POTENTIAL FOR LEAKAGE AMONG PRINCIPAL AQUIFERS IN THE MEMPHIS AREA, TENNESSEE

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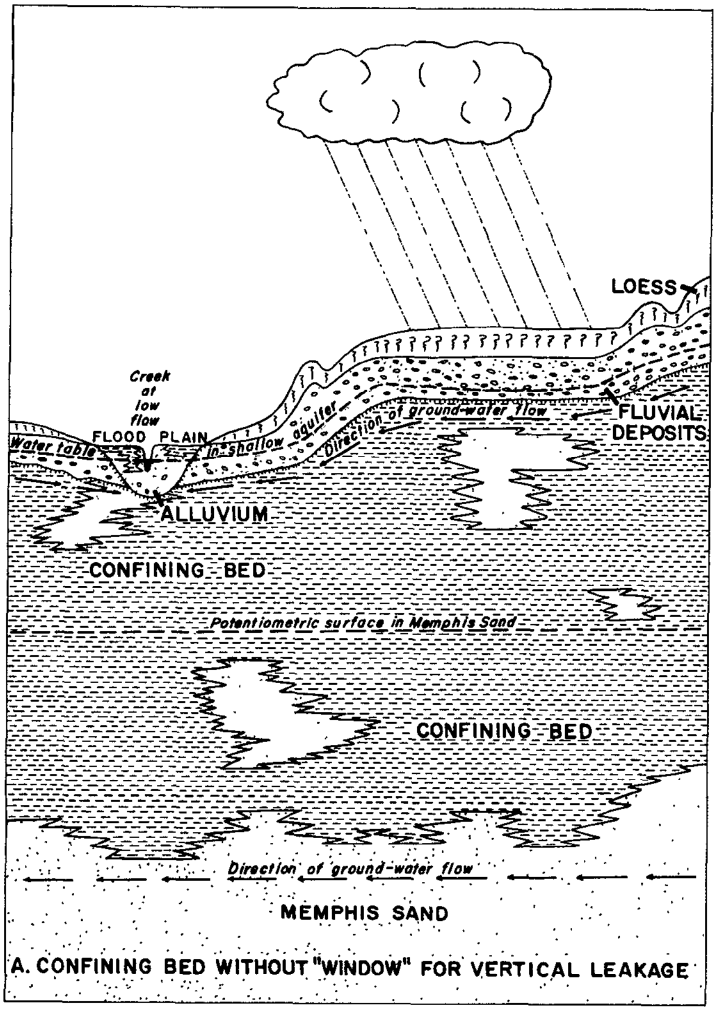
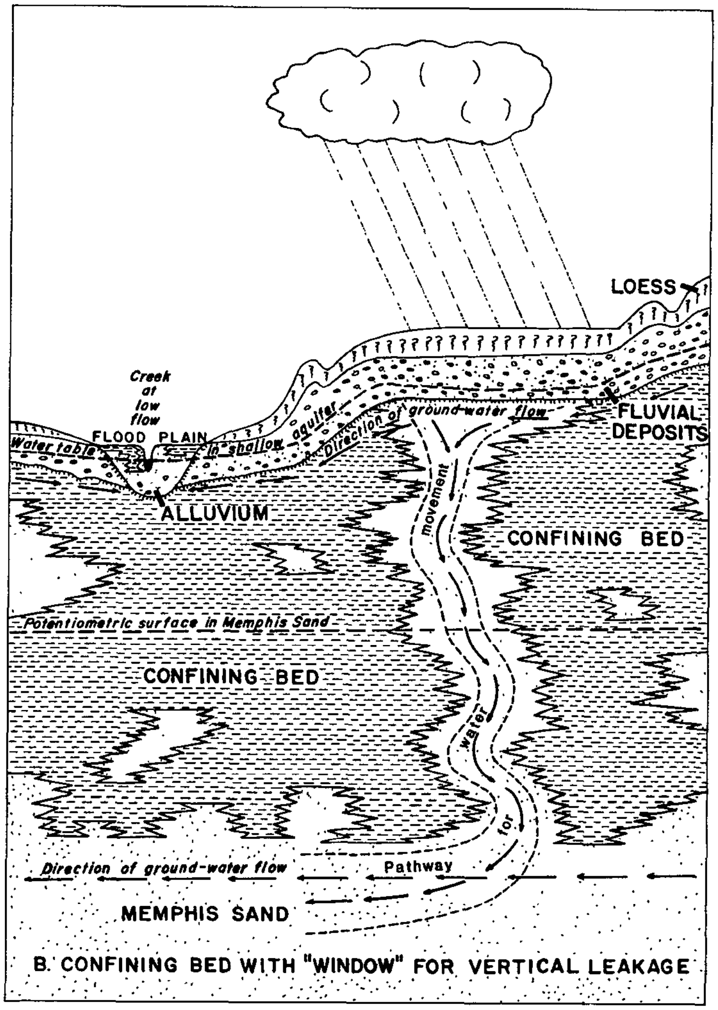
Water-Resources Investigations Report 85-4295



A. CONFINING BED WITHOUT "WINDOW" FOR VERTICAL LEAKAGE



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Prepared in cooperation with the

TENNESSEE DEPARTMENT OF HEALTH AND ENVIRONMENT,
OFFICE OF WATER MANAGEMENT
and the
CITY OF MEMPHIS,
MEMPHIS LIGHT, GAS AND WATER DIVISION

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D. D. Graham and W. S. Parks

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Memphis, Tennessee

1986

UNITED STATES DEPARTMENT OF THE INTERIOR

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CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS

Factors for converting inch-pound units to International System of Units (SI) are shown to four significant digits.

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon (gal)	0.003785	cubic meter (m^3)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Well-Numbering System: Wells are identified according to the numbering system used by the U.S. Geological Survey throughout Tennessee. The well number consists of three parts: (1) an abbreviation of the name of the county in which the well is located; (2) a letter designating the 7 1/2-minute quadrangle or 7 1/2-minute quadrant of the 15-minute quadrangle, on which the well is plotted; and (3) a number generally indicating the numerical order in which the well was inventoried. The symbol Sh:P-99, for example, indicates that the well is located in Shelby County on the "P" quadrangle and is identified as well 99 in the numerical sequence. Quadrangles are lettered from left to right, beginning in the southwest corner of the county.

POTENTIAL FOR LEAKAGE AMONG PRINCIPAL AQUIFERS IN THE MEMPHIS AREA, TENNESSEE

D. D. Graham and W. S. Parks

ABSTRACT

The principal aquifers in the Memphis area consist primarily of sand or sand and gravel, and the confining beds consist of clay, silt, sand, and lignite. Water-table aquifers are the alluvium and the fluvial deposits of Quaternary age; artesian aquifers are the Memphis Sand and the Fort Pillow Sand of Tertiary age. The Jackson Formation and upper part of the Claiborne Group serve as the confining bed separating the water-table aquifers from the Memphis Sand, and the Flour Island Formation separates the Memphis Sand from the Fort Pillow Sand.

Thickness of the Jackson-upper Claiborne confining bed ranges from 0 to 360 feet, and aggregate thickness of clay beds thicker than 10 feet in this confining bed ranges from 0 to 250 feet. The Jackson-upper Claiborne confining bed is thin or absent in, at least, four areas in the Memphis urban area--in the eastern part along Wolf River, in the southeastern part along Nonconnah Creek, in the south-central part along Nonconnah and Johns Creeks, and in the western part along the Mississippi River. Thickness of the Flour Island confining bed ranges from 160 to 310 feet, and aggregate thickness of clay beds thicker than 10 feet ranges from 70 to 240 feet.

Differences in total hydraulic head among the principal aquifers in the Memphis urban area result in vertical hydraulic gradients which create a potential for interaquifer exchange of water. Throughout this area, the gradient is downward from the water-table aquifers to the Memphis Sand. In the central part of the Memphis urban area, the vertical hydraulic gradient is upward from the Fort Pillow Sand to the Memphis Sand, and in the eastern and western parts, it is downward from the Memphis Sand to the Fort Pillow Sand.

The vertical distribution of carbon-14 data for water from the fluvial deposits, Memphis Sand, and Fort Pillow Sand shows an increase in the relative age of the water with depth. The areal distribution of carbon-14 data for water from the upper part of the Memphis Sand indicates that relatively recent water has been brought into the major cone of depression in the potentiometric surface of the Memphis Sand, either by horizontal movement or from downward vertical leakage. Carbon-14 and tritium isotope data indicate that some water derived from relatively recent precipitation has entered the Memphis Sand in the vicinity of the southern part of the Sheahan well field.

The normal, near-surface geothermal gradient in the Memphis area was determined to be 0.6 degrees Celsius per 100 feet. Deviations from the normal geothermal gradient, in areas affected by intense pumping from the Memphis Sand, indicate that downward vertical leakage occurs from the water-table aquifers through the Jackson-upper Claiborne confining bed to the Memphis Sand. The areal distribution of the depth to the coolest water in the Memphis urban area indicates that most of this leakage occurs within the major cone of depression in the potentiometric surface of the Memphis Sand.

The velocity of downward vertical leakage of water from the Memphis Sand through the Flour Island confining bed to the Fort Pillow Sand was determined to be 6.6×10^{-4} feet per day by analysis of borehole temperature data from an observation well in the northeastern part of the Memphis area. From this velocity and the head difference between the Memphis Sand and the Fort Pillow Sand at this locality, the hydraulic conductivity of the Flour Island confining bed was determined to be 1.14×10^{-2} feet per day.

INTRODUCTION

Artesian aquifers in the Memphis area have served as reliable sources of water for about 100 years. Since 1886, more than 3.3 trillion gallons of water have been withdrawn from the Memphis Sand ("500-foot" sand) and the Fort Pillow Sand ("1,400-foot" sand). Currently, these aquifers serve as the only major sources of water for municipal and industrial use. Although withdrawals in 1984 averaged about 190 million gallons per day (Mgal/d) and are likely to increase to meet the demands of an expanding metropolitan area, no serious problems of ground-water availability are anticipated through the next half century (U.S. Army Corps of Engineers, 1981). Extensometer data indicate that land subsidence, a potential problem where this much water is withdrawn from unconsolidated aquifers, is not occurring at Memphis (Graham, 1982, p. 15-17).

The discovery by the U.S. Environmental Protection Agency (1979) that landfills containing hazardous wastes exist in the Memphis area has focused public awareness on a significant potential problem--the vulnerability of the ground-water resource to contamination. The possibility that leachates from hazardous-waste sites and other contaminants from near-surface sources might enter the water-table aquifer and be transmitted downward through the confining bed to the underlying Memphis Sand has become a matter of public concern.

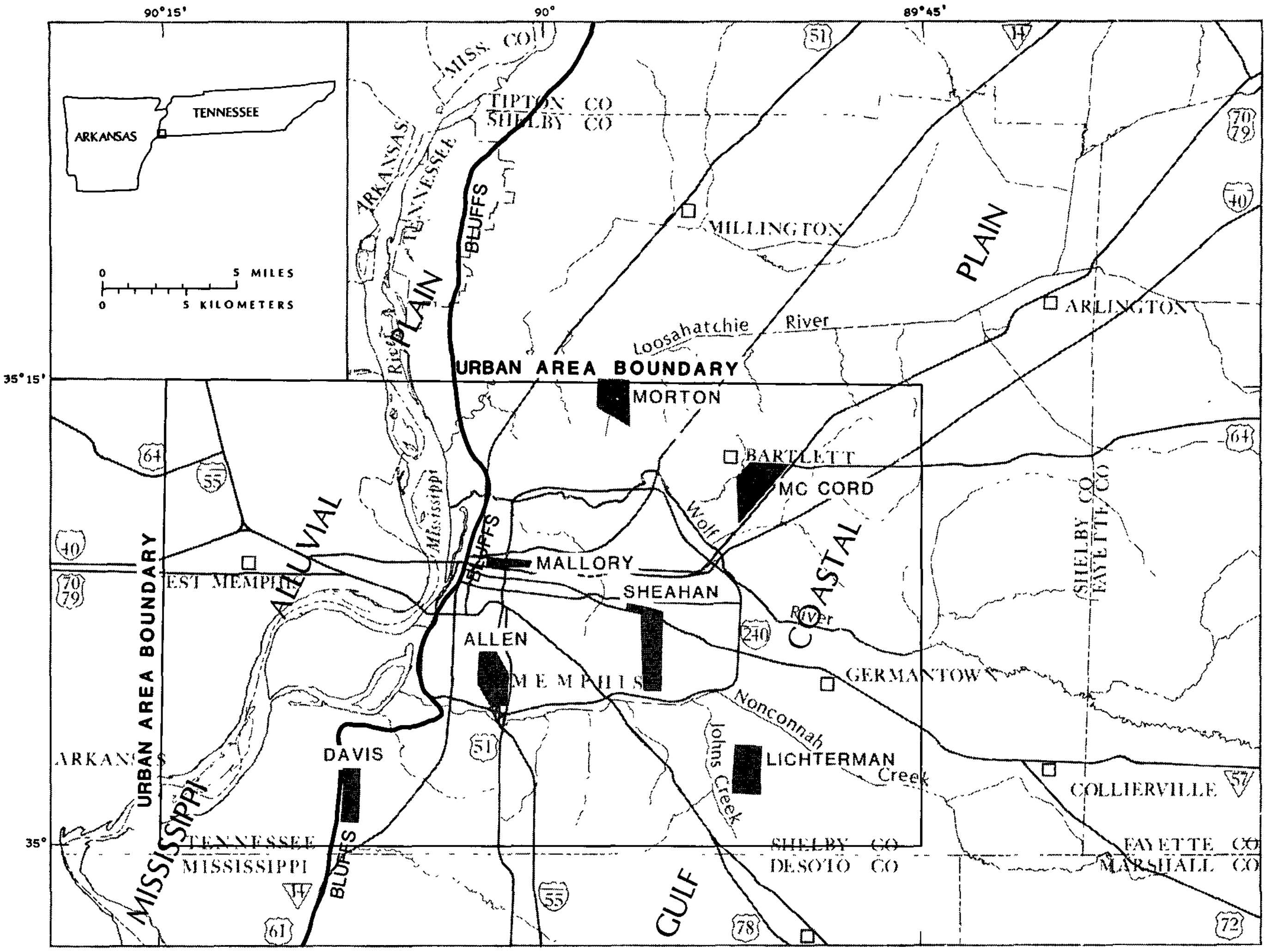
Waste-disposal practices at Memphis prior to 1969, when the Tennessee Legislature passed the Tennessee Solid Waste Disposal Act, were summarized by Parks and Lounsbury (1976, p. 27-30). Recent investigations by the U.S. Geological Survey indicate that leachates from several abandoned landfills containing hazardous wastes have been entering the water-table aquifer (Parks and others, 1981, 1982; Graham, 1985). No contamination of the underlying Memphis Sand has yet been detected (Graham, 1982, p. 15; 1985, p. 33). Nevertheless, the presence of these landfills containing hazardous wastes has intensified the need for a more complete understanding of the freshwater aquifer system of the Memphis area.

To better assess the potential for interaquifer exchange of ground water, the Geological Survey, in cooperation with the Tennessee Department of Health and Environment, Office of Water Management, and the City of Memphis, Memphis Light, Gas and Water Division (MLGW), initiated this investigation in 1984. Land-use decisions, including the selection of sites for future municipal well fields and landfills, would benefit from a knowledge of the location of the greatest potential for leakage into the Memphis Sand, the aquifer of primary importance as a source of water supply.

The area of this investigation is the "Memphis area" as defined in recent reports of the Geological Survey (Criner and Parks, 1976, p. 2). It comprises about 1,300 mi^2 and includes parts of three states--Tennessee, Arkansas, and Mississippi (fig. 1). Most of the detailed maps prepared for this investigation were limited to the area of the eight Geological Survey 7 1/2-minute quadrangles that include the Memphis urban area. This area comprises about 485 mi^2 and is referred to throughout this report as the "Memphis urban area" (fig. 1). The limitation on the size of the area studied in detail was necessary because of the sparsity of wells with geophysical logs and of water-level observation wells outside the eight-quadrangle area.

Previous Investigations

Information concerning the ground-water hydrology and general geology of the principal shallow aquifers in the Memphis area are described in reports by Safford (1890), Glenn (1906), Wells (1931, 1933), Fisk (1944), Kazmann (1944), Schneider and Cushing (1948), Schneider and Blankenship (1950), Caplan (1954), Lanphere (1955), Stearns and Armstrong (1955), Stearns (1957), Criner and Armstrong (1958), Plebuch (1961), Criner and others (1964), Cushing and others (1964), Krinitzsky and Wire (1964), Boswell and others (1965, 1968), Moore (1965), Nyman (1965), Bell and Nyman (1968), Hosman and others (1968), Cushing and others (1970), Parks (1973, 1974, 1975, 1977, 1978, 1979a, 1979b), Criner and Parks (1976), Parks and Lounsbury (1976), Graham (1979, 1982, 1985), Rima (1979), Parks and others (1981, 1982), and Brahana (1982).



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

Figure 1.--Major physiographic subdivisions in Memphis area and the Memphis urban area with locations of Memphis Light, Gas and Water well fields.

Several previous investigations have pointed to the possibility that water from the shallow water-table aquifers could enter the Memphis Sand by vertical downward leakage. Criner and Armstrong (1958, p. 17) cited the results of pumping tests of wells in the Memphis Sand that indicated a contribution of water from a source other than the aquifer. They indicated that the likely source of this additional water was from the fluvial deposits (terrace deposits in early reports). They also indicated that observed water levels in the Memphis Sand were higher than would be predicted based on computed values of transmissivity and storage and the amount of water being withdrawn from the aquifer.

Criner and others (1964, p. 16, 18, 30) indicated that in some parts of the Memphis area the upper confining bed is absent and the Memphis Sand is overlain directly by the fluvial deposits and that some recharge to the Memphis Sand from the fluvial deposits occurs in these areas. The fact that Nonconnah Creek, formerly a perennial stream, has periods of abnormally low flow in its lower reach during part of the year and is sometimes dry during the latter part of the dry season is cited (p. 30) as evidence that some recharge to the Memphis Sand is derived from the water-table aquifers.

Moore (1965, p. F27-F29) indicated that some water from the fluvial deposits could be entering the Memphis Sand in the southern part of Shelby County. The evidence cited is a lowering of the water table in the fluvial deposits and the fact that Nonconnah Creek is dry during part of the year. He also indicated, without citing specific evidence, that seepage from overlying formations into the Memphis Sand may occur in isolated areas outside of Shelby County.

According to Nyman (1965, p. B6-B8), test drilling along the Wolf River in the Germantown-Collierville area by the U.S. Army Corps of Engineers indicated that at places the alluvium rests directly on the Memphis Sand and, where this occurs, water can move freely from one unit to the other. He further suggested a possible hydraulic connection between the Memphis Sand and Nonconnah Creek in areas where the capping clay is thin or absent north of the Lichterman well field. A series of discharge measurements along Nonconnah Creek just south of the southern part of the Sheahan well field indicated a loss of streamflow, which could be caused by seepage into the Memphis Sand (Nyman, 1965, p. B8).

Bell and Nyman (1968, p. 7-8) estimated that downward leakage through the upper confining bed of the Memphis Sand in the Memphis area amounted to about 2 Mgal/d. They postulated that in some areas the confining bed may have been breached by erosion, creating "windows" through which water could enter the Memphis Sand from overlying formations. They also indicated that the confining bed may be locally absent beneath the alluvial deposits in eastern Arkansas, west of Memphis.

Criner and Parks (1976, p. 22) speculated that leakage induced by a deepening of the major cone of depression in the potentiometric surface of the Memphis Sand might be, in part, the cause for a decrease in the rate of water-level decline in the Memphis area.

Parks and Lounsbury (1976, p. 26) suggested that contamination of the Memphis Sand could occur if contaminants enter into and concentrate in the shallow water-table aquifers. "Windows" in the confining bed might then provide a pathway for the downward vertical movement of water and contaminants into the Memphis Sand. As a result of geological mapping of the Memphis urban area by Parks (1973, 1974, 1975, 1977, 1978, 1979a, 1979b), it was concluded that areas exist where the confining bed is thin or absent.

Purpose and Scope

The purpose of this investigation was to make an assessment of the potential for leakage of water among the principal aquifers in the Memphis area with special emphasis on the potential for downward vertical leakage from the water-table aquifers to the Memphis Sand. This investigation consisted of the following elements:

* geologic information from geophysical logs of wells and test holes was compiled and interpreted, and maps showing the thickness of the confining beds above and below the the Memphis Sand and the aggregate thickness of clay beds within these confining beds were prepared;
* water-level data from the shallow water-table aquifers, the Memphis Sand, and the Fort Pillow Sand were collected and maps showing the configuration of the water table and potentiometric surfaces in these aquifers along with derivative maps showing head differences between the aquifers were prepared;
* concentrations of selected isotopes of carbon and hydrogen in water from the principal aquifers were determined and the resulting information was evaluated for its relevance as an indication of leakage;
* temperature data, collected using borehole geophysical methods, were compiled and evaluated to establish the normal geothermal gradient in the area and to interpret deviations from the normal gradient as indications of vertical inter-aquifer water movement; and
* a summary assessment of the potential for leakage was made.

