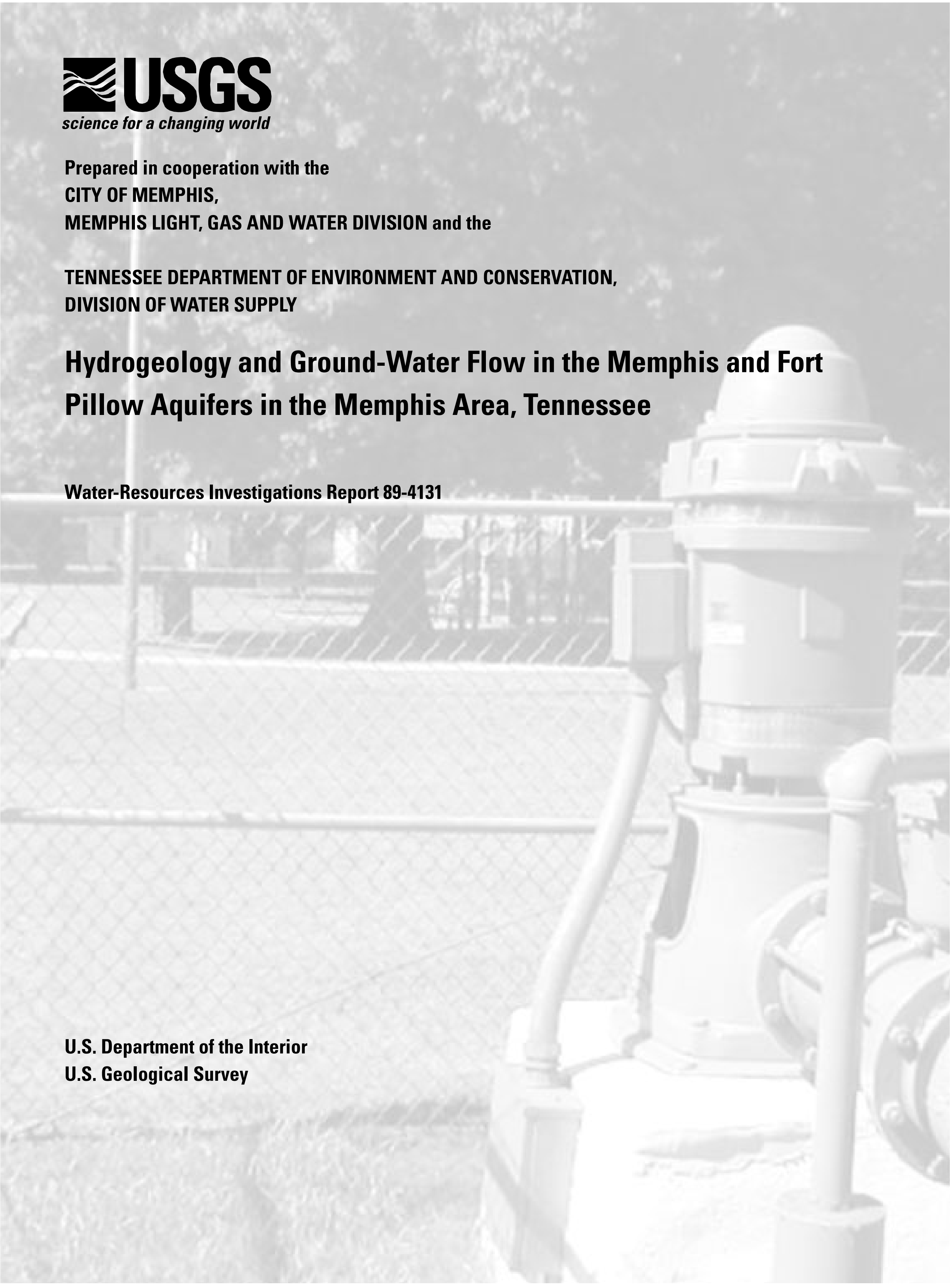

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MEMPHIS LIGHT, GAS AND WATER DIVISION and the

TENNESSEE DEPARTMENT OF ENVIRONMENT AND CONSERVATION,
DIVISION OF WATER SUPPLY

Hydrogeology and Ground-Water Flow in the Memphis and Fort Pillow Aquifers in the Memphis Area, Tennessee

Water-Resources Investigations Report 89-4131

U.S. Department of the Interior
U.S. Geological Survey

Cover photograph: Public-supply well in Shelby County, Tennessee. Photograph taken by L.B. Thomas, U.S. Geological Survey.

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Nashville, Tennessee
2001

U.S. DEPARTMENT OF THE INTERIOR
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CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND WELL-NUMBERING SYSTEM

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	3.528×10^{-6}	meter per second (m/s)
square foot per second (ft^2/s)	0.0929	square meter per second (m^2/s)
cubic foot per second (ft^3/s)	2.83×10^{-2}	cubic meter per second (m^3/s)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon per day (gal/d)	4.384×10^{-8}	cubic meter per second (m^3/s)
gallon per minute (gal/min)	6.309×10^{-5}	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	4.384×10^{-2}	cubic meter per second (m^3/s)
gallon per day per foot [(gal/d)/ft]	1.438×10^{-7}	square meter per second (m^2/s)
inch per year (in/yr)	0.0254	meter per year (m/a)

Sea Level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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 topographic 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:U-2, for example, indicates that the well is located in Shelby County on the "U" quadrangle and is identified as well 2 in the numerical sequence. Quadrangles are lettered from left to right, beginning in the southwest corner of the county.

Hydrogeology and Ground-Water Flow in the Memphis and Fort Pillow Aquifers in the Memphis Area, Tennessee

By J.V. Brahana *and* R.E. Broshears

ABSTRACT

On the basis of known hydrogeology of the Memphis and Fort Pillow aquifers in the Memphis area, a three-layer, finite-difference numerical model was constructed and calibrated as the primary tool to refine understanding of flow in the aquifers. The model was calibrated and tested for accuracy in simulating measured heads for nine periods of transient flow from 1886-1985. Testing and sensitivity analyses indicated that the model accurately simulated observed heads areally as well as through time.

The study indicates that the flow system is currently dominated by the distribution of pumping in relation to the distribution of areally variable confining units. Current withdrawal of about 200 million gallons per day has altered the prepumping flow paths, and effectively captured most of the water flowing through the aquifers. Ground-water flow is controlled by the altitude and location of sources of recharge and discharge, and by the hydraulic characteristics of the hydrogeologic units.

Leakage between the Fort Pillow aquifer and Memphis aquifer, and between the Memphis aquifer and the water-table aquifers (alluvium and fluvial deposits) is a major component of the hydrologic budget. The study indicates that more than 50 percent of the water withdrawn from the Memphis aquifer in 1980 is derived from vertical leakage across confining units, and the leakage from the shallow aquifer (potential source of contamination) is not uniformly distributed. Simulated leakage was concentrated along the upper reaches of the Wolf and Loosahatchie Rivers, along the upper reaches of Nonconnah Creek, and the surficial aquifer of the Mississippi River alluvial plain. These simulations are supported by the geologic and geophysical evidence suggesting relatively thin or sandy confining units in these general locations. Because water from surficial aquifers is inferior in quality and more susceptible to contamination than water in the deeper aquifers, high rates of leakage to the Memphis aquifer may be cause for concern.

A significant component of flow (12 percent) discharging from the Fort Pillow aquifer was calculated as upward leakage to the Memphis aquifer. This upward leakage was generally limited to areas near major pumping centers in the Memphis aquifer, where heads in the Memphis aquifer have been drawn significantly below heads in the Fort Pillow aquifer. Although the Fort Pillow aquifer is not capable of producing as much water as the Memphis aquifer for similar conditions, it is nonetheless a valuable resource throughout the area.

INTRODUCTION

The Memphis area has a plentiful supply of ground water suitable for most uses, but the resource may be vulnerable to pollution. Withdrawal of nearly 200 million gallons per day (Mgal/d) ranks Memphis second only to San Antonio, Texas, among the nation's cities that depend solely on ground water for municipal-water supply. For the past century, most of the city's ground water has been pumped from the Memphis aquifer, a Tertiary sand unit that is confined in most of the Memphis area. Industrial, public supply, and private withdrawals also have been made from the Fort Pillow aquifer, but these generally have amounted to less than 10 percent of the total pumping in the area.

There has been increasing concern that contaminated ground water in the area's surficial aquifers may leak downward to the Memphis aquifer (Parks and others, 1982; Graham and Parks, 1986; M.W. Bradley, U.S. Geological Survey, written commun., 1987). To assess the potential for such leakage, a cooperative investigation was initiated in 1978 between the City of Memphis, Memphis Light, Gas and Water Division (MLGW) and the U.S. Geological Survey. This investigation is part of a series of studies pursuing a more complete understanding of ground-water flow and chemistry in the area. The main tool of this investigation is a ground-water flow model of the major aquifers in the Memphis area. This flow model integrates all available information on the geology, hydrology, and ground-water chemistry of the region. The model has helped to quantify the potential for leakage between principal aquifers, and it may be a valuable predictive tool to assist water managers in managing ground-water resources.

Approach and Scope

The necessary approaches to this investigation were:

1. to describe the hydrogeologic framework of the Memphis area, with emphasis on the Memphis aquifer and Fort Pillow aquifer;
2. to develop a conceptual model of ground-water flow in the Memphis area;
3. to test the conceptual model through the application of a multilayer, finite-difference ground-water flow model.

As defined for this investigation, the Memphis area comprises a rectangular zone of roughly 1,500 square miles (mi^2), measuring about 45 miles from east to west by 35 miles from north to south. The Memphis area lies near the center of the northern part of the Mississippi embayment and includes all of Shelby County, Tennessee, and parts of Fayette and Tipton Counties, Tennessee, DeSoto and Marshall Counties, Mississippi, and Crittenden and Mississippi Counties, Arkansas (fig. 1).

The study area includes all of metropolitan Memphis, as well as undeveloped, outlying areas where ground water is affected by pumping from metropolitan well fields. Although the study focuses on the Memphis area, the aquifers and confining units are regional in occurrence, and extend far beyond the Memphis area boundaries. Descriptions and maps necessary to define the regional hydrogeology are included within this report only as an aid to understanding ground-water flow in the Memphis area. Readers interested in a full discussion of the regional hydrogeology of the Memphis and Fort Pillow aquifers in the northern Mississippi embayment are referred to Arthur and Taylor (1990).

Previous Investigations

A substantial body of literature exists on the hydrology and hydrogeology of aquifer systems in the Memphis area. The most recent, comprehensive studies include those of Graham and Parks (1986), who studied the potential for leakage in the Memphis area, and Parks and Carmichael (1989a, 1989b, 1989c), who described the geology and ground-water resources of three aquifers in West Tennessee. Extensive bibliographies of previous ground-water studies are included in Brahana (1982a, table 2 and p. 35-40) and in Graham and Parks (1986, p. 41-44). A series of potentiometric maps and a description of historic water-level changes and pumpage from the Memphis aquifer and Fort Pillow aquifer in the Memphis area are included in Criner and Parks (1976). Historic water levels in individual wells are also documented by the U.S. Geological Survey (1936-1973). The potentiometric surface in the Memphis aquifer for 1978 and 1980 in the Memphis area is shown in Graham (1979, 1982), and for 1985 for West Tennessee is shown in Parks and Carmichael (1989d). The potentiometric surface of the Fort Pillow aquifer for 1980 for the northern Mississippi embayment is shown in Brahana and Mesko (1988, fig. 11), and for 1985 for West Tennessee is shown in Parks and Carmichael (1989e, fig. 2).

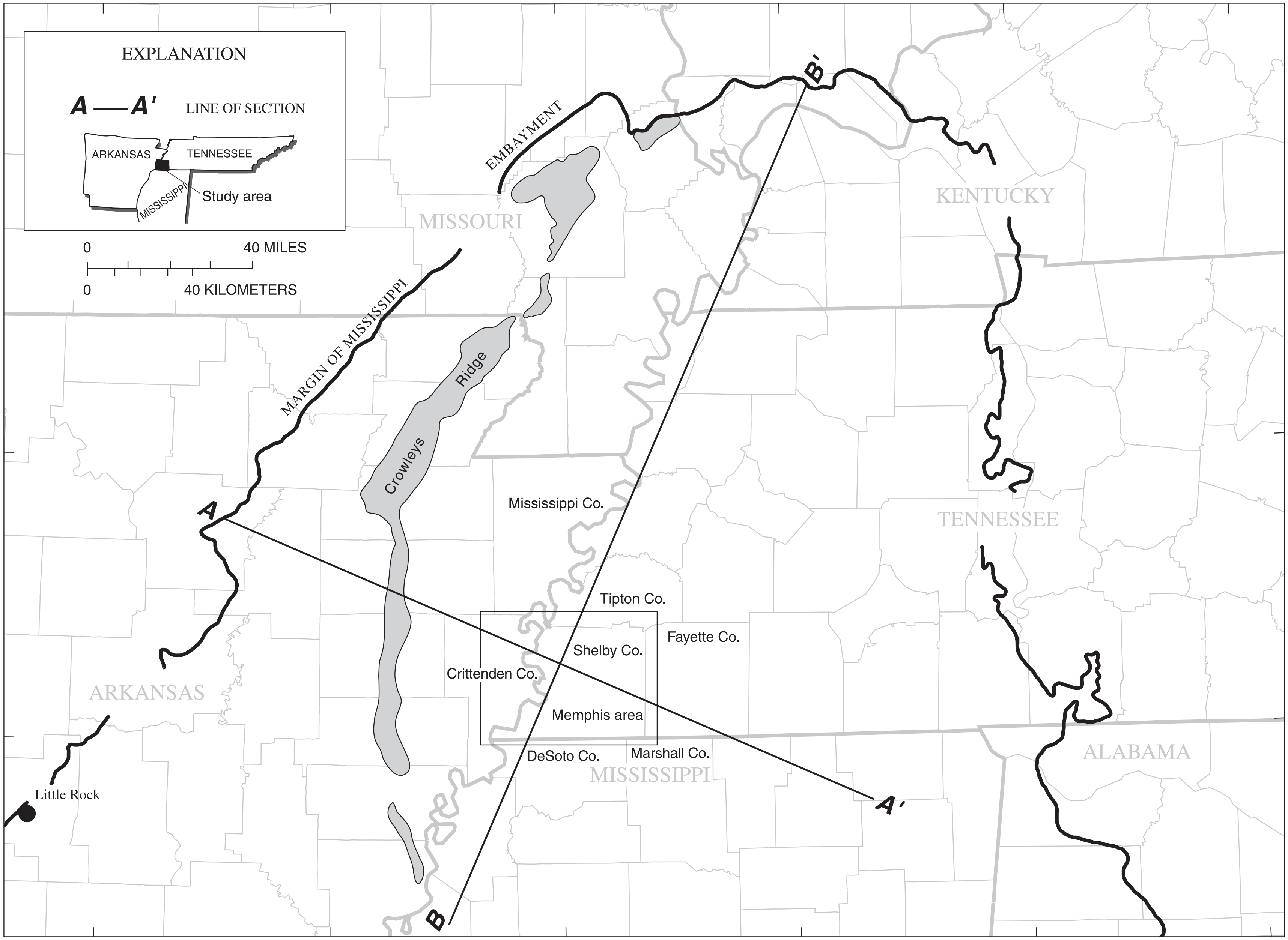


Figure 1. Location of the Memphis area and hydrogeologic sections along lines A-A′ and B-B′ in the Mississippi embayment.

