GROUND-WATER QUALITY AND GEOCHEMISTRY OF AQUIFERS ASSOCIATED WITH COAL IN THE ALLEGHENY AND MONONGAHELA FORMATIONS, SOUTHEASTERN OHIO

By Allan C. Razem and Alan C. Sedam

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CONVERSION FACTORS

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

Multiply inch-pound units	By	To obtain metric units
inch (in.)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

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ABSTRACT

Ground water from aquifers associated with coal beds in the Allegheny and Monongahela Formations in southeastern Ohio is predominantly a calcium magnesium bicarbonate type. Sodium bicarbonate type water is less common. Isolated areas of sodium chloride and calcium sulfate types also are present. The water is predominantly very hard, and has a median hardness concentration of 258 milligrams per liter as calcium carbonate and a median dissolved-solids concentration of 436 milligrams per liter. Few wells contain water with dissolved-solids concentrations in excess of 1,000 milligrams per liter.

Bicarbonate concentration in ground water was found to be significantly different among coals, whereas concentrations of bicarbonate, hardness, calcium, magnesium, sodium, iron, manganese, and strontium were significantly different between ground water in the Allegheny and Monongahela Formations. Many constituents are significantly correlated, but few correlation coefficients are high.

The presence of sulfate or iron is attributed to the kinetic mechanism operating during the oxidation of pyrite. The position along the sulfide or ferrous-iron oxidation pathways controls the reaction products of pyrite found in solution, and the formation of either the sulfate or iron constituents. The availability and rate of diffusion of oxygen in the formations exerts control on the water quality.

Discriminant-function analysis correctly classifies 89 percent of the observations into the Allegheny or Monongahela Formations. As a verification, 39 of 41 observations from another study were correctly classified by formation.

The differences in water chemistry between the Allegheny and the Monongahela Formations are gradational and are attributed to the oxidation of iron sulfide. The diffusion and availability of oxygen, which controls the chemical reaction, is regulated by the porosity and permeability of the rock with respect to oxygen and the presence or absence of carbonates, which controls the pH.

INTRODUCTION

Ground water generally is not available in large quantities in southeastern Ohio, but it is the most readily obtainable water for most of the rural and village populations. Ground water is also the source of base flow of streams, and directly affects quantity and quality of most streams in southeastern Ohio. One of the major impacts on the ground-water system in southeastern Ohio is surface mining of coal. An assessment and prediction of the consequences of surface mining on ground water is difficult because chemical-quality data are sparse.

Purpose and Scope

The purpose of this report is to describe the water quality and the principal geochemical controls of water quality in surficial aquifers associated with coal in the Allegheny and Monongahela Formations in southeastern Ohio (fig. 1).

One hundred ground-water-quality samples were collected from wells completed in the Monongahela and Allegheny Formations, the two principal coal-producing formations in southeastern Ohio (fig. 2). Sixteen samples each were collected from aquifers associated with the Lower Kittanning (No. 5), Middle Kittanning (No. 6), and Upper Freeport (No. 7) coal beds of the Allegheny Formation and the Meigs Creek (No. 9) and Uniontown (No. 10) coal beds of the Monongahela Formation. Fifteen samples were collected from aquifers associated with the Pittsburgh (No. 8) and five samples from the Waynesburg (No. 11) coal beds of the Monongahela Formation.

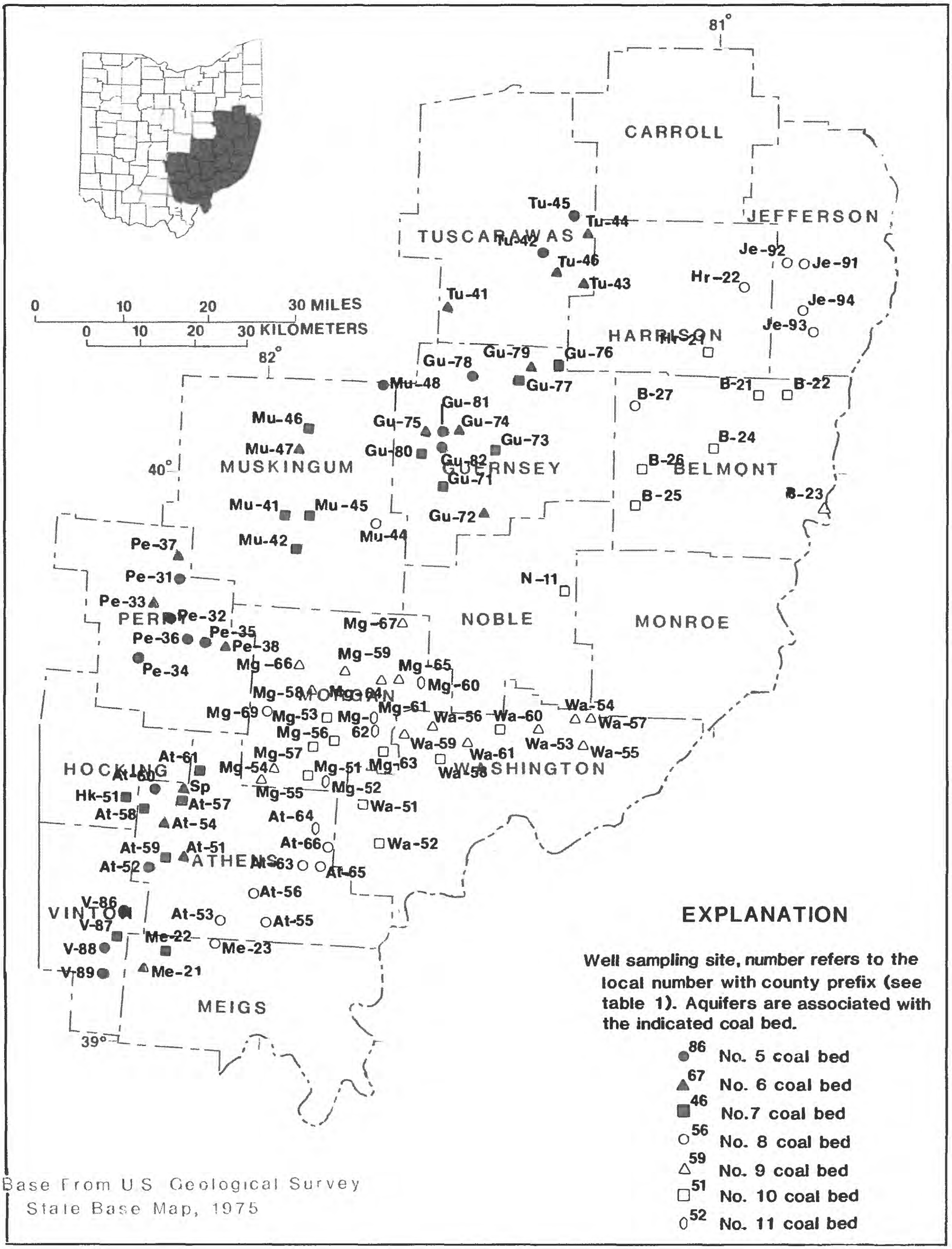
Sampling Strategy and Methods

Samples were collected from the uppermost aquifer associated with each coal bed; well depth typically ranged from 50 to 100 feet. A coal-associated aquifer, for the purposes of this study, is defined as an aquifer in which the identified coal either is the producing zone or directly overlies the producing zone. Samples were collected from domestic wells that penetrated only one coal bed. Aquifers and associated coal beds were identified by field checking drillers' logs with topographic maps, geologic maps, and mineral-resource maps. Well owners also provided information in some cases.

Samples were collected from domestic wells at the tap nearest the well after a sufficient amount of water had been removed to ensure a sample representative of the aquifer. Field measurements of temperature, specific conductance, alkalinity, and pH were made.

Base From U.S. Geological Survey
State Base Map, 1975

Figure 1.--Location of the study area.



Base From U.S. Geological Survey
State Base Map, 1975

Figure 2.--Location of the wells sampled and the associated coal in the study area.

Samples collected for analyses of dissolved constituents were filtered in the field using a 0.45-micrometer filter. Samples were treated (U.S. Geological Survey, 1977) and chilled in the field and sent to the U.S. Geological Survey laboratory in Doraville, Ga., for analysis.

HYDROGEOLOGIC SETTING OF SOUTHEASTERN OHIO

Physiography

The study area lies principally within the unglaciated Allegheny Plateau (Fenneman, 1938). The Wisconsin (most recent) glacial advance stopped at the extreme northern and western edges of the study area. Only the northwestern part of Perry County (fig. 3), which was covered earlier by the Illinoian glacial advance, has been glaciated.

Erosion of the glaciated area has resulted in a land surface that resembles the rugged, more maturely dissected terrain characteristic of the unglaciated region. Throughout southeastern Ohio, local relief ranges up to 500 feet.

The outcrop pattern from west to east is a progression of older-to-younger units that trend north-northeast. The rocks have a regional southeastern dip of about 30 feet per mile toward the Appalachian basin. The regional trend of the Pennsylvanian rock system is modified locally by numerous low structural features (Lamborn, 1951, p. 13).

Geology

Lithology and Stratigraphy

The bedrock of southeastern Ohio is a sedimentary sequence that consists predominantly of shales, sandstones, and limestone ranging from Mississippian to Permian in age. Most of the study area (fig. 3) is comprised of a complex repetitive succession of shales, sandstones, limestones, coals, and clays of Pennsylvanian age. The carbonate content increases from the older to younger Pennsylvanian rocks; therefore, the Monongahela Formation contains more carbonates than the Allegheny Formation. The lithologic character of the principal units and the relative positions of the important coals are shown in figure 4.

The designation of the Pottsville, Allegheny, Conemaugh, and Monongahela as "Formations" follows the usage of the U.S. Geological Survey. Many geologists in Ohio classify the same units as groups. Collins' review of Ohio geology (1979) explains the criteria used to classify the Mississippian, Pennsylvanian, and Permian systems in Ohio.

