Predicted Hydrologic Effects of Pumping from the Lichterman Well Field in the Memphis Area, Tennessee

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1819-B

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

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By DALE J. NYMAN

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1965

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

**For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 50 cents (paper cover)**

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PREDICTED HYDROLOGIC EFFECTS OF PUMPING FROM THE LICHTERMAN WELL FIELD IN THE MEMPHIS AREA, TENNESSEE

By Dale J. Nyman

ABSTRACT

The Lichterman well field is scheduled to go into operation early in 1965 to supplement the municipal water-supply system for the city of Memphis, Tenn. Although the initial rate of withdrawal from the well field will be about 8 mgd (million gallons per day), the ultimate design capacity of the field is 20 mgd.

A study of sand samples, drillers' logs, and geophysical logs collected during preliminary test drilling at the site for the Lichterman well field was used as a basis for defining three zones of sand favorable for the construction of high-capacity (1,000 gallons per minute or more) water wells. The three zones occur in the "500-foot" sand and are here designated (in descending order) as zone A, zone B, and zone C. The depth to the top of these zones below land surface has the following ranges: zone A, 125 to 225 feet; zone B, 200 to 350 feet; and zone C, 700 to 775 feet. Zones A and B range from 0 to 100 feet in thickness, and zone C ranges from 10 to 100 feet in thickness. Within the well field proper these zones are expected to react to the stress of pumping as separate hydrologic units, but outside the well field the three zones are expected to react as a single hydrologic unit.

The "500-foot" sand in the Germantown-Collierville area is recharged chiefly by precipitation on the outcrop area of the sand to the east, but the evidence indicates that additional recharge is entering the aquifer from the Wolf River. In spite of this additional recharge, water levels in the "500-foot" sand are declining at an average rate of about two-thirds of a foot per year, owing to municipal and industrial pumpage in the Memphis area. However, this decline is not expected to alter the excellent quality of the water in the "500-foot" sand at the site of the Lichterman well field.

Pumping in the Lichterman well field will create a cone of depression in the free-water (piezometric) surface of the "500-foot" sand. The decline in water levels will be directly proportional to the rate of pumping and inversely proportional to the distance from the well field. The resultant changes in hydraulic gradients will alter the direction of ground-water movement in the vicinity of the well field and increase the rate of movement toward the well field from areas of recharge. The lowering of water levels might also accelerate locally the changeover from artesian conditions to semiartesian or water-table conditions in the "500-foot" sand.

Within the well field proper, water levels are expected to fluctuate as individual wells are turned on and off to accommodate the demand for water. The presence of clay beds in the aquifer will tend to limit the specific capacity of individual

production wells, but could serve to limit interference between wells if adjacent wells are screened in different sections of the aquifer. Interference between wells might also be lessened by pumping those wells having the highest specific capacities for the longest periods of time.

INTRODUCTION

The Lichterman pumping-station and well-field facilities are being constructed to supplement the municipal water-supply system for the city of Memphis, Tenn. The site chosen for this new facility is located south and east of Memphis in the Germantown-Collierville area of Shelby County. (See fig. 1). The well field is scheduled to be completed and placed in operation early in 1965, initially pumping about 8 mgd (million gallons per day) but with a maximum future capacity of about 20 mgd.

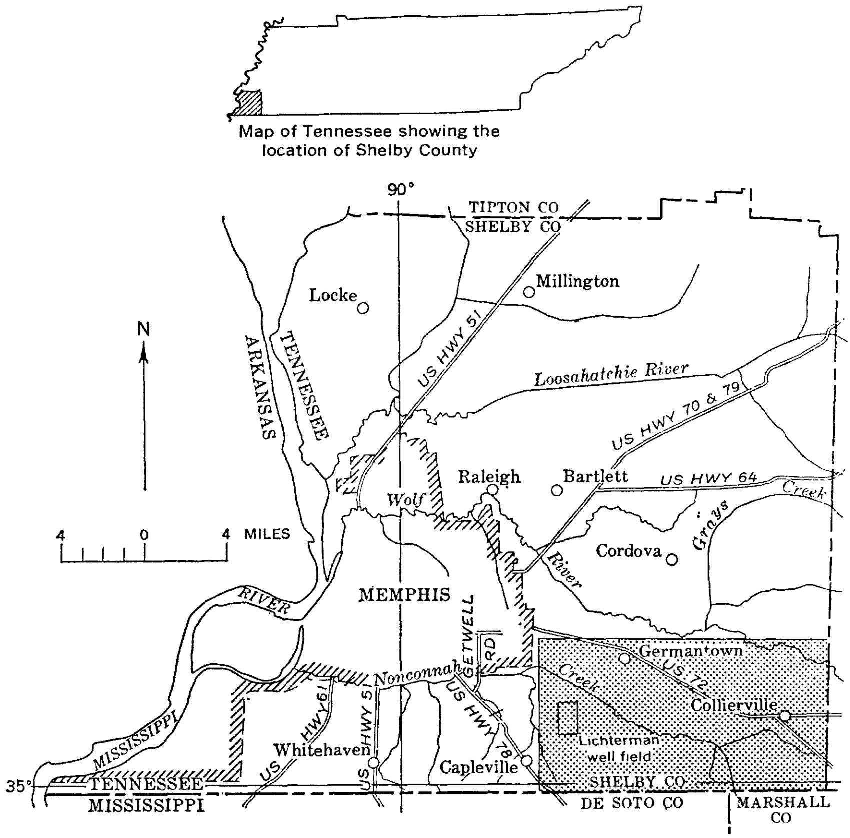

FIGURE 1.—Shelby County showing the location of Germantown-Collierville area (stippled) and the Lichterman well field.

The purpose of this report is to describe the probable effects on the hydrologic system of pumping 8 to 20 mgd from the Lichterman well field. The geologic setting of the new well-field site and the hydrologic features of the Germantown-Collierville area are described to provide a suitable background for the discussion of the local and regional hydrologic effects of pumping.

This report was prepared in cooperation with the Memphis Light, Gas, and Water Division. The author appreciates the assistance given him by Mr. J. J. Davis, Director of the Water Division; the late Mr. A. J. Rumley, Superintendent of Water Supply for the Water Division; and Mr. Hugh Mills, successor to Mr. Rumley. The author also thanks Messrs. E. C. Handorf and W. M. Craddock of the Memphis and Shelby County Health Department for information concerning the quality of water in Nonconnah Creek, and the City officials of Germantown and Collierville, who allowed tests to be made on their wells and for providing pumpage information. Special appreciation must go to all local well drillers and property owners who allowed their wells to be measured during the course of the study.

GEOLOGIC SETTING

Geologic units underlying the Germantown-Collierville area include two important aquifers (water-bearing formations): the "500-foot" sand and the "1,400-foot" sand (table 1). Wells in the Lichterman field will be developed in the "500-foot" sand, but the "1,400-foot" sand will serve as an auxiliary source that may be tapped if adequate production cannot be obtained from the shallower unit. Both of these aquifers and the regional geology have been described by Criner and others (1964). The geologic units underlying the Germantown-Collierville area are described below, from oldest to youngest, beginning with the lower of the two important aquifers, the "1,400-foot" sand.

"1,400-FOOT" SAND

The "1,400-foot" sand is an undeveloped but potentially important source of water in the Germantown-Collierville area. It lies at a depth of approximately 1,100 feet below land surface and ranges from 150 to 200 feet in thickness. Studies of sand samples collected during the drilling of test hole Sh:L-34 (pl. 1) show that the upper half of the "1,400-foot" sand consists mostly of fine sand and that the lower half is dominantly fine and medium sand. Elsewhere in the Memphis area the "1,400-foot" sand is primarily fine to medium or medium grained. The unit contains a minor amount of lignite and a few clay lenses.

