# Flow Pattern and Related Chemical Quality of Ground Water in the "500-Foot" Sand in the Memphis Area, Tennessee

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1853

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

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*By* EDWIN A. BELL *and* DALE J. NYMAN

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# FLOW PATTERN AND RELATED CHEMICAL QUALITY OF GROUND WATER IN THE "500-FOOT" SAND IN THE MEMPHIS AREA, TENNESSEE

By Edwin A. Bell and Dale J. Nyman

## ABSTRACT

The "500-foot" sand is the major source of water suply for the Memphis area. Thick layers of impervious clay above and below the sand confine the water in the aquifer under artesian pressure and also protect the aquifer from contamination.

Recharge from rainfall enters the "500-foot" sand in the outcrop, or intake, area south and east of Memphis. Recharge from other aquifers enters the sand wherever the confining beds are breached or absent. Some of the recharge that enters the "500-foot" sand in eastern Arkansas moves down the gradients created by pumping in the Memphis area. All discharge from the "500-foot" sand in the Memphis area results from well pumping.

Since 1886 continuous withdrawals at gradually increasing rates of pumping have lowered water levels and altered hydraulic gradients in the area. These withdrawals have resulted in changes in direction and velocity of movement of water through the "500-foot" sand. Water in the sand in the southeastern part of the Memphis area normally moves from the outcrop area east and south of Memphis northwestward toward points of withdrawal. In the northwestern part of the area, water moves southeastward toward points of withdrawal.

A flow-net analysis of the aquifer shows that the rate of water movement through the "500-foot" sand in 1964, toward the major cones of depression in the Memphis area, was about 350 feet per year, or 1 mile in 15 years. A flow-net analysis projected for the year 1975 indicates the rate will increase by about 20 percent in the 12-year period 1964–75.

Water in the "500-foot" sand in the Memphis area is generally a calcium magnesium sodium bicarbonate type. It is soft, low in dissolved solids, high in concentrations of iron and carbon dioxide, and slightly to moderately corrosive. The softest and least mineralized water occurs in the southeastern part of the area, and the water becomes slightly harder and more mineralized as it moves downdip toward Memphis. The hardest and most mineralized water occurs in the northwestern part of the area.

The variations in chemical quality of water en route through the "500-foot" sand are virtually proportional to increases or decreases of the major chemical constituents. The variations are chiefly attributed to the mixing or blending of water from different directions or sources of recharge as wells are pumped. As water levels are lowered by continuous pumping in the future, increasing rates of recharge from the outcrop areas and from shallow aquifers will probably

cause little, if any, change in chemical quality of the water. Certainly, the effects on quality are not expected to be detrimental.

Although future changes in chemical quality of water in the "500-foot" sand in the Memphis area will probably be neither intense nor extensive, some changes can be anticipated as a result of man's activities associated with the continued growth and development of the area. Increased pumping at existing pumping centers will deepen existing cones of depression and thereby increase gradients. These increases will not necessarily cause a change in chemical quality unless the increases in pumping are unevenly distributed. If a major well field were developed in the "500-foot" sand in the southwestern part of the Memphis area, little change in quality would result because water would be caused to move toward the well field from both the northwest and southeast. This movement would not affect the blending of updip and downdip water at other well fields.

If water were impounded in the Wolf River a few miles upstream from Memphis, the impoundment could furnish recharge, at least temporarily, to the "500-foot" sand. It is improbable that any detrimental effects on the chemical quality of the water supply of Memphis would result, because the water in the impoundment would probably be softer and less mineralized than the water in the "500-foot" sand in that area.

## INTRODUCTION

The municipal water supply of the city of Memphis is one of the best in the United States in terms of abundance and quality. The sole source of this excellent water supply is ground water from two artesian aquifers (water-bearing sands). The aquifer that supplies about 95 percent of the water for municipal use is the "500-foot" sand, which is confined throughout most of the Memphis area by thick layers of overlying and underlying clay. A deep aquifer, the "1,400-foot" sand, supplies the remaining 5 percent of the water. Two additional aquifers, the terrace deposits and the alluvium, occur at shallow depths (less than 200 ft.) but are not used for municipal supply, chiefly because of the susceptibility of these shallow aquifers to contamination from the land surface. Also, the terrace deposits would yield only a small part of the water needed for the municipal supply, and the water is harder than that in the "500-foot" sand. Water in the alluvium is not desirable because of its high content of iron and its hardness.

The "500-foot" sand is a prolific artesian aquifer, and its natural confinement protects the water from contamination. Nevertheless, the continuous decline of water levels caused by gradually increasing rates since 1886, when the first well was drilled, has significantly altered the pattern of water movement in the aquifer. The decline has caused the water to move toward the Memphis area from all directions. Under these circumstances, water having a different chemical quality could conceivably be moving through the aquifer toward pumping centers in the Memphis area. The result would be a change in the chemical quality of the supply. The change in quality could be undetected until the initial slug of "alien" water reached one or more of the withdrawal centers.

## PURPOSE AND SCOPE

The movement of water through the "500-foot" sand is slow enough to afford an excellent opportunity to examine the chemical character of the water upgradient or "upstream" from centers of withdrawal because water at increasing distances "upstream" is correspondingly further, in time, from the centers of withdrawal. The water that will be withdrawn during the next several decades is already no more than a few miles upgradient from the points of withdrawal. The purpose of this report is to appraise the chemical quality of the water moving through the "500-foot" sand toward points of withdrawal in the Memphis area and to determine the possibility of future changes in the quality of the water. This information will be useful to water managers for identifying potential effects on the chemical quality of the water supply within the next several decades so that undesirable effects, if any, can be alleviated or eliminated.

The report is based on a detailed study of the movement and chemical quality of the water in the "500-foot" sand. Information on the movement of water within the aquifer was interpreted from two flow-net maps. The first map was prepared from water-level measurements made in 87 wells on April 21 and 22, 1964. The second map was prepared from predicted water levels for the year 1975 and was used to estimate the average time of travel of ground water toward the major pumping centers during the 20-year period ending 1985.

Information on the chemical quality of the water in the sand and in the adjacent strata was obtained chiefly from comprehensive analyses of 40 water samples collected during April and June 1964. The 40 samples included 5 samples from streams in the Wolf River basin, 11 samples from wells in the terrace deposits, and 24 samples from wells in the "500-foot" sand. Some additional chemical-quality data were obtained from local industries and utility districts.

To evaluate the interpretations of these data, seven test wells were augered in the Wolf River and Nonconnah Creek basins.

## COOPERATION AND ACKNOWLEDGMENTS

This report and the investigation on which it is based were started in July 1963 in cooperation with the Memphis Light, Gas and Water Division, city of Memphis. This investigation is a part of the continuing program of cooperative investigations of the water resources of the Memphis area, begun in 1940, to provide technical information for the development of local water supplies.

Officials of many city and county agencies, representatives of industries and utility districts, drilling contractors, and well owners helped to make this report possible by furnishing information and granting the use of their facilities for collecting data. The authors particularly appreciate the contributions of the following: J. J. Davis, Director, Hugh Mills, Drilling Superintendent, and J. W. Murphrey, Chemist, all of the Memphis Light, Gas and Water Division, for providing data from the city records; E. C. Handorf, Engineer-Director, and W. M. Craddock, Sanitarian, Bureau of Sanitary Engineering, Memphis and Shelby County Health Department, for information on well locations; and J. C. Paine, Assistant County Engineer, for his assistance in obtaining approval for test augering along county roads.

