Hydrology of Aquifer Systems in the Memphis Area, Tennessee

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1779-O

Prepared in cooperation with the city of Memphis, Memphis Light, Gas, and Water Division

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By J. H. CRINER, P-C. P. SUN, *and* D. J. NYMAN

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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A hydrogeologic delineation, analysis, and evaluation of the principal water-bearing formations in the Memphis area, Tennessee

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CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

TABLES

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

HYDROLOGY OF AQUIFER SYSTEMS IN THE MEMPHIS AREA, TENNESSEE

By J. H. Criner, P–C. P. Sun, and D. J. Nyman

ABSTRACT

The Memphis area as described in this report comprises about 1,300 square miles of the Mississippi embayment part of the Gulf Coastal Plain. The area is underlain by as much as 3,000 feet of sediments ranging in age from Cretaceous through Quaternary.

In 1960, 150 mgd (million gallons per day) of water was pumped from the principal aquifers. Municipal pumpage accounted for almost half of this amount, and industrial pumpage a little more than half. About 90 percent of the water used in the area is derived from the "500-foot" sand, and most of the remainder is from the "1,400-foot" sand; both sands are of Eocene age. A small amount of water for domestic use is pumped from the terrace deposits of Pliocene and Pleistocene age.

Both the "500-foot" and the "1,400-foot" sands are artesian aquifers except in the southeastern part of the area; there the water level in wells in the "500-foot" sand is now below the overlying confining clay. Water levels in both aquifers have declined almost continuously since pumping began, but the rate of decline has increased rapidly since 1940. Water-level decline in the "1,400-foot" sand has been less pronounced since 1956.

The cones of depression in both aquifers have expanded and deepened as a result of the annual increases in pumping, and an increase in hydraulic gradients has induced a greater flow of water into the area. Approximately 135 mgd entered the Memphis area through the "500-foot" sand aquifer in 1960, and, of this amount, 60 mgd originated as inflow from the east and about 75 mgd was derived from leakage from the terrace deposits, from the north, south, and west and from other sources. Of the water entering the "1,400-foot" sand, about 5 mgd was inflow from the east, and about half that amount was from each of the north, south, and west directions. The average rate of movement of water outside the area of heavy withdrawals is about 70 feet per year in the "500-foot" sand and about 40 feet per year in the "1,400-foot" sand. The average rate of depletion of storage in each aquifer since pumping began is about 1 mgd.

Most of the recharge to the "500-foot" and "1,400-foot" sands occurs in outcrop areas about 30–80 miles east of Memphis. Also, water leaks from the terrace deposits to the "500-foot" sand in some places, and there may be some leakage from streams where the confining clay is thin or is breached by faults or streams.

The quality of water from both the principal aquifers is very good. Iron, carbon dioxide, and hydrogen sulfide are the only constituents found in undesirable quantities. Water from the terrace deposits is hard but generally contains less iron and carbon dioxide than water from either of the principal aquifers.

The hydraulic characteristics of both aquifers were determined by pumping tests and by applying the knowledge of the geology of the area; these characteristics indicate that the aquifers are capable of producing more water than is currently being pumped from them. The "500-foot" sand will produce more water per unit decline of water level than will the "1,400 -foot" sand. There appears to be no reason why the development of water supplies from both aquifers should not continue, but well spacing will remain a factor which could affect future development. Greater well spacing will tend to prolong the useful life of a well and the aquifers.

INTRODUCTION

In 1960, industrial and municipal supply wells in the Memphis area pumped about 150 million gallons of water a day. Pumping has increased continuously since 1898, the earliest date for which records are available, and the rate of this increase has accelerated greatly since 1940. Decline of water levels has accompanied increases in the pumpage, and in 1928 the city of Memphis began a program of periodic water-level measurements to determine ways to reduce the rate of decline. The U.S. Geological Survey was requested to assist in this study, and a continuing cooperative program of investigations was begun in 1940. Early investigations showed the need for proper spacing of wells, which has been practiced to the present time.

PURPOSE AND SCOPE OF INVESTIGATION

The present investigation was started in 1958 as a quantitative study of the two principal aquifers that supply water to the Memphis area. The objectives were to delineate these aquifers, evaluate their hydraulic characteristics, show the relation between pumpage and water-level change, and determine the factors affecting the economical development and use of ground water. The study was based partly on the premise that the questions posed by Kazmann (1944, p. 17–18) must be answered as completely as possible to provide for orderly development and management of the ground-water resources. These questions are repeated and discussed in the concluding section of this report.

Work consisted of (1) delineation of the "500-foot" and "1,400-foot" sands by a series of subsurface contour maps based on drillers' logs and geophysical logs of wells, (2) collection of water-level records from a network of about 150 observation wells, 55 of which were equipped with automatic recorders, (3) preparation of contour maps showing water levels and the amount of water-level decline in the "500-foot" sand, (4) analyses of pumping tests of wells in both aquifers, (5) calculation of the amount of ground water moving into the area through each aquifer before development began and during 1960, (6) preparation of a ground-water budget for the "500-foot" sand, based on 1960 records, and (7) inventory of ground-water withdrawal and study of its relation to water-level decline.

LOCATION AND GENERAL FEATURES OF THE AREA

The Memphis area (fig. 1), about 1,300 square miles in this report, includes all Shelby County and parts of Fayette and Tipton Counties, Tenn., and contiguous parts of Arkansas and Mississippi. The area is near the center of the upper half of the Mississippi embayment in the Gulf Coastal Plain.

The climate of the Memphis area is warm and humid, having hot summers, mild winters, and a frost-free period of about 230 days between late March and early November. The average annual temperature is 61.9°F; the hottest month is July, which has an average temperature of 81.1°F; and the coldest month is January, which has an average temperature of 41.5°F.

The average annual rainfall Memphis (fig. 2), based on an 89-year period of record (1872–1960), is 48.48 inches. The maximum annual rainfall recorded was 76.85 inches in 1957, and the minimum was 30.54

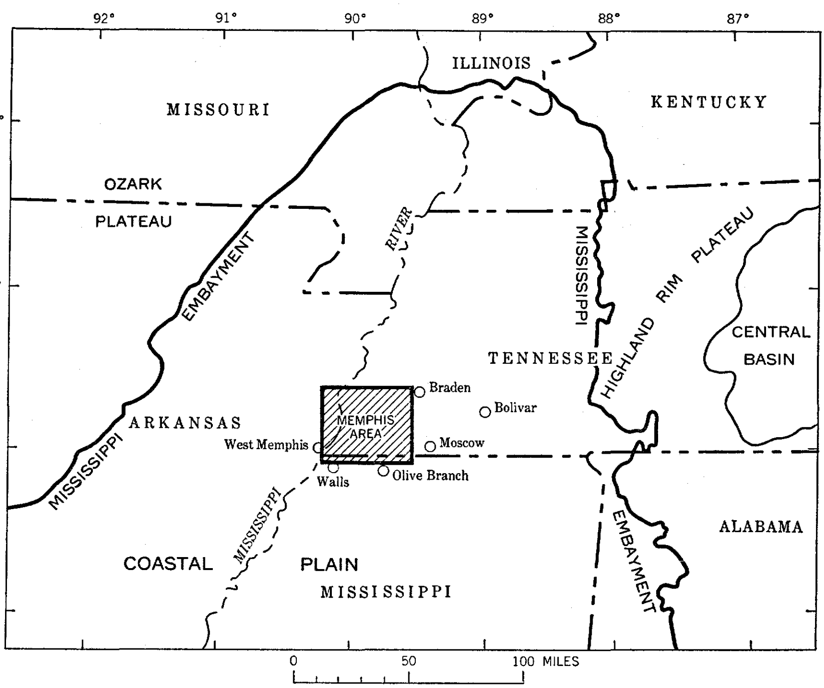


FIGURE 1.—Generalized physiographic map of the northern Mississippi embayment showing the location of the project area.

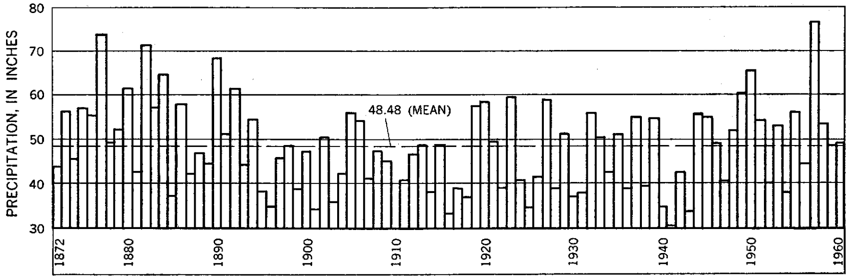


FIGURE 2.—Graph showing annual precipitation at Memphis, Tenn.

inches in 1941. The wet season usually begins in late November and ends in April. Rainfall at Moscow and Bolivar (fig. 1) in the outcrop or recharge area of the principal aquifers, is slightly greater than that in the Memphis area.

The Memphis area (fig. 1) consists mostly of a gently rolling upland ranging in elevation from about 400 feet in the eastern part of Shelby County to about 200 feet on the alluvial plain of the Mississippi River. The maximum topographic relief is about 200 feet, but the local relief of individual topographic features seldom exceeds 40 feet. The upland area is terminated by a bluff 50 to 150 feet high along the eastern margin of the alluvial plain of the Mississippi River. This virtually flat plain, which is approximately 210 feet above sea level, is about 3 miles wide along the east side of the Mississippi River except in the vicinity of Memphis; at Memphis the river flows along the base of the bluff.

The principal streams that drain the Memphis area are the Wolf and Loosahatchie Rivers and Nonconnah Creek, all of which flow north-northwestward and discharge into the Mississippi River. These streams have wide flood plains that are generally adequate to accommodate flood waters during the rainy reason. Some sections of the channels of these and smaller tributaries have been artificially deepened for more effective drainage of the lowland areas. In the past all three major streams have flowed throughout the year; however, in recent years Nonconnah Creek was dry in its lower reach for short periods during the dry season from July to October.

Memphis is a large industrial center; the principal industries produce hardwood lumber and cotton and associated products. The Memphis Chamber of Commerce reported 765 industries in Memphis (1958–59), 120 of which have their own water-supply wells. More than half the total ground-water pumpage from the area is from these wells.

The 1960 U.S. Census shows that the population of Memphis and Shelby County has approximately doubled since 1930. The successive census figures are as follows:

Population of Memphis and Shelby County, Tenn.

Year	*Memphis*	*Shelby County*
1930	253,143	306,482
1940	292,942	358,250
1950	396,012	482,393
1960	497,524	627,019

PREVIOUS INVESTIGATIONS

The earliest reports describing the geology and the ground-water resources of the Memphis area were by Safford (1869, 1890) and Glenn (1906). Wells (1931) described the artesian water supply of Memphis and, in a subsequent report (1933), the ground-water resources of West Tennessee, including a more detailed discussion of ground-water conditions in the Memphis area. Since the beginning of the cooperative program in 1940, progress reports have been published by Kazmann (1944), Schneider and Cushing (1948), and Criner and Armstrong (1958).

Regional and local studies relating to the geology of the Memphis area were made by Fisk (1944), Caplan (1954), Stearns and Armstrong (1955), and Stearns (1957).

Records of water levels from 1936 through 1955 have been reported by the U.S. Geological Survey (issued annually). Earlier measurements were reported by Wells (1931, 1933).

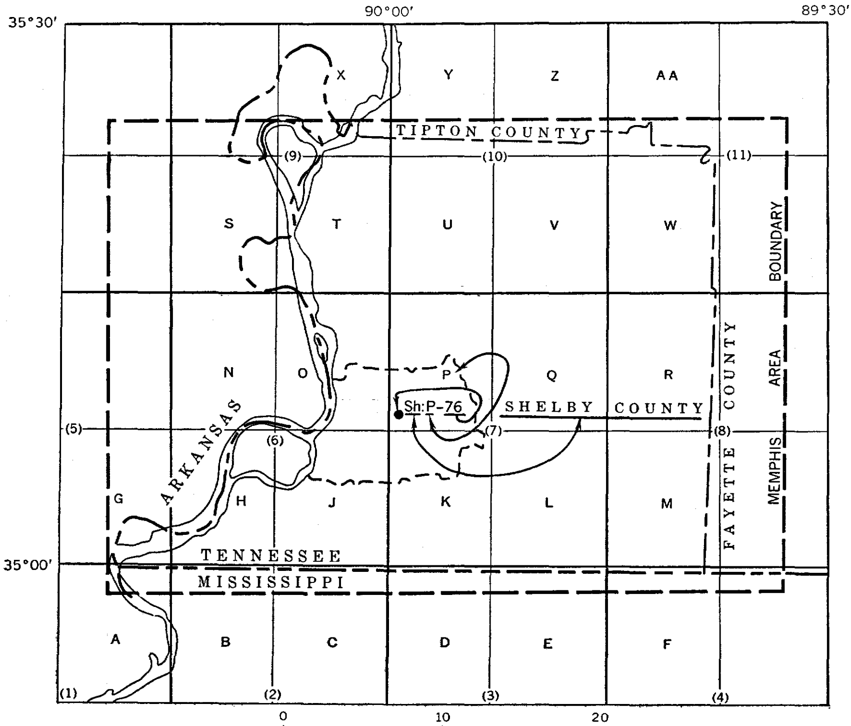
ACKNOWLEDGMENTS

The assistance and cooperation of many city and county officials, industry representatives, drilling contractors, and well owners were helpful in the collection of data for this report. Mr. J. J. Davis, Director, Water Division, and Messrs. A. J. Rumley and Hugh Mills, Memphis Light, Gas, and Water Division, provided essential well and water-use data from the city records and assisted greatly in the investigation. Mr. E. C. Handorf and Mr. W. M. Craddock, of the Memphis and Shelby County Health Department have, through their interest in the Memphis area water supply, contributed substantially to the study. Drilling contractors, industries, and individual well owners also were especially helpful in providing well data, permitting use of wells for geophysical and hydraulic tests, and furnishing information on water use in the area.

WELL-NUMBERING SYSTEM

Figure 3 illustrates the standard system for numbering wells in this report. Each well number consists of of three units: (1) an abbreviation of the name of the county in which the well is located; (2) a letter designating the 7½-minute topographic quadrangle, or 7½-minute quadrant of a 15-minute quadrangle, in which the well is located; and (3) a number generally indicating the numerical order in which the wells were inventoried.

The index map (fig. 3) shows the 15-minute topographic quadrangles of the U.S. Army Corps of Engineers that include Shelby County and adjacent areas described in this report. The example, well Sh: P–76, is in Shelby County, in the northwest quadrant (7½-minute quadrangle designated "P") of the Bartlett 15-minute quadrangle and is identified as well 76 in the numerical sequence.



15-MINUTE TOPOGRAPHIC QUADRANGLES

1. HORSESHOE LAKE (1954) NE¼
2. HORN LAKE (1961) N½
3. HERNANDO (1944) N½
4. BYHALIA (1948) NW¼
5. EDMONSON (1951) SE¼
6. MEMPHIS (1961)
7. BARTLETT (1961)
8. COLLIERVILLE (1948) W½
9. JERICHO (1952)
10. MILLINGTON (1961)
11. MASON (1954) W½

FIGURE 3.—Map showing topographic quadrangles in the Memphis area and showing the well-numbering system used in Tennessee.

In this report the county designation "Sh" is omitted in figures. Well numbers in adjoining counties in Tennessee are preceeded by the county abbreviation. Wells in adjoining States are not numbered.

At Memphis, the Memphis Light, Gas, and Water Division many years ago established their own well-numbering system. According to this plan, blocks of numbers were assigned for the city's five existing well fields (pl. 1) and other blocks of numbers were reserved for future well fields. The block assignments are as follows:

1–49	Parkway Field
50–99	Sheahan Field
100–149	Allen Field
150–199	Miscellaneous wells at scattered locations (abandoned)
200–249	McCord Field
250–299	(Not assigned)
300–349	Hickory Hill (Lichterman) Field (proposed)

Listed below are city-owned wells in use as of January 1962 and those that have been withdrawn from use. Well numbers followed by the letters "A," "B," and so on, indicate first, second, and so on, replacement wells for those withdrawn from use. For convenient reference, the wells owned by the Memphis Light, Gas, and Water Division are listed below, together with the corresponding numbers assigned by the U.S. Geological Survey.