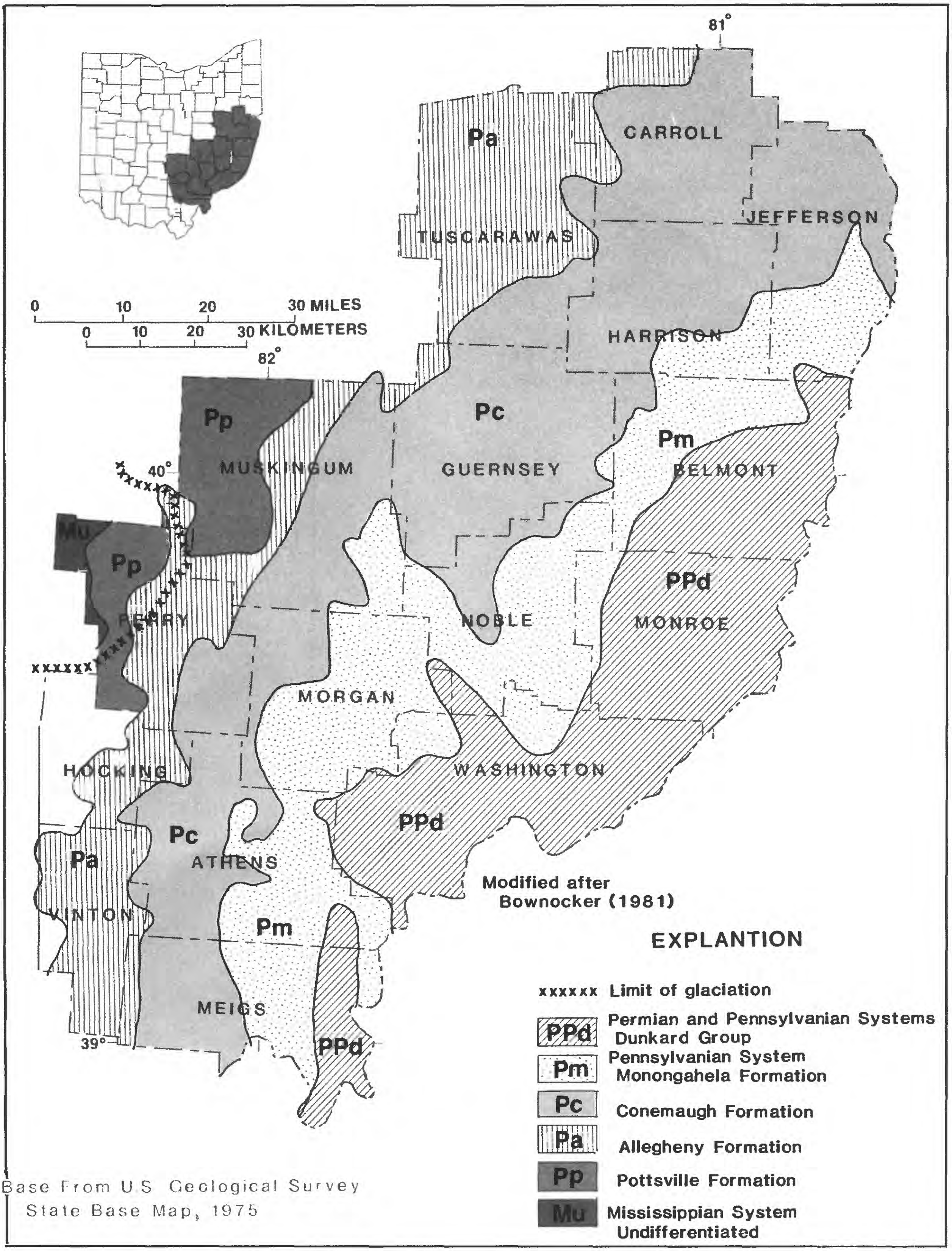


Figure 3.--Surficial geology in southeastern Ohio.

System	Group, Formation		Description	Important coal beds
Permian	Dunkard Group	Greene	Mostly red shales and thin limestones, localized coals and sandstone bodies. Present only in small areas.	No. 12 Washington
Pennsylvanian and Permian		Washington	Sandstones, shales, and minor coals. Sandstones are typically micaceous, fine to medium grained, and have thin conglomeratic zones. Locally, sandstones may be massively developed.	
Pennsylvanian	Monongahela		Important coal-bearing strata and associated beds of clay, shale, sandstone, and limestone. Sandstones tend to be fine to medium grained, micaceous, and patchy in development. Compared to other Pennsylvanian units, the Monongahela has a smaller proportion of sandstone and a larger proportion of limestone. Limestones tend to be marly, freshwater types. Secondary porosity along fractured surfaces is well developed locally.	No. 11 Waynesburg No. 10 Uniontown No. 9 Meigs Creek No. 8 Pittsburgh
	Conemaugh		Thick repetitious succession of shales and patchy sandstones interspersed with thin, discontinuous coals and clays and widespread limestones. The lower limestones are of marine origin, whereas those in the upper part are marly, freshwater types. Secondary porosity along fractured surfaces is well developed locally.	
	Allegheny		Repetitious succession of important coal-bearing strata interspersed with several fine to coarse-grained massive, cross-bedded sandstones and thin, persistent limestones. Sandstones, though widespread, have considerable local lateral variation. Solution cavities are developed locally in the limestones.	No. 7 Upper Freeport No. 6A Lower Freeport No 6 Middle Kittanning No. 5 Lower Kittanning No. 4A Clarion No. 4 Brookville
	Pottsville		Succession of sandstone, shales, clays, coals, and thin limestones. Locally, sandstones are open-textured, conglomeratic, massive, cross-bedded, and commonly are found as deposits filling old channels in eroded terrains. Lateral gradations include shale and coal. Non-deposition during the Early Pennsylvanian precluded the development of the basal conglomerate of the Sharon Member in most of southeastern Ohio.	No. 3 Lower Mercer No. 2 Quakertown No. 1 Sharon
			Thin, discontinuous zone of impure nodular iron ore and ferruginous sandstone. The unit marks the disconformity between Mississippian and Pennsylvanian strata. Age of the deposit is conjectural, but generally it is included at the base of the Pottsville Formation.	
Mississippian	Undifferentiated		Variable sequence of sandstones and shales; Maxville Limestone is present in patches at the top. In places, various units are conglomeratic and sandstones are massive. Lateral and vertical gradation to siltstone and shale is common. Ground-water potential is limited to extreme western areas. Eastward, the section contains salt water. To the north, post-Mississippian erosion has removed part of the section.	

Figure 4.--Generalized geologic section for southeastern Ohio.

Approximately 24 beds of minable coal in 32 counties have been identified (Brant and Delong, 1960, p. 3). According to figures given for the estimated original reserve for Ohio (Brant and Delong, 1960, p. 5), the coals listed in figure 4 constitute 92 percent of the State's original reserves. The coals selected for their association with aquifers in this study comprise 76 percent of the original reserves. Ranked in order of their current economic importance (Collins, 1979, p. 22) are the Pittsburgh (No. 8), Meigs Creek (No. 9), Middle Kittanning (No. 6), Lower Freeport (No. 6A), and the Waynesburg (No. 11) coals. Much of the Lower Kittanning (No. 5) and Upper Freeport (No. 7) coals have been mined out.

The coal units considered in this study were selected on the basis of economic importance, accessibility, and availability of geologic data. Therefore, the investigation is mainly concerned with the Allegheny and Monongahela Formations. Coals in the Conemaugh Formation and the Permian section are too sparse to be considered in this study.

Depositional Environment

Branson (1962, p. 3) suggests that classification of the paleogeographic setting of the Pennsylvanian System should include four distinct facies: Basinal, reef, platform, and continental. The latter two facies characterize the section in Ohio.

The disconformity between the Mississippian and basal Pennsylvanian units is a pronounced break in the sedimentary section of Ohio. Much of east-central Ohio is thought to have been at a higher elevation than areas to the northeast and to the south where thick basinal facies of coarse clastics were accumulating in separate basins of the Appalachian geosyncline (Fuller, 1955). These basins later coalesced when the sediments encroached upon the shallower continental platforms that underlie the Ohio part of the Pottsville Formation (Stearns and Mitchum, 1962). The Pottsville section in Ohio is relatively thin compared to the Appalachian geosynclinal basin sections.

Stout (1931) recognized the Pennsylvanian System as a threefold division involving seven basic cyclothems as the sequence passed from marine to nonmarine conditions. The divisions are based on depositional environment -- that is, whether the limestone beds were of marine or nonmarine origin.

	Formation		Bed	Depositional environment
Upper	Monongahela	No. 11	Waynesburg coal	Non-marine
		No. 10	Uniontown coal	
		No. 9	Meigs Creek coal	
		No. 8	Pittsburgh coal	
Middle	Conemaugh		Skelley limestone	Transitional
		No. 7	Upper Freeport coal	
		No. 6	Middle Kittanning coal	
	Allegheny		Hamden limestone	Marine
		No. 5	Lower Kittanning coal	
		No. 4	Brookville coal	
Lower	Pottsville	No. 1	Sharon coal	
			Harrison ore	

On the basis of formation thickness, Stout and others (1943) noted that the Pottsville contains 42 percent sandstone, the Allegheny contains 40 percent, the Conemaugh less than 30 percent, and the Monongahela only about 15 percent. The Lower Pennsylvanian sandstones were cleaner, and contained as much as 99 percent silica in basal Pottsville sediments. In the Monongahela, mineralogical content of sandstones ranged from 62 to 90 percent quartz, 2 to 21 percent undifferentiated clay and silt minerals, 0.1 to 1 percent heavy minerals, 2 to 10 percent feldspar, 1 to 8 percent mica, and 1 to 9 percent rock fragments (Collins, 1979, p. E14). Thus, the nonmarine sediments of the Late Pennsylvanian were less quartzitic and more shaly.

Generalized Ground-Water Flow Systems in Strata Associated with Coal

In general, bedrock aquifers of southeastern Ohio are characterized by low yields (generally less than 5 gallons per minute). The lenticular nature of many stratigraphic units restricts horizontal flow of ground water. However, horizontal flow is generally not as greatly restricted as vertical flow. Downward drainage of saturated zones is inhibited by underlying clay layers or shale; thus, ground water is likely to move laterally toward hillside springs or seeps (fig. 5). In turn, these discharges may infiltrate lower units or be carried as surface runoff to some point where water returns to the aquifers by losing streams.

Because of the rugged topography in the region, many of the shallow water-bearing units have been dissected into isolated remnants of what were once areally extensive strata. There are no regional aquifers that contain water of potable quality in southeastern Ohio. Sandstones of Mississippian age and some of the Pottsville sandstones, which are regional aquifers in other parts of Ohio, are saline in southeastern Ohio. The most persistent units are the Pennsylvanian limestones, but these are thin; secondary permeability, such as fractures and joints, is localized.

GROUND-WATER QUALITY OF AQUIFERS IN THE ALLEGHENY AND MONONGAHELA FORMATIONS

The discussion of the ground-water quality in this report focuses on the major inorganic constituents and selected minor constituents and properties. Samples generally represent natural conditions, however, a few analyses show apparent contamination (indicated by high concentrations of chlorides, sulfates, and other constituents) at some sampling sites.

General Description

The variation in geology throughout the study area is one of influences on variability of ground-water quality. The effects of the geology on the distribution of the water-quality characteristics will be discussed in later sections, but some generalizations can be made here.

The water type of the shallow aquifers generally is calcium magnesium bicarbonate. Sodium bicarbonate and mixed bicarbonate sulfate types are less common (fig. 6). The measured hardness ranges from 1 mg/L to 3,113 mg/L; the median value is 258 mg/L as