Physiographic Setting

The Memphis area is situated in two major physiographic subdivisions (fig. 1). The eastern three-quarters of the area is in the Gulf Coastal Plain section and the western one-quarter is in the Mississippi Alluvial Plain section of the Coastal Plain physiographic province (Fenneman, 1938). The principal river in the area is the Mississippi River; the major tributaries are the Wolf River, the Loosahatchie River, and Nonconnah Creek.

The Gulf Coastal Plain is characterized by gently rolling to steep topography formed as a result of the erosion of geologic formations of Tertiary and Quaternary age. During the later stages of Pleistocene glaciation, this topography was covered by a relatively thick blanket of loess that makes up the present land surface. The gently rolling to steep topography is broken at many places by the flat-lying alluvial plains of the streams that cross the area. Perhaps the most distinctive feature of the Gulf Coastal Plain is the loess-covered bluffs that rise abruptly above the Mississippi Alluvial Plain at its eastern boundary. Land-surface altitudes in the Gulf Coastal Plain are as low as 190 feet above sea level at the mouth of Nonconnah Creek in southwestern Shelby County, Tenn., and are as high as 470 feet above sea level in southwestern Fayette County, Tenn. Maximum local relief between the Gulf Coastal Plain and the Mississippi Alluvial Plain is about 200 feet along the bluffs in northwestern Shelby County.

The Mississippi Alluvial Plain is flat-lying and is characterized by features of fluvial deposition--point bars, abandoned channels, and natural levees. Land-surface altitudes are as low as 180 feet above sea level on the banks of the Mississippi River in extreme northwestern DeSoto County, Miss., and as high as 230 feet above sea level adjacent to the bluffs in southwestern Tipton County, Tenn. Maximum local relief is probably no more than 10 or 20 feet, except where the alluvial plain has been built up above flood levels by man-emplaced fill.

HYDROGEOLOGIC SETTING

The Memphis area is in the north-central part of the Mississippi embayment, a broad trough or syncline that plunges southward along an axis which approximates the Mississippi River (Cushing and others, 1964, p. B21). This trough or syncline is filled with a wedge of several thousand feet of sediments of Cretaceous, Tertiary, and Quaternary age that dip gently westward into the embayment and southward down its axis. A summary of the post-Midway geologic units underlying the Memphis area and the hydrologic significance of the units is given in table 1.

The principal freshwater aquifers in the Memphis area, in descending order, are: (1) the alluvium, (2) the fluvial (terrace) deposits, (3) the Memphis Sand ("500-foot" sand), and (4) the Fort Pillow Sand ("1,400-foot" sand). The alluvium and fluvial deposits make up the shallow water-table (unconfined) aquifers, which are separated from the underlying artesian aquifers by the Jackson-upper Claiborne confining bed. The Memphis Sand and the Fort Pillow Sand artesian (confined) aquifers are separated by the Flour Island confining bed. Most of the water used for municipal and industrial supplies in the Memphis area is derived from the Memphis Sand and Fort Pillow Sand. Hydrogeologic sections showing principal aquifers and confining beds are shown in figure 2.

Water-Table Aquifers

Water-table aquifers in the Memphis area consist of the alluvium and the fluvial deposits (table 1). The alluvium consists of sand, gravel, silt, and clay that occur beneath the Mississippi Alluvial Plain and the alluvial plains of streams draining the Gulf Coastal Plain. The upper part generally consists of fine sand, silt, and clay and the lower part of sand and gravel. Thickness of the alluvium ranges from 0 to 175 feet. It is commonly 100 to 150 feet thick beneath the Mississippi Alluvial Plain and is generally less than 50 feet thick beneath the alluvial plains of the Wolf River, the Loosahatchie River, and Nonconnah Creek in the Gulf Coastal Plain. In the Memphis area, the alluvium provides water to many domestic, farm, and irrigation wells in the

Table 1.--Post-Midway geologic units underlying the Memphis area and their hydrologic significance

[Alluvium is shown here in the conventional position as the youngest stratigraphic unit. Actually it almost nowhere overlies the loess but may overlie any of the older stratigraphic units]

System	Series	Group	Stratigraphic unit	Thickness	Lithology and hydrologic significance
Quaternary	Holocene and Pleistocene		Alluvium	0-175	Sand, gravel, silt, and clay. Underlies the Mississippi Alluvial Plain and alluvial plains of streams in the Gulf Coastal Plain. Thickest beneath the Alluvial Plain, where commonly between 100 and 150 feet thick; generally less than 50 feet thick elsewhere. Provides water to domestic, farm, industrial, and irrigation wells in the Mississippi Alluvial Plain.
	Pleistocene		Loess	0-65	Silt, silty clay, and minor sand. Principal unit at the surface in upland areas of the Gulf Coastal Plain. Thickest on the bluffs that border the Mississippi Alluvial Plain; thinner eastward from the bluffs. Tends to retard downward movement of water providing recharge to the fluvial deposits.
Quaternary and Tertiary(?)	Pleistocene and Pliocene(?)		Fluvial deposits (terrace deposits)	0-100	Sand, gravel, minor clay and ferruginous sandstone. Generally underlie the loess in upland areas, but are locally absent. Thickness varies greatly because of erosional surfaces at top and base. Provides water to many domestic and farm wells in rural areas.
Tertiary	Eocene	?	Jackson Formation and upper part of Claiborne Group, includes Cockfield and Cook Mountain Formations (capping clay)	0-360	Clay, silt, sand, and lignite. Because of similarities in lithology, the Jackson Formation and upper part of the Claiborne Group cannot be reliably subdivided based on available information. Most of the preserved sequence is the Cockfield and Cook Mountain Formations undivided, but locally the Cockfield may be overlain by the Jackson Formation. Serves as the upper confining bed for the Memphis Sand.
		Claiborne	Memphis Sand ("500-foot" sand)	500-890	Sand, clay, and minor lignite. Thick body of sand with lenses of clay at various stratigraphic horizons and minor lignite. Thickest in the southwestern part of the Memphis area; thinnest in the northeastern part. Principal aquifer providing water for municipal and industrial supplies east of the Mississippi River; sole source of water for the City of Memphis.
	?	Wilcox	Flour Island Formation	160-310	Clay, silt, sand, and lignite. Consists primarily of silty clays and sandy silts with lenses and interbeds of fine sand and lignite. Serves as the lower confining bed for the Memphis Sand and the upper confining bed for the Fort Pillow Sand.
	Paleocene		Fort Pillow Sand ("1400-foot" sand)	125-305	Sand with minor clay and lignite. Sand is fine to medium. Thickest in the southwestern part of the the Memphis area; thinnest in the northern and northeastern parts. Once the second principal aquifer supplying the City of Memphis; still used by an industry. Principal aquifer providing water for municipal and industrial supplies west of the Mississippi River.
			Old Breastworks Formation	180-350	Clay, silt, sand, and lignite. Consists primarily of silty clays and clayey silts with lenses and interbeds of fine sand and lignite. Serves as the lower confining bed for the Fort Pillow Sand, along with the underlying Porters Creek Clay and Clayton Formation of the Midway Group.

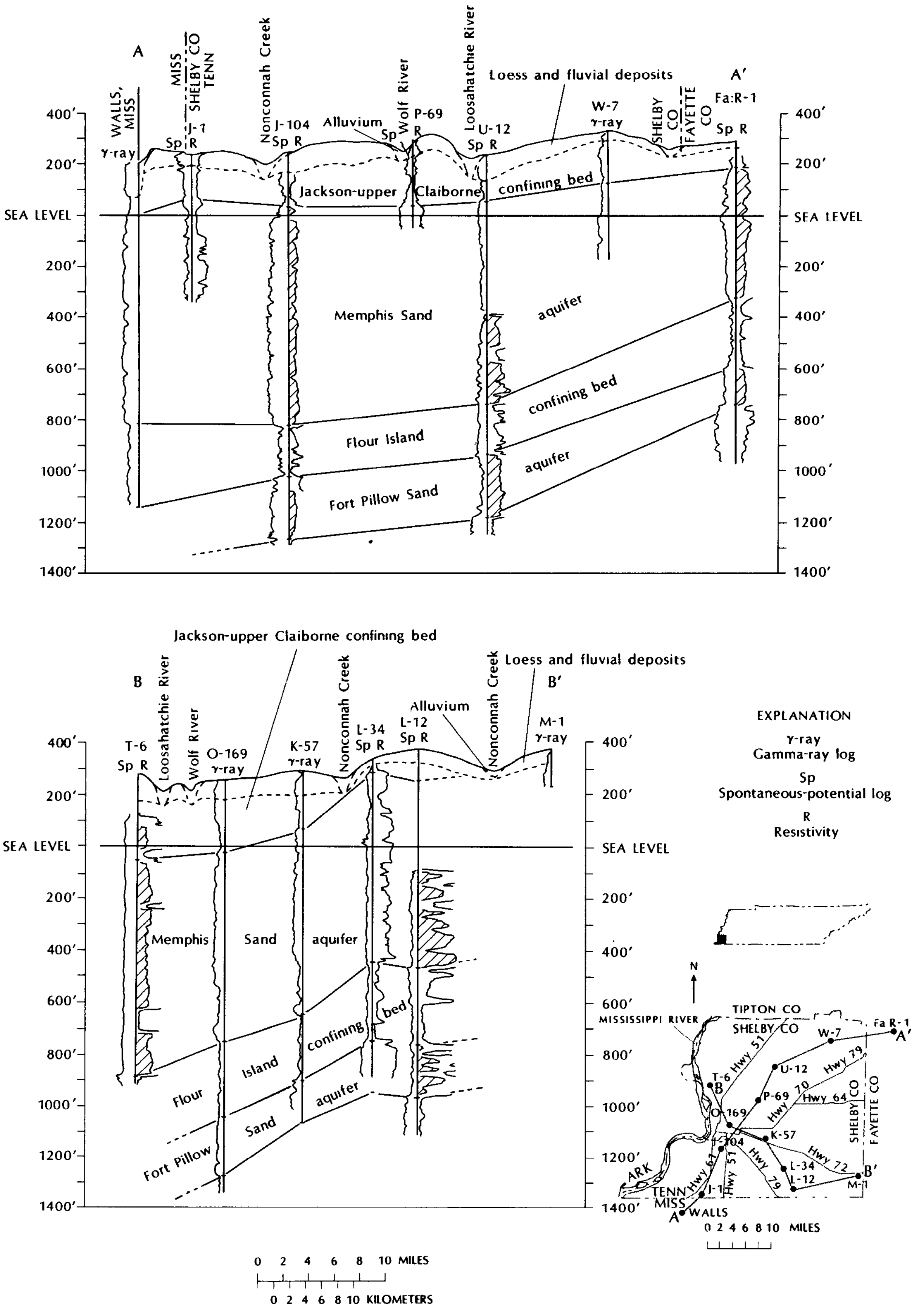


Figure 2.--Hydrogeologic sections showing the principal aquifers and confining beds in the Memphis area (modified from Criner and others, 1964, plate 1).

Mississippi Alluvial Plain of Arkansas and Mississippi, but the alluvium is not presently used as a major source of ground water in Tennessee.

Fluvial deposits occur beneath the uplands and valley slopes of the Gulf Coastal Plain and are the remnants of ancient alluvial deposits of either present streams or an ancient drainage system (Russell and Parks, 1975, p. B30). The fluvial deposits consist primarily of sand and gravel with minor lenses of clay and thin layers of iron-oxide cemented sandstone or conglomerate. These fluvial deposits range from 0 to 100 feet in thickness. The thickness is highly variable because of erosional surfaces at both top and base; locally the fluvial deposits are absent. In the Memphis area, the fluvial deposits provide water to many domestic and farm wells in rural areas of the Gulf Coastal Plain. Many of these wells, however, are being abandoned as public water-supply systems are extended into these areas.

Recharge to the shallow water-table aquifers is primarily from the infiltration of rainfall. Recharge is greatest during the winter and spring when rainfall is greatest and evaporation and transpiration are least. Immediately adjacent to streams, some recharge to the alluvium occurs during floods, when stream stage is temporarily higher than the water table. Generally, however, ground water is discharged to the streams and sustains base flow. Where the alluvium and the fluvial deposits coexist at the juncture between the lower valley slopes and alluvial plains, the water-table aquifers are in direct hydraulic connection.

Artesian Aquifers

The principal artesian aquifers in the Memphis area are the Memphis Sand and the Fort Pillow Sand (table 1). The Memphis Sand occurs in the subsurface throughout the Memphis area. The upper part of the aquifer is at or near the surface in the southeastern part of the Memphis area, where the upper confining bed is absent (Criner and Parks, 1976, fig. 5). The Memphis Sand consists of a thick body of fine to very coarse sand with subordinate lenses of clay and silt at various stratigraphic horizons. Locally, the clay, silt, or sand contains thin lenses of lignite. The Memphis Sand ranges from 500 to 890 feet in thickness. It is thinnest in the northeastern part of the Memphis area in northwestern Fayette County, Tenn., and thickest near the Mississippi River in southwestern Shelby County, Tenn.

The Memphis Sand currently provides about 95 percent of the water used for municipal and industrial water supplies in the Memphis area and is the sole source of water for the City of Memphis. The Memphis Sand was first used as a source of water at Memphis in 1886; since then, withdrawals have increased at an irregular rate (Criner and Parks, 1976). In 1984, municipal and industrial pumpage from the Memphis Sand in the Memphis area averaged about 180 Mgal/d.

Recharge to the Memphis Sand generally occurs east of the Memphis area, where it is at or near the surface, principally along a broad belt trending northeastward across western Tennessee (Graham, 1982, fig. 3). Within this belt, recharge occurs by infiltration of rainfall directly into the Memphis Sand or by downward seepage of water from the overlying water-table aquifers. Water entering the aquifer at the outcrop area moves slowly westward towards the axis of the Mississippi embayment (Graham, 1982, p. 8).

The Fort Pillow Sand occurs in the subsurface throughout the Memphis area. It consists primarily of fine to medium sand with some local interbeds of clay and lignite. The Fort Pillow Sand ranges from 125 to 305 feet in thickness. It is thinnest in northern Shelby and northwestern Fayette Counties, Tenn., and is thickest in Crittenden County, Ark. In 1984, pumpage from the Fort Pillow Sand in the Memphis area averaged about 10 Mgal/d or about 5 percent of the water used for municipal and industrial supplies. MLGW ceased pumping from the Fort Pillow Sand in 1974 and now regards this aquifer as a supplementary source, if needed, to meet future demands (Criner and Parks, 1976, p. 10).

Recharge to the Fort Pillow Sand occurs east of Memphis, where it is at or near the surface, principally along a belt trending northeastward across western Tennessee. The Fort Pillow crops out immediately east of the Memphis Sand. The stratigraphic relation of the Fort

Pillow Sand and the Memphis Sand in the subsurface in the eastern part of the recharge area is not completely understood. In this area, the Memphis Sand may overlap the confining bed separating these two aquifers and may directly overlie the Fort Pillow Sand. If so, these two artesian aquifers would share a common source of recharge. Water entering at or near the outcrop area moves slowly westward towards the axis of the Mississippi embayment (Graham, 1982, p. 8).

Confining Beds

The principal artesian aquifers of the Memphis area are separated from one another and from the water-table aquifers by layers of sediments--clay, silt, fine sand, and lignite--of significantly lower hydraulic conductivity than the aquifer sediments--fine to very coarse sand and gravel (table 1). These layers of low hydraulic conductivity areally act as confining beds which inhibit vertical interaquifer exchange of water. These confining beds are variable in lithology and thickness, which results in local differences in the ability of the beds to retard movement of water from one aquifer to another. Principal confining beds in the Memphis area are the Jackson Formation-upper Claiborne Group and the Flour Island Formation. Maps of the thickness of these confining beds and clay beds thicker than 10 feet within the confining beds (figs. 3-6) are based on a correlation of electric and gamma-ray logs (fig. 2).

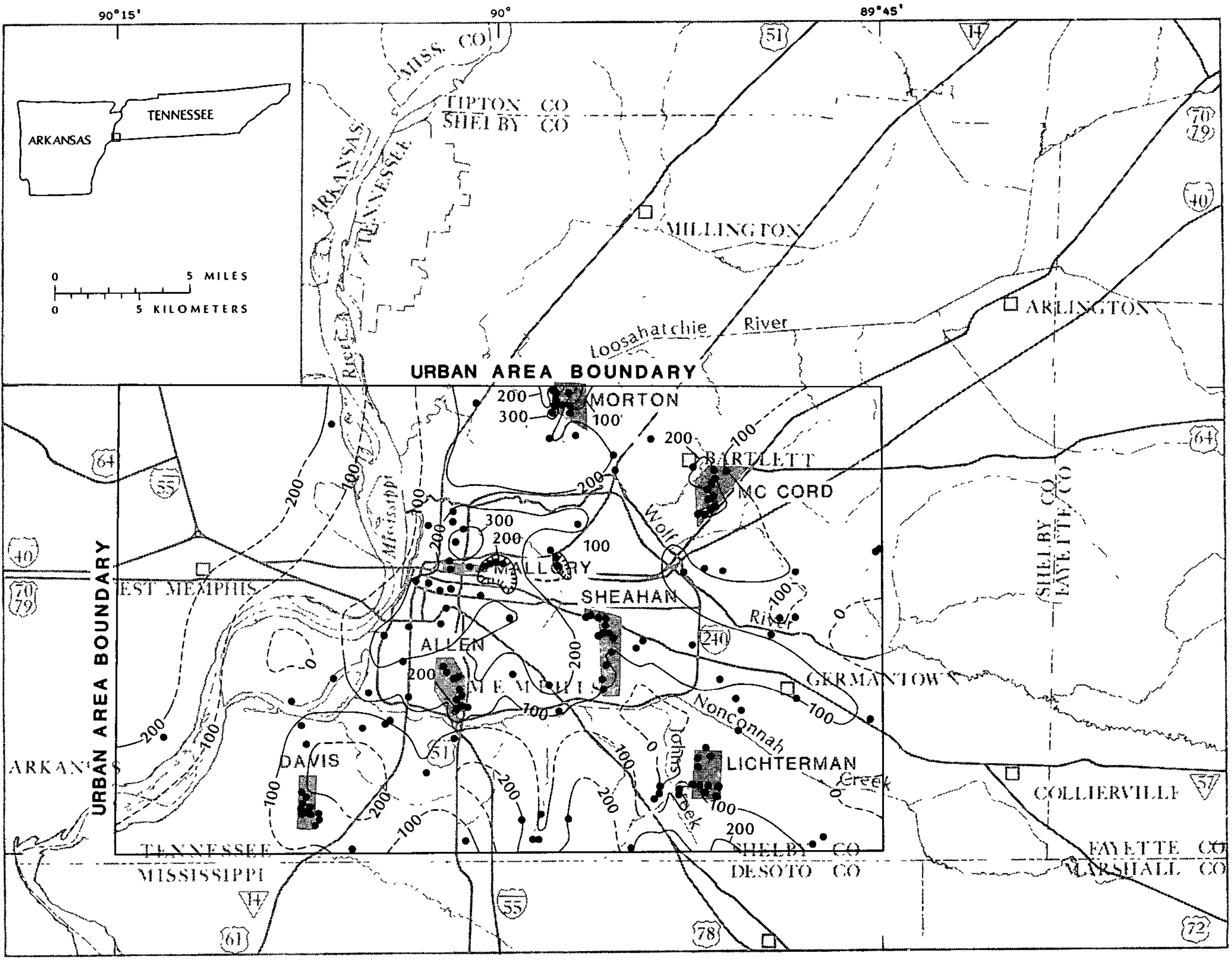
The Jackson Formation and upper part of the Claiborne Group serve as a confining bed between the water-table aquifers and the Memphis Sand. Because of lithologic similarities, the Jackson Formation and upper part of the Claiborne Group cannot be reliably subdivided in the subsurface of the Memphis area based on available information. This confining bed includes strata of the Cockfield and Cook Mountain Formations undivided in the upper part of the Claiborne Group, and locally, of the Jackson Formation. The Jackson-upper Claiborne confining bed consists primarily of clay, silt, and fine sand with minor lenses of lignite. Within the confining bed, the sediments are very lenticular, and locally, individual beds may not be areally extensive. The clays in the confining bed are predominantly of the montmorillonite type (Nyman, 1965, p. B5; Bell and Nyman, 1968, p. 20). For the present investigation, the clay, silt, sand, and lignite of the Jackson Formation and the upper part of the Claiborne Group were considered, for mapping purposes, to be a single hydrologic unit.