City	*Geological Survey*	*City*	*Geological Survey*	*City*	*Geological Survey*
1	Sh:O–125	15A	Sh:O–150	30	Sh:O–175
1A	126	16	151	31	176
2	127	16A	152	32	177
2A	128	17	153	33	178
3	129	18	154	34	179
4	130	19	155	35	180
4A	131	19A	156	36	P– 77
5	132	20	157	37	78
6	133	20B	158	38	O–181
6A	134	21	159	39	182
7	135	21A	160	40	183
7A	136	22	161	41	184
9	137	22A	162	42	185
9A	138	22B	163	43	186
10	139	22C	164	44	187
10A	140	23	165	45	188
11	141	23A	166	46	189
11A	142	24	167	47	190
12	143	24A	168	50	K– 37
12A	144	25	169	51	38
13	145	26	170	52	39
13A	146	26A	171	53	40
14	147	27	172	54	41
14A	148	28	173	54A	42
15	149	29	174	55	43

City	Geological Survey	City	Geological Survey	City	Geological Survey
55A	Sh:K- 44	80	Sh:P- 84	123	Sh:J-116
56	45	81	K- 69	124	117
57	46	82	70	125	118
57A	47	83	71	126	119
57B	48	84	72	127	120
57C	49	85	73	128	121
58	50	86	74	130	122
59	51	86S	75	131	123
60	52	87	76	133	124
61	53	88	77	134	125
61A	54	101	J- 96	135	126
62	55	102	97	136	127
63	56	103	98	137	128
64	57	104	99	193	P- 76
65	58	105	100	201	Q- 29
66	59	106	101	202	30
67	60	107	102	203	31
68	61	108	103	204	32
69	62	109	104	205	33
70	63	110	105	207	34
71	64	111	106	208	35
72	65	112	107	209	36
73	66	113	108	210	37
74	P- 79	114	109	218	38
75	80	115	110	219	39
76	81	116	111	220	40
77	K- 67	117	112	221	41
77A	68	118	113	222	42
78	P- 82	121	114	307	L- 39
79	83	122	115	324	40

GENERAL GEOLOGY OF THE AQUIFER SYSTEMS

The Memphis area is in the northern part of the East Gulf Coastal Plain, near the axis of the Mississippi embayment structural trough (fig. 1). About 3,000 feet of unconsolidated clay, silt, sand, and gravel has been deposited in this area, and these sediments provide a record of the several invasions and recessions of the sea and the intervening periods of erosion that have occurred since the beginning of Cretaceous time. This wedge-shaped sequence of deposits thickens southward toward the Gulf of Mexico and westward toward the Mississippi River.

Stearns and Armstrong (1955, p. 6–7) and Stearns (1957, p. 1084–1085) described the depositional environmental relations and defined three sedimentary rock types that best illustrate these relations in the northern part of the Mississippi embayment. These types are described briefly as follows:

Back-beach clay and sand.—Back-beach beds consist of light-colored clay, lignite, and discontinuous beds of sand. The clay beds, in contrast with those of a more marine environment, are characterized by the presence of leaf imprints and the general absence of glauconite. These clay and sand deposits are of limited areal extent and therefore cannot be traced easily in the subsurface, even by means of geophysical logs of closely spaced wells. The irregularly interbedded sediments in the upper part of the Claiborne Group (table 1) are typical of the back-beach deposits.

Shallow-water near-shore sand.—Well-sorted sand interbedded with glauconitic and fossiliferous clay is characteristic of the shallow-water near-shore deposits. The sand is areally extensive, in contrast with the back-beach deposits. Where sand beds grade laterally or vertically into back-beach beds, they contain lignite and wood fragments; where they grade into deeper-water clay beds, they contain glauconite. The sandy middle unit ("1,400-foot" sand) of the Wilcox Group (table 1) in the Memphis area is typical of the shallow-water near-shore deposits.

Deeper water clay and shale.—The deeper water clay and shale is medium gray to dark gray and contains marine fossils, calcareous beds, and glauconite. These beds are thick and areally extensive and therefore are easily recognized and traced in the subsurface by means of drillers' logs and geophysical logs of wells. In the Memphis area, typical deposits of this category are the marine facies of the Jackson(?) Formation and the upper clay unit of the Wilcox Group.

DESCRIPTION OF THE GEOLOGIC UNITS

The Memphis area is underlain by about 3,000 feet of clay, silt, sand, and gravel ranging in age from Cretaceous through Recent. These sediments were deposited on the limestone rocks of Paleozoic age that form the bedrock floor of the Mississippi embayment syncline. This report deals primarily with the geology related to the two principal aquifers in the Memphis area, and for this reason only the stratigraphic units of Eocene and younger age are discussed in detail. These units (table 1) include the major aquifers, the "1,400-foot" sand of the Wilcox Group, and the "500-foot" sand of the Claiborne Group (Kazmann, 1944, p. 2).

WILCOX GROUP

On the basis of drillers' logs and geophysical logs of wells in the Memphis area, the Wilcox Group is divided into a lower clay unit, a middle sand unit ("1,400-foot" sand), and an upper clay unit (Criner and Armstrong, 1958, p. 3).

The lower unit of the Wilcox Group consists of gray to greenish-gray lignitic clay which grades upward into silt and fine-grained sand deposits. The percentage of sand increases upward in this unit, perhaps representing a transitional phase between the marine Porters

TABLE 1.—*Geologic units underlying the Memphis area*

System	Series	Group	Stratigraphic unit	Thickness (feet)	Description and relation to water
Quaternary	Recent		Alluvium	0–200	Alluvial sand, clay, and gravel. Few domestic wells. Could be important source of water for some industrial uses.
	Pleistocene		Loess	0–100	Wind-deposited silt. (Topographically higher than alluvium.) Low permeability. Not a source of ground water.
	Pleistocene and (or) Pliocene [1]		Terrace deposits	0–160	Alluvial sand and gravel. Several domestic wells. Could be major source of water for industrial and irrigation uses.
Tertiary	Eocene		Jackson(?) Formation (lower part may include some Claiborne beds)	0–330	Gray, bluish-gray, greenish-gray, and tan clay; minor amounts of lignite and fine-grained sand. Generally impermeable and considered to be upper confining beds for water in "500-foot" sand.
		Claiborne	"500-foot" sand (upper part may include some Jackson(?) beds)	500–800	Fine- to coarse-grained sand; minor amounts of lignite and tan clay and silt; thin clay and lignite lenses. Thick clay bed locally at base. Coarse channel sands locally at base. Very good aquifer from which 90 percent of water in Memphis area is obtained.
		Wilcox	Upper clay unit	200–395	Gray, greenish-gray, and brown carbonaceous clay. Thin lignite and fine-grained sand lenses locally. Low permeability confines water in "500-foot" and "1,400-foot" sands.
			Middle sand unit ("1,400-foot" sand)	150–300	Fine- to medium-grained sand; minor amounts of lignite and clay lenses. Second principal aquifer which supplies about 10 percent of water used in Memphis area.
			Lower clay unit	190–250	Gray, greenish-gray, and brown carbonaceous clay, and lignite; sandy near top. Impermeable lower confining bed for water in "1,400-foot" sand.

[1] See p. O39.

Creek Clay and the predominately sandy middle unit of the Wilcox. The clay unit ranges in thickness from 190 feet in test well Fa: W–1 about 30 miles northeast of Memphis near Braden, Fayette County, to 250 feet in well Sh: U–12, 3.5 miles south of Millington, Shelby County (pl. 1).

The middle sand unit, referred to as the "1,400-foot" sand by Criner and Armstrong (1958, p. 3), consists mostly of unconsolidated well-sorted fine- to medium-grained sand. Logs of a few wells in the Memphis area show thin interbedded lenses of clay, but these beds probably are not areally extensive. The sand ranges in thickness from 150 feet in test well Fa: W–1 near Braden, Fayette County, to 240 feet in well Sh: U–12, 3.5 miles south of Millington, Shelby County (pl. 1). The thickness increases westward to 300 feet in an oil-test well 7 miles west of West Memphis, Ark.

The upper unit of the Wilcox Group in the Memphis area consists of dark-gray or brown lignitic clay containing local lenses of silty and sandy clay from 1 to 50 feet thick. Thin beds of fine-grained sand cemented with iron oxide form "rock" layers a few inches thick in many parts of the unit. The upper clay of the Wilcox grades upward to a sandy clay; however, the contact with the overlying sand of the Claiborne Group is distinct, as is indicated by geophysical logs (pl. 1) of wells in the area. The thickness of the upper clay section varies greatly, ranging from 200 to 395 feet in the Sheahan well field in the south-central part of Shelby County.

CLAIBORNE GROUP

The Claiborne Group in the Memphis area is represented by the "500-foot" sand, which has been divided into lower and upper parts by Criner and Armstrong (1958, p. 7–8). This subdivision was based on the different lithologies of the two parts and on their separation in much of the area by clay beds as much as 150 feet thick. Electrical logs and drillers' logs of wells show that the lower part of the Claiborne varies greatly in thickness and contains a greater number of clay beds that are thicker and more extensive than those in the upper part. Even the thickest of the clay beds, however, are not continuous, so that no particular bed can be considered as a hydrologic boundary between distinctive lower and upper parts. In this report, therefore, the "500-foot" sand is considered as a single hydrologic unit. Generally the Claiborne Group is characterized by a greater proportion of clay in the lower part and by a gradation in sand particle size from fine to medium grained in the lower part to medium to coarse grained in the upper part. The thickest and most extensive clay bed underlies the central part of the Memphis area and is in the lower part of the Claiborne Group.

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The thickness of the Claiborne Group ranges from 500 feet in test well Fa: W-1 near Braden, Fayette County, to 800 feet in well Sh: J-104 in the southern part of the city of Memphis (pl. 1). The top of the "500-foot" sand was indicated in geophysical logs of wells as the level at which the sediments change from predominantly sand to predominantly clay or silt. The contacts were picked to define a hydrologic unit ("500-foot" sand regardless of geologic age. For this reason the upper part of the unit as shown on plate 1 may include some sandy beds belonging to the overlying Jackson(?) Formation.

JACKSON(?) FORMATION

The Jackson(?) Formation overlies and confines the "500-foot" sand. Locally the two units interfinger with one another, and the contact between them represents a hydrologic boundary rather than a precise stratigraphic horizon (pl. 1).

The Jackson(?) Formation is composed of dark-gray to greenish-gray, dark-blue, or dark-brown clay. It is generally carbonaceous and contains very fine quartz sand along bedding planes. The formation is absent in southeastern Shelby County but is as much as 330 feet thick in the Parkway well field.

Fisk (1944, fig. 67, p. 62) distinguished a lower marine and an upper nonmarine facies in the Jackson(?) Formation. The marine facies closely follows the present course of the Mississippi River and extends northward at least 25 miles to Lauderdale County; there an exposure contains glauconite, foraminifera, shark teeth, and bones of sea animals. Fossil plants and leaves are abundant, and seams of lignite as much as 10 feet thick are common in the nonmarine facies.

TERRACE DEPOSITS AND ALLUVIUM

The terrace deposits ranges from a few feet to about 160 feet in thickness and are composed mostly of coarse-grained quartz sand and fine-grained iron-stained quartz and chert gravel. Thin lenses of silty ocher-colored clay are common in the lower part. The bottom 3 inches to 4 feet of sand and gravel generally is cemented with limonite. Although the contact with the Jackson(?) Formation represents an erosional surface, thin lenses of reworked Jackson(?) clay and sand form a transitional zone at the base of the terrace deposits in many places; geophysical logs show a gradation from one unit to the other.

The terrace deposits occur as an irregular belt parallel to the Mississippi River and also occur along the larger streams in the area. The deposits thin gradually eastward and are absent in many places as a result of erosion or nondeposition.

Two terraces were recognized by Glenn (1906, p. 41–44), who designated the higher as Pliocene and the lower as Pleistocene. Fisk

(1944, p. 63) considered them both to be of Pleistocene age. Because geophysical logs show no consistent correlation points, by means of which the terrace deposits can be divided in the subsurface, they are considered as a single unit in this report.

The alluvium ranges from 0 to 200 feet in thickness and is composed of sand, clay, silt, and gravel. It is confined to narrow strips along the principal streams and in most places is subject to flooding and reworking. The coarsest material is generally near the present stream channels, and the finest is near the featheredges of the deposits.

The alluvium is lithologically similar to the underlying terrace deposits, and the contact cannot be determined from geophysical logs. However, samples of the alluvium locally contain carbonaceous material and decaying vegetation which aid in distinguishing between the two units.

GEOLOGIC STRUCTURE

The Memphis area is near the axis of the Mississippi embayment syncline, which plunges southward at a rate of about 10 feet per mile in the vicinity of Memphis. The syncline began to form in Late Cretaceous time (Fisk, 1944, p. 8, 64; and Caplan, 1954, p. 5) as a result of regional subsidence centered along the present coast of the Gulf of Mexico. The axis of the structural trough approximately follows the present course of the Mississippi River.

As the region subsided, faulting of the unconsolidated sediments and the underlying Paleozoic rocks occurred, forming a rectangular pattern of faults and fractures trending northeast and northwest (Fisk, 1944, p. 64, 66). One of the major faults in this system, the Big Creek fault (Fisk, 1944, p. 66), trends northeast from near West Helena, Ark., along the western edge of the Memphis area to Reelfoot Lake near the Tennessee-Kentucky border; at Reelfoot Lake it appears to be related to the New Madrid (Missouri) fault system. This fault is of particular significance because it apparently restricts the movement of ground water from the west into the Memphis area.

A major fault is suggested by an abrupt bend in the Mississippi River near the mouth of Nonconnah Creek and by electrical logs of wells that indicate as much as 50 feet of displacement of geologic units in the Hickory Hill well field in the south-central part of the area. If such a fault exists, it has so far had little effect on the movement of water in the "500-foot" sand.

HYDROLOGY OF THE AQUIFER SYSTEMS

GEOLOGIC CONTROL OF GROUND WATER IN THE MEMPHIS AREA

The size, shape, and degree of interconnection of the open spaces between rock particles control the amount of water that can be accepted, stored, and eventually discharged to wells or by natural subsurface ground-water movement. In the Memphis area all ground water is obtained from unconsolidated deposits of sand and gravel.

Deposits of rounded well-sorted rock particles are the most permeable water-bearing materials because ground water can move freely through them toward pumping wells and into the aquifer in its recharge area. Mechanical analyses of sand samples from the "500-foot" and "1,400-foot" sands in the Memphis area show the sand particles to be well sorted but angular to subangular in shape. Although compaction and cementation affect the water-bearing properties of sand aquifers, these processes are of minor significance in the Memphis area, where cemented beds are rare and are seldom more than 1 foot thick. Faulting may also affect the ground-water conditions in an area by displacement of strata or by formation of a semi-impermeable barrier along the faulted zone. In the Memphis area the only structural deformation believed to affect ground-water movement is the previously described Big Creek fault, which restricts the inflow of ground water from the west. Relative positions of aquifers and confining clay beds also affect ground-water conditions in the Memphis area. In the outcrop area of the "500-foot" and "1,400-foot" sands east of Shelby County, water-table conditions exist. West of the outcrop, or recharge, area, however, confining beds of clay overlie the aquifers, and the water is under artesian pressure. As the water moves downdip in the westward dipping aquifers, the pressure surface becomes progressively higher above the confining clay beds which overlie the aquifers.

TEXTURE OF AQUIFER MATERIALS

More than 400 sand samples collected from many drilled wells in the Memphis area were analyzed to determine the distribution of particle size and the degree of sorting. These analyses give an indication of the hydraulic characteristics of the rocks because the size and sorting of the sand grains determine, to a great degree, the permeability and porosity. Coarse-grained sediments are less porous than fine-grained sediments; but because the pores are larger in the coarse-grained sediments, they are more permeable and will allow water to move through them more readily. Poorly sorted sediments are both less porous and less permeable than well-sorted sediments.