TABLE 1.—*Geologic units underlying the Germantown-Collierville area*

System	Series	Group	Stratigraphic Unit	Thickness (ft)	Description and relation to water
Quaternary	Recent		Alluvium	0–100	Sand, clay, and gravel deposited on flood plains of rivers and creeks. Furnishes water to a few domestic wells.
	Pleistocene		Loess	0–20	Buff-colored silt; forms vertical bluffs where exposed. Not a source of ground water.
Quaternary and Tertiary(?)	Pleistocene and Pliocene(?)		Terrace deposits	0–80	Unsorted sand, clay, and gravel above the level of the flood plains. Supplies some domestic wells.
Tertiary	Eocene	Jackson (?) —?—?—?—	Capping clay (upper part may be equivalent to Jackson(?) Formation)	0–150	Gray, bluish-gray, brown, or tan clay; quartz silt and very fine sand along bedding planes. Unit generally becomes sandier where thinner, more clayey and impermeable where thicker. Unit, where present, confines the water in the "500-foot" sand.
		Claiborne undifferentiated	"500-foot" sand	500–700	Fine to coarse sand and minor amounts of lignite, light-colored clay, and silt. Contains discontinuous clay lenses as much as 50 feet thick. Lenses of coarse sand in the upper half of unit and locally at base. A prolific aquifer in the Germantown-Collierville area.
		Wilcox	Upper clay unit	200–350	Gray, greenish-gray, and brown carbonaceous clay. Locally lignitic and containing thin lenses of fine sand. The unit forms the aquiclude separating the "500-" and "1,400-foot" sands.
			"1,400-foot" sand	150–200	Fine to medium sand; minor amounts of lignite and a few clay lenses. A potentially important aquifer in the Germantown-Collierville area.
			Lower clay unit	190–220	Gray, greenish-gray, and brown carbonaceous clay; lignitic; becomes increasingly sandy upwards. Unit is the lower confining layer for the "1,400-foot" sand.

UPPER CLAY UNIT

Between the "1,400-foot" sand and the "500-foot" sand is an interval of gray to brown clay here referred to as the upper clay unit of the Wilcox Group. In places this clay contains thin lenses of fine sand and lignite. The upper clay unit ranges from 200 to 350 feet in thickness and serves as an effective hydrologic barrier between the two aquifers.

"500-FOOT" SAND

The "500-foot" sand of the Claiborne Group was subdivided by Criner and Armstrong (1958, p. 7, 8) into lower and upper units. The lower unit is composed mostly of beds of fine and some medium sand that has thick clay beds in western Shelby County. A basal coarse sand occurs locally. In contrast, the upper unit contains extensive strata of coarse sand which are very permeable and hence very favorable for supplying water to wells. For this reason, wells have been developed in the upper unit almost to the total exclusion of the lower unit. A study of drill cuttings, drillers' logs, and geophysical logs collected during preliminary test drilling at the site for the Lichterman well field has revealed the presence of three zones of coarse sand within the "500-foot" sand that are very favorable for the construction of high capacity (1,000 gallons per minute or more) water wells. These three zones are herein designated (in descending order) zone A, zone B, and zone C. This designation is only for the purpose of describing the subsurface geology of the Lichterman well field and is not intended to suggest a reclassification, or formal subdivision, of the "500-foot" sand.

The spatial relations of zones A, B, and C beneath the Lichterman well field are illustrated on plate 1. The depths to the tops of these zones below land surface have the following ranges: zone A, 125 to 225 feet; zone B, 200 to 350 feet; and zone C, 700 to 775 feet. Zones A and B are in the upper part of the "500-foot" sand, but are not persistent throughout the well field. Instead, these zones are as much as 100 feet thick in some parts of the well field and absent in other parts. Zone C is in the lower part of the "500-foot" sand and is apparently continuous throughout the well field. It ranges from 10 to 100 feet in thickness, reaching its maximum thickness in the southern part of the well field. Zone C is believed to be correlative with the basal coarse sand of the lower part of the Claiborne as described by Criner and Armstrong (1958).

Zones B and C are separated by a thick section of fine to medium sand near the middle of which is a bed of sandy clay from 10 to 25 feet thick. Although this bed of sandy clay is continuous throughout the western half of the well field, it is discontinuous in the eastern half of the well field.

CAPPING CLAY

The water in the "500-foot" sand is confined above by a capping clay which is termed the Jackson(?) Formation in the literature. Besides confining the water in the "500-foot" sand, the capping clay also retards direct vertical recharge to the aquifer. The capping clay is dark-colored and carbonaceous or sandy; it contains very thin beds of quartz silt and very fine sand. The dominant mineral in the capping clay is montmorillonite (F. H. Kellog, Memphis State Univ., written commun.), a mineral that shrinks in volume with loss of water. The compaction of similar clay units as water levels decline and the water in the clay units seeps into adjacent aquifers has resulted in land subsidence in some parts of the United States. However, land subsidence has not been detected in the Memphis area even though water levels have declined considerably since pumping began.

TERRACE DEPOSITS

Overlying the capping clay are terrace deposits that are continuous throughout the report area except where they have been removed by rivers and creeks. These deposits are mainly a mixture of reddish coarse quartz sand, silt, and clay containing variable amounts of quartz and chert gravel. The abundance of silt and the local presence of clay lenses in the terrace deposits reduce the overall permeability of the deposits. Moreover, the terrace deposits usually extend only a few feet below the water table. The resulting thin zone of saturation in the deposits is sufficient to provide only enough water for domestic use.

LOESS

The loess (windblown sediments) overlying the terrace deposits is composed mostly of silt and clay and thus has an extremely low permeability. The loess cap is nearly continuous and promotes runoff; very little precipitation can sink in to recharge the underlying terrace deposits.

ALLUVIUM

Alluvium underlies the flood plains of the rivers and creeks, its depth and width varying in relation to the size of the surface stream. The alluvial deposits are composed of gravel, sand, and clay transported and deposited by the streams. In general, the median grain size of the alluvium increases with depth. For example, extensive shallow test drilling along the Wolf River in the Germantown-Collierville area by the Corps of Engineers indicates that the upper 10 to 20 feet of the alluvium consists of sandy clay which grades into a lower stratum of fine or medium sand. In places, the base of the alluvium rests directly upon the "500-foot" sand. Where this relation occurs, water can move freely from one unit to the other.

HYDROLOGY OF THE GERMANTOWN-COLLIERVILLE AREA

The water in the "500-foot" sand in the Germantown-Collierville area is under artesian pressure wherever the capping clay is present. In those capped areas, water from the "500-foot" sand will rise in a well above the base of the capping clay. However, even where the capping clay is not present, the aquifer may show artesian characteristics if the upper part of the aquifer is less permeable than the lower part. As stated by Poole (1961, p. 25, 26), "* * * less permeable material making up the top part of the aquifer may act temporarily as a confining layer owing to its lower capacity to transmit water. During long periods of pumping, however, the upper material would be drained, the confining effect thus being dissipated, and the aquifer would function under water-table conditions. Such hydrologic conditions may be classified as 'semiartesian,' since they reflect characteristics which are common to both artesian and water-table aquifers."

Thus, in the outcrop area of the "500-foot" sand and at places where the capping clay is breached, water in the "500-foot" sand occurs either under water-table (unconfined) or semiartesian conditions. Elsewhere in the Germantown-Collierville area the water in the "500-foot" sand occurs under artesian conditions.

RECHARGE AND DISCHARGE

Under natural conditions, ground water moves through an aquifer from areas of recharge where water levels are high in relation to areas of discharge where water levels are lower. The rate of movement is very slow, seldom exceeding a few feet per day, and is governed by the permeability and the porosity of the aquifer materials and by the hydraulic gradient, or slope, of the water table or piezometric surface.

Recharge (the addition of water) to the "500-foot" sand in the Germantown-Collierville area is accomplished principally by the infiltration of rainfall either into the aquifer in the outcrop area or into the terrace deposits and thence into the aquifer where the latter is overlain solely by the relatively permeable terrace deposits. The aquifer might also be recharged by seepage from other aquifers such as the "1,400-foot" sand or the alluvium wherever local hydraulic gradients favor such movement. Discharge (the subtraction of water) from the "500-foot" sand is accomplished by pumping from wells, by seepage into the streams, and by movement into adjacent aquifers. A minor amount of water is discharged from the "500-foot" sand in the outcrop area by evaporation from the soil and by transpiration through the leaves of plants.