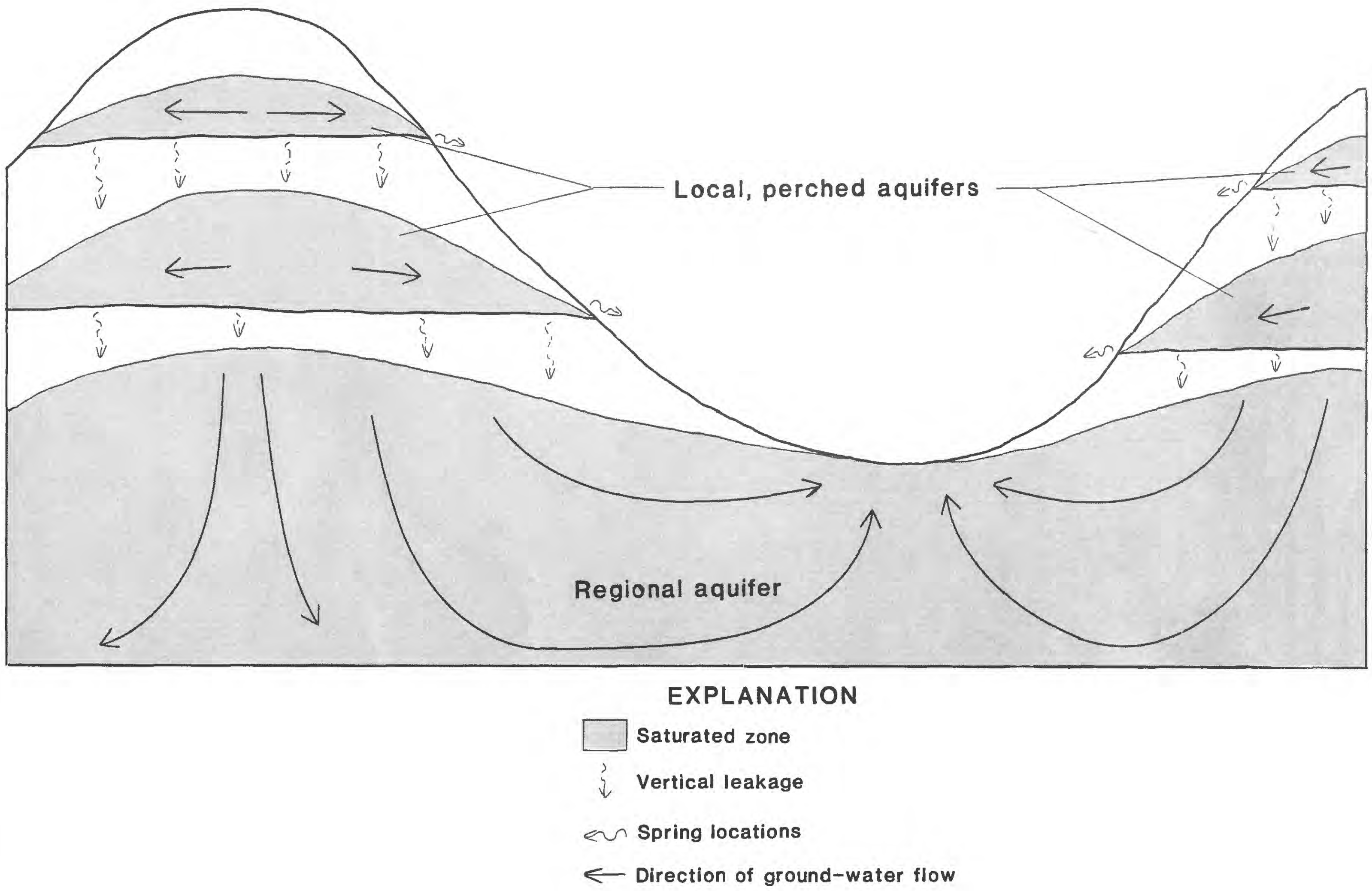


Figure 5.--Conceptual diagram of typical ground-water flow system in southeastern Ohio.

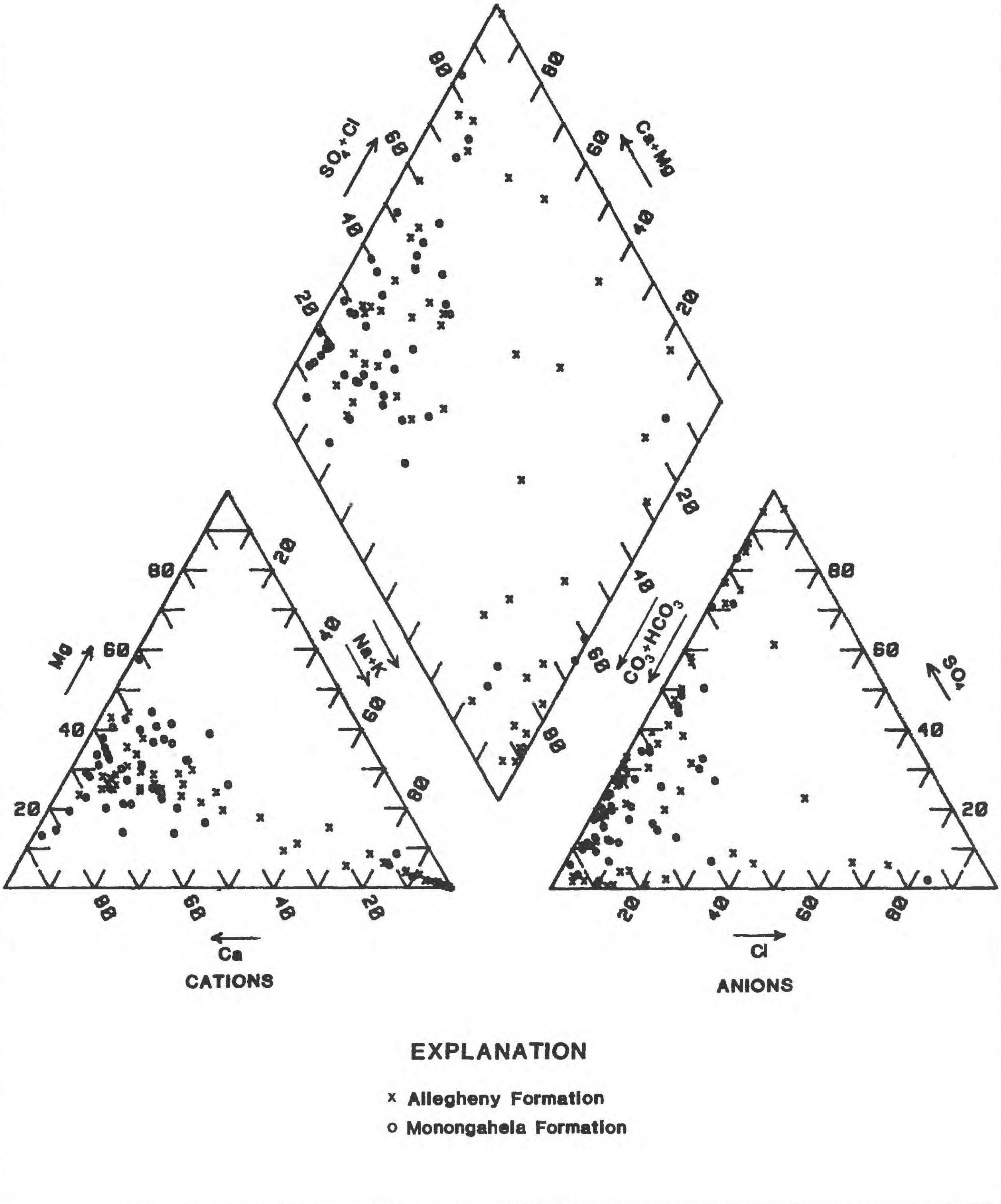


Figure 6.--Water-analysis diagram showing ground-water-quality characteristics of selected aquifers associated with coal in southeastern Ohio.

calcium carbonate, which is classified as very hard water. The median observed value for dissolved-solids concentration in the study area is 436 mg/L. The Ohio Environmental Protection Agency's recommended limits (1978) for public supply were exceeded for sulfate (250 mg/L) in 17 percent of the samples; manganese (0.05 mg/L), in 34 percent of the samples; iron (0.3 mg/L), in 19 percent of the samples; fluoride (1.8 mg/L) in 5 percent of the samples; chloride (250 mg/L), in 4 percent of the samples; and dissolved solids (500 mg/L) in 38 percent of the samples. The chemical analyses for samples from each well are presented in table 1 (at back of report). Summary statistics for the various properties and constituents by formation are presented in table 2.

A good indicator of general water quality is dissolved solids. Figure 7 shows the distribution of dissolved-solids concentration across southeastern Ohio. Most of the study area has shallow aquifers that contain fresh water. Fresh water is defined as having a dissolved-solids concentration of less than 1,000 mg/L. Only a few sites yield water having a dissolved-solids concentration of more than 1,000 mg/L. These high values can be attributed to oil- and gas-well drilling or road salt (high chlorides), mining activity (high sulfates, iron, and manganese), agricultural or domestic wastes, or natural deposits.

An inexpensive, rapid method for estimating dissolved-solids concentration is measurement of specific conductance. A linear relation exists between specific conductance and dissolved solids under most conditions. The numerical value for dissolved-solids concentration, in milligrams per liter, generally is 0.55 to 0.75 the value of specific conductance in microsiemens per centimeter (µS/cm) at 25°C (Hem, 1970, p. 99). In southeastern Ohio, these two characteristics form a linear relation in regression analysis such that the dissolved-solids concentration of water from shallow aquifers is 0.71 times the value of the specific conductance (fig. 8). Ninety percent of the variation in the data is explained by this relation. The relation becomes less useful when specific conductance increases to more than 1,600 µS/cm, probably because of high concentrations of sulfate and chloride. The linear relationship is useful in extrapolating analyses to other areas in southeast Ohio where comprehensive results are unavailable, or for quick reconnaissance of large areas.

Relationships among specific conductance and other constituents such as sulfate, hardness, and chloride are less well defined. This is attributable to the variable geology, which causes different concentrations of ions to be present in the ground water.

Table 2.--Statistical summary of selected ground-water-quality characteristics from the Allegheny and Monongahela Formations in southeastern Ohio

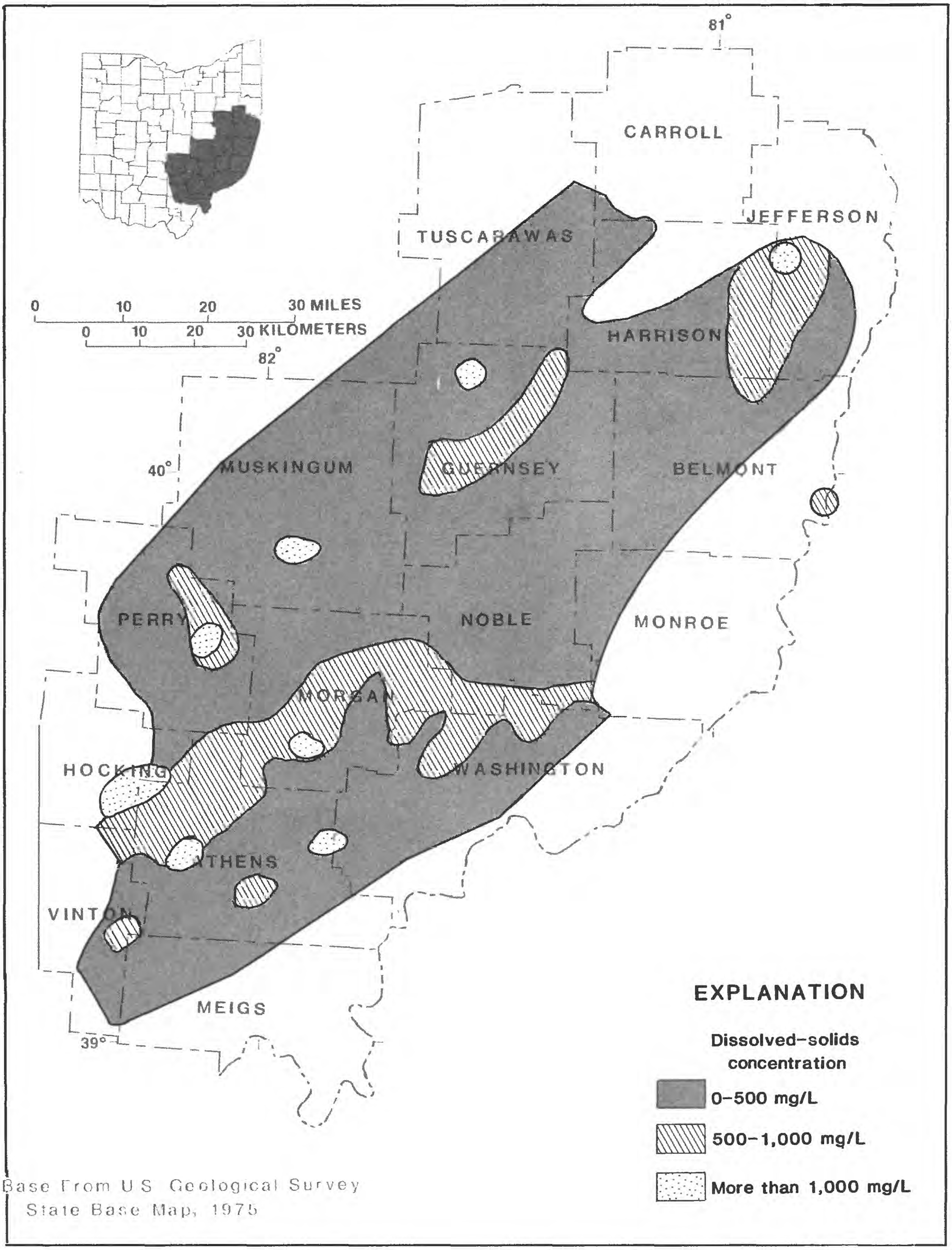
[Q_1, 25th percentile; Q_3, 75th percentile. < indicates concentration was below detection limit.]

