GROUND-WATER STUDY 3

by

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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

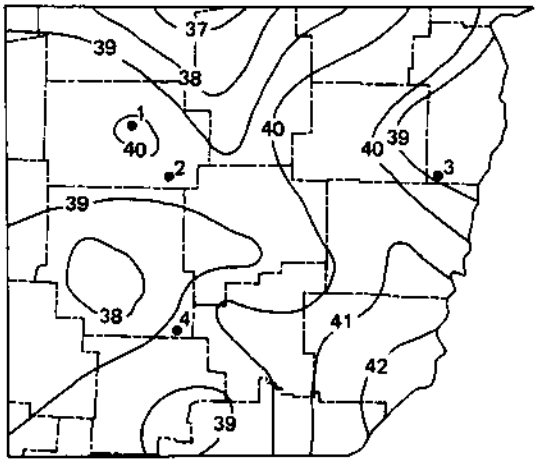
The area has a continental climate and low relief.

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).

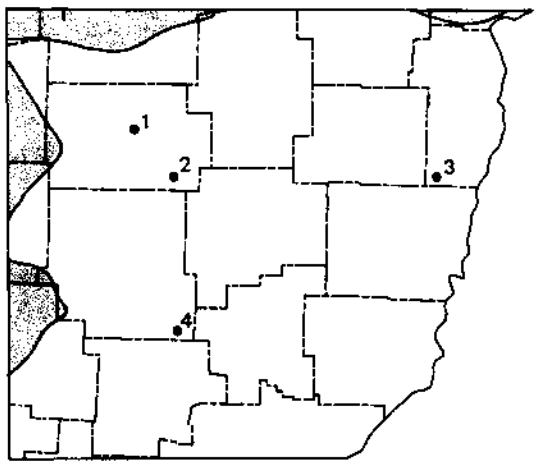
The extent of mining in the area is shown in figure 2.0-4. Most of the mined areas were forested or used for agriculture before mining.



EXPLANATION

–39– Line of equal mean annual precipitation Interval 1 inch

• Location of the study watersheds



EXPLANATION

Glaciated region

Unglaciated region

• Location of the study watersheds

0 50 Miles

0 50 Kilometers

Figure 2.0-1. Precipitation

Figure 2.0-2. Physiography

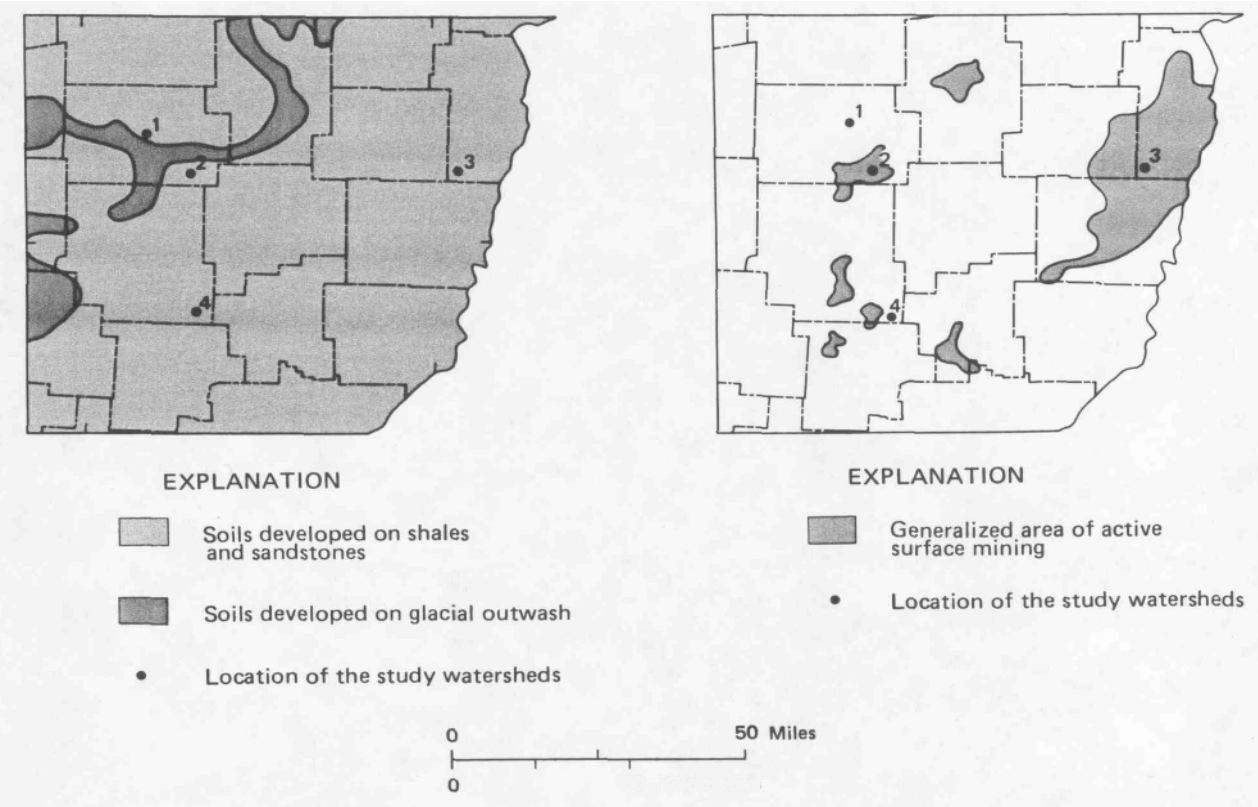


Figure 2.0-3.— Soils

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).

