STATE OF INDIANA
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DIVISION OF WATER

BULLETIN NO. 35

HYDROGEOLOGY OF THE PRINCIPAL AQUIFERS IN SULLIVAN AND GREENE COUNTIES, INDIANA

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Prepared by the
GEOLOGICAL SURVEY
UNITED STATES DEPARTMENT OF THE INTERIOR
in cooperation with the
DIVISION OF WATER
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Robert F. Jackson, Chief

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By L. W. Cable and T. M. Robison

ABSTRACT

The rocks that underlie Sullivan and Greene Counties may be placed in two general categories--consolidated and unconsolidated. Based on their water-bearing properties the consolidated rocks are subdivided into three major hydrologic units. Aquifers in unit 1 are relatively thickbedded limestone and sandstone bodies. This unit contains the best consolidated rock aquifers of the two county area. The average yield from wells in this unit is 10 gpm with yields of as much as 100 gpm reported. The aquifers of unit 2 are sandstone bodies which occur throughout the strata of this unit. The average yield of wells in this unit is 5 gpm, and maximum yields are about 20 gpm. Unit 3 is similar in most respects to unit 2; however, in this unit there are fewer water-bearing sandstone bodies and, as a consequence, numerous dry holes are drilled.

Aquifers in the unconsolidated rocks of the area are coarse sand and gravel deposits which are principally glacial in origin. These deposits are located predominantly along the stream valleys. The valleys of the Wabash and White Rivers contain the thickest and, therefore, the best unconsolidated rock aquifers of the area. Yields from wells in these aquifers average 350 gpm with yields of as much as 1,000 gpm reported.

Partial or complete analyses of over 300 samples of water indicate that the consolidated rocks of the area yield calcium bicarbonate, sodium bicarbonate, and sodium chloride water, and the unconsolidated rocks yield calcium bicarbonate water.

INTRODUCTION

Purpose and Scope

The purpose of this report is to evaluate the ground-water resources of Sullivan and Greene Counties, Indiana with respect to the hydrogeology of the consolidated and unconsolidated rocks and the chemical quality of the water in these rocks, and to provide information that will aid in the location and development of the principal sources available for domestic, agricultural, industrial, and municipal use. The chief problems are related to ground-water availability and potential of sources now being used. Further consideration is given these two aspects with respect to future water supply development. This report identifies the principal sources of ground water, describes the hydrogeologic characteristics and potential of these sources, and defines the chemical quality of the water and factors affecting water quality.

Previous Investigations

The results of generalized geologic-ground-water resources studies were published by Leverett (1897 and 1905) and Harrell (1935). Preliminary evaluations of the ground-water resources of both Greene and Sullivan Counties are published separately in reports by Watkins and Jordan (1961 and 1962).

Cooperation and Acknowledgements

The investigation of the ground-water resources of these counties has been conducted by the U. S. Department of the Interior, Geological Survey, in cooperation with the Indiana Department of Natural Resources, Division of Water, as a part of the State-wide investigation of the ground-water resources of Indiana. The authors wish to express their sincere thanks to all persons who contributed time, information, and assistance during the collection, tabulation, and processing of data for this report. We are especially grateful to the following State agencies for information furnished by them and used in this report: the Geological Survey, the Division of Oil and Gas, and the Division of Water, all of the Indiana Department of Natural Resources.

Physiography and Climate

Sullivan and Greene Counties, of west-central Indiana (fig. 1), are within the Wabash Lowland and Crawford Upland physiographic provinces (Malott, 1922, p. 59-256). All of Sullivan County and approximately two-thirds of adjoining Greene County form a part of the Wabash Lowland. This region is topographically low and is generally characterized by wide alluvial plains and aggraded valleys. The remainder of Greene County is part of the Crawford Upland. In this part of the area the variety of topographic form and diversity of relief, which is so characteristic of this physiographic province, is much in evidence. The land becomes quite rugged with numerous hills and ridges separated in places by deep valleys. The entire two-county area is drained by the Wabash and White Rivers and their tributaries.

Continuous records of air temperature and precipitation at Elliston, Indiana (fig. 1) have been kept since 1913 by the U. S. Weather Bureau.

Based on normals for the period 1931-1960 the average annual precipitation is 42.08 inches and the average annual air temperature is 54.3° F. The average monthly precipitation is shown in Table 1.

Table 1.--Average monthly precipitation at

Elliston, Indiana, 1931-1960.

Month	Precipitation (inches)
January---------	3.45
February--------	2.60
March-----------	3.75
April-----------	3.88
May-------------	4.44
June------------	4.91
July------------	3.43
August----------	3.37
September-------	3.34
October---------	2.54
November--------	3.44
December--------	2.89

Ground-Water Occurrence and Movement

The principal source of ground water is precipitation that seeps into the soil and rock through open spaces (interstices) between individual particles. The size and degree of interconnection of the interstices (porosity) are factors important to the infiltration of water into the ground. Water in the soil or rock moves downward under the force of gravity until it reaches a level below which the interstices become saturated. This level marks the top of the zone of saturation and is termed the water table. Water in this zone is called ground water, and rocks that will yield sufficient ground water to be a source of supply are referred to as aquifers.