Constituent or property	Geologic Formation									
	Allegheny (48 samples)					Monongahela (47 samples)				
	Minimum	Maximum	Median	Q_1	Q_3	Minimum	Maximum	Median	Q_1	Q_2
Specific conductance (µS/cm at 25°C)	110	4,350	682	506	1,042	260	4,250	690	545	925
pH	5.6	9.2	7.4	7	8	6.9	9.1	7.4	7.2	7.6
Bicarbonate (mg/L)	32	650	310	200	400	80	840	340	290	400
Carbonate (mg/L)	18[a]	73[a]	37[a]	26[a]	59[a]	41[b]	84[b]	(b)	(b)	(b)
Nitrogen. $NO_2 + NO_3$, dissolved (mg/L)	<.1	10	<.1	<.1	0.2	<.1	14	.6	<.1	2.7
Orthophosphorus (mg/L)	<.01	.12	<.01	<.01	<.01	<.01	.07	<.01	<.01	<.01
Organic carbon, total (mg/L)	.3	4	.8	.6	1.2	.2	2.5	.7	.5	1.1
Hardness, as $CaCO_3$ (mg/L)	5	1,227	199	48	330	1	3,113	295	213	402
Noncarbonate hardness as $CaCO_3$ (mg/L)	0	940	27	0	116	0	2,596	42	0	122
Calcium, dissolved (mg/L)	1.1	260	55	13	87	.3	520	77	59	110
Magnesium, dissolved (mg/L)	.4	140	17	3.4	27	.1	440	27	12	36

Table 2.--Statistical summary of selected ground-water-quality characteristics from the Allegheny and Monongahela Formations in southeastern Ohio--Continued

Constituent or property	Geologic Formation									
	Allegheny (48 samples)					Monongahela (47 samples)				
	Minimum	Maximum	Median	Q_1	Q_3	Minimum	Maximum	Median	Q_1	Q_2
Sodium, dissolved (mg/L)-	2.2	870	60	14	147	1.8	850	25	10	44
Potassium, dissolved (mg/L)----------------	.7	8.2	2.4	1.5	3.8	.1	8.6	1.4	.9	2.5
Chloride, dissolved (mg/L)	1.1	1,100	15	5	43	2.6	1,300	12	6.6	31
Sulfate, dissolved (mg/L)	2	1.800	73	20	212	5	2,700	68	43	130
Fluoride, dissolved (mg/L)	.1	4.7	.3	.2	.6	.1	2.7	.2	.2	.3
Silica, dissolved (mg/L)-	3.9	34	11	9	17	6.3	33	11	9	13
Iron, dissolved (µg/L)---	4	17,000	49	18	467	3	28,000	17	8	47
Manganese, dissolved (µg/L)----------------	2	30,000	49	18	217	1	5,200	7	3	21
Strontium, dissolved (µg/L)-------	22	3,700	445	170	850	3	8,600	666	360	1,100
Hydrogen sulfide (mg/L)--	<.1	1	<.1	<.1	.2	<.1	.3	<.1	<.1	<.1
Solids, sum of constituents, dissolved (mg/L)-------	69	2,702	445	315	724	127	4,048	445	349	625

[a] 7 samples
[b] 3 samples



Base From U.S. Geological Survey
State Base Map, 1975

Figure 7.--Distribution of dissolved-solids concentration in ground water in southeastern Ohio.

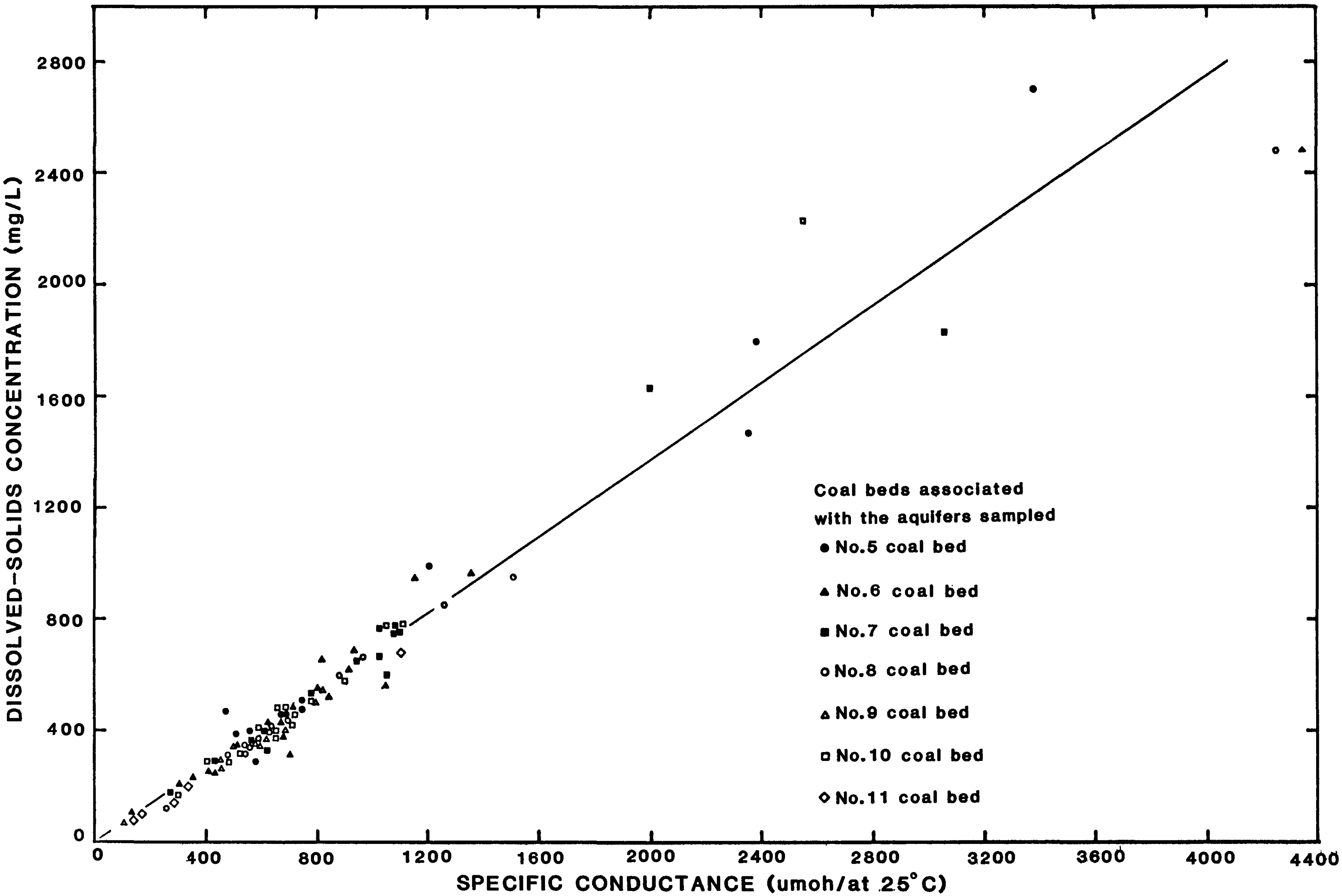


Figure 8.—Specific conductance as a function of dissolved-solids concentration of water from selected aquifers associated with coal in southeastern Ohio.

Analysis of Geologic and Geochemical Controls

Statistical and graphical methods were used to evaluate water-quality data in an attempt to characterize geologic formations and coal-associated aquifers. The complex lithofacies changes caused by numerous transgressions and regressions during deposition made classification by simple, univariate statistics difficult; therefore, several statistical techniques -- including analysis of variance, correlations, and discriminant-function analysis -- were used.

In this study, analysis of variance was used to determine whether there are significant differences in selected constituents between coals within each formation and between formations. Bicarbonate is the only constituent that is significantly different between coals in both formations. Constituents that are significantly different at a significance level of 0.05 between formations are bicarbonate, hardness, calcium, magnesium, sodium, iron, manganese, and strontium. As mentioned previously, the Monongahela Formation contains more calcareous rocks than the Allegheny Formation. The dominant depositional environment of the Monongahela Formation was freshwater, whereas the depositional environment of the Allegheny Formation was predominantly marine, grading into a transitional phase between marine and nonmarine.

Concentration of ionic constituents associated with carbonates consistently show higher median values in the more calcareous Monongahela Formation than in the more siliceous Allegheny Formation (tables 2 and 3, fig. 9). These constituents include bicarbonate, hardness, calcium, magnesium, and strontium. Higher median values of iron and manganese (table 3) from aquifers associated with the Lower Kittanning (No. 5) and Middle Kittanning (No. 6) coal beds of the Allegheny Formation are attributed to dissolution of sediments deposited in a reducing marine environment.

Spearman correlation coefficients were calculated for 19 selected properties and chemical constituents (table 4) to determine which of them are significantly correlated at a level of 0.05. Although many significant correlations exist, few correlation coefficients are high. The calculated constituents, such as dissolved solids and hardness, obviously have the highest correlations with the constituents from which they were calculated.

Discriminant-function analysis (Davis, 1973) was used to predict the geologic formation on the basis of water quality. The high degree of accuracy of predictions made during calibration and verification of the discriminant-function analysis supported the concept that distinct geochemical processes were responsible for the dominant chemical constituents in each formation.

Table 3.--Median values of selected ground-water-quality characteristics from coal-associated aquifers in the Allegheny and Monongahela Formations in southeastern Ohio

[< indicates concentration was below detection limit.]