Water quality in aquifers in the Memphis area has been summarized by Brahana and others (1987), and data describing selected water-quality parameters in the water-table aquifers in the Memphis area have been described by McMaster and Parks (1988). Parks (1973, 1974, 1975, 1977b, 1978, 1979a, 1979b) mapped the surface and shallow subsurface geology of the Memphis metropolitan area. A summary of some current and possible future environmental problems related to geology and hydrology in the Memphis area is given in a report by Parks and Lounsbury (1976). Parks and others (1982) described the installation and sampling of observation wells at selected waste-disposal sites.

Analog simulation of water-level declines in the Sparta aquifer (equivalent to the upper part of the Memphis aquifer) in the Mississippi embayment was summarized by Reed (1972). A two-dimensional digital flow model of the Memphis aquifer was described by Brahana (1982a). This model was used as a predictive tool to estimate aquifer response to various hypothetical pumpage projections (Brahana, 1982b). Arthur and Taylor (1990) evaluated the Memphis and Fort Pillow aquifers (as part of the Mississippi embayment aquifer system) in a regional study that encompassed the northern Mississippi embayment. Fitzpatrick and others (1989) described the geohydrologic characteristics and digital model-simulated response to pumping stresses in the Sparta aquifer (equivalent to upper part of Memphis aquifer) in east-central Arkansas.

Reports describing the general geology and ground-water hydrology of the Memphis area include Fisk (1944), Schneider and Blankenship (1950), Caplan (1954), Stearns and Armstrong (1955), Stearns (1957), Cushing and others (1964), Krinitzsky and Wire (1964), Moore (1965), Boswell and others (1965, 1968), Hosman and others (1968), and Cushing and others (1970).

In addition to published reports, there is a substantial body of unpublished hydrogeologic data for the Memphis area. These data include borehole geophysical logs, well-completion data, driller's records, geologic logs, summaries of pumping tests, inventories of pumpage, and individual well records and maps of water levels. Most of these records are located in the files of the U.S. Geological Survey, Water Resources Division; Tennessee Division of Geology; Tennessee Division of Water Resources; and City of Memphis, Memphis Light, Gas and Water Division.

HYDROLOGIC SETTING

Climate and Precipitation

The Memphis metropolitan area is characterized by a temperate climate, with a mean annual air temperature of about 62^{o} F, and abundant precipitation. About 48 inches of precipitation per year is typical, although annual amounts recorded have ranged from 31 to 77 inches.

The distribution of rainfall is nonuniform in space and time. Mean annual precipitation increases approximately 4 inches per year from west to east across the Mississippi embayment (Cushing and others, 1970). The driest part of the year is late summer and fall, and the wettest is late winter.

Topography and Drainage

Land-surface altitudes in the Memphis area range from about 200 feet above sea level on the flat alluvial plain of the Mississippi River to about 400 feet above sea level in the upland hills of eastern Shelby County. A bluff 50 to 150 feet high separates the alluvial plain from the upland. Other than the bluff, local relief seldom exceeds 40 feet.

The Mississippi River dominates surface-water flow in the area. From the upland in the east, it receives drainage from three main tributary streams—Nonconnah Creek, Wolf River, and Loosahatchie River. Along most reaches, these three tributaries flow throughout the year. One notable exception is Nonconnah Creek upstream from the mouth of Johns Creek. Since the 1950's, Nonconnah Creek has been dry in its upstream reaches for short periods during the dry season from July to October (Criner and others, 1964).

Hydrogeologic Framework

The Memphis area is located near the axis of the Mississippi embayment, a regional downwarped trough of Paleozoic rock that has been filled with more than 3,000 feet of unconsolidated sediments (Criner and Parks, 1976). These sediments include uncemented sand, clay, silt, chalk, gravel, and lignite. On a regional scale, the sediments form a sequence of nearly parallel, sheetlike layers of similar lithology. The layers reflect the trough-like shape of the Paleozoic strata (fig. 2).

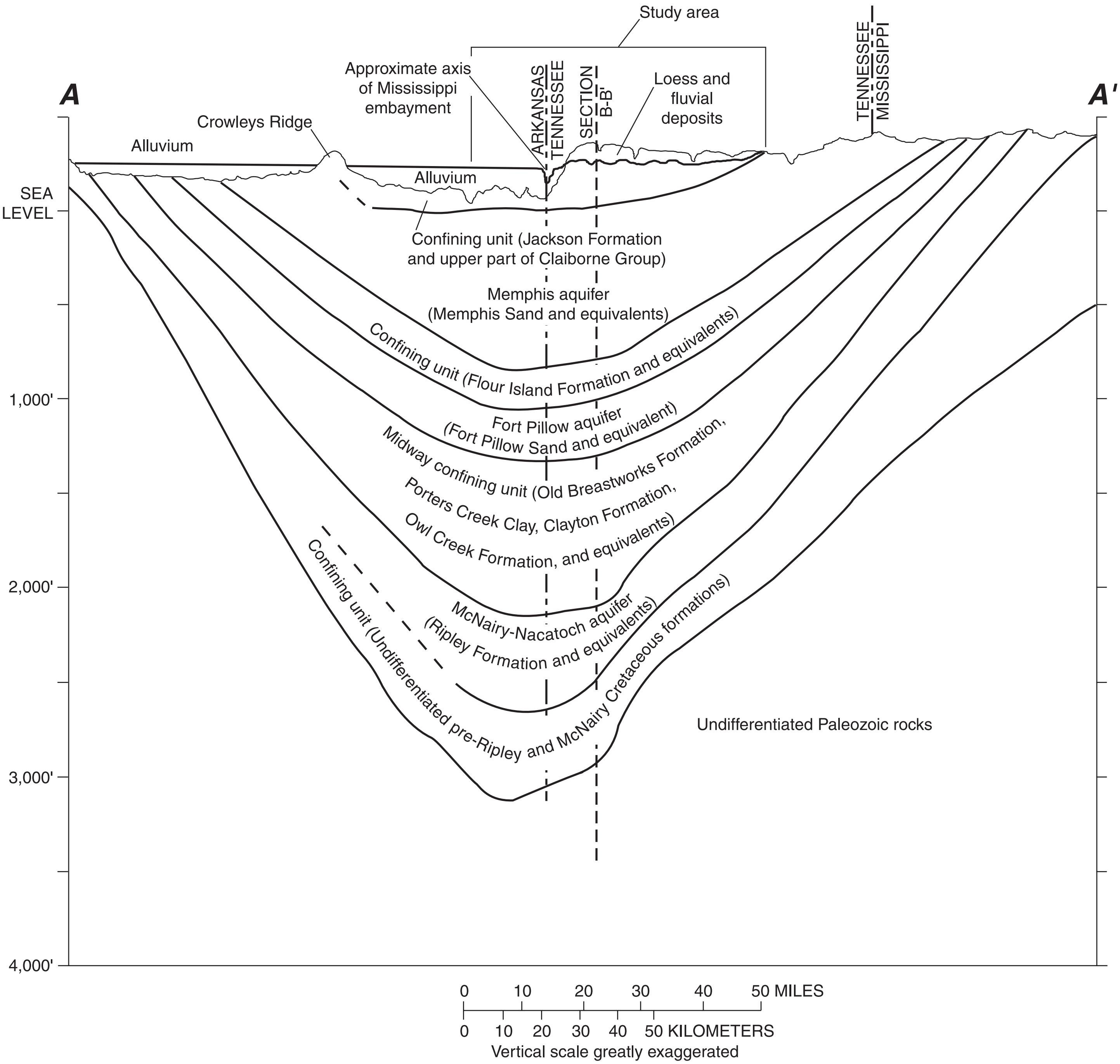


Figure 2. Hydrogeologic section showing principal aquifers and confining units, west to east, through the Mississippi embayment along line A-A'.

On a local scale, however, there are complex lateral and vertical gradations in the lithology of each layer. Of particular interest to this study are variations in thickness and sand percentage of the major clay layers. These confining clay units control the ground-water interchange between the sand layers that form the major aquifers. Zones where the confining clays are thin or sandy are potential sites of high leakage, and the most likely pathways for pollutant migration (Graham and Parks, 1986).

The structural axis of the northern Mississippi embayment is approximately coincident with the Mississippi River, passing south-southwest through the western part of the study area in eastern Crittenden County, Ark. (fig. 1). The sedimentary rock layers which comprise the embayment gently dip 10 to 35 feet per mile from both the west and east toward the axis of the embayment (fig. 2). These layers thicken to the south-southwest (fig. 3).

The thickness, lithology, and hydrologic significance of each stratigraphic unit in the Memphis area are described briefly in table 1. Five of these units represent major water-bearing zones: the alluvium, the surficial fluvial deposits, the Memphis Sand, the Fort Pillow Sand, and the Ripley Formation and McNairy Sand. With the exception of the alluvium and fluvial deposits, water-bearing zones are confined by clay layers over much of the Memphis area. Reported ground-water conditions and hydraulic characteristics of selected units that are the focus of this report have been generalized in table 2.

Water-Table Aquifers

Water-table aquifers in the Memphis area consist of the alluvium and fluvial deposits which are mostly unconfined (Graham and Parks, 1986, p. 5). These aquifers outcrop throughout the study area, and generally occur at shallow depths (table 2).

An interpretive water-table map of the alluvium and fluvial deposits was constructed for "average," steady-state conditions, designated 1980 (fig. 4). The map was based on the most complete set of water-level data available (Graham and Parks, 1986), supplemented by historic water-levels (Wells, 1933), stream stages, and where no other data were available, estimates based on topographic maps, land surface elevations, and extrapolated depths to water (Brahana and Mesko, 1988).

Alluvium

Alluvium occurs at land surface in the stream valleys of the study area. The alluvium is not a major ground-water source in the Memphis area, even though it is a major water-bearing zone and can supply large quantities of water to wells. This lack of use is related to its limited area of occurrence and to the hardness and high iron concentration of the water. West, north, and south of the study area, the alluvium of the Mississippi River alluvial plain is one of the most productive regional aquifers in the Mississippi embayment, supplying over a billion gallons per day to irrigation wells in Arkansas and Mississippi (Boswell and others, 1968; Ackerman, 1989).

The thickness of the alluvium may vary significantly over very short distances (Krinitzsky and Wire, 1964). In the Mississippi River alluvial plain, which lies west of the bluffs (fig. 4), the alluvium is commonly 100 to 175 feet thick (Boswell and others, 1968); along valleys of upland streams tributary to the Mississippi River east of the bluffs (fig. 4), thickness generally is less than 50 feet (Graham and Parks, 1986). Alluvium includes gravel, sand, silt, and clay; the latter is commonly rich in organic matter. Abrupt vertical and horizontal variations in lithology are common.

The alluvium is separated from the Memphis aquifer by a confining unit made up of clays and fine-grained sediments of the Jackson Formation and underlying upper part of the Claiborne Group, which has variable thickness and lithology. Where this confining unit is thin or sandy, leakage of ground water from one aquifer to the other may be substantial. The generalized thickness of this confining unit is shown in figure 5.

Rivers dominate the hydrology of the water-table aquifers. Local streams, as shown by figure 4, are in direct hydraulic connection with these aquifers, functioning as drains during much of the year. Seasonal variations of water level in the alluvium are typically less than 10 feet, although variations of as much as 15 feet have been reported (Plebuch, 1961; Broom and Lyford, 1981; Brahana and Mesko, 1988, fig. 13). During floods when stream stage is temporarily higher than the water table, some recharge to the alluvium occurs. No long-term declines in water level in the alluvium in the Memphis area are known.

Aquifer hydraulic characteristics of the Mississippi River alluvial aquifer in Arkansas and Missouri have been reported by Halberg and Reed (1964), Albin

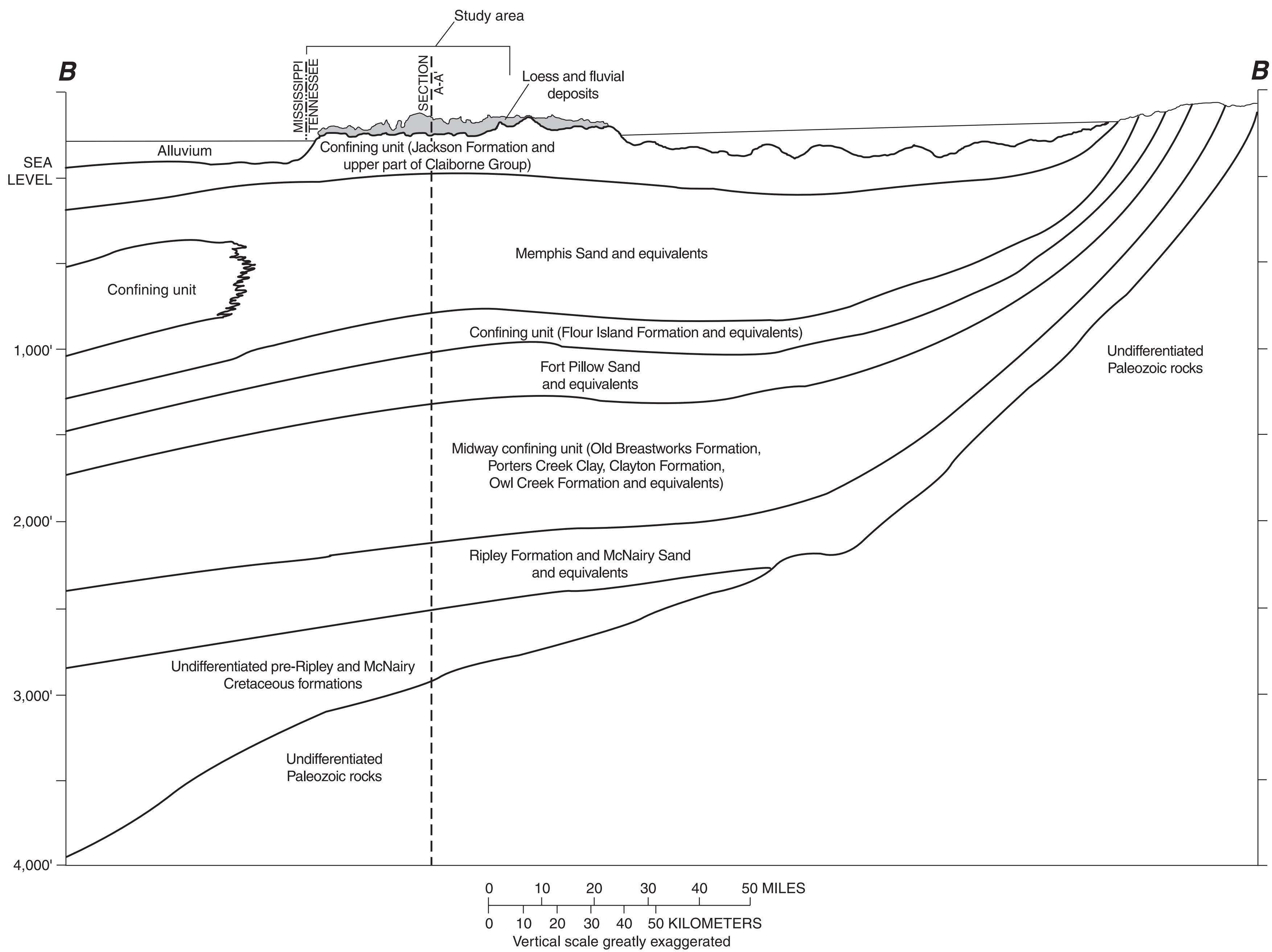


Figure 3. Hydrogeologic section showing principal aquifers and confining units, south to north, through the Mississippi embayment along line B-B′.