Comparison of one sample with another can best be made by comparing their respective sorting coefficients. The sorting coefficient is defined as the square root of the 25 percentile divided by the 75 percentile (Trask, 1932, p. 72). A value of 1 (unity) represents the highest possible degree of sorting. A sorting coefficient smaller than 2.5 indicates a well-sorted sample; 3, a normal sample; and 4.5 or higher, a poorly sorted sample. Sorting coefficients of samples from both the "500-foot" and "1,400-foot" sands (fig. 4) range from 1.1 to 1.3. The steepness of the curves (fig. 4), also shows that the sand is well sorted.

The size-distribution curves also show that the grain size of material from the "1,400-foot" sand is fine to medium and that the grain size of material from the upper part of the "500-foot" sand is medium to coarse. Analyses of samples from the lower part of the "500-foot" sand are not shown in figure 4, but the particle-size distribution in the lower part is known to be similar to that in the "1,400-foot" sand.

In summary, particle-size distribution and sorting coefficient of aquifer materials are a measure of the aquifer's capability to transmit water to wells and therefore are useful in determining the best zone in the aquifer to be screened in a well and the type and opening size of screen to be used.

EFFECTS OF GROUND-WATER WITHDRAWAL

The most conspicuous effect of withdrawal of water from an aquifer is the decline of water level that causes a cone of depression to form in the water surface surrounding the point of withdrawal. The size of

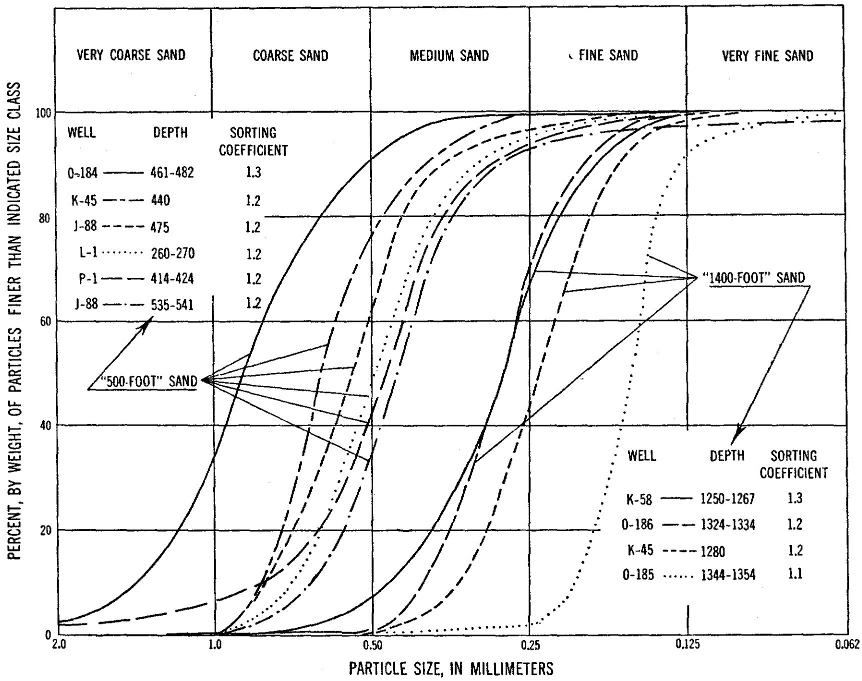

FIGURE 4.—Graphs showing the particle-size distribution in samples from the "500-foot" and "1,400-foot" sands.

the cone of depression formed by pumping a well or group of wells depends on the rate and amount of withdrawal and the hydraulic characteristics of the aquifer. Near the edge of the cone, the water-level depression or drawdown is small and, in effect, immeasurable because it is less than fluctuations caused by atmospheric-pressure changes and other influences. The theoretical distance to the edge of the cone of depression for a typical well field in the "500-foot" sand in the Memphis area pumping at an average rate of 10 mgd (million gallons per day) is about 5 miles from the center of withdrawal.

Increases in the annual rate of withdrawal have accelerated the lowering of the piezometric surface in the entire Memphis area so that the hydraulic gradient (slope of the water or pressure surface) is continually steeping. Consequently, larger amounts of water are transmitted into the area to supply the increased withdrawal. Figure 5 shows the Memphis municipal pumpage since 1898, and figure 6 shows the total municipal and industrial pumpage from the "500-foot" and the "1,400-foot" sands and the resulting water-level declines in the Memphis area from 1935 through 1960. As the rate of withdrawal increases, the regional cone of depression is expanded and deepened.

Under natural conditions, water was discharged from the "500-foot" and "1,400-foot" sands by subsurface flow to the west, thence southward along the axis of the embayment. Beginning with the first well drilled into the "500-foot" sand in 1886 (Lundie, 1898, p. 5–6), pumping has constantly increased, causing ground water to move into the enlarging cone of depression, thus eventually causing natural discharge as subsurface flow to stop.

THE "500-FOOT" SAND AQUIFER

DELINEATION

The "500-foot" sand in the Memphis area is delineated as a hydrologic unit although it includes all the deposits of the Claiborne Group. Geophysical logs of wells were used to identify the top and bottom of the aquifer as limited by the overlying and underlying confining clay. Most of the logs show distinct differences between the aquifer and the confining clay beds; however some show gradational changes from predominantly clay to predominantly sand beds. In the absence of a distinct and abrupt sand-clay contact, the boundary is selected arbitrarily at the middle of the transition zone in order to determine the average thickness of the aquifer. Delineated on this basis, the aquifer also may include some sandy beds of the lower part of the Jackson (?) Formation. In some parts of the area the Jackson (?) is not present, and the "500-foot" sand is overlain directly by terrace deposits com-

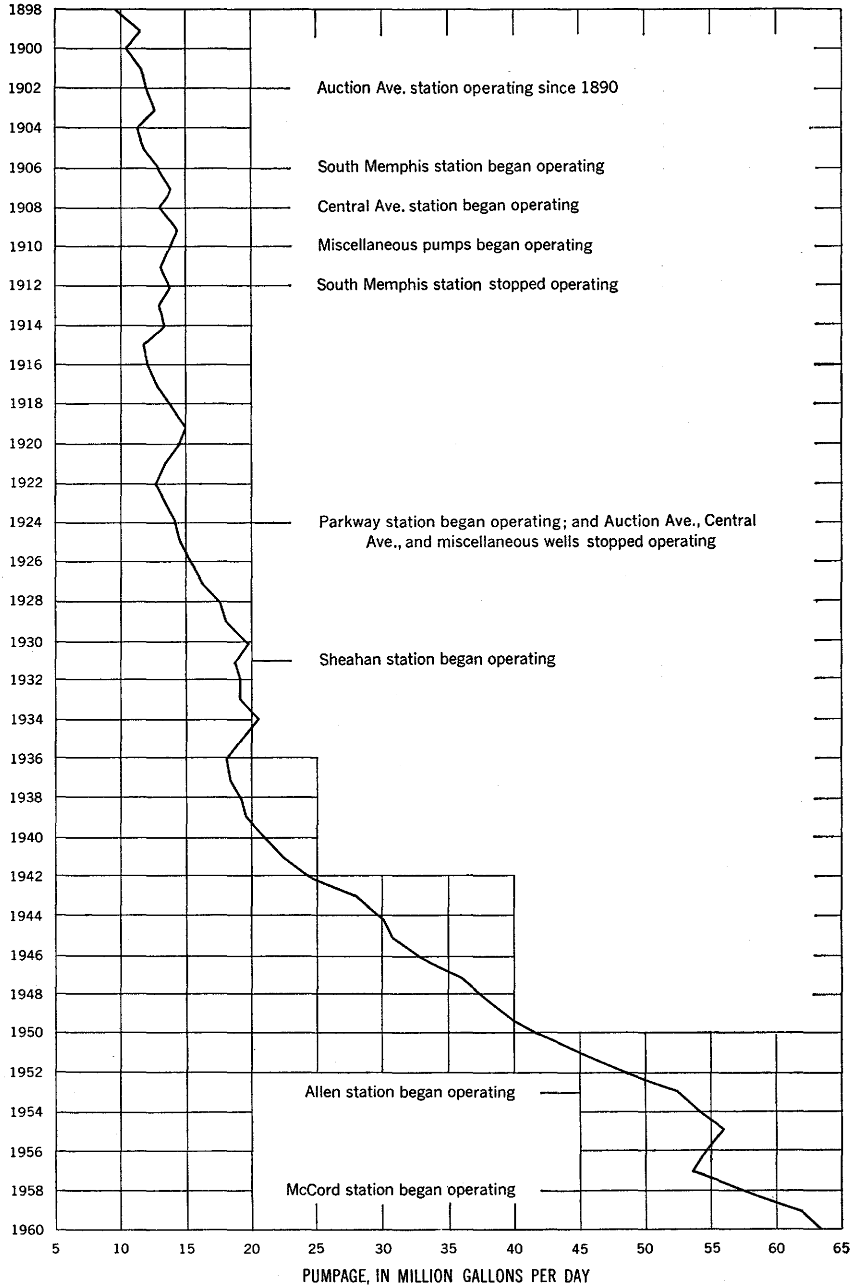

FIGURE 5.—Memphis municipal pumpage, 1898–1960.

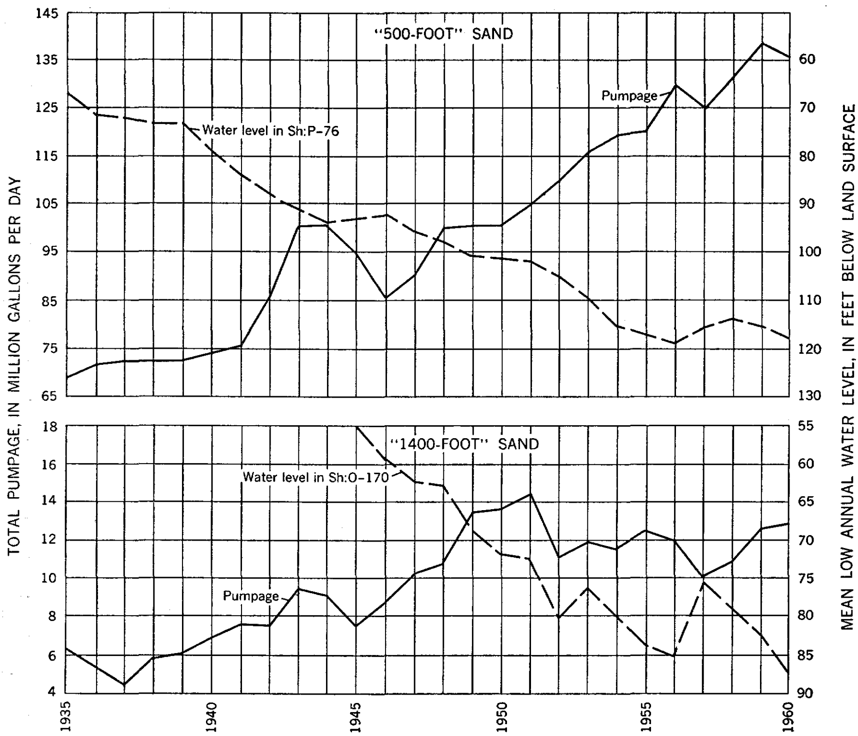

FIGURE 6.—Relation between total pumpage from the "500-foot" and "1,400-foot" sands and water-level declines in the Memphis area, 1935–60.

posed of coarse sand and gravel. These deposits are hydrologically connected with the "500-foot" sand in such areas but are not considered a part of the aquifer.

Plates 2 and 3 show the elevation and configuration of the top and bottom, respectively, of the "500-foot" sand in the Memphis area. These maps and the geologic section (pl. 1) show that the "500-foot" sand ranges from 500 to 800 feet in thickness, averaging about 700 feet thick, and dips toward the northwest at a rate of about 13 feet per mile. The volume of the aquifer, calculated from the contour maps, is about 25 trillion (25×10^{12}) cubic feet in the 1,300 square mile area shown in plates 2 and 3.

WATER LEVELS

DECLINE CAUSED BY PUMPING

Ground-water withdrawal from the "500-foot" sand for municipal and industrial use in the Memphis area has increased from about 68 mgd in 1935, the first year for which records are available, to about 135 mgd in 1960. This withdrawal, which averages about 100 mgd for the period, has formed a major cone of depression under the city of Memphis, where most of the pumping is concentrated, and has formed smaller superimposed cones under the Parkway, Allen, and Sheahan well fields (pl. 4). The regional relation between ground-water withdrawal and water-level decline in the "500-foot" sand is best illustrated by the hydrograph of well Sh: P–76 (fig. 7). This well is in the center of the major or regional cone of depression and is approximately equidistant from the smaller superimposed cones of depression caused by pumping in the Parkway, Allen, and Sheahan well fields. During 1935–60 an average rate of withdrawal of about 100 mgd resulted in a water-level decline of about 50 feet in well Sh: P–76, or about one-half foot decline for each million gallons pumped per day. Figure 8 shows progressively smaller declines in well Sh: O–1, 8 miles north of the center of pumping, and in well Sh: Q–1, 10 miles east of the center of pumping. Figure 9 shows still smaller declines in wells Sh: U–2, 15 miles north, and Fa: W–2 (Fayette County), 30 miles northeast of the center of heavy pumping.

The rate of water-level decline has increased since the early 1950's, at which time the rate of pumping increased to an average of about 120 mgd (1950–60) compared with an average of about 90 mgd for the preceding period (1935–59). The maximum decline for the period 1950–60 is about 47 feet in the Allen well field (pl. 5), which was placed in operation in early 1953. About 75 percent of this decline occurred in the first year of operation of this field. Smaller declines occurred in the Parkway and Sheahan well fields (pl. 5) during this period because these fields have been in operation since 1924 and 1931, respectively (fig. 5), and the rates of decline in each have decreased as their cones of depression have expanded and established a stable hydraulic gradient. The 24-foot decline in the McCord well field occurred after early 1958, when the field began operation. As in the Allen well field, the rate of decline in the early years of operation is greater than that in subsequent years, provided the rate of groundwater withdrawal remains the same.