The capping clay which confines the water in the "500-foot" sand has apparently been breached in the Germantown-Collierville area along the Wolf River and possibly along the Nonconnah Creek. Three test holes augered along the Wolf River gave proof of the absence of the capping clay there. No similar evidence is known that the capping clay is breached along the Nonconnah Creek, but the possibility of a breach in the clay is indicated by the thinning of the capping clay and the thickening of a sand unit within the capping clay northward from the Lichterman well field toward Nonconnah Creek. Hence, the possibility exists that the sand provides a hydraulic connection between the "500-foot" sand and Nonconnah Creek.

Further evidence of a possible hydraulic connection between the aquifer and Nonconnah Creek is offered by anomalous flow measurements obtained along certain reaches of Nonconnah Creek. Interpretation of a series of discharge measurements that were made of Nonconnah Creek upstream from the Getwell Road bridge (fig. 1) on October 24, 1962, suggested that 0.1 cfs (cubic feet per second) must have been diverted to underflow within 1½ miles of the bridge. Moreover, during the fall months of the past several years, the channel of Nonconnah Creek in the vicinity of this bridge has been observed to be completely dry, although still farther upstream and downstream from the bridge the channel had some flow. Such a loss of stream flow could indicate seepage from Nonconnah Creek into the "500-foot" sand.

DECLINE OF WATER LEVELS CAUSED BY PUMPING IN THE MEMPHIS AREA

Water levels in the Germantown-Collierville area show a declining trend attributable to the increasing demands for ground water in Memphis. The influence of pumping in the Memphis area is evident from the hydrographs of wells Sh: L–1, Sh: L–10, and Sh: L–5 (fig. 2). Observation well Sh: L–1 in the Lichterman well field has the longest water-level record in the Germantown-Collierville area. Over the period of record, the water level in this well declined about 14 feet from 1941 to 1962, an average of two-thirds foot per year. During the wet years from 1948 to 1951, recharge from rainfall in the outcrop area of the "500-foot" sand nearly balanced pumpage because less water was pumped. The arresting of the downward trend of the water level during 1958 and 1959, probably due to the heavy rainfall of 1957, incidates that a reserve of ground water had been built up in the outcrop area. Persistent declines of water level in other years correspond with increased rates of pumping in the Memphis area. The hydrographs of Sh: L–10 and Sh: L–15 show similar downward trends of water level during the period of record.

CHEMICAL QUALITY OF GROUND WATER

The quality of ground water is determined by its ability to dissolve minerals, the character and abundance of the minerals in the physical environment, such as an aquifer through which the water moves, and how long the water remains in contact with its physical environment. The aquifers of the Germantown-Collierville area are composed chiefly of fairly insoluble quartz sand; therefore, water in these aquifers should be only slightly mineralized.

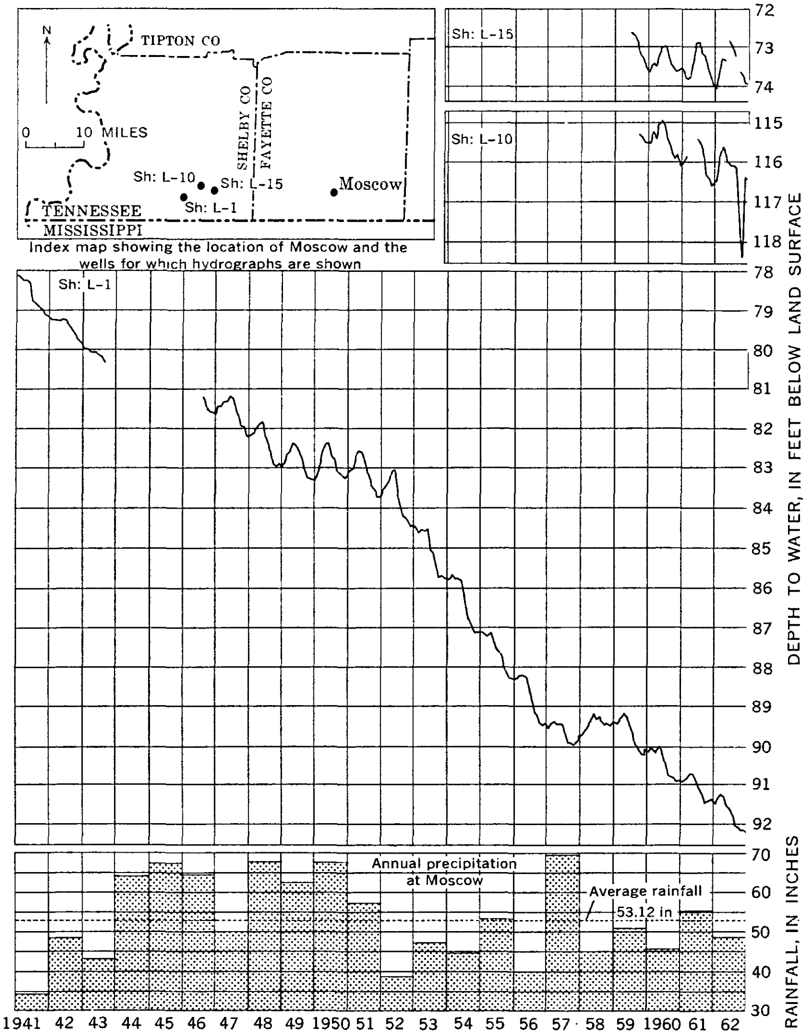

FIGURE 2.—Hydrographs of wells Sh: L-1, Sh: L-10, and Sh: L-15 and annual precipitation at Moscow.

Analyses of water samples collected from wells screened in the "500-foot" sand show that the water flowing toward the Lichterman well field is of low mineral content and for the most part more than meets the current standards set for drinking water (Bean, 1962, p. 1316; U.S. Public Health Service, 1962). The locations of wells from which seven water samples were taken are shown on figure 3. The bar diagrams beside the well numbers indicate the concentrations of several chemical constituents. Table 2 lists the concentrations of all major ions and the physical properties of the water in these same seven samples. The analyses and bar digrams indicate that the water from all these wells is of similar quality, with the exception of well Sh: E-2; the sample from this well contained twice as much dissolved solids as the mean of the other six samples. All the samples were mildly acid at the time of analysis.

The good quality of the water pumped in the Germantown-Collierville area results from the fact that the water has traveled only a short distance from the outcrop (recharge) area and has thus been in contact with the formation only a short time. Because the movement of the ground water is primarily westward, the quality of water pumped at the Lichterman well field in future years should be similar to the quality of the water that is now present in that part of the area east of the well field.

TABLE 2.—*Summary of chemical analyses of water from selected wells in the Germantown-Collierville area*

[Results in parts per million except temperature, specific conductance, and pH]

Constituent or property	Well (date collected)						
	E-2 (8-17-62)	L-8 (9-4-62)	L-13 (8-16-62)	L-40 (8-16-62)	L-42 (7-27-62)	M-2 (7-27-62)	M-15 (3-16-60)
Temperature (°F)	63	63	62.5	63	64	63	62
Silica (SiO_2)	7.8	7.8	11	17	9.8	8.8	8.9
Iron (Fe)	.16	.02	.06	.19	.06	.02	.00
Calcium (Ca)	8.6	4.1	3.5	5.1	4.8	4.3	3.2
Magnesium (Mg)	4.2	2.6	2.6	1.9	2.4	.7	1.2
Sodium (Na)	16	6.0	7.9	7.7	9.0	6.9	8.1
Potassium (K)	1.0	.8	.7	.6	.9	.6	.6
Bicarbonate (HCO_3)	39	33	38	36	32	20	23
Carbonate (CO_3)	0	0	0	0	0	0	0
Sulfate (SO_4)	6.8	2.0	1.6	3.1	7.6	3.6	4.4
Chloride (Cl)	22	3.5	4.0	4.0	6.5	5.5	6.0
Fluoride (F)	.0	.0	.0	.2	.0	.0	.0
Nitrate (NO_3)	4.0	.8	.7	.0	1.1	2.3	1.6
Dissolved solids (calculated)	90	44	51	58	58	42	45
Dissolved Solids (residue on evaporation at 80°C)	95	47	55	54	61	38	44
Hardness as $CaCO_3$	38	20	19	21	22	14	13
Hardness as noncarbonate	6	0	0	0	0	0	0
Specific conductance (micromhos at 25°C)	151	63	69	76.9	83	59	62
pH	6.2	6.4	6.2	6.4	6.2	6.1	6.1
Color	0	0	0	0	0	0	0