## GEOHYDROLOGY OF THE "500-FOOT" SAND

The "500-foot" sand is a hydrologic unit in the Memphis area (fig. 1) that is continuous through western Tennessee and adjacent parts of eastern Arkansas and northern Mississippi. Cushing, Boswell, and Hosman (1964, pl. 2) showed the correlation of geologic units that form this hydrologic unit.

### GEOLOGIC SETTING

The geology of the "500-foot" sand in the Memphis area is described in several ground-water reports. The more recent of which are those by Criner, Sun, and Nyman (1964), Moore (1965), and Nyman (1965). The geologic units that underlie and overlie the "500-foot" sand are shown schematically on plate 1. These units from oldest to youngest, are the Wilcox Group, which includes the "1,400-foot" sand; the Claiborne Group, which is represented by the "500-foot" sand; the Jackson(?) Formation, which is the clay capping the "500-foot" sand; and the terrace deposits, loess, and alluvium. A description of these geologic units in the Memphis area is summarized in table 1 (from Criner and others, 1964).

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). The impermeable lower clay unit is the lower confining bed for water in the middle sand unit, or "1,400-foot" sand. The upper clay unit of the Wilcox Group, ranging in thickness from 200 to 395 feet, virtually isolates the "500-foot" sand from the "1,400-foot" sand throughout Shelby County.

The Claiborne Group, represented by the "500-foot" sand in the Memphis area, ranges in thickness from 500 to 850 feet. It is mostly a heterogeneous deposit consisting of beds of coarse, medium, and fine

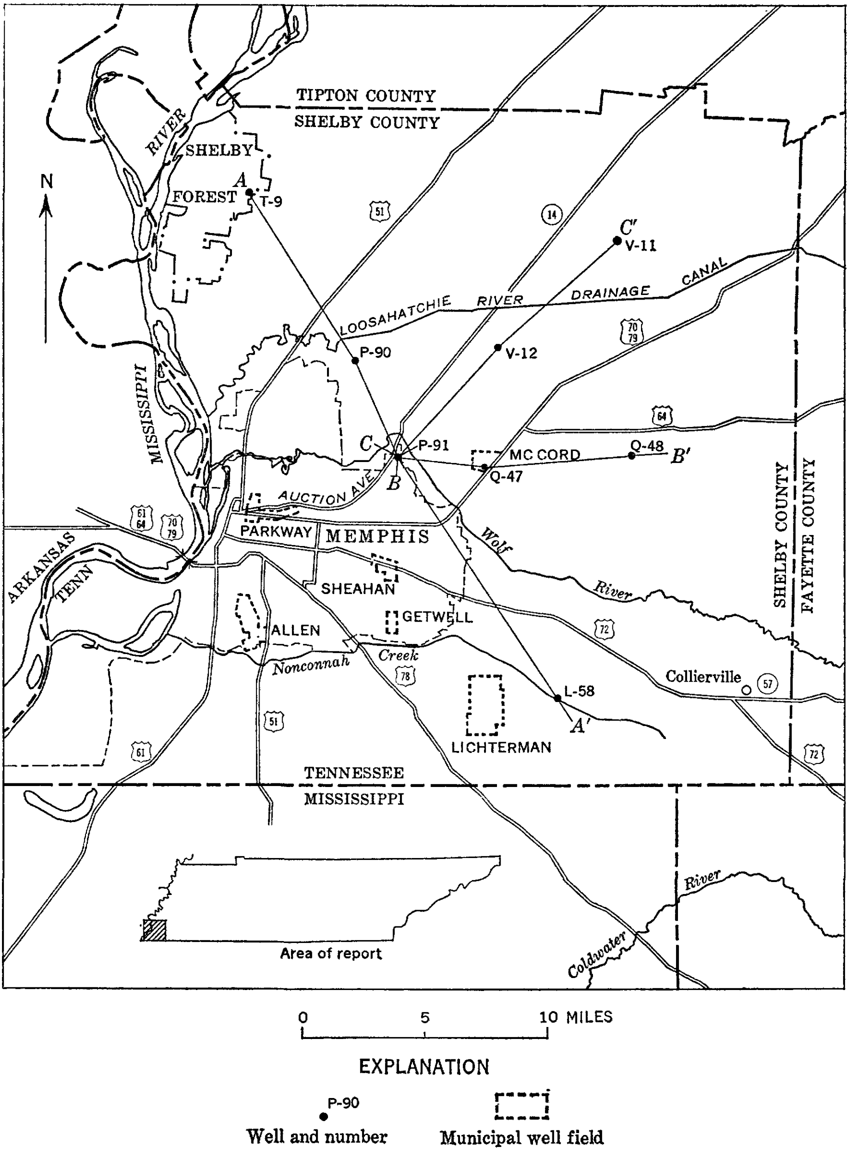


FIGURE 1.—Location of municipal well fields and sections *A–A′*, *B–B′*, and *C–C′* through selected wells in the terrace deposits (pl. 4).

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. Yields water to a few domestic wells. Could be an important source of water for certain industrial uses. Water is a calcium bicarbonate type, very hard, and high in dissolved solids and iron |
| Quaternary | Pleistocene | | Loess | 0–100 | Wind-deposited silt. (Topographically higher than alluvium.) Low permeability. Not a source of ground water |
| Quaternary / Tertiary | Pleistocene and (or) Pliocene | | Terrace deposits | 0–160 | Alluvial sand and gravel. Supplies several domestic wells. Could be a major source of water for industrial and irrigation uses. Water in eastern half of area is predominantly a sodium bicarbonate type, soft, and moderately high in dissolved solids and iron. In the western half, predominantly a calcium magnesium bicarbonate type, moderately hard to very hard, and high in dissolved solids and iron |
| 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 sand. Generally impermeable and considered to be the upper confining bed for water in the "500-foot" sand |
| Tertiary | Eocene | Claiborne | "500-foot" sand (upper part may include some Jackson(?) beds) | 500–800 | Fine to coarse sand; minor amounts of lignite and tan clay and silt; thin clay and lignite lenses. Coarse channel sands locally at base. Very good aquifer from which 95 percent of water used in Memphis area is obtained. Water is a calcium magnesium sodium bicarbonate type, generally soft, low in dissolved solids, and high in iron and carbon dioxide. The water contains some hydrogen sulfide and is slightly corrosive. A sodium bicarbonate water characterizes the eastern and southern parts of the area, where the water is softest and least mineralized; a calcium bicarbonate water with substantial amounts of magnesium characterizes the remainder of the area |
| Tertiary | Eocene | Wilcox | Upper clay unit | 200–395 | Gray, greenish-gray, and brown carbonaceous clay. Thin lignite and fine sand lenses locally. Low permeability confines water in "500-foot" and "1,400-foot" sands |
| Tertiary | Eocene | Wilcox | Middle sand unit ("1,400-foot" sand) | 150–300 | Fine to medium sand; minor amounts of lignite and clay lenses. A secondary aquifer which supplies about 5 percent of water used in Memphis area. Water is a sodium bicarbonate type, soft, low in dissolved solids, and high in iron, and contains some carbon dioxide. It is softer but more mineralized than water in the "500-foot" sand |
| Tertiary | Eocene | Wilcox | Lower clay unit | 190–250 | Gray, greenish-gray, and brown carbonaceous clay, and lignite; sandy near top. Forms impermeable lower confining bed for water in "1,400-foot" sand |

sand intercalated with thin beds of clay. Although the hydraulic properties of individual beds vary considerably within short distances, these finite variations are masked by the consistency of the hydraulic properties of the entire aquifer. Thus, the "500-foot" sand is an excellent acquifer in the Memphis area.