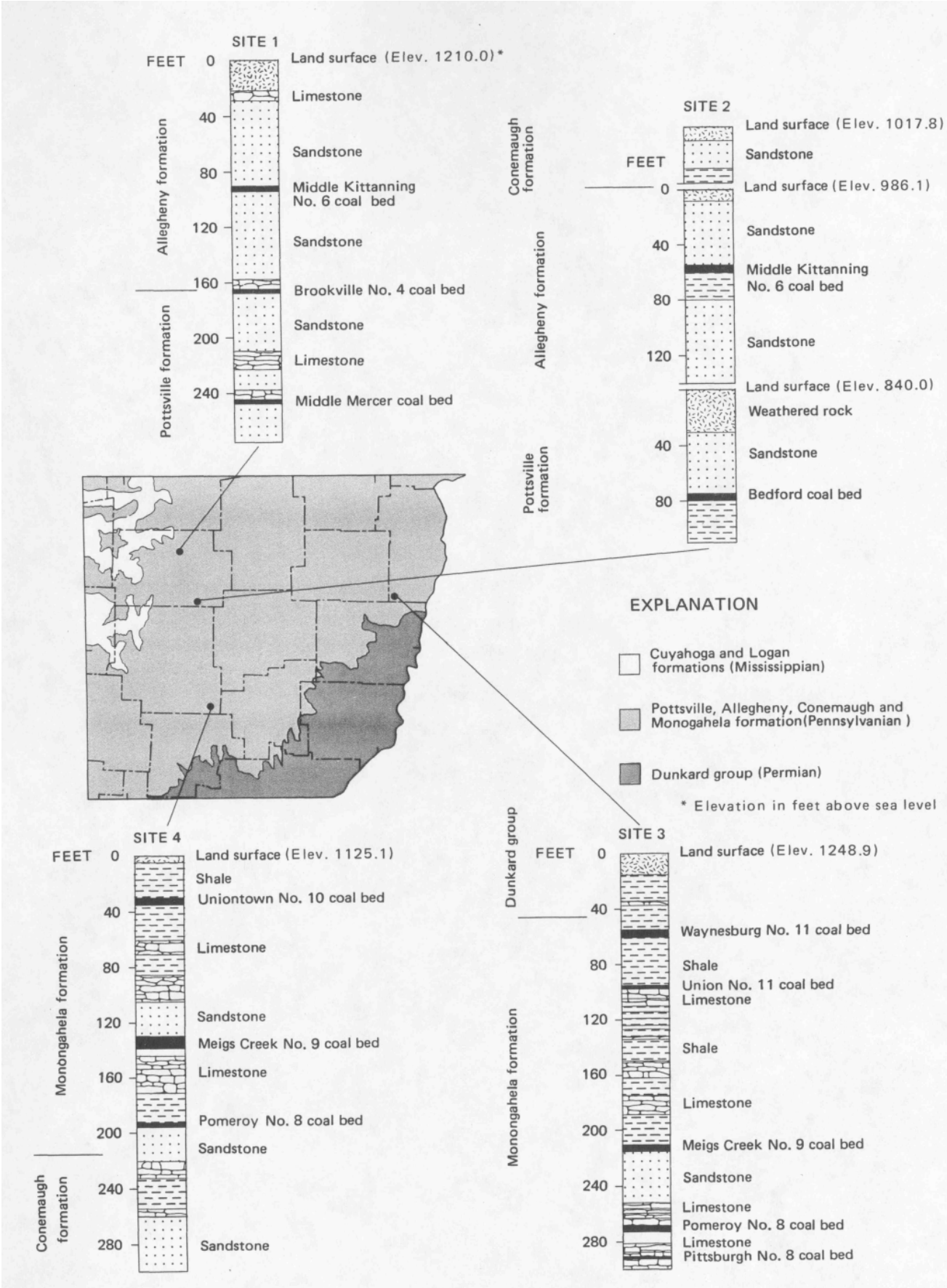


Figure 3.0-1.— Stratigraphic sections of the four watersheds.

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.