The thickness of the Jackson-upper Claiborne confining bed is highly variable in the Memphis urban area, ranging from 0 to 360 feet (fig. 3). Because this confining bed contains much fine sand and sandy silt, a better indicator of areal differences in its ability to retard the movement of water between the water-table aquifers and the Memphis Sand is the aggregate thickness of clay beds within the unit. Aggregate thickness of clay beds thicker than 10 feet in the Jackson-upper Claiborne confining bed ranges from 0 to 250 feet (fig. 4).

The Flour Island Formation underlies the Memphis Sand and separates it from the deeper Fort Pillow Sand. This lower confining bed of the Memphis Sand consists primarily of silty clay and sandy silt with lenses of fine sand and lignite that are not areally extensive. The thickness of the Flour Island Formation is variable in the Memphis urban area, ranging from 160 to 310 feet (fig. 5). The Flour Island is thickest in the southeastern and northwestern parts of the area and thinnest near the center. Aggregate thickness of clay beds thicker than 10 feet within this confining bed ranges from about 70 to 240 feet (fig. 6). Aggregate thickness of clays is least near the central and northeastern parts of the Memphis urban area and greatest in the southeastern part.

EVIDENCES FOR LEAKAGE

The principal evidences for leakage considered during the present investigation are: (1) variations in the thicknesses of the confining beds and the aggregate thicknesses of clay beds within the confining beds, (2) differences in hydraulic heads between the principal aquifers, (3) vertical and areal variations in carbon-14 and tritium concentrations in water from the aquifers, and (4) local deviations from the normal geothermal field as shown by geophysical temperature logs.



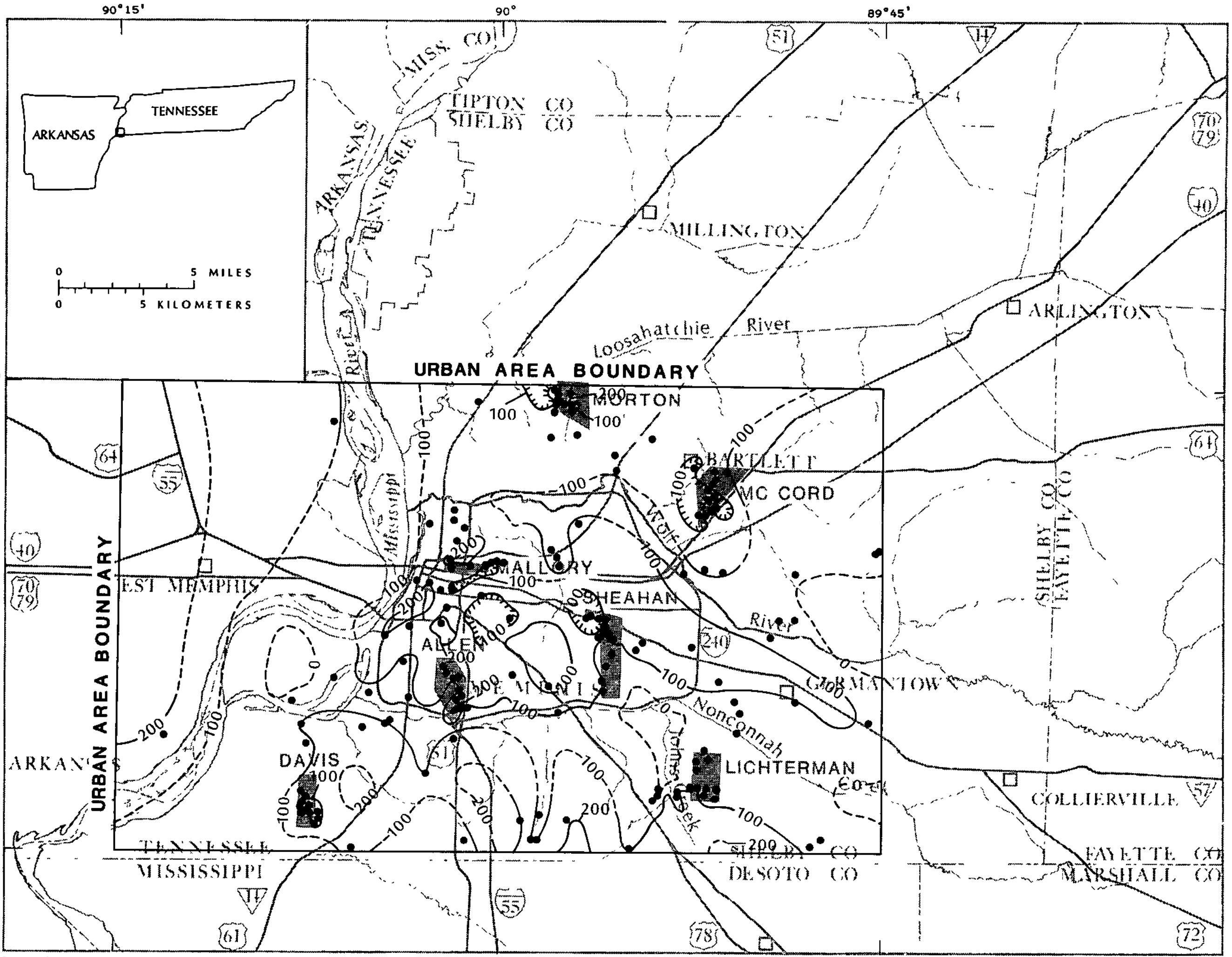
Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

EXPLANATION

—100— LINE OF EQUAL THICKNESS OF THE JACKSON-UPPER CLAIBORNE CONFINING BED--Dashed where approximately located. Hachures indicate depression. Interval 100 feet.

● WELL WITH GEOPHYSICAL LOG

Figure 3.--Thickness of the Jackson-upper Claiborne confining bed in the Memphis urban area.



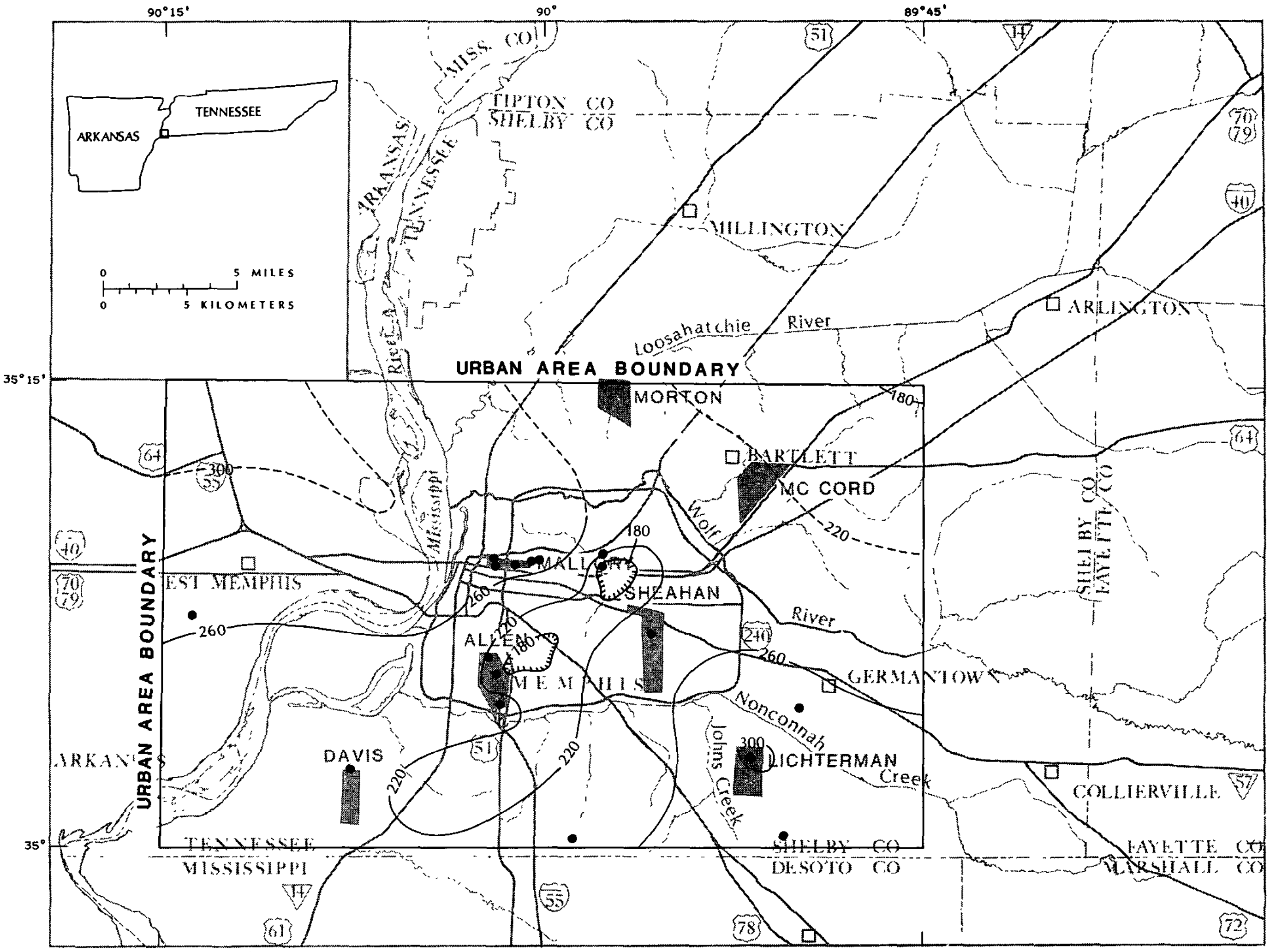
Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

EXPLANATION

—100- - - LINE OF EQUAL AGGREGATE THICKNESS OF CLAY BEDS IN THE JACKSON-UPPER CLAIBORNE CONFINING BED--Dashed where approximately located. Hachures indicate depression. Interval 100 feet.

● WELL WITH GEOPHYSICAL LOG

Figure 4.--Aggregate thickness of clay beds thicker than 10 feet in the Jackson-upper Claiborne confining bed in the Memphis urban area.



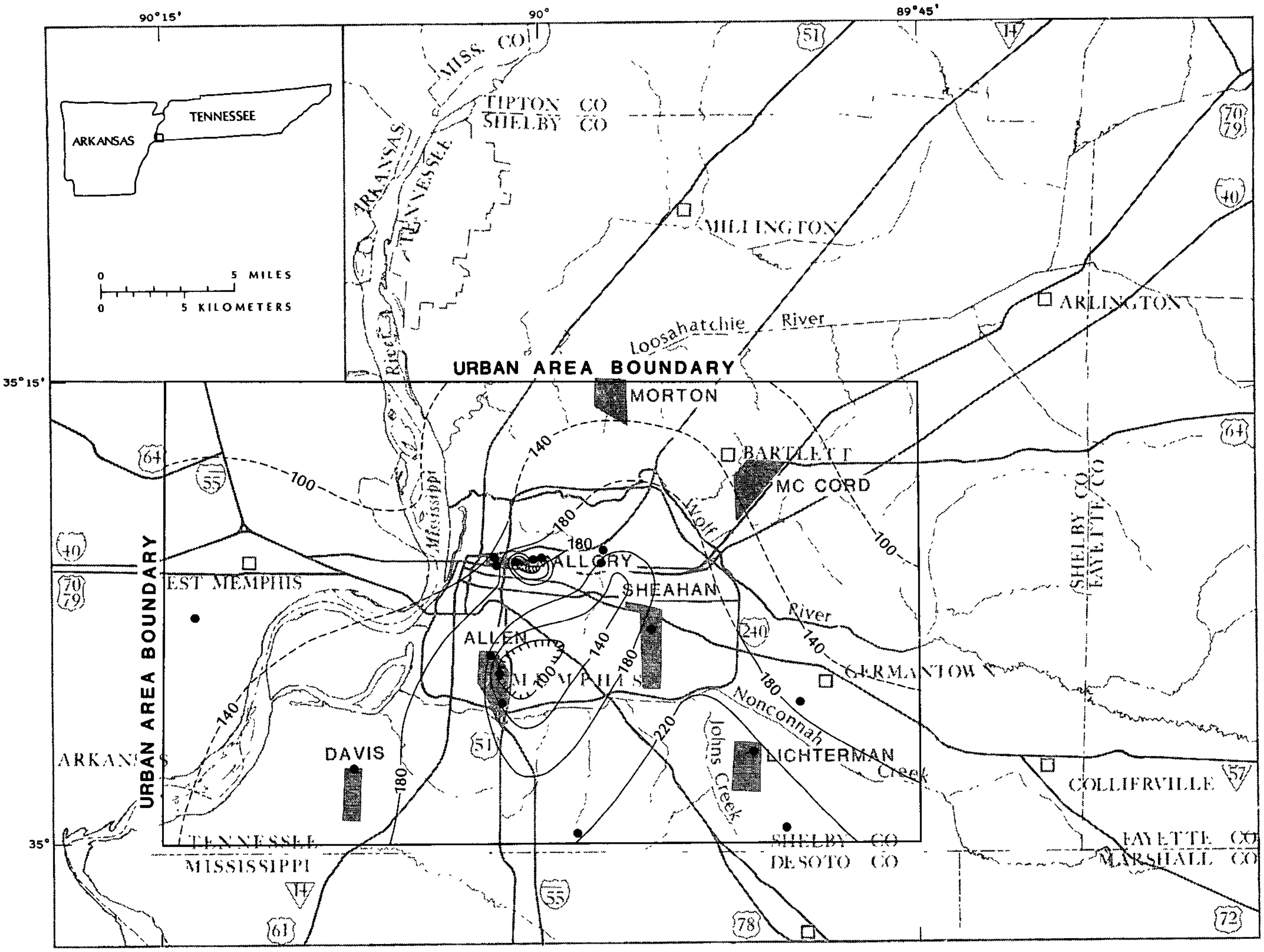
Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

EXPLANATION

—260— LINE OF EQUAL THICKNESS OF THE FLOUR ISLAND CONFINING BED–Dashed where inferred. Hachures indicate depression. Interval 40 feet.

● WELL WITH GEOPHYSICAL LOG

Figure 5.–Thickness of the Flour Island confining bed in the Memphis urban area.



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

EXPLANATION

—140— LINE OF EQUAL AGGREGATE THICKNESS OF CLAY BEDS IN THE FLOUR ISLAND CONFINING BED--Dashed where inferred. Hachures indicate depression. Interval 40 feet.

● WELL WITH GEOPHYSICAL LOG

Figure 6.--Aggregate thickness of clay beds thicker than 10 feet in the Flour Island confining bed in the Memphis urban area.

Thickness of confining beds

Four areas are obvious where the Jackson-upper Claiborne confining bed is thin or absent and contains little or no clay (figs. 3 and 4). These areas are: (1) in eastern part of the Memphis urban area along and north of the Wolf River, (2) in the southeastern part along Nonconnah Creek, (3) in the south-central part along Nonconnah and Johns Creeks in the vicinity of the southern part of the Sheahan well field, and (4) in the western part in a belt along the Mississippi River. These four areas are important because the thinness of the confining bed and lack of thick clay beds indicate areas with high potential for leakage. The existence and boundaries of these areas, particularly the belt along the Mississippi River, are highly interpretative because of the sparsity of geophysical-log control. The areas along the Wolf River and along Nonconnah Creek are the westward extensions of a much larger area in the southeastern part of the Memphis area where the confining bed overlying the Memphis Sand is known to be absent (Criner and Parks, 1976, figs. 4-7).

The Flour Island confining bed is relatively thick and contains much clay at most places (figs. 5 and 6). Therefore, downward leakage from the Memphis Sand to the Fort Pillow Sand or upward leakage from the Fort Pillow Sand to the Memphis Sand probably is small.

Water Levels

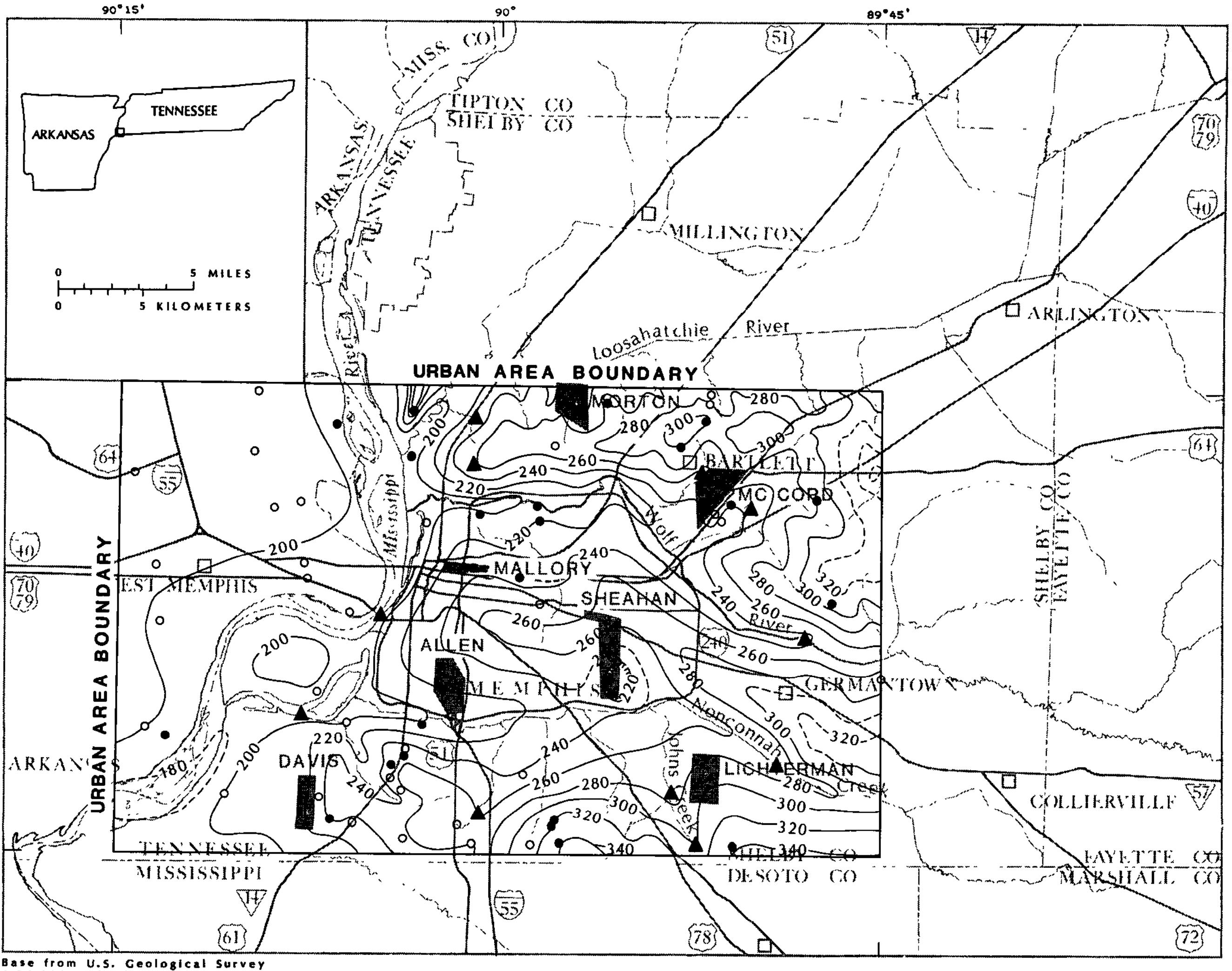
Differences in hydraulic head among the aquifers in the Memphis area result in vertical hydraulic gradients which create a potential for interaquifer exchange of water. To determine the areal distribution of the head differences between the various aquifers, water-level information for each of the aquifers was collected in the fall of 1984 and water-table and potentiometric maps were prepared (figs. 7, 9, and 10).

Water-Table Conditions

The water-table configuration in the shallow aquifers (fluvial deposits and alluvium) is a subdued replica of the land-surface topography (fig. 7). Water levels are generally at higher altitudes beneath land surface in upland areas than in valleys. The water-table map shows the altitude of the top of the saturated zone (the water level as measured in unused wells screened in the water-table aquifers). The altitude of the water table ranges from 180 to 360 feet above sea level. Although the water-table map was drawn using water-level measurements made in the fall of 1984 as primary control, low-stage records for unlined streams in the area and historic water levels in wells no longer available for measurement were used as supplemental control.