The Jackson(?) Formation, termed the "capping clay" by Nyman (1965, p. 5) overlies the "500-foot" sand and is predominantly a clay unit that, in places, grades into sandy silt or silty sand. In general, the Jackson(?) Formation is thickest in the northwestern part of the area and thins updip toward the southeast. The formation is as much as 330 feet thick in the Parkway well field, but is absent in the vicinity of Collierville, southeast of Memphis. A study of recent electric logs indicates that the capping clay is relatively thin at the Sheahan and Allen well fields and is absent at several test-hole sites on the Wolf River flood plain east of Germantown Road. Under the present hydraulic gradients, however, the capping clay effectively isolates the water in the "500-foot" sand from water in the overlying formations throughout most of the Memphis area.

The terrace deposits, loess, and alluvium overlie the Jackson(?) Formation. The terrace deposits and alluvium are used as sources of water for domestic wells in the parts of the Memphis area not served by public supply systems. These units are hydraulically connected to the "500-foot" sand where the Jackson(?) Formation is absent, where the clay is thin, or where the formation is chiefly made up of fine sand.

## SOURCES OF RECHARGE

Recharge to the "500-foot" sand is generally available from two sources—rainfall on the outcrop areas, and water from other aquifers. As outlined by Moore (1965), the outcrop or intake area of the "500-foot" sand occupies a broad belt that strikes northeastward across western Tennessee and includes the southeastern part of Shelby County. Most of the recharge to the "500-foot" sand in the Memphis area enters the aquifer in the part of the intake area that is southeast of Memphis (Criner and others, 1964).

Water from other aquifers enters the "500-foot" sand either by leakage through the confining beds above and below the "500-foot" sand or by infiltration through breaches in the confining beds. Leakage through the confining beds is probably negligible owing to the extremely low vertical permeability of the confining beds. For example, if the vertical coefficient of permeability of the upper confining bed is 0.001 gpd per sq ft (gallons per day per square foot), the rate of downward leakage of water through the upper confining bed into the aquifer in 1964, under the prevailing hydraulic gradient of 0.1 foot per foot, was about 2 gpm per sq mi (gallons per minute per square mile). The amount of downward leakage through the upper confining bed in the Memphis area, which occurs where the piezometric surface of the "500-foot" sand is below the water level of the shallow aquifers overlying the confining bed, is estimated to be about 2 mgd (million gallons per day). Similarly, leakage from the lower confining bed was calculated to be about 200,000 gpd. The sum of these two figures represents only 1½ percent of the total daily withdrawal from the "500-foot" sand in the Memphis area in 1964.

In addition to leakage through the confining beds, water from other aquifers can enter the "500-foot" sand as recharge through breaches or "windows" in the confining beds. Although the upper and lower confining beds are areally extensive, the upper surfaces of both confining beds have been exposed to subaerial erosion. Thus, it can be postulated that in certain localities one or both confining beds could have been removed or cut through by erosion. The probable location for breaches to occur in the lower confining bed is along the eastern margin of the outcrop area of the "500-foot" sand, about 50 miles east of Memphis, where the lower confining bed is probably thin. The probable location for breaches to occur in the upper confining bed is along the western margin of the outcrop area, about 10 miles east of Memphis, where this confining bed is thin. There is also some indication from logs of wells in eastern Arkansas that the upper confining bed is locally absent beneath the alluvial deposits in the area west of Memphis.

Wherever either of the confining beds is absent, a free interchange of water is possible between the "500-foot" sand and the aquifer adjacent to it.

### AREAS OF DISCHARGE

Virtually all discharge from the "500-foot" sand in the Memphis area is the result of withdrawal through wells. Prior to 1965, the city of Memphis had established four municipal well fields: Parkway in the west-central part of Memphis, Allen in the southwestern part, McCord in the northeastern part, and Sheahan in the east-central part. The Sheahan well field is separated into two fields, the north well field (Sheahan proper) and the south well field (Getwell). In July 1965, the Litchterman well field, in the southeastern part of the Memphis area, was placed in operation. The well fields are at least 6 miles apart.

In addition to the Memphis municipal well fields, 10 utility districts, which operate pumping and distribution systems for public supplies, are scattered through Shelby County. Industrial well fields are interspersed with the public supply wells, but most are concentrated in two small areas. Many of the large industrial users of water are grouped in the northern part of the Memphis area; a few large users are in the southwestern part of the city. Small domestic supplies are obtained from many individual wells in the "500-foot" sand in the parts of the Memphis area not served by public supplies.

In 1964 about 68 mgd (million gallons per day) was pumped for public supplies at Memphis, 62 mgd for large industries, and 4 mgd for utility districts. In addition, an estimated 11 mgd was pumped for small industrial and domestic supplies scattered throughout Shelby County. The areal distribution of municipal and major industrial pumping in the area during 1964 is shown in figure 2.

## EFFECTS OF PUMPING ON WATER LEVELS

Water levels in the "500-foot" sand in the Memphis area have steadily declined because of continuous increases in pumping since 1886, when the first well was drilled. For example, near the Auction Avenue well field (near Parkway Pumping Station) water levels have declined from an initial level of about 230 feet above mean sea level to about 150 feet above mean sea level in 1964. The downward trend of area water levels in the "500-foot" sand since 1932 was described by Criner, Sun, and Nyman (1964, p. 18–27).

The pumping of water from the "500-foot" sand has had a significant effect upon the aquifer's piezometric or free-water surface (the imaginary surface that coincides with the static head of water in an aquifer). The configuration of the piezometric surface of the "500-foot" sand in the Memphis area, as of April 1964, is shown on plate 2, map *A*. The depressions in the piezometric surface are cone shaped. The largest cone of depresson, defined by the 170-foot contour in the western part of Memphis, includes many industrial wells in addition to the Parkway and Allen municipal well fields. In the area defined by this cone are some of the oldest wells in Memphis; hence, the cone is the result of the longest period of sustained pumping in the Memphis area. In contrast, the cone of depression of the Sheahan well field, as defined by the piezometric contours, is small. This cone is not clearly defined owing to the lack of water-level measurements within the field of pumping.