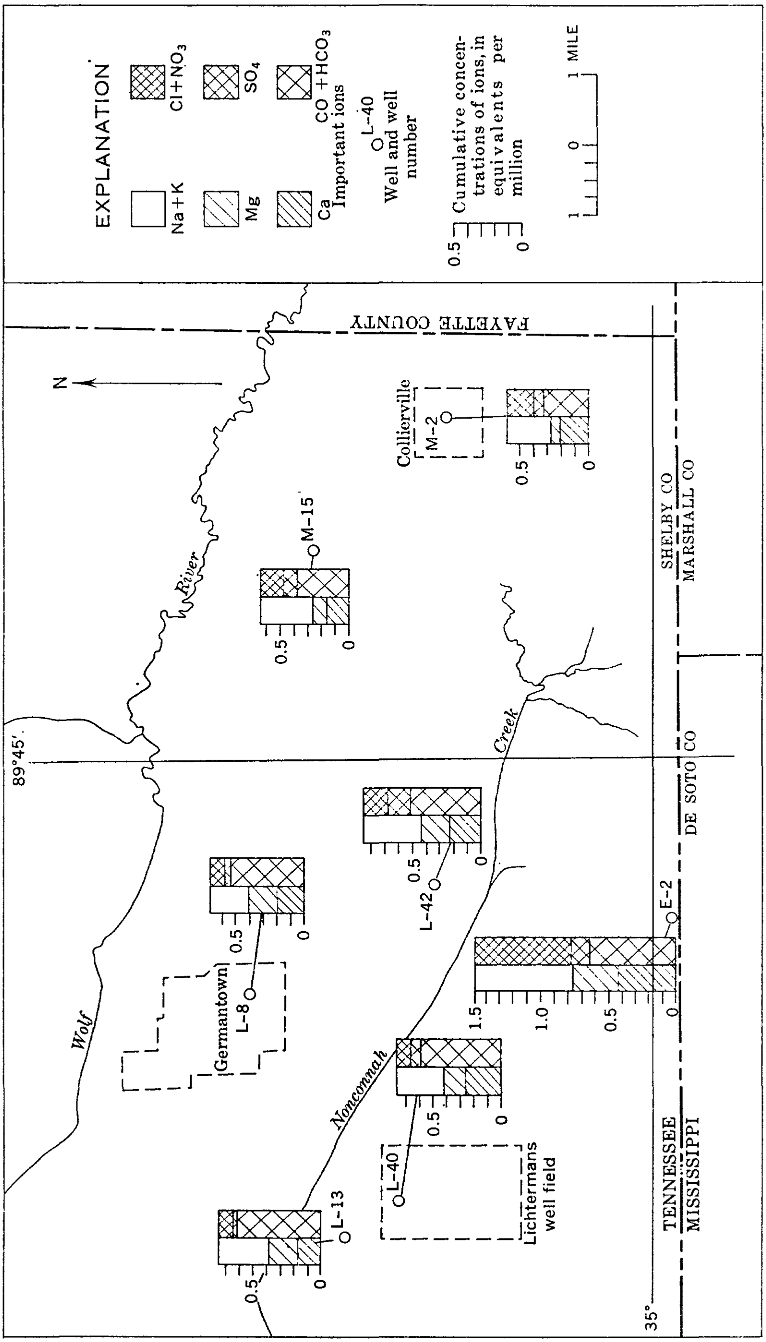

FIGURE 3.—Graphic presentation of the general chemical quality of samples of water in the Germantown-Collierville area.

THE HYDROLOGIC EFFECTS OF PUMPING IN THE LICHTERMAN WELL FIELD

Pumping in the Lichterman well field will, of necessity, create a cone of depression in the free-water (piezometric) surface of the "500-foot" sand. This cone, in itself, is not a cause for concern because, to withdraw water from the aquifer, gradients must be established that will induce water to move toward the well field from surrounding parts of the aquifer. It follows that the cone of depression will progressively deepen until enough water is diverted toward the well field from areas of recharge or natural discharge to balance the rate of withdrawal. When this balance occurs, water levels in the producing aquifer will tend to remain steady and a state of equilibrium can be said to exist. Should the pumping rate be changed either before or after equilibrium conditions are reached, water levels will tend to change accordingly, reflecting the adjustment of the cone of depression to the new pumping rate.

If the total production of the Lichterman well field is held relatively constant the resultant cone of depression would form and equilibrium conditions would for all practical purposes of this analysis be reached within the first few hundred days of pumping. Thereafter, the depth of the cone could be expected to increase or decrease in direct proportion to changes in pumpage. The problem of determining the effects of pumping in the Lichterman well field would then become one of calculating the ultimate drawdown or change of water level that would result from the anticipated rates of pumping. For the purposes of this report, it would suffice to calculate the ultimate drawdown to be caused by the initial rate of pumping from the Lichterman well field (8 mgd) and the maximum rate (20 mgd). This procedure would provide two values representing the minimum and maximum drawdown caused by pumping in the Lichterman well field.

Although total production from the Lichterman well field is expected to be maintained at a fairly constant level, the rate of pumping from individual wells within the well field will change radically from day to day as one group of wells is turned on and another group is turned off. Such shifts in the pumping regimen will cause water levels in parts of the well field to rise and in other parts of the field to fall. These opposing fluctuations of water level, however, tend to so counterbalance each other that beyond a radius of a few thousand feet from the well field proper the net effect of wells being turned on and off will be negligible.

Thus, the cone of depression to be created by pumping in the Lichterman well field can be expected to form rapidly, and, except for the central or apex section of the cone, reach a fairly stable position indicating the establishment of near equilibrium conditions. In ensuing sections of this report, conditions in the outermost, or stable, part of the cone will be used to interpret the regional effects of pumping. These sections are followed by a discussion of some of the effects to be noted in the unstable, or apex, section of the cone.

REGIONAL EFFECTS

The ultimate drawdown or decline of water levels to be caused by pumping in the Lichterman well field will depend on the rate of withdrawal and, for any given rate of withdrawal, will decrease with distance from the center of withdrawal. The Thiem formula (Wenzel, 1936, p. 23) provides a convenient method for calculating the ultimate or steady-state drawdown caused by pumping. This formula is applicable only after pumping has continued long enough for equilibrium conditions to have been established, and is based on the assumptions that the pumped aquifer is (1) homogeneous, isotropic, and uniform in thickness, and (2) the piezometric surface is horizontal before pumping is started. If the pumped aquifer system diverges from these assumptions, the results obtained from the Thiem formula will be in error to the degree that these assumptions are not met.

Although the aquifer system represented by the "500-foot" sand at the Lichterman well field does not fully meet all the assumptions, the divergence of the system from the assumptions is not so great as to preclude the use of the Thiem formula. The first assumption is very nearly met if it is considered that the flow through the aquifer diverges from these assumptions, the results obtained from the Thiem formula is to be applied. The second assumption is likewise nearly met even though the general level of the piezometric surface of the "500-foot" sand slopes gradually from east to west and is dimpled by several other cones of depression (fig. 6). The existence of a nearly horizontal slope is borne out by the fact that throughout the Memphis area, local gradients rarely, if ever, exceed a slope of ½ of one percent.

The Thiem formula may be expressed as follows:

$$s_1 - s_2 = \frac{528\, Q \log \frac{r_2}{r_1}}{T}$$

in which

s_1 and s_2 = drawdown at two observation wells, in feet;
Q = rate of pumping, in gallons per minute;
r_1 and r_2 = distances to the two observation wells from the center of pumping, in feet;
T = coefficient of transmissibility of the aquifer, in gallons per day per foot.