Prior to 1958, when the McCord well field began operation, water levels in the field declined slowly and steadily (fig. 10) as a result of overall pumpage in the Memphis area. In 1958, the water level in an observation well near the McCord well field (fig. 10) declined about 18 feet for an average pumping rate of 12.5 mgd. Thus the relation between the water-level decline in this observation well and the pumpage of the well field was about 1.5 feet for each 1 mgd pumped. The next pronounced change in the rate of pumping occurred during the summer of 1960 when, between June and August, the pumping rate decreased from about 11.5 to 7.5 mgd. The water level in wells near

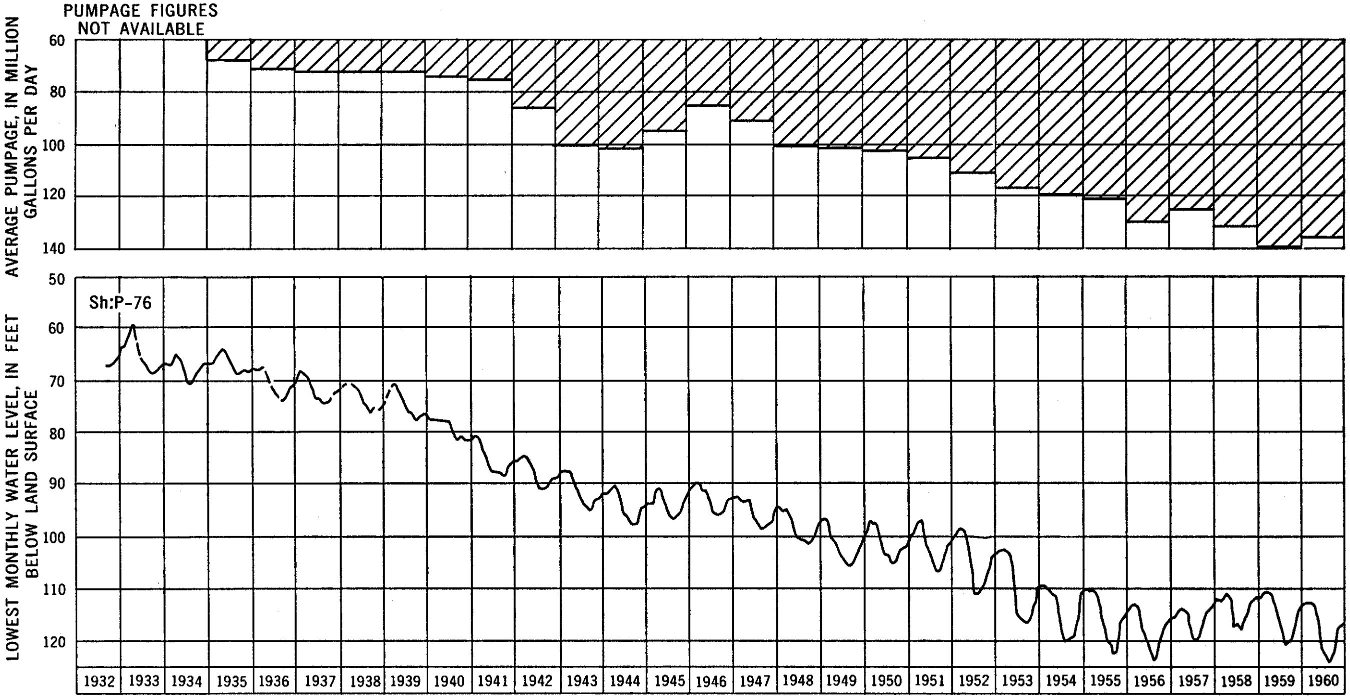

Figure 7.—Relation between ground-water withdrawal from the "500-foot" sand and water-level decline in the center of concentrated pumping.

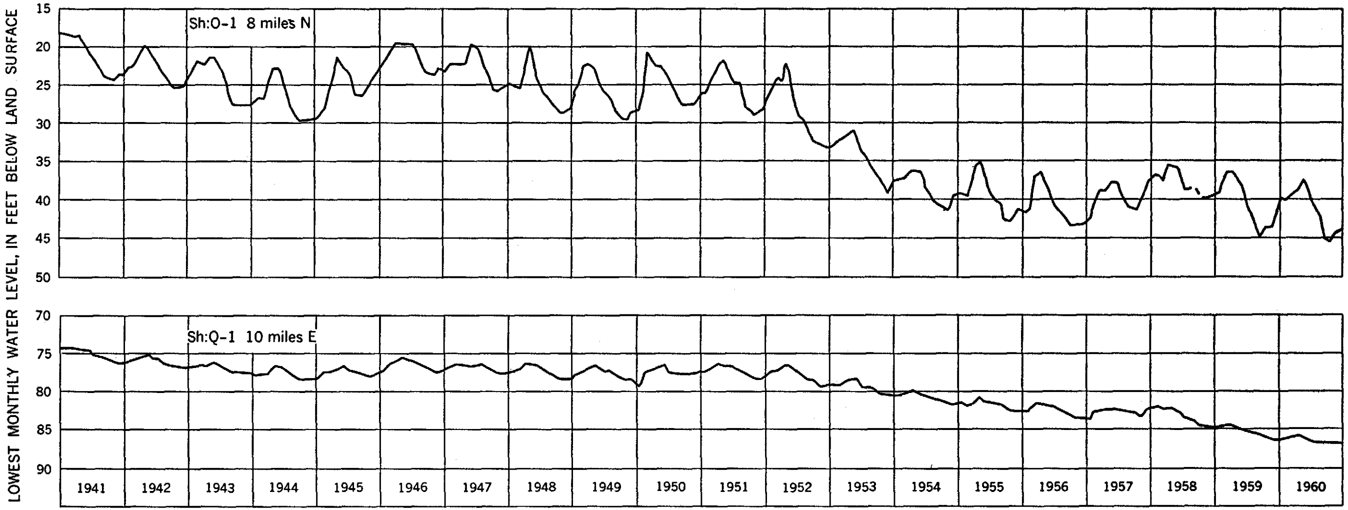

Figure 8.—Declines of water level in the "500-foot" sand, 8 and 10 miles from the center of concentrated pumping in the Memphis area.

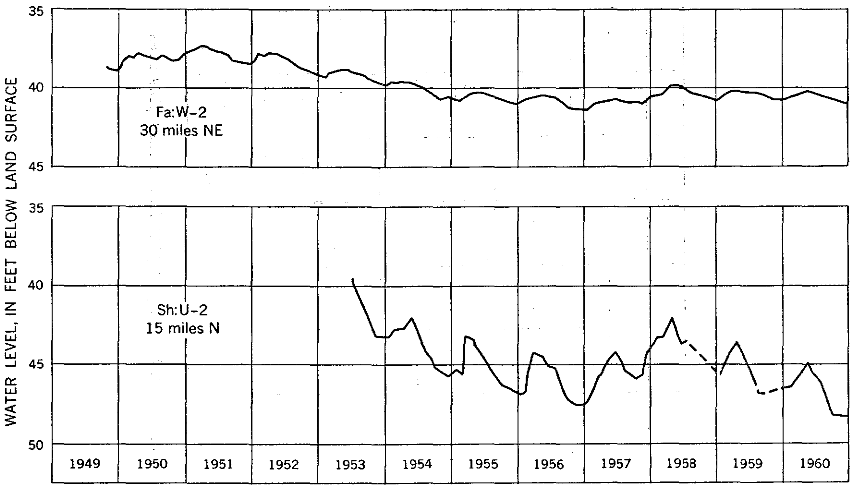

FIGURE 9.—Declines of water level in the "500-foot" sand, 15 and 30 miles from the center of concentrated pumping in the Memphis area.

the well field rose about 4 feet. Normally during this part of the year, the water level declines about 2 feet. Therefore, the effective recovery resulting from the pumpage reduction was about 6 feet. This again indicates a ratio between water-level rise or decline in the selected observation wells and pumpage of about 1.5 feet for each 1 mgd change in rate of pumping. Similiar determinations for the Allen (fig. 11) and Sheahan (fig. 12) well fields indicate ratios of 1.1 to 1 and 1.5 to 1 (feet of decline or rise to each million gallons per day increase or decrease in pumping) for these fields, respectively. The production ratio for the Allen well field is less because pumping has not continued long enough for the piezometric surface to stabilize in this newer well field. The production ratio for all well fields in the area should increase as water levels decline toward more stable pumping levels.

The distribution of production wells in the Parkway well field with respect to observation wells make it impossible to show a consistent relationship between the water level and the pumpage in this well field (fig. 13). The fluctuations resulting from seasonal and intermittent pumping are the only discernible parts of water-level changes. Figure 13 shows that a reduction of pumpage during 1945–49 did not cause a rise of water level in observation well Sh: O–153. This well is in the eastern part of the well field where the pumping rate was increased to offset the reduction in pumping in the western part of the well field. However, records of short-term observation wells indicate that the relation between water level and pumping differs little from that of the other well fields or of the entire Memphis area.

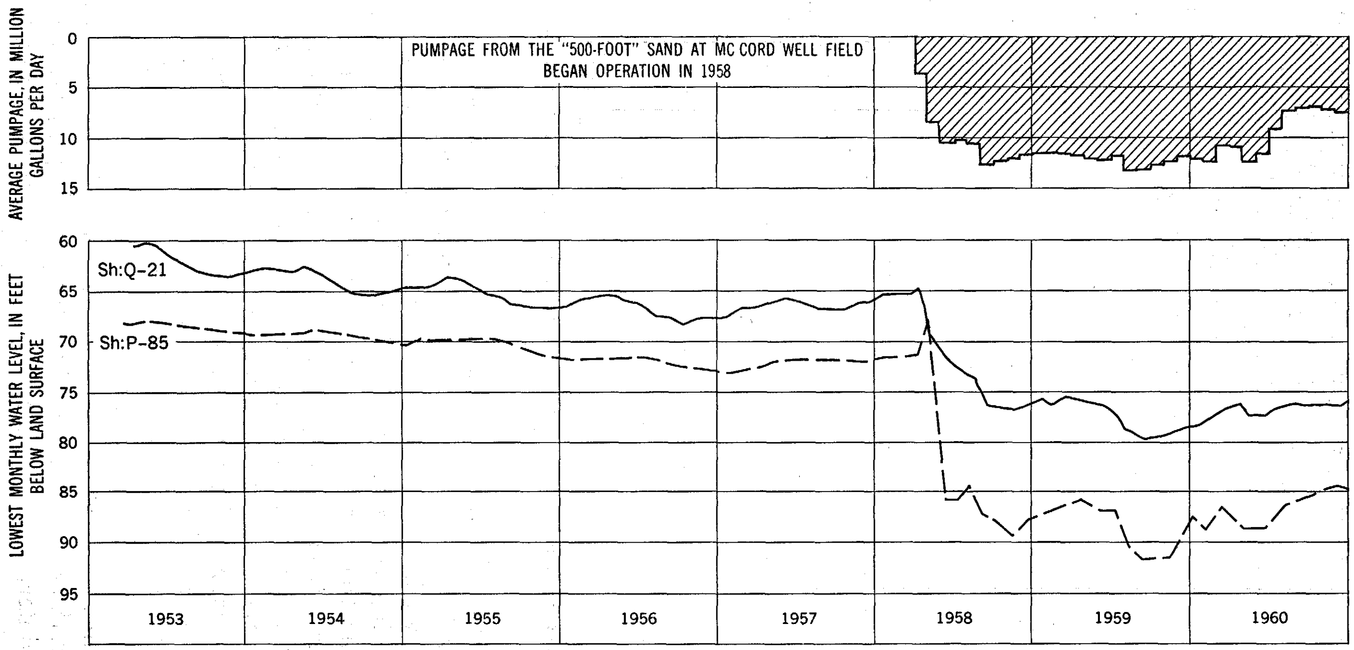

FIGURE 10.—The relation between pumping and water level ("500-foot" sand) in the McCord well field, Memphis, Tenn.

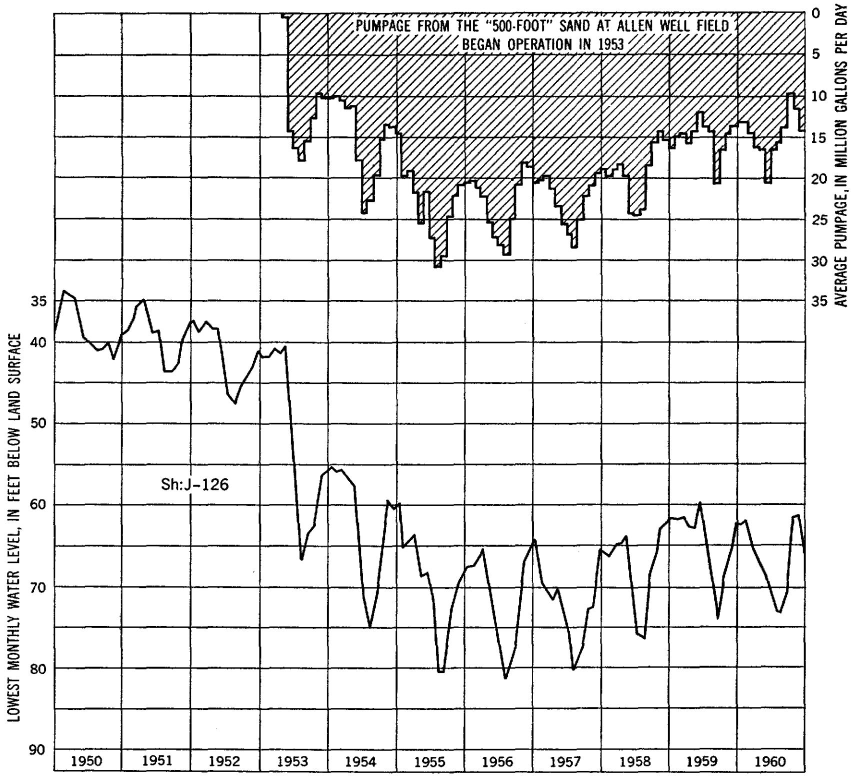

FIGURE 11.—The relation between pumping and water level ("500-foot" sand) in the Allen well field, Memphis, Tenn.

The hydrographs from observation wells equipped with recording gages generally show that those wells within or near the area of greatest withdrawal have their lowest water level in August each year, reflecting the highest monthly rate of withdrawal. Figures 7–9 show the declining trend of water level in the "500-foot" sand at various distances from the center of pumping as well as the annual low water level. The lowest annual water level occurs progressively later in observation wells that are farther from the center of pumping. The greater the distance, the greater the lag in the time of arrival of the effect of pumping. The lowest annual water level in observation well Fa:W-2 (fig. 9), which is 30 miles from the theoretical center of pumping, occurs in late December or early January, or about 4 months after the annual low water level in Memphis. The effect of cyclical pumping in the Memphis area, where the pumping is greater in summer than winter, is a wavelike motion of alternate low and high water levels traveling outward at a decreasing rate from the center of pumping. The cause of this wavelike phenomenon is believed to be a com-

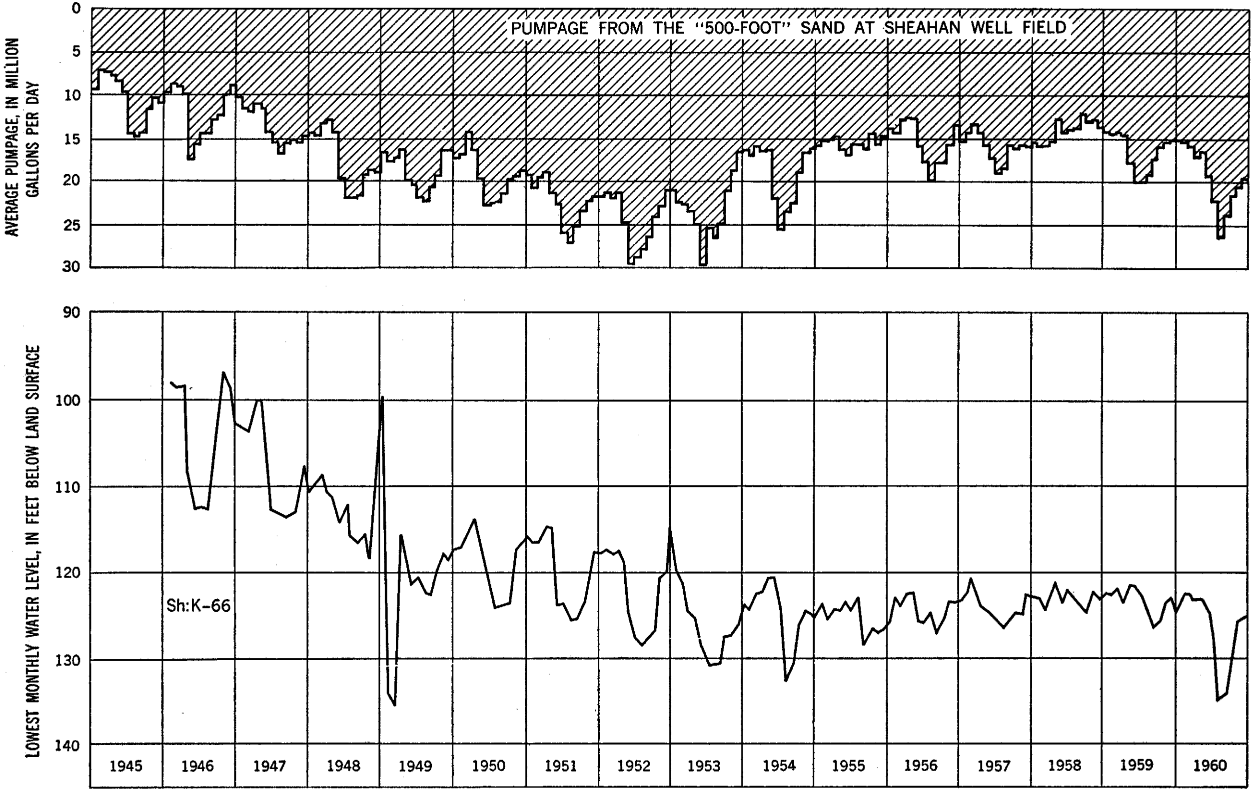

FIGURE 12.—The relation between pumping and water level ("500-foot" sand) in the Sheahan well field, Memphis, Tenn.