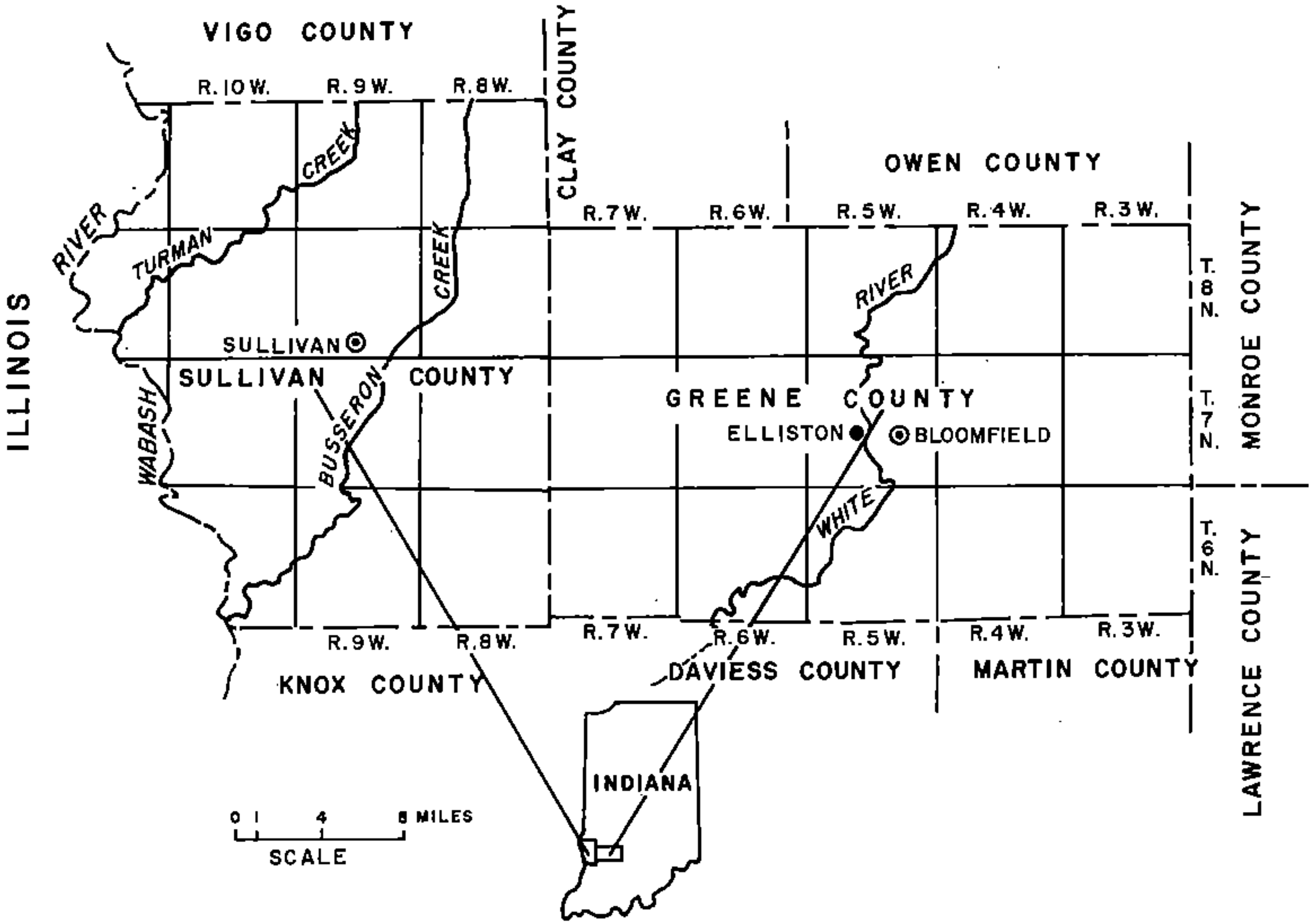


FIGURE 1. -- Index map of Indiana showing the location of Sullivan and Greene Counties.

Not all the water that seeps below land surface reaches the zone of saturation. Above the zone of saturation is the zone of aeration (suspended water) where some water is withdrawn by evaporation and transpiration and where some water is locked in the interstices by molecular attraction. Rocks in the zone of aeration are not completely saturated.

Two principal types of ground water occur in the zone of saturation, unconfined and confined. Water occurs under unconfined (water-table) conditions if the aquifer is directly overlain by unsaturated material whose permeability (ability to transmit water) is similar to that of the aquifer. The water level in wells tapping such an aquifer will coincide approximately with the water level in the aquifer. Conversely, water in an aquifer is said to occur under confined (artesian) conditions if the water is under pressure because the aquifer is directly overlain by a layer of rock whose permeability is less than that of the aquifer. Such a layer retards ground-water movement and is termed "confining layer". The retardation of ground-water movement will result in an increase in hydrostatic pressure in the aquifer and this will cause the water level in wells tapping the aquifer to rise above the base of the confining layer.

The surface that coincides with the static water level in wells is termed "piezometric surface". The piezometric surface is imaginary in an artesian aquifer because it represents not a real surface but indicates the distribution of hydrostatic pressure in the aquifer. However, under water-table conditions the piezometric surface is real because it represents the top of the zone of saturation.

Figure 2 shows diagrammatically the basic fundamentals of the source, occurrence, and movement of ground water. For a more complete explanation of the fundamentals of ground-water hydrology see Baldwin and McGuinness (1963).

HYDROGEOLOGY

Both consolidated and unconsolidated rocks underlie Sullivan and Greene Counties and both contain significant water-bearing zones that are distinctly separate hydrologic units. The stratigraphy of these rocks and a summary of their hydrologic properties is shown in table 2. For this report a small municipal or industrial requirement is regarded as less than 100 gpm (gallons per minute); a moderate requirement is 100 to 300 gpm: and a large requirement is greater than 300 gpm.

The geologic names used in this report are those used by the Indiana Geological Survey and are not necessarily recognized by the U. S. Geological Survey.

Consolidated Rocks as Sources of Water

The consolidated rocks of the area are Mississippian and Pennsylvanian

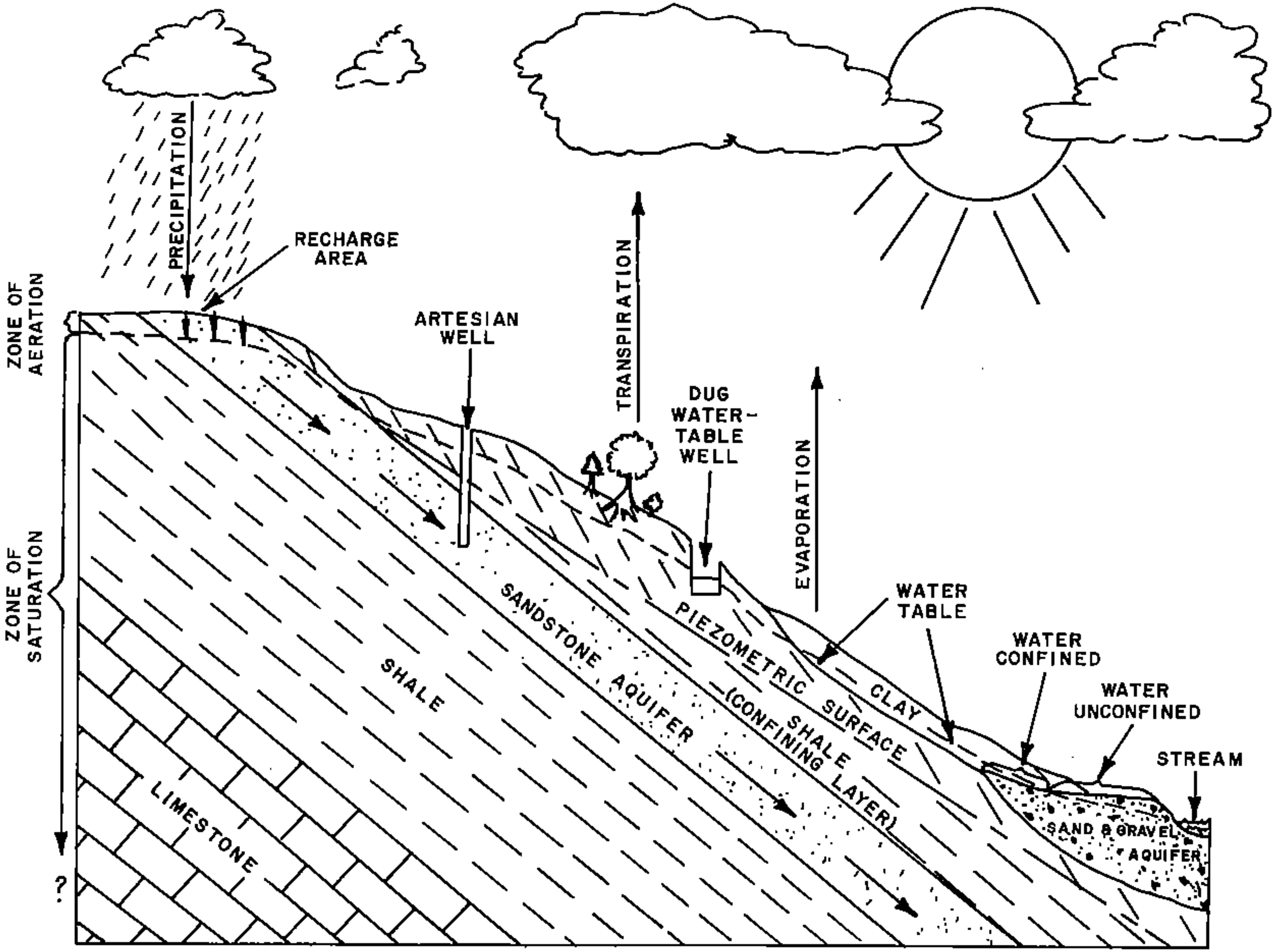


FIGURE 2. -- Fundamental principle of the source, occurrence, and movement of ground water.