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The Thiem formula can be further modified by assuming that r_2 represents the distance from the center of pumping to the outer limit of the cone of depression where drawdown (s_2) would be negligible. By substitution, the Thiem formula can be written:

$$s_1 - 0 = s_1 = \frac{528\ Q \log r_2/r_1}{T}$$

in which s_1 represents the drawdown caused by pumping at a distance r_1 from the center of pumping.

DECLINE OF WATER LEVELS

To calculate the drawdown (s_1) at any given distance (r_1) from the Lichterman well field using the Thiem formula, values must be assigned for the other variables; Q, T, and r_2. The rate of pumping (Q) from the Lichterman well field is expected to start at about 8 mgd or approximately 6000 gpm (gallons per minute), and may eventually increase to 20 mgd (14,000 gpm). The regional coefficient of transmissibility (T) of the "500-foot" sand as determined by J. H. Criner (U.S. Geol. Survey, written commun.) is 200,000 gpd per ft. (gallons per day per foot). The distance (r_2) from the center of pumping to the outer limits of the cone of depression is not definitely known, but can be estimated with sufficient accuracy for the purpose of this report. Moore (1965, p. 39) identified the extent of drawdown due to pumping in the Memphis area as ranging from 15 to 40 miles from the center of pumping. Hence, an estimate of 20 miles is considered reasonable for the probable extent of the cone of depression to be formed around the Lichterman well field. Even if this estimate is greatly in error, it would not introduce a serious error in the results obtained from the Thiem formula because the term r_1 is used merely to compute the log of a ratio (r_2/r_1) the value of which changes only slightly with the numerator, r_2. For example, if the estimate of r_2 is in error by 100 percent, the log of the ratio and, hence, the results obtained would be in error by only 30 percent.

By substituting the values just mentioned for the appropriate variables in the Thiem formula, the ultimate drawdown for any given pumping rate can be calculated for any distance from the Lichterman well field. The solution to the Thiem formula for pumping rates of 6000 gpm (8.5 mgd) and 14,000 gpm (20 mgd) is shown in figure 4, a theoretical plot of drawdown versus distances ranging from 3000 to 70,000 feet (13 miles). The distance from the Lichterman well field to the other four large municipal well fields in the Memphis area are marked on the graph to indicate the probable decline in water levels in those fields as a result of pumping in the Lichterman well field. These drawdowns are summarized as follows:

Well field	Drawdown, in feet, at pumping rates of— 6,000 gpm	14,000 gpm
Parkway	2	6
Allen	4	9
McCord	4	10
Sheahan	8	18

Thus, pumping in the Lichterman well field will increase the lift required to pump water at each of the existing pumping centers by the amounts indicated. Increasing the lift, in turn, will increase slightly the rate of power consumption and, hence, the cost of pumping the same quantities of water.

CHANGES IN DIRECTION OF GROUND-WATER MOVEMENT

The dashed flow lines on figure 5, a contour map of the piezometric surface of the "500-foot" sand, indicate that ground water is presently flowing in a general northwesterly direction across the Germantown-Collierville area. This general pattern of ground-water flow is chiefly the result of pumping in the Memphis area. Northwest of the Germantown-Collierville area the flow lines tend to converge toward established centers including those of the Memphis water-supply system. The flow lines do not imply definite quantities of water.

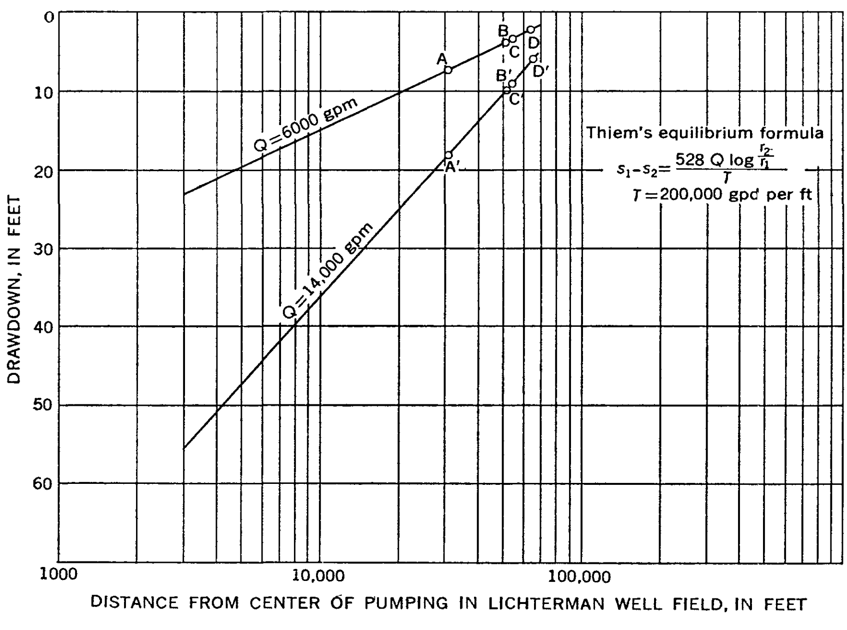

FIGURE 4.—Relation of theoretical drawdown to horizontal distance from the Lichterman field. A′–D′ represents the drawdown caused by pumping Lichterman at 14,000 gpm; A′ representing the drawdown at Sheahan, B′ at McCord, C′ at Allen, and D′ at Parkway.

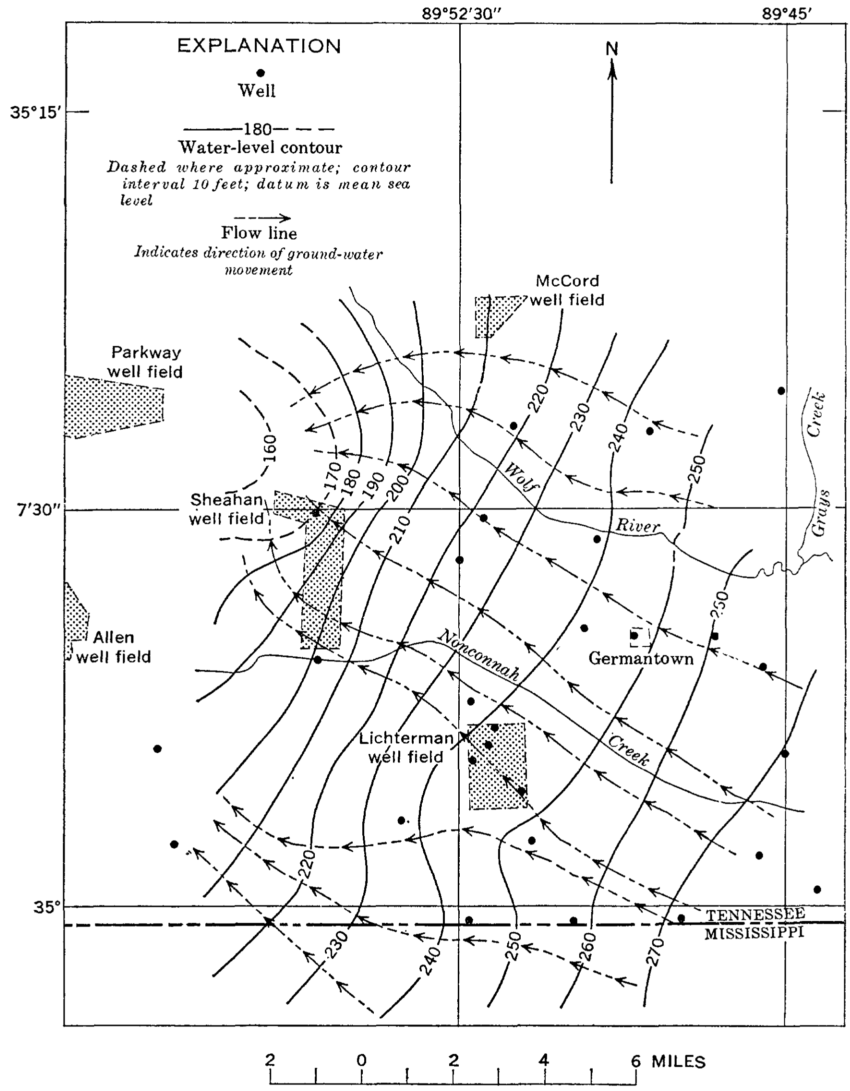

Figure 5.—Water levels and flow lines in the vicinity of the Lichterman well field during August 1962.

