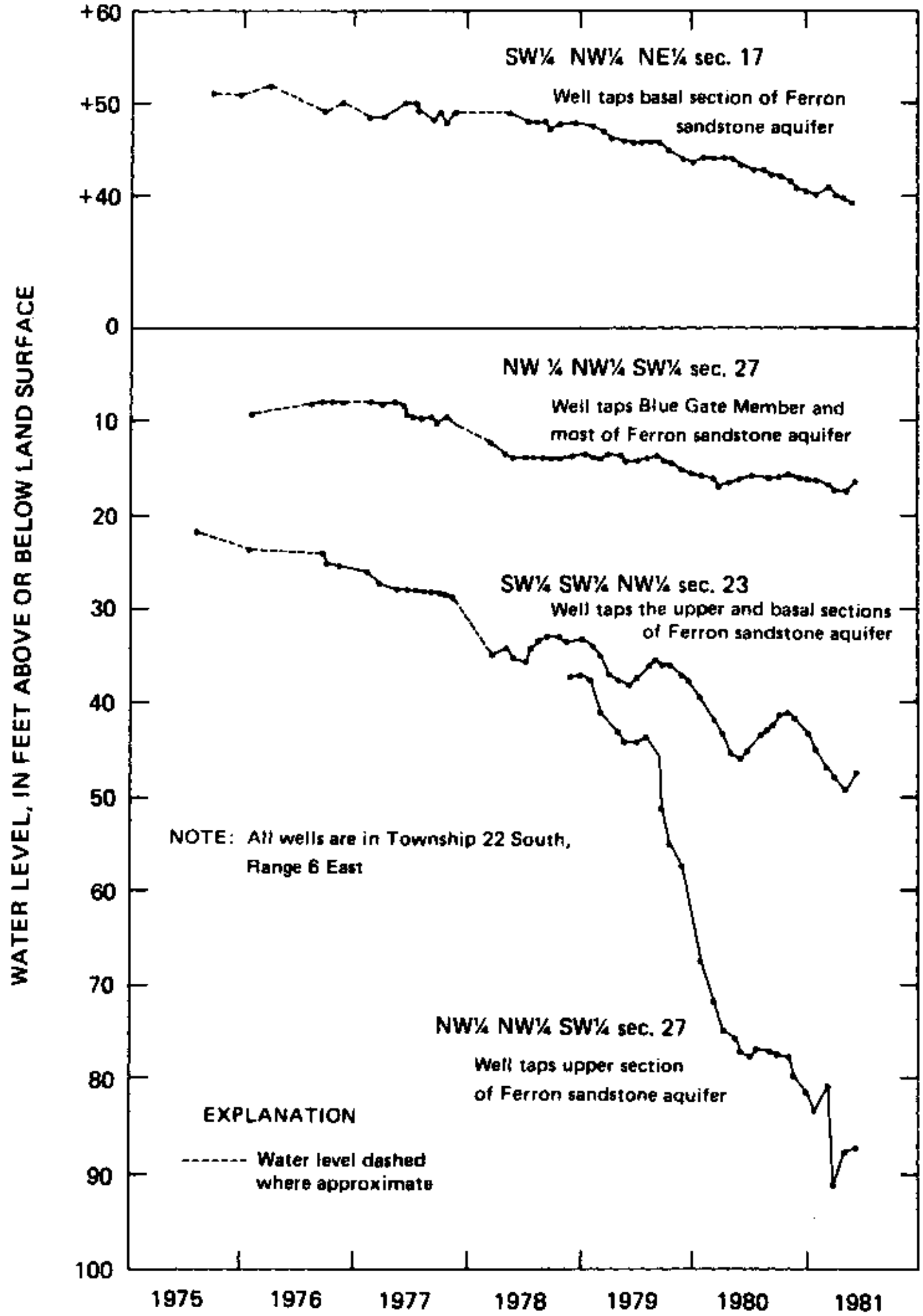

Figure 4.1-2.— Water levels in four wells completed in the Ferron Sandstone aquifer. (Water levels during 1980-81 from Consolidated Coal Company.)