Constituent or property	Geologic formation and coal-bed number					
	Allegheny Formation			Monongahela Formation		
	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10
Number of samples	16	16	16	15	16	16
Specific conductance (µS/cm at 25°C)	655	572	982	670	757	685
pH	7.7	7.2	7.4	7.4	7.4	7.4
Bicarbonate (mg/L)	245	242	395	360	375	315
Nitrogen, NO_2 + NO_3, dissolved (mg/L)	<.1	<.1	<.1	<.1	1.0	1.7
Orthophosphorus (mg/L)	<.01	<.01	<.01	<.01	<.01	<.01
Organic carbon, total (mg/L)	1	.6	.8	.7	.6	.7
Hardness, as $CaCO_3$ (mg/L)	165	196	234	260	309	320
Noncarbonate hardness, as $CaCO_3$ (mg/L)	14	27	22	32	52	50
Calcium, dissolved (mg/L)	48	53	60	72	90	73
Magnesium, dissolved (mg/L)	11	15	20	19	24	27
Sodium, dissolved (mg/L)	103	17	57	27	24	25
Potassium, dissolved	2.5	1.2	2.4	1.6	1.1	1.5
Chloride, dissolved (mg/L)	17	7	23	13	12	10
Sulfate, dissolved (mg/L)	125	51	73	56	69	115
Fluoride, dissolved (mg/L)	.4	.3	.4	.2	.2	.2
Silica, dissolved (mg/L)	10	14	9	10	10	12
Iron, dissolved (µg/L)	70	130	26	14	16	32
Manganese, dissolved (µg/L)	72	73	26	16	5	7
Strontium, dissolved (µg/L)	330	570	470	660	670	805
Hydrogen sulfide (mg/L)	<.1	<.1	<.1	<.1	<.1	<.1
Solids, sum of constituents, dissolved (mg/L)	461	339	651	417	496	444

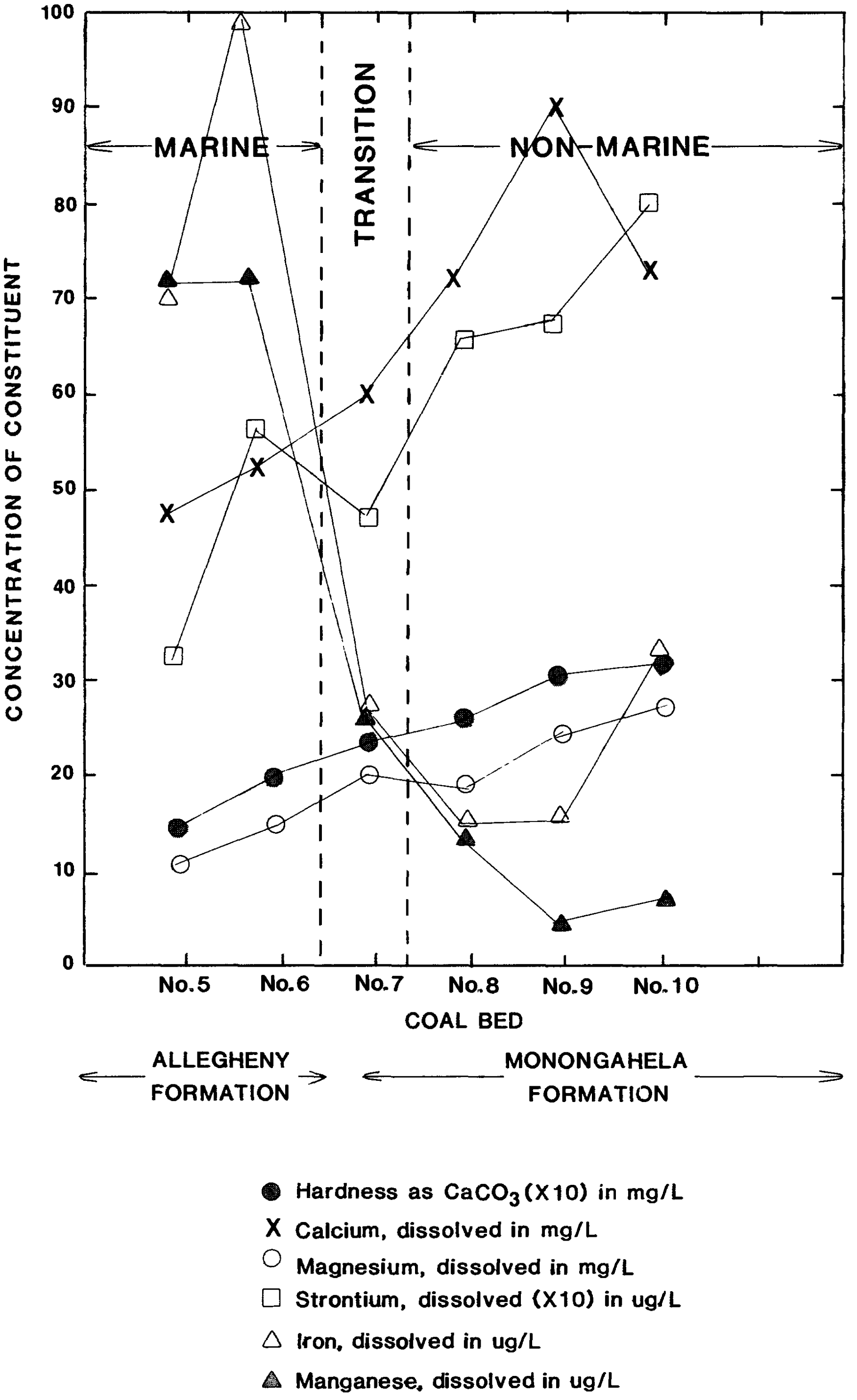


Figure 9.--Variations of median values of selected water-quality constituents with coal beds and geologic formations in southeastern Ohio.

Table 4.--Spearman correlation coefficients of selected ground-water-quality characteristics from the Allegheny and Monongahela Formations in southeastern Ohio

[Coefficients omitted if not significant at P=95%]

Constituent or property (numbers refer to footnotes)																			Constituent or property
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	
1.00		0.65		0.45	0.31	0.41	0.44	0.53	0.48	0.56	0.55	0.31	-0.30			0.47		0.99	1
	1.00	.25		-.55	-.61	-.57	-.50	-.46			-.46	.59	-.41	-0.25	-0.25				2
		1.00						.35	.22	.43		.34	-.35			.30		.63	3
			1.00						.40				-.25					.22	4
				1.00	.82	.97	.96	-.33	.30		.80	-.40		.27		.70		.47	5
					1.00	.80	.77	-.35	.24		.74	-.43				.42		.36	6
						1.00	.88	-.36	.27		.76	-.39	.24	.29	.25	.66		.43	7
							1.00	-.27	.33		.79	-.38		.24		.72		.46	8
								1.00	.33	.54		.61	-.41					.56	9
									1.00		.48	.26		.37	.45	.50		.52	10
										1.00		.28					.28	.49	11
											1.00	-.26		.35	.28	.61		.62	12
												1.00	-.26				.27	.31	13
													1.00	.33	.38			-.31	14
														1.00	.64	.30			15
															1.00	.24			16
																1.00		.49	17
																	1.00		18
																		1.00	19

1. Specific conductance (µS/cm at 25°C)
2. pH
3. Bicarbonate (mg/L)
4. Carbon, total organic (mg/L)
5. Hardness, as $CaCO_3$ (mg/L)
6. Noncarbonate hardness, as $CaCO_3$ (mg/L)
7. Calcium, dissolved (mg/L)
8. Magnesium, dissolved (mg/L)
9. Sodium, dissolved (mg/L)
10. Potassium, dissolved (mg/L)
11. Chloride, dissolved (mg/L)
12. Sulfate, dissolved (mg/L)
13. Fluoride, dissolved (mg/L)
14. Silica, dissolved (mg/L)
15. Iron, dissolved (µg/L)
16. Manganese, dissolved (µg/L)
17. Strontium, dissolved (µg/L)
18. Hydrogen sulfide (mg/L)
19. Solids, sum of constituents, dissolved (mg/L)

This multivariate method allows the complex geology and multiple processes to be evaluated in such a way that a weighted combination of all the geochemical variables is reduced to an equation that maximizes the chemical differences in ground water between the formations.

A quadratic discriminant-function equation gave better results than a linear equation, so all findings are from a quadratic equation. The analyses from the 95 water-quality samples from the coal-related aquifers were used for constructing and calibrating a quadratic discriminant equation. No further analysis was made of aquifers associated with the Waynesburg (No. 11) coal bed of the Monongahela Formation because only five water-quality samples were obtained. Forty analyses from 11 wells from another project (U.S. Bureau of Mines, 1978) in the study area were used to verify the reliability of the equation. The discriminant-function analysis was also used to determine the minimum number of water-quality variables needed for acceptable classification.

Thirteen water-quality constituents and properties were used to produce a discriminant function. The 13 constituents and properties are:

specific conductance
pH
bicarbonate
noncarbonate hardness
calcium
magnesium
sodium
potassium
sulfate
fluoride
iron
manganese
hydrogen sulfide

Although using more variables would have resulted in a better equation (fewer misidentifications), these 13 constituents and properties are commonly analyzed in studies of ground-water quality. Fewer variables produced an equation with an unacceptably high rate of misidentifications (more than 10) during calibration.

During calibration of the discriminant model, only 10 out of 95 observations were misclassified; only 2 out of 41 observations were misclassified during verification.

The high percentage of correctly classified observations indicate that there are geochemical processes unique to the Allegheny and Monongahela Formations. Some constituents, such as sodium and chloride, probably are not unique to either formation but rather are the result of local contamination. Other geochemical processes that result in combinations of certain constituents probably are dominant only in one formation. For example, iron and manganese are usually in higher concentration in the reducing environment of the marine shales and sandstones of the Allegheny Formation, whereas sulfate concentrations are high in the carbonate aquifers of the Monongahela.

CONCEPTUAL GEOCHEMICAL MODEL OF THE ALLEGHENY AND MONONGAHELA FORMATIONS

A conceptual geochemical model shown in figure 10 describes the gradational geochemical processes that dominate each formation. The model, which is based on oxidation of pyrite, uses oxygen as the oxidizing agent because the other oxidizing agent, ferric ion, is insoluble in the neutral or basic water usually found in the study area (Nordstrom, 1982). Production of iron and fully oxidized sulfate is dependent on the availability and diffusion of oxygen to the pyrite disseminated in the rocks. The porosity and permeability of the formations, as well as consumption of oxygen during oxidation processes of the formations, limits oxygen availability for pyrite oxidation.

The kinetic mechanisms and reaction pathways that determine whether the iron or sulfate processes will be dominant can be expressed by the overall reaction:

$$(1)\quad FeS_2 + \frac{15}{4} O_2 + \frac{7}{2} H_2O \Rightarrow Fe(OH)_3 + 4H^+ + 2SO_4{}^{2-}$$

The ferrous iron oxidation pathway is expressed as:

$$(2)\quad FeS_2 \Rightarrow Fe^{2+} + S_2{}^{2-}$$

$$(3)\quad Fe^{2+} + \frac{1}{4} O_2 + H^+ \Rightarrow Fe^{3+} + \frac{1}{2} H_2O$$

$$(4)\quad Fe^{3+} + 3H_2O \Rightarrow Fe(OH)_3 + 3H^+$$

and the sulfate oxidation pathway is:

$$(5)\quad S_2{}^{2+} + \frac{3}{2} O_2 \Rightarrow S_2\ O_3{}^{2-}$$

$$(6)\quad S_2O_3{}^{2-} + 2O_2 + H_2O \Rightarrow 2SO_4{}^{2-} + 2H^+$$

Both formations contain pyrite. With the introduction of oxygen, the pyrite will dissolve and initially release ferrous iron (reaction 2) and sulfide (Nordstrom and others, 1979). As the availability of oxygen increases, the sulfur is partially oxidized to an intermediate thiosulfate species (reaction 5); if enough oxygen is present, sulfate is produced (reaction 6). When