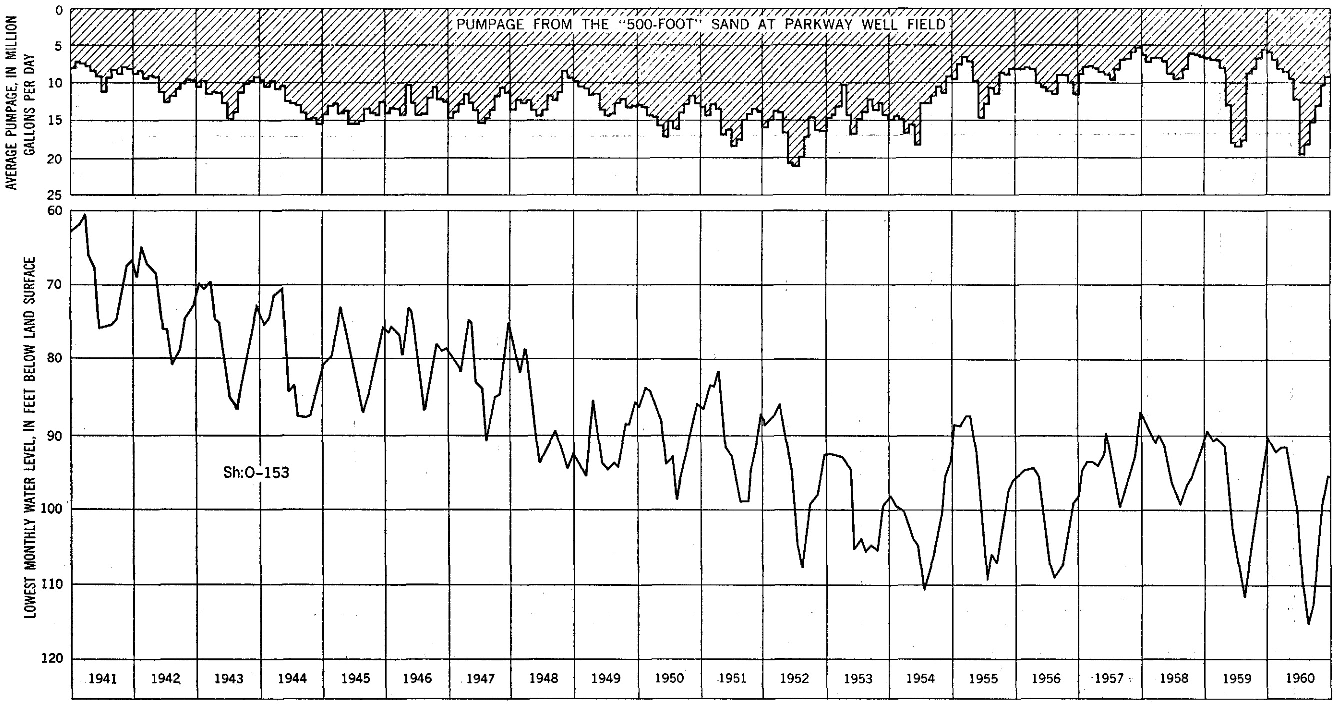

FIGURE 13.—The relation between pumping and water level ("500-foot" sand) in the Parkway well field, Memphis, Tenn.

bination of several factors including the degree of confinement, elasticity, and transmissibility of the aquifer. This effect should be considered when proposing locations of future well fields so that advantage can be made of the time lag of arrival of low water level. In a practical example, a typical well field about 20 miles from Memphis would be pumping at its lowest seasonal rate at a time when water levels are lowest and pumping most water at the time when water levels are highest.

Hydrographs of observation wells in the "500-foot" sand (figs. 7–9) indicate that the annual decline of the piezometric surface can be reasonably estimated for given rates of pumping. These figures show the fluctuations and general decline of water level in the Memphis area near the center of pumping (fig. 7), about 8 and 10 miles from the center of pumping (fig. 8), and 15 and 30 miles from the center of pumping (fig. 9). The theoretical center of pumping in the area is about the location of observation well Sh: P–76 (pls. 4, 6). Figure 9 shows that the seasonal fluctuation of water level in well Fa: W–2 about 30 miles northeast of Memphis in Fayette County is nearly 1 foot. The overall water-level trend is a declining one, although there are short periods of a rising water level caused by reductions in pumping rate, recharge to the aquifer, or both. This observation-well record reflects the regional water-level fluctuations and is less affected by small changes in pumping in Memphis. The seasonal range of water-level fluctuation in well Sh: U–2 in Memphis (fig. 9) has been about 3.5 feet except in 1957, a year of record-high rainfall. The record of this well also indicates the regional water-level trend, but the effect of changes in pumping in Memphis is more pronounced in this record than in that of well Fa: W–2.

FLUCTUATION

Precipitation causes water-level fluctuations in wells by recharging the aquifer in its outcrop area, by seeping through the overlying clays, where they are thin or missing, and, to a minor extent, by loading. The effect of recharge to the aquifer caused by unusually high precipitation is illustrated in the hydrograph of well Fa: W–2 for 1957 (fig. 9). The water level in this well under normal conditions of rainfall and pumping in the Memphis area would have declined about 0.3 foot in 1957. Instead, the water level rose about 0.8 foot, an effective change of 1.1 feet. Past records indicate that a reduction of pumpage of 10–20 mgd in Memphis would have been required to cause a 1.1-foot change in water level in this observation well. The annual average daily pumpage in 1957 was only about 1 mgd less than in the previous year. Therefore, the rise of water level in 1957 was largely due to recharge from heavy rainfall in the outcrop area of the "500-foot" sand.

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Loading of an aquifer, as by passing railroad trains and by rainfall, may also cause water-level fluctuations; but for a specific load the net water-level change is zero, and no rising or declining trend results. Generally, the water level rises as a load is applied then decreases rapidly even though the load may remain. Wells (1931, p. 25) believed that the Mississippi River added water to the "500-foot" sand, because a series of water-level measurments in wells along the river were higher when the river was high. Data collected by Kazmann (oral communication, 1954), however, indicated that loading of the aquifer by the weight of rapidly rising water in the river caused the water level also to rise in certain wells. In agreement with Kazmann's conclusion, it is doubtful that the river would have furnished water to the aquifer even if there had been a hydraulic connection between the river and the aquifer, because at that time (1931) the water level in the aquifer was about as high as the level of the river.

Atmospheric-pressure fluctuations may cause as much as a foot of change in water-level, depending partly on the rapidity of the change in pressure. These are basically daily-cycle fluctuations and are considered only during strict aquifer performance tests when water-level measurements are corrected for barometric effect. Within a short time the pressure-influenced water level regains its original level, often with the assistance of a reverse change in atmospheric pressure. The net change in water level resulting from atmospheric pressure change is zero over a period of time, generally 1 day.

HYDRAULIC CHARACTERISTICS

The amount of water that can be pumped from an aquifer perennially depends primarily on the capacity of the aquifer to transmit water from areas of recharge to areas of discharge, the amount of water available for recharge, and the amount of water in storage in the aquifer. To estimate the amount of water that can be pumped perennially with proper accuracy, the hydraulic characteristics of the aquifer must be known. Aquifer performance or pumping tests are the most economical method of determining the hydraulic characteristics. These characteristics are permeability (P), transmissibility (T), and storage (S). These and other terms used to describe the hydrologic properties of rocks were defined by Meinzer (1923), Wenzel (1942), and Ferris and others (1962).

Pumping tests consist of observing the rate of drawdown in observation wells for a given uniform rate of pumping in a nearby well or of observing the rate of water level recovery in a pumped well, or observation wells, after pumping stops. Pumping-test data were analyzed by standard methods, and the results were approximately the same as the values of the hydraulic characteristics. For this reason the less laborious semilog-plot method is used in this report.

Figure 14 shows a semilog plot and sample analysis of pumping-test

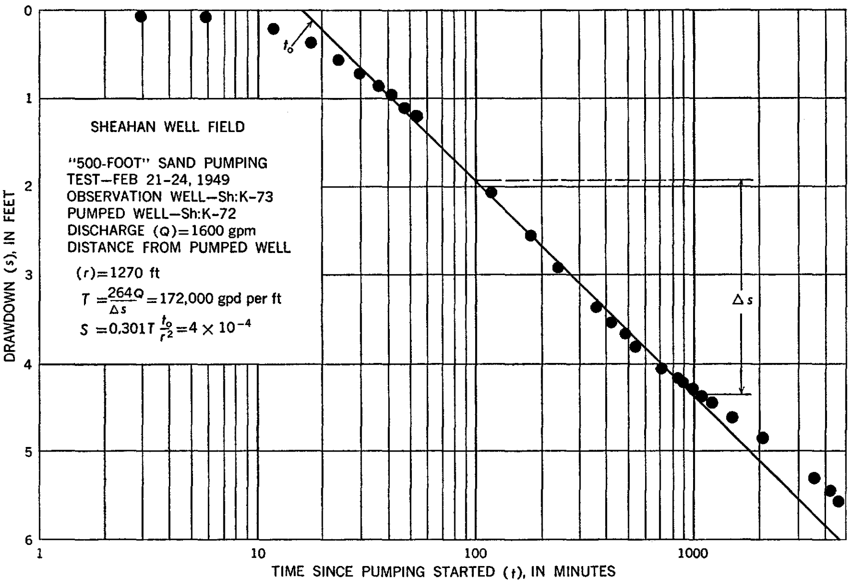

FIGURE 14.—Sample computations of transmissibility and storage coefficients for the "500-foot" sand using plotted pumping-test data.

data from wells in the "500-foot" sand. The figure also shows the procedure for computing the hydraulic characteristics of the aquifer.

The numerical values of hydraulic characteristics determined by pumping tests reflect the effects of all material within the zone of influence of pumping in the aquifer. This zone extends horizontally to the perimeter of the cone of depression of the pumping well. Its vertical influence may not extend to the bottom of the aquifer because of the anisotropy of the formation and partial penetration of the wells. As a result, a single pumping test provides hydraulic constants determined by the part of the aquifer affected during the test. These values are adequate for predicting aquifer response for that particular affected area under conditions generally the same as those prevailing during the period of the test. The values of the hydraulic characteristics of the total volume of the aquifer were determined by averaging the results of all tests and adjusting them for partial penetration of wells and other factors.

The wells that were used in all tests of the "500-foot" sand in the Memphis area are less than 500 feet deep and penetrate from 5 to 15 percent of the total thickness of the aquifer. Local clay lenses are present in above and (or) below the screens of some wells. The wells range in diameter from 4 to 20 inches; well screens range in diameter from 3 to 12 inches and in length from 10 to 120 feet.

Specific capacity of wells ranges from 10 to 100 gpm per foot of drawdown. The coefficient of transmissibility determined by analyses of data from these tests ranged from 100,000 to 410,000 gpd per ft, and the coefficient of storage from 1×10^{-4} to 3×10^{-3}. The average adjusted coefficients of the "500-foot" sand for the total thickness of the aquifer throughout the entire area are about 400,000 gpd per ft and 3×10^{-3} for T and S, respectively. Average values are used in this report to make quantitive determinations, and these values will be adequate for future determinations where artesian conditions prevail.

RECHARGE AND MOVEMENT

Recharge to the "500-foot" sand aquifer generally occurs in the areas where it lies at or near the land surface. Percolation of rainfall directly through the sandy soil in the outcrop area and seepage from streams recharge the aquifer where it crops out in the rolling hills 30–60 miles east of Memphis. The annual precipitation at Moscow and Bolivar, Tenn., in the recharge area, is slightly greater than at Memphis (fig. 2), and rainfall is fairly well distributed throughout the year.

In addition to recharge in the outcrop area, the "500-foot" sand locally receives some water from the overlying terrace deposits wherever the clay bed that generally underlies the terrace deposits is sandy or thin and where streams have cut deeply into the clay bed. Nonconnah Creek, formerly a perennial stream, now has periods of abnormally low flow in its lower reach during part of the year and has been dry during the latter part of the dry season in recent years. This change in its regimen is attributed to increased recharge to the "500-foot" sand as a result of the decline of water level in the aquifer within the past few years. Recharge to the aquifer probably is increasing as the effect of pumping in the Memphis area reaches the outcrop area and areas where seepage can occur.

The rate of water movement depends on the transmissibility of the aquifer and the hydraulic gradient. In general, the greater the rate of discharge, the more rapid the movement of water through the aquifer along the flow path. However, limitations on the maximum possible rate of movement are determined by the aquifer characteristics, not by the rate of discharge.

The movement of water in the Memphis area before development of the "500-foot" sand began was probably along the dip of the formation—locally westward in the area and regionally southward down the dip of the embayment. Water-level records indicate that the hydraulic gradient between Collierville and Memphis was about 5×10^{-4} in 1886. Using this value for the hydraulic gradient and an average transmissibility of 4×10^5 gpd per ft for the "500-foot" sand aquifer, about 1 million gallons of water moved across each 1-mile section of the aquifer each day in 1886. The eastern boundary of the area is about 30 miles in length; therefore, the average rate of water entering the Memphis area in 1886 was about 30 mgd. If we assume that stable conditions existed at that time, the rate of natural discharge was equal to the recharge rate.

The present direction of movement of ground water in the Memphis area is generally toward central Memphis from all directions as shown on plate 4. Water-level contours (pl. 4) indicate that more water is derived from the east-southeast; probably because transmissibility is greater in that part of the area, the dip of the "500-foot" sand is toward the northwest (figs. 5, 6), and the nearest area of recharge lies to the southeast. The amount of water moving across the 260-foot contour on plate 4 is about 60 mgd. Total inflow is tabulated in the section on pumping.

The amount of water moving into the area from the west is small, probably because the Big Creek fault forms a hydraulic boundary restricting inflow. Further increases in pumping in the Memphis area will produce steeper gradients and induce a greater amount of water to flow toward the centers of pumping.

The present rate of movement of ground water in the "500-foot" sand in the southeastern part of the area is estimated to be approximately 70 feet per year toward the west-northwest under a hydraulic gradient of about 5 feet per mile (9×10^{-4}). At the edge of the area of heavy withdrawal, approximately 3 miles from the present city limits (pl. 3), the gradient steepens to about 10 feet per mile and the rate of ground-water movement increases accordingly to about 140 feet per year. In and near the well fields, the velocity of flow is even greater. In the northeastern part of the area, the hydraulic gradient is about 3 feet per mile, and the rate of movement about 40 feet per year.

PUMPING

An average of about 135 mgd was pumped from the "500-foot" sand in 1960. A little less than half this amount was for municipal use, and a little more than half was for industrial use. Pumping records reported monthly to U.S. Geological Survey indicate that industrial pumping is nearly constant and that municipal pumping may vary as much as 100 percent from summer to winter. Figure 6 shows the average daily pumping rate for each year since 1935. The effect of the areal distribution of pumping is shown on the piezometric map (pl. 4) and on the isodecline map (pl. 5).

As previously stated, the natural discharge moving out of the Memphis area toward the west and thence southward along the axis of the embayment was about 30 mgd in 1886. Natural discharge probably ceased when the water level was lowered to about 200 feet above mean sea level in central Memphis. The hydraulic gradient created by pumping in Memphis probably was sufficient to stop the natural discharge from the area by 1940.