Table 2.--Generalized stratigraphic section and hydrologic properties of Mississippian and younger rocks in Sullivan and Greene Counties

System		Series	Deposit or formation	Principal aquifers and hydrologic units	Average yield (gpm)	Average well depth (feet)	Quality of water	Potential production considered adequate for:
Quaternary		Recent	Alluvium	Sand and gravel	350	60	Usually very hard and deficient in fluoride. Excessive iron very common.	Large industrial or municipal requirements.
		Pleistocene	Glacial					
Carboniferous	Pennsylvanian	Upper Pennsylvanian	Matton of Kosanke and others (1960)	Unit 3	5	150	Shallow water usually similar to that in Quaternary rocks. At depth, water is usually soft, frequently high in fluoride, with less iron and higher concentrations of bicarbonate, total dissolved solids and chloride.	Domestic, farm, small industrial or municipal requirements.
			Bond of Kosanke and others (1960)					
			Patoka of Wier and Gray (1961)					
			Shelburn	Unit 2	5			
		Middle Pennsylvanian	Dugger					
			Petersburg					
			Linton					
		Lower Pennsylvanian	Staunton					
			Brazil				Shallow water moderately hard, becoming soft with depth. Bicarbonate and total dissolved solids concentrations increase with depth. Excessive iron much less common than in overlying rocks.	Small to moderate industrial or municipal requirements.
			Mansfield	Unit 1	10			
	Mississippian	Chester and Upper Meramec	Limestone shale, and sandstone					

in age. (See Patton, 1956). These strata dip to the west and southwest at an average rate of from 25 to 35 feet per mile and crop out in wide belts across the bedrock surface. Mississippian rocks are composed chiefly of sandstone, shale, and limestone. The limestone beds are relatively thick, compared to those in the overlying Pennsylvanian section, and are the principal sources of ground water. Bedded sandstone is also a source of water.

The Pennsylvanian rocks are a part of the eastern shelf area of the Eastern Interior structural basin. They consist of shale, sandy shale, and fine- to medium-grained sandstone with many thin, readily distinguishable beds of limestone, coal, and underclay. These rocks are arranged in repetitive sequence or cycles known as cyclothems (Weller, 1930; Wanless and Weller, 1932). Each cyclothem ideally consists of ten distinct lithologic members and extends from the base of a sandstone to the base of the next higher sandstone. The basal sandstone member generally is the principal water-bearing zone of the sequence.

The consolidated rocks of the two-county area can be subdivided into 3 major hydrologic units on the basis of their water-bearing properties. (See table 2). No attempt has been made to map individual aquifers within these units.

Hydrologic Unit 1

Unit 1 includes all rocks of Mississippian age plus the basal Pennsylvanian Mansfield Formation (See pl. 1). The relatively thick-bedded limestones and sandstones are the best aquifers of this unit. The limestone aquifers are Mississippian in age and occur along the eastern edge of the area in Greene County. Thick sandstone bodies of both Mississippian and Pennsylvanian age above these limestone beds are the principal source of ground water in the area to the west. Properly constructed wells in this unit should readily yield 20 to 30 gpm (gallons per minute). Yields as high as 100 gpm have been reported.

Several wells with relatively high yields occur in the sandstone area of unit 1. The location, casing record, and lithology of these wells indicates that the water is being produced from the vicinity of the Mississippian-Pennsylvanian contact. (See pl. 1). This contact may be a significant source of water in which relatively high-yield wells could be developed. No detailed subsurface map of this contact is available at this time.

The best aquifers of the consolidated rock of Sullivan and Greene Counties are the limestone and sandstone bodies of hydrologic unit 1. With proper well construction yields sufficient for small to moderate industrial or municipal requirements may be obtained.

Springs are common in the limestone terranes of eastern Greene County. Some of these springs are perennial and may serve as sources of ground water. Yields adequate for domestic, farm, and, in a few cases, small industrial requirements occur. For information concerning the location, yield, and water quality of the more important springs in this area see Watkins and Jordan (1961, table 4).

Hydrologic Unit 2

Unit 2 includes all rocks between the base of the Brazil Formation and the top of the Shelburn Formation. (See pl. 1). The cyclic nature of the Pennsylvanian rocks, or cyclothems, becomes much more obvious in this section. The basal sandstone members of the cyclothems are the principal water-bearing zones. Each sandstone member commonly contains two phases--a sheet phase and a channel phase. The channel phase has the best potential as a source of water because of its greater thickness. Wells drilled in unit 2 will, in all likelihood, penetrate one or more of these water-bearing sandstones owing to their occurrence throughout the strata of this unit. Yields from wells in unit 2 average 5 gpm and rarely exceed 20 gpm. For a more detailed study of the geologic and hydrologic characteristics of aquifers in this part of the Pennsylvanian section of west-central Indiana, see Cable, Watkins, and Robison (1971).

The potential production from the water-bearing rock of unit 2 is substantially less than that of unit 1. The amount of water normally produced from wells in unit 2 is adequate for farm, domestic, and in some cases, small industrial and small municipal requirements.

Hydrologic Unit 3

Unit 3 includes all consolidated rocks above the Shelburn Formation. (See pl. 1). These rocks are similar in most respects to those of unit 2. Cyclothems are well developed, and the basal sandstone member is the best source of water. In unit 3, however, the sandstone bodies generally are not as continuous as those of unit 2 and they occur less frequently than in unit 2. Therefore, wells drilled into unit 3 are less likely to penetrate a sandstone aquifer than are those drilled into unit 2. There is a substantial increase in the number of dry holes drilled in unit 3 as compared to unit 2. Where water wells are made in unit 3, their yields are similar to those of unit 2.

Bedrock Topography

The topography and elevation of the bedrock surface in Sullivan and Greene Counties is shown on plate 2. The configuration of this surface is the result of long periods of weathering and erosion that began in late Palezoic time, approximately 300 million years ago. As a result of glaciations during the Pleistocene Epoch or "Great Ice Age", which began about 1 million years ago, approximately four fifths of the area was blanketed by glacial deposits. (See pl. 3). The bedrock surface beneath these glacial deposits is a gently rolling plain with moderate relief. Where bedrock is at the land surface it is quite rugged and hilly. There is greater local relief in the unglaciated area and bedrock is exposed at higher elevations of the land surface. Many of the valleys in the unglaciated area are filled with glacial outwash deposits and (or) lake sediments. (See pl. 3).

Unconsolidated Rocks as Sources of Water

The chief sources of ground water in the unconsolidated rocks of Sullivan and Greene Counties are the glacial outwash and alluvium of the Wabash and White River valleys. These deposits are composed mostly of relatively well-sorted coarse sand and gravel from which water may be produced in relatively large quantities. Similar sand and gravel deposits occur in some of the valleys of the principal tributaries of the Wabash and White Rivers. These deposits are also potential sources of water. Information is not sufficient, however, for a detailed mapping of the sand and gravel deposits of either the Wabash and White River valleys or their major tributaries or for an adequate appraisal of their aquifer capabilities. Outside of the major stream valleys the unconsolidated rock is mostly till and lake sediment. (See pl. 3). These deposits do not as a rule contain good aquifers and the underlying bedrock aquifers generally are the best sources of ground water.