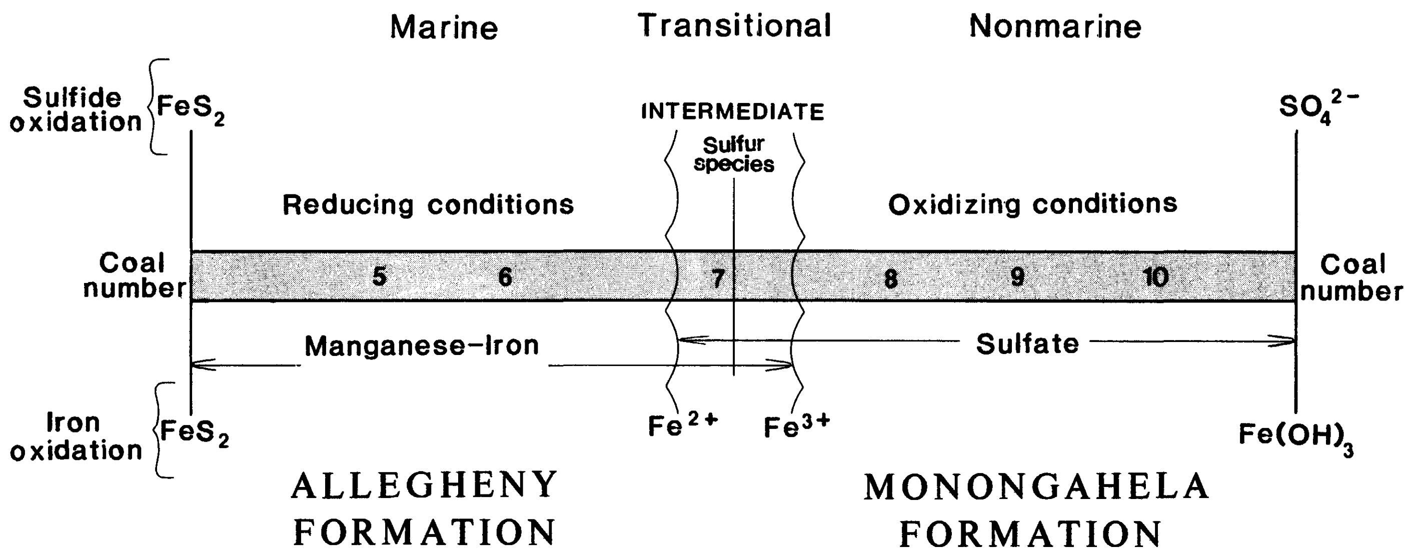


Figure 10.—Conceptual model that describes the major geochemical processes in the Allegheny and Monongahela Formations in southeastern Ohio.

the sulfur is oxidized to sulfate, the pH would be expected to drop (Nordstrom, 1982); however, the carbonate rocks in the Monongahela Formation buffer the reaction. Because the pH remains near neutral, ferric iron is insoluble.

The initial oxidation of pyrite releases the ferrous iron, but the sulfur remains at the mineral surface (Nordstrom, 1982). The tight shales and other clastics inhibit the diffusion of additional oxygen, which would react to form intermediate sulfur species and eventually produce sulfate.

During mining operations and subsequent exposure of large surface areas of bedrock to oxygen, the Allegheny Formation may be especially susceptible to pyrite oxidation. First, an unstable sulfur rind is quickly oxidized, producing acid and sulfate. Second, there is more pyrite available for oxidation because the undisturbed formation retards oxygen movement more than spoils material. Third, significant amounts of carbonate rocks are not available to buffer acid production and, if pH drops, ferric ion becomes an oxidizing agent regardless of whether oxygen is present or not.

SUMMARY AND CONCLUSIONS

One hundred ground-water quality samples were collected from domestic wells in southeastern Ohio to describe the water quality and geochemical controls of surficial coal-associated aquifers in southeastern Ohio. The samples were collected from aquifers associated with the coal beds of the Allegheny and Monongahela Formations.

The waters of the shallow, coal-associated aquifers in southeastern Ohio generally are calcium magnesium bicarbonate in type; a sodium bicarbonate type is less common. The water is predominantly very hard (median hardness concentration of 258 mg/L as calcium carbonate) and has a median dissolved-solids concentration of 436 mg/L. Only isolated areas yield water having dissolved-solids concentrations of more than 1,000 mg/L.

Complex lithologic facies changes caused by marine transgressions and regressions, and nonmarine deposition produce a ground-water-quality distribution that makes classification according to formation or coal difficult. Only bicarbonate concentration was found to be significantly different among individual coal beds, whereas concentrations of bicarbonate, hardness, calcium, magnesium, sodium, iron, manganese, and strontium were significantly different between the Allegheny and Monongahela Formations. Many constituents are significantly correlated, but few correlation coefficients are high.

Discriminant-function analysis (based on 13 water-quality constituents and properties) correctly classifies 89 percent of the observations collected in this study into the Allegheny or Monongahela Formations. As a verification, 39 of 41 observations from another study were correctly classified by formation. This demonstrates that certain geochemical processes are more dominant in one formation than in the other.

The difference in water chemistry between the Allegheny and the Monongahela Formations is gradational, and is attributed to processes involved in the oxidation of iron sulfide (pyrite). The diffusion and availability of oxygen, which controls the chemical reaction, is regulated by the porosity and permeability of the rock with respect to oxygen and also by the presence or absence of carbonates that buffer the pH.

In general, the dissolved-solids concentration is about 500 mg/L before mining in either formation. The dissolved-iron concentration is expected to be higher in the Allegheny, whereas dissolved sulfate is expected to be higher in the Monongahela.

In the Monongahela Formation, acid produced as a result of pyrite oxidation is buffered by the carbonate rocks. However, in the Allegheny Formation, acid production is not buffered and pH decreases. When pH is low enough, then the ferric ion also acts as an oxidizing agent, and oxidation of the remaining pyrite becomes more complete.

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Table 1.--Selected ground-water-quality analyses from southeastern Ohio, 1983

[Double dash, concentration not determined; ND, constituent not detected in water sample; mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25°Celsius]

Local identifier	Associated coal bed	Latitude	Longitude	Well depth (feet)	Date of sample	Specific conductance (µS/cm)	pH (standard units)	Bicarbonate, FET-fld[1] (mg/L as HCO_3)	Carbonate, FET-fld[1] (mg/L as CO_3)
ALLEGHENY FORMATION									
AT-52	No. 5	39 19 31	082 15 51	80	83-02-01	750	8.0	370	--
AT-60	do.	39 26 02	082 11 58	120	83-02-07	2,350	7.2	480	--
GU-78	do.	40 08 44	081 33 09	108	83-03-29	2,380	7.0	360	--
GU-81	do.	40 05 58	081 35 51	98	83-04-08	630	8.0	400	--
GU-82	do.	40 05 21	081 35 57	90	83-04-08	750	9.1	340	59
MU-48	do.	40 07 37	081 46 35	85	83-04-07	470	7.7	240	--
PE-31	do.	39 47 33	082 11 41	102	83-03-14	1,200	6.8	200	--
PE-32	do.	39 45 02	082 13 02	70	83-03-14	595	7.3	380	--
PE-34	do.	39 41 10	082 15 29	58	83-03-15	560	7.0	98	--
PE-35	do.	39 42 09	082 07 36	45	83-03-15	3,380	8.2	120	--
PE-36	do.	39 42 06	082 08 46	65	83-03-15	670	7.4	52	--
TU-42	do.	40 21 21	081 22 40	65	83-04-20	430	8.0	230	--
TU-45	do.	40 25 05	081 19 10	76	83-04-21	740	7.6	340	--
V-86	do.	39 14 08	082 18 55	60	83-03-30	505	9.2	190	73
V-88	do.	39 11 47	082 20 07	105	83-03-30	640	7.8	240	--
V-89	do.	39 08 50	082 21 13	77	83-04-01	485	8.0	250	--
Spring	No. 6	39 27 52	082 10 39	--	83-02-07	940	6.4	92	--
AT-51	do.	39 20 04	082 11 29	195	83-01-31	4,350	8.0	560	--
AT-54	do.	39 24 07	082 13 13	90	83-02-01	940	8.6	510	26
GU-72	do.	39 55 20	081 32 42	114	83-03-25	440	7.8	242	--
GU-74	do.	40 04 31	081 34 17	100	83-03-28	360	7.4	190	--
GU-75	do.	40 03 52	081 39 16	55	83-03-28	110	6.9	37	--
GU-79	do.	40 10 34	081 26 07	50	83-04-07	510	7.0	190	--
ME-21	do.	39 09 57	082 15 10	105	83-02-22	145	6.6	32	--
MU-47	do.	40 01 40	081 54 41	198	83-04-07	685	7.0	230	--

Table 1.--Selected ground-water-quality analyses from southeastern Ohio, 1983--Continued

Local identifier	Associated coal bed	Latitude	Longitude	Well depth (feet)	Date of sample	Specific conductance (µS/cm)	pH (standard units)	Bicarbonate, FET-fld[1] (mg/L as HCO_3)	Carbonate, FET-fld[1] (mg/L as CO_3)
				ALLEGHENY FORMATION--Continued					
PE-33	No. 6	39 46 15	082 14 39	160	83-03-14	520	8.4	250	18
PE-37	do.	39 50 25	082 10 31	85	83-03-15	415	7.7	260	--
PE-38	do.	39 41 37	082 04 51	90	83-03-16	810	7.0	310	--
TU-41	do.	40 17 04	081 39 09	96	83-04-20	1,450	5.6	--	--
TU-43	do.	40 18 52	081 18 34	86	83-04-21	625	7.4	330	--
TU-44	do.	40 24 07	081 16 39	57	83-04-21	680	7.4	330	--
TU-46	do.	40 20 50	081 21 24	67	83-04-22	315	7.0	146	--
AT-57	No. 7	39 27 04	082 10 44	40	83-02-02	1,020	7.3	310	--
AT-58	do.	39 25 41	082 16 48	120	83-02-02	945	7.0	310	--
AT-59	do.	39 24 07	082 13 30	63	83-02-06	775	7.2	440	--
AT-61	do.	39 28 20	082 09 57	75	83-02-07	1,050	7.4	360	--
GU-71	do.	39 56 58	081 37 15	100	83-03-25	1,080	8.9	650	37
GU-73	do.	40 01 21	081 31 07	95	83-03-25	1,020	7.4	450	--
GU-76	do.	40 10 32	081 20 47	140	83-03-29	1,100	8.6	610	41
GU-77	do.	40 08 25	081 26 37	185	83-03-29	560	7.7	290	--
GU-80	do.	40 03 02	081 38 54	86	83-04-08	610	7.8	440	--
HK-51	do.	39 26 08	082 17 07	72	83-04-01	1,990	7.3	370	--
ME-22	do.	39 11 17	082 12 30	85	83-02-22	940	8.7	450	31
MU-41	do.	39 55 52	081 55 00	100	83-03-17	430	7.6	270	--
MU-42	do.	39 52 04	081 53 08	250	83-03-17	3,050	7.9	570	--
MU-45	do.	39 55 51	081 51 42	71	83-03-28	265	6.8	130	--
MU-46	do.	40 02 22	081 54 05	114	83-04-07	615	7.4	240	--
V-87	do.	39 11 55	082 19 24	150	83-03-30	1,080	7.2	420	--

Table 1.--Selected ground-water-quality analyses from southeastern Ohio, 1983--Continued