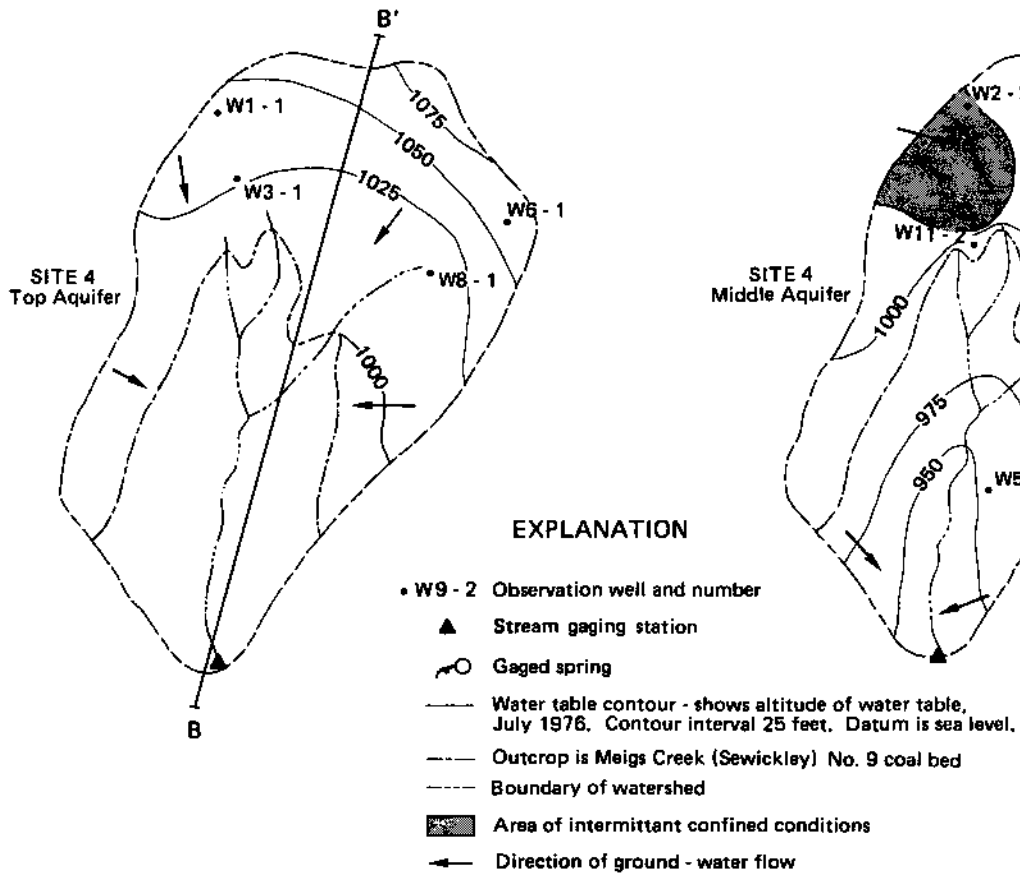


Figure 4.1-1.— Ground-water movement in the top aquifer. (From U.S. Bureau Mines, 1983, fig. 14.)

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

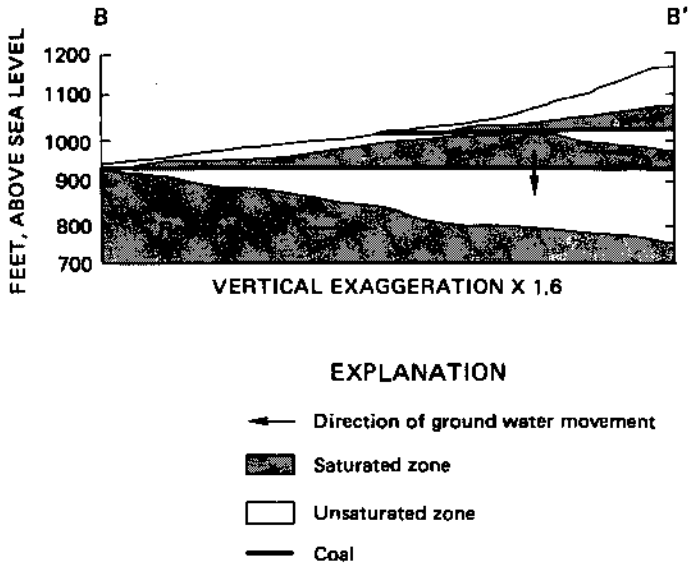


Figure 4.1-3.— Pre-mining cross section showing ground-water occurrence and movement. (From U.S. Bureau of Mines, 1983, fig. 12.)

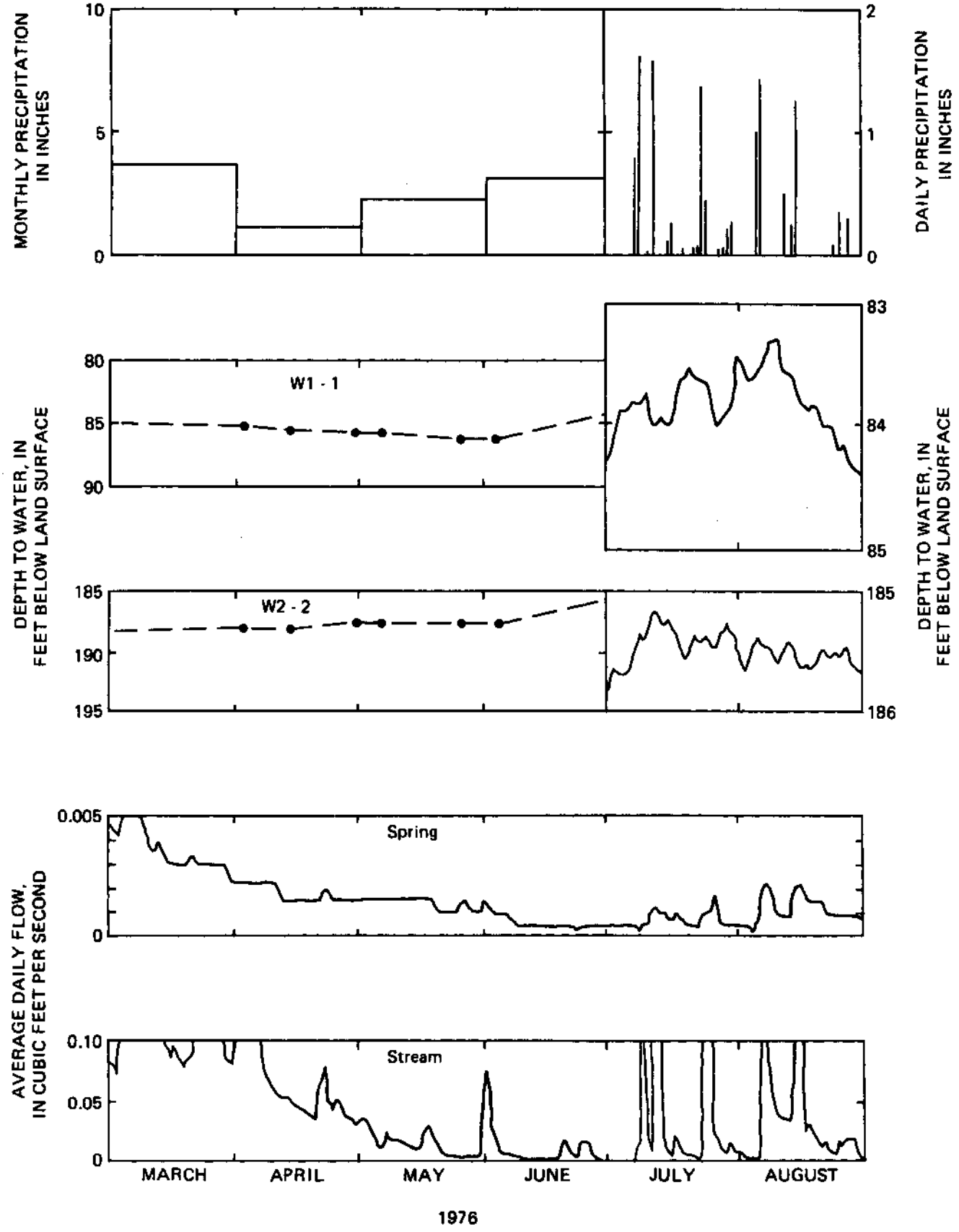


Figure 4.1-4.— Graphs of precipitation, ground-water levels, spring flow, and streamflow at site 2 for part of 1976. (From U.S. Bureau of Mines, 1978b.)