During Pleistocene time the Wabash and White Rivers served as major sluiceways for glacial melt waters. (See Thornbury, 1950). Thick valley trains of glacial outwash were built along these valleys and their major tributaries so that the present valley floors stand considerably above the bedrock surface. In places, the valley-fillings contain thick and extensive beds of water-bearing sand and gravel that are capable of the development of large-capacity wells. Yields of approximately 1,000 gpm have been obtained from wells in these aquifers in sections 3, 4, 14, and 15, T. 6 N., R. 10 W. of Sullivan County and in section 7, T. 6 N., R. 6 W. of Greene County.

The water in the aquifers of these valleys may occur under either unconfined (water-table) or confined (artesian) conditions. However, the water generally is unconfined in the Wabash River valley aquifers and generally is confined in the aquifers of the White River valley. The confined conditions in the White River valley are the result of extensive deposition of lacustrine silt and clay over outwash during the latter part of the Pleistocene Epoch. (See pl. 3). Yields from properly constructed wells in these river valleys should be adequate for large industrial or large municipal requirements.

Test holes should be drilled in the valley fill of the stream valleys in order to determine the location, extent, thickness, and saturated thickness of an aquifer before attempting to drill and develop large-capacity wells. In the bedrock surface beneath the unconsolidated valley-fill deposits there generally is a buried channel that, in the report area, marks the pre-Pleistocene course of the river. The areas overlying the buried channels are likely places for exploration and possible development of large-capacity wells because it is here that the saturated valley-fill deposits will be thickest. However, the exact location of the buried channel can be difficult to determine because the position of this channel is in no way related to the position of the present stream. Test drilling is the most common method used for determining the position of the buried channel.

Figure 3 shows schematically the best method of locating a buried channel by test drilling. Illustration A in the figure is a plan of a stream valley showing the flood plain, the present stream channel, the buried channel and a line of test holes (A-A'). The cross section along A-A' is shown in illustration B. This illustration does not represent a particular location in the Sullivan-Greene County area. It is an example used to illustrate the practicality of test-drilling to obtain required information for maximum development of available sources.

Lines of test holes should be drilled straight across the flood plain of a valley in order to locate the buried channel and evaluate the aquifer capabilities of the valley fill with a minimum of test drilling. The spacing between the test holes will depend on the size of the valley. The cross section shows the thickest water-bearing materials occurring between test holes 2 and 3; therefore, the buried channel occurs between these test holes. A test hole (no. 6) should be drilled between test holes 2 and 3 in order to determine maximum thickness of the saturated valley-fill. If a more accurate determination of the position of the buried channel is desired, additional test holes should be drilled between test holes 2 and 6 and between test holes 6 and 3. The trend of the buried channel can be determined by drilling additional lines of test holes across the valley.

Water-Level Fluctuations

Seasonal fluctuations of water levels in wells occur with cyclic regularity. These fluctuations are the result of seasonal variations in the ratio of recharge to discharge in the aquifer. When the amount of recharge exceeds that of discharge, the supply of water in the aquifer is replenished and the water level in wells in the aquifer will rise; conversely, when the amount of discharge from the aquifer exceeds that of recharge, water is withdrawn from storage and the water level in a nonpumped well will be highest in mid spring and will decline steadily throughout the spring and summer months, reaching its lowest point in mid autumn. This is the result principally of an increase in the amount of water withdrawn from the soil by evaporation and transpiration during the late spring and summer months. The general increase in the amount of water used for agricultural, recreational, and domestic purposes

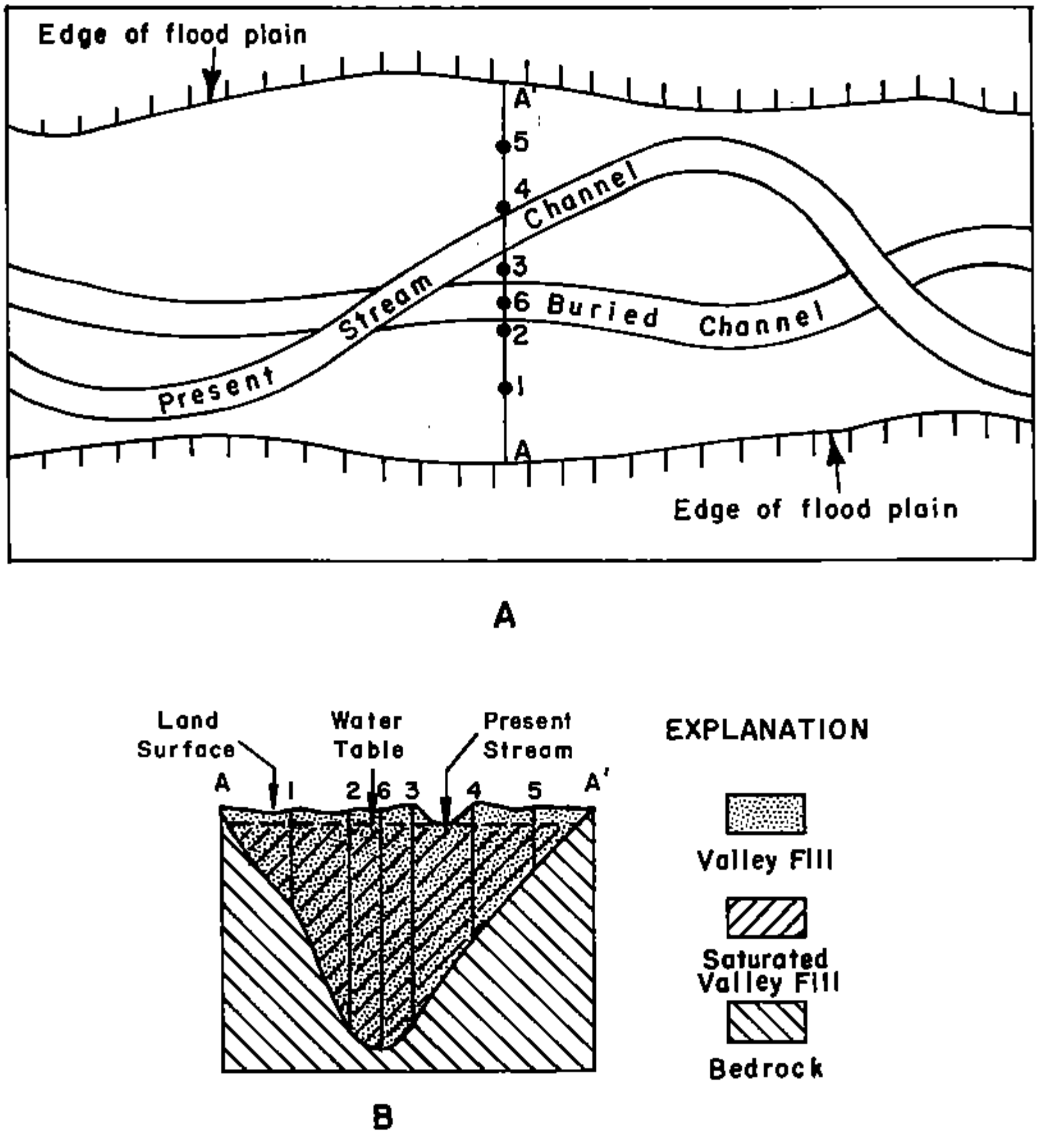


FIGURE 3.—Method of locating a buried channel in a stream valley by test drilling (Modified from McLaughlin, 1954).

during this period is also a contributing factor. After the low point is reached, the water level will begin a rising trend and will generally rise steadily throughout the late autumn and winter months.