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

[Modified frcm Criner and Parks, 1976; Moore and Brown, 1969; Plebuch, 1961; Schneider and Blankenship, 1950]

System	Series	Group	Stratigraphic unit	Thick-ness	Hydrologic unit	Lithology and hydrologic significance
Quaternary	Holocene and Pleistocene		Alluvium	0-175	Surficial Aquifer	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 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 underlies 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 (“capping clay”)	0-370	Confining Unit	Clay, silt, sand, and lignite. Because of similarities in lithology, the Jackson Formation and upper part the Claiborne Group cannot be reliably subdivided based on available information. Most of the preserved sequence is equivalent to the Cook Mountain and overlying Cockfleld Formations, but locally the Cockfield may be overlain by the Jackson Formation. Serves as the upper confining unit for the Memphis Sand.
		Claiborne	Memphis Sand (“500-foot” sand)	500-890	Memphis aquifer	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; primary source of water for the City of Memphis.
	?	Wilcox	Flour Island Formation	140-310	Confining unit	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 confing unit for the Memphis Sand and the upper confining unit for the Fort Pillow Sand.
	Paleocene		Fort Pillow Sand (“1400-foot” sand)	92-305	Fort Pillow aquifer	Sand with minor clay and lignite. Sand is fine to medium. Thickest in the southwestern part of 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	Midway confining unit	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 unit for the Fort Pillow Sand, along with the underlying Porters Creek Clay, Clayton Formation, and Owl Creek Formation.

Table 1. Post-Paleozoic geologic units underlying the Memphis area and their hydrologic significance—Continued

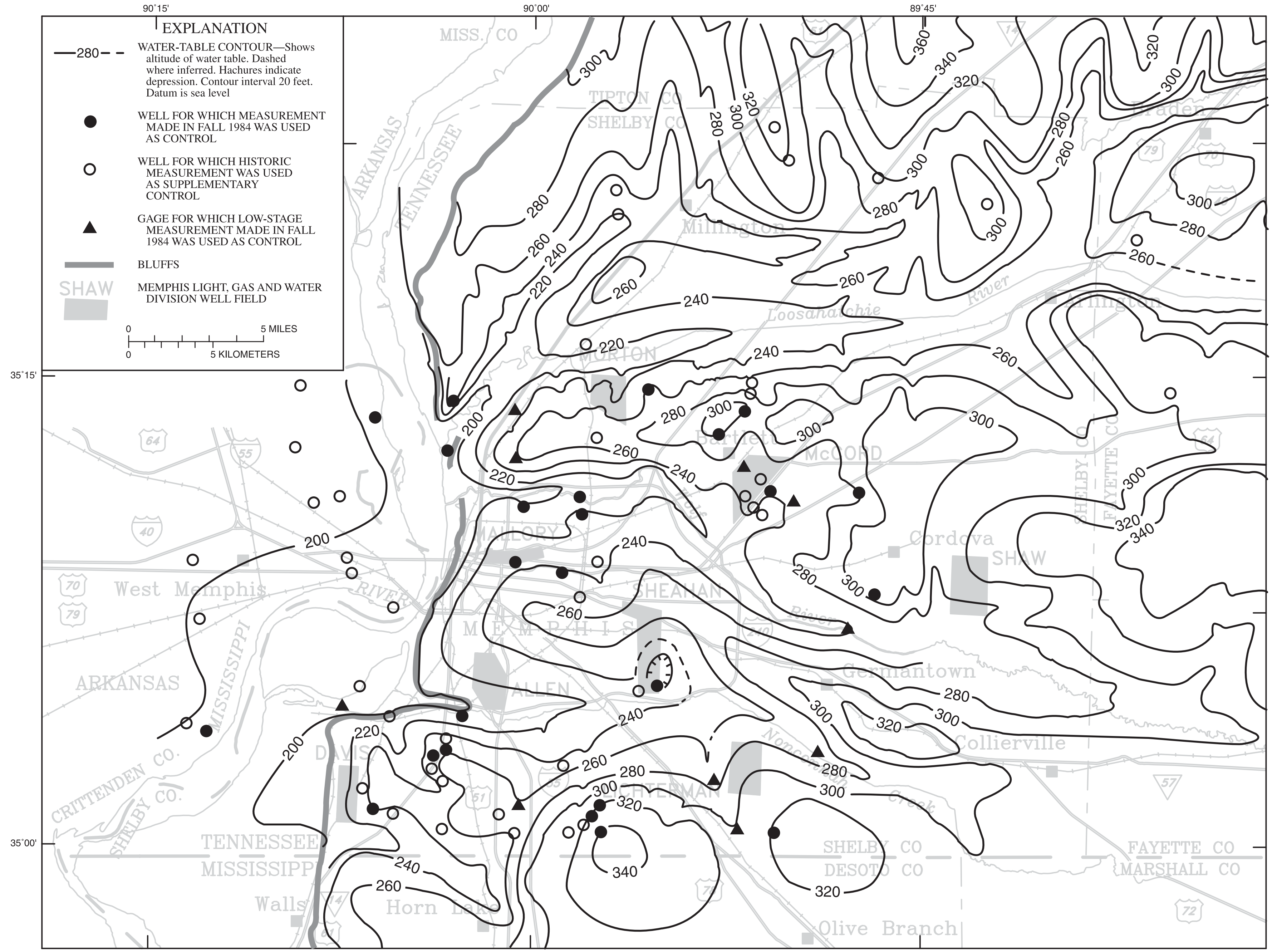
System	Series	Group	Stratigraphic unit	Thick-ness	Hydrologic unit	Lithology and hydrologic significance
Tertiary	Paleocene	Midway	Porters Creek Clay	250-320	Midway confining unit	Clay and minor sand. Thick body of clay with local lenses of clayey, glauconitic sand. Principal confining unit separating the Fort Pillow Sand and the Ripley Formation and McNairy Sand.
			? Clayton Formation	40-120		Clay, sand, and minor limestone. Calcareous clay and glauconitic sand with local lenses of limestone in basal part; fossiliferous. Because of lithologic similarities, upper boundary is difficult to recognize. Confining unit.
Cretaceous	Upper Cretaceous		? Owl Creek Formation	40-90		Clay and sand. Calcareous clay and glauconitic sand; fossiliferous. Because of lithologic similarities, the Owl Creek Formation is difficult to distinguish from the overlying Clayton Formation without fossil verification. Confining unit.
			Ripley Formation and McNairy Sand	360-570	McNairy-Nacatoch aquifer	Sand and clay; minor sandstone, limestone, and lignite. Ripley changes facies northeast of Memphis to McNairy Sand. Ripley consists primarily of glauconitic sands and calcareous clays with minor interbeds of calcareous sandstone or sandy limestone; McNairy consists primarily of nonglauconitic sands and non-calcareous clays with local lenses of lignite. Aquifer with low potential for use in Memphis area because of lesser amounts of sand and poorer quality of water than aquifers above. Base of Ripley and McNairy is base of freshwater in the Memphis area.
			Coon Creek Formation	0-60	Confining unit	Clay and sand. Shaley clays with thin interbeds of fine sand; locally glauconitic and fossiliferous; locally contains some thin layers of rock. Probably present only in northeastern Shelby and northwestern Fayette Counties, Tenn. Confining unit.
			Demopolis Formation	270-390		Clay and chalk. Calcareous clays and chalks; glauconitic and fossiliferous. Some layers of chalk form indurated layers. Serves as the principal confining unit separating the Ripley Formation and McNary Sand and Coffee Sand.
			Coffee Sand	0-120	Coffee aquifer	Sand and minor clay. Sand is fine to medium; locally glauconitic or lignitic. Clay occurs as local lenses, particularly at the base. Absent locally in north-central Shelby County, Tenn., where the Demopolis Formation overlies igneous intrusive rock. Contains brackish or saline water; not considered a freshwater aquifer in the Memphis area. Underlain by Paleozoic dolomitic limestones of Ordovician age.

Table 2. Generalized ground-water characteristics and hydraulic properties of select hydrogeologic units in the Memphis area

Hydrogeologic unit	Generalized present-day flow directions	Depth commonly encountered (feet)	Thickness (feet)	Water-bearing character	Hydraulic properties of unit		
					T (ft^2/d)	S (unitless)	K′ (ft/d)
Alluvium	Toward major streams—downstream.	Surface	0-175	Unconfined aquifer Mississippi River alluvium confined in many places.	8,500-50,000 (a)	$1x10^{-4}$ to $4x10^{-2}$ (a)	--
Terrace (fluvial) deposits.	To valleys	Surface	0-100	Unconfined aquifer	No measurements	No measurements	--
Jackson Formation and upper part of Claibome Group (capping clay).	--	0-100	0-370	Confining layer	--	--	No measurements
Memphis Sand	Into pumping center	0-600 500 common	500-890	Confined aquifer in most of Memphis area; unconfined in southeast part of area.	2,700-45,000 (a) 6,700-54,000 (b)	$1x10^{-4}$ to $6x10^{-4}$ (a) $1x10^{-4}$ to $2x10^{-1}$ (b)	--
Flour Island Formation	--	1,000-1,400	140-310	Confining layer	--	--	$.8\text{-}4.4x10^{-11}$
Fort Pillow Sand	Into pumping center, primarily east to west.	1,200-1,500 1,400 common	92-305	Confined aquifer	2,700-21,000 (a) 12,000-19,000 (b)	$2x10^{-4}$ to $2x10^{-3}$ (a) $1.2x10^{-4}$ to $6.1\ x10^{-4}$ (b)	--
Porters Creek Clay, Clayton and Owl Creek Formations.	--	1,400-1,700	150-770	Confining layer	--	--	No measurements
McNairy Sand	Southeast to northwest	2,650	360-430	Confined aquifer	No measurements	No measurements	--

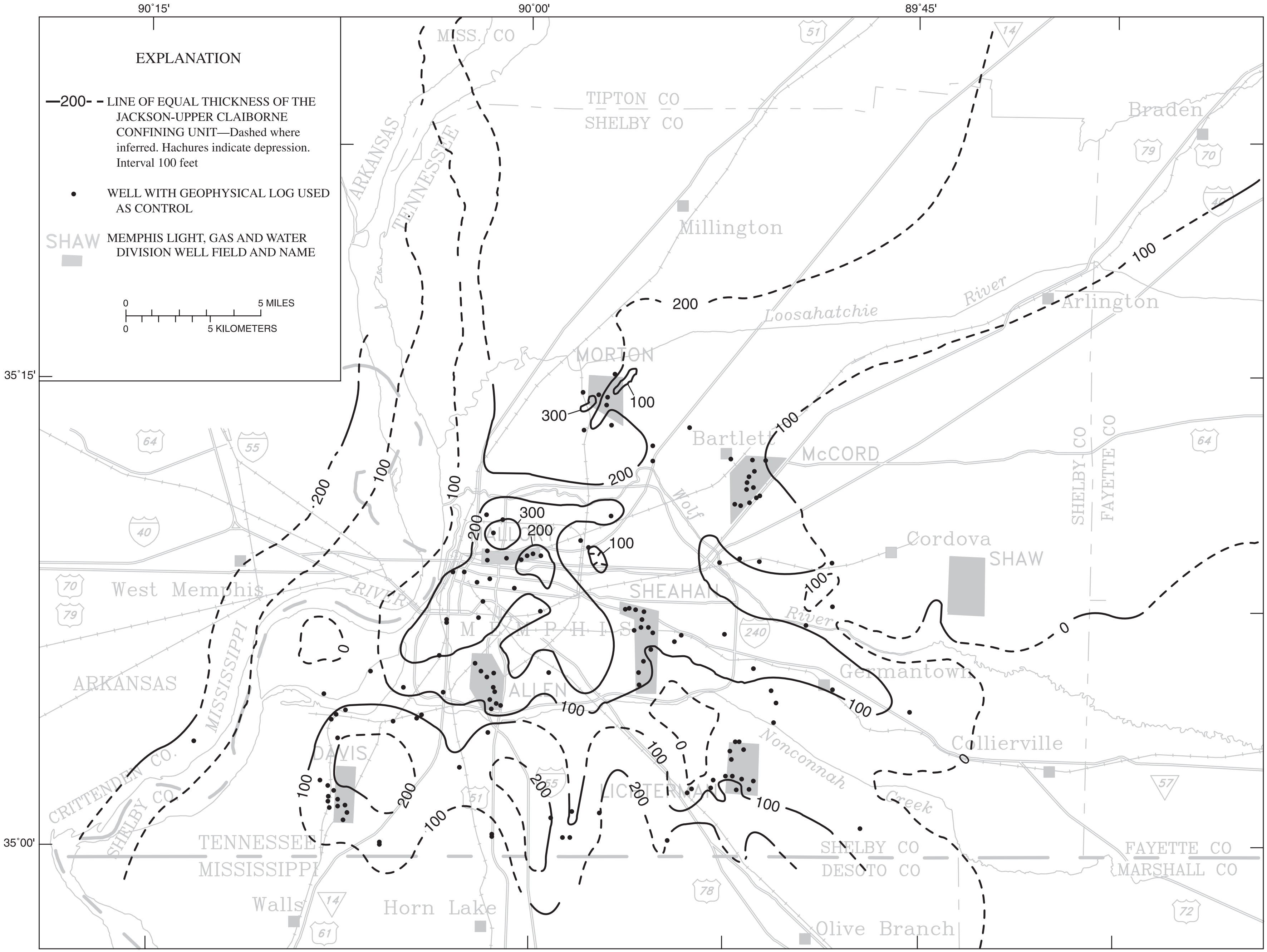
(a) Results from test conducted in the northern Mississippi Embayment, see table 3.

(b) Results for the Memphis area from Criner and others, 1964; Moore, 1965; Hosman and others, 1968; Brahana, 1982a; Arthur and Taylor, 1990; and Parks and Carmichael, 1989a.



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

Figure 4. Generalized altitude of the water table in the alluvium and fluvial deposits in the Memphis area, 1980.