The total amount of water pumped from the "500-foot" aquifer between 1886 and 1960 is estimated to be about 1.9 trillion gallons (1.9×10^{12}). If it is assumed that $S=3\times10^{-3}$ and that the water level declined 60 feet between 1886 and 1960, then the total amount of water pumped from storage is about 12 billion gallons. This quantity is less than 1 percent of the total pumpage since 1886—that is, an average of about 1 percent of the water pumped each year was derived through depletion of storage in the aquifer.

A water-control budget for the "500-foot" sand aquifer was computed using the low-water-level contours for 1960 (pl. 4) and checked against the average daily pumping rate for 1960. Inflow into the Memphis area was determined to be generally as follows:

Inflow	*Million gallons per day*
Across eastern boundary	60
Across northern boundary	20
Across southern boundary	25
Across western boundary [1]	29
Depletion of storage	1
Total	135
Average daily pumping rate for 1960	135

[1] Includes leakage from rocks above aquifer and inflow of water from other sources.

THE "1,400-FOOT" SAND AQUIFER

DELINEATION

Delineation of the "1,400-foot" sand in the Memphis area is based on the same hydrologic considerations as is delineation of the "500-foot" sand. The upper and lower boundaries (pls. 6, 7) were determined primarily by interpretation of electric and gamma-ray logs which show distinct contacts (pl. 1) of the sand with its confining clay formations. The confining clay formations are thick and for practical purposes may be considered impermeable. The aquifer is continuous throughout the area and dips toward the west at a rate of about 25 feet per mile. The sand probably crops out 60–80 miles east of Memphis although in some areas it is overlapped by the "500-foot" sand (Schneider and Blankenship, 1950). The thickness of the aquifer increases from about 150 feet in the eastern part of the Memphis area to about 300 feet in the western part. The volume of the aquifer in the 1,300 square mile area is about 7 trillion cubic feet (7×10^{12}).

WATER LEVELS

DECLINE CAUSED BY PUMPING

The relation between water-level fluctuations and pumping in municipal well fields is shown in figures 15 and 16, The two observation wells represented are in the Parkway and Sheahan well fields and clearly show the effect of changes in pumping rates, although the water-level fluctuations cannot be correlated quantitatively with the pumping from each well field because fluctuations caused by natural phenomena obscure the fluctuations caused by pumping. These two municipal well fields and one industrial plant well field are the only ones in Shelby County having one or more wells screened in the "1,400-foot" sand. Nearly all the observation wells are close to production wells in these fields, and intermittent pumping of the production wells often masks any areal water-level trend that might be noted in an observation well several hundred feet from a well field.

The water-level fluctuations in observation wells at greater distances from the areas of heavy withdrawal (fig. 17) are less pronounced, and the hydrographs of these wells reflect regional trends of water level.

The hydrographs in figure 17 show that, except for during 1957 and 1958, the average seasonal fluctuation in well Fa : W–1, about 30 miles northeast of Memphis, is about 1.2 feet; and in well Sh : U–1, about 15 miles north of Memphis, it is about 3.5 feet, or about three times that in well Fa : W–1. The ratio of the logarithms of the two distances mentioned above is also 3, so that a rule can be inferred as follows, relating distance to seasonal fluctuations:

$$\frac{\log 30}{\log 15}\times \text{seasonal fluctuation at 30 miles} = \text{seasonal fluctuation at 15 miles.}$$

This may be a general rule for predicting water-level fluctuations and decline in the Memphis area and possibly other similar areas where no observation wells exist, but it has not been proven.

In wells in the "1,400-foot" sand, water levels declined at an almost constant rate until 1952 as a result of gradual increases in pumping. In 1952 pumping was decreased (fig. 17). However, the trend of decline continued (fig. 17) until 1957 because drought conditions in the outcrop or recharge area of the aquifer prevented immediate replenishment of the water pumped from the Memphis area. Since 1957 the water level has remained about constant. No significant trend of decline is expected until several more wells are developed in this aquifer or until another prolonged drought occurs.

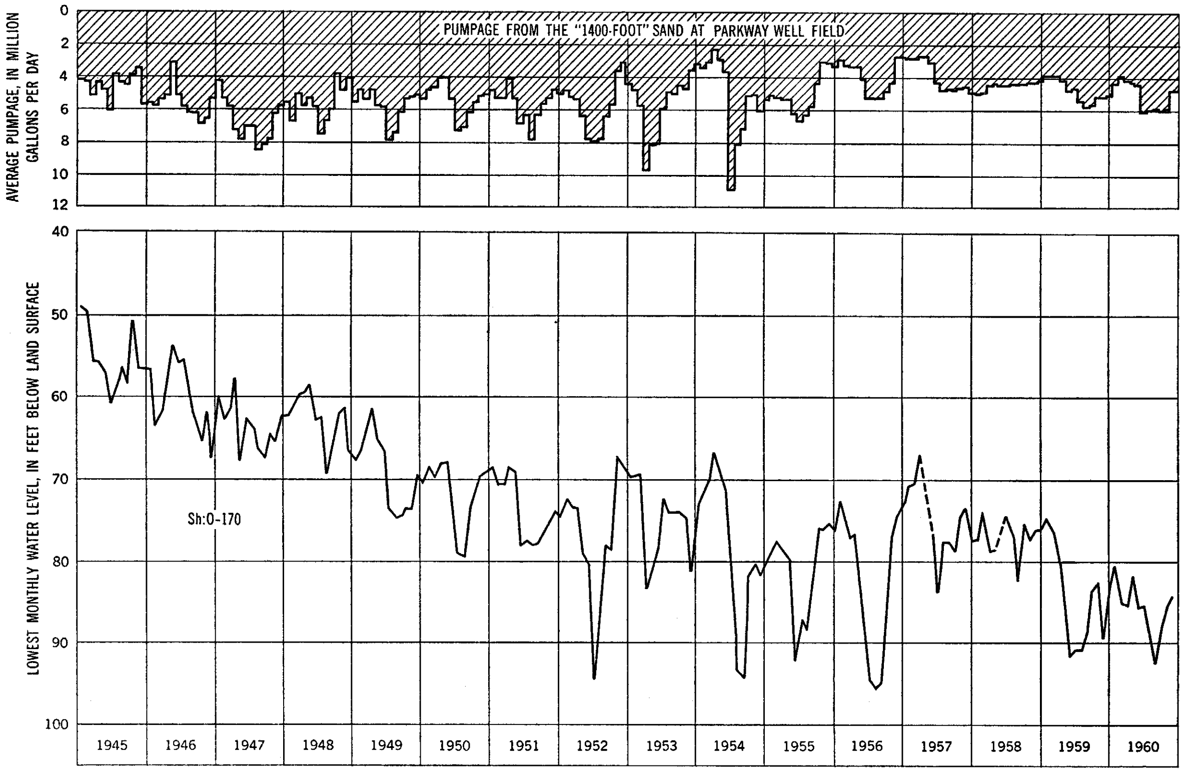

Figure 15.—The relation between pumping and water level ("1,400-foot" sand) in the Parkway well field, Memphis, Tenn.

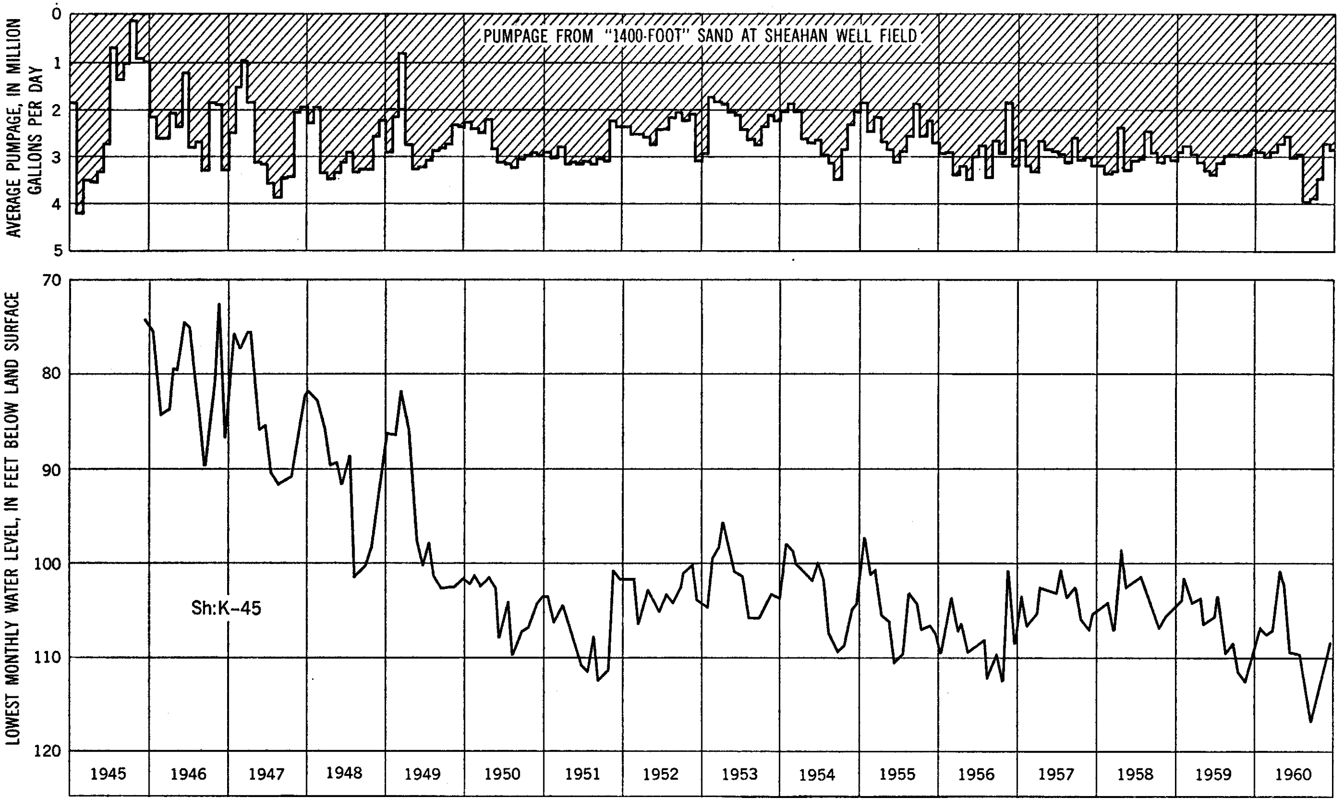

Figure 16.—The relation between pumping and water level ("1,400-foot" sand) in the Sheahan well field, Memphis, Tenn.

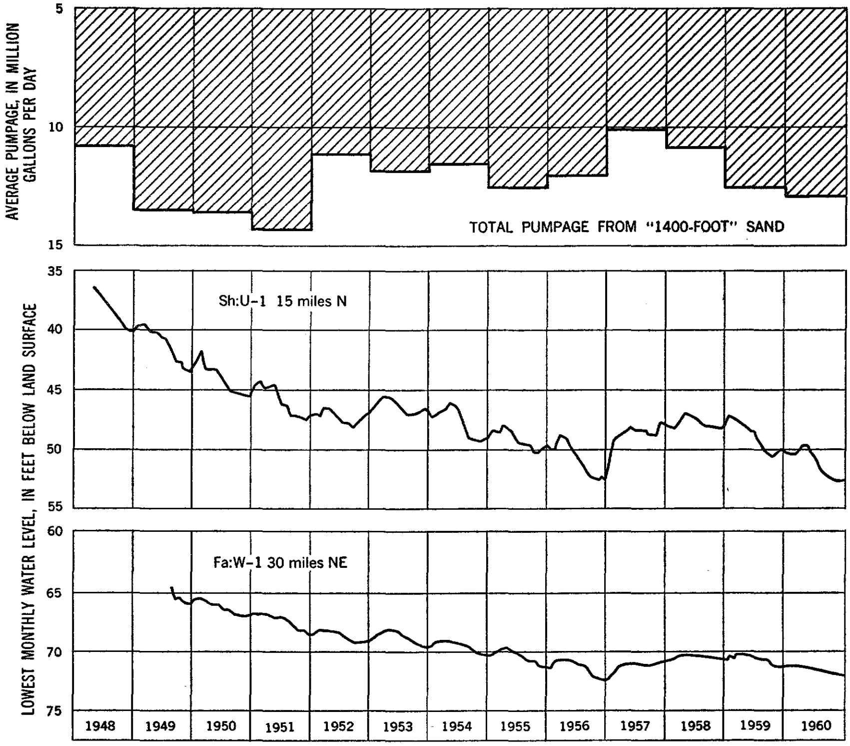

FIGURE 17.—The relation between total pumpage from the "1,400-foot" sand in the Memphis area and water levels in wells Sh : U–1 and Fa : W–1, 15 and 30 miles, respectively, from the center of pumping.

FLUCTUATION

Water levels in the "1,400-foot" sand fluctuate in response to the same causes discussed earlier for the "500-foot" sand. Fluctuations resulting from atmospheric-pressure changes are slightly more pronounced because the aquifer is under higher artesian pressure and its barometric efficiency is greater. Water level fluctuations resulting from loading are negligible because of the structural support of the greater thickness of material above the aquifer.

Since 1957, water levels have fluctuated primarily in response to rainfall in the outcrop area of the "1,400-foot" sand aquifer. Hydrographs (fig. 17) show that water levels rose from 1957 to 1959 during a period of normal to above normal precipitation even though pumping increased slightly over the same period. The regional rise of water level is similar to the rise of water level in the "500-foot" sand (fig. 9) during the same period.

HYDRAULIC CHARACTERISTICS

The numerical values of the hydraulic characteristics of the "1,400-foot" sand determined from seven tests in the three well fields in Memphis cover a rather narrow range.

	Average	Minimum	Maximum
T	3×10^{-4}	90,000	140,000
S	3×10^{-4}	1.5×10^{-4}	4×10^{-4}

An example of test data is shown in figure 18. The highest values of the coefficients were from tests at the Parkway well field (pl. 6), where the thickness of the "1,400-foot" sand is about 15 percent greater than in the other well fields.

The yields of the wells used in the tests ranged from 400 to 1,600 gpm (gallons per minute). The wells range in diameter from 8 to 24 inches. The well screens are 8–10 inches in diameter, 55–120 feet in length, and penetrate less than 50 percent of the thickness of the aquifer.

The aquifer-test results indicate that the "1,400-foot" sand is almost an ideal artesian aquifer. The changes of water level in observation wells in response to changes in the rate of withdrawal were almost instantaneous, indicating near-perfect vertical confinement between the clay boundaries. The barometric efficiency of the aquifer ranged from 75 to more than 95 percent, also indicating near perfect confinement.

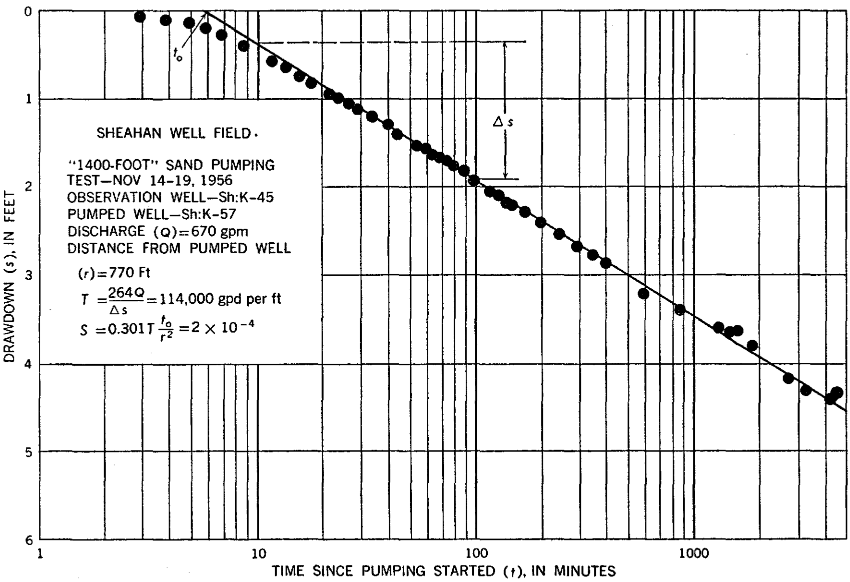

FIGURE 18.—Sample computations of transmissibility and storage coefficients for the "1,400-foot" sand using plotted pumping-test data.