4.0 PROBABLE HYDROLOGIC CONSEQUENCES

4.2 PROPOSED SURFACE MINING

HYDROLOGIC EFFECTS OF SURFACE MINING CAN BE PREDICTED

Discharge from the mine is predicted to average 0.3 ft^3/s; in the upper section of the Ferron Sandstone aquifer, drawdowns greater than 5 feet would extend about 2.5 miles from the mine after 15 years.

A three-dimensional digital-computer model was used to simulate ground-water flow in the Ferron Sandstone aquifer and to predict the effects of dewatering the proposed surface mine on potentiometric surfaces and the base flow of streams (8). Although predictions made with the model are considered to be semiquantitative, the model provides the most realistic method available to analyze the effects of mine dewatering on the aquifer.

Discharge from the surface mine is predicted to average about 0.3 ft^3/s during the proposed 15 years of operation. Water discharged from the surface mine would be balanced by a decrease in storage in the Ferron Sandstone aquifer, by a decrease in water entering the underground Emery Mine, by a decrease in natural leakage from the aquifer, and by an increase in leakage from the Blue Gate Member.

The predicted drawdown of the potentiometric surface of the upper section of the Ferron Sandstone aquifer (the section in which surface mining is proposed) after 15 years of mine dewatering is shown in figure 4.2-1. Other sections of the aquifer also would be affected, but drawdowns would not be as great.

Model calculations indicate that leakage from the Blue Gate into the Ferron would increase by about 0.05 ft^3/s. Practically all (98 percent) of the increased leakage would occur within the area of drawdown greater than 5 feet shown in figure 4.2-1. Dewatering of the surface mine may further deteriorate water quality in the upper section of the Ferron in the area between the mine and the head of Miller Canyon. However, water quality in the upper section of the Ferron may improve in other areas as it did near the underground mine, particularly in the area west of the surface mine.

Modeling results indicate that dewatering of the surface mine would not affect the base flow of streams. If water from the mine were discharged into Christiansen Wash, however, streamflow would increase accordingly. The predicted mine discharge of 0.3 ft^3/s would almost be equal to the minimum observed flow of Christiansen Wash during 1979.

Water entering the surface mine would be mainly from the Ferron Sandstone aquifer, which contains 1,000 to 8,000 mg/L of dissolved solids. Some water from the Blue Gate Member, which contains about 20,000 mg/L of dissolved solids, also will enter the mine. Chemical quality of the mine water, therefore, would vary with time and probably would have dissolved-solids concentrations within a range of 2,000 to 10,000 mg/L. The dissolved-solids