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

Figure 5. Generalized thickness of the Jackson-upper Claiborne confining unit in the Memphis area.

and Hines (1967), Broom and Lyford (1981), and Luckey (1985). Transmissivity ranges from 8,500 to 50,000 ft^2/d, and storage coefficient for the deeper, more confined part of the aquifer ranges from 1 x 10^{-4} to 4 x 10^{-2} (table 2). No values of aquifer hydraulic characteristics of alluvium at other locations in the Memphis area have been reported.

Water from the alluvium is hard and has relatively high concentrations of iron, dissolved solids, and barium (Brahana and others, 1987, tables 2 and 3). Lenses of clay rich in organic matter and associated geomicrobial activity are thought to be the source of high concentrations of hydrogen sulfide, carbon dioxide, and iron in this formation (Wells, 1933).

Fluvial Deposits

Fluvial deposits occur at land surface in the uplands east of the bluffs (fig. 4). Although at one time the fluvial deposits were an important source of domestic water, present pumpage from this formation is negligible. Since about 1950, when the city of Memphis expanded its municipal supplies to serve outlying areas, few wells have been drilled into the fluvial deposits. Many of the wells that existed in 1950 have not remained operational and have been abandoned, plugged, or destroyed. Wells in the fluvial deposits are capable of large yields, greater than 100 gal/min, signifying a potentially large source of water in the study area.

Fluvial deposits range in thickness from 0 to 100 feet (table 1). Thickness is highly variable, because of surfaces at both top and base (Graham and Parks, 1986). Locally, the fluvial deposits may be absent. The lithology of fluvial deposits is primarily sand and gravel, with minor layers of ferruginous sandstone.

Fluvial deposits are separated from the Memphis aquifer by sediments of the Jackson Formation and the upper part of the Claiborne Group (fig. 5). As with the alluvium, if the underlying confining unit is thin or sandy, leakage between water-table aquifers and the Memphis aquifer may be substantial.

Wells (1933), Graham (1982), and Graham and Parks (1986, fig. 8) reported seasonal water-level fluctuations in the fluvial deposits in the range of from 2 to 10 feet. Long-term declines of water levels within the fluvial deposits have not been documented, except in one location in the southern part of Sheahan well field (fig. 4). During the period 1943 to 1955, pumpage from the Memphis aquifer in the south Sheahan area dewatered the fluvial deposits around the southern part of the well field (Graham and Parks, 1986, figs. 7 and 8). Before pumping began in 1933 from the Sheahan well field, the fluvial deposits in the southern part of the well field supplied small domestic wells, but these wells were reported to be dry in 1985 (W.S. Parks, U.S. Geological Survey, written commun., 1985).

No measurements of aquifer hydraulic characteristics have been reported for the fluvial deposits in the Memphis area. Based on lithology, saturated thickness, and mode of occurrence, transmissivity probably is within the range of 5,000 to 10,000 ft^2/d, and storage coefficient probably is in the range of 0.1 to 0.2 (Freeze and Cherry, 1979).

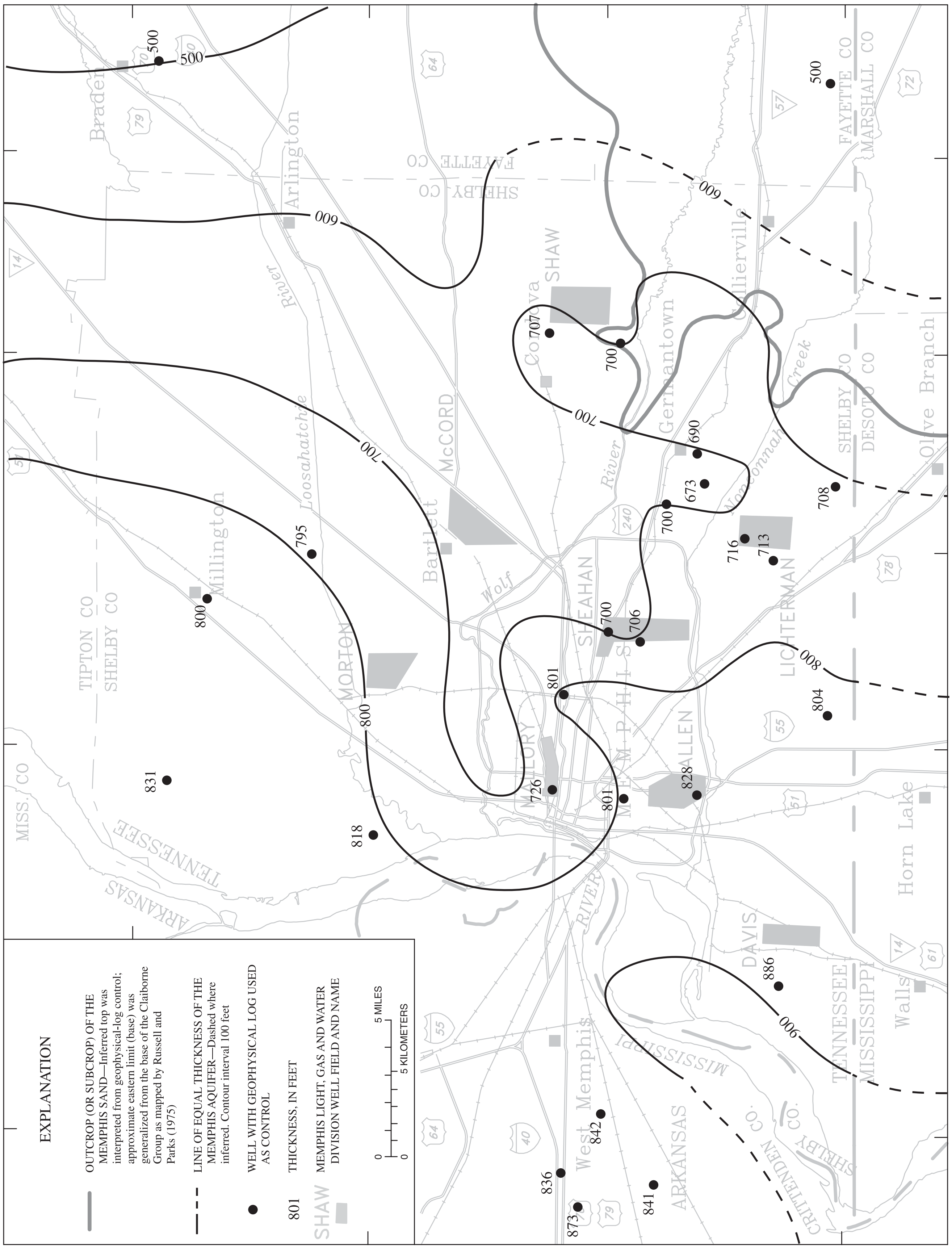
Water quality in the fluvial deposits is highly variable. The distribution of dissolved-solids concentrations, which ranges from 76 mg/L iron to 440 mg/L, shows more variation in these deposits than in any other aquifer in the area (Brahana and others, 1987, tables 2 and 3). Some of the variation may be related to the thickness of overlying loess, which may contribute much of the dissolved solids in the aquifer (Wells, 1933). Dissolved-solids concentrations are lowest in the east-central part of the Memphis area, between the Loosahatchie and Wolf Rivers (Brahana and others, 1987, fig. 5).

Memphis Aquifer

The Memphis aquifer is the most productive aquifer in the study area, providing approximately 98 percent of total pumpage (188 Mgal/d) to the city of Memphis in 1980 (Graham, 1982). Total pumpage since 1886 is calculated to be more than 3.2 trillion gallons, using published pumping values (Criner and Parks, 1976, fig. 2; Graham, 1982, table 2).

The Memphis aquifer is a fine- to coarse-grained sand interbedded with layers of clay and minor amounts of lignite. The formation occurs at depths ranging from 0 to 600 feet (table 2) and varies in thickness from 500 to 890 feet (table 1) based on interpretations of geophysical logs. Generalized thickness of the Memphis aquifer in the Memphis area, based on work by Parks and Carmichael (1989a), has been extrapolated to a slightly wider range from less than 500 to more than 900 feet (fig. 6).

The Memphis aquifer is separated from the underlying Fort Pillow aquifer by 140 to 310 feet of clay of the Flour Island Formation, and from the overlying alluvium and terrace deposits by 0 to 370 feet of clay and sandy clay of the Jackson Formation and



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

Modified from W.S. Parks and J.K. Carmichael, 1989a

Figure 6. Generalized thickness of the Memphis aquifer in the Memphis area.

upper part of the Claiborne Group. The effectiveness of the Jackson Formation and upper part of the Claiborne Group as a confining unit appears to vary because of areal differences in sand content and layer thickness (Graham and Parks, 1986). Due to this variability, rates of leakage from surficial aquifers are spatially heterogeneous.

Water levels in the Memphis aquifer are strongly influenced by pumping (fig. 7). Water levels within the outcrop area, which occurs in the southeastern part of the Memphis area, range from about 280 to 290 feet above sea level (Graham, 1982, plate 1; Parks and Carmichael, 1989a, fig. 7). Recharge to the Memphis aquifer occurs primarily in the outcrop area (fig. 7). The deepest pumping cone of depression in the Memphis aquifer is less than 100 feet above sea level; the water levels at most other pumping centers are in the range of 120 to 170 feet above sea level (Graham, 1982, plate 1; Parks and Carmichael, 1989a, fig. 7). The widespread and irregular distribution of pumping centers in the Memphis aquifer in the Memphis area causes a complex flow pattern as ground water flows inward from all directions to several pumping centers (fig. 7).

Long-term water-level declines in the Memphis aquifer are greater than 120 feet in the area of maximum drawdown near the Mallory well field. East of the pumping centers near the areas of outcrop, long-term declines have not been detected (Parks and Carmichael, 1989a, fig. 10). Seasonal variations in water levels are commonly less than 2 feet in areas unaffected by pumping.

Data from 23 representative aquifer tests in the Memphis aquifer (table 3; fig. 8) from throughout the northern Mississippi embayment show transmissivity ranges from 2,700 to 45,000 ft^2/d, and storage coefficients range from 1×10^{-4} to 6×10^{-4}. Confined conditions are typical for the Memphis aquifer, except in areas of outcrop.

The Memphis aquifer in the Memphis area (table 2) is reported to have a range of transmissivity from 6,700 to 54,000 ft^2/d, and a range of storage coefficients from 1×10^{-4} to 2×10^{-1} (Criner and others, 1964; Moore, 1965; Hosman and others, 1968; Brahana, 1982a; Arthur and Taylor, 1990; Parks and Carmichael, 1989a, p. 27).

Ground water in the Memphis aquifer is a calcium-magnesium-sodium bicarbonate type (Hosman and others, 1968; Brahana and others, 1987, table 2). In the study area, water in the Memphis aquifer is characterized by a pH generally less than 7, and except for a limited area in the northwestern part of the study area, the dissolved-solids concentration is generally less than 100 mg/L.

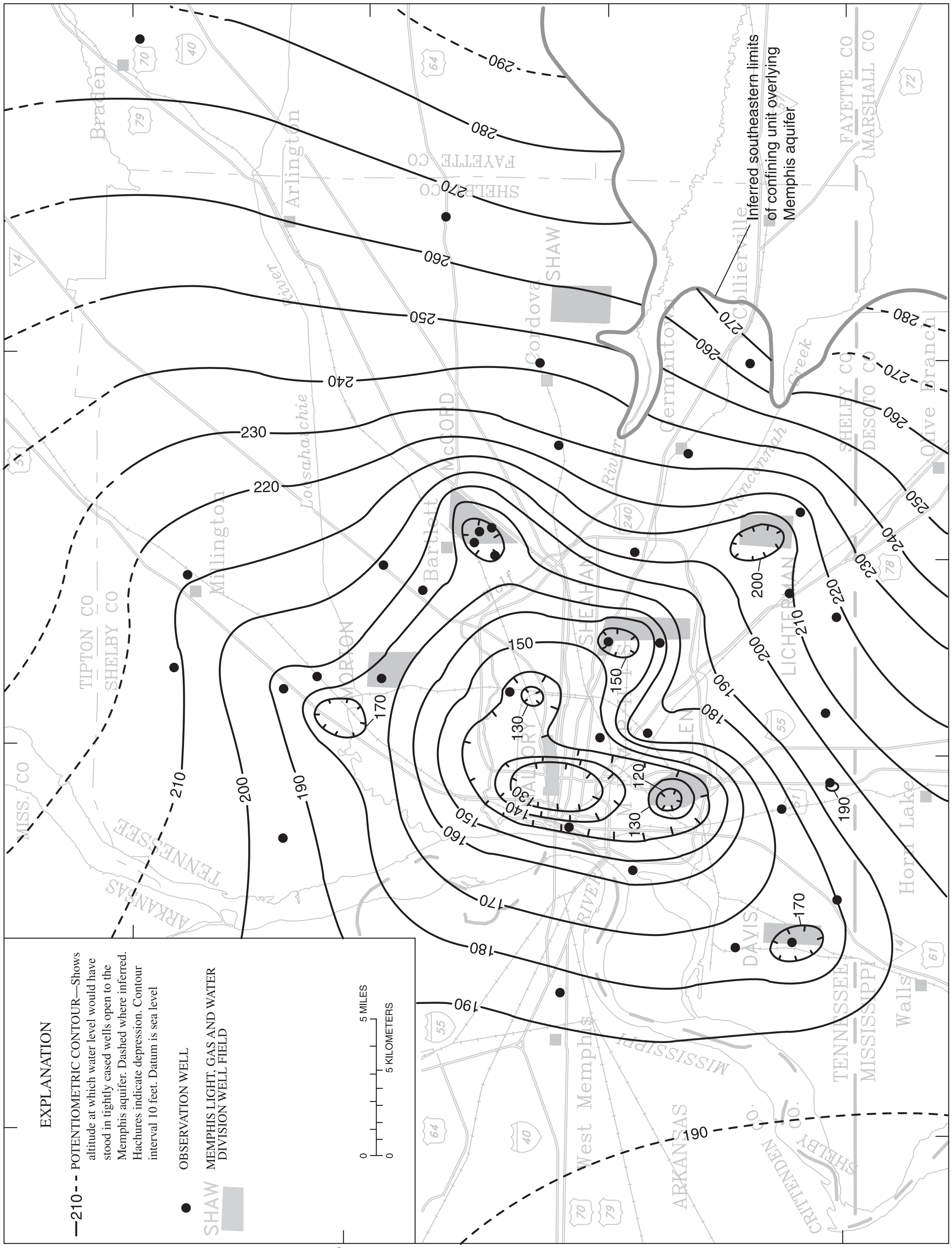
Fort Pillow Aquifer

The Fort Pillow aquifer is a major regional aquifer throughout much of the northern Mississippi embayment (Hosman and others, 1968; Arthur and Taylor, 1990; Parks and Carmichael, 1989b). In the Memphis study area, the Fort Pillow aquifer currently (1989) provides water to supplement supplies at Millington, Tenn., the U.S. Naval Air Station near Millington, one industrial user in Memphis, and the Shaw well field east of Memphis (fig. 9). The Fort Pillow aquifer is the sole source of water for West Memphis, Marion, and other small towns in eastern Arkansas, and for the town of Walls in Mississippi (fig. 9). In 1984, pumpage from the Fort Pillow aquifer averaged about 10 Mgal/d (Graham and Parks, 1986). Although the Fort Pillow aquifer is much deeper in the subsurface than the Memphis aquifer, the Fort Pillow is the preferred aquifer in eastern Arkansas for municipal and domestic supplies because it provides water that requires less treatment than water from the Memphis aquifer.