Figure 6 shows the probable position of the water-level contours and flow lines after pumping in the Lichterman well field at a rate of 8.5 mgd has been in progress long enough for equilibrium conditions to be established. Because the amount of water pumped in the Lichterman field will be small in comparison with the total pumpage of the Memphis area, the regional pattern of ground-water flow will not change much. Most of the ground water will continue to flow northwestward. However, pumping in the Lichterman field will divert some of the water that otherwise would flow into other nearby pumping centers as indicated by the flow lines converging at the well field (fig. 6).

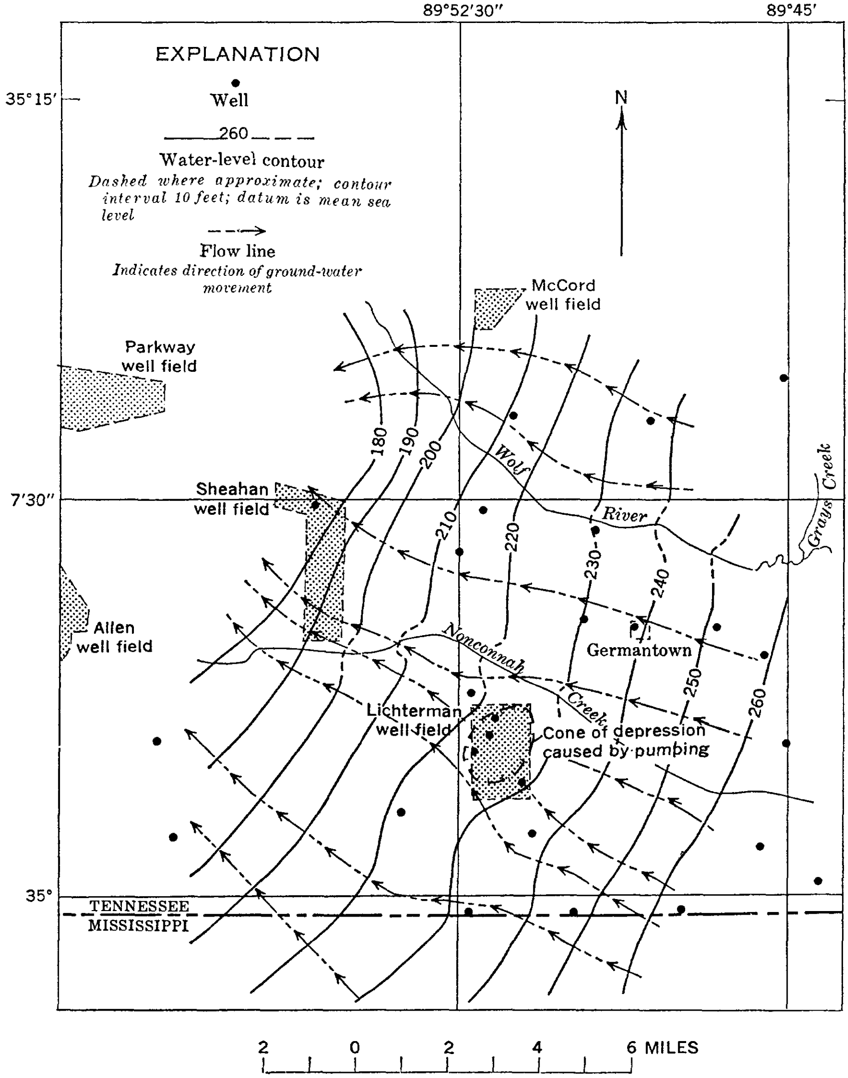

FIGURE 6.—Water levels and flow lines after pumping in the Lichterman well field at a rate of 8.5 mgd.

INDUCED RECHARGE FROM NEARBY STREAMS

At places in the Wolf River flood plain between Germantown and Collierville where the capping clay is absent and the alluvium immediately overlies the "500-foot" sand, interchange of water takes place between the aquifer and the stream. Where the piezometric surface drops below the river level between the 240- and 260-foot contours (fig. 5), a gradient is created from the river toward the "500-foot" sand. East of the 260-foot contour, however, water is flowing from the aquifer into the stream.

Pumping in the nearby Lichterman well field might hasten the eastward migration of the 260-foot contour line by increasing the drawdown along the Wolf River north of Collierville. The drawdown would also increase the flow of water from the river to the aquifer. However, it is expected that the amount of recharge to the "500-foot" sand from the Wolf River will always be small compared to that from other sources of recharge. Nevertheless, where the capping clay has been breached by stream erosion, such as in the Wolf River flood plain, the water-level contours will be distorted (figs. 5, 6) and the expected drawdown will be less than that predicted from the Thiem formula.

CHANGE FROM ARTESIAN TO WATER-TABLE CONDITIONS

As water levels are progressively lowered by the expanding cone of depression, the formation of this cone will be influenced locally by a change from artesian to semiartesian or water-table conditions. This change will occur wherever the water level in the "500-foot" sand is lowered below the base of the capping clay. The base of the capping clay, however, is not a uniformly flat or sloping plane, but rather it is an undulating surface that is anomalously higher at some places than at others. Consequently, the change of conditions will not take place everywhere in the area at the same time; it will occur first where the base of the clay is highest and water levels are lowest. The change to semiartesian or water-table conditions might appear to be desirable from the standpoint that there will be a decrease in the rate of water-level decline wherever the changeover occurs. However, as the pumping continues or increases, the continued decline of the water levels will decrease the vertical thickness of saturated materials comprising the aquifer. The decrease in saturated thickness will reduce the capacity of the aquifer to transmit water. Consequently, should the changeover occur in the Lichterman well field proper, there will be a gradual reduction in the specific capacities of the wells. Although the specific capacities of the wells will be reduced very slowly, in time the net effect will be a significant reduction in the overall capacity of the well field. In order to maintain the specific capacities of the wells, the capacity of the aquifer to transmit water should not be reduced. This reduction can be avoided by setting the pump intakes not lower than a few feet above the base of the clay capping the section of the aquifer screened by each production well.

LOCAL EFFECTS

Within the Lichterman well field proper, water levels are expected to be in a constant state of flux owing to the probable day-to-day changes in pumping schedules. Hence, without advance knowledge of exact pumping schedules and rates, it is impossible to predict with any degree of accuracy the total amount of drawdown at any point within, or close to, the well field. Nevertheless, an understanding of how the pumping schedules and rates of individual wells in the well field might affect the amount of drawdown to be incurred by pumping should prove helpful to the well-field operator by enabling him to select pumping schedules and rates that will tend to minimize the total drawdown in the well field. Toward this end, the following discussion is concerned with the effects of pumping a single well and the effects of interference between wells.

EFFECT OF PUMPING A SINGLE WELL

The potential production of individual wells in the Lichterman well field is proportional to the transmissibility of the zones of sand in which the wells are screened. In the immediate area of the well field, lenses of clay or sandy clay from a foot to a few tens of feet in thickness subdivide the aquifer and control ground-water movement. The aquifer is about 700 feet thick, but if the aquifer is subdivided by clay, a well screened in one or more of the sand intervals would initially draw nearly all of its water from the interval or intervals opposite the well screen. Moreover, drawdown in the well would be dependent upon the transmissibility of the intervals of sand opposite the well screen. However, if the well were pumped continuously for many days or weeks, the transmissibility of the aquifer as a whole would tend to have more and more effect on the flow of water to the well.

The coefficient of transmissibility of the "500-foot" sand ranges from 100,000 gpd per ft to 410,000 gpd per ft (Criner and others, 1964, p. 30). In the Lichterman well field area, however, the "500-foot" sand is believed (J. H. Criner, U.S. Geol. Survey, written commun.) to have a transmissibility of 200,000 gpd per ft. Theoretically, the specific capacity (the yield of the well per foot of drawdown) of a well screened in an aquifer with a transmissibility of 200,000 gpd per ft should be about 80 gpm per ft of drawdown after one day of pumping, but this value is at least three times larger than the highest specific capacities determined from tests on actual wells in the well field. The discrepancy between theoretical and actual specific capacities is attributed to the fact that the coefficient of transmissibility of the part of the aquifer screened by individual wells is considerably less than the transmissibility of the entire aquifer. Following is a description of a method that can be used to estimate the transmissibility of a section of the aquifer to be screened by a proposed well from which a fairly accurate prediction of specific capacity can be made.