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
	W 1-1*	1.8	1.0	1.8	0.28	0.12
	W 4-2	.81	–	–	.26	–
1	W 6-2	–	–	3.2	–	–
	W 8-2	.58	.80	–	–	.17
	W10-2	–	–	.81	–	–
	W11-2	3.0	–	14	–	–
	W 1-1	–	–	110	–	–
	W 3-1	–	–	220	–	–
4	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.

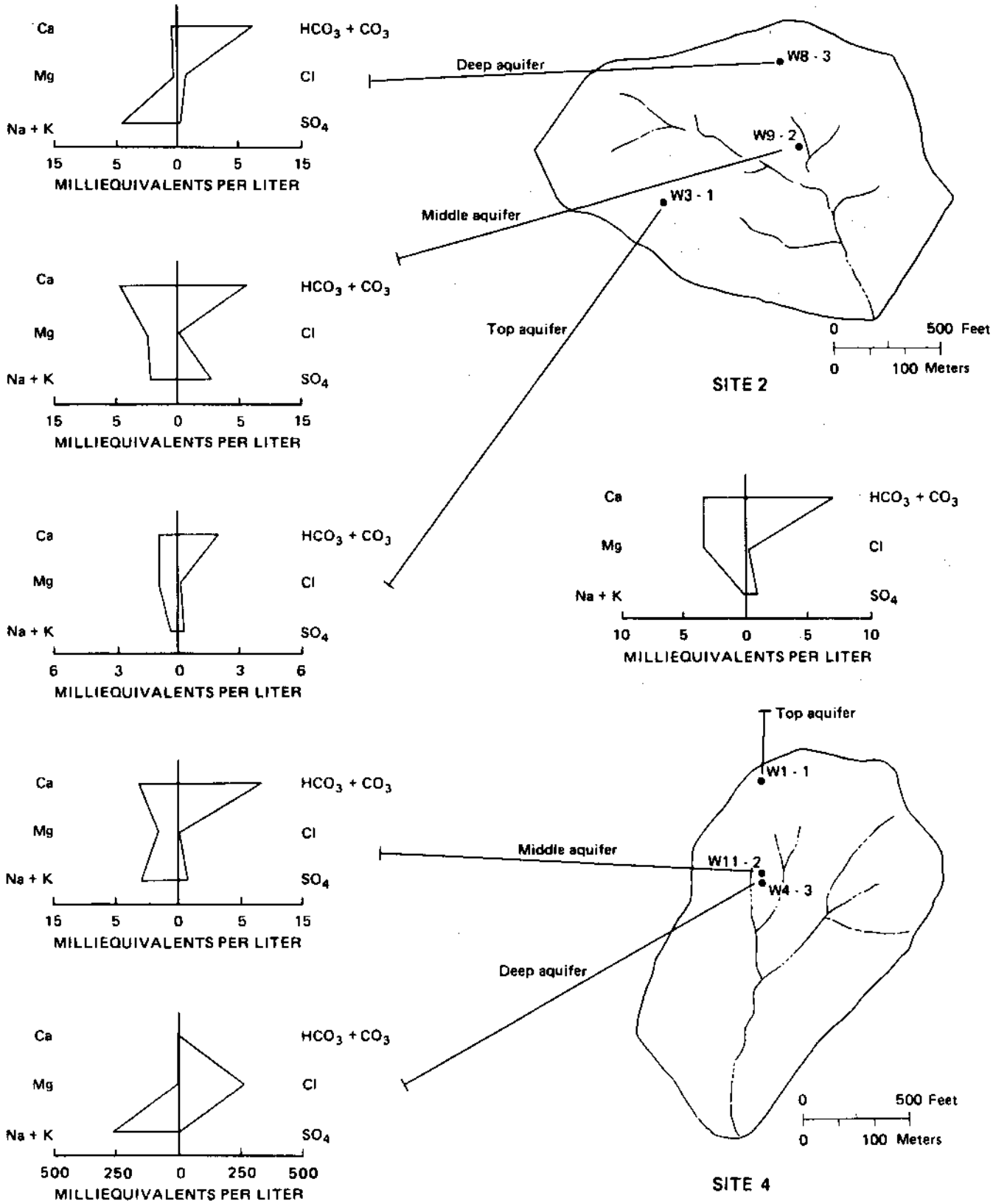


Figure 4.2-1.— Stiff diagrams showing premining water quality at sites 2 and 4.