The Fort Pillow aquifer is characteristically a fine- to medium-grained sand containing clay lenses and minor amounts of lignite. Thickness of the aquifer is commonly about 250 feet and ranges from about 125 to 305 feet (table 1). The generalized thickness of the Fort Pillow aquifer in the Memphis area, based on work of Parks and Carmichael (1989b), is shown in figure 10.

The Fort Pillow aquifer is confined above by 140 to 310 feet of clay of the Flour Island Formation, as defined by interpretation of geophysical logs (table 1). The Flour Island Formation is thought to be a leaky confining unit. Generalized thickness of the Flour Island confining unit in the Memphis area is based on the work of Graham and Parks (1986, fig. 5) and E. Mahoney, Vanderbilt University (written commun., 1989) (fig. 11). Head differences between the Memphis aquifer and Fort Pillow aquifer (Graham and Parks, 1986) occur as a result of pumping and are affected by the vertical hydraulic characteristics and thickness of the Flour Island Formation.

Water levels in the Fort Pillow aquifer (fig. 9) in 1980 were from slightly less than 160 to more than 240 feet above sea level. Water levels are highest in



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

Hydrology modified from D.D. Graham, 1982; Geology modified from J.H. Criner and W.S. Parks, 1976.

Figure 7. Altitude of the potentiometric surface of the Memphis aquifer in the Memphis area, 1980.

Table 3. Results of selected aquifer tests

[Data source: 1, Davis and others (1973); 2, Moore (1965); 3, Newcome (1971); 4, Hosman and others (1968); 5, Luckey (1985); 6, Broom and Lyford (1981); 7, Albin and Hines (1967); 8, Halberg and Reed (1964); --, not reported; ft^2/d, square feet per day; ft/d, feet per day]

Test no. (keyed to fig. 8)	Location	Transmissivities (T) (ft^2/d)	Hydraulic conductivity (K) (ft/d)	Storage coefficient (S)	Water-bearing formation	Data source
1	Mayfleld, Ky.	37,000-41,000	--	0.0001-0.0004	Memphis Sand	1
2	Union City, Tenn.	8,300	--	.0003	Memphis Sand	1
3	Tiptonville, Tenn.	18,000	--	.0003	Memphis Sand	2
4	Dresden, Tenn.	7,200	--	.0006	Memphis Sand	2
5	Kenton, Tenn.	15,000	--	--	Memphis Sand	2
6	Dyersburg, Tenn.	19,000	--	.0004	Memphis Sand	2
7	Milan, Tenn.	16,000	--	--	Memphis Sand	2
8	Ripley, Tenn.	22,000	--	--	Memphis Sand	2
9	Bells, Tenn.	5,600	--	.0005	Memphis Sand	2
10	Covington, Tenn.	29,000	--	--	Memphis Sand	2
11	Stanton, Tenn.	27,000	--	.0001	Memphis Sand	2
12	Arlington, Tenn.	21,000	--		Memphis Sand	2
13	Memphis, Tenn.	41,000	--	.0014	Memphis Sand	2
14	Somerville, Tenn.	2,700	--	--	Memphis Sand	2
15	Memphis (McCord), Tenn.	43,000	--	.0002	Memphis Sand	2
16	Memphis (Mallory), Tenn.	26,000	--		Memphis Sand	2
17	Memphis, Tenn.	45,000	--		Memphis Sand	2
18	Memphis (Sheahan), Tenn.	35,000	--		Memphis Sand	2
19	Memphis (Allen), Tenn.	31,000	--		Memphis Sand	2
20	Memphis (Lichterman), Tenn.	27,000	--		Memphis Sand	2
21	Germantown, Tenn.	23,000	--		Memphis Sand	2
22	Collierville, Tenn.	23,000	--		Memphis Sand	2
23	Clarksdale, Miss.	6,600	100	.0006	Memphis Sand	3
24	Blytheville, Ark.	21,000	--	.002	Fort Pillow Sand	4
25	Memphis (Mallory), Tenn.	17,000-19,000	--	.0002-.0006	Fort Pillow Sand	4
26	Madison Co., Tenn.	10,000	--	.0015	Fort Pillow Sand	4
27	Marks, Miss.	2,700	29	--	Fort Pillow Sand	3
28	Stoddard Co., Mo.	15,000	--	.002	Alluvium	5
29	Stoddard Co., Mo.	20,000	--	.001	Alluvium	5
30	Wayne Co., Mo.	47,000	--	.0009	Alluvium	5
31	Butler Co., Mo.	50,000	--	.001	Alluvium	5
32	Clay Co., Ark.	30,000	360	.0011	Alluvium	6
33	Jackson Co., Ark.	39,000	320	.022	Alluvium	7
34	Craighead Co., Ark.	37,000	380	.022	Alluvium	6
35	Jackson Co., Ark.	8,500	--	--	Alluvium	6
36	Jackson Co., Ark.	10,000	100	.007	Alluvium	6
37	Poinsett Co., Ark.	48,000	390	.001	Alluvium	6
38	St. Francis Co., Ark.	43,000	330	.04	Alluvium	8
39	Lee Co., Ark.	13,000-19,000	130	.00073	Alluvium	6
40	Monroe Co., Ark.	24,000	--	--	Alluvium	6
41	Monroe Co., Ark.	32,000	290	.0004	Alluvium	6
42	Phillips Co., Ark.	34,000	247	.0001	Alluvium	6

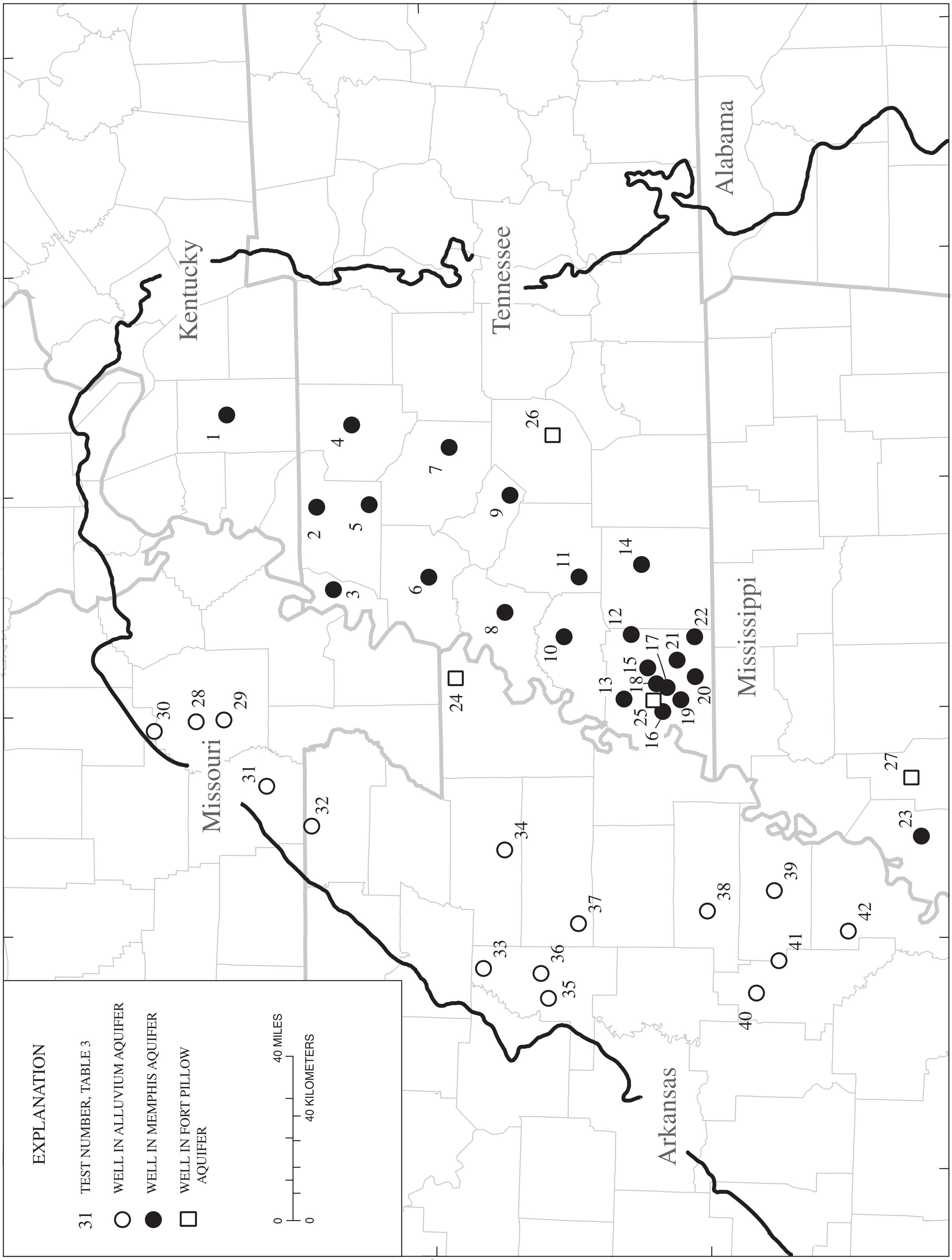
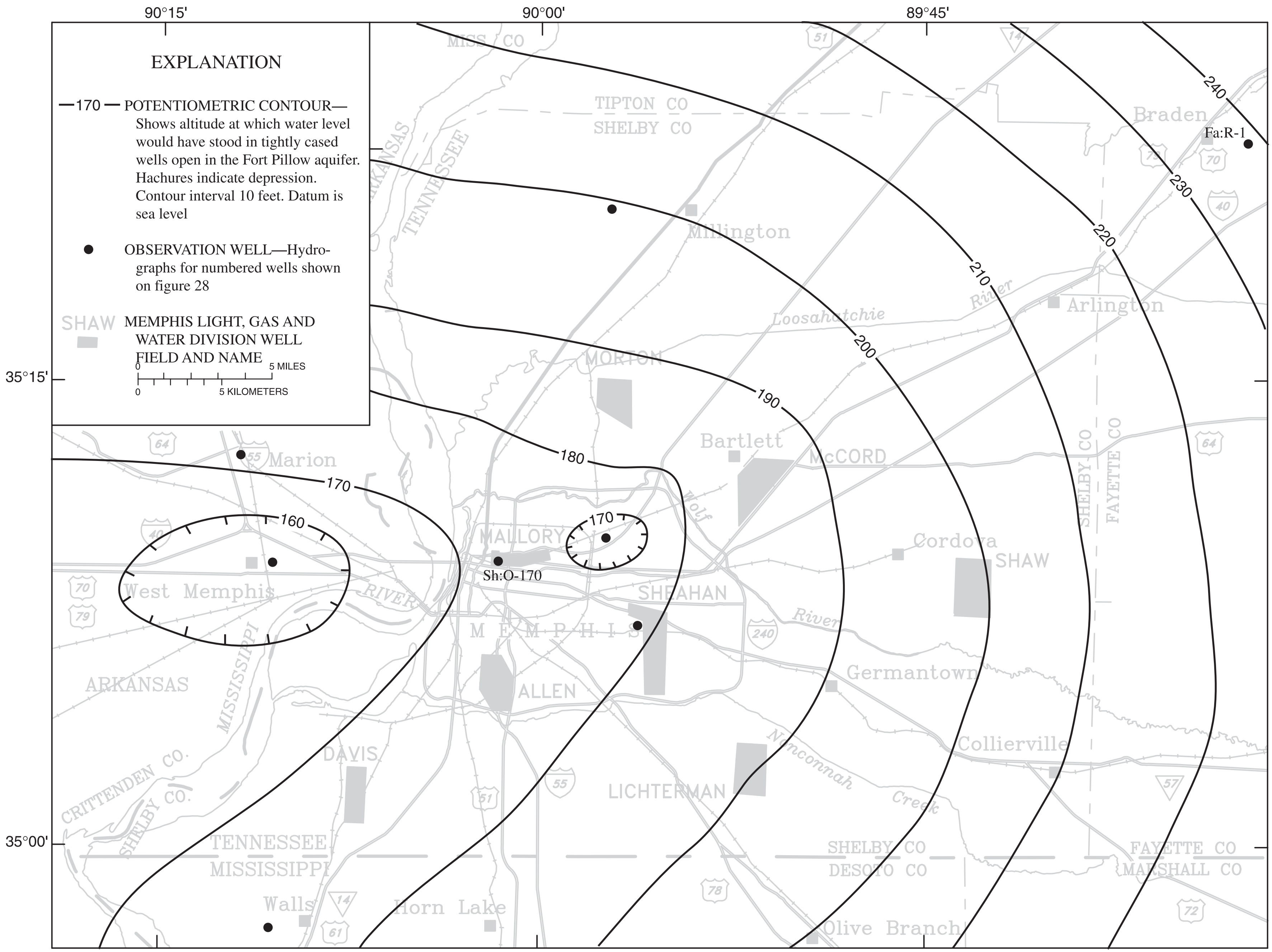
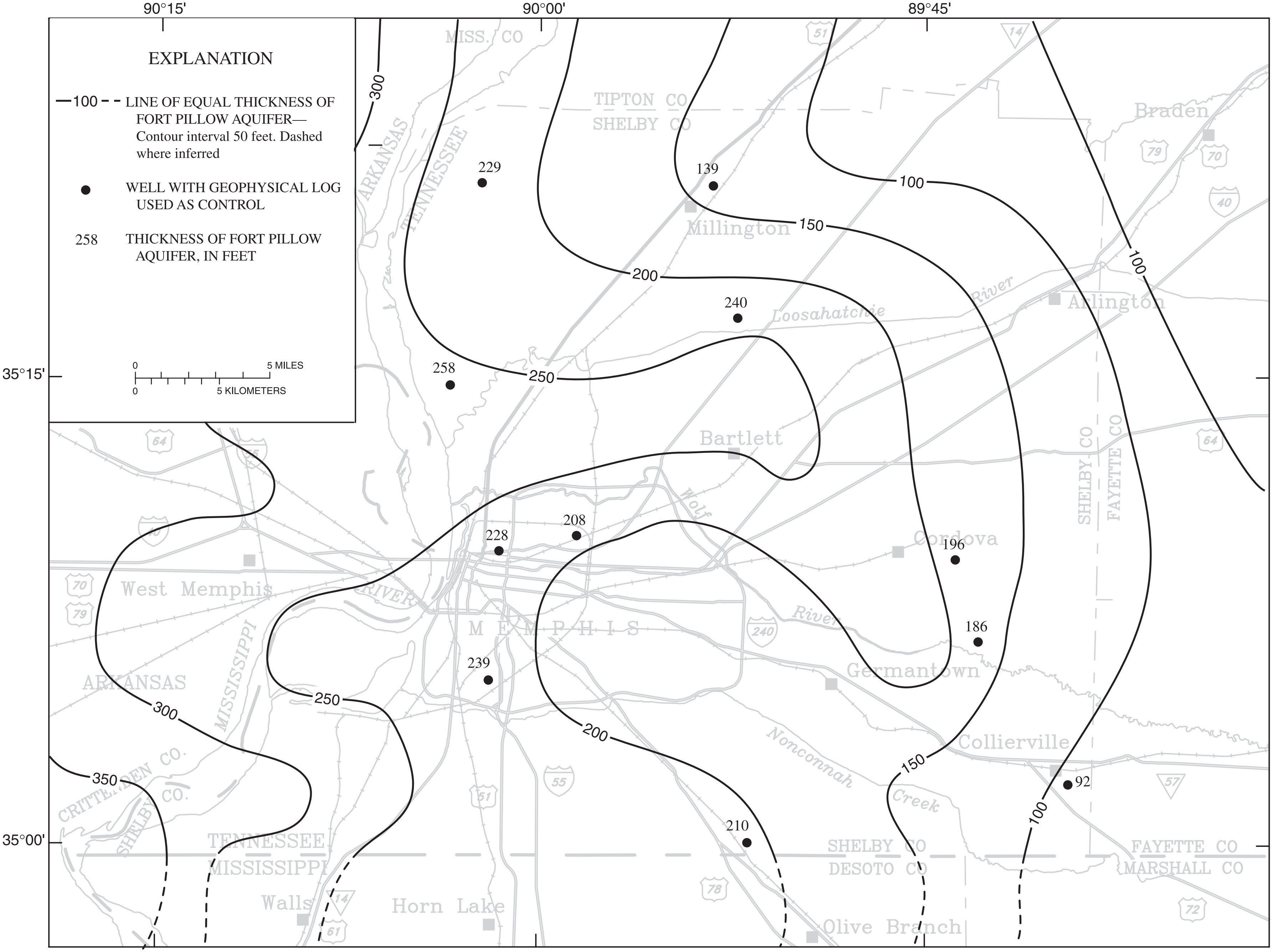


Figure 8. Location of selected aquifer tests.