Transmissibility is the product of the coefficient of permeability and the thickness in feet of the water-bearing material. The coefficient of transmissibility of the aquifer as a whole can be approximated by adding the estimated transmissibilities of the individual beds making up the aquifer. The thickness and generalized texture of each bed can be obtained from the fence diagram (pl. 1). Approximate permeabilities of individual beds can be obtained by comparing their textures with those of sand samples whose permeabilities have been determined in the laboratory. Laboratory permeabilities determined for various sand samples collected from wells owned by the Memphis Light, Gas, and Water Division, as well as samples from well site Sh: L–1 in the Lichterman well field, are given in the following table:

Average values for the coefficient of permeability for grades of sand in the Memphis area

Grade	Permeability in gpd per sq ft
Dominantly coarse sand	850
Dominantly medium sand	600
Dominantly fine sand	300
Dominantly fine sand and clay	200

Even though field conditions cannot be duplicated in the laboratory, these values are considered to approximate those for sand in place. Table 3 illustrates how the transmissibility of the "500-foot" sand at well site Sh: L–38 may be approximated by estimating and totaling the transmissibilities of the individual beds.

The specific capacity of a well screened in any part of the aquifer can be predicted by using data in table 3. For example, assume that a 12-inch well is to be screened opposite the interval from 215 to 295 feet. The effective transmissibility for such a well is computed by totaling the estimated transmissibilities of each of the permeable beds in the screened interval. In this example, the effective transmissibility is 59,500 (17,000+42,500) gpd per ft. Using this value for transmissibility, the theoretical specific capacity of the well can be determined by applying a modification of the Theis nonequilibrium

TABLE 3.—*Estimated transmissibilities of individual beds in the "500-foot" sand at well Sh: L–38*

Depth (ft)	Description	Estimated permeability [1] (gpd per ft^2)	Thickness of interval (ft)	Estimated transmissibility (gpd per ft)
75–140	Medium sand	600	65	39,000
140–170	Coarse sand	850	30	25,500
170–215	Clay	0	45	0
215–235	Coarse sand	850	20	17,000
235–245	Clay	0	10	0
245–295	Coarse sand	850	50	42,500
295–305	Clay	0	10	0
305–365	Medium sand	600	60	36,000
365–380	Clay	0	15	0
380–420	Fine sand	300	40	12,000
420–465	Medium sand	600	45	27,000
465–485	Clay	0	20	0
485–520	Fine sand	300	35	10,500
520–705	Medium sand	600	185	111,000
705–715	Coarse sand	850	10	8,500
715–725	Medium sand	600	10	6,000
725–785	Coarse sand	850	60	51,000
785–795	Medium sand	600	10	6,000
795	Clay	0		0
Total			720	400,000

[1] Based on preceding table.

formula. According to Cooper and Jacob (1946) the Theis formula for computing the drawdown in a pumped well can be written:

$$s_w=\frac{264Q}{T}\log\frac{0.3Tt}{r_w^2S}$$

Rearranging the terms in a form suitable for direct solution of the theoretical specific capacity, the equation becomes:

$$Q/s_w=\frac{1}{\frac{264}{T}\log\frac{0.3Tt}{r_w^2S}}$$

in which

Q/s_w=theoretical specific capacity of a 100-percent efficient well, in gallons per minute per foot of drawdown;
T=coefficient of transmissibility, in gallons per day per foot;
t=time, in days, since pumping began;
r_w=effective radius of the pumped well, in feet;
S=coefficient of storage, a dimensionless ratio of the volume of water taken into or released from storage per unit surface area of the aquifer per unit change in the component of head normal to that surface.

If the aquifer is artesian, a value of 0.001 can be estimated for the coefficient of storage (S). Moreover, if the well is 100 percent efficient, the effective radius of the well is equal to the actual radius of the well (0.5 ft). Thus, after one day of pumping:

$$Q/s_w = \frac{1}{\frac{264}{59{,}500} \log \frac{58{,}500 \times 1}{(0.5)^2 \times 0.001}}$$

$$= \frac{1}{0.037} = 27 \text{ gpm per foot.}$$

If a well is screened opposite only a part of one or more permeable beds in the aquifer, the theoretical specific capacity of the well as calculated in the previous example would need to be corrected for partial penetration. The procedure for making this correction is described by Turcan (1964, p. E147). The formula is:

$$\frac{Q_0}{s_w} = \frac{Q}{s_w}\left[p\left(1+7\sqrt{\frac{r_w}{2pm}}\cos\frac{p\pi}{2}\right)\right],$$

in which

$\frac{Q_0}{s_w}$ = specific capacity of a partially penetrating well, in gallons per minute per foot;

$\frac{Q}{s_w}$ = specific capacity of a well screened in the full thickness of the aquifer, in gallons per minute per foot;

m = thickness of the aquifer screened, in feet;

r_w = effective radius of the pumped well, in feet;

p = percentage of the aquifer screened.

Assume that the well in the previous example is equipped with only 40 instead of the 70 feet of screen that would be required for complete penetration of the section of the aquifer penetrated by the well. Then

$$Q/s_w = 27 \text{ gpm per ft; } m = 70 \text{ feet; } r_w = 0.5 \text{ foot,}$$

and

$$p = 40/70 = 57 \text{ percent.}$$

Substituting these values in the partial penetration formula:

$$\frac{Q_0}{s_w} = 27\left[0.57\left(1+7\sqrt{\frac{0.5}{2\times 0.57\times 70}}\cos\frac{0.57\times 3.14}{2}\right)\right]$$

$$= 27 \times 0.766 = 20.7 \text{ gpm per foot.}$$

Thus, the corrected theoretical specific capacity for the partially penetrating well is only 20.7 gpm per ft as compared with the 27 gpm per ft for the fully penetrating well.

The foregoing discussion has shown how the coefficient of transmissibility (*T*) of a section of the aquifer to be screened can be estimated and used to compute the capacity of a well. The transmissibility is estimated by first multiplying the permeability of each permeable bed in the section of the aquifer to be screened (estimated by comparison with similar rock materials of known permeability) by the thickness of the bed to get the transmissibility of that interval, then, by adding the individual *T* values, to get the estimated transmissibility of the section of the aquifer to be screened. The coefficient of the storage (*S*) can be estimated from previous pumping tests, but even a moderately large error in this estimate should not significantly affect the accuracy of the calculations. These values for *T* and *S* may then be used to predict the response of the aquifer to pumping by individual wells. These calculations, however, assume that the wells are 100 percent efficient, a condition that is rarely attained. Generally, a well that is 80 percent efficient is considered to be an excellent well.

The actual specific capacities of the wells in the two previous examples thus might be 20 percent less than the theoretical values, or 22 gpm per ft for the fully penetrating well and 17 gpm per ft for the partially penetrating well. To insure the maximum efficiency or degree of development, a well should be pumped during development at a rate one and one-half times the rate that the well will be pumped when it is placed in service (Sayre and Livingston, 1945, p. 96, 97).

INTERFERENCE BETWEEN WELLS

The drawdown at any point in the Lichterman well field is the summation of the effects of individual drawdowns produced by each of the pumping wells. Thus the total decline in water level in each pumping well includes not only the drawdown in the well caused by its own pumping, but also the drawdown or interference caused by pumping other wells in the well field. Theoretically, if each of the well discharges is known, the problem of calculating the total decline of water level at any point in the well field at any time in the future can be resolved by using the Theis (1935) nonequilibrium formula to compute the drawdown caused by each discharging well and then summarizing the results. Such calculations, however, would be valid only insofar as the assumptions on which the Theis formula is based are met. Owing to the anisotropism of the "500-foot" sand beneath the Lichterman well field, calulations of drawdown based on the Theis formula could be in error by as much as 100 percent. Nevertheless, the arrangement of terms in the Theis formula provides a means of determining the effect of different factors on the amount of interference to be expected between wells. The Theis nonequilibrium formula is written:

$$s=\frac{114.6QW(u)}{T}$$

where

s=drawdown, in feet;
Q=rate of pumping, in gpm;
T=coefficient of transmissibility, in gpd per foot

$$W(u)=\text{well function of } u=\int_{1.87^2rS/Tt}^{\infty}\frac{e^{-u}}{u}\,du,$$

in which

$$u=\frac{1.87r^2S}{Tt}$$

and

r=distance from pumping well to point of observation, in feet;
S=coefficient of storage (nondimensional);
t=time since pumping started, in days.