Figure 4 shows the hydrograph of observation well Greene 3 and the monthly precipitation at Elliston, Indiana over a 4½ year period. This well is in the SW¼, SW¼, Sec. 20, T. 7 N., R. 6 W. of Greene County and taps confined water in a sand and gravel aquifer. The hydrograph demonstrates the cyclic nature of annual water-level fluctuations in nonpumped wells; it also shows the relation of water-level fluctuation to precipitation. Although the amount of water-level fluctuation will vary from well to well, the general shape of the hydrograph shown in figure 4 is considered to be representative of nonpumped wells in Sullivan and Greene Counties.

QUALITY OF WATER

The chemical quality of the ground water in Sullivan and Greene Counties was determined from the partial analysis of over 300 samples and the complete analysis of 20 samples. A tabulation of the complete analyses is given in table 3. Most of the partial analyses can be found in the preliminary reports for these counties (Watkins and Jordan, 1961; 1962). The significance of, and recommended limits for, the various constituents are given in table 4.

Hardness

As shown by figure 5, the water from the unconsolidated rocks is very hard (see hardness classification in table 4). This is largely due to the solution, as bicarbonate, of calcareous material in the rocks by recharge water containing carbon dioxide.

The water in the shallow Pennsylvanian rocks, having previously passed through the overlying unconsolidated rocks, is also very hard. However, water derived from the deeper Pennsylvanian rocks is usually much softer probably because the calcium and magnesium ions have been replaced with sodium ions through contact with ion-exchange materials, such as certain clay minerals that are present in clay and shale beds and disseminated throughout most other rock types. There has been a progressive depletion of exchangeable sodium ions in the ion-exchange materials toward the surface owing to contact with progressively larger volumes of hard water.

The outcrop area of the Mississippian rocks is largely unglaciated. Recharge water reacts with the numerous calcareous beds in these rocks to produce hardness in the shallow zone. The base-exchange minerals in the shallow zone have probably been depleted of much of their sodium through constant contact with calcium-rich water so that they are relatively inactive as softening agents. At depth, however, considerable

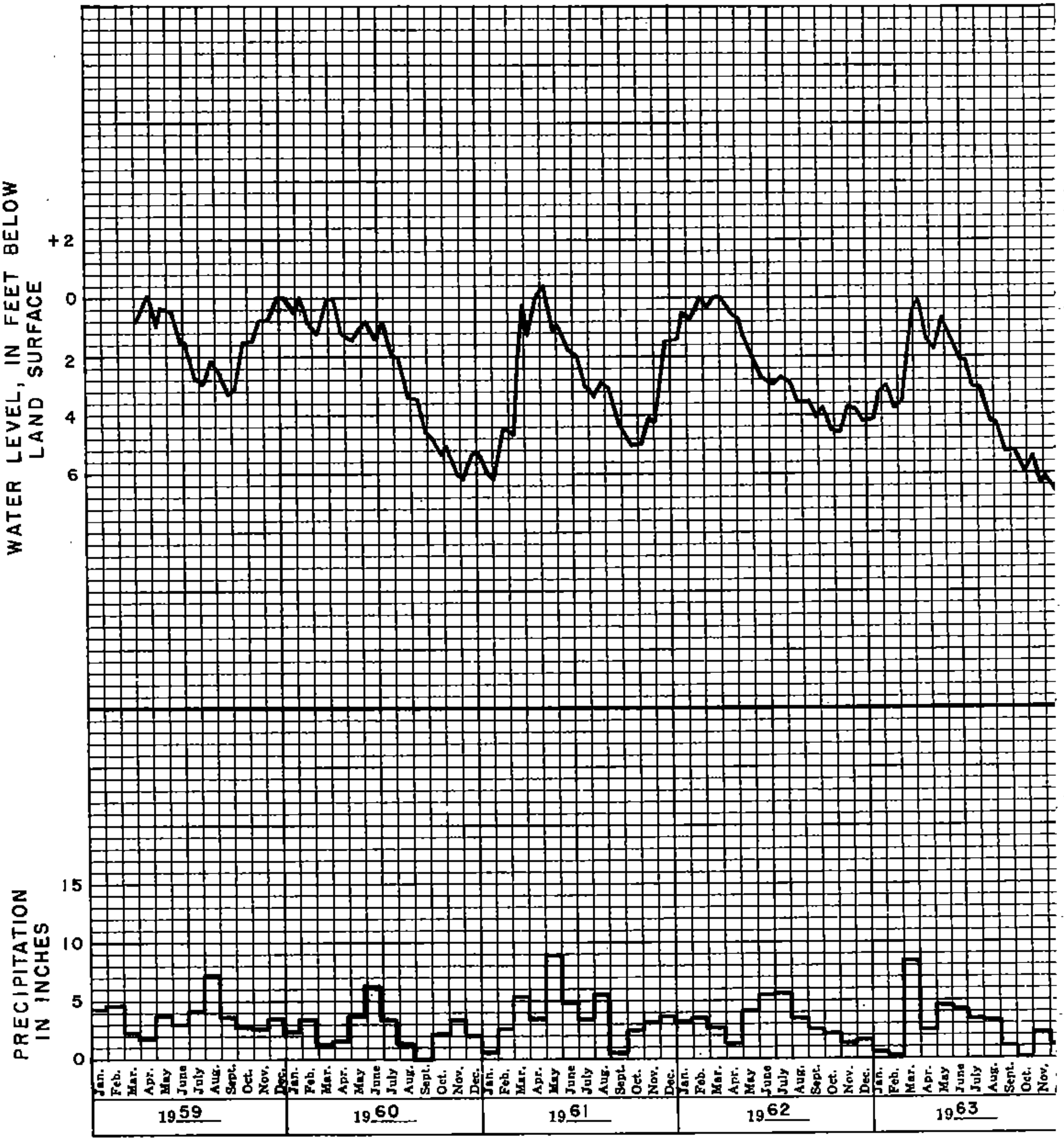


FIGURE 4.-- Hydrograph of observation well Greene 3 and precipitation at Ellist showing relation of water-level fluctuation to seasonal variation in recharge.

Table 3.--Chemical Analyses of Ground Water in Sullivan and Greene Counties, Indiana