Tests made in the same well fields in 1944 and later show that the hydraulic characteristics of the aquifer have not changed appreciably in about 15 years.

The hydraulic constants determined for the "1,400-foot" sand are more reliable than those for the "500-foot" sand, and the constants may be used more etxensively because the "1,400-foot" sand is more uniform in texture and thickness.

RECHARGE AND MOVEMENT

In some part of the outcrop area where the "1,400-foot" sand is in contact with the bottom of the "500-foot" sand, the "500-foot" sand outcrop serves as the recharge area for both aquifers (Schneider and Blankenship, 1950, chart 1). Where the sand is exposed at the surface, it receives recharge from precipitation and from seepage from streams. The rate of recharge is influenced by the rate and amount of precipitation, as indicated by hydrographs of wells in the "1,400-foot" sand (fig. 17) which show that the water levels rose in 1957, a year of unusually high rainfall.

The rate of recharge before the development of wells in the aquifer began, based on available data and the assumption that recharge was equal to the natural discharge at that time was about 5 mgd to the Memphis area. The present rate of recharge is unknown but is less than the pumping rate for the area.

The amount of water moving toward a well is proportional to the hydraulic gradient of the cone of depression. Generally, the hydraulic gradient increases as the rate of pumping increases. If the pumping rate remains constant, the cone of depression expands and the hydraulic gradient tends to flatten, other factors being equal, until an equilibrium slope is established. The 1960 rate of withdrawal from the "1,400-foot" sand was about 13 mgd, and this quantity has not varied more than 20 percent during the past decade. The hydrographs of wells Fa: W−1 and Sh: U−1 (fig. 17) show that the hydraulic gradient established in the "1,400-foot" sand has flattened and remained about constant several miles from the area of heavy withdrawal for the past decade also. The gradient 15–30 miles from central Memphis is about 3 feet per mile (or 5.7×10^{-4}), and the rate of movement of water is about 40–50 feet per year.

Water-level data for 1924 (Schneider and Cushing, 1948, p. 9) show that the hydraulic gradient before development of wells in the "1,400-foot" sand was 2.5×10^{-4} and that the transmissibility was 1.2×10^{5} gpd per ft. Based on these figures the average amount of water that moved westward across a 1-mile section of the "1,400-foot" sand aquifer was about 0.16 mgd, compared to 1 mgd for the "500-foot" sand aquifer.

This rate of movement is equal to the natural discharge and recharge before the development of wells in the aquifer.

PUMPING

The average daily rate of withdrawal of water from the "1,400-foot" sand in the Memphis area between 1935 and 1960 is shown in figure 6. During the period 1947–60 the annual pumpage ranged from 10 to 14 mgd and averaged about 12 mgd. The slope of the present hydraulic gradient in the area 15–30 miles from the center of heavy withdrawal has developed in response to this constant rate of withdrawal, and near-equilibrium conditions of discharge, recharge, and water level now exist.

In 1924, before the development of wells in the "1,400-foot" sand, was equal to the amount of recharge, or about 5 mgd. Pumps within the area now intercept all the water that formerly was discharged naturally from the area.

Total discharge, or the amount of water withdrawn from 1924 to 1960, is about 120 billion gallons. If we use a coefficient of storage of 3×10^{-4} and a total water-level decline of 74 feet (in the Parkway well field), the amount of storage depletion in the aquifer is about 12 billion gallons. The average annual rate of depletion of storage in the aquifer is 10 percent of the present average daily rate of pumping, or about 1 mgd.

OTHER AQUIFERS

The Ripley Formation of Cretaceous age may be a major source of water in the future. The top of the Ripley lies about 2,600 feet below land surface at Memphis, and, at present, only one well, in the Parkway well field, is screened in the formation. The piezometric surface of this aquifer is more than 100 feet above land surface, and when this well was allowed to flow, it produced about 35 gpm. The water contains more than 1,000 ppm (parts per million) total dissolved solids and is not fit for most uses without treatment.

Terrace deposits consisting of sand and gravel of Pleistocene and (or) Pliocene age may also be a major future source of water. These deposits lie at or near land surface where they are present and may be as much as 160 feet thick. Several domestic wells screened in this aquifer yield as much as 50 gpm, and it is probable that large capacity wells could be developed in some places in the area. Water from the terrace deposits is hard but generally contains less iron than does the water from either of the principal aquifers. Water from the terrace deposits is suitable for some industrial uses without treatment, though none of the industries in the area use water from this source.

QUALITY OF WATER

Water that moves through underground formations comes into contact with and dissolves soluble material in the rocks, thereby changing the chemical quality of the water. Differences in the quality of ground water reflect differences in the geologic environment in the water-bearing formations. Formations lying at considerable depth below the surface and those which yield water derived from distant sources usually contain water that is more highly mineralized than do those which lie at shallow depth or obtain water from nearby sources. A complete discussion of the significance of the chemical and physical characteristics of water was prepared by Lohr and Love (1954, p. 3–13).

The value of a water supply is largely dependent on the quality of the water required for various uses. Water from the two principal aquifers in the Memphis area is of good chemical quality for municipal use and contains chemical constituents in concentrations well below those recommended by the U.S. Public Health Service for water used on interstate carriers. Iron concentration and hardness of water are usually the most troublesome chemical qualities. Iron concentration, hardness, and total dissolved solids in selected samples from the two principal aquifers are shown in figure 19.

The bacteriological quality of water from the "500-foot" and "1,400-foot" sand aquifers in the Memphis area is excellent because of the great depth to the water and because a local ordinance requires filling of abandoned wells with clay and cement. The only aquifer which could become seriously polluted from the land surface is the terrace deposits, and this aquifer is not used extensively for supply where pollution would be likely.

Industrial wastes and sewage do not currently pose a pollution problem, because these materials are discharged to the Mississippi River and are not allowed to accumulate in large amounts at any place in the area. Discharge of waste water to wells is prohibited by municipal ordinance in Memphis and Shelby County.

WATER IN THE "500-FOOT" SAND

The chemical quality of water in the "500-foot" sand is good. The only dissolved constituents that are troublesome are iron, free carbon dioxide, and, in a few places, hydrogen sulfide. Iron is easily removed by aeration and filtration, and most free carbon dioxide and hydrogen sulfide escape as the water is pumped from the ground or during the aeration for iron removal.

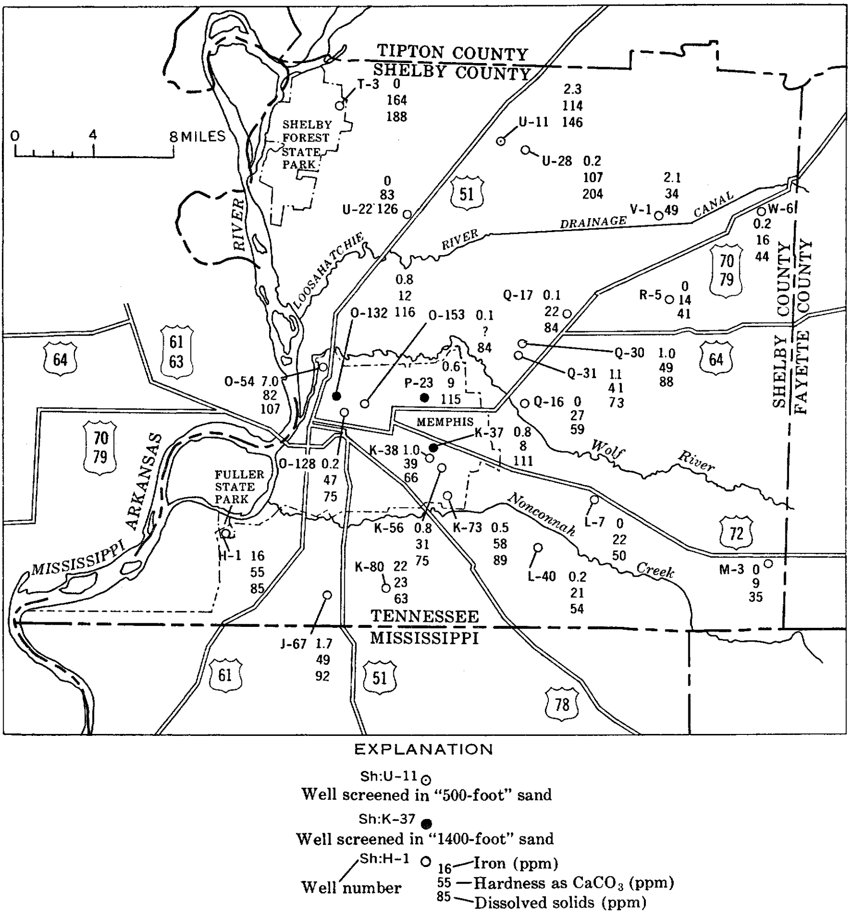

FIGURE 19.—Iron concentration, hardness, and total dissolved solids of water from selected wells in the "500-foot" and "1,400-foot" sands.

The water temperature ranges from 61° to 64°F, depending on the depth from which the water is pumped. The temperature of the ground water in the Memphis area increases about 1°F per 100 feet of depth below the ground surface, starting at 61° F at a depth of about 100 feet.

The water is generally soft. The average hardness determined from random sampling is about 40 ppm, having a range from 10 to 170 ppm. The highest values, above 60 ppm, may be a result of harder water leaking from the overlying terrace deposits and mixing with water in the "500-foot" sand. More water will probably be induced from the shallower formation as pumping continues to increase.

Determinations of pH made immediately after samples were collected showed the water to be acid, but a neutral condition was approached within a few minutes after collection as a result of the escape of carbon dioxide. The average pH of the water after it has been standing for a few hours is about 6, indicating a slightly acid condition. A typical chemical analysis of water from the "500-foot" sand is shown in table 2. The sample was analyzed several days after it was collected, and for this reason the pH determination was comparatively high.

TABLE 2.—*Typical chemical analysis of water from the "500-foot" sand*

[Chemical analysis of water from well sh:O-128 in the "500-foot" sand. Well data: diameter, 10 inches; depth, 567 ft; drilled, 1943. Water data: color, 6; pH, 7.0; temperature, 62° F; date of collection, 4-2-51; specific conductance (micromhos at 25° C) 123. Analysis by U.S. Geol. Survey]

Constituent	*Parts per million*	*Equivalents per million*	*Constituent*	*Parts per million*	*Equivalents per million*
Aluminum (Al)	0. 0	-------	Sulfate (SO_4)	3. 2	0. 067
Silica (SiO_2)	13	-------	Chloride (Cl)	3. 0	. 085
Iron (Fe)	. 44	-------	Fluoride (F)	. 0	. 000
Calcium (Ca)	10	0. 499	Nitrate (NO_3)	. 4	. 006
Magnesium (Mg)	5. 5	. 452	Dissolved solids	81	-------
Sodium (Na)	8. 2	. 357	Hardness as $CaCO_3$:		
Potassium (K)	1. 3	. 033	Total	48	-------
Bicarbonate (HCO_3)	72	1. 180	Noncarbonate	0	-------

The water for municipal use in Memphis is treated for iron removal only. This treated water, which includes water from the "1,400-foot" sand, contains about 100 ppm total dissolved solids. A few of the industries requiring water of special chemical quality treat the water for the removal of certain constituents, but most of them use the water untreated. The Memphis Light, Gas, and Water Division is equipped to add chlorine to the water as a protective measure, but chlorine is not routinely added.

WATER IN THE "1,400-FOOT" SAND

The chemical quality of water from the "1,400-foot" sand is good (table 3), but the water is generally more highly mineralized than water from the "500-foot" sand. The hardness (as $CaCO_3$) is lower, ranging from 5 to 17 ppm. Water from the "1,400-foot" sand is untreated for municipal use, except for iron removal, and is mixed with water from the "500-foot" sand in the municipal system. Treatment for iron removal also removes the small amount of free carbon dioxide and hydrogen sulfide from the water.

Table 3 shows a typical chemical analysis of water from the "1,400-foot" sand. The pH is neither representative of water in the formation nor representative of water immediately after pumping, because the analysis was made several days after collection of the water sample.

During this time the escape of free carbon dioxide from the water caused an increase in the pH. No carbon dioxide or pH determinations have been made immediately after collection of water samples from this formation, but such analyses probably would be similar to those made of water from the "500-foot" sand.

TABLE 3.—*Typical chemical analysis of water from the "1,400-foot" sand*

[Chemical analysis of water in well Sh:K-58 in the "1,400-foot" sand. Well data: diameter, 8 inches; depth 1,305 ft; drilled in 1941. Water data: color, 17; temperature 70°F; date of collection, 4-2-51; specific conductance (micromhos at 25°C), 160. Analysis by U.S. Geol. Survey]

Constituent	*Parts per million*	*Equivalents per million*	*Constituent*	*Parts per million*	*Equivalents per million*
Aluminum (Al)	0. 7		Sulfate (SO_4)	5. 1	0. 106
Silica (SiO_2)	12		Chloride (Cl)	2. 0	. 056
Iron (Fe)	. 60		Fluoride (F)	. 1	. 005
Calcium (Ca)	2. 7	0. 135	Nitrate (NO_3)	. 5	. 008
Magnesium (Mg)	1. 3	. 107	Disolved solids	112	
Sodium (Na)	35	1. 522	Hardness as $CaCO_3$		
Potassium (K)	2. 5	. 064	Total	12	
Bicarbonate (HCO_3)	101	1. 655	Noncarbonate	0	

Samples collected in 1927 and at infrequent intervals afterward indicate that the quality of water in the "1,400-foot" sand has remained constant. If leakage to the aquifier occurred in substantial amounts from rocks either below or above, it would undoubtedly be noted in the chemical analyses of the water because of the difference in quality of water in adjacent formations. The constancy of quality in the area where the pressure head is lowered considerably is further indication that the clays confining this artesian aquifier have very low permeability.

WATER IN OTHER AQUIFERS

Chemical analyses of the few samples of water obtained from the terrace deposits in the Memphis area show that the water is generally hard but that it contains less iron and carbon dioxide than does the water from the two principal aquifers. The average hardness (as $CaCO_3$) of water from the "500-foot" sand is about 40 ppm, and the average hardness of water from the terrace deposits, about 200 ppm. If the "500-foot" sand is locally recharged by seepage from the terrace deposits in any part of the area, sampling for chemical quality may be used to indicate the location and amount of such recharge. This should be one of the objectives of a continuing investigation.

Analyses of several samples of water from the only well screened in the Ripley Formation (about 2,600 ft deep) in the Memphis area show that the water contains more than 1,000 ppm total dissolved solids and is saline. The chemical quality of the water has not changed appreciably since the first sample was collected in 1927. Samples of water from this aquifer 80–100 miles east of Memphis contain as little

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as one tenth of the amount of dissolved solids found in water at Memphis, thus indicating the rate of change in chemical quality as the water moves downdip toward Memphis.

FACTORS AFFECTING FUTURE USE AND DEVELOPMENT

The foremost consideration at present is whether or not pumping from the principal aquifers in the Memphis area can continue to increase each year, as it has in the past, without causing the abandonment of many wells or a major change in the chemical quality of the water. The answer is a qualified "yes," although, as the development of new wells in the aquifers continues, pumping costs rise primarily as a result of declining piezometric surface and the higher initial cost of developing new wells at greater depths. Other factors which may affect future development include loss of artesian head, change in chemical quality as a result of induced recharge from adjacent formations or from surface water in certain locations, change in hydraulic characteristics of the aquifer, development of wells in shallower or deeper aquifers, development of surface-water supplies where water-quality tolerances are lower, and discovery of new industrial processes which may reduce or increase water consumption. All these factors are of immediate concern in long-range water management, but none appear to offer reasons for curtailment of development of wells at the current rate in either of the principal aquifers. Some of the factors, such as development of surface-water supplies and development of wells in deeper or shallower aquifers, would tend to conserve water in the "500-foot" and "1,400-foot" sands.