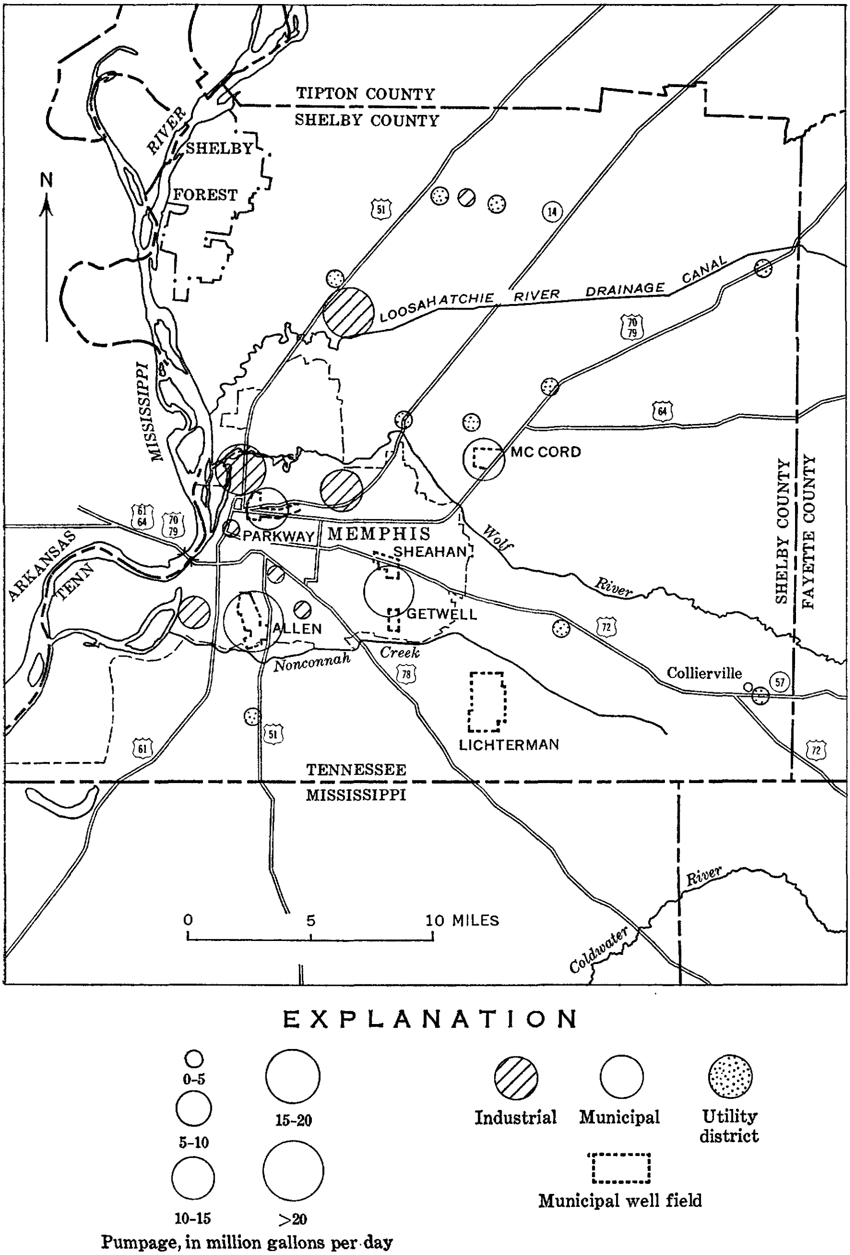


FIGURE 2.—Areal distribution of pumping during 1964.

## MOVEMENT OF WATER IN THE "500-FOOT" SAND

Water in the "500-foot" sand, as in any other aquifer, moves from areas of recharge to points of discharge. Thus, the pattern or direction of movement is determined by the geographic distribution of the areas of recharge and of discharge which are delineated by "highs" and "lows" on piezometric-contour maps. Determination of the rate of ground-water movement requires the solution of one or more equations of ground-water flow. In this report a flow-net map, which is a graphical solution to a two-dimensional equation for groundwater flow, is used to determine the approximate direction and rate of movement through the "500-foot" sand toward areas of discharge in the Memphis area.

### FLOW NET

A flow net consists of a set of curved equipotential lines and a set of curved flow lines that intersect at right angles to form a pattern of "squares." In this sense, the corners of the "squares" are right angles and the mean distances between the two pairs of opposite sides are equal. Under ideal conditions, where the fully saturated water-bearing material is homogeneous and isotropic, the equipotential lines and flow lines intersect at right angles to form a system of "squares" in which the ratio of the mean distances between the two pairs of opposite sides is unity.

The equipotential lines of a flow net are similar to the contour lines on a piezometric map because the equipotential lines connect points within the flow system having an equal head or potential energy. The flow lines of a flow net are constructed perpendicular to the equipotential lines and, thus, parallel the direction of flow. The flow lines, in effect, constitute flow boundaries, and each pair of adjacent flow lines defines a flow channel which carries part of the total quantity of water moving through the aquifer toward areas or points of discharge. Moreover, each flow channel that terminates at a common point or area of discharge carries an equal part or percentage of the total quantity of water to be discharged from that point.

The construction of the flow net for the "500-foot" sand was accomplished mostly by trial and error. The control for the equipotential lines was obtained from the same water-level data that were used to construct the piezometric-contour map (pl. 2, map *B*). A system of "squares" was devised between the 170- and 180-foot piezometric contours, and the system was then extended up and down the hydraulic gradient. A succession of many slight adjustments of both equipotential and flow lines was needed to design the flow net (pl. 2).

Although the flow net could be improved, particularly by dividing the "squares" into smaller "squares," a perfect system of "squares" that would fit all the water-level data could not be constructed because the flow net is two dimensional whereas the aquifer system is three dimensional. The flow net is, therefore, an idealization of the actual flow system in two dimensions.

The flow net (pl. 2) is believed to be an accurate representation of the flow system as of April 1964. To "look upstream" and thereby accomplish the purpose of this report, a flow net must be constructed that represents the flow system as it will be in the years ahead. This construction can be done by imposing on the present flow system the effect of foreseeable future activities on water levels in the "500-foot" sand. Among the activities that could affect the flow net and, hence, must be considered are the operation of the Lichterman well field, the expansion of industries, particularly in the area southwest of Memphis, and the impoundment of the Wolf River.

Each of these three activities was considered in the preparation of the flow-net map shown on plate 2, map *B*. This map is believed to be an accurate representation of the flow system as it will be in the year 1975. The principal differences between the present and the future (pl. 2, maps *B*, *C*) flow systems are the addition of a cone of depression surrounding the Lichterman well field, the expansion of the established cones of depression to reflect the increase in industrial pumping throughout Memphis, and the imposition of a constant head or line source along the Wolf River a few miles upstream from the city limits.

## VELOCITY OF MOVEMENT

A flow net can be used to determine the velocity of flow through an aquifer. By construction, the rate or velocity of water movement through any "square" in the flow net must satisfy the equation

$$v=C\ \ q/A_w \tag{1}$$

where

$v$ = the velocity of water movement,

$C$ = the conversion constant,

$q$ = the quantity of water moving through the "square" in a unit of time,

$A_w$ = the saturated area perpendicular to the direction of flow.

To facilitate the computation of the rate of movement through any "square" within a flow net, equation 1 can be modified by substituting for $A_w$ the value given by:

$$A_w = mwp \tag{2}$$

where

$m$ = the effective thickness of the aquifer,

$w$ = the mean width of the flow channel between two successive flow lines,

$p$ = the porosity of the aquifer expressed as a decimal.

Thus, equation 1 becomes

$$v = C\ q/mwp. \tag{3}$$

For $v$ in feet per year, $q$ in millions of gallons per day, $m$ in feet, and $w$ in miles, equation 3 may be rewritten

$$v = 9.25 \times 10^3\ q/mwp. \tag{4}$$

Thus, the velocity of water movement along any given flow channel is directly proportional to the quantity of water moving through the channel and inversely proportional to the effective thickness of the aquifer, the mean width of the flow channel, and the porosity of the aquifer.

Velocities of ground-water movement through the "500-foot" sand in 1975 can be computed by using equation 4 and the flow net given on plate 2, map $C$, if values are assigned for $m$ and $p$. A value of 300 feet was assigned for $m$ even though the thickness of the "500-foot" sand in the Memphis area ranges from 500 to 850 feet. This value was used because all the water pumped from the "500-foot" sand in the Memphis area is withdrawn from wells screened in the upper third of the aquifer. A value of 0.2 was assigned for $p$, the porosity of the aquifer, even though the actual porosity of dense mixed-grained sand ranges from 0.20 to 0.30 (Terzaghi and Peck, 1948). Any errors introduced into the computations by using these values for $m$ and $p$ will enhance the final conclusions of this report by maximizing the computed distance that ground water will travel in a given period of time.

By substituting the assigned values for $m$ and $p$, equation 4 reduces to

$$v = 154\ q/w. \tag{5}$$

Solutions to equation 5 were obtained by means of the graph (fig. 3) showing the relation between $v$ and $w$ for different values of $q$.