By examination of the arrangement of the variables in the Theis equation, certain conclusions can be drawn pertinent to the amount of drawdown at any point in the area of influence of pumping. The factors that tend to increase the amount of drawdown(s), are: high pumping rates (Q), low transmissibilities (T), and large values for the factor $W(u)$ which is generally referred to as the well function of u. Inasmuch as $W(u)$ is inversely proportional to u, it follows that the value of $W(u)$ decreases as the value of u increases. Therefore, drawdown increases with the length of time (t), since pumping started and decreases with distance from the pumped well.

Thus, to minimize the interference between wells, two basic procedures should be followed. These are: (1) Those wells having the highest specific capacities (indicative of high T values) should be pumped at the highest rates for the longest periods of time, and (2) to make up any deficit in total production, those wells that are most distant from the wells already in operation should be turned on.

Interference between wells might also be minimized, and the added cost of pumping caused by such interference could be reduced, by screening adjacent wells in different zones of the "500-foot" sand. This procedure should be very worthwhile in those parts of the well field where the three zones of the "500-foot" sand are separated by local clay lenses (fig. 5).

CONCLUSIONS

1. Water for high-capacity wells may be obtained from three zones of coarse sand in the "500-foot" sand. These zones differ in thickness and in depth below land surface from place to place and are separated by beds of finer grained sand or lenses of clay.
2. Pumping in the Lichterman well field, initially at a rate of 8.5 mgd and later increasing to about 20 mgd, will superimpose an additional water-level decline on that which has already been caused by pumping other wells in the Memphis areas. This decline will have several effects:
   (a) Some of the ground water that otherwise would leave the area by flowing northwestward toward the center of pumping in the Memphis area will be diverted toward the Lichterman well field.
   (b) Where breaching of the capping clay provides a hydraulic connection between streams and the aquifer, additional recharge will be induced into the "500-foot" sand.
   (c) The present artesian conditions will change to semiartesian or water-table conditions at places in the area where the base of the capping clay is high enough to be above the declining water level. This change will probably begin at certain sites within the well field and then expand in all directions, but will be more rapid eastward.
3. The transmissibility of the aquifer can be estimated without resorting to pumping tests by adding up the estimated transmissibilities of the individual beds. These values are obtained by multiplying the thicknesses of the beds by the coefficients of permeability of similar-textured rocks from the Memphis area as determined in the laboratory. Using this method, the transmissibility of the aquifer at well Sh: L–38 is estimated to be about 400,000 gpd per ft.
4. The presence of beds of clay within the "500-foot" sand serves to decrease the specific capacity of individual wells from a theoretical value of about 75 gpm per ft of drawdown to less than 25 gpm per ft of drawdown.
5. Interference between wells in the Lichterman well field can be minimized by pumping those wells with the highest specific capacities for the longest periods of time and by screening different intervals of the aquifer in wells that are closely spaced.
6. Additional quantities of water can be obtained without causing additional interference between wells by screening adjacent wells in different zones of the "500-foot" sand where they are separated by clay layers.

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EXPLANATION

Gravel

Clay or sandy clay

Zones of sand available for the development of water wells:

- Medium and coarse or very coarse sand — *Most favorable*
- Medium or fine and medium sand — *Moderately favorable*
- Fine sand — *Usually unfavorable*

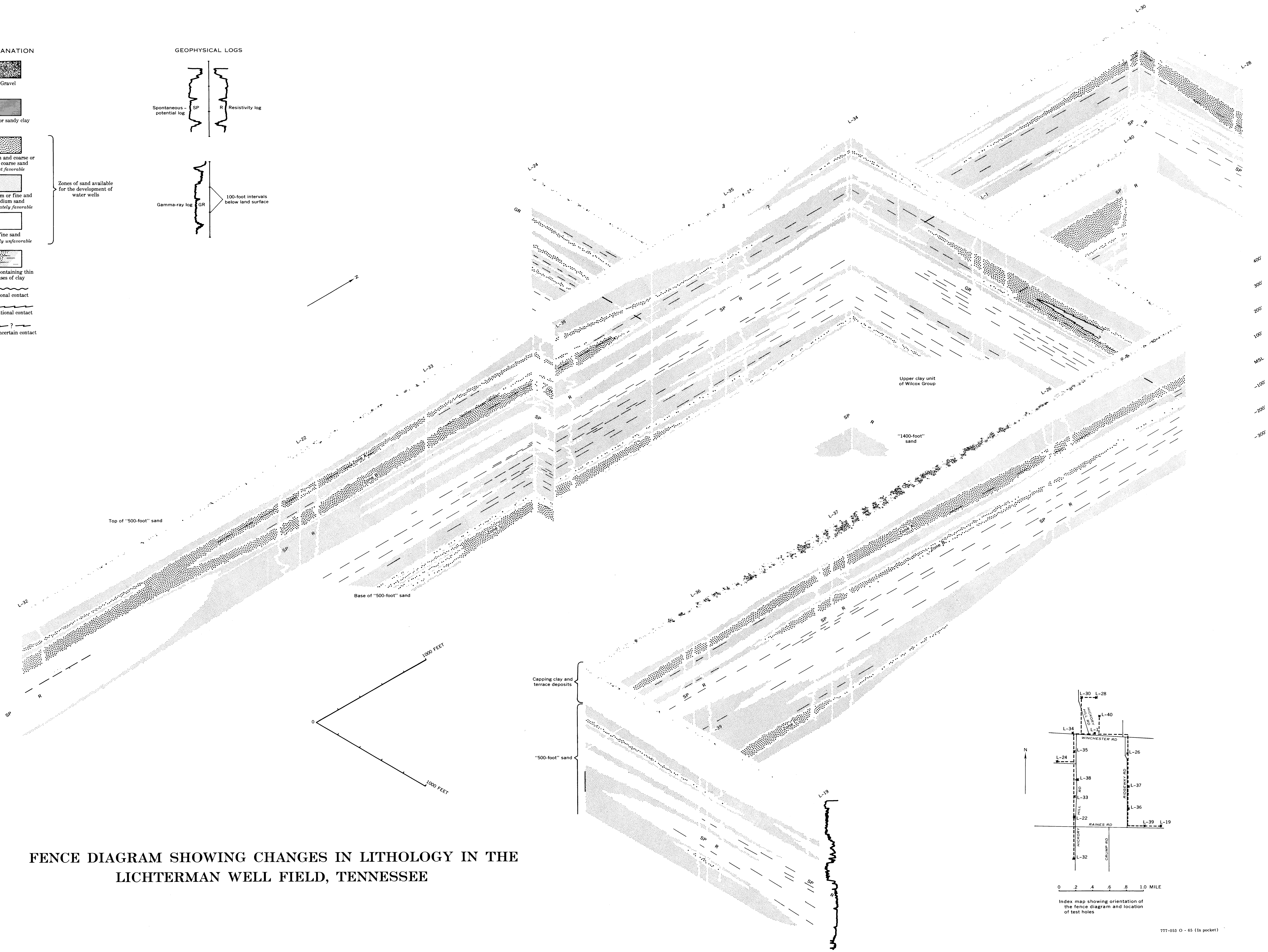
Sand containing thin lenses of clay

Erosional contact

Gradational contact

Very uncertain contact

GEOPHYSICAL LOGS



FENCE DIAGRAM SHOWING CHANGES IN LITHOLOGY IN THE LICHTERMAN WELL FIELD, TENNESSEE

Index map showing orientation of the fence diagram and location of test holes

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