Water wells can be developed in either of the principal aquifers anywhere in the Memphis area, but the amount of water discharged by a well per unit drawdown of water level, defined as specific capacity, cannot be predicted accurately because of the nonhomogeniety of the sands and the sporadic presence of clay beds of varying thicknesses in some parts of the area. The size, capacity, and type of construction of a well, the size and length of the well screen, the kind of gravel envelope around the screen, the pumping rate, and the hydraulic properties of the water-bearing formation in the vicinity of the well affect the specific capacity. Theoretically, transmissibility can be used to predict specific capacity of a proposed well where other factors are known. The specific capacity of wells in the Memphis area ranges from a few to more than 100 gpm per foot of drawdown for wells of all sizes and all types of construction. The specific capacity of an average 10-inch well in the "500-foot" sand is about 30 gpm per foot of drawdown.

In the area east of a southwest-trending line through Collierville, Tenn., and Olive Branch, Miss., the water level in the "500-foot" sand has declined below the top of the aquifer, and nonartesian conditions now prevail in that area. As pumping continues to increase, the artesian-nonartesian boundary will migrate toward Memphis, and, eventually, when the water level in Memphis has declined 300–400 feet below land surface, nonartesian conditions will encompass the entire area. When the present annual pumping rate is doubled, the boundary will have advanced to the present city limits of Memphis. If the current annual increase in pumping rate continues and if the present areal pumping pattern continues to develop, nonartesian conditions will reach the city limits of Memphis in about 30 years (1990). Variations in the future pumping pattern may hasten or delay the approach of nonartesian conditions in the "500-foot" sand. The present practice of wider well and well-field spacing will tend to preserve the artesian condition.

The impending loss of artesian head in the aquifer is not cause for alarm. On the contrary, water levels should fluctuate less and decline more slowly. Some water may be induced from the overlying terrace deposits and cause a change in the chemical quality of water, although probably not a significant amount. The amount of land subsidence resulting from dewatering of the aquifer will probably be immeasurably small unless the water level declines several hundred feet below the top of the aquifer. Nonartesian conditions will result in a relatively small additional cost of developing deeper wells and a slightly higher cost of pumping.

Development of wells in, and use of water from, the "500-foot" sand probably will continue so long as the quality of the water is satisfactory. The coefficient of transmissibility for the "1,400-foot" sand is about 1.2×10^5 gpd per ft, and for the "500-foot" sand about 4×10^5. The ratio is about 1 to 3, indicating that three times as much water may move through the "500-foot" sand. The hydraulic diffusivity, defined as the ratio of the coefficient of transmissibility to the coefficient of storage, for the "1,400-foot" sand is 4×10^8, and the "500-foot" sand it is 1.33×10^8. The ratio is 3 to 1, which indicates that the effect of any change in the rate of discharge travels three times farther in the "1,400-foot" sand. The estimated rate of movement of water under natural conditions, prior to development of the "1,400-foot" sand aquifer, was about 0.16 mgd for each 1-mile-wide section of the aquifer; for the "500-foot" sand, about 1 mgd. These values indicate that the ultimate capacity or economic yield of the "1,400-foot" sand is about 16 percent of that of the "500-foot" sand under similar conditions.

ADEQUACY OF THE AQUIFER ANALYSIS

Determinations of the rate of movement of water, the natural and artificial discharge, the indication and effect of recharge, and the hydraulic characteristics of the two principal aquifers in the Memphis area are results of the application of mathematical formulas to the data collected for these purposes. Geological and geophysical data collected during the investigation contributed to, and tended to verify, these results. The analyses are adequate for the current (1960) rate of pumping and location of well fields. Only the total amount of water involved and its rate of movement is expected to change significantly in the future. The hydraulic characteristics described in this report may be used to predict the results of these changes throughout the area except where the "500-foot" sand is no longer under artesian pressure. Tests will have to be conducted in areas where nonartesian conditions exist to determine the hydraulic characteristics of the aquifer. In such areas, however, pumping is expected to have a less pronounced effect on the water level than it has in the artesian part of the area.

In general the aquifer analysis as presented in this report is sufficiently adequate to predict with reasonable accuracy the future water-level changes for given rates of pumping, either greater or smaller than the present rate. The analysis also indicates that greater amounts of water may be pumped from both aquifers without impairing the water supply or seriously affecting the quality of water.

CONCLUSIONS

The two principal aquifers of the Memphis area are the "500-foot" and "1,400-foot" sands, from which practically all the water used in the area is pumped. The present (1960) rate of withdrawal is about 150 mgd, 135 mgd of which is pumped from the "500-foot" sand. Of the inflow to the area through the "500-foot" sand, excluding leakage from streams and adjacent aquifers, about 45 percent is from the east, about 20 percent is from the south, about 15 percent is from the north, and about 10 percent or less is from the west. The remaining 10 percent of the water derived annually from the "500-foot" sand comes from depletion of storage as a result of declining water level and from leakage from the overlying terrace deposits which, in turn, may be partly recharged by streams and by precipitation. Faults in the area may influence water movement and water levels by retarding the inflow of water from the west.

Pumping tests were made to determine the hydraulic characteristics of that section of the "500-foot" sand aquifer adjacent to the well screens. From the values obtained, the full thickness of the aquifer is estimated to have a coefficient of transmissibility of about 4×10^5 gpd per ft and a coefficient of storage of about 3×10^{-3}. The long-range effect on water levels in the area may be determined by using these coefficients for any given rate of pumping and computing the future drawdown. For example, if the present pumping rate from the "500-foot" sand remains constant, water levels will cease to decline within a few years. However, if the annual pumping rate from the "500-foot" sand continues to increase at the present rate of approximately 5 mgd per year, water levels will decline at about the same rate as at present unless future wells and well fields are located at greater distances from the present centers of pumping.

The water level in the "500-foot" sand in the southeastern part of the Memphis area has declined to a few feet below the top of the aquifer. The line marking the boundary between artesian and nonartesion conditions is slowly advancing toward Memphis, and, in about 30 years, nonartesian conditions may exist over the entire area. No detrimental effect can be forecast, though the quality of the water pumped may change slightly as water is induced from adjacent formations and streams. Water-level fluctuations and the overall decline in water levels probably will be less pronounced than at the present, although transmissibility will decrease as the aquifer is drained.

The "1,400-foot" sand, an almost ideal artesian aquifer, is a secondary aquifer because it is only about one fourth as thick as the "500-foot" sand and, therefore, can furnish only one fourth as much water or less. The coefficient of transmissibility in the "1,400-foot" sand is 1.2×10^5 gpd per ft, or about the same as that in the "500-foot" sand per unit of thickness. The storage coefficient is 3×10^{-4} indicating that less water is derived from storage per foot of water-level decline than is derived from the "500-foot" sand. The effect of pumping on the water level in this aquifer is also more pronounced at greater distances from the center of pumping than is the effect on the water level in the "500-foot" sand, primarily because of the greater artesian head in the "1,400-foot" sand.

The present (1960) rate of pumping from the "1,400-foot" sand in the Memphis area is about 13 mgd, and a total of about 120 billion gallons is estimated to have been withdrawn since the first wells were developed in 1924. The aquifer is primarily a standby source of water for the city of Memphis.

Part of this investigation was directed toward answering specific questions relating to water supply that might be asked by those charged with planning for an expanding community. Kazmann (1944, p. 17–18) expressed the problems of the Memphis area water supply in the form of nine questions. These questions require that the maximum amount of water that can be pumped safely from the aquifers be determined. That limit cannot be determined at present because the change from artesian to nonartesian conditions and the decentralization of pumping tends to increase the maximum safe amount of water that may be obtained in the area. Therefore, the answers to Kazmann's questions are qualified and reflect the status of knowledge of the area for the period ending with this investigation. The questions will continue to be the basis for a logical continuing investigation if supplemented by other pertinent questions which are listed in the final pages of this report.

1. What is the origin of the ground water obtained in the Memphis area?

At present about 90 percent of the water obtained from the "500-foot" sand originates as underground inflow into the area. Less than 1 percent of the water comes from depletion of the storage of the aquifer. The remainder, about 10 percent, is leakage from the overlying terrace deposits or from other sources of recharge in the area.

About 10 percent of the water obtained from the "1,400-foot" sand comes from depletion of the storage of the aquifer. The other 90 percent probably originates as inflow into the area.

2. Is more water being taken from the underground sources than nature puts back each year? If so, what is the excess of average withdrawal over input? If not, what is the ultimate safe yield of the water-bearing formations?

Presently, the answer is yes. More water is being taken from the aquifers than is being replaced each year because of the annual increase in pumping. However, if the annual pumping rate remained constant, equilibrium conditions would be reached within a few years, and the amount of recharge would equal discharge on an annual basis.

If each aquifer is considered as a unit ending at the boundary of the Memphis area and if a comparison is made of what is added to each of these units by inflow and any other processes with what has been taken out, then the difference is the amount of depletion of storage of each aquifer in the area. The average annual rate of depletion of storage of the "500-foot" sand in the area is less than 1 percent of the annual pumping rate, or about 1 mgd. Therefore, 99 percent of the water taken annually from the "500-foot" sand within the area is replaced by recharge.

Similarly, about 90 percent or more of the water that has been taken from the "1,400-foot" sand in the area has been replaced. Rising water levels in this aquifer indicate that recharge has been greater than discharge during the past 4 years.

3. Are the water-bearing formations continuous between the outcrops (if any) and the well fields?

The answer is yes. This continuity is shown by the influence of pumping from both the "500-foot" and the "1,400-foot" sands on the water levels in observation wells 30 miles northeast of Memphis (figs. 9, 17). Recharge to the aquifers resulting from above-normal rainfall in 1957 is also noted (figs. 9, 17) in both observation wells. These facts indicate that the two aquifers are hydraulically continuous between their outcrop areas and the well fields in the Memphis area. Continuity within the area is proven by geophysical logs.

4. How much water are the formations capable of transmitting each day?

Throughout their total thickness in the Memphis area, the "500-foot" sand has a coefficient of transmissibility of 4×10^5 gpd per ft, and the "1,400-foot" sand, about 1.2×10^5 gpd per ft. The amount of water the formations are capable of transmitting is indicated by these coefficients and by the hydraulic gradient in each aquifer in the area. The present steepest gradient outside the area of heavy pumping is about 10 feet per mile in the "500-foot" sand, and about 4 mgd is transmitted in each 1-mile-wide section of the aquifer along a north-south line in the vicinity of well Sh: Q–1 (pl. 2). The present steepest gradient is about 3 feet per mile in the "1,400-foot" sand, and about 0.36 mgd is transmitted in each 1-mile-wide section of the aquifer in the vicinity of the Sheahan well field (pl. 2). The extent to which these gradients can be increased is unknown, but it is certain that both aquifers can supply more water than is presently pumped from them.

5. Is the limit on water withdrawals set by the recharge to the formations or the transmissibility of the formations?

The limit on water withdrawal for a well field or for a small part of the Memphis area depends on the transmissibility of the aquifer and the geohydrologic conditions in the vicinity of the well field. For example, the presence of a local clay lens in the aquifer will lower the limit of withdrawal for a well field. Similar clay lenses may be so spaced in or near the outcrop area to prevent maximum recharge that would otherwise take place. The present annual pumping rate in the Memphis area is not great enough to determine which of the two factors limit the rate of withdrawal. If the rates of recharge under ultimate development of the aquifers are assumed to be the same as those prior to development, then the limit on withdrawal would be set by the recharge to the formations. However, perennial streams flowing across the sandy outcrop areas strongly suggests the possibility of large amounts of rejected recharge. The amount and maximum possible rate of recharge may be great enough that withdrawals may be limited by the transmissibilities of the formations. This limitation appears to be the most likely conclusion.

6. Are the chemical quality and temperature of ground water changing or are they constant within certain limits?

The water samples analyzed since 1927 show that the chemical quality of water from both aquifers varies little with time except for the hardness of "500-foot"-sand water which appears to be increasing in the north-central part of the area (fig. 19). The temperature of water in the "500-foot" sand ranges from 61° to 64° F depending on the depth of the well; the temperature of water in the "1,400-foot" sand ranges from 70° to 71° F.

7. What directions are the most promising for the establishment of new well fields and what is the most desirable well spacing?

The preferable direction for the establishment of new well fields in the "500-foot" sand is unknown, although the southeastern part of the area is indicated because the greater rate of inflow is from that direction. The hydraulic characteristics of the aquifer under nonartesian conditions, the hydrologic condition of the outcrop area, and the influence of geologic features in the area could alter the selection of preferable direction as pumping continues.

The question of well spacing is primarily a problem of economics relating to water production and transportation. Obviously, the greater distance between production wells causes less interference, but the cost of distributing the water on the land surface is greater. The drawdown in a well pumping 1,000 gpm from the "500-foot" sand is about 50 feet. If the allowable interference of another pumping well is 10 percent of its own drawdown and the wells are similar in construction and depth to presently used wells in the Memphis area, the well spacing should be 1,000 feet or more. If the wells are constructed using longer screens, a greater thickness of the aquifer would be effective, and closer well spacing would be allowable.

The preferable direction for the development of new well fields in the "1,400-foot" sand is roughly north and south of Memphis or perpendicular to the flow path of water moving downdip in the aquifer into the area. Well spacing, under requirements similar to those for the "500-foot" sand should be 1,000 feet or more.

8. What is the relationship between ground-water levels and quantities of water pumped in the area?

Water levels decline in the Memphis area as a result of increases in pumping. The water levels would cease to decline if the total annual pumping rate remained constant for a few years. Generally, for the "500-foot" sand, the decline in Memphis is about 1 foot for each 1-mgd increase in water production in Memphis. In observation wells about 30 miles northeast of Memphis, the water-level decline is less than 0.1 foot for each 1-mgd increase in water production in Memphis.

The water-level decline in the "1,400-foot" sand is at present as much as four times greater than that in the "500-foot" sand for each 1-mgd increase in water production.

9. How much water is being obtained from each water-bearing formation?

Approximately 1.9 trillion gallons of water was pumped from the "500-foot" sand from 1886 to 1960. Records of pumpage are accurate, and during the past several years more than half the daily pumpage in the area was metered and reported monthly to the U.S. Geological Survey. The 1960 rate of pumping was about 135 mgd. All the water pumped from the "1,400-foot" sand is metered also, and more than 95 percent of the daily pumpage is reported monthly. The total amount of water pumped from the "1,400-foot" sand from 1924 to 1960 was about 120 billion gallons. The 1960 rate of pumping was about 13 mgd.

Supplemental questions which need to be answered during the continuing investigation in order to promote further efficient management of the water supply in the Memphis area are:

1. What is the amount of recharge perennially available, and can the aquifers accept and transmit the total available recharge?
2. What are the steepest hydraulic gradients that can be established in the aquifers?

3. What are the hydraulic characteristics of the aquifers under impending nonartesian conditions, and will surface-water resources in the area be affected?
4. What are the effects of faults and similar structural controls on water production?
5. What are the interference effects, resulting from different heads or water levels in the aquifers, between aquifers?
6. What is the change in chemical quality of water as production from the aquifers continues? Is it significant, and is there a trend toward greater change?
7. Will streamflow be significantly affected as the effect of pumping in Memphis extends to the outcrop area of the two principal acquifers?
8. Should the shallower terrace deposits or alluvium be considered a major source of water, or are they being drained by leakage to the "500-foot" sand?
9. What are the legal and economic aspects of continued development?

There are no apparent reasons why development of wells in the two principal aquifers of the Memphis area should not continue, although the supply is not unlimited. Any evidence of overdevelopment would probably be noted during the continuing future investigation in sufficient time to prepare solutions to the problem or to recommend that alternate sources of supply be developed. The potential water production from the two aquifers is much greater than the present yield, and the possibility of overdevelopment of either aquifer in the immediate future is remote.

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INDEX

[Italic numbers indicate major references]

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