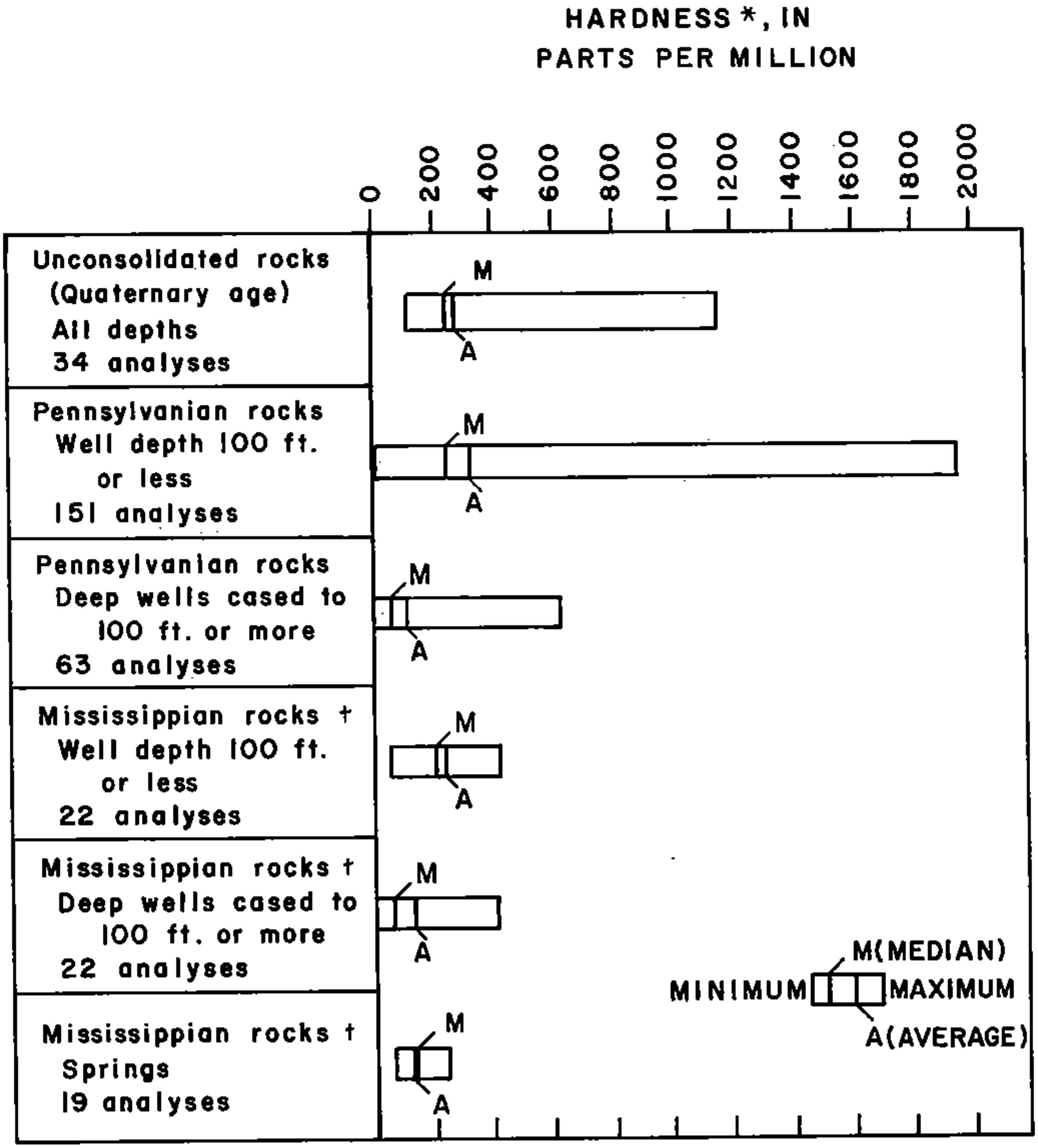
(Results given in parts per million except as indicated)

Well location	County	Well Depth (feet)	Date of Collection	Temperature (°F.)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved Solids (Calculated)	Hardness as $CaCO_3$	Noncarbonate Hardness	Specific Conductance (Micromhos at 25° C.)	pH
Mississippian and Pennsylvanian - Unit 1																						
SW¼SE¼ sec. 15, T. 6 N., R. 3 W.	Greene	Spring	2-8-60	53	9.4	0.07	0.07	18	3.5	4.0	0.8	53	0	18	3.0	0.2	1.8	85	60	16	148	7.3
NW¼SE¼ sec. 31, T. 7 N., R. 4 W.	Greene	56	2-8-60	53	13	.16	.86	63	25	16	1.0	320	0	17	2.4	.2	4.5	301	260	0	522	8
SW¼NE¼ sec. 25, T. 6 N., R. 6 W.	Greene	78	3-28-57	55.5	9.2	1.0	.00	58	31	13	3.3	350	0	17	4.0	.2	.1	309	272	0	547	7.3
NW¼SW¼ sec. 19, T. 8 N., R. 4 W.	Greene	88	5-26-58	57.5	28	.08	.02	30	8.7	12	.8	105	0	9.2	17	.2	18	178	111	25	283	6.6
NE¼SW¼ sec. 14, T. 7 N., R. 4 W.	Greene	112	5-26-58	61	11	.39	.05	29	5.2	2.8	.7	80	0	22	11	.1	.4	122	84	28	209	6.6
NW¼SE¼ sec. 35, T. 7 N., R. 5 W.	Greene	125	12-16-57	56	12	.08	.16	13	7.4	124	1.3	388	0	1.2	1.5	.3	1.7	354	63	0	577	8.0
NW¼SW¼ sec. 16, T. 6 N., R. 6 W.	Greene	137	2-18-60	54	7.6	.28	.03	1.4	1.3	784	1.9	704	30	34	700	1.3	2.1	1,880	9	0	3,320	8.5
SW¼NE¼ sec. 6, T. 8 N., R. 5 W.	Greene	175	12-19-57	56	8.5	.04	.00	1.4	.5	188	1.3	384	33	4.6	28	.8	1.0	454	8.	0	748	8.8
NW¼NE¼ sec. 30, T. 6 N., R. 4 W.	Greene	230	5-16-62	57	8.0	.18	.00	37	14	270	3.2	476	0	315	12	.4	1.5	897	150	0	1,340	7.6
SW¼NE¼ sec. 25, T. 6 N., R. 6 W.	Greene	252	4-8-57	57	6.9	.13	.03	.8	1.7	428	.8	811	51	2.2	114	4.5	.0	1,010	9	0	1,680	8.8
Pennsylvanian - Unit 2																						
SE¼SW¼ sec. 23, T. 6 N., R. 9 W.	Sullivan	63	2-18-60	51	6.8	.78	.01	31	17	200	.8	666	0	.4	17	1.8	.9	604	148	0	1,020	7.9
NE¼NW¼ sec. 2, T. 7 N., R. 8 W.	Sullivan	108	2-18-60	52	14	.17	.04	69	55	44	1.9	94	0	400	9.0	.2	2.9	642	398	321	901	7.2
NW¼SW¼ sec. 21, T. 8 N., R. 7 W.	Greene	160	2-18-60	56	30	1.7	.06	189	62	38	1.8	530	0	290	9.0	.2	.3	867	677	242	1,260	8.1
NE¼NE¼ sec. 21, T. 9 N., R. 8 W.	Sullivan	192	2-18-60	62	7.7	.20	.08	.2	.6	343	1.2	722	66	.4	33	1.8	.1	810	3	0	1,330	8.9
Pennsylvanian - Unit 3																						
NE¼SE¼ sec. 19, T. 6 N., R. 10 W.	Sullivan	53	3-28-57	56	23	.02	.00	123	54	23	.4	411	0	76	66	.1	75	643	530	192	1,040	7.4
SW¼SE¼ sec. 16, T. 8 N., R. 10 W.	Sullivan	138	4-8-64	52	9.3	.47	.04	24	11	375	2.1	730	0	9.4	220	1.1	.9	1,010	105	0	1,790	7.8
SE¼NW¼ sec. 35, T. 8 N., R. 10 W.	Sullivan	175	2-18-60	58	7.0	.53	.07	5.2	4.4	1,600	7.8	1,320	0	8.4	1,670	2.0	.5	3,960	31	0	6,760	8.1
NE¼NW¼ sec. 2, T. 7 N., R. 10 W.	Sullivan	184	4-8-64	50	7.4	.07	.00	1.7	.6	706	1.4	1,100	0	1.4	408	3.2	1.4	1,670	6	0	2,920	7.9
Quaternary - unconsolidated deposits																						
NW¼NE¼ sec. 29, T. 8 N., R. 5 W.	Greene	58	4-8-57	56	14	.17	.08	63	17	8.0	1.2	189	0	68	11	.0	1.6	277	227	72	469	7.4
NE¼SW¼ sec. 14, T. 8 N., R. 11 W.	Sullivan	100	4-8-64	52	10	.12	.23	73	20	5.4	1.1	280	0	38	8.0	.1	5.9	291	264	51	513	7.2

Table 4.--Significance of dissolved mineral constituents and properties of ground water