Water-levels in the water-table aquifers, in areas unaffected by pumping, fluctuate both seasonally and over long periods in reponse to changes in the amount of water in storage. Water levels are low in the fall and early winter because of the depletion of water in storage by the contribution of water from the water-table aquifers to the base flow of streams during the summer and early fall. Water levels are high in the spring and early summer as a result of recharge from rainfall during the winter and spring. Long periods of excess or deficient rainfall also affect the amount of water in storage in the water-table aquifers. Water-level changes under these conditions are more gradual. Graham (1982, p. 10-11) has shown that the hydrograph of well Sh:P-99, in the fluvial deposits in a wooded area of Overton Park at Memphis, indicates a definite correlation between the amount of water in storage from year to year and variations in annual rainfall in the Memphis area. A hydrograph of well Sh:P-99 is shown in figure 8; location of the well is shown in figure 13.

A depression in the water-table surface is located in the southeastern part of the Memphis urban area in the southern part of the Sheahan well field (fig. 7). Because there are no withdrawals from the water-table aquifers in this area, the presence of the cone of depression indicates that pumping stress in the Memphis Sand has lowered water levels in the overlying water-table aquifer. The long-term water-level data for well Sh:K-75 (fig. 8), on which this depression is primarily based, shows continuous declines dating back to 1951, almost to the beginning of pumping in the southern part of the Sheahan well field which began in 1948. This data for well Sh:K-66 (fig. 8), in the northern part of Sheahan well field, shows similar declines in the Memphis Sand.



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

EXPLANATION

320 WATER-TABLE CONTOUR--Shows altitude of water table. Dashed where inferred. Hachures indicate depression. Contour interval 20 feet. Datum is sea level

● WELL FOR WHICH MEASUREMENT MADE IN FALL 1984 WAS USED AS CONTROL

○ WELL FOR WHICH HISTORIC MEASUREMENT WAS USED AS SUPPLEMEMNTARY CONTROL

▲ GAGE FOR WHICH LOW-STAGE MEASUREMENT MADE IN FALL 1984 WAS USED AS CONTROL

Figure 7.--Altitude of the water table in the alluvium and fluvial deposits in the Memphis urban area, fall 1984.

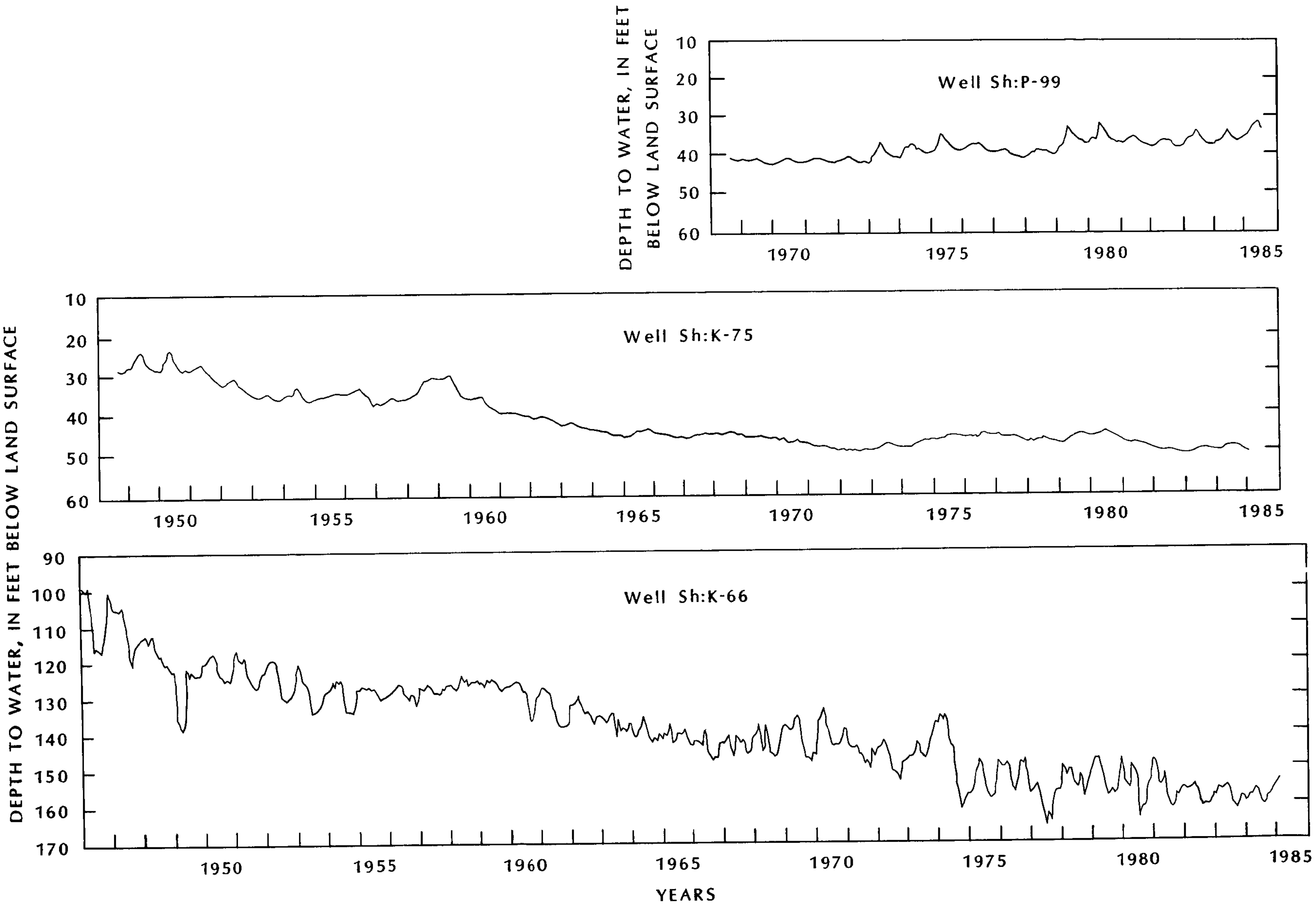


Figure 8.--Hydrographs of observation wells Sh:P-99 and Sh:K-75 in the fluvial deposits and Sh:K-66 in the Memphis Sand.

These declines indicate that pumping in the Memphis Sand has induced leakage from the water-table aquifer.

Artesian Conditions

The potentiometric surface of the Memphis Sand indicates small cones of depression around major pumping centers that are superimposed on a large regional cone which reflects the composite effect of pumping in the Memphis area (fig. 9). The small cones of depression shown on the Memphis Sand potentiometric map are centered at MLGW well fields or areas of major industrial pumping. The altitude of the potentiometric surface in the Memphis Sand ranges from less than 130 to 270 feet above sea level with the lowest altitudes at Mallory and Allen well fields.

Water levels in the Memphis Sand are commonly at their lowest during August or early September and are commonly highest during March or April. Water levels in the Memphis Sand have declined in the Memphis area in response to long-term increases in pumping, but these declines have not been uniform throughout the area because of the non-uniform distribution of withdrawal from wells fields with time. Continued water-level declines near pumping centers are caused by limitations on the ability of the aquifer to transmit water rapidly from the recharge area to areas of concentrated pumping rather than by a lack of available recharge. This is indicated by the fact that water levels have not declined in the recharge area. In outlying parts of the Memphis area, annual water-level fluctuations are caused by variations in annual rainfall combined with a delayed response to distant pumping; fluctuations in and near large well fields are caused primarily by changes in pumping rates (Graham, 1982, p. 10-12).

The potentiometric surface of the Fort Pillow Sand slopes generally to the to the west (fig. 10). Distortions in this surface are caused by pumping at West Memphis, Ark., and by an industry at Memphis. These pumping centers cause local cones of depression in the potentiometric surface. The altitude of the potentiometric surface in the Fort Pillow Sand ranges from less than 140 to 220 feet above sea level with the lowest altitude at West Memphis, Ark.

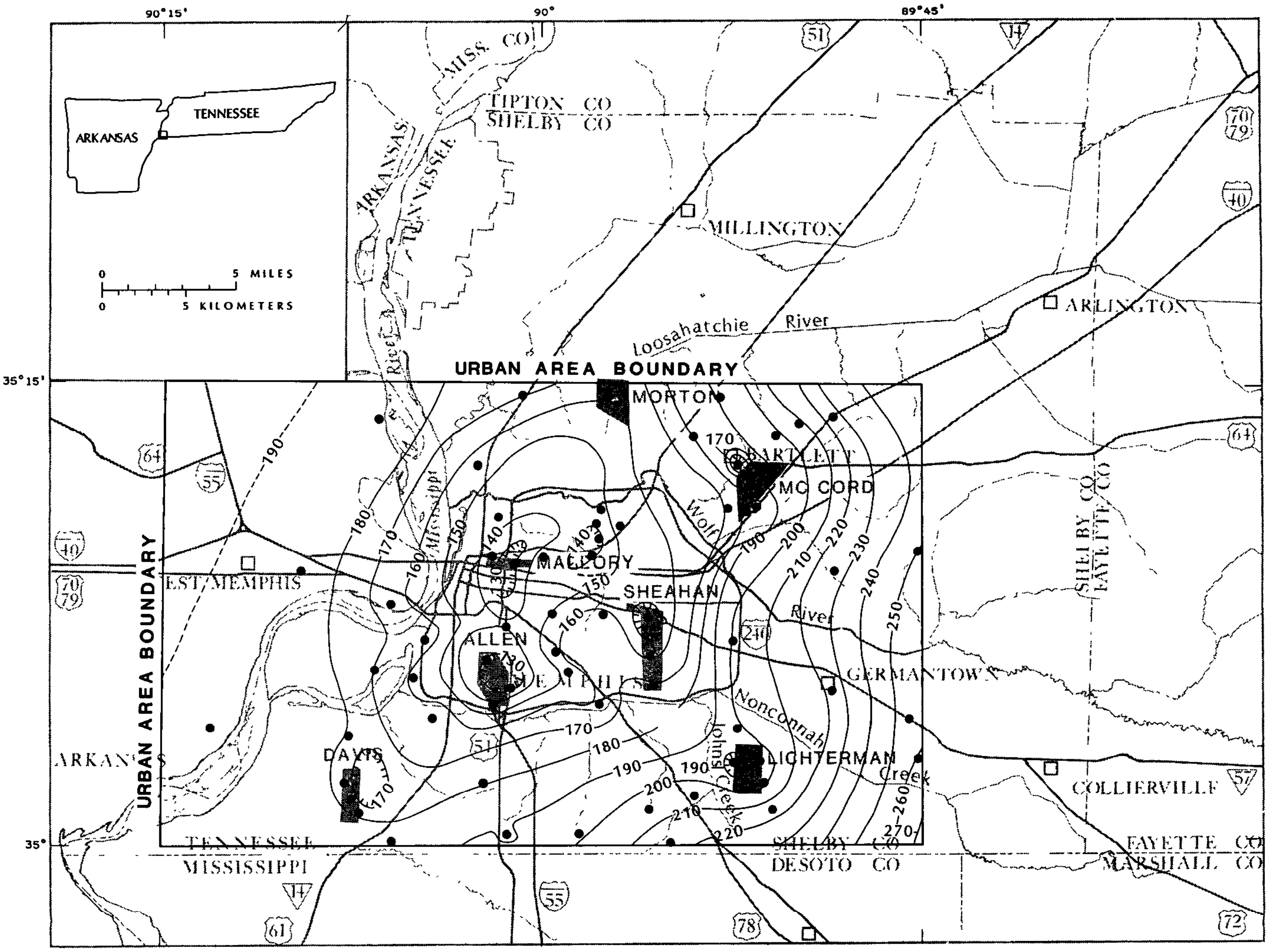
Water levels in the Fort Pillow Sand in wells near the recharge area are commonly lowest each year during October or November and are commonly highest during May or June. Closer to pumping centers, seasonal water-level trends are generally obscured by the effects of pumping. Near the pumping centers, water-level fluctuations are caused primarily by changes in pumping rates.

Head Differences

Head differences between the water-table aquifers and the Memphis Sand were determined by overlaying the potentiometric map for the Memphis Sand (fig. 9) with the water-table map (fig. 7) and preparing a derivative map (fig. 11). Head differences between the Memphis Sand and the Fort Pillow Sand were similarly determined by overlying the potentiometric map for the Fort Pillow Sand (fig. 10) with the potentiometric map for the Memphis Sand (fig. 9) and preparing a derivative map (fig. 12).

Head differences between the water-table aquifers and the Memphis Sand range from 0 to 130 feet in the Memphis urban area (fig. 11). Areally, the total hydraulic head (as related to altitude above sea level) in the water-table aquifers equals or is greater than total hydraulic head in the Memphis Sand. Therefore, throughout this area, the vertical hydraulic gradient is downward as is the movement of water from the water-table aquifers to the Memphis Sand. Head differences are generally greatest beneath the uplands, where the altitude of the water table in the fluvial deposits is high, and beneath MLGW well fields, where the potentiometric surface in the Memphis Sand has been lowered by pumping. Head differences are generally least beneath the Mississippi Alluvial Plain and the alluvial plains of major streams, where the altitude of the water table in the alluvium is low.

Head differences between the Memphis Sand and the Fort Pillow Sand range from minus 40 to plus 50 feet in the Memphis urban area (fig. 12). Throughout the central part of the Memphis urban



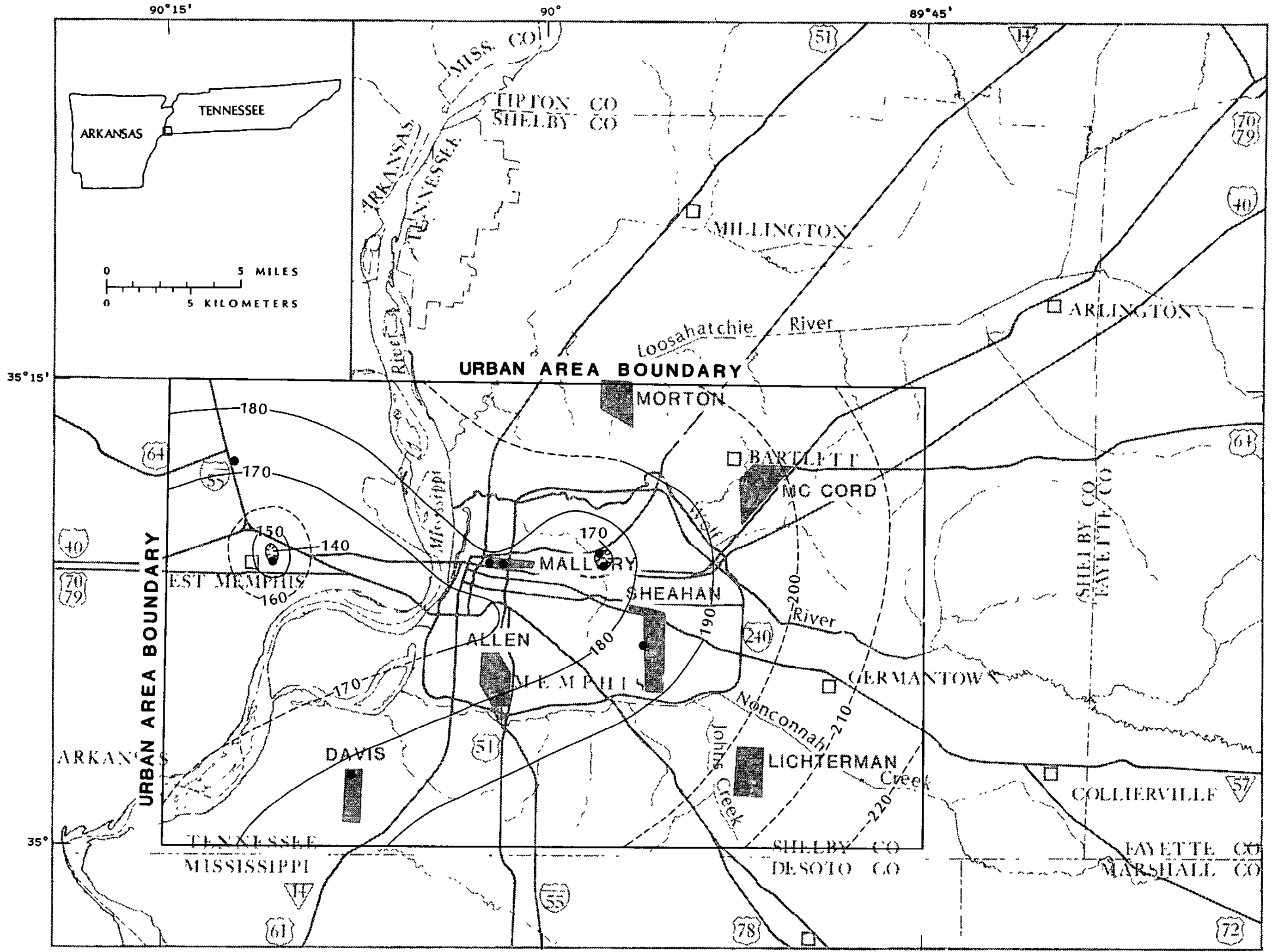
Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

EXPLANATION

190 POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Hachures indicate depression. Contour interval 10 feet. Datum is sea level

● OBSERVATION WELL

Figure 9.--Altitude of the potentiometric surface in the Memphis Sand in the Memphis urban area, fall 1984.



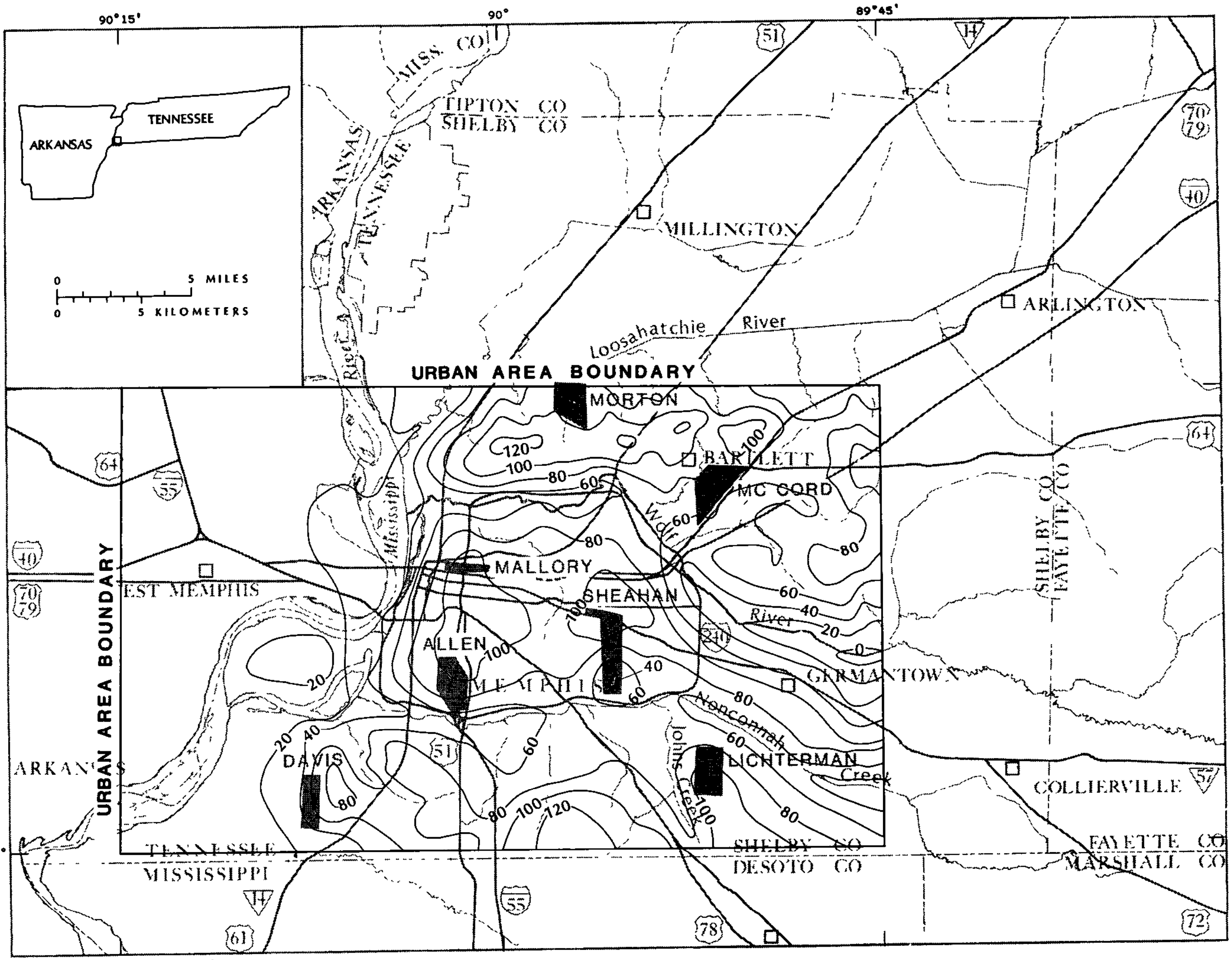
Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

EXPLANATION

190 POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Dashed where inferred. Hachures indicate depression. Contour interval 10 feet. Datum is sea level

● OBSERVATION WELL

Figure 10.--Altitude of the potentiometric surface of the Fort Pillow Sand in the Memphis urban area, fall 1984.