Local identifier	Nitrogen, $NO_2 + NO_3$, dissolved (mg/L as N)	Orthophosphorus, dissolved (mg/L as P)	Carbon, organic, total (mg/L as C)	Hardness (mg/L as $CaCO_3$)	Hardness, noncarbonate (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)
ALLEGHENY FORMATION--Continued									
AT-52	ND	0.090	2.2	32	0	9.1	2.2	190	1.8
AT-60	ND	ND	.6	521	127	150	35	350	6.6
GU-78	ND	ND	1.3	973	740	240	90	140	6.9
GU-81	ND	.050	.9	20	0	5.5	1.6	150	1.9
GU-82	ND	.100	.9	5	0	1.1	.4	180	1.0
MU-48	ND	ND	.7	57	0	14	5.2	87	2.0
PE-31	ND	ND	1.0	660	517	160	63	28	6.0
PE-32	.30	ND	1.4	283	139	80	20	11	5.6
PE-34	ND	ND	.7	259	179	59	27	15	1.8
PE-35	ND	ND	1.0	336	265	86	29	710	5.1
PE-36	1.2	ND	2.7	136	99	42	7.3	83	1.8
TU-42	ND	ND	1.1	195	28	55	14	11	1.7
TU-45	ND	ND	1.0	244	0	66	19	68	4.9
V-86	ND	ND	.8	11	0	3.1	.8	120	.8
V-88	ND	.040	1.0	44	0	12	3.4	140	3.0
V-89	ND	ND	.7	67	0	21	3.4	80	8.2
Spring	.19	ND	.5	332	257	83	30	80	3.7
AT-51	ND	.020	1.4	273	0	70	23	870	5.4
AT-54	ND	.040	1.0	13	0	3.2	1.1	260	1.1
GU-72	ND	.020	.7	189	0	52	14	18	.7
GU-74	.13	ND	.6	177	27	46	15	14	1.7
GU-75	.22	ND	.6	45	17	13	3.1	2.2	1.0
GU-79	.20	ND	1.1	203	70	55	16	26	1.6
ME-21	.11	.010	.3	34	0	8.9	2.8	14	.7
MU-47	.26	ND	.6	293	116	74	26	22	2.4

Table 1.--Selected ground-water-quality analyses from southeastern Ohio, 1983--Continued

Local identifier	Nitrogen, $NO_2 + NO_3$, dissolved (mg/L as N)	Orthophosphorus, dissolved (mg/L as P)	Carbon, organic, total (mg/L as C)	Hardness (mg/L as $CaCO_3$)	Hardness, noncarbonate (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)
ALLEGHENY FORMATION--Continued									
PE-33	0.33	0.020	0.6	24	0	5.9	2.2	110	1.4
PE-37	ND	ND	.8	181	0	50	13	16	3.3
PE-38	ND	ND	.7	321	90	87	25	55	3.1
TU-41	ND	ND	1.8	760	--	170	81	5.3	4.8
TU-43	ND	ND	.6	324	67	90	24	11	2.6
TU-44	ND	ND	1.2	336	77	93	25	14	4.2
TU-46	ND	ND	.5	148	31	43	9.9	6.0	1.5
AT-57	1.0	ND	1.3	565	311	170	34	12	2.4
AT-58	1.6	.020	.8	477	223	130	37	25	1.4
AT-59	ND	ND	.5	293	0	79	23	65	1.8
AT-61	.22	ND	1.6	190	0	43	20	160	2.7
GU-71	ND	.120	1.0	8	0	2.3	.6	340	2.5
GU-73	ND	ND	1.3	452	105	120	36	50	3.9
GU-76	ND	.010	.5	13	0	3.4	1.0	310	.9
GU-77	.62	ND	.6	244	33	62	21	38	4.4
GU-80	ND	.010	.6	65	0	17	5.4	130	2.4
HK-51	.20	ND	.9	1,227	940	260	140	31	3.5
ME-22	.10	.070	.4	12	0	3.3	1.0	260	1.5
MU-41	.11	ND	.5	224	42	58	19	13	1.5
MU-42	ND	ND	.7	63	0	15	5.9	690	3.3
MU-45	.22	ND	.8	116	12	30	10	12	.7
MU-46	10	ND	4.0	277	87	68	26	17	2.0
V-87	3.6	ND	1.7	465	153	110	46	77	2.4

Table 1.--Selected ground-water-quality analyses from southeastern Ohio, 1983--Continued

Local identifier	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Iron, dissolved (µg/L as Fe)	Manganese, dissolved (µg/L as Mn)	Strontium, dissolved (µg/L as Sr)	Aluminum, dissolved (µg/L as Al)	Solids, sum of constituents, dissolved (mg/L)	Hydrogen sulfide, total (mg/L as H_2S)
ALLEGHENY FORMATION--Continued										
AT-52	73	9.0	1.1	10	98	23	170	ND	479	0.3
AT-60	400	270	.4	15	990	210	1,900	ND	1,466	ND
GU-78	210	900	.3	10	15,000	1,100	3,100	200	1,794	.2
GU-81	33	2.0	.4	11	22	18	100	ND	402	.2
GU-82	30	3.0	.8	8.9	6	4	22	ND	513	ND
MU-48	12	56	.5	10	16	50	270	100	305	.3
PE-31	29	590	.1	12	33	1,100	1,200	ND	989	ND
PE-32	8.6	140	.3	12	19	77	340	ND	465	ND
PE-34	7.4	220	.1	24	510	240	110	ND	403	ND
PE-35	4.0	1,800	.3	6.6	10	120	1,800	ND	2,702	ND
PE-36	2.0	290	.1	3.9	62	60	500	200	456	ND
TU-42	1.7	55	.2	18	750	300	370	ND	271	ND
TU-45	21	130	.4	9.6	500	600	770	ND	488	.2
V-86	8.3	5.1	.8	8.7	17	4	36	200	390	.2
V-88	14	120	.4	12	79	49	250	ND	423	ND
V-89	28	11	.6	11	370	68	320	100	287	ND
Spring	4.7	440	.3	8.9	14	20	770	100	697	ND
AT-51	1,100	120	.8	9.5	140	30	3,300	ND	2,478	.2
AT-54	52	ND	1.9	8.1	33	5	100	ND	--	1.0
GU-72	23	9.8	.4	17	760	100	1,200	ND	256	.0
GU-74	1.9	48	.2	15	8	9	300	300	236	ND
GU-75	1.1	20	ND	10	27	6	41	ND	69	ND
GU-79	33	90	.2	10	220	110	170	300	326	ND
ME-21	1.4	36	.3	34	18	29	44	100	114	.2
MU-47	110	22	.2	18	4	99	650	ND	388	.2

Table 1.--Selected ground-water-quality analyses from southeastern Ohio, 1983--Continued

Local identifier	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Iron, dissolved (µg/L as Fe)	Manganese, dissolved (µg/L as Mn)	Strontium, dissolved (µg/L as Sr)	Aluminum, dissolved (µg/L as Al)	Solids, sum of constituents, dissolved (mg/L)	Hydrogen sulfide, total (mg/L as H_2S)
ALLEGHENY FORMATION--Continued										
PE-33	6.9	53	0.3	13	35	4	120	100	353	ND
PE-37	6.9	26	.4	13	120	47	1,900	ND	259	ND
PE-38	20	190	.2	20	7,600	1,300	530	ND	562	ND
TU-41	32	930	.2	18	17,000	30,000	1,300	ND	--	.2
TU-43	2.1	120	.3	17	220	140	610	ND	430	.2
TU-44	1.5	130	.4	13	700	240	870	ND	445	.2
TU-46	3.1	49	.2	18	2,300	220	190	100	205	.2
AT-57	11	360	1.0	30	49	630	480	100	774	.2
AT-58	17	270	.3	18	65	35	300	ND	652	.3
AT-59	6.9	130	.2	11	680	850	460	ND	535	ND
AT-61	140	46	.6	8.9	88	340	430	ND	599	ND
GU-71	30	12	1.6	5.5	12	23	79	200	790	.2
GU-73	76	150	.3	6.1	870	190	3,700	200	669	ND
GU-76	46	6.1	4.7	7.0	17	3	240	300	763	ND
GU-77	1.3	88	.5	12	17	3	2,000	100	372	ND
GU-80	9.7	11	.6	10	24	83	510	100	403	.8
HK-51	6.6	1,000	.2	10	210	10	1,500	ND	1,635	ND
ME-22	80	ND	2.1	8.0	20	48	61	100	--	.3
MU-41	8.2	30	.2	18	27	20	650	100	281	ND
MU-42	730	100	1.0	8.1	20	30	690	ND	1,834	ND
MU-45	1.9	37	.3	22	49	21	120	100	178	ND
MU-46	34	58	.3	7.7	10	4	210	300	332	.2
V-87	50	250	.2	8.8	26	2	790	100	752	ND

Table 1.--Selected ground-water-quality analyses from southeastern Ohio, 1983--Continued

Local identifier	Associated coal bed	Latitude	Longitude	Well depth (feet)	Date of sample	Specific conductance (µS/cm)	pH (standard units)	Bicarbonate, FET-fld[1] (mg/L as HCO_3)	Carbonate, FET-fld[1] (mg/L as CO_3)
MONONGAHELA FORMATION									
AT-53	No. 8	39 13 48	082 05 37	100	83-02-01	540	7.3	340	--
AT-55	do.	39 14 07	082 02 37	135	83-02-02	560	7.6	300	--
AT-56	do.	39 16 13	082 13 17	210	83-02-02	1,500	8.9	490	41
AT-63	do.	39 19 59	082 55 48	180	83-02-08	260	6.9	80	--
AT-65	do.	39 20 49	081 52 40	61	83-02-08	600	7.2	360	--
AT-66	do.	39 21 22	081 52 23	144	83-02-08	4,250	7.5	390	--
B-27	do.	40 07 58	081 10 57	70	83-04-22	480	7.6	360	--
HR-22	do.	40 19 21	080 55 51	260	83-04-21	880	7.2	260	--
JE-91	do.	40 20 20	080 49 34	185	83-04-22	970	7.5	390	--
JE-92	do.	40 20 37	080 51 48	245	83-04-22	3,600	6.9	690	--
JE-93	do.	40 14 14	080 48 07	145	83-04-22	700	7.5	380	--
JE-94	do.	40 14 01	080 48 15	260	83-04-22	1,250	7.4	840	--
ME-23	do.	39 11 29	082 06 15	105	83-02-22	540	7.0	220	--
MG-69	do.	39 33 36	081 59 13	75	83-03-23	545	7.0	330	--
MU-44	do.	39 55 19	081 45 29	125	83-03-17	670	7.5	410	--
B-23	No. 9	39 55 10	080 46 02	161	83-04-13	925	8.6	510	41
MG-54	do.	39 28 41	081 58 22	140	83-02-14	675	7.4	390	--
MG-55	do.	39 28 31	081 58 29	110	83-02-14	830	7.4	450	--
MG-58	do.	39 38 14	081 53 31	89	83-02-15	1,050	7.3	400	--
MG-59	do.	39 40 53	081 50 52	105	83-02-18	850	7.2	440	--
MG-64	do.	39 38 36	081 46 38	95	83-02-19	465	7.6	270	--
MG-65	do.	39 38 39	081 46 26	120	83-02-19	795	7.5	340	--
MG-66	do.	39 40 12	081 55 34	75	83-02-19	595	7.0	380	--
MG-67	do.	39 43 36	081 42 29	90	83-02-18	610	7.4	370	--
WA-57	do.	39 35 11	081 18 55	106	83-02-23	505	6.9	190	--
WA-56	do.	39 34 56	081 39 59	45	83-02-23	720	7.4	390	--
WA-55	do.	39 33 49	081 19 04	90	83-02-23	455	7.4	290	--

Table 1.--Selected ground-water-quality analyses from southeastern Ohio, 1983--Continued