Constituent or property	Significance
Iron (Fe)--	Excessive amounts cause: "red water"; yellowish- or reddish-brown laundry and fixture stains; slimy iron bacteria growths in wells, pipes and tanks; bitter taste. The U. S. Public Health Service recommends that iron should not exceed 0.3 ppm on the basis of taste and laundry use.*
Manganese (Mn)------------------------------------	Similar to iron. Causes dark stains. U. S. Public Health Service recommends that the manganese concentration should not exceed 0.05 ppm.*
Calcium (Ca) and Magnesium (Mg)------------------	Principal cause of hardness. (See Hardness.)
Sodium (Na)---------------------------------------	High concentrations may cause water to be unsuitable for agriculture.
Potassium (K)-------------------------------------	Chemically similar to sodium.
Bicarbonate (HCO_3) and Carbonate (CO_3)-----------	Principal alkaline factors in water. (See Hardness.)
Sulfate (SO_4)-------------------------------------	In combination with calcium forms hard scale in boilers. In high concentrations imparts bitter taste to water. U. S. Public Health Service recommends that the sulfate concentration should not exceed 250 ppm, based largely on taste.*
Chloride (Cl)-------------------------------------	In high concentrations chloride increases the corrosiveness of water and imparts a salty taste. The U. S. Public Health Service recommended maximum is 250 ppm, based upon taste.*
Fluoride (F)--------------------------------------	In low concentrations fluoride reduces tooth decay. In higher concentrations tooth mottling or bone damage may occur. The U. S. Public Health Service recommendations are based on the annual average of maximum daily air temperatures. For the Sullivan-Greene area the recommended limits are: minimum= 0.7 ppm; optimum = 0.9 ppm; maximum = 1.2 ppm.*
Nitrate (NO_3)-------------------------------------	A high nitrate concentration may cause methemoglobinemia (blue-baby disease) in infants. The U. S. Public Health Service recommends a limit of 45 ppm.*
Dissolved Solids----------------------------------	U. S. Public Health Service recommends a limit of 500 ppm.*
Hardness as $CaCO_3$---------------------------------	Consumes soap by formation of scum. Primarily due to calcium and magnesium. When these constituents are combined with bicarbonate they cause temporary or carbonate hardness. A widely used hardness scale is: 60 ppm, soft; 61 to 120 ppm, moderately hard; 121 to 200 ppm, hard; more than 200 ppm, very hard.
Hydrogen-ion concentration (pH)------------------	Measure of alkalinity-acidity. 0 to 7 denotes decreasing acidity; 7 neutrality; 7 to 14 increasing alkalinity

*U. S. Public Health Service (1962)



* Total hardness as $CaCO_3$

† Greene County only

FIGURE 5. -- Hardness of ground water in Sullivan and Greene Counties.

softening takes place, but to a lesser extent than in the Pennsylvanian rocks.

Bicarbonate (HCO_3)

The bicarbonate concentration in well water from the consolidated rocks tends to increase with well depth. This is largely due to a series of reactions involving sodium ions, carbon dioxide and carbonate minerals. The higher values in the Pennsylvanian rocks may be attributed to higher concentrations of carbon dioxide, derived mainly from coal and other carbonaceous rocks, and to higher sodium ion concentrations. The maximum, minimum, median and average bicarbonate concentrations of ground waters sampled in the area are shown in figure 6.

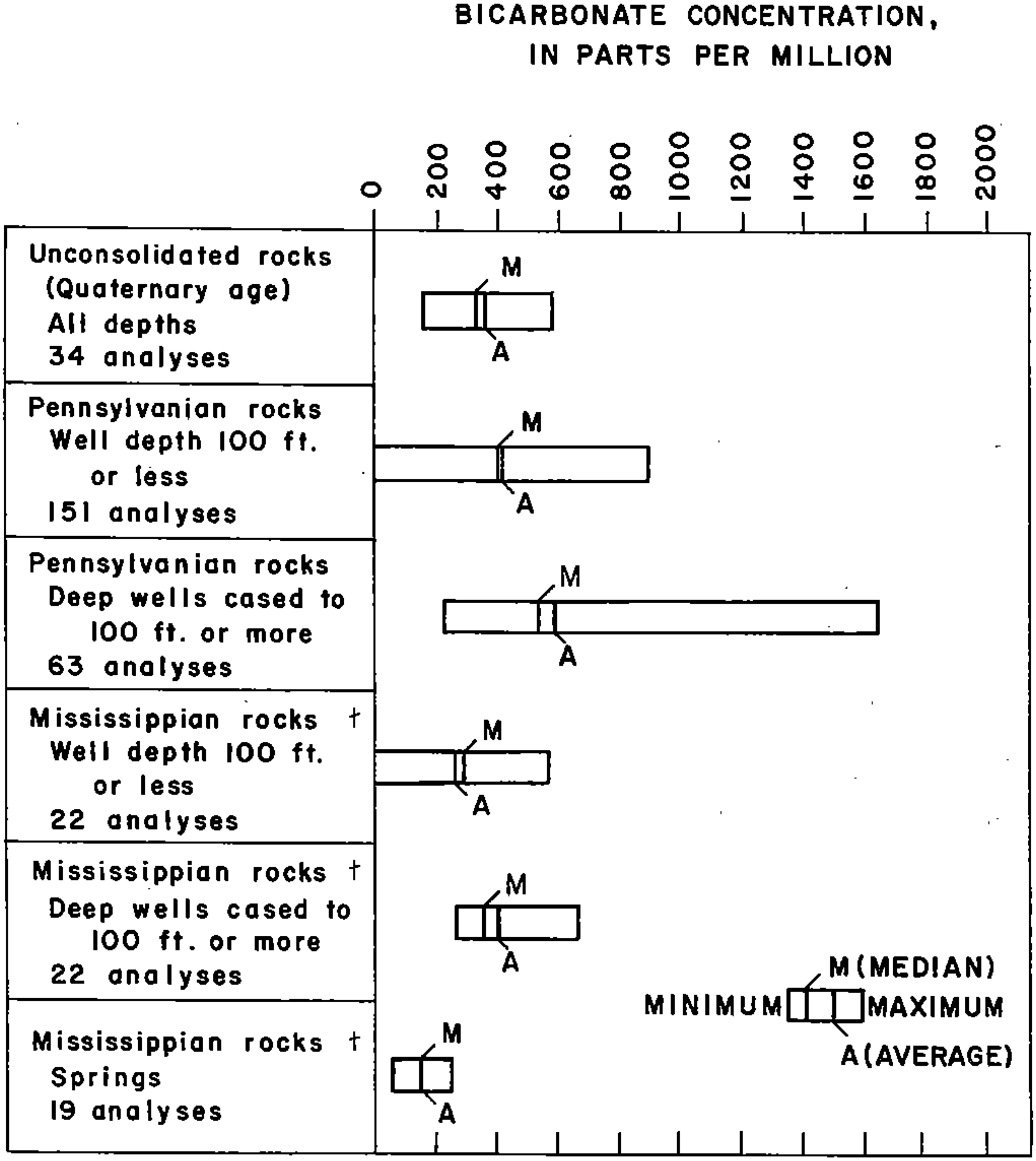
Sulfate (SO_4)

The average and median sulfate concentrations in water from all of the rock types are well below the recommended maximum (table 4). The higher median value for the shallow Pennsylvanian rocks, shown in figure 7, as compared to the median values of the unconsolidated rocks and deeper Pennsylvanian rocks, may be attributed to the introduction of air into pyrite-bearing rocks as the result of short well casings. Well logs illustrating the occurrence of pyrite in the Pennsylvanian rocks can be found in the report of Watkins and Jordan (1962).