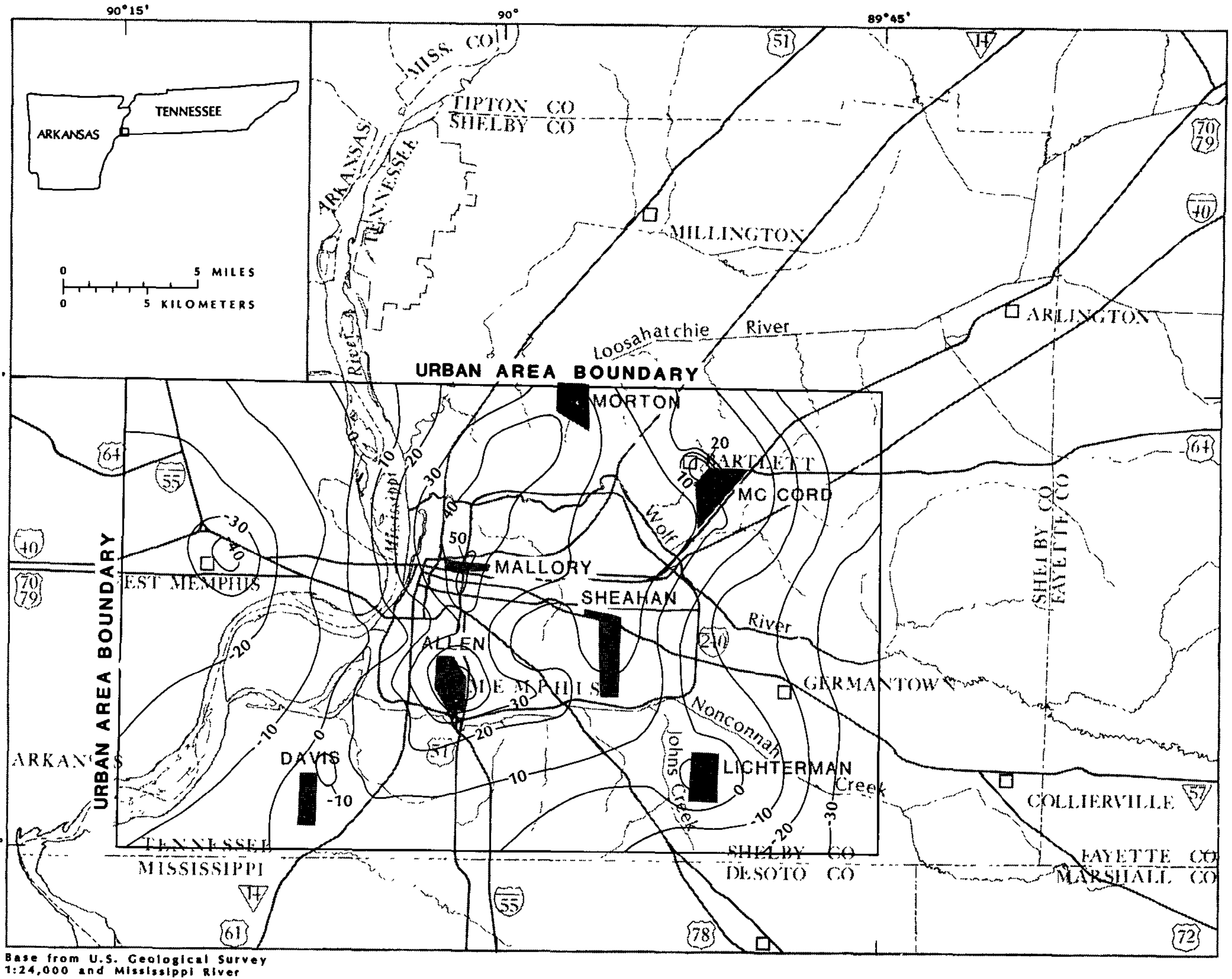


Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

EXPLANATION

—60— LINE OF EQUAL HEAD DIFFERENCE--Distance of head in water-table aquifers above head in Memphis Sand. Hachures indicate depression. Interval 20 feet.

Figure 11.--Head differences between the water-table aquifers and the Memphis Sand in the Memphis urban area, fall 1984.



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

EXPLANATION

40 LINE OF EQUAL HEAD DIFFERENCE--Positive where head is higher in the Fort Pillow Sand than in the Memphis Sand. Negative (-) where head is higher in the Memphis Sand than in the Fort Pillow Sand. Interval 10 feet.

Figure 12.--Head differences between the Memphis Sand and the Fort Pillow Sand in the Memphis urban area, fall 1984.

area total hydraulic head in the Fort Pillow Sand equals or is higher (plus) than the total hydraulic head in the Memphis Sand, and the vertical hydraulic gradient creates a potential for the upward movement of water from the Fort Pillow Sand to the Memphis Sand. Head differences in the central part of the Memphis urban area are generally highest in areas where intensive pumping from the Memphis Sand in MLGW well fields has caused lowering of the potentiometric surface. In the eastern and western parts of the Memphis urban area, the total hydraulic head in the Fort Pillow Sand is less (minus) than that of the Memphis Sand, and the vertical hydraulic gradient is downward. Movement of water is from the Memphis Sand into the Fort Pillow Sand. The greatest differences in head are near West Memphis, Ark., where pumping has lowered the potentiometric surface in the Fort Pillow Sand, and along the eastern boundary of the Memphis urban area, where the potentiometric surface of the Memphis Sand is high.

Isotope Data

Isotopes of carbon and hydrogen occur in trace amounts large enough to be determined quantitatively through routine analyses. Carbon isotopes can be used to approximate the apparent age of water; tritium can be used to give a qualitative indication of the presence of very recent recharge to an aquifer. In the present investigation, samples of ground water were analyzed to determine concentrations of two isotopes of carbon (carbon-14 and carbon-13) and one of hydrogen (tritium).

Carbon Isotopes

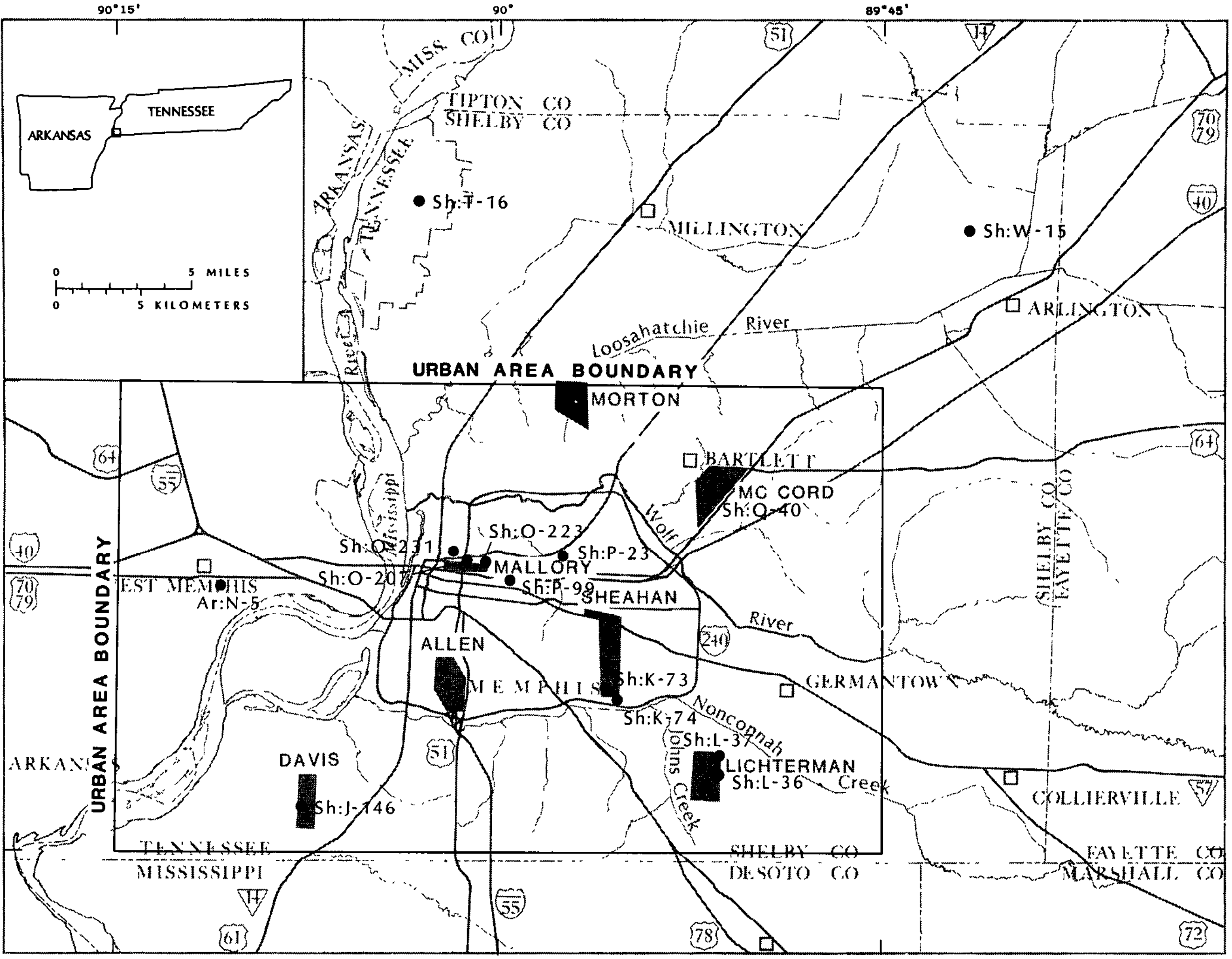
Carbon isotope data for water from 14 wells (fig. 13) in the Memphis area--one in the fluvial deposits, twelve in the Memphis Sand, and one in the Fort Pillow Sand--were obtained. Unadjusted carbon-14, carbon-13/carbon-12, and adjusted carbon-14 values are given in table 2, along with the correction factors used. Methodology for adjusting carbon-14 data is discussed in the section entitled "Supplemental Explanation of Isotope Data" at the end of this report.

The vertical distribution of the adjusted carbon-14 values in the aquifers as indicated by analyses of water from three wells, which are located close to one another near the center of pumping at Memphis, is shown in figure 14. These analyses indicate a vertical distribution of adjusted carbon-14 decreasing with increasing depth at this location.

Water from well Sh:P-99, in the fluvial deposits at a depth of 59 feet, had an adjusted carbon-14 of 118.1 (percent modern). Carbon-14 values can exceed 100 percent of the modern standard if some of the water post-dates the testing of thermonuclear weapons because the carbon-14 content of atmospheric carbon dioxide has, at times, been doubled by these weapons (Mook, 1980, p. 52). Graham (1982, p. 10-11) has shown a direct correlation between water levels in this well and variations in annual rainfall in the Memphis area, indicating that some water from this well is very recent. Carbon-14 derived from the dissolution of snail shells in the overlying loess also may have increased the adjusted carbon-14 value.

Water from well Sh:O-231, in the upper part of the Memphis Sand at a depth of 518 feet, had an adjusted carbon-14 of 79.0 (percent modern). Water from well Sh:P-23, in the Fort Pillow Sand at a depth of 1,414 feet, had the greatest apparent age with an adjusted carbon-14 of 12.2 (per-cent modern).

Not shown in figure 14 are the adjusted carbon-14 concentrations for wells Sh:O-207 and Sh:O-223, both in the lower part of the Memphis Sand and about 1,200 feet apart in the Mallory well field. Water from Sh:O-207, at a depth of 758 feet, had an adjusted carbon-14 concentration of 99.6 (percent modern); water from Sh:O-223, at a depth of 772 feet, had an adjusted carbon-14 concentration of 99.2 (percent modern). These high values of adjusted carbon-14 are inconsistent with the other isotope data for the Memphis area, particularly when considering the depths of these wells. The values indicate the presence of recent water in the discharge from these two wells, which is not explainable on the basis of available information.



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

EXPLANATION

● Sh:K-74 OBSERVATION WELL--Location and number

Figure 13.--Wells in the Memphis area from which water samples were collected for carbon and hydrogen isotope analysis.

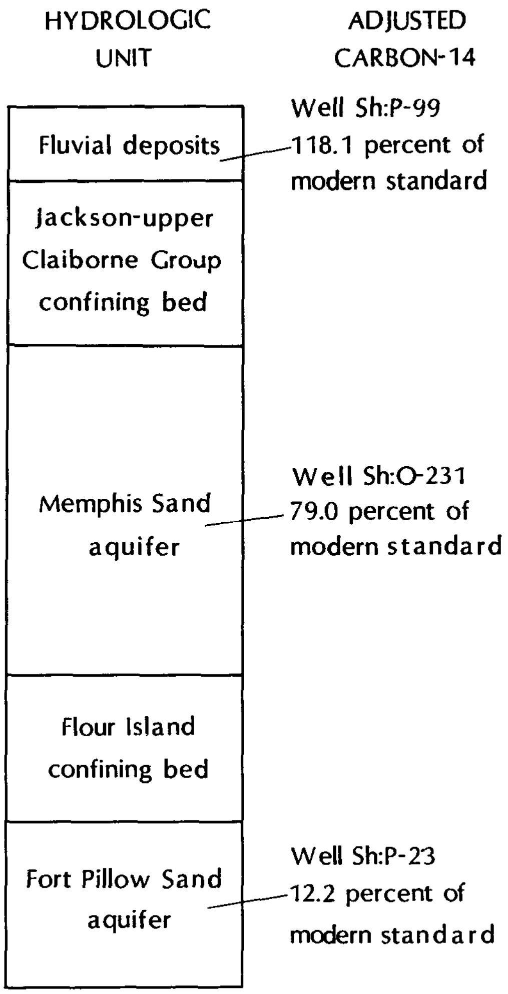


Figure 14.--Vertical distribution of carbon isotope data in the geological sequence of the Memphis area.

The areal distribution of adjusted carbon-14 values for water from eight wells in the upper part of the Memphis Sand is shown in figure 15. The apparent age of water in the upper part of the Memphis Sand is least (adjusted carbon-14 is greatest) in the southeastern part of the Memphis area and is greatest in the western and northwestern parts. This relation is what would be expected when considering the general east to west direction of flow of water in the Memphis Sand before intensive pumping began at Memphis, as indicated by the potentiometric-surface map of Criner and Parks (1976, fig. 4), and the distances from the outcrop recharge area, as indicated by Moore (1965, plate 5). The northwestward deflection of the "75 value" line of adjusted carbon-14 around Memphis (fig. 15) indicates that younger water has been brought into the major cone of depression in the potentiometric surface of the Memphis Sand by intense pumping, either from horizontal movement or downward vertical leakage.

The adjusted carbon-14 values for wells Sh:K-73 and Sh:K-74 are 100.0 and 103.0 (percent modern), respectively. These wells are both 273 feet deep and are about 650 feet apart in the southern part of the Sheahan well field. These values exceed that of Sh:L-37, adjusted carbon-14 of 89.4 (percent modern) and that of Sh:O-231, adjusted carbon-14 of 79.0 (percent modern). Wells Sh:K-73 and Sh:K-74 are located between

Table 2.--Carbon and hydrogen isotopes in water from aquifers in the Memphis area

[Correction factor "P" is computed by dividing the per-mil C-13/C-12 ratio by -25.0 per mil; adjusted C-14, percent modern, is calculated by dividing the carbon-14, percent modern, by "P." pCi/L, picocuries per liter; TU, tritium units. Aquifers from which water samples were taken are: QTf, fluvial deposits; Tm, Memphis Sand; Tfp, Fort Pillow Sand]

Well No.	Well depth (feet)	Carbon 14 (percent modern)	C-13/C-12 stable-isotope ratio (per mil)	Correction factor P	Adjusted C-14 (percent modern)	Tritium, total (pCi/L)	Tritium, total (TU)	Aquifer
Ar:N-5	445	26.6	-20.6	0.82	32.4	--	--	Tm
Sh:J-146	446	62.1	-20.8	.83	74.8	--	--	Tm
Sh:K-73	273	85.0	-21.2	.85	100.0	60	18.6	Tm
Sh:K-74	273	84.5	-20.5	.82	103.0	38	11.9	Tm
Sh:L-36	485	58.1	-21.6	.86	67.6	1	.3	Tm
Sh:L-37	382	75.1	-21.0	.84	89.4	3	.8	Tm
Sh:O-207	758	80.7	-20.3	.81	99.6	--	--	Tm
Sh:O-223	772	77.4	-19.5	.78	99.2	--	--	Tm
Sh:O-231	518	64.8	-20.5	.82	79.0	2	.6	Tm
Sh:P-23	1414	7.3	-15.1	.60	12.2	--	--	Tfp
Sh:P-99	59	79.1	-16.8	.67	118.1	12	3.7	QTf
Sh:Q-40	441	62.6	-21.5	.86	72.8	2	.6	Tm
Sh:T-16	584	40.4	-14.8	.59	68.5	4	1.2	Tm
Sh:W-15	338	59.0	-18.9	.76	77.6	3	.9	Tm

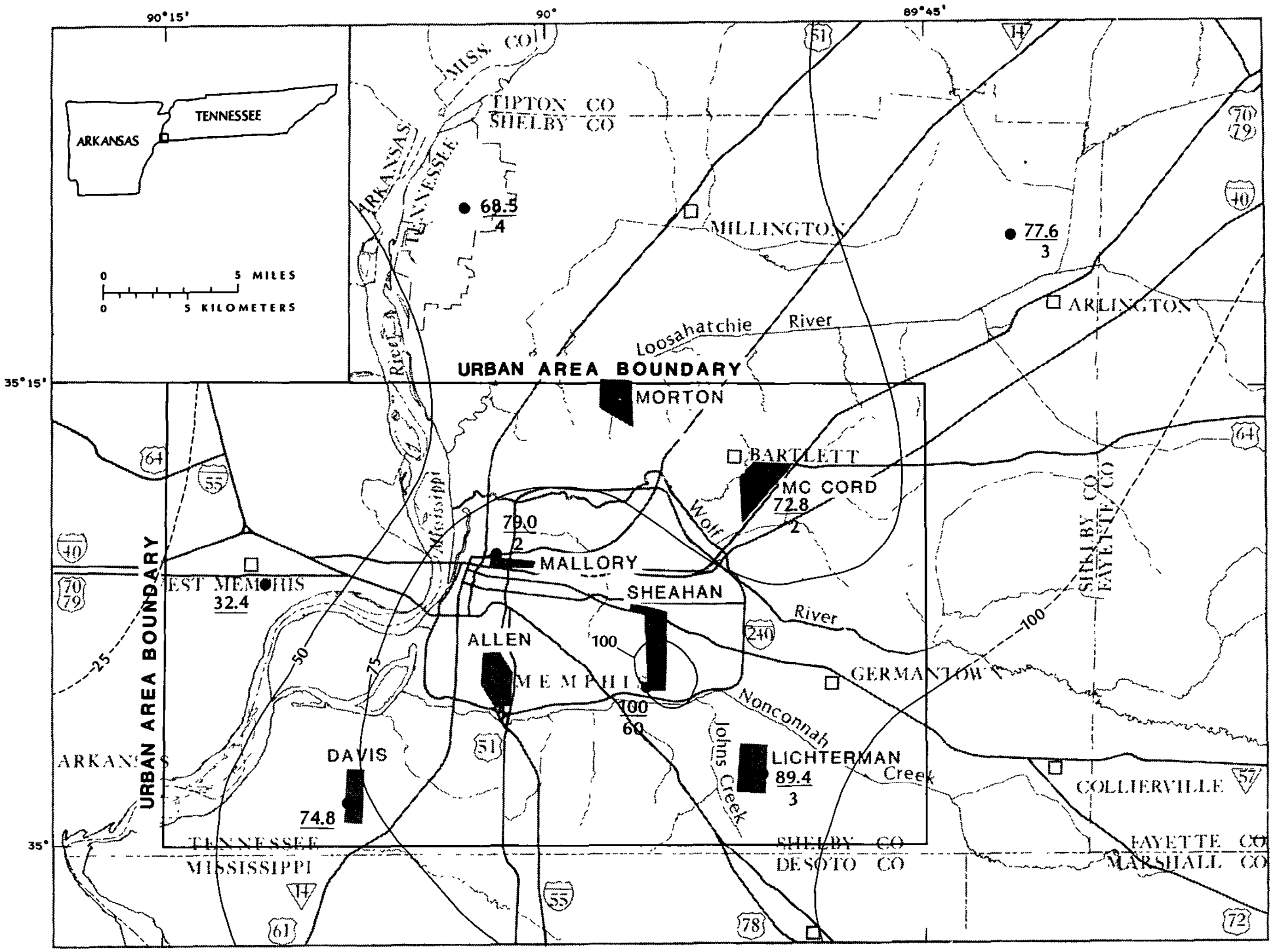
Sh:L-37 in the Lichterman well field (the well nearest to the outcrop recharge area in the southeastern part of the Memphis area) and Sh:O-231 in the Mallory well field (the well nearest to the center of the major cone of depression in the potentiometric surface of the Memphis Sand at Memphis) (fig. 9). The high values of adjusted carbon-14 for Sh:K-73 and Sh:K-74 strongly suggests that relatively recent water has been introduced into the Memphis Sand in the area of these wells.