## TRAVELTIME

If the velocities of ground-water flow toward pumping centers in the Memphis area are known, the traveltime or the distance that water moves through the "500-foot" sand during a specified time period can be calculated from the equation $d = vt$. Distances were deter-

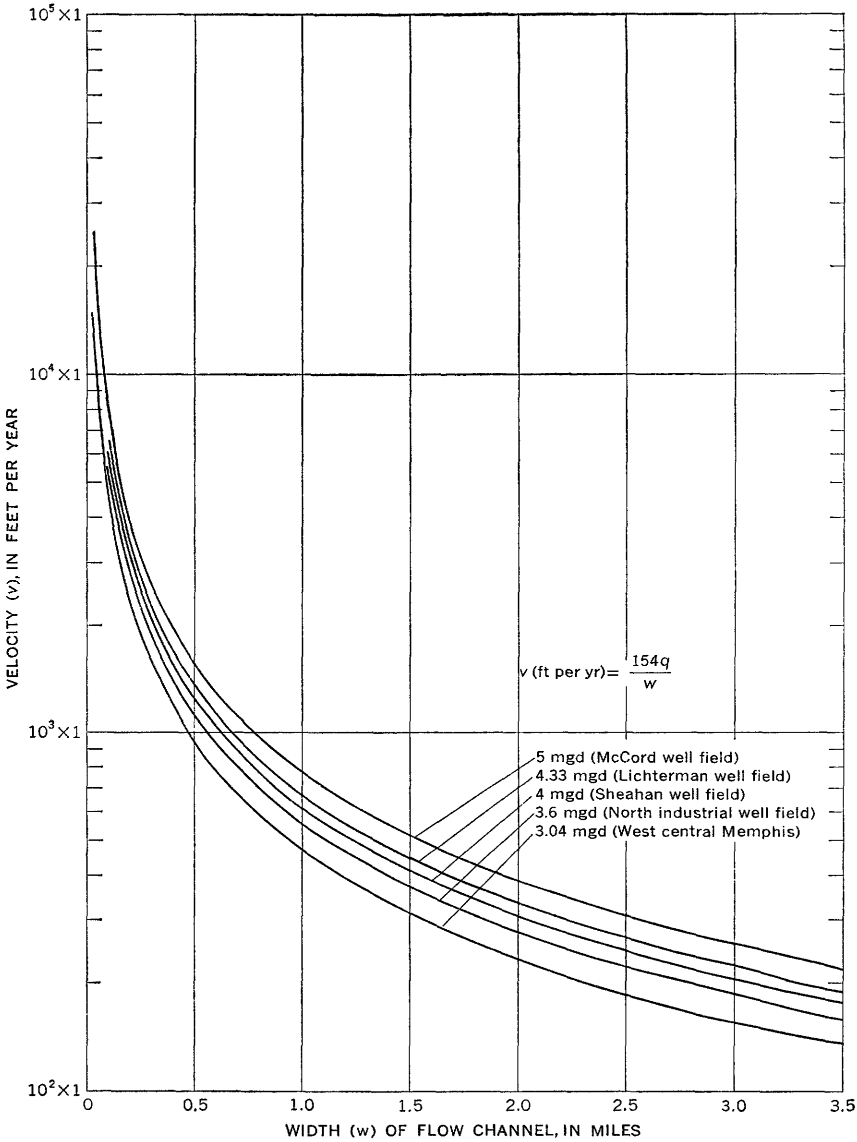


FIGURE 3.—Velocity of water movement through a flow channel as related to width of channel. Curves define velocities of water movement computed from estimates of rates of pumping in 1975 (pl. 2, map *D*).

mined in this way for 5-, 10-, and 20-year intervals and then plotted along the flow lines of plate 2, map *C*. Connecting lines were drawn between the plotted points to show the areal extent of the aquifer from which water will probably move to the pumping centers in each interval of time. The results are shown on plate 2, map *D*. Because flow paths are perpendicular to the lines of equipotential, the flow paths represent the shortest distance and also the steepest hydraulic gradient between successive lines of equipotential. Thus, the greatest velocity and distance through which water will travel in specified intervals of time toward the centers of pumping is along the indicated flow paths. As indicated on plate 2, map *D*, the rate of movement of water through the "500-foot" sand is slow. For example, water will move toward the large center of pumping in the western part of Memphis at a rate of about 2 miles in 25 years under the predicted hydraulic gradient. The rate of movement toward the same center of pumping in 1964 was about 1 mile in 15 years. It is the slow movement of ground water that makes it possible to "look upstream" and examine the chemical character of the water that will be withdrawn in the years to come.

## CHEMICAL QUALITY OF WATER EN ROUTE THROUGH THE "500-FOOT" SAND

The chemical quality of water in the "500-foot" sand is briefly described in previous ground-water reports on the Memphis area. The water is a calcium magnesium sodium bicarbonate type. Sodium is the principal cation in the southern and eastern parts of the area, where the water is softest and least mineralized. Calcium and magnesium are the principal cations in the rest of the Memphis area. Generally the water is soft, low in dissolved solids, high in concentrations of iron and free carbon dioxide, and slightly corrosive. Hydrogen sulfide in insignificant amounts has been reported, and its presence is also indicated by odors at the aerators. The average temperature of the water is 63°F. Besides aeration, filtration, and chlorination, little treatment of water from the "500-foot" sand is required for municipal, domestic, and most industrial uses.

To say that the water in the "500-foot" sand is good or excellent has little meaning unless one uses a standard for comparison. The U.S. Public Health Service (1962) and E. L. Bean (1962) gave exacting standards for public supplies. On the basis of analyses of finished water from the Allen, McCord, Parkway, and Sheahan filtration plants in September 1961, the excellence of Memphis water is readily seen by comparison with these two standards (figs. 4, 5). In comparison with U.S. Public Health service standards, the highest concentration of constituents in the Memphis municipal supply is slightly more

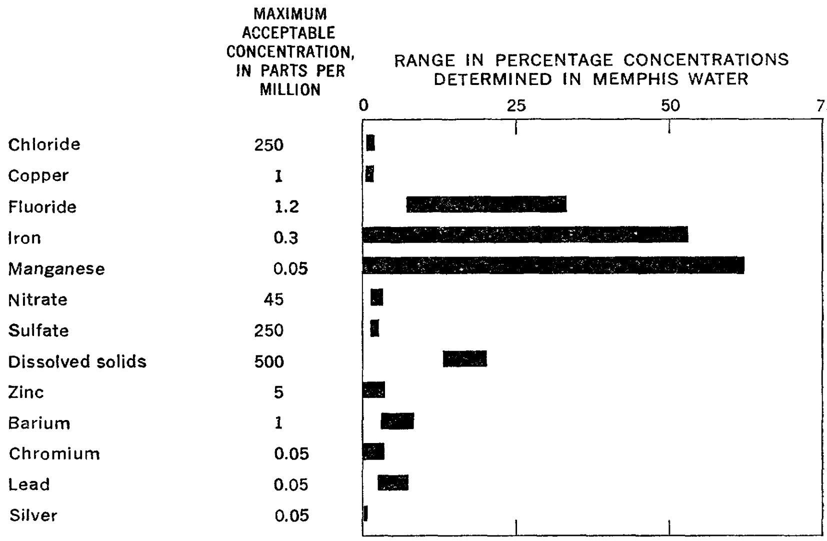


FIGURE 4.—Comparison of chemical analyses of water from Memphis municipal supply with the U.S. Public Health Service standards (1962). No constituent exceeds the maximum acceptable concentrations.

than 50 percent of the permissible amounts. The highest concentrations of aluminum, iron, and manganese in the "500-foot" sand exceed the permissible limits of Bean's standard, which gives very low permissible ranges.