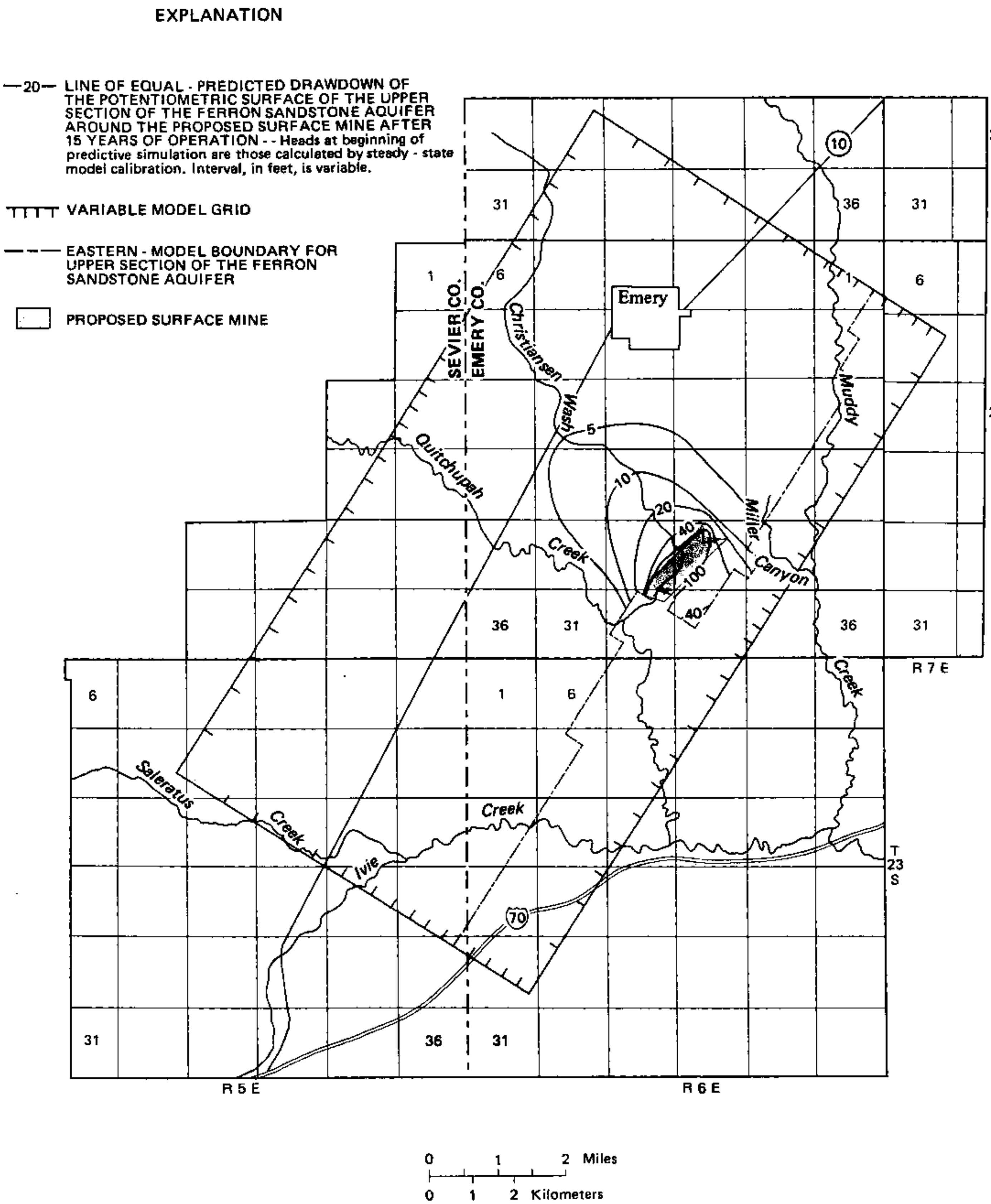

Figure 4.2-1.— Variable grid used in the three-dimensional digital-computer drawdown of the potentiometric surface of the upper section of the Ferron Sandstone aquifer around the proposed surface mine after 15 years of operation. (From Lines and Morrissey, 1983, fig. 20.)

concentrations of 12 samples obtained monthly from Christiansen Wash downstream from the proposed surface mine during the 1979 water year ranged from 582 to 4,470 mg/L (5). Thus, at least during some periods, the dissolved-solids concentration of water in Christiansen Wash would be increased if mine water were discharged into the stream.

5.0 GROUND-WATER MONITORING

NETWORK OF OBSERVATION WELLS NEEDED

The observation wells are needed to monitor changes in potentiometric surfaces and changes in water quality caused by mine dewatering.

A network of observation wells would be needed near the underground Emery Mine and the proposed surface mine to monitor changes in potentiometric surfaces and water quality in the Ferron Sandstone aquifer. Observation wells would be constructed so that each well is completed in a selected part of the aquifer. The wells would be grouped in clusters of three: one well would be completed in the Blue Gate Member; one, the upper section of the Ferron; and, one, the lower section of the Ferron.

Five or six clusters of observation wells in which water levels are measured monthly probably would be adequate to monitor changes in potentiometric surfaces. In addition, wells completed in the upper section of the Ferron (the section that will be mined) would need to be pumped annually to obtain samples for chemical analyses and to detect possible changes in water quality. One possible network of observation wells is shown in figure 5.0-1.

The quantity of water discharge from the mines would need to be continuously monitored. Temperature, specific conductance, and pH of the mine-discharge water would be monitored daily and samples collected for chemical analysis at least monthly.