The increase in sulfate concentration with depth in the Mississippian rocks may be chiefly due to solution of gypsum (hydrated calcium sulfate). Gypsum beds have been encountered at depths of several hundred feet. However, no detailed mineralogical studies that might reveal lesser amounts of gypsum in the shallower rocks have been made.

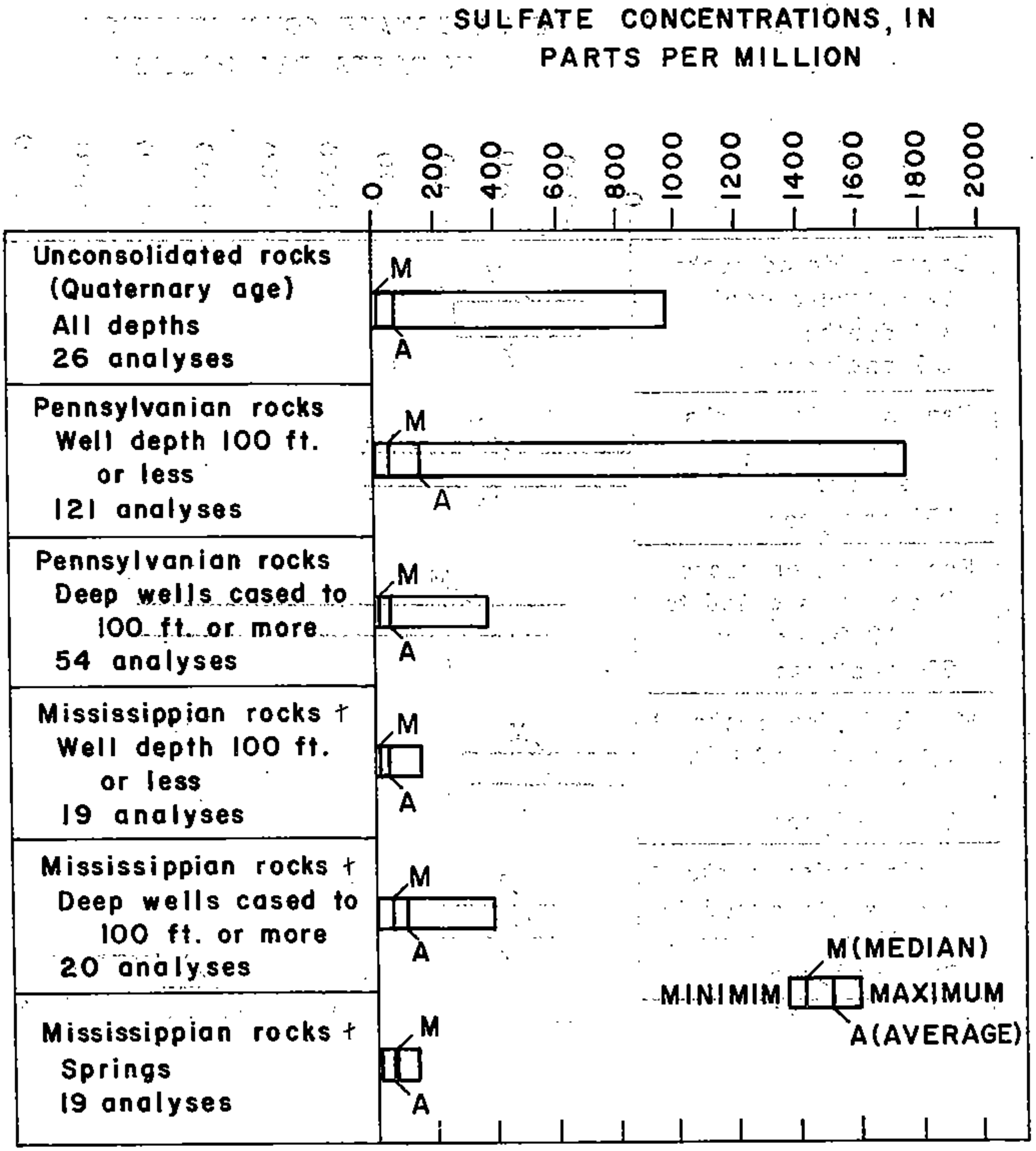
Fluoride (F)

In the area studied, as in neighboring areas, fluoride concentrations bear a definite relationship to water hardness (Cable, Watkins and Robison, 1971, p. 28, 30), hard waters usually having concentrations that are below the recommended level (table 4), and soft waters usually having concentrations that are within or above the recommended levels (table 4). The water from the unconsolidated rocks, being hard, is also low in fluoride. As was shown in figure 5, hardness in water from the Pennsylvanian and Mississippian rocks tends to vary with depth, the deeper wells generally yielding softer water. Therefore, the deeper wells can frequently be expected to yield water having fluoride concentrations that are within or above the recommended levels, particularly in the Pennsylvanian rocks.



† Greene County only

FIGURE 6. —— Bicarbonate concentrations in ground water of Sullivan and Greene Counties.



† Greene County only

FIGURE 7.—— Sulfate concentrations in ground water of Sullivan and Greene Counties.

Chloride

Some wells in the area yield high-chloride water, that is, having a chloride concentration greater than 250 ppm (parts per million). Some of these occurrences are due to a natural upward seepage of high-chloride water from deep formations. Others are caused by oil and gas operations, either by direct infusion of high-chloride water into the aquifer from the oil (or gas)-well bore holes or by surface spillage and infiltration. The former is more likely to cause excessive chloride in bedrock water, while the latter is more likely to affect streams and unconsolidated aquifers. An analysis of a low-flow sample from a small stream in north-central Sullivan County indicated a chloride concentration in excess of 11,000 ppm. Most of the oil and gas operations are in Sullivan County and it is here that most of the contamination occurs. Areas in which high-chloride water occurs at normal water-well depth are outlined on plate 3 of the preliminary reports for each of the two counties (Watkins and Jordan, 1961 and 1962). Many of the outlined areas correspond to the location of oil fields.

Where oil-field contamination is involved, high-chloride water may be encountered at any depth. However, high-chloride water due to natural seepage in the consolidated rocks is more predictable. At the towns of Lyons and Switz City in Greene County and at Pleasantville in Sullivan County high-chloride water has been encountered at depths as shallow as 130 feet. In other parts of the two counties, west of the White River, the depth to high-chloride water in the consolidated rocks is estimated to range from slightly over 100 feet to more than 200 feet.

No occurrences of high-chloride water have been noted in the Mississippian rocks east of the White River. Fresh water has been obtained at well depths of over 400 feet. This condition is primarily due to two factors: the higher hydraulic head east of the White River and the presence of cavernous limestones. The higher fresh-water hydraulic head retards the upward migration of the high-chloride water and causes it to seek release at lower elevations to the west. The cavernous limestones are capable of transmitting large quantities of water at or near the surface with this ability decreasing with depth, thereby favoring the fresh-water circulation.

Total Dissolved Solids

The values shown on figure 8 were derived both from complete and partial analyses. The concentrations for the partial analyses were estimated from a formula using the three principal negative ions: bicarbonate, sulfate and chloride (Collins, 1928). In most of the samples bicarbonate was the predominant negative ion. However, in most instances where the concentration in samples from the unconsolidated rocks and shallow Pennsylvanian rocks exceeded 1,000 ppm, sulfate was the predominant ion. The maximum concentration shown for the deep Pennsylvanian rocks was due chiefly to chloride ion.