Although the chemical quality of water in the "500-foot" sand is generally excellent, it is not uniform everywhere in the Memphis area (pl. 3, map *A*). Slight variations in quality occur in water within the sand, and larger differences in quality occur between the water in the "500-foot" sand and that in the overlying and underlying aquifers.

## VARIATIONS IN CHEMICAL QUALITY OF WATER

The ranges in concentration of the principal chemical constituents and physical properties of water samples collected from wells in the "500-foot" sand in the Memphis area during the 20-year period 1945–64 are listed in table 2. Although the concentrations differ within the area, the differences are generally small. Dissolved solids range from 32 to 204 ppm (parts per million) but are less than 100 ppm in about three-fourths of the samples. Hardness ranges from 9 to 184 ppm but is less than 70 ppm in most of the water samples. The concentration of iron ranges from 0 to 16 ppm, although concentrations greater than 2.9 ppm were found in the analyses of only four samples.

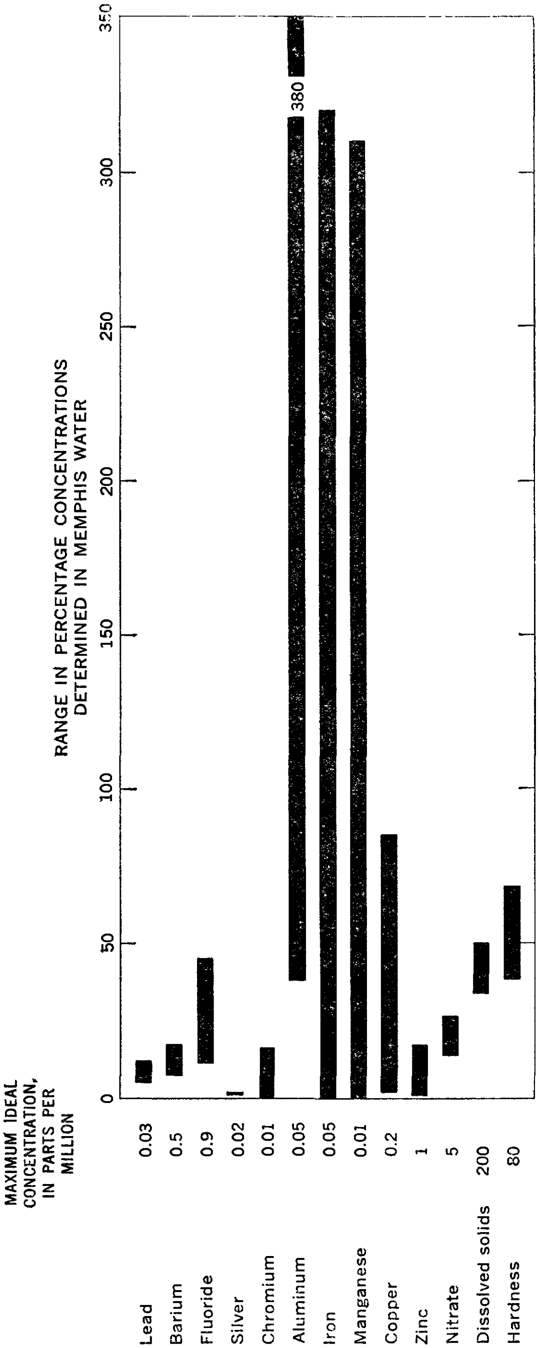


FIGURE 5.—Comparison of chemical analyses of water from Memphis municipal supply with Bean's "ideal quality" standards (1962). Only aluminum, iron, and magnesium exceed the maximum ideal concentrations.

TABLE 2.—*Ranges in concentration of significant chemical constituents, in parts per million, and physical properties of water in the "500-foot" sand in the Memphis area, 1945–64*

[Chemical analyses of 78 samples]

| Constituent or property | Minimum | Maximum | Median |
|---|---|---|---|
| Silica ($SiO_2$) | 1.3 | 29 | 12 |
| Iron (Fe) (total) | .0 | 16 | .43 |
| Calcium (Ca) | 2.0 | 36 | 10 |
| Magnesium (Mg) | .7 | 24 | 4.3 |
| Sodium (Na) | 3.3 | 16 | 7.7 |
| Potassium (K) | .2 | 3.8 | .8 |
| Sodium and Potassium (Na+K) [a] | 4.6 | 32 | ([c]) |
| Bicarbonate ($HCO_3$) | 17 | 239 | 63 |
| Sulfate ($SO_4$) | .0 | 9.0 | 3.1 |
| Chloride (Cl) | .5 | 22 | 4.0 |
| Nitrate ($NO_3$) | .0 | 4.0 | .2 |
| Fluoride (F) | .0 | .7 | .1 |
| Carbon Dioxide ($CO_2$) [b] | 32 | 78 | ([c]) |
| Hardness as $CaCO_3$ | 9 | 184 | 42 |
| Dissolved solids (Residue on evaporation) | 32 | 204 | 79 |
| Temperature (°F) | 61 | 68 | 63 |
| pH | 5.5 | 7.9 | 6.7 |

[a] 6 analyses.
[b] 4 analyses.
[c] Not determined.

Variations of chemical quality of water in the "500-foot" sand in the Memphis area are not dominated by variations of any single constituent. Instead, the variations are characterized by proportional increases or decreases of the significant ions—calcium, magnesium, sodium and potassium, bicarbonate, sulfate, and chloride. This characterization is shown by the increasing proportional concentrations of dominant ions from the southern and eastern parts of the county toward the major center of pumping in downtown Memphis, and by the decreasing proportional concentrations from the northern part of the area toward downtown (pl. 3, map *D*). Contours of hardness (pl. 3, map *B*) indicate that similar directional variations of hardness also occur in the area.

The concentration of iron in the water is least in the eastern and southern parts of the area and greatest in the northern part and in the centers of pumping, although the areal variation of the concentration is erratic. Because iron is generally not a good constituent on which to base geochemical interpretations of water analyses (Hem, 1959), no further attention will be given to iron in this report.

## RELATION TO CHEMICAL QUALITY OF WATER IN OTHER AQUIFERS

Chemical analyses of water from 11 wells in the terrace deposits show that the water is harder and contains more dissolved solids than the water in the "500-foot" sand. The softest and least mineralized water in the shallow aquifers is, as in the "500-foot" sand, in the southern and eastern parts of Shelby County. The hardest and most mineralized water in the Memphis area is in the shallow aquifers in the northwestern part of the county.

The water in the shallow aquifers is locally influenced by surficial conditions, and its chemical quality varies more than the quality of water in the "500-foot" sand. The variation of the quality of water in the aquifers is shown on profiles on plate 4. The relatively high concentrations of sodium and chloride in water from well V–11 (section *C–C′*) and of sodium, chloride, and nitrate in water from well P–90 (section *A–A′*) are localized and are not typical of water in the formation.

Water in the "1,400-foot" sand is a sodium bicarbonate type, very soft, and low in dissolved solids, but it is slightly more mineralized than water in the "500-foot" sand. All available chemical analyses of water from the "1,400-foot" sand are for samples collected near Parkway and Sheahan well fields. Within that part of the Memphis area, the quality of water in the "1,400-foot" sand is virtually uniform.

## CHANGES IN CHEMICAL QUALITY WITH TIME

The "500-foot" sand has probably remained saturated with water since its deposition about 40–50 million years ago. The quality of the original water can only be surmised, because the chemical quality of water now in the aquifer is the net effect of all changes that have occurred within the hydrologic system. These changes have been the result of either natural processes or man's activities.