The adjusted carbon-14 value of 89.4 (percent modern) for water from a depth of 382 feet in well Sh:L-37 is greater than the value of 67.6 (percent modern) for water from a depth of 485 feet in Sh:L-36, both in the Lichterman well field about 1,200 feet apart. This higher value of adjusted carbon-14 for water from Sh:L-37 than for water from Sh:L-36 may indicate induced recharge of recent water in the upper part of the Memphis Sand.

Tritium

Tritium isotope concentrations were determined in water taken from nine wells in the Memphis area (fig. 13). All of the wells sampled are in the Memphis Sand, except well Sh:P-99 which is in the fluvial deposits. Tritium concentrations, in picocurries per liter and tritium units, for water from these wells are given in table 2.

Relatively high tritium concentrations were found in water from wells Sh:P-99 in the fluvial deposits and Sh:K-73 and Sh:K-74 in the Memphis Sand. Water from well Sh:P-99 had a tritium concentration of 12 picocurries per liter (pCi/L) (3.7 TU), indicating the presence of recent recharge. This concentration in water from the fluvial deposits may reflect mixing of recent precipitation with older ground water or may indicate that the recharge contained tritium near background concentrations. Water from wells Sh:K-73 and Sh:K-74, in the southern part of the Sheahan well field, had tritium concentrations of 60 pCi/L



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

EXPLANATION

75 LINE OF EQUAL ADJUSTED CARBON-14—Dashed where inferred. Interval 25 percent of modern standard.

● 89.4 / 3 OBSERVATION WELL—Top number represents carbon-14, percent of modern standard; bottom number represents tritium, picocuries per liter.

Figure 15.—Distribution of adjusted carbon-14 and tritium in water from the upper part of the Memphis Sand in the Memphis area.

(18.6 TU) and 38 pCi/L (11.9 TU), respectively. These data indicate that water from recent precipitation has entered the Memphis Sand by vertical leakage in the vicinity of these wells.

Geothermal Gradient

Anomalous temperature distributions may be caused by the spatial redistribution of heat by moving ground water (Domenico and Palciauskas, 1973; Freeze and Cherry, 1979, p. 508). The temperature distribution in an aquifer is a variable that is directly dependent on the velocity and direction of water flow through it (Stallman, 1963). The vertical distribution of temperature can provide indirect information about the vertical movement of water. The geothermal gradient is less near the surface in recharge areas than it is in discharge areas. In recharge areas, the gradient increases with increasing depth; in discharge areas, it decreases with increasing depth (Domenico and Palciauskas, 1973). In general, the geothermal gradient is greater in rocks with low permeability than in rocks with high permeability (Keys and MacCary, 1971, p. 99).

Schneider (1972) found significant distortion of the geothermal field around observation well Sh:K-45 in the Sheahan well field at Memphis, which he related to both upward and downward movement of water caused by pumping of a nearby production well. Distortion of the geothermal field above a depth of 300 feet was interpreted as being caused by downward leakage of water from the fluvial deposits into the Memphis Sand. Temperatures in the upper part of the well were warmer than would be expected when considering a normal geothermal gradient for the area.

During the present investigation, temperature data were collected by making geophysical temperature logs to establish the normal, near-surface, geothermal gradient and to determine the nature and magnitudes of any deviations from this normal gradient. The locations of the wells in which these temperature logs were made are shown in figure 16, and a summary of the temperature data is given in table 3.

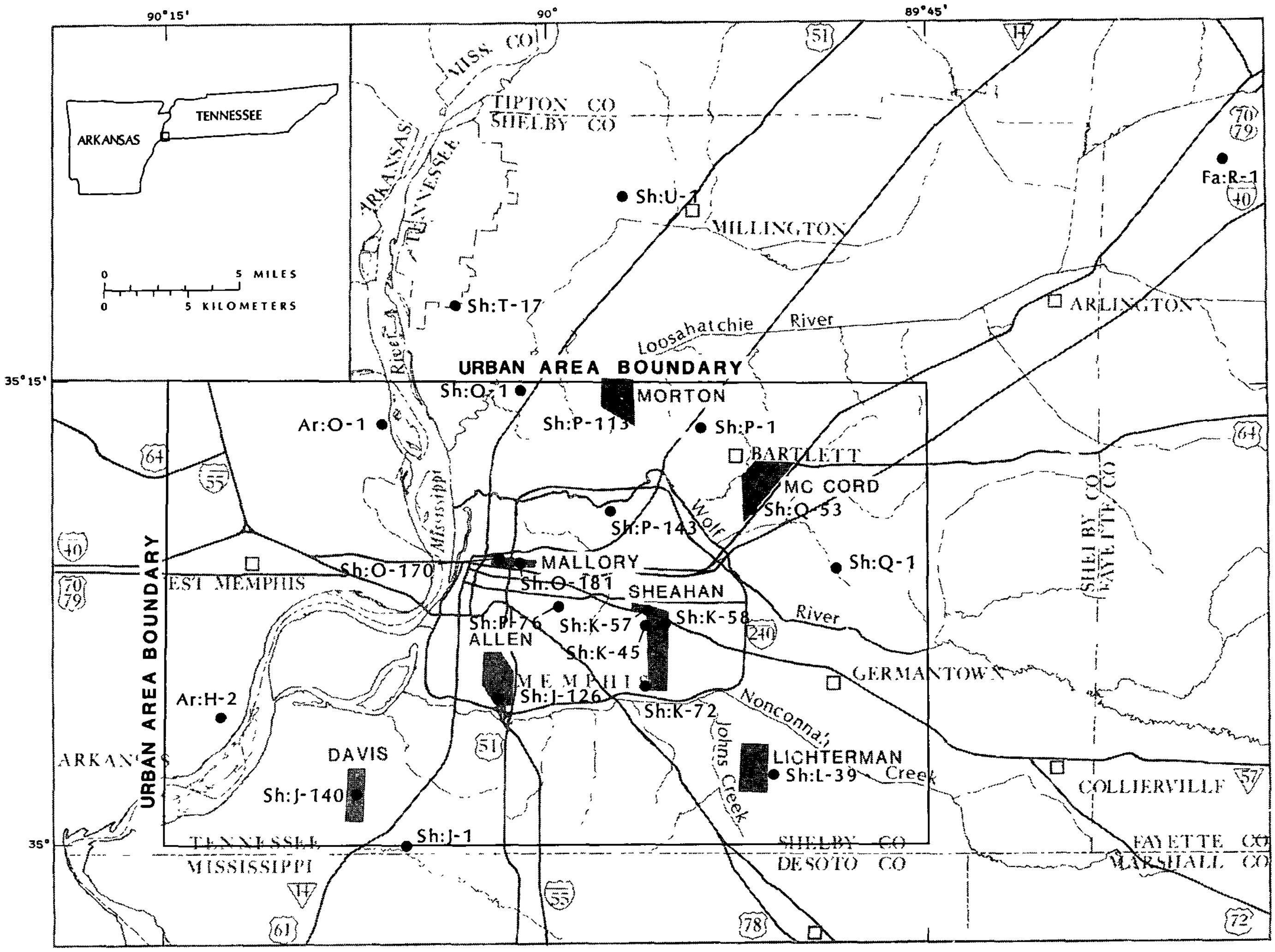
Normal Gradient

To establish the normal near-surface geothermal gradient in the Memphis area relatively undisturbed by pumping, a temperature log was run to a depth of 1,083 feet in observation well Fa:R-1 (table 3). This well is located in Fayette County, about 25 miles from the center of pumping at Memphis (fig. 16). Recorded temperatures ranged from 16.0 °C at 100 feet to 21.9 °C at 1,083 feet. The average temperature gradient in this interval is 0.6 °C per 100 feet (fig. 17). A down-hole temperature measurement of 32.2 °C at a depth of 2,627 feet near the bottom of well Sh:O-169 at Memphis is also shown along with a down-hole temperature of 35.0 °C measured at a depth of 3,389 feet in well Sh:T-18. Well Sh:T-18 is located in northwestern Shelby County about 15 miles from the center of pumping at Memphis. The average temperature gradient from 100 to 3,389 feet, as shown in figure 17, is 0.6 °C per 100 feet, the same as in well Fa:R-1; and it is concluded that the normal near-surface undisturbed geothermal gradient below a depth of 100 feet in the Memphis area is 0.6 °C per 100 feet.

Local Deviations

Geophysical temperature logs have been made in 24 wells in the Memphis area. The first series of these logs were made in 1977 when MLGW was abandoning their deep wells in the Fort Pillow Sand in Mallory and Sheahan well fields. These wells were logged to obtain geologic and hydrologic data before most of the wells were filled and capped. The temperature logs showed a significant distortion of the geothermal field in the upper parts of these wells similar to that found by Schneider (1972). In 1981, two observation wells were logged to determine if this distortion in the geothermal field was present in areas away from the intense pumping at Memphis. Wells Fa:R-1, in the Fort Pillow Sand in northwestern Fayette County, and Ld:F-4, in the Memphis Sand in Lauderdale County outside the Memphis area, showed geothermal gradients of 0.6 and 0.4 °C per 100 feet, respectively, and no distortion of the geothermal field.

In 1984 in conjunction with the present project, 17 additional observation wells in the



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

EXPLANATION

● Sh:P-113 OBSERVATION WELL--Location and number

Figure 16.--Wells in the Memphis area in which geophysical temperature logs were made.

Table 3.--Summary of up-hole and down-hole temperatures from geophysical logs and calculated geothermal gradients in the Memphis area

Well No.	Up-hole temperature at or below 100-foot depth[1]			Coolest temperature at or below 100-foot depth			Down-hole temperature at total depth logged			Geothermal gradient to total depth
	(°C)	Depth (feet)	Geologic unit[2]	(°C)	Depth (feet)	Geologic unit[2]	(°C)	Depth (feet)	Geologic unit[2]	(°C/100 ft)
Ar:H-2	16.3	100	Qal	16.3	100	Qal	18.0	510	Tm	0.41
Ar:O-1	16.2	100	Qal	16.2	100	Qal	17.6	499	Tm	.35
Fa:R-1	16.0	100	Tm	16.0	100	Tm	21.9	1083	Tob	.60
Sh:J-1	16.5	100	Tjc	16.0	260	Tm	16.0	339	Tm	- .21
Sh:J-126	16.3	120	Tjc	16.1	200	Tm	16.2	260	Tm	- .07
Sh:J-140	16.5	140	Tjc	16.2	260	Tm	17.3	550	Tm	.20
Sh:K-45	17.3	140	Tjc	16.4	300	Tm	21.5	1219	Tfp	.39
Sh:K-57	18.2	120	Tjc	16.4	380	Tm	22.0	1293	Tfp	.32
Sh:K-58	17.2	140	Tjc	16.4	320	Tm	22.2	1297	Tfp	.43
Sh:K-72	16.8	120	Tjc	16.1	230	Tm	16.1	293	Tm	- .40
Sh:L-39	16.5	180	Tm	16.4	230	Tm	16.7	347	Tm	.12
Sh:O-1	16.1	100	Tjc	16.1	100	Tjc	17.1	420	Tm	.31
Sh:O-170	17.4	140	Tjc	16.6	380	Tm	21.7	1330	Tfp	.36
Sh:O-181	17.0	110	Tjc	16.4	400	Tm	21.3	1366	Tfp	.34
Sh:P-1	16.2	140	Tjc	16.2	140	Tjc	16.8	340	Tm	.30
Sh:P-76	17.4	160	Tjc	16.5	370	Tm	16.6	453	Tm	- .27
Sh:P-113	16.5	180	Tjc	16.5	180	Tjc	17.5	531	Tm	.28
Sh:P-143	17.8	100	Tjc	16.5	280	Tm	16.9	441	Tm	- .26
Sh:Q-1	17.4	120	Tjc	16.7	260	Tm	17.0	379	Tm	- .15
Sh:Q-53	16.8	120	Tjc	16.3	300	Tm	18.4	797	Tm	.24
Sh:T-17	15.6	140	Tjc	15.6	140	Tjc	17.3	671	Tm	.32
Sh:U-1	16.2	100	Tjc	16.0	240	Tjc	18.2	838	Tm	.27

[1] Temperature in the earth at a depth of about 100 feet below land surface generally is thought to be unaffected by seasonal or short-term climatic variations and the temperature at this depth approximates the mean annual air temperature for the area. Therefore, the up-hole temperature was determined from geophysical logs at a depth of 100 feet, except where the water level (WL) in the well was below 100 feet. Then, the up-hole temperature was determined at a depth below the water level where the water temperature seemed unaffected by the air temperature in the well.

[2] Geologic unit at depth of the up-hole and down-hole temperatures are: Qal, Alluvium; Tjc, Jackson Formation-upper Claiborne Group; Tm, Memphis Sand; Tfp, Fort Pillow Sands; Tob, Old Breastworks Formation.

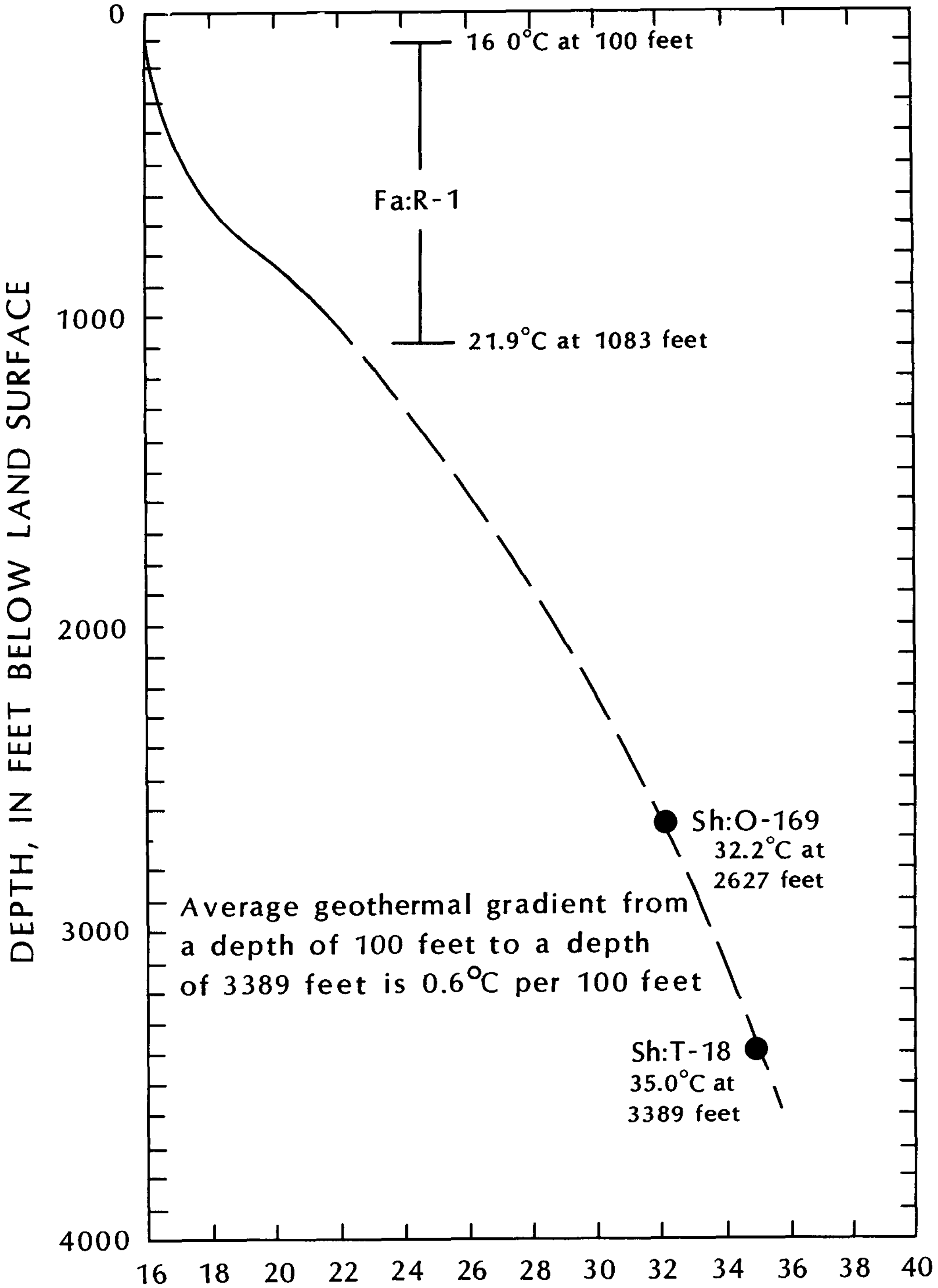


Figure 17.--The normal geothermal gradient in the Memphis area.

Memphis area were logged. With a few exceptions, these logs confirmed the distortion of the geothermal field in the upper part of the wells located in areas of intense pumping and a normal geothermal gradient in areas away from intense pumping at Memphis. All of the wells logged had not been pumped for long-periods of time--most for many decades--and therefore, the water in the wells was in thermal equilibrium with the surrounding formations.

Temperature logs of wells Fa:R-1 and Sh:K-45 illustrate characteristic differences in the geothermal profile between areas undisturbed by pumping and areas of intense pumping (fig. 18). Well Fa:R-1 is in an area undisturbed by pumping (fig. 16). The temperature log shows the normal near-surface geothermal gradient. The coolest temperature recorded in this well was 16.0 °C at a depth of 100 feet. Well Sh:K-45 (fig. 16) is in the northern part of the Sheahan well field (fig. 1). The coolest temperature recorded in this well was 16.4 °C at a depth of 300 feet. In general, in the Memphis area, the coolest temperatures in wells in areas undisturbed by pumping are at lesser depths than in wells in areas of intense pumping. The depth of the coolest temperature below land surface recorded in the wells logged in the Memphis area is shown in figure 19.

The coolest up-hole temperature recorded was 15.6 °C at a depth of 140 feet in Sh:T-17 in the north-central part the Memphis area. This temperature is 1 °C cooler than the 16.6 °C mean air temperature at Memphis based on 52 years of record (National Oceanic and Atmospheric Administration, 1983). Other cool up-hole temperatures were 16.1 °C at 100 feet in Sh:O-1, 16.2 °C at 140 feet in Sh:P-1, 16.2 °C at 100 feet in Ar:O-1, 16.3 °C at 100 feet in Ar:H-2, and 16.5 °C at 180 feet in Sh:P-113. These up-hole temperatures were the coolest temperatures recorded in each of these wells. All but one of these wells are outside areas of intense pumping, and the temperature logs indicate a normal geothermal gradient. Sh:P-113 is in MLGW's new Morton well field in which pumping began in 1982, about 2 years before the log was made.

Other wells that had relatively cool up-hole temperatures but had the coolest water at depth are Sh:J-126 with 16.3 °C at 120 feet, but 16.1 °C at 200 feet; Sh:J-140 with 16.5 °C at 140 feet, but 16.2 °C at 260 feet; Sh:L-39 with 16.5 °C at 180 feet, but 16.4 °C at 230 feet; Sh:K-72 with 16.8 °C at 120 feet, but 16.1 °C at 230 feet; and Sh:Q-53 with 16.8 °C at 120 feet, but 16.3 °C at 300 feet.

Sh:K-72 is in the southernmost part of the Sheahan well field in which pumping began in 1948; Sh:J-126 is in the southernmost part of the Allen well field in which pumping began in 1952; Sh:Q-53 is in the center of the McCord well field in which pumping began in 1958; Sh:L-39 is in the southeasternmost part of the Lichterman well field in which pumping began in 1965; and Sh:J-140 is in the center of the Davis well field in which pumping began in 1971. Most of these wells are on the margins of older well fields or in the center of newer well fields.

The warmest up-hole temperature recorded was 18.2 °C at a depth of 120 feet in SH:K-57. The coolest temperature in this well was 16.4 °C at 380 feet. Other wells with relatively warm up-hole temperatures but the coolest temperature at depth are Sh:O-181 with 17.0 °C at a depth of 110 feet, but 16.4 °C at 400 feet; Sh:K-58 with 17.2 °C at 140 feet, but 16.4 °C at 320 feet; Sh:K-45 with 17.3 °C at 140 feet, but 16.4 °C at 300 feet; Sh:O-170 with 17.4 °C at 140 feet, but 16.6 °C at 380 feet; Sh:P-76 with 17.4 °C at 160 feet, but 16.5 °C at 370 feet; and Sh:P-143 with 17.8 °C at 100 feet, but 16.5 °C at 280 feet.