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

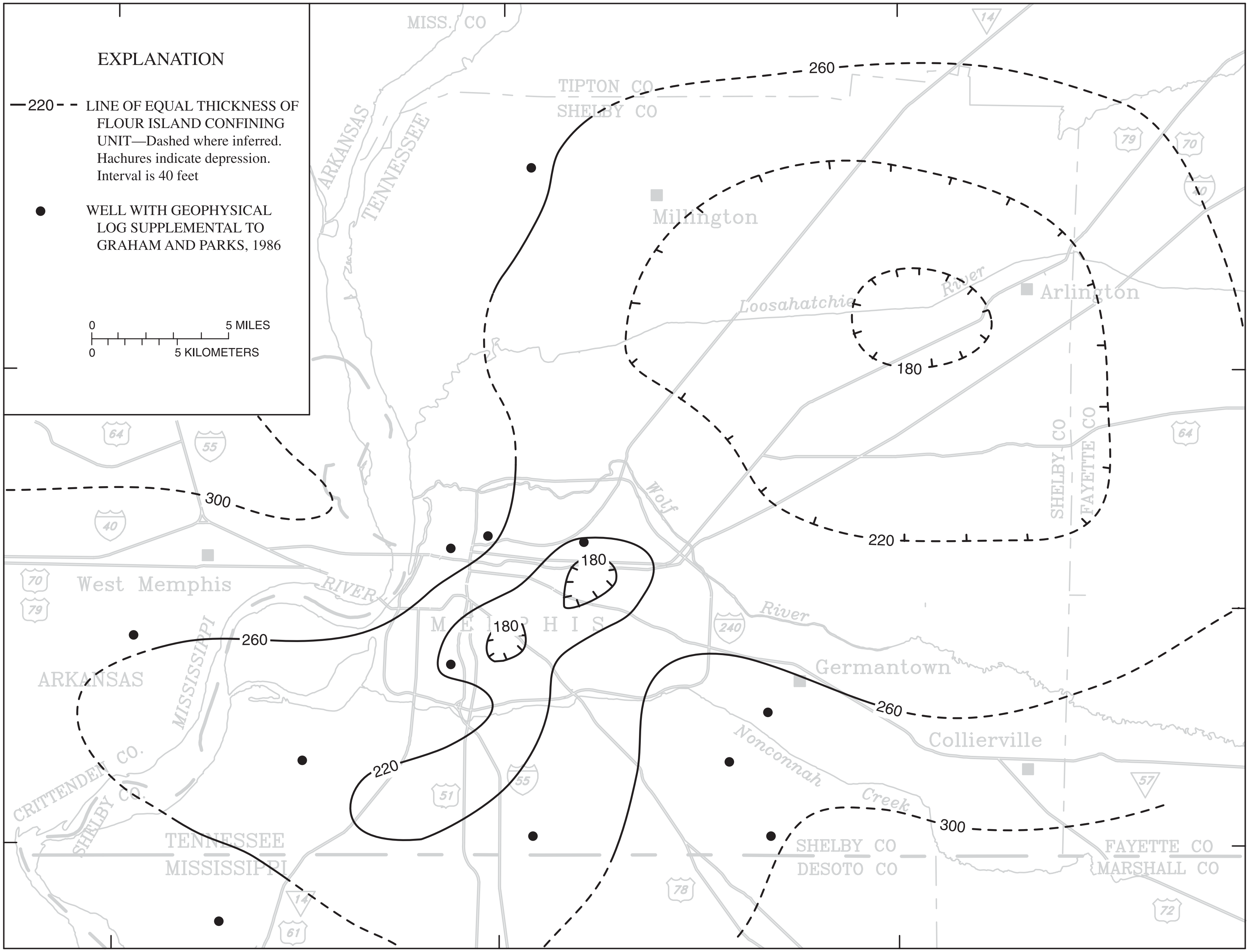
Figure 9. Altitude of the potentiometric surface of the Fort Pillow aquifer in the Memphis area, 1980.



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

Modified from W.S. Parks and J.K. Carmichael, 1989b, figure 2.

Figure 10. Generalized thickness of the Fort Pillow aquifer in the Memphis area.



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

Modified from D.D. Graham and W.S. Parks, 1986

Figure 11. Generalized thickness of the Flour Island confining unit in the Memphis area.

the eastern part of the area, nearest the outcrop, and lowest in the west near the centers of pumping. The regional movement of ground water in the Fort Pillow aquifer is toward the axis of the Mississippi embayment (Hosman and others, 1968).

The hydrograph for well Fa:R-1 (location on fig. 9), which taps the Fort Pillow aquifer about 27 miles east of the center of pumping at Memphis, shows a long-term decline of about 0.4 foot per year (ft/yr) (Graham, 1982). Regionally, declines of about 1 ft/yr are not uncommon (Hosman and others, 1968; Brahana and Mesko, 1988, fig. 13). Graham (1982) noted that the hydrograph of well Sh:O-170 (location on fig. 9) near the center of historic pumping in Memphis showed approximately 20 feet of recovery when all municipal (MLGW) pumpage from the Fort Pillow aquifer ceased in the early 1970's. Seasonal variations of nonstressed water levels are commonly less than 2 feet (Graham, 1982, fig. 4).

Hydraulic conductivity of the Fort Pillow aquifer throughout its area of occurrence in the northern Mississippi embayment is reported to range from 25 to 470 ft/d. This corresponds to a range of transmissivity from about 670 to 85,000 ft^2/d. Storage coefficient is reported to range from 2×10^{-4} to 1.5×10^{-2} (Hosman and others, 1968; Boswell, 1976; Parks and Carmichael, 1989b). Data from aquifer tests of the Fort Pillow aquifer (table 3, fig. 8) indicate that transmissivity ranges from 2,700 to 21,000 ft^2/d, and storage coefficients range from 2×10^{-4} to 2.0×10^{-3}.

Within the Memphis area, hydraulic characteristics have a narrower range (table 2) than described previously for the entire embayment. In the Memphis area, transmissivity of the Fort Pillow aquifer is reported to range from 12,000 to 19,000 ft^2/d, and storage coefficient is reported to range from 1.2×10^{-4} to 6.1×10^{-4} (Criner and others, 1964).

Water from the Fort Pillow aquifer is a soft, sodium bicarbonate type with a median dissolved-solids concentration of 116 mg/L (Brahana and others, 1987). Iron concentrations range from 170 to 1,900 micrograms per liter, and pH typically is about 7.4.

McNairy-Nacatoch Aquifer

The McNairy-Nacatoch aquifer, which encompasses sands of the Ripley Formation, McNairy Sand (table 1), and equivalent Upper Cretaceous Nacatoch Sand in Arkansas, is the basal freshwater aquifer in the study area. The McNairy-Nacatoch aquifer has not been used as a source of water supply in Memphis, but it has the potential for such use; north and east of the study area, it is a major regional aquifer (Brahana and Mesko, 1988).

The McNairy-Nacatoch aquifer ranges in thickness from 360 to 570 feet and is fine- to coarse-grained, glauconitic sand. The McNairy-Nacatoch aquifer occurs deeper than 2,500 feet below land surface at Memphis, and is confined and hydraulically separated from the overlying Fort Pillow Sand by about 750 feet of clays of the Midway and lower Wilcox Groups (table 1). These confining clays, herein called the Midway confining unit, are a major hydrologic boundary in the northern Mississippi embayment. Arthur and Taylor (1990) simulated the Midway confining unit as a lower no-flow boundary. Brahana and Mesko (1988) used flow modeling to evaluate leakage across the Midway confining unit; they found less than 0.5 ft^3/s moved across this confining unit in the study area.

Hydrogeologic evaluation of the McNairy-Nacatoch aquifer in the Memphis area is based on unpublished data from a single observation well in the Mallory well field and on extrapolation of regional data (Boswell and others, 1965; Davis and others, 1973; Luckey and Fuller, 1980; Edds, 1983; Brahana and Mesko, 1988). The static water level in this well is approximately 350 feet above sea level, which is about 100 feet above land surface (W.S. Parks, U.S. Geological Survey, written commun., 1985). Seasonal variation in water level is about 2 feet, and no long-term decline is evident. Head values in the McMairy-Nacatoch aquifer are approximately 180 feet higher than heads measured in the overlying Fort Pillow aquifer (Brahana and Mesko, 1988, figs. 10 and 11). Water-level declines in the McNairy-Nacatoch aquifer due to pumping in the overlying Fort Pillow aquifer have not been observed.

In addition to head differences, significant differences in water quality exist between the McNairy-Nacatoch aquifer and the Fort Pillow aquifer. Concentrations of dissolved solids, for example, are 10 times greater in the McNairy-Nacatoch aquifer than in the Fort Pillow aquifer.

Although the data from the McNairy-Nacatoch aquifer are sparse, they are consistent on both a local and regional scale. These differences in hydrology and water chemistry strongly support the contention that clays in the Midway confining unit (Porters Creek Clay, Clayton Formation, and Owl Creek Formation, table 2) act as an effective confining unit (figs. 2 and 3), and isolate the Fort Pillow aquifer from deeper aquifers.

CONCEPTUALIZATION OF THE GROUND-WATER FLOW SYSTEM

The hydrogeologic information presented in the previous section forms the basis for a conceptual model of ground-water flow in the Memphis area. This conceptualization accounts for the ability of each major unit to store and transmit water, as indicated by its lithology and stratigraphy, and by hydrologic data. Water-quality data are also used to lend credence to hypotheses regarding the hydrologic isolation or communication between aquifers. The conceptual model represents a simplification of reality but preserves and emphasizes the major elements controlling ground-water flow in the study area. This conceptual model can be tested quantitatively by depicting each of its elements mathematically in a digital model of ground-water flow. The relation between the hydrogeologic framework, the conceptual model, and the digital ground-water flow model is shown in figure 12.

The alluvium and fluvial deposits form the uppermost water-table aquifers in the conceptual model. Water levels respond seasonally to recharge, evapotranspiration, and minor pumping, but on the time scale of interest to this investigation, the water-table aquifers are at steady state. The one documented exception to steady state occurred about 1943 in the southern area of the Sheahan well field. Conceptually, the water-table aquifers serve the important function of providing a potentially large reservoir of vertical leakage to the underlying confined aquifers. Horizontal flow in the water-table aquifers are defined by the water-level map (fig. 4), but are of incidental interest in this investigation. Recharge to the aquifer is primarily from the infiltration of rainfall on the outcrop. Discharge from these aquifers is primarily to streams, as baseflow, and vertically to deeper aquifers as downward leakage.

The Jackson-upper Claiborne confining unit is conceptualized as a leaky confining unit with variable thickness (fig. 5) and lithology. Leakance values for this confining unit were poorly defined by aquifer test data (table 2), and much quantitative testing of alternative leakance parameters and distributions were undertaken. In general, pumping from the Memphis aquifer has induced flow from the shallow water-table aquifers downward to the Memphis aquifer through the Jackson-upper Claiborne confining unit. Leakage has increased with time as the head difference between the water-table aquifers and the Memphis aquifer has increased.

Flow in the Memphis aquifer has been transient since the onset of pumping in 1886. Recharge occurs in the outcrop area in the southeastern and eastern parts of the study area (fig. 13), and flow is predominantly into the centers of pumping from all directions (fig. 7). An increasing component of recharge is derived from leakage through time from the super and subjacent aquifers across nonhomogeneous confining units. Pumping represents the major source of discharge from the system, and the areal and temporal variation of pumping through time is the major reason this aquifer is not at steady state. Prior to pumping, discharge was westward to the subcrop of the Memphis aquifer beneath the alluvium, and upward beneath the Mississippi River alluvial plain. Up dip pinch out of the Memphis Sand defines the limit of occurrence of the Memphis aquifer, and no-flow boundaries around the eastern, northern, and western boundaries conceptually represent ground-water conditions where the pinch out occurs. A major effort of quantitative testing was focused on the Memphis aquifer and its related hydrogeology, including its transmissivity, storage, boundary configuration, and pumping.

The Flour Island confining unit is conceptualized as a confining unit that is less variable in thickness (fig. 11) and less leaky than the Jackson-upper Claiborne confining unit. Flow directions across the Flour Island confining unit are in response to dynamically changing heads in the overlying Memphis aquifer and underlying Fort Pillow aquifer. Quantitative testing of the vertical hydraulic conductivity of this unit was a specific focus of this investigation.