### EFFECTS OF NATURAL PROCESSES

The water in the "500-foot" sand was probably harder and more mineralized initially than it is now. Flushing of the aquifer by natural recharge and discharge since its deposition resulted in a gradual reduction in the concentrations of minerals available to water moving through the aquifer. Possibly, flushing virtually depleted the "500-foot" sand of soluble material.

Wind-blown deposits of loess (Wells, 1933) that subsequently accumulated on top of the "500-foot" sand in the recharge area made available an additional source of minerals that could be leached and carried downward to the sand by water from precipitation seeping through the loess to the "500-foot" sand. As a result, relatively large amounts of calcium and other ions were leached from the loess and added to the water in the "500-foot" sand.

Measurements of the pH of water in the "500-foot" sand in western Tennessee (Lanphere, 1955; Moore, 1962) indicate that the water is slightly acidic. Hence, solids would probably not be precipitated from the water as it moves downgradient from the outcrop area.

Water entering the "500-foot" sand, as recharge from leakage through the confining beds or squeezed out of clay lenses within the aquifer, has probably undergone an ionic exchange with the clayey material. The effect of ionic exchange on the chemical quality of water in the "500-foot" sand is not known. X-ray diffraction analyses of samples of the capping clay from six wells in the Memphis area show that the clay is montmorillonitic and a calcium type. The montmorillonitic characteristics seem to be most pronounced near the Parkway and Lichterman well fields. Probably the water leaking from the clays into the "500-foot" sand has been softened by an exchange of calcium and sodium ions because calcium ($Ca^{+2}$) in water more readily replaces sodium ($Na^{+1}$) in the crystal lattice of montmorillonite than the reverse (Grim, 1951).

## EFFECTS OF MAN'S ACTIVITIES

Changes imposed in the environment by man's activities span only a brief period of years compared with the geologic and hydrologic changes that have occurred since the deposition of the "500-foot" sand.

Since 1886, development of the "500-foot" sand as a major source of water supply in the Memphis area has caused a continuous decline of the piezometric surface and changes in velocity and direction of flow toward centers of pumping. Some alteration in the chemical quality of the water because of changing hydrologic conditions would seem to be inevitable. However, the change within a finite interval of time may be so slight that a significant effect would not be apparent.

The chemical quality of water withdrawn from the "500-foot" sand in the Memphis area in 1964 is little different from the quality indicated by the first analysis in 1887. For example, 99 ppm dissolved solids were in a sample collected from a well (O–182) in the Parkway well field in April 1964. By comparison, five chemical analyses of Memphis artesian water, dating back to 1887 and 1888 (Glenn, 1906), show that total solids ranged from 85 to 93 ppm. The wells from which the five samples were collected are not identified, but most of the wells then in the area were near the former Auction Avenue pumping station, west of the present Parkway well field.

Little, if any, change in the chemical composition of the water from the "500-foot" sand with time can be detected in the analyses of water samples collected at different times from the same well. Fourteen previously sampled production wells were resampled in 1964. The longest interval of elapsed time between sample collections was 19 years, and the shortest, 2 years. The analytical data for each of the 14 wells are shown graphically on plate 3, map *C*. The data for 12 wells indicate hardly any change in composition. The concentrations of dissolved solids in the water in some of these 12 wells increased slightly, and in others it decreased by a small percentage. The data for 2 of the 14 wells, however, indicate that the water was softer and less mineralized in 1964 than it was at the time of collection of the first sample. One of these wells (J–67) is in the southwestern part of the Memphis area, and the other (V–2) is in the north-central part of the area.

## RELATION OF CHEMICAL QUALITY TO MOVEMENT OF WATER THROUGH THE "500-FOOT" SAND IN THE MEMPHIS AREA

As water moves through the "500-foot" sand in the Memphis area, it may be altered in chemical quality by (1) gaining constituents from the aquifer; (2) losing constituents to the aquifer; (3) exchanging base ions with clays above, below, or within the aquifer; or (4) mixing with water of a different quality.

Generally, water moving through an aquifer tends to gain constituents from the aquifer and, hence, to increase its concentration of dissolved solids, owing to increased length of time that the water is in contact with the aquifer. Downdip increases in calcium, magnesium, and iron were recognized by Moore (1962) from the chemical analyses of water from three selected wells in the "500-foot" sand in the northwestern part of Tennessee. Corresponding increases in hardness and in total dissolved solids are indicated by analyses of water from wells in the Memphis area (pl. 3, maps *A*, *B*) wherever the water moves in a northwesterly direction, the same general direction as the aquifer dips.

In contrast, water in the "500-foot" sand in the northwestern part of Shelby County moves in a southeasterly direction toward centers of pumping and appears to become softer and less mineralized. This apparent improvement in chemical quality is believed to result from the mixing of the downdip water with the less mineralized water from updip directions. In fact, water moving updip from the north and west (Arkansas) toward the large center of pumping at Memphis is harder and more mineralized than water moving downdip from the outcrop area east of Memphis. There are two possible explanations. Either the water moving updip has been in contact with the aquifer for a longer period of time or water from the alluvial aquifer has recharged the "500-foot" sand through breaches in the upper confining bed in eastern Arkansas.

The quality of water withdrawn in the major centers of pumping results from a mixing of the flows from both updip and downdip. This is illustrated on plate 3, map *D*. For example, the quality of water from a well (O–182) at the Parkway well field shows proportional parts of the quality of water from both the east, or updip, and the west, or downdip. Analyses showed a slight increase of hardness and dissolved solids during the period 1945–64 (pl. 3, map *C*), which was probably caused by an increasing contribution of flow from the west, or downdip.

Correspondingly, the slight decreases in hardness and dissolved solids in water from a well (Q–40) in the McCord well field during the period 1958–64 and from a well (K–38) at the Sheahan well field during the period 1952–64 indicate increasing contributions of less mineralized water from an easterly direction. Possibly, some of these local effects could be attributed to water seeping downward from the confining clays as the hydrostatic head is lowered by pumping, but adequate evidence is lacking.

Similar interpretations can be made for each of the other pumping centers in the Memphis area if the relative contributions of water from the updip and downdip directions are accounted for. In general, water moving downdip from southeast to northwest is less mineralized than the water moving updip from northwest to southeast. The chemical quality of the water from any given well is, therefore, dependent upon the percentages of updip and downdip water that contribute to the blend at the well.

## POSSIBLE FUTURE VARIATIONS IN CHEMICAL QUALITY

Memphis, like other metropolitan areas, is rapidly growing and expanding industrially, so that increasing demands for water are certain to continue. To meet these demands, the rate of withdrawal from the "500-foot" sand will continue to increase. This will doubtless require not only an increase in pumping at existing pumping centers but also the development of additional pumping centers. As a result, water levels will continue to decline, perhaps more rapidly in some parts of the area than in others. Thus, changes in the rate and direction of ground-water movement can be anticipated. Because of the relation between water movement and water quality in the "500-foot" sand, the future chemical character of the water supply from the aquifer will depend upon the type and degree of changes in the flow system that are brought about by future activities. Among the activities that could possibly change the flow system are increased rates of pumping from existing pumping centers, development of additional pumping centers, and impoundment of the Wolf River.

### EFFECTS OF INCREASED RATES OF PUMPING

The principal hydrologic effect to be expected from increased rates of pumping from existing pumping centers is increased velocities or rates of ground-water movement. Plate 3, map 3, shows that merely increasing the velocity of ground-water movement will not necessarily change the blend of updip and downdip waters. If, however, the pumping rates of some wells are increased and those of others are not, the blend of water from all wells might be affected.