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

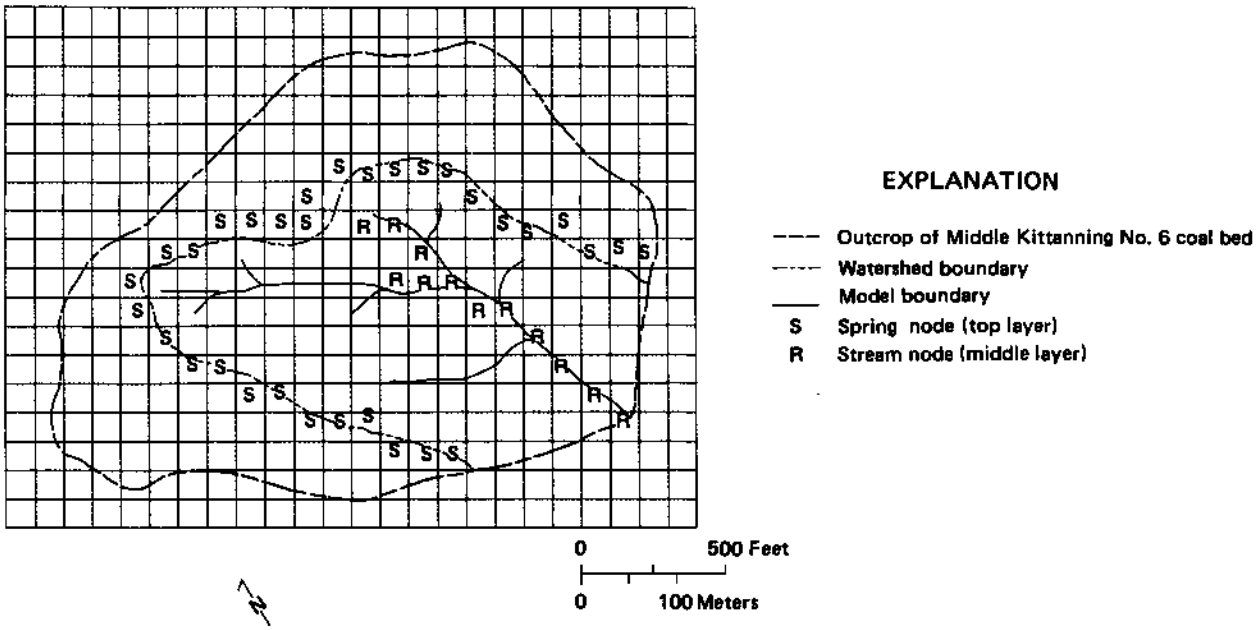


Figure 4.3-1— Ground-water-flow model grid for site 2.

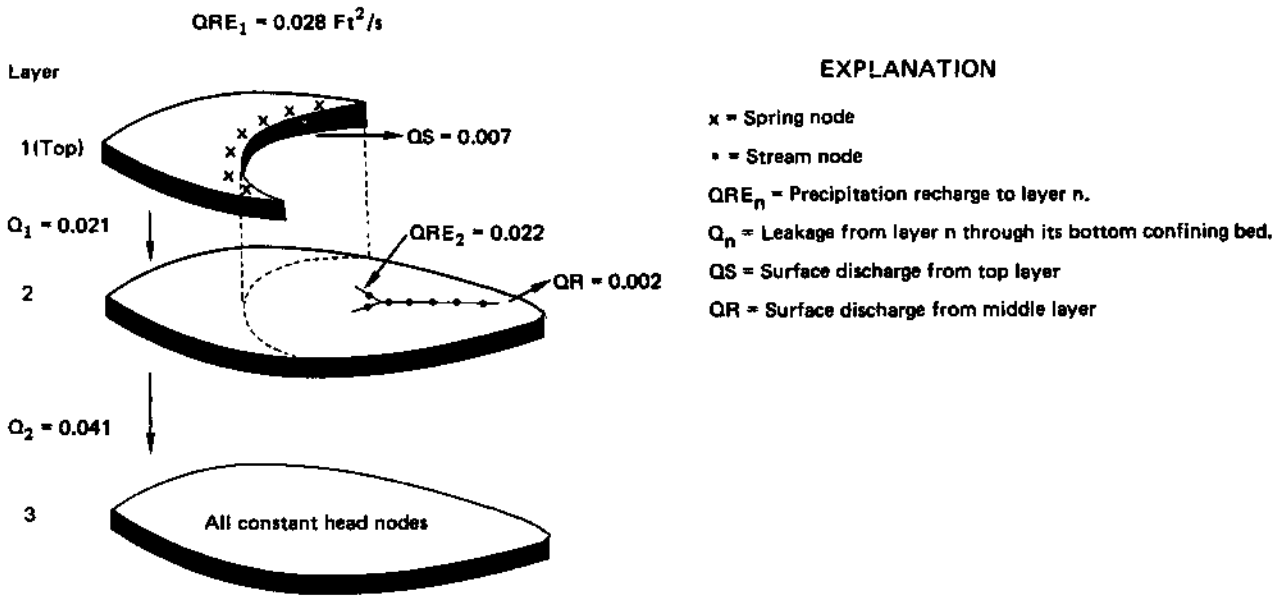


Figure 4.3-2.— Schematic diagram of components of ground-water flow model for site 2.

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.