Local identifier	Associated coal bed	Latitude	Longitude	Well depth (feet)	Date of sample	Specific conductance (µS/cm)	pH (standard units)	Bicarbonate, FET-fld[1] (mg/L as HCO_3)	Carbonate, FET-fld[1] (mg/L as CO_3)
MONONGAHELA FORMATION--Continued									
WA-54	No. 9	39 35 00	081 19 21	80	83-02-23	585	7.4	330	--
WA-53	do.	39 34 32	081 24 34	55	83-02-23	1,150	7.0	260	--
WA-59	do.	39 32 28	081 43 16	40	83-03-23	825	9.1	340	84
WA-61	do.	39 33 48	081 34 12	60	83-03-24	1,350	7.4	480	--
B-21	No. 10	40 08 26	080 54 31	118	83-04-13	790	7.6	470	--
B-22	do.	40 08 18	080 52 00	114	83-04-13	690	7.3	290	--
B-24	do.	40 02 37	081 00 41	102	83-04-14	450	7.6	230	--
B-25	do.	39 57 00	081 10 19	38	83-04-14	430	7.6	300	--
B-26	do.	40 00 15	081 10 04	57	83-04-13	630	7.4	400	--
HR-21	do.	40 11 09	081 00 33	80	83-04-21	645	7.5	280	--
MG-51	do.	39 28 25	081 51 31	80	83-02-08	300	7.6	170	--
MG-53	do.	39 34 17	081 51 33	96	83-02-14	1,100	7.2	430	--
MG-56	do.	39 31 07	081 50 46	80	83-02-15	1,050	7.4	400	--
MG-57	do.	39 31 06	081 51 05	75	83-02-15	2,550	7.0	540	--
MG-63	do.	39 33 04	081 45 37	100	83-02-19	690	7.8	320	--
N-11	do.	39 47 38	081 20 02	110	83-03-24	725	7.6	340	--
WA-51	do.	39 26 33	081 47 48	60	83-02-15	595	7.2	340	--
WA-52	do.	39 21 05	081 47 28	80	83-02-19	680	7.2	230	--
WA-58	do.	39 30 59	081 39 40	75	83-03-23	905	7.6	310	--
WA-60	do.	39 33 57	081 29 55	126	83-03-24	520	7.4	290	--
AT-64	No. 11	39 22 21	081 54 37	100	83-02-08	310	7.6	170	--
MG-52	do.	39 28 10	081 50 38	80	83-02-08	175	6.3	55	--
MG-60	do.	39 37 53	081 40 26	75	83-02-18	1,100	7.0	230	--
MG-61	do.	39 34 17	081 45 42	100	83-02-19	140	6.2	40	--
MG-62	do.	39 33 58	081 45 39	85	83-02-19	285	6.2	72	--

Table 1.--Selected ground-water-quality analyses from southeastern Ohio, 1983--Continued

Local identifier	Nitrogen, $NO_2 + NO_3$, dissolved (mg/L as N)	Orthophosphorus, dissolved (mg/L as P)	Carbon, organic, total (mg/L as C)	Hardness (mg/L as $CaCO_3$)	Hardness, noncarbonate (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)
MONONGAHELA FORMATION--Continued									
AT-53	1.3	ND	0.7	256	0	56	28	27	1.1
AT-55	ND	ND	.4	203	0	65	9.8	41	1.2
AT-56	.12	.060	.8	7	0	2.0	.5	380	.9
AT-63	11	ND	.7	98	32	27	7.4	13	.7
AT-65	1.1	ND	.5	298	3	60	36	26	1.7
AT-66	.13	ND	.6	214	0	62	14	850	3.1
B-27	.52	ND	1.3	258	13	72	19	3.4	1.4
HR-22	ND	ND	1.1	402	207	91	42	30	2.7
JE-91	.15	ND	1.3	474	171	120	42	37	2.4
JE-92	ND	ND	2.5	3,113	2,596	520	440	13	6.7
JE-93	2.0	ND	.5	370	80	90	35	3.9	2.3
JE-94	ND	ND	1.3	123	0	32	10	270	5.4
ME-23	13	ND	.8	260	89	86	11	28	.8
MG-69	ND	ND	.6	289	38	100	9.4	1.8	.7
MU-44	.42	ND	.4	357	101	78	39	8.9	1.6
B-23	ND	ND	1.3	88	0	17	11	200	1.9
MG-54	1.6	ND	.5	289	0	66	30	43	1.1
MG-55	2.5	ND	.6	415	46	110	34	23	.9
MG-58	14	ND	.5	453	79	130	31	25	.7
MG-59	12	ND	.6	469	130	120	41	13	.8
MG-64	1.0	ND	.2	238	27	64	19	6.0	.4
MG-65	1.1	ND	.7	1	0	.3	.1	210	.1
MG-66	.13	ND	.3	325	35	110	12	5.7	1.0
MG-67	ND	ND	.7	367	75	92	33	7.5	1.1
WA-57	7.8	.020	.8	206	96	59	14	36	2.5
WA-56	.49	ND	.3	424	118	110	36	14	1.3
WA-55	3.0	ND	.4	242	42	77	12	4.9	.9

Table 1.--Selected ground-water-quality analyses from southeastern Ohio, 1983--Continued

Local identifier	Nitrogen, $NO_2 + NO_3$, dissolved (mg/L as N)	Orthophosphorus, dissolved (mg/L as P)	Carbon, organic, total (mg/L as C)	Hardness (mg/L as $CaCO_3$)	Hardness, noncarbonate (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)
MONONGAHELA FORMATION--Continued									
WA-54	5.9	ND	0.9	294	57	88	18	24	2.4
WA-53	ND	ND	.7	677	520	150	73	34	2.5
WA-59	ND	.010	.7	5	0	1.4	.5	250	8.6
WA-61	ND	ND	1.1	588	265	160	45	73	2.0
B-21	.63	ND	1.0	295	0	68	29	76	2.8
B-22	3.4	ND	1.2	340	122	88	29	10	2.2
B-24	.24	.010	.7	182	0	51	13	25	1.5
B-25	ND	ND	1.1	193	0	57	12	18	1.3
B-26	1.6	ND	.7	334	42	94	24	6.2	2.8
HR-21	1.9	ND	1.2	331	109	86	28	5.4	1.1
MG-51	2.7	ND	.7	139	0	42	8.3	4.3	.5
MG-53	4.4	ND	.3	607	254	140	62	9.9	1.8
MG-56	2.7	ND	.5	568	240	120	65	39	2.7
MG-57	.50	ND	.3	1,500	1,074	300	180	80	3.5
MG-63	.48	ND	1.6	310	60	71	32	44	3.3
N-11	2.1	ND	1.1	254	0	75	16	66	1.1
WA-51	ND	.070	.2	260	0	71	20	30	.8
WA-52	.38	ND	.3	351	170	96	27	25	.7
WA-58	5.2	ND	.7	367	123	69	47	59	1.5
WA-60	2.6	ND	1.0	246	21	54	27	22	1.2
AT-64	2.5	ND	.7	150	11	46	8.4	9.6	.3
MG-52	7.6	ND	.4	54	9	14	4.5	14	.4
MG-60	.13	ND	.8	549	372	150	42	29	1.5
MG-61	1.6	ND	.2	47	20	12	4.1	5.6	.6
MG-62	7.4	ND	.2	114	41	29	10	11	.7

Table 1.--Selected ground-water-quality analyses from southeastern Ohio, 1983--Continued

Local identifier	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Iron, dissolved (µg/L as Fe)	Manganese, dissolved (µg/L as Mn)	Strontium, dissolved (µg/L as Sr)	Aluminum, dissolved (µg/L as Al)	Solids, sum of constituents, dissolved (mg/L)	Hydrogen sulfide, total (mg/L as H_2S)
MONONGAHELA FORMATION--Continued										
AT-53	13	29	0.1	11	6	2	660	ND	333	0.3
AT-55	21	56	.3	12	24	91	610	ND	355	.2
AT-56	180	51	2.6	7.3	ND	3	92	ND	949	.3
AT-63	10	15	.1	14	13	5	150	100	127	ND
AT-65	6.8	68	.2	8.9	29	1	360	100	385	ND
AT-66	1,300	43	.7	12	30	240	1,100	100	2,478	ND
B-27	4.3	35	.3	6.3	7	4	230	200	319	ND
HR-22	34	255	.2	9.0	13	21	1,700	100	594	.2
JE-91	80	180	.3	11	15	16	1,300	ND	666	ND
JE-92	4.0	2,700	.2	10	7,300	5,200	2,700	ND	4,048	ND
JE-93	7.0	100	.1	9.6	29	6	680	ND	435	ND
JE-94	57	54	.4	6.7	600	60	1,400	ND	851	.2
ME-23	31	37	.1	27	12	16	250	100	329	ND
MG-69	3.3	57	.2	9.1	12	28	330	ND	344	ND
MU-44	12	63	.2	11	14	7	1,700	ND	417	ND
B-23	39	10	2.7	8.9	15	4	540	ND	625	ND
MG-54	9.6	84	.2	9.4	12	2	1,000	100	436	ND
MG-55	9.6	140	.2	10	4	8	690	100	550	ND
MG-58	45	130	.1	14	48	2	690	100	573	.2
MG-59	28	100	.2	12	17	1	650	ND	532	ND
MG-64	13	32	.2	9.1	6	1	330	200	277	ND
MG-65	66	52	.3	10	4	ND	3	ND	506	ND
MG-66	6.6	40	.2	12	18	14	400	100	375	ND
MG-67	11	56	.2	14	5	270	770	ND	398	ND
WA-57	52	82	.1	9.7	17	10	820	ND	350	.3
WA-56	5.2	120	.3	7.4	33	2	930	ND	487	ND
WA-55	7.1	35	.2	11	3	6	360	200	291	ND

Table 1.--Selected ground-water-quality analyses from southeastern Ohio, 1983--Continued

Local identifier	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Iron, dissolved (µg/L as Fe)	Manganese, dissolved (µg/L as Mn)	Strontium, dissolved (µg/L as Sr)	Aluminum, dissolved (µg/L as Al)	Solids, sum of constituents, dissolved (mg/L)	Hydrogen sulfide, total (mg/L as H_2S)
MONONGAHELA FORMATION--Continued										
WA-54	23	38	0.2	12	47	17	500	100	369	ND
WA-53	3.8	510	.9	16	28,000	3,700	1,800	ND	952	ND
WA-59	7.7	45	1.2	6.4	6	2	55	ND	659	ND
WA-61	29	400	.3	13	6,000	410	2,900	ND	968	ND
B-21	4.6	96	.3	12	5	3	5,300	ND	525	ND
B-22	14	130	.2	12	31	2	1,100	ND	429	ND
B-24	2.6	58	.2	14	49	11	1,000	100	280	ND
B-25	2.9	15	.3	17	1,200	210	660	300	273	ND
B-26	2.7	67	.2	7.7	66	9	470	100	402	ND
HR-21	12	130	.1	10	20	5	630	ND	411	.2
MG-51	4.8	5.0	ND	20	8	14	120	ND	169	ND
MG-53	29	320	.2	15	34	9	1,500	200	791	ND
MG-56	25	330	.2	9.2	41	9	980	200	789	ND
MG-57	69	1,300	.2	17	130	190	8,600	200	2,224	ND
MG-63	9.1	140	.2	7.9	12	5	420	100	465	ND
N-11	15	110	.2	8.1	8	3	950	ND	460	ND
WA-51	2.7	83	.2	13	5,700	500	490	100	395	ND
WA-52	48	120	.2	33	62	4	360	ND	463	ND
WA-58	24	220	.3	8.4	20	4	1,200	100	583	ND
WA-60	8.4	59	.2	7.8	14	4	400	300	323	ND
AT-64	8.9	20	ND	23	11	1	200	100	200	ND
MG-52	6.5	9.0	ND	32	18	4	70	100	108	ND
MG-60	130	200	.3	24	3	730	940	100	692	ND
MG-61	2.9	26	ND	21	38	9	57	100	92	ND
MG-62	12	31	.1	20	17	28	180	ND	149	ND

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[1] FET-fld, fixed-endpoint titration (field determination).