Wells Sh:O-170 and Sh:O-181 are in the Mallory well field in which pumping began in 1925; and Sh:K-45, K-57, and K-58 are in the northern part of the Sheahan well field in which pumping began in 1933. Sh:P-76 is in the area of the abandoned Central Avenue well field, which was pumped from 1907 to 1925, and is centered among Mallory, Allen, and Sheahan well fields near the center of the major cone of depression in the potentiometric surface in the Memphis Sand. Sh:P-143 is on the margin of a smaller cone of depression formed by an area of intense industrial pumping. All of these wells are in areas affected by intense pumping over long periods of time.

Sh:U-1 had a relatively cool up-hole temperature of 16.2 °C at 100 feet, but the coolest temperature was 16.0 °C at 240 feet. The temperature log also shows a distortion of the

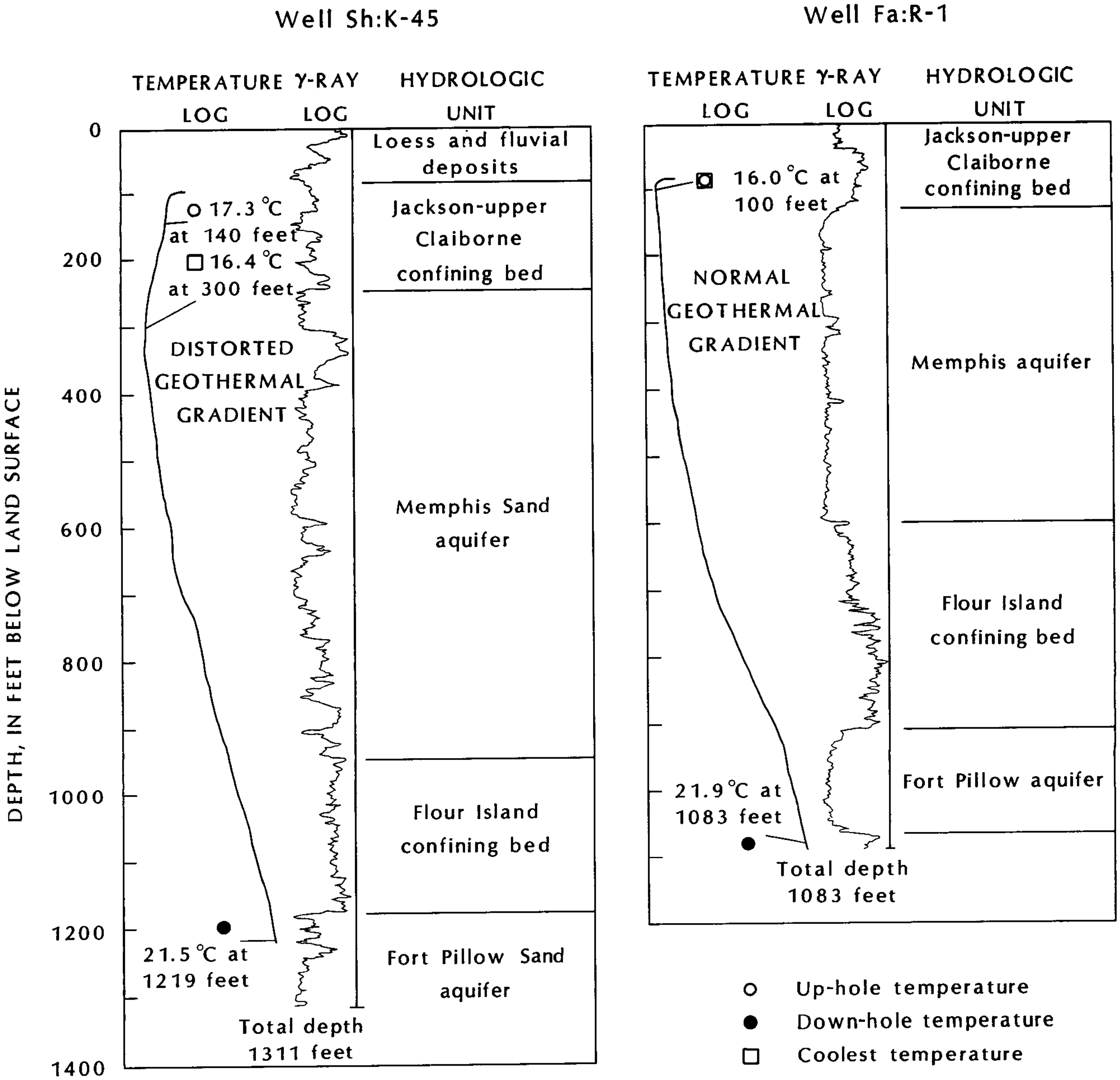
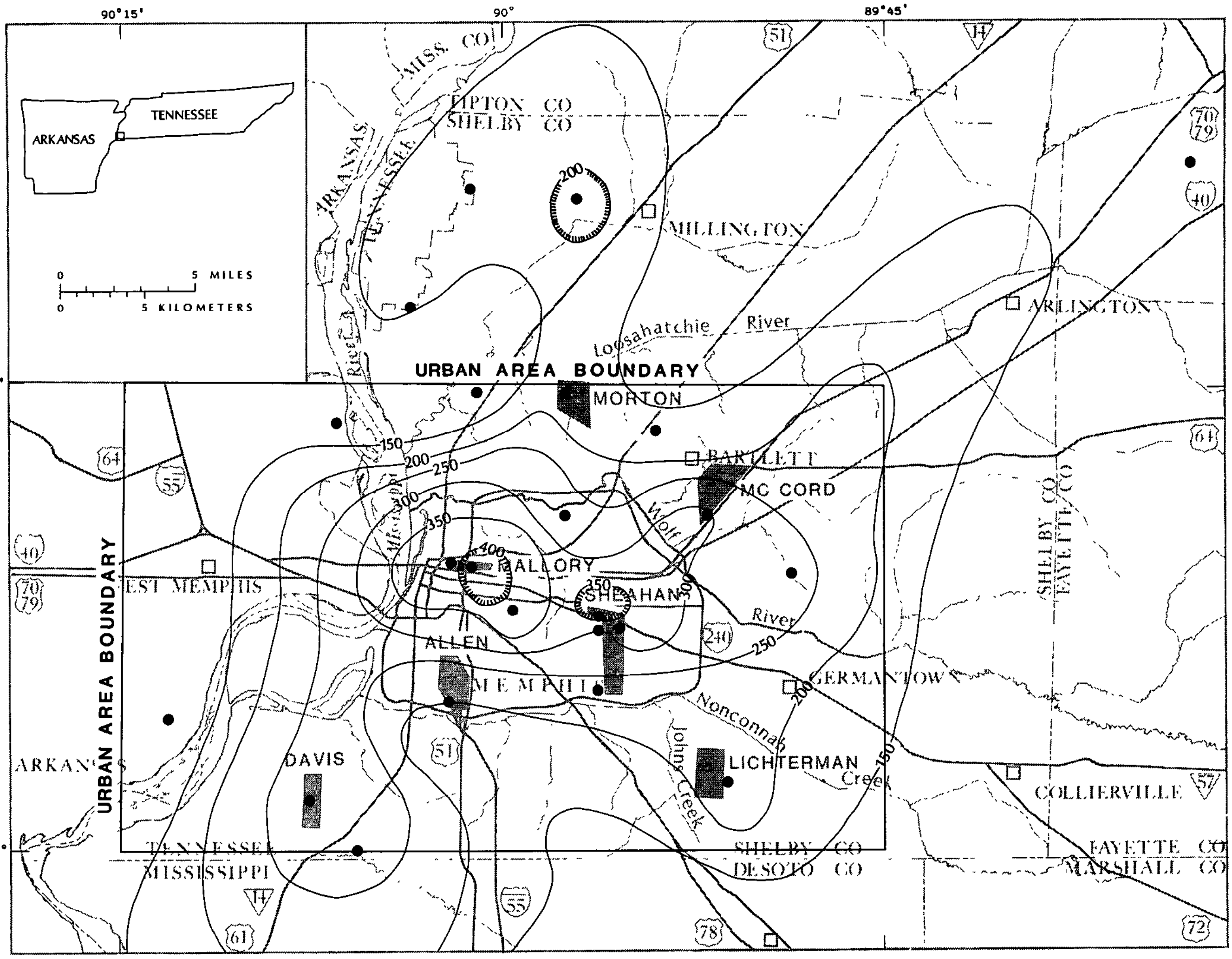


Figure 18.--Temperature and gamma-ray logs of wells Sh:K-45 and Fa:R-1 showing the normal and distorted geothermal gradients as related to depth and hydrologic unit.



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

EXPLANATION

——200—— LINE OF EQUAL DEPTH OF THE COOLEST WATER IN UNUSED WELLS–Hachures indicate depression. Interval 50 feet. Datum is land surface.

Figure 19.–Depth below land surface of the coolest temperature recorded in the wells logged in the Memphis area.

thermal field as if the well was in an area of intense pumping. This well is located at the site of an abandoned gunpowder plant which operated during World War II. Water was supplied to this plant by many large capacity wells. Consequently, the distortion in the geothermal field in Sh:U-1 probably is a remnant from the time that this area was intensely pumped.

Sh:Q-1 had a relatively warm up-hole temperature of 17.4 °C at 120 feet, but the coolest temperature was 16.7 °C at 260 feet. The temperature log also shows a distortion of the thermal field as if the well was in an area of intense pumping. This well is located east of Memphis, far removed from any area of intense pumping. The well is, however, in an area where the confining bed separating the fluvial deposits from the Memphis Sand is relatively thin and contains little clay. This is a key observation well in the Memphis area, the record of which shows long-term declines of water levels in the Memphis Sand related to pumping at Memphis. Perhaps these declines in water levels have caused an acceleration of downward leakage from the fluvial deposits, particularly at low water-level times in the late summer and early fall. Thus, this leakage may have caused a warming of the near-surface formations.

Sh:J-1 has a relatively cool up-hole temperature of 16.5 °C at 100 feet, but the coolest temperature was 16.0 °C at 260 feet. The temperature log also shows a distortion in the thermal field as if the well was in an area of intense pumping. This well is located in an area far removed from intense pumping where the confining bed separating the fluvial deposits and the Memphis Sand is thick and contains thick clay beds. Consequently, the temperature relation in this well is not explainable based on present information. Perhaps the clay beds in the confining bed are thin or absent short distances away from Sh:J-1, and a pathway for downward leakage of water from the fluvial deposits is provided similar to that in Sh:Q-1.

The calculated geothermal gradients (table 3) are all less than the normal geothermal gradient of 0.6 °C per 100 feet as determined during the present investigation, except for Fa:R-1 on which this normal geothermal gradient was partly based. These other geothermal gradients indicate recharge by vertical leakage within the Memphis area. The gradients include negative values (-) for some wells. These negative values result from a calculation of the geothermal gradient for wells where the up-hole temperature, at or below 100 feet, is greater than the down-hole temperature, at the total depth logged. Generally, the geothermal gradients do not seem to show any particular relation when gradients for wells in areas outside of intense pumping are compared to those for wells in areas of intense pumping. This lack of a comparative relation probably is the result of the shallow depth of some wells, screened in the upper part of the Memphis Sand, for which the logs did not provide enough of the geothermal profile to determine the extent of the distortion in the profile at the well sites.

The areal distribution of the depth to the coolest water below land surface (fig. 19) is very similar to the major cone of depression (fig. 9) indicating a general component of vertical leakage in the area of intense pumping at Memphis. Generally, the coolest temperature occurs in the Memphis Sand in the area of the major cone of depression, but it occurs in the water-table aquifers or Jackson-upper Claiborne confining bed outside the area of intense pumping (table 3 and fig. 19).

Estimates of Ground-Water Velocity

Geophysical temperature logs can be valuable in an assessment of the leakage potential of an area. Under favorable conditions, an estimate of ground-water velocity in the vertical direction, v_z, and hydraulic conductivity, K, can be computed from temperature profile data using the method described by Stallman (1963) and published type curves (Bredehoeft and Papadopulos, 1965). Sorey (1971) describes the successful application of this method in several field studies.

Bredehoeft and Papadopulos (1965) state that the appropriate differential equation for steady, one-dimensional vertical flow of heat and fluid through saturated, isotropic, homogeneous porous media is:

$$(\partial T^{2}{}_{z}/\partial z^{2})-(c_{o}p_{o}v_{z}/k)(\partial T_{z}/\partial z)=0 \qquad (1)$$

where

T_z = temperature at any depth z;
z = depth in the calculated interval, positive downward;
v_z = specific discharge (Darcian velocity) in z direction;
c_o = specific heat of fluid;
p_o = density of fluid;
k = thermal conductivity of solid-fluid complex.

For the boundary conditions,

$T_z = T_o$
= uppermost temperature measurement at z = 0
$T_z = T_L$
= lowermost temperature measurement at z = L

where L is the length of vertical section over which temperatures are considered and the z coordinate is positive downward, the solution can be written as

$$\frac{T_z - T_o}{T_L - T_o} = f(\beta, z/L) = [\exp(\beta z/L)-1]/[\exp(\beta)-1]$$

where $\beta = v_z c_o p_o L/k$. Bredehoeft and Papadopulos (1965) include type curves and tabulations of the function $f(\beta, z/L)$ for selected values of the parameters. To determine vertical ground-water velocity, v_z, from the temperature measurements, the appropriate value of ß is found by matching a plot of z/L versus $(T_z-T_o)/(T_L-T_o)$ to the type curves. Then knowing thermal conductivity, k, and $c_o p_o$, one can calculate v_z from the equation

$$vz = \beta k/Lc_o p_o \qquad (2)$$

The normal geothermal profile (fig. 17) indicates a significant deviation from linearity between 120 and 910 feet. The deviation indicates that water is moving downward from the Memphis Sand through the lower confining bed to the underlying Fort Pillow Sand. Water-level measurements in well Fa:R-1 in the Fort Pillow Sand and nearby well Fa:R-2 in the Memphis Sand (fig. 16) indicate that the head in the Fort Pillow Sand is 38.1 feet lower than in the Memphis Sand at this location. This head difference would create a potential for movement of water into the Fort Pillow Sand. The movement of water into the Fort Pillow Sand at this location is limited by a thick layer of clay between the two aquifers (about 140 feet of clay in a confining bed about 280 feet thick). Temperature data from well Fa:R-1 can be used to estimate the rate of downward water movement and the hydraulic conductivity of the confining bed that separates the two aquifers using equations 1 and 2 and Darcy's Law.

Birch and others (1942, p. 251-259) and Clark (1966, p. 477-479) indicate that a reasonable value for thermal conductivity, k, for saturated clay is 2×10^{-3} cal/sec cm °C. Sorey (1971, p. 966) suggests that thermal conductivities for saturated, unconsolidated sediments vary little from sand to clay so that it generally is not necessary to determine thermal conductivities in the field or laboratory to use equation 2. This value of thermal conductivity, along with a value of 1 cal/gm °C for the specific heat of water in the confining bed and aquifers and a value of 1 gm/cm^3 for the density of the water are used in the following calulations.

To obtain ß, a plot of z/L versus $(T_z-T_o)/(T_L-T_o)$ was matched with type curves from Bredehoeft and Papadopulos (1965, p. 326); this results in an interpolated value of 2.8 for ß (fig. 20). Using this value in equation 2, an estimated value for the vertical ground-water velocity in the vicinity of this well is 2.33×10^{-7} cm/sec or 6.6×10^{-4} ft/d.

The accuracy of an estimate of the vertical ground-water velocity obtained using this method is limited by the necessity to use assumed values for the thermal conductivity of the materials (solid and fluid) in the confining bed and estimates of the specific heat and density of the water. The accuracy of the estimate is also limited by deviations from the theoretical assumptions of isotropy and homogeneity in the confining bed. The accuracy of the temperature log used to obtain the vertical temperature profile is limited by possible convection currents in the well and by possible instrumental drift.

Well Fa:R-1 is completed at a depth of 1,025 feet; Fa:R-2 is completed at a depth of 365 feet. With a head difference between these wells of

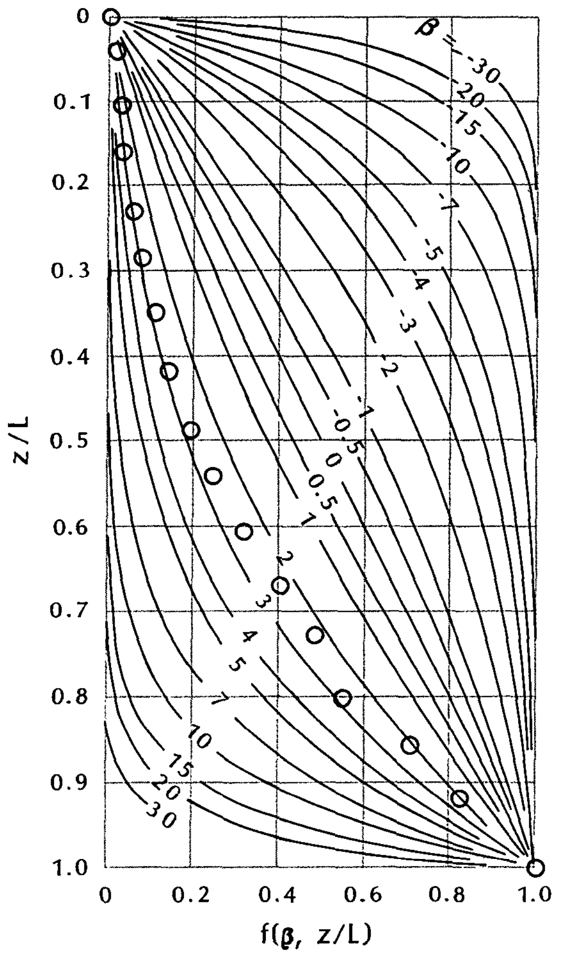


Figure 20.--Nondimensional plot of temperature data between the depths of 120 and 910 feet in well Fa:R-1 matched with type curves from Bredehoeft and Papadopulos (1965).

38.1 feet, the vertical head gradient is 0.058. From Darcy's law:

$$v_z = K(dh/dz)$$

where

K is the hydraulic conductivity;
dh/dz is the vertical head gradient; and
v_z is the vertical velocity.

Solving for K and substituting the value of vertical velocity determined above and the measured vertical gradient between the two aquifers:

$$K = (v_z)/(dh/dz)$$
$$= (6.6 \times 10^{-4})/(0.058)$$
$$= 1.14 \times 10^{-2} \text{ ft/d}$$

This value is in agreement with published values for the hydraulic conductivity of silt, clay, and mixtures of sand, silt, and clay (U.S. Department of the Interior, 1977, p. 29). The vertical velocity between the Fort Pillow Sand and the Memphis Sand is limited by the relatively thick confining bed of low hydraulic conductivity. The value of hydraulic conductivity estimated above, along with information about the thickness of the confining bed (figs. 5 and 6) and head differences throughout the area (fig. 12), could be used to estimate the amount of water that is exchanged between these two aquifers. Such application is beyond the scope of this project.

An unsuccessful attempt was made to use the technique described above to provide an estimate of the vertical exchange of water between the fluvial deposits and the Memphis Sand. The temperature data obtained from geophysical logs indicate, in areas of intense pumping, the ground water is not in thermal equilibrium in the confining bed between the fluvial deposits and the Memphis Sand. This is indicated by the fact that in several of the wells the water gets colder with depth in the upper part of the well. The analytical solution used above is not straightforward in this situation, and more detailed information is needed before temperature-profile data can be used to quantitatively estimate the exchange of water between the fluvial deposits and the Memphis Sand.