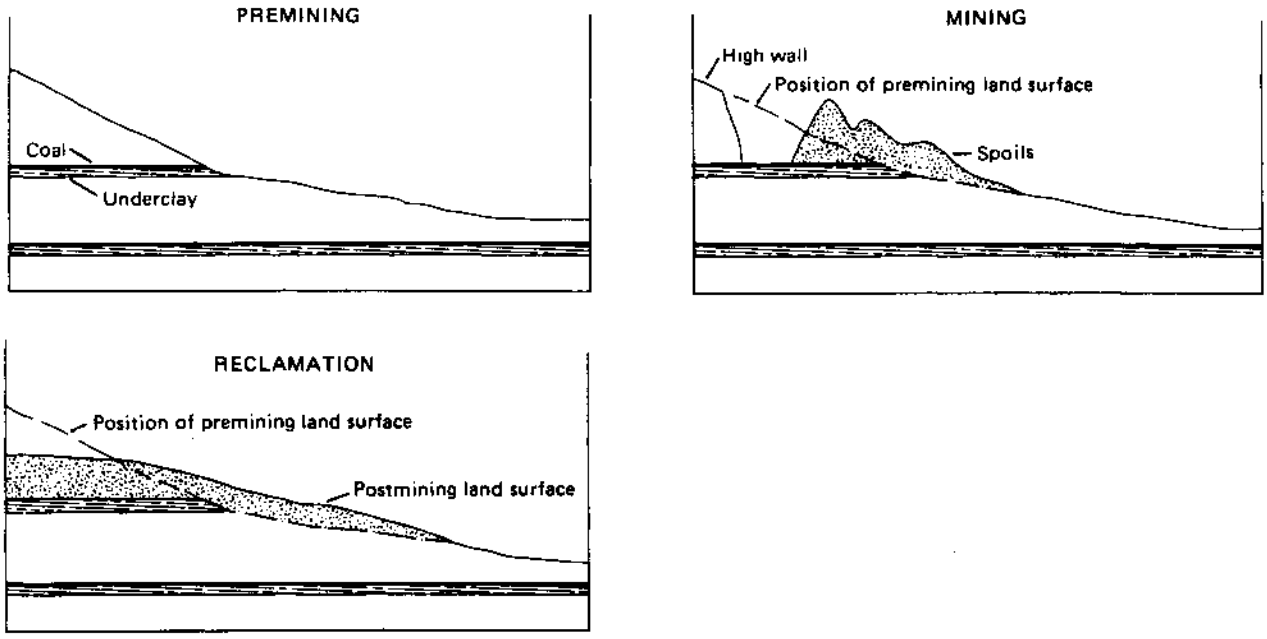


Figure 5.1-1.— Schematic sections illustrating surface-mining process. (From Helgesen and Razem, 1981, fig. 2.)

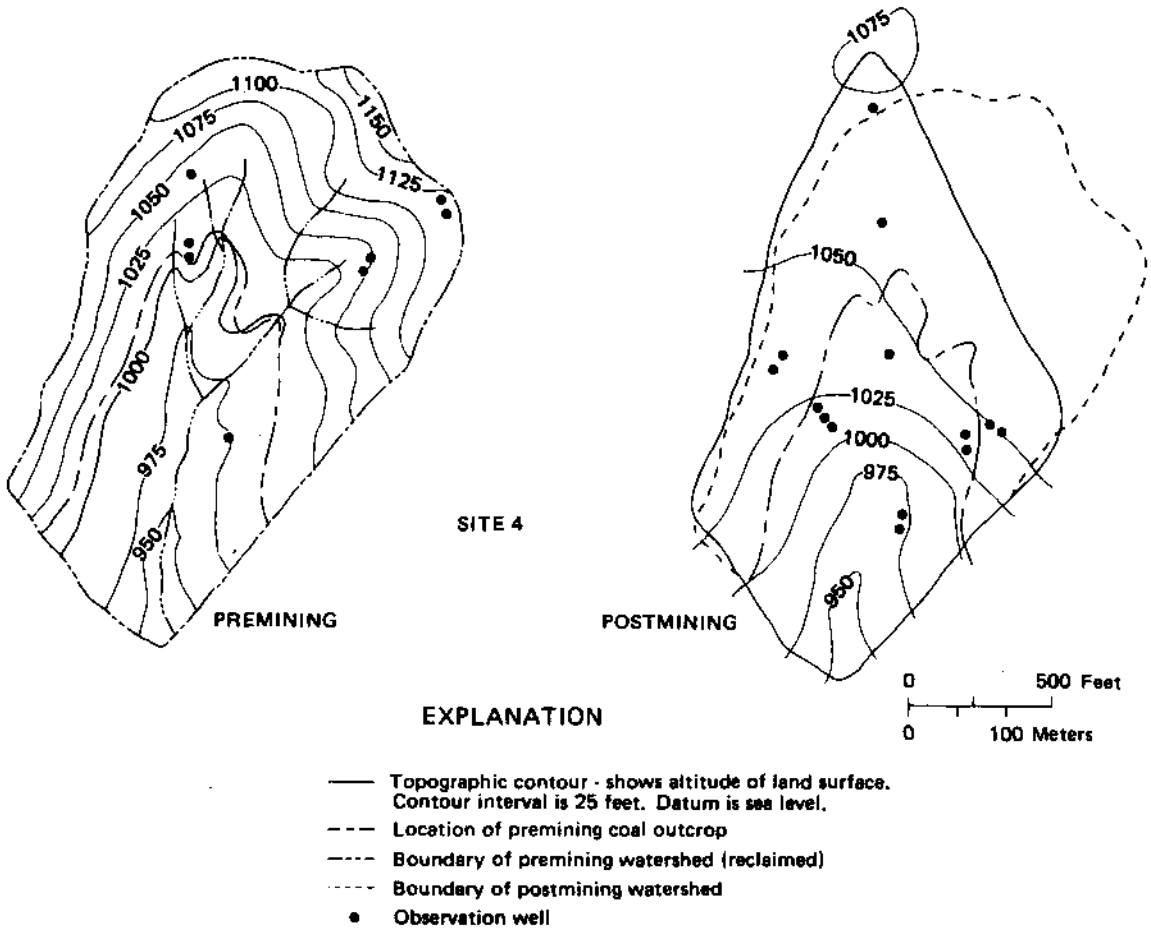


Figure 5.1-2.— Effects of mining on topography and drainage.
(From U.S. Bureau of Mines, 1983, figs. 2 and 24.)

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.