Flow in the Fort Pillow aquifer has been transient since about 1924, not only in response to pumping from this aquifer in the study area, but to major regional pumping in Arkansas. Recharge to the Fort Pillow aquifer occurs primarily in the outcrop areas east and north of the study area. Vertical leakage provides some recharge at locations where heads in the overlying Memphis aquifer are higher than heads in the Fort Pillow aquifer. Discharge from the system is primarily to a temporally and areally varying pumping distribution particularly in Arkansas (Arthur and Taylor, 1990). Some discharge from the Fort Pillow aquifer occurs as horizontal flow southward, and some

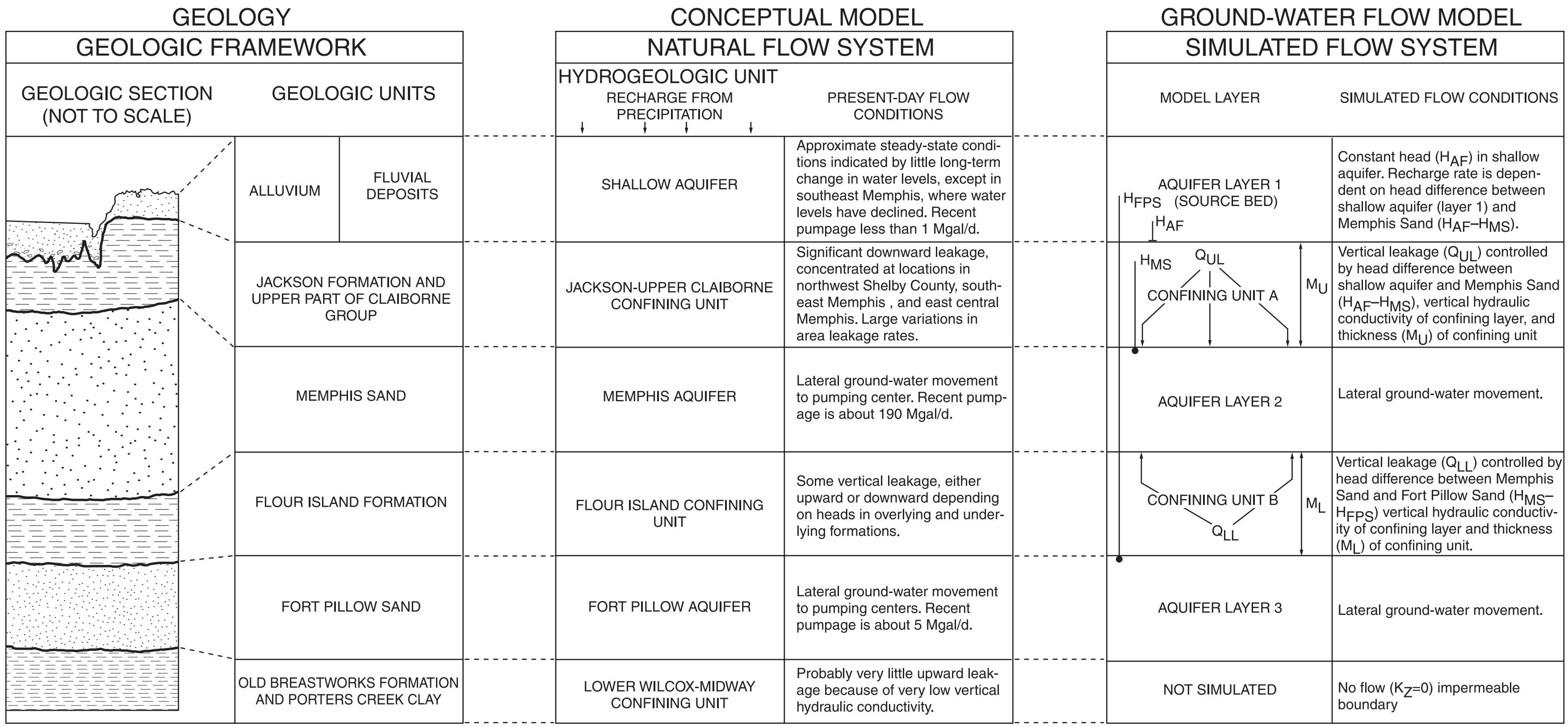
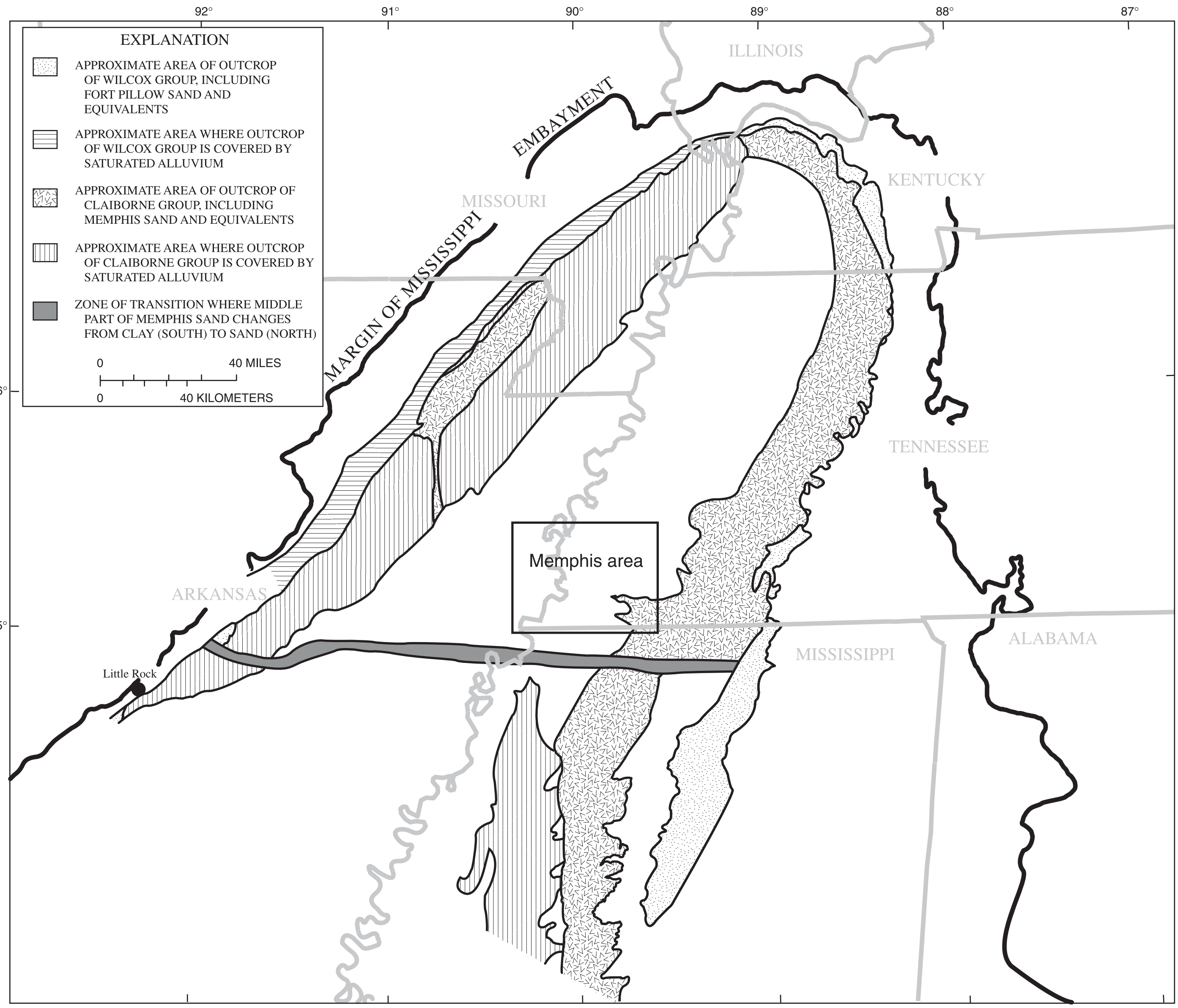


Figure 12. Relation between units of the geologic framework, the natural flow system of the conceptual model, and the simulated flow system of the ground-water flow model.



Geology modified from R.L. Hosman, A.T. Long, and T.W. Lambert and others, 1968, Plate 7; and J.H. Criner and W.S. Parks, 1976, figure 4.

Figure 13. Areal geology of the northern Mississippi embayment.

occurs as vertical flow upward. No-flow boundaries define the up-dip limits of the Fort Pillow aquifer. Higher leakance through the overlying Flour Island confining unit simulates horizontal outflow to the south, more than 50 miles from the study area. Quantification of hydraulic parameters of the Fort Pillow aquifer (transmissivity, storage coefficient, boundary configuration, and pumping) was the focus of quantitative testing and verification.

The Midway confining unit was conceptualized as being a no-flow boundary. The concept was tested by Brahana and Mesko (1988) and found to be a valid assumption. Alternative testing was not undertaken in this study.

SIMULATION OF THE GROUND-WATER FLOW SYSTEM

The validity of the conceptual model can be assessed in part by constructing a digital model of the ground-water flow system. In the digital model, differential equations depicting the physical laws governing ground-water flow in porous media are solved to simulate the movement of water through the system. The digital model code used in this study was developed by McDonald and Harbaugh (1988) and has the following attributes:

1. Flow is simulated in a sequence of layered aquifers separated by confining units;
2. Flow within the confining units is not simulated, but the hydraulic effect of these units on leakage between adjacent aquifers is taken into account;
3. A modular design facilitates hydrologic simulation by several alternative methods; and
4. The model code has been documented and validated in hydrogeologic settings similar to those which occur in the study area.

For this model the study area is discretized in space and time, and finite-difference approximations of differential equations depicting ground-water flow are solved at each node. The solution algorithm employs an iterative numerical technique known as the strongly implicit procedure—SIP (Weinstein and others, 1969). The theory and use of the model is documented by McDonald and Harbaugh (1988).

A three-layer model (fig. 12) was constructed to simulate the regional flow system in the Memphis and Fort Pillow aquifers. The uppermost layer represents the shallow aquifer. Flow within the shallow aquifer was not simulated; rather, the layer consisted of an array of constant-head nodes representing water levels at steady state during any given stress period. This layer serves as the ultimate source of recharge to the aquifers, either by leakage, or where the Memphis and Fort Pillow aquifers outcrop, as a source of simulated direct recharge.

The second and third layers represent the Memphis and Fort Pillow aquifers, respectively. The areal extent of the formations that make up the Memphis and Fort Pillow aquifers are shown in figure 13.

Layers of the model are separated by leaky confining units. These units are depicted by arrays of leakance terms. Leakance is calculated by dividing the vertical hydraulic conductivity by the thickness of the confining unit (McDonald and Harbaugh, 1988, p. 5-11). Leakance values are high in areas where confining units are thin or absent, and are low where the units are thick and tight.

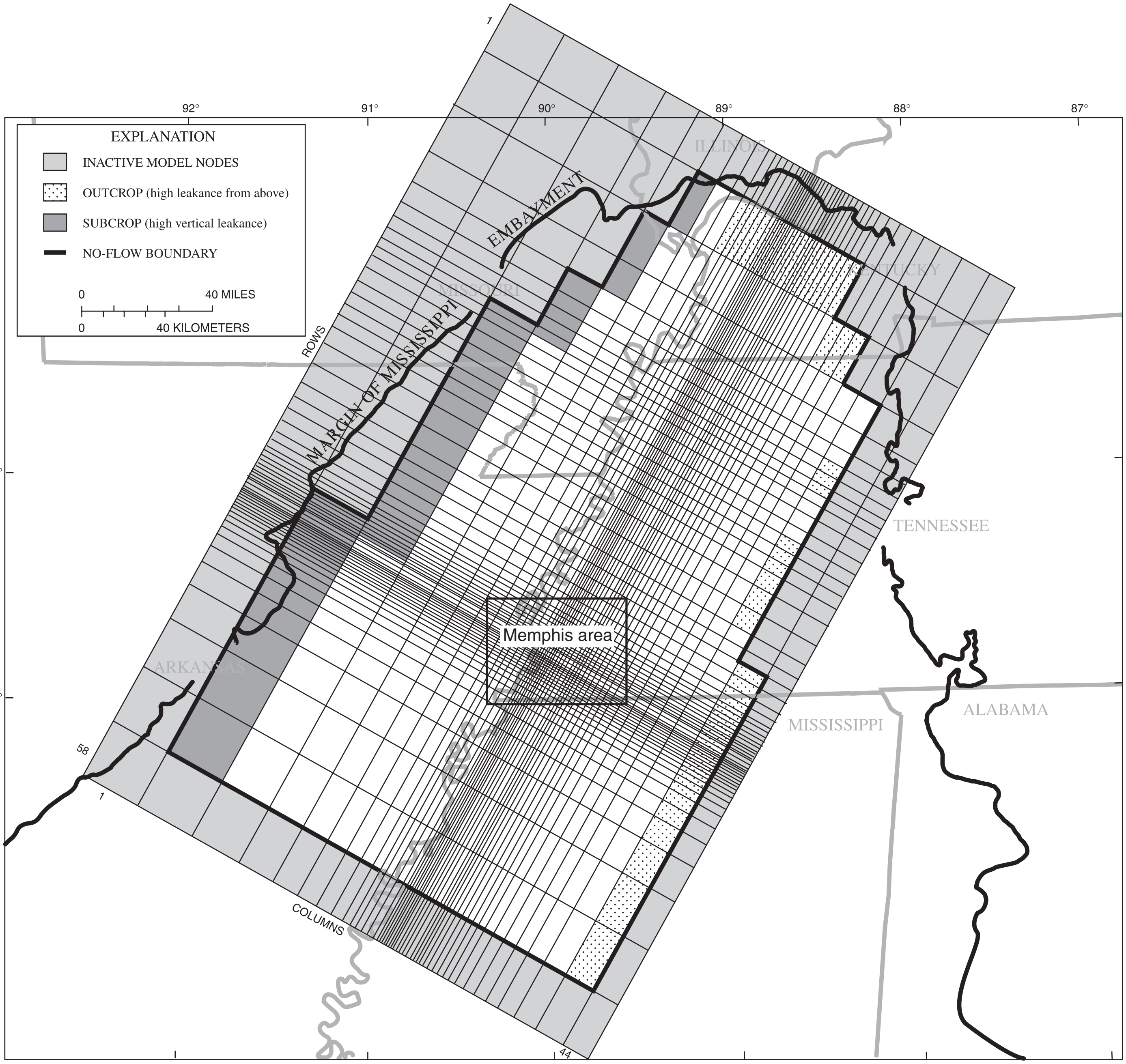
Finite-Difference Grid

The area simulated by the digital model (fig. 14) is much larger than the Memphis study area. Evaluation of the larger area allows simulation of regional flow in the aquifer using realistic representations of the natural boundaries of the Memphis and Fort Pillow aquifers on the western, northern, and eastern margins of the Mississippi embayment.

Approximately 10,000 mi^2 of the northern Mississippi embayment is divided by a variably-spaced, finite-difference grid of 58 rows, 44 columns, and 3 layers. The grid, in relation to the areas of outcrop and subcrop of the Memphis and Fort Pillow aquifers, is shown in figures 14 and 15 and is oriented to minimize the number of inactive nodes. Directional properties of transmissivity were not used to determine grid alignment, because on a regional scale there is no evidence of anisotropic transmissivity in the Mississippi embayment area (Hayes Grubb, U.S. Geological Survey, oral commun., 1986). An evaluation of an aquifer test of the Memphis aquifer in the Memphis area using tensor analysis (Randolph and others, 1985) was conducted after the grid was aligned. This evaluation indicated a slight anisotropy (2.3 to 1) with respect to principal axes oriented within 15^{o} of the grid of this model (Morris Maslia, U.S. Geological Survey, written commun., 1985).