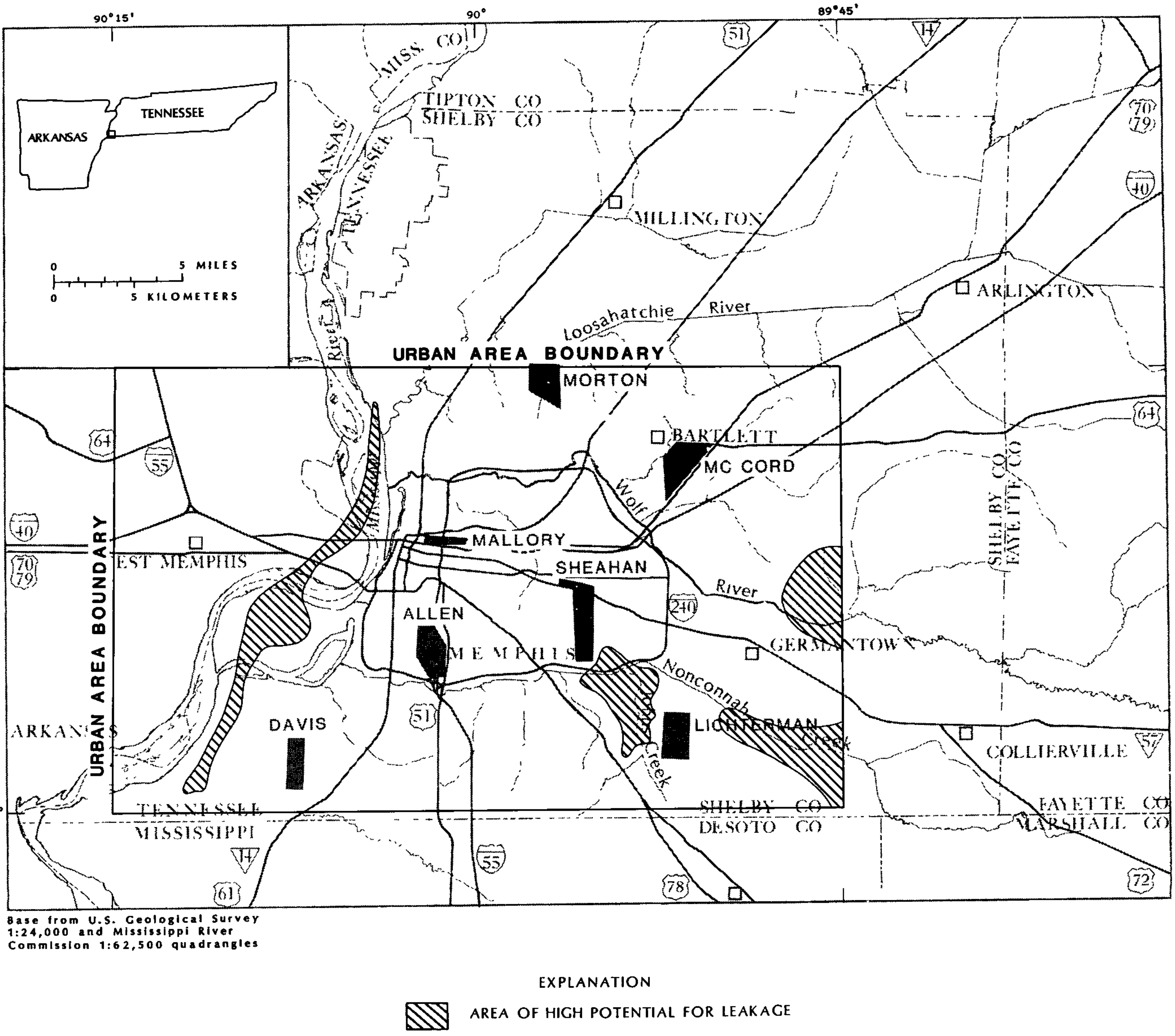
POTENTIAL FOR LEAKAGE

The confining beds overlying and underlying an artesian aquifer generally are not completely impermeable, and an interchange of water occurs naturally between the artesian aquifer and shallower or deeper aquifers by leakage through the confining beds. The amount of leakage that occurs depends on the thickness and hydraulic conductivity of the confining bed and the differences in hydraulic head between the aquifers. In the Memphis area, the potential for leakage is least where a confining bed is thick and contains much clay and where head differences are small, and it is greatest where a confining bed is thin or absent and where head differences are large. At most places, the potential for leakage falls between these extremes. Because the characteristics of the confining beds and the differences in the hydraulic heads can vary greatly over relatively short distances in the Memphis area, an assessment of the potential for leakage among the aquifers can only be generalized. Much additional work would be needed to assess specific areas or sites.

The results of the present investigation indicate that a general component of downward vertical leakage of water occurs from the water-table aquifers through the Jackson-upper Claiborne confining bed to the Memphis Sand. Maps showing the areal distribution of carbon isotope data from the upper part of the Memphis Sand (fig. 15) and the depth to the coolest temperature (fig. 19) indicate that pumping from the Memphis Sand has induced downward leakage in the area of the major cone of depression in the potentiometric surface of the Memphis Sand (fig. 9). Pumping from the Memphis Sand in MLGW well fields has also caused local increases in head differences between the water-table aquifers and the Memphis Sand and, thus, local increases in vertical hydraulic gradients. These increased hydraulic gradients create a potential for an accelerated downward movement of water through the Jackson-upper Claiborne confining bed. The isotope data (table 2) and geothermal data (table 3) indicate that downward vertical leakage occurs from the water-table aquifers through the confining bed to the Memphis Sand in MLGW well fields.

Four areas in the Memphis urban area were identified where the Jackson-upper Claiborne confining bed is thin or absent and a high potential exists for the movement of water from the water-table aquifers directly into the Memphis Sand (fig. 21). These areas are: (1) in the eastern part along and north of the Wolf River, (2) in the southeastern part along Nonconnah Creek, (3) in the south-central part along Nonconnah and Johns Creeks, and (4) in the western part in a belt along the Mississippi River. The identification of these areas is based primarily on a map of the thickness of the Jackson-upper Claiborne confining bed (fig. 3). Additional evidence is available that indicates water from the water-table aquifers is entering the Memphis Sand in the area in the south-central part along Nonconnah and Johns Creeks. This area is upgradient in the direction from which water moves through the Memphis Sand towards the southern part of the Sheahan well field (fig. 9). It may be the source of some of the water pumped by wells in this part of this well field.

Downward vertical leakage of water from the water-table aquifers to the Memphis Sand along



Base from U.S. Geological Survey 1:24,000 and Mississippi River Commission 1:62,500 quadrangles

Figure 21.--Areas of high potential for downward vertical leakage from the water-table aquifers to the Memphis Sand in the Memphis urban area.

Nonconnah Creek south of Sheahan well field has been previously suspected. According to Nyman (1965, p. B8), an interpretation of discharge measurements made along Nonconnah Creek suggested that 0.1 ft^3/s of water must have been diverted to underflow along a 1 1/2-mile segment of Nonconnah Creek south of the Sheahan well field. He also stated that for several years during the fall months the channel of Nonconnah Creek in this area was observed to be completely dry, although still farther upstream and downstream the channel had some flow. Since Nyman's investigation, the channel and flood plain of Nonconnah Creek has been greatly modified by dredging, the emplacement of fill, and construction of bridges and Interstate I-240.

Evidences, identified during the present investigation, that downward vertical leakage of water occurs from the water-table aquifers to the Memphis Sand in the southern part of the Sheahan well field near Nonconnah Creek are: (1) a map of the water-table surface indicates a depression in the water table (fig. 7); (2) the hydrograph of observation well Sh:K-75 shows a continuous decline of the water level in the water-table aquifer, dating back almost to the begining of pumping from the Memphis Sand in this area (fig. 8); (3) a map of the head differences between the water-table aquifers and the Memphis Sand show that these head differences range from 40 to 60 feet and provide a potential for downward vertical leakage (fig. 11); (4) isotope data,for both carbon-14 and tritium concentrations, indicate that recent water has entered the Memphis Sand in the vicinity of wells Sh:K-73 and Sh:K-74 (table 2); and (5) geothermal data show that in well Sh:K-72 the uphole temperature was 16.8 °C at a depth of 120 feet and the coolest temperature was 16.1 °C at 230 feet, which indicates downward vertical leakage (table 3).

In addition to downward vertical leakage from the water-table aquifers to the Memphis Sand, head differences between the Memphis Sand and the Fort Pillow Sand in the central part of the Memphis urban area indicate a vertical hydraulic gradient that creates a potential for upward vertical leakage from the Fort Pillow Sand through the Flour Island confining bed to the Memphis Sand (fig. 12). Because the Flour Island confining bed is relatively thick and contains much clay (figs. 5 and 6), upward leakage from the Fort Pillow Sand to the Memphis Sand is probably small.

SUMMARY AND CONCLUSIONS

The principal freshwater aquifers in the Memphis area are: (1)the alluvium, (2) the fluvial deposits, (3) the Memphis Sand, and (4) the Fort Pillow Sand. The alluvium and fluvial deposits make up the water-table (unconfined) aquifers, and the Memphis Sand and Fort Pillow Sand are the artesian (confined) aquifers. The Memphis Sand provides about 95 percent of the water used in the Memphis area for municipal and industrial water supplies, and the Fort Pillow Sand provides about 5 percent. Pumpage in 1984 was about 190 Mgal/d from these two aquifers.

The principal confining beds in the Memphis area are (1) the Jackson Formation and upper part of the Claiborne Group and (2) the Flour Island Formation. The Jackson-upper Claiborne confining bed separates the water-table aquifers from the Memphis Sand, the Flour Island confining bed separates the Memphis Sand from the Fort Pillow Sand.

The Jackson-upper Claiborne confining bed in the Memphis urban area ranges from 0 to 360 feet in thickness, and aggregate thickness of clay beds thicker than 10 feet within this confining bed ranges from 0 to 250 feet. Four general areas in the Memphis urban area were identified where the Jackson-upper Claiborne confining bed is thin or absent; consequently, the potential for leakage from the water-table aquifers to the Memphis Sand is high. These general areas are: (1) in the eastern part of the Memphis urban area along and north of Wolf River, (2) in the southeastern part along Nonconnah Creek, (3) in the south-central part along Nonconnah and Johns Creeks in the vicinity of the southern part of the Sheahan well field, (4)in the western part in a belt along the Mississippi River. The existence and boundaries of these areas, particularly the belt along the Mississippi River, are highly interpretative because of the lack of geophysical logs of wells in these areas.

The Flour Island confining bed in the Memphis urban area ranges from 160 to 310 feet in thickness, and aggregate thickness of clay beds thicker than 10 feet ranges from 70 to 240 feet. The Flour Island confining bed is thickest in the southeastern and northwestern parts of the Memphis urban area and is thinnest in the central part. Aggregate thickness of clay beds thicker than 10 feet is greatest in the southeastern part and least in the central part.

A water-table map for the shallow aquifers--alluvium and fluvial deposits--shows a depression in the the water-level surface in the south-central part of the Memphis urban area in the southern part of the Sheahan well field. This depression, which is based mostly on the record of water levels in one observation well, indicates that pumping stress in the Memphis Sand has lowered water levels in the overlying water-table aquifer.

Head differences between the water-table aquifers and the Memphis Sand range from 0 to 130 feet in the Memphis urban area. Areally, the total hydraulic head, as related to sea level, in the water-table aquifers equals or is greater than total hydraulic head in the Memphis Sand. Therefore, throughout the entire area, the vertical hydraulic gradient creates a potential for downward movement of water from the water-table aquifers to the Memphis Sand.

Head differences between the Memphis Sand and the Fort Pillow Sand range from about minus 40 to plus 50 feet in the Memphis urban area. Throughout the central part, total hydraulic head in the Fort Pillow Sand equals or is greater (plus) than total hydraulic head in the Memphis Sand, and the vertical hydraulic gradient creates a potential for upward movement of water from the Fort Pillow Sand to the Memphis Sand. In the eastern and western parts of the Memphis urban area, total hydraulic head in the Fort Pillow Sand is less (minus) than that of the Fort Pillow Sand, and the vertical hydraulic gradient creates a potential for downward movement of water from the Memphis Sand to the Fort Pillow Sand.

The vertical distribution of carbon-14 data from the fluvial deposits, Memphis Sand, and Fort Pillow Sand near the center of pumping at Memphis show an increase in the relative age of the water with depth. The areal distribution of carbon-14 data for water from the upper part of the Memphis Sand indicates that relatively recent water has been brought into the major cone of depression in the potentiometric surface of the Memphis Sand at Memphis, either by horizontal movement through the aquifer or by downward leakage. Carbon-14 and tritium isotope data indicate that some water from recent precipitation has entered the Memphis Sand in the southern part of the Sheahan well field.

The normal near-surface geothermal gradient in the Memphis area below a depth of 100 feet was determined to be 0.6 °C per 100 feet. Temperature logs made in observation wells in areas away from areas of intense pumping showed, with a few exceptions, normal geothermal gradients. Temperature logs made in abandoned wells and observation wells in MLGW well fields generally showed a pronounced distortion in the geothermal field. The coolest temperature recorded in the well fields was 15.6 °C, which is 1 °C cooler than the mean annual air temperature based on 52 years of record at Memphis, and the warmest temperature recorded was 18.2 °C. The geothermal gradients for wells in areas affected by pumping from the Memphis Sand are less than the normal gradient for the Memphis area, indicating recharge by downward vertical leakage.

The depth to the coolest temperature ranged from 100 to 400 feet below land surface in the Memphis area. The areal distribution of the depth to coolest temperature is similar to the potentiometric surface in major cone of depression in the Memphis Sand, indicating a general component of downward vertical leakage in the area of intense pumping from the Memphis Sand at Memphis.

From temperature data from an observation well in the northeastern part of the Memphis area about 25 miles from the center of pumping at Memphis, a velocity of 6.6×10^{-4} ft/d was determined for water moving from the Memphis Sand through the Flour Island confining bed into the Fort Pillow Sand. Using this velocity and a measurement of head difference between these aquifers at this location, a hydraulic conductivity of the Flour Island confining bed was determined to be 1.14×10^{-2} ft/d. The hydraulic conductivity of the Jackson-upper Claiborne confining bed or the velocity of ground water moving through this confining bed cannot be determined using temperature data.

The results of the present and previous investigations indicate that a general component of downward vertical leakage from the water-table aquifers to the Memphis Sand occurs in the Memphis area. This downward vertical leakage probably is greatest in areas where the Jackson-upper Claiborne confining bed is thin or absent and in MLGW well fields where this leakage is induced by pumping stress in the Memphis Sand. Where the confining bed is absent, water moves directly from the water-table aquifers into the Memphis Sand. In the central part of the

Memphis urban area, a potential exists for upward vertical leakage from the Fort Pillow Sand into the Memphis Sand. Because the Flour Island confining bed is relatively thick and contains much clay, any interchange of water between the Fort Pillow Sand and the Memphis Sand probably is small.

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SUPPLEMENTAL EXPLANATION OF ISOTOPE DATA

During this investigation, samples of ground water were analyzed to determine concentrations f isotopes of carbon and hydrogen. Carbon-14, a adioactive isotope of carbon, can be used to pproximate the apparent age of water; tritium, n isotope of hydrogen, can be used to give a ualitative indication of the presence of very ecent recharge to an aquifer. Supplemental nformation pertaining to the interpretation of he isotope data collected in the investigation ollows.

Carbon-14

Carbon-14 is a radioactive isotope of carbon with a half-life of 5,730 years (Mook, 1980, p. 3). It is produced naturally by the process of itrogen transmutation caused by the bombardment of the atmosphere by cosmic rays (Libby, 965). Carbon-14 is also a product of thermouclear weapons testing (Mook, 1980, p. 52).

Carbon-14 formed in the upper atmosphere s oxidized to carbon dioxide and is transported to he lower atmosphere where some of it enters the ydrologic cycle. When water containing dissolved norganic carbon moves below the water table and s cut off from contact with the atmosphere, the arbon-14 content decreases at a rate controlled y its half-life. This provides the basis for arbon-14 dating of ground water. However, the arbon-14 content of ground water is also ffected by chemical reactions involving carbonte species. Carbonate minerals in aquifers are ommonly older than 50,000 years and contain no arbon-14. Carbonate species added to the ground water by the dissolution of these minerals dilute he original carbon-14 content of the recharge water--thus indicating an anomalously greater pparent age of the water.

One technique commonly used to adjust arbon-14 measurements for dissolution of carbonte minerals uses the concentration of the stable sotope carbon-13 (Pearson, 1965; Pearson and White, 1967; Pearson and others, 1972). The technique assumes the "dilution" of carbon-14 in the water is proportional to the "dilution" of carbon-13. A simplification of Pearson's 1965 method leads to a correction factor defined by the following equation:

$$P = (\text{C-13/C-12}) \text{ per mil } / -25.0 \text{ per mil} \qquad (3)$$

where

P is the correction factor;

C-13/C-12 is the carbon-13/carbon-12 ratio of the sample relative to a standard; and -25.0 per mil is a constant derived from measurement of the carbon-13/carbon-12 ratio of CO_2 in modern soils.

To use the above correction factor "P," the analytically determined carbon-14 activity, expressed as percent of the modern standard (percent modern), is divided by the value for "P" to obtain an adjusted carbon-14. Carbon-14 values in this report have been adjusted using this method (table 2).

Some reactions may increase the concentration of carbon-14 in ground water. For example, oxidation of fulvic and humic acids generates dissolved carbonate species; but in the Memphis area, this source is small and is neglected in this study. Fossil snail shells less than 25,000 years old occur in the Pleistocene loess that overlies the fluvial deposits (Snowden and Priddy, 1968, p. 119-124). The snails contain small amounts of carbon-14. The fluvial deposits, which make up the shallow water-table aquifer in upland areas, receives its recharge from precipitation that passes through the loess. The carbon-14 contributed by the dissolution of the geologically young snail shells may introduce some error into age determinations using the above correction method, which is based on the assumption that no additional carbon-14 has been added by the dissolution of carbonate minerals. Any addition of carbon-14 from the dissolution of the snail shells would directly increase the analytically determined carbon-14 activity and would also cause a slight over-correction to be applied, thus resulting in higher values for adjusted carbon-14.

The calculation of "P" in equation (3) assumes that carbon dioxide gas originally contained carbon-13 of -25 per mil and carbon-14 of 100 percent modern. If other sources of carbon dioxide have added to the dissolved carbonate species, then the factor "P" can "over correct" or "under correct" the change in carbon-14 due to "dilution," depending on the carbon-13 content of the source. For example, inorganic carbon in ground water can be derived from the degradation of organic material (Freeze and Cherry, 1979, p. 135, 290). The carbon-13 in organic matter is variable and, depending on the particular degradation reactions, may produce carbon dioxide that is enriched in carbon-13. In the Memphis area, lignite (several tens of millions of years old) is present in the Memphis Sand and Fort Pillow Sand and in the overlying and underlying confining beds. Dissolved carbonate derived from this source, if enriched in carbon-13, would introduce error into the carbon-14 adjustments listed in table 2 by increasing the value of the carbon-13/carbon-12 ratio. The effect of the error would be to adjust the carbon-14 concentration lower than it would be if all of the carbon was derived from inorganic sources.

Interaquifer exchange of water can also affect carbon-14 concentrations and determinations of apparent age due to mixing of dissolved carbonate species. If exchange of water occurs between aquifers, the age determined from carbon-14 concentrations will not represent the true age of the water in the aquifer sampled, but an intermediate value that lies between the age of the water and the age of the water leaking into it. At present, the interpretation of carbon isotope data from aquifers in the Memphis area is limited by a lack of knowledge about all sources of carbon in the system and the chemical reactions occurring. Therefore, additional information about the geochemistry of the ground water and the lithology of the aquifers and confining beds is needed before interpretations of the carbon isotope data can be used to assign age values (in years) to water with any degree of certainty. Nevertheless, carbon isotope data, used in conjunction with other types of hydrogeologic information provides supporting evidence in areas where leakage is suspected.

Tritium

Tritium is the radioactive isotope of hydrogen with an atomic weight of 3, and a half-life of 12.35 years. It is produced either naturally in the earth's atmosphere by the interaction of cosmic-rays with the atmosphere, or artificially since 1952, by the atmospheric testing of thermonuclear weapons. The atmospheric tests increased tritium concentrations by two to three orders of magnitude above natural background levels in precipitation. Due to the cessation of atmospheric tests and its short half-life, tritium concentrations in precipitation reached a maximum in 1963 and have decreased since then. Tritium concentrations in precipitation in the late 1970's ranged from about 20 to 100 tritium units (TU), according to Egboka and others (1982). The abundance of man-made tritium and its short half-life make the isotope useful for detecting the influx of recent (post-1952) precipitation into ground-water reservoirs. Tritium is useful in ground-water studies because it is not significantly affected by reactions other than radioactive decay and, as part of the water molecule, it travels with the water in an aquifer and at the same velocity (Freeze and Cherry, 1979, p. 136-137).

Ground water that originated as precipitation prior to 1953 had an initial tritium concentration of between 5 and 10 TU; tritium concentrations of hundreds of tritium units indicate that all or most of the water entered the ground after 1953 (Freeze and Cherry, 1979, p. 136-137). After considering normal decay, any detectable concentration of tritium in ground water is reason to suspect the introduction of recent precipitation into the aquifer (Fontes, 1980, p. 81).

In confined aquifers, the occurrence of minor amounts of tritium indicates the influx of water from shallower aquifers (Fontes, 1980, p. 84). In the present investigation, tritium isotope data were used to give a qualitative indication of the possible introduction of recent recharge to the Memphis Sand in areas where leakage from the overlying fluvial deposits is suspected.

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