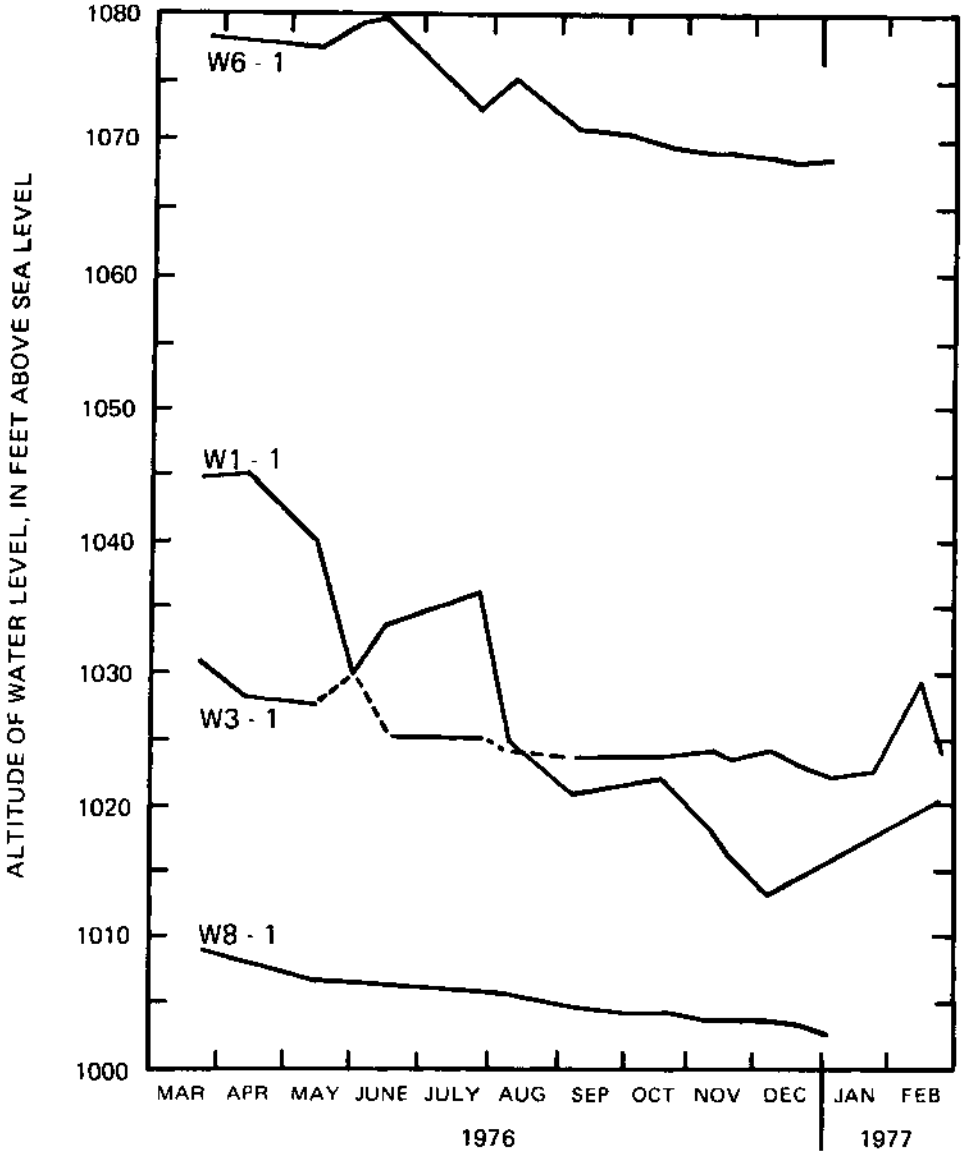


Figure 5.2-1.— Hydrographs for observation wells completed in the top aquifer at site 4.