In the long-term outlook, the rate of pumping from existing centers will probably increase gradually to some limit and then remain relatively constant. If this limit should be reached, the blend of updip and downdip water would either remain relatively constant or vary within narrow limits in response to temporary differences in pumping rates.

### EFFECTS OF ADDITIONAL PUMPING CENTERS

The establishment of additional pumping centers in the Memphis area will create new cones of depression in the piezometric surface. This will locally alter the rate and direction of ground-water movement. Although these effects will diminish with distance away from the new pumping centers, the pattern of flow and, hence, the blend of water at each of the existing pumping centers will be affected. If, for example, a new well field were located updip (southeastward) from the McCord well field, the flow of water from the southeast toward the McCord well field would be intercepted by the new field. As a result, the water supply from the McCord well field could be expected to increase in mineral concentration because the percentage of downdip water in the blend at the McCord pumping station would increase. If a new well field were developed downdip from the Parkway well field, it would intercept the downdip contribution of water to the Parkway Station and result in a decrease in the mineral concentration of the water from the Parkway well field.

The establishment of additional well fields in a northeasterly or southwesterly direction (perpendicular to the direction of dip) from the centers of pumping in Memphis would result in little, if any, change in the chemical quality of the supply from existing centers because the blends of updip and downdip water would not be changed.

Thus, the net effect on the chemical quality of the water from the "500-foot" sand in the Memphis area in the next few decades will depend chiefly upon the location of sites chosen for additional well fields and the location of these new sites relative to the existing pumping centers. Sites updip, or southeastward, from existing pumping centers will result in an increase in the mineral concentration of the water from the existing pumping centers; sites downdip will result in a decrease in the mineral content of the water from the existing centers.

## EFFECTS OF IMPOUNDING THE WOLF RIVER

If, as has been proposed, water were impounded in the Wolf River basin a few miles upstream from the Memphis city limits, some hydrologic effects could be expected. Much of the area that would be inundated in Shelby County by the proposed impoundment is within an area where the upper confining bed is absent and the "500-foot" sand is directly overlain by permeable alluvial materials. As the alluvial materials are hydraulically connected with the river, a free interchange of water between the river and the "500-foot" sand is possible. Moreover, the increased hydrostatic head that would be created by the impoundment would steepen the hydraulic gradient from the impoundment toward the adjoining aquifers. The rate of infiltration that would be induced from the impoundment would depend on the steepness of the hydraulic gradient and the temperature of the water. A high rate of infiltration would result from high viscosity of warm water in summer and fall, and a low rate would result from a low viscosity of cold water in winter and spring. The infiltration rate could be expected to decrease with time as fine sediments accumulate on the bottom of the impoundment, although the rate would still fluctuate with the seasonal fluctuations of water temperature. Hence, the initial favorable condition for induced recharge to the aquifer would, in time, be offset by a decrease in permeability of the alluvial materials underlying the impoundment.

If the proposed impoundment is made, its effect on the chemical quality of water in the "500-foot" sand would depend on the chemical quality of the water in the impoundment, the rate of infiltration into the "500-foot" sand, and the chemical composition of the formations through which the water would move. A comparison of analyses of water from the river and from the "500-foot" sand near the outcrop area shows little difference in their chemical composition in 1964. As the water filtered through the alluvial material, however, the infiltrating water would probably increase in hardness and dissolved solids before reaching the "500-foot" sand. The effects on the quality of the water in the "500-foot" sand would decrease with time as the rate of infiltration from the impoundment decreased, owing to the accumulation of silt on the bottom of the impoundment.

## SUGGESTED SAFEGUARDS

Safeguarding the excellent quality of the water supply in the Memphis area is, and should be, a major concern of those officials responsible for development and operation of public water supplies and for the protection of the water resources. The natural isolation of the "500-foot" sand from surface contamination is a safeguard for the quality of the water supply from the aquifer. This is proved by the fact that after nearly 80 years of development and use, the water supply has undergone little change in quality. Precautions have been taken in the form of local ordinances that specify the construction of wells to prevent surficial seepage, prohibit disposal of wastes into the aquifer, and require proper sealing of unused wells. The vigorous enforcement of these ordinances has helped to insure a lasting supply of excellent quality water for the community.

Continued growth of the Memphis area will result in not only additional development of the aquifer but also in many other activities that could affect the hydrology and the chemical quality of the water resources of the area. Because of these effects, a periodic monitoring of the chemical quality of water at key points would be desirable to provide an additional means of safeguarding the water supply against the intrusion of undersirable or "alien" water. Owing to the slow movement of ground water, an opportunity is afforded to "look upstream" and thereby determine the chemical composition of the future water supply. If the presence of any undesirable element is detected, an advance warning would allow time to eliminate or alleviate the condition before the undesirable or "alien" water reached the withdrawal point in the supply system.

Continued efficiency in developing the water resources of the Memphis area will require specific knowledge of the possible changes in hydrology and chemical quality of water that could result from future development. For optimum economy within the system, alternative actions need to be considered. To make such decisions wisely, water managers need to have adequate knowledge of the effects of proposed developments. Thus, as the water-supply systems expand with the growth of the Memphis area, it will be increasingly necessary to have up-to-date information on the chemical quality of the water.

The selection of key points for periodic sampling should be guided by current knowledge of the movement of water through the "500-foot" sand. One criterion for the selection of sampling sites should be to choose locations that are at least 1 mile "upstream" from the point of withdrawal and along the flow path having the steepest hydraulic gradient. This location would assure that information on the quality of the water supply is available sufficiently in advance of any changes to allow time for corrective action.

Another criterion for the selection of sampling sites should be to choose sites a few miles downgradient from known sources of recharge. As most of the recharge to the "500-foot" sand enters the aquifer in the outcrop area east of Memphis, a network of six or eight wells scattered along the western margin of the outcrop belt would make possible the determination of the chemical composition of the water as it enters the "500-foot" sand. Similarly, a series of wells along the Mississippi River would enable the determination of the chemical composition of the water moving into the Memphis area from eastern Arkansas.

The periodic sampling and analysis of the water moving through the "500-foot" sand using these criteria would assure the availability of up-to-date water-quality data on which to base decisions on the development and use of the supply.

## CONCLUSIONS

1. The water in the "500-foot" sand is less mineralized than the water in any other aquifer in the area.
2. The chemical composition of the water in the "500-foot" sand has changed little since 1886, when the first well was drilled.
3. Variations in the chemical composition of water in the "500-foot" sand are characterized by proportional increases or decreases in the concentrations of the dominant ions. In general, the concentrations increase as the water moves northwestward (downdip).
4. The chemical quality of water withdrawn in the major centers of pumping is the result of mixing of water moving from updip and downdip directions.
5. The blends of updip and downdip water at established pumping centers will remain almost constant until additional well fields are established. If an additional well field is developed on the updip side of an existing pumping center, the water from the existing pumping center will increase in mineral content. Conversely, if the new well field is downdip from an existing well field, the water from the existing well field will decrease in mineral content.
6. The impoundment of the Wolf River a few miles upstream from Memphis would have little effect on the chemical quality of water in the "500-foot" sand.
7. Monitoring the chemical quality of water in the "500-foot" sand at selected points in the flow system and adjusting the distribution of pumping as needed is suggested as an additional safeguard to conserve the excellent quality of the water supply.

8. Hydrologic and chemical quality data indicate that the "500-foot" sand in the Memphis area will provide an abundance of water of excellent quality for years to come.

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