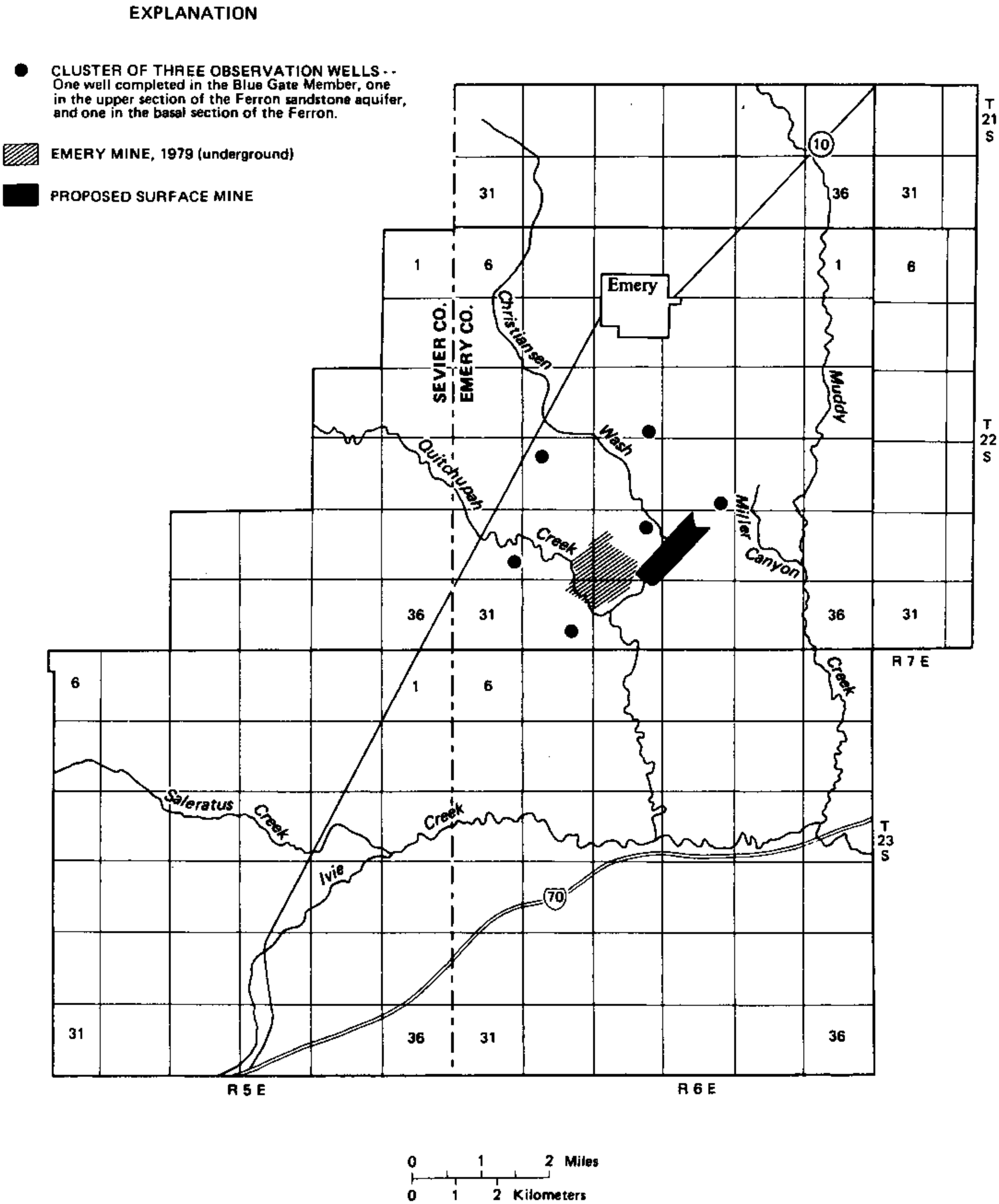

Figure 5.0-1.— A hypothetical network of observation wells used to monitor water levels and water quality near the Emery mine and the proposed surface mine.

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