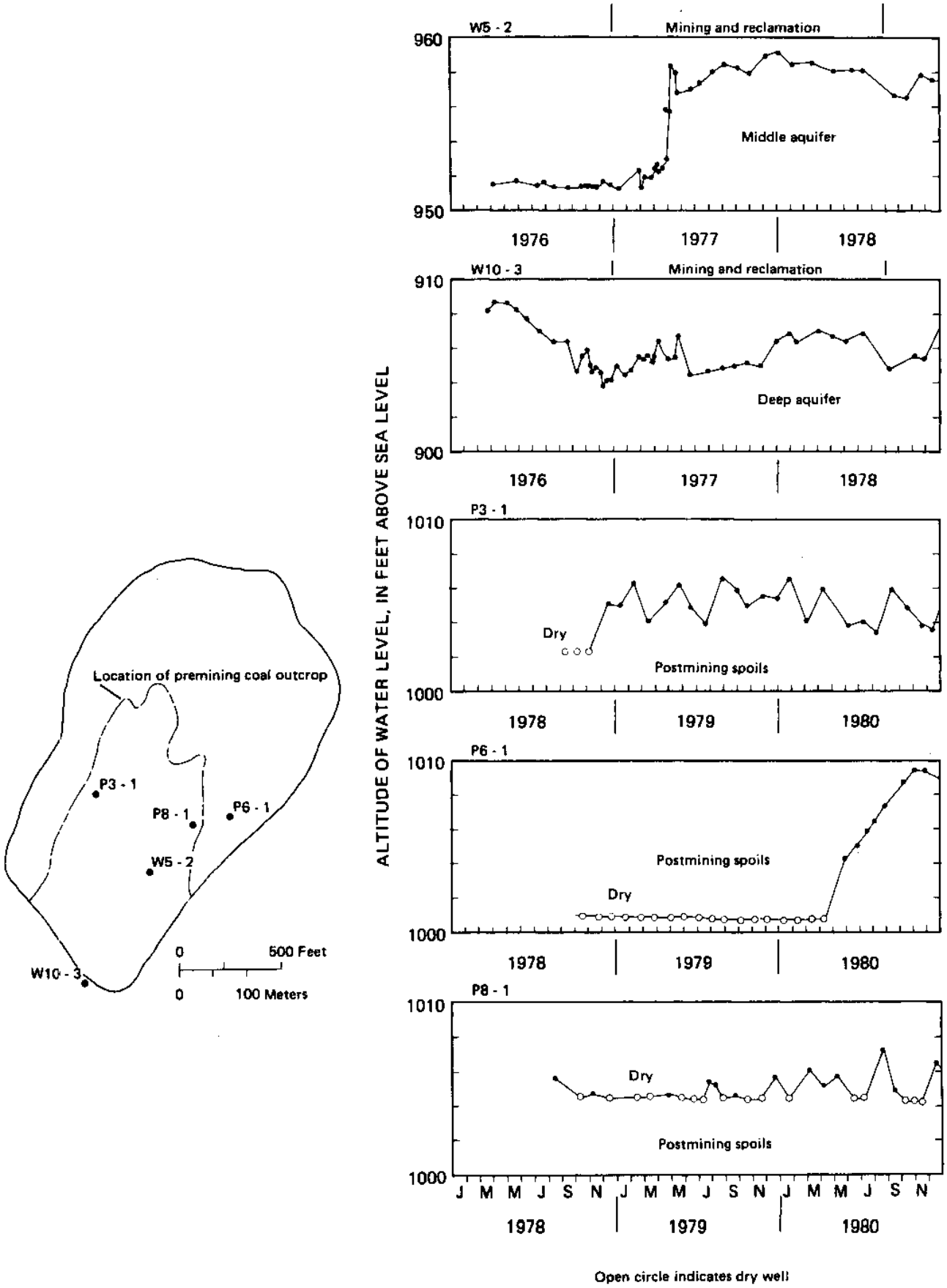


Figure 5.2-2.— Hydrographs of observation wells at site 4.
(From U.S. Bureau of Mines, 1983, fig. 47.)

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.

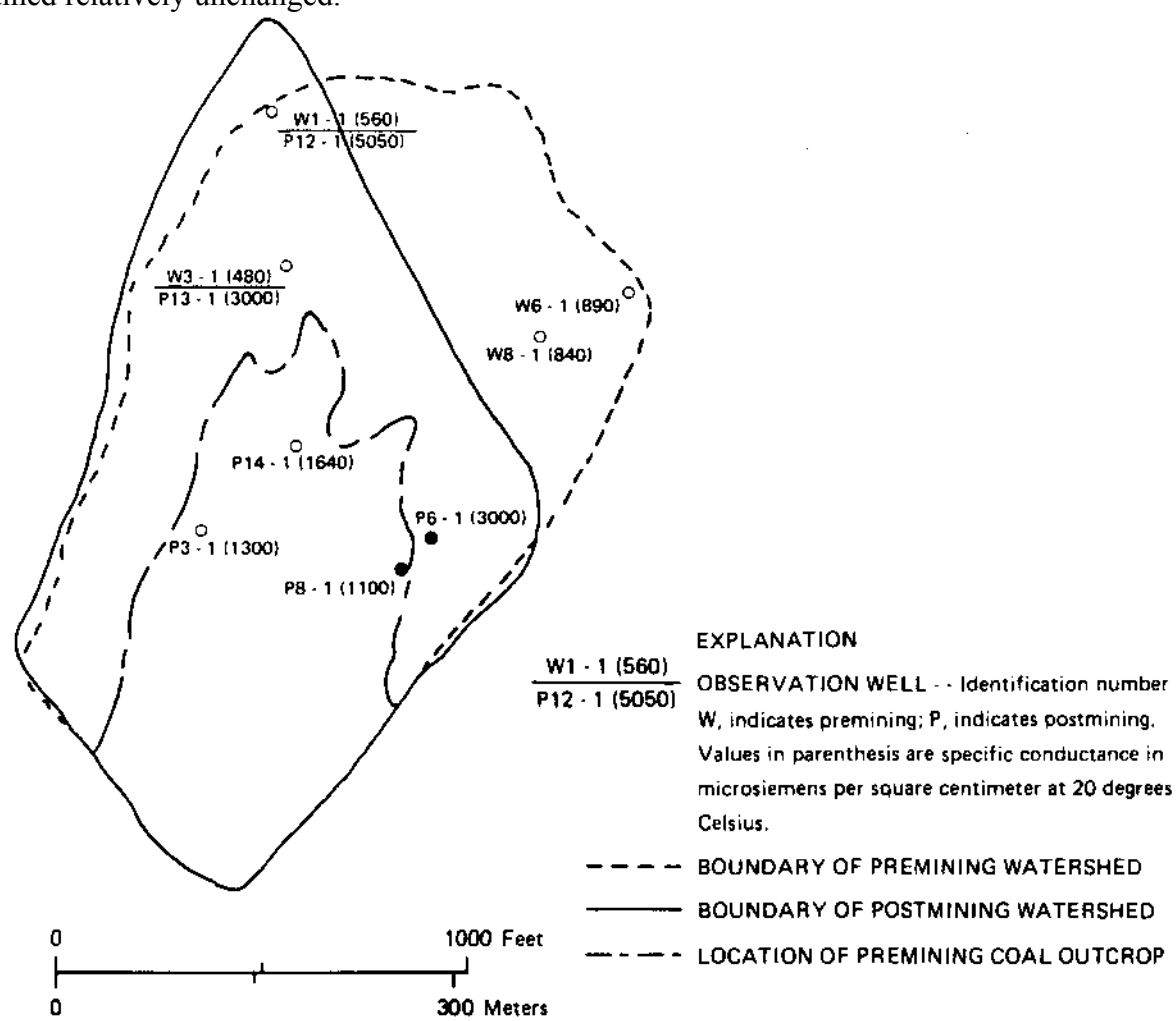


Figure 5.3-1.— Pre-mining and post-mining specific conductance values from site 4.

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