Geology modified from R.L. Hosman, A.T. Long, and T.W. Lambert and others, 1968, Plate 7; and J.H. Criner and W.S. Parks, 1976, figure 4.

Figure 14. Regional digital model representation of aquifer layer 2 (Memphis aquifer) in the northern Mississippi embayment.



Geology modified from R.L. Hosman, A.T. Long, and T.W. Lambert and others, 1968, Plate 7; and J.H. Criner and W.S. Parks, 1976, figure 4.

Figure 15. Regional digital model representation of aquifer layer 3 (Fort Pillow aquifer) in the northern Mississippi embayment.

The grid spacing varies from a minimum of 3,200 feet in the Memphis area to 100,000 feet at the western boundary of the model. This variable spacing provides computational efficiency while affording the highest node density within the Memphis study area. Grid block size within the Memphis study area varies from 0.45 mi^2 to slightly more than 8 mi^2 (see fig. 25). A grid block size of about 1 mi^2 is typical for the area of intense pumping in metropolitan Memphis. To reduce the potential for numerical instability during model simulation, block dimensions varied by no more than 1.5 times the dimensions of adjacent blocks.

Hydrologic Parameters

The flow model requires arrays of input data that define the distribution of "average" hydrologic parameters and conditions affecting ground-water flow within each grid block. These parameters include initial head distributions, boundary conditions, hydraulic properties of the aquifers and confining beds, and pumping stresses.

Initial Head Distributions

The initial head distributions used in the model are general estimates of pre-development, steady-state conditions. Data are sparse, and many data points were extrapolated. Initial water levels for the shallow aquifer (layer 1) in the Memphis area are estimated to be the same as water levels in 1980 (fig. 4), except that the cone of depression in the area of the south Sheahan well field was not present under initial conditions. Prior to pumping, water levels in the shallow aquifers in the south Sheahan area are estimated to be about 240 feet above sea level. Initial heads for the shallow aquifer (layer 1) in the Memphis area are based on data from Wells (1933), Boswell and others (1968, plate 1), Krinitzsky and Wire (1964), and Graham and Parks (1986, fig. 7).

Initial heads in the Memphis aquifer for the entire modeled area prior to development were derived from Arthur and Taylor (1990), Hosman and others (1968, plate 7), and Reed (1972). Within the Memphis area, estimated potentiometric surface of the Memphis aquifer prior to development in 1886 is shown in figure 16 (Criner and Parks, 1976, fig. 4).

Initial head data for the Fort Pillow aquifer in the modeled area are from Arthur and Taylor (1990), Criner and Parks (1976, fig. 4), Hosman and others (1968, plate 4), Plebuch (1961), and Schneider and Cushing (1948). The estimated potentiometric surface of the Fort Pillow aquifer within the Memphis area prior to development in 1924 is shown in figure 17.

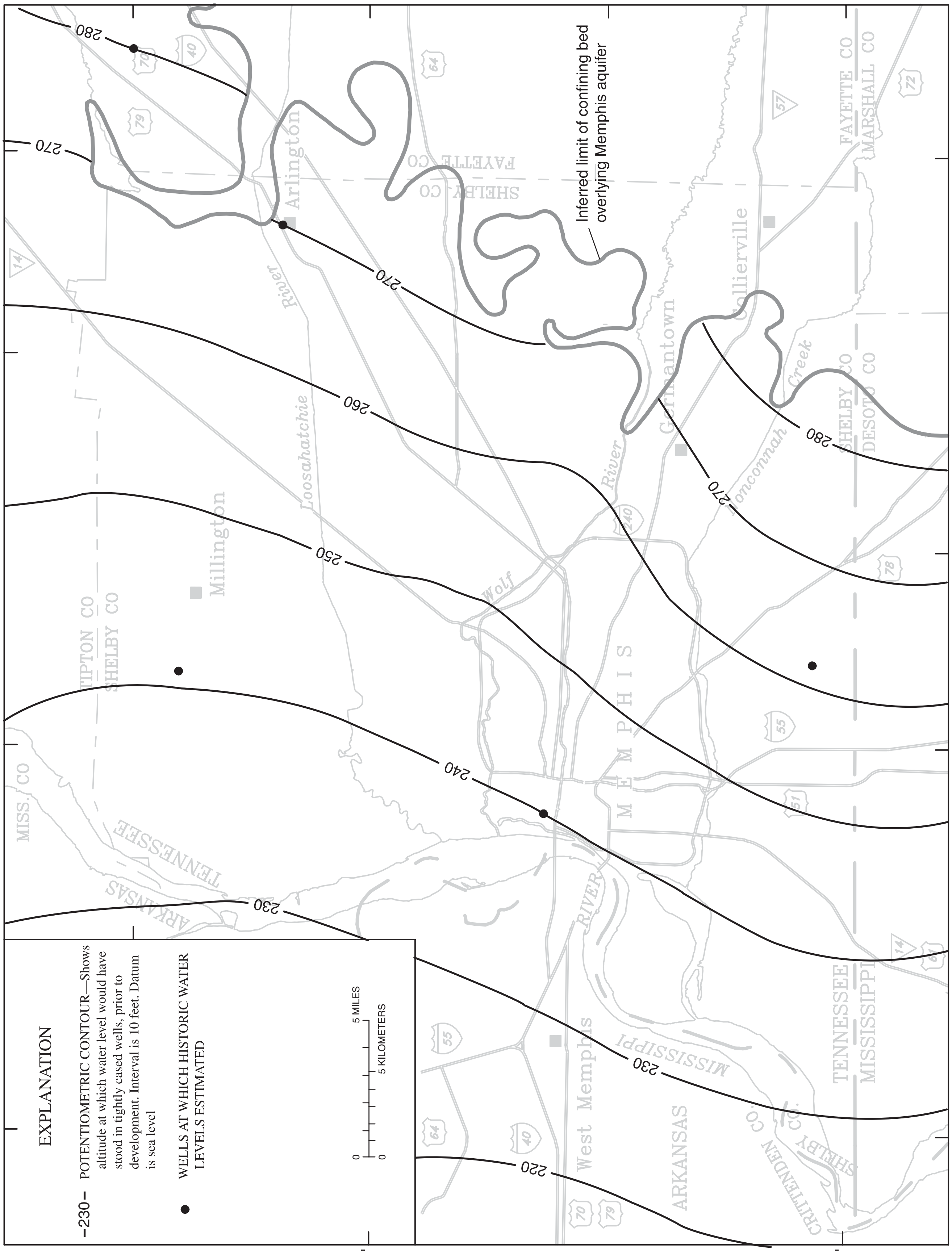
Boundary Conditions

Boundary conditions include lateral no-flow boundaries for the Memphis and Fort Pillow aquifers, a no-flow condition beneath the Fort Pillow aquifer, and constant heads for the uppermost layer. To the north, east, and west for the Memphis and Fort Pillow aquifers, no-flow boundaries correspond with the updip extent of respective outcrop and subcrop areas (figs. 14 and 15). On the south, a no-flow boundary is specified that is roughly perpendicular to water-level contours (parallel to ground-water flow). This boundary is not truly "no flow"; however, the low aquifer transmissivity and distance from the area of interest are assumed to cause negligible effects on simulation in the area of interest.

Constant heads in the uppermost layer, which corresponds to the water-table aquifer, represent long-term, steady-state water-table altitudes. Head declines have been documented in only one isolated area in the shallow water-table aquifer. In this area of water-level decline, the water levels were decreased step-wise in sequential stress periods to reflect estimated declines in the local water table.

Simulated flow to and from the uppermost layer represents deep recharge and discharge from the system. Inasmuch as the focus of the study was on the deeper aquifers, a detailed evaluation of the hydrologic budget of the shallow aquifer was outside the scope of this report. However, the calculated value of regional recharge used in the model was hydrologically reasonable and compared favorably with values used in Arthur and Taylor (1990) and Brahana and Mesko (1988).

The Midway confining unit underlying the Fort Pillow aquifer is assumed to be impermeable, and its upper surface is specified as a "no-flow" boundary. This assumption is supported by lithologic, chemical, and hydrologic data (Brahana and Mesko, 1988, figs. 8, 10, and 11, and table 2).



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

From J.H. Criner and W.S. Parks, 1976, figure 4

Figure 16. Estimated potentiometric surface of the Memphis aquifer prior to development in 1886.

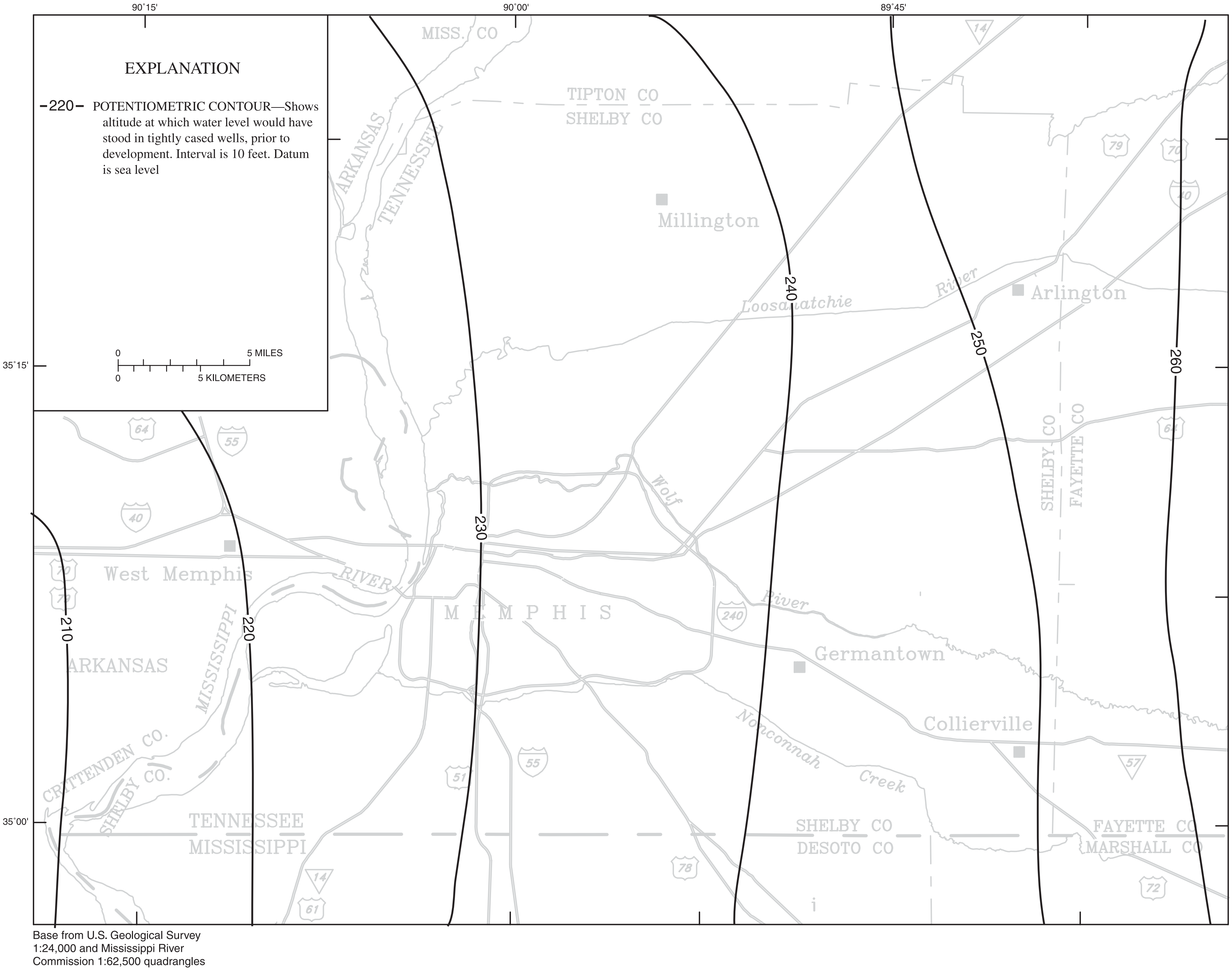


Figure 17. Estimated potentiometric surface of the Fort Pillow aquifer prior to development in 1924.

Aquifer Hydraulic Properties

Average storage coefficient and transmissivity for each grid block for each aquifer were required for model simulation. Initial estimates for these hydraulic properties were based on pumping tests, geologic data such as lithology and layer thickness, and estimates and calculations made by other investigators (Schneider and Cushing, 1948; Criner, Sun, and Nyman, 1964; Halberg and Reed, 1964; Bell and Nyman, 1968; Boswell and others, 1968; Hosman and others, 1968; Cushing and others, 1970; Newcome, 1971; Reed, 1972; Parks and Carmichael, 1989a and b). The model-derived storage coefficient and transmissivity for the Memphis aquifer represent the values that provided the best fit between calculated and observed potentiometric levels (heads) (table 2 and figs. 18 and 19).

Transmissivity values determined by calibration for the Memphis aquifer in the Memphis area ranged from less than 10,000 ft^2/d to 50,000 ft^2/d, with values commonly in the range from 20,000 ft^2/d to 50,000 ft^2/d (fig. 19). These values agree with the average transmissivity determined by flow-net analyses (U.S. Geological Survey, unpublished data, 1985), and are within the range of reported values (table 2). Transmissivity decreases south of Shelby County, which reflects the change to clay facies in the middle part of the Memphis Sand (Hosman and others, 1968). The best match of heads was simulated using values of transmissivity that more closely matched those of the Sparta aqufier (Fitzpatrick and others, 1989) than those of the entire clay and sand unit. The storage coefficients for the Memphis aquifer ranged from 2×10^{-4} to 2×10^{-1} (fig. 18).

Leakance values were initially determined by dividing estimates of the vertical hydraulic conductivity of reported lithologies (U.S. Geological Survey, unpublished data, 1984; Freeze and Cherry, 1979) by the generalized thickness of the confining units (Graham and Parks, 1986, figs. 3-6). These values were refined during the calibration process; areal distribution of leakance by calibration is shown in figure 20.

Leakance of the upper confining layer, the Jackson Formation and upper part of the Claiborne Group, was characterized by a wide range of values, from 1×10^{-8} feet per day per foot to 1×10^{-3} feet per day per foot. This range reflects the diverse lithology of the Jackson-upper Claiborne confining unit as well as variations in thickness of the unit (fig. 5).

Most transmissivity values determined by calibration for the Fort Pillow aquifer in the Memphis area ranged from 6,000 to 24,000 ft^2/d (fig. 21). The storage coefficients used in the calibrated model for the Fort Pillow aquifer in the Memphis area varied by less than a factor of 2, from 5×10^{-4} to 1×10^{-3} (fig. 22), sigifying uniformly confined conditions for the Fort Pillow aquifer. Leakance values for the lower confining unit, the Flour Island Formation, were from 1×10^{-12} feet per day per foot to 2×10^{-12} feet per day per foot (fig. 23), reflecting similar lithology and little variation in thickness (fig. 11) of the Flour Island confining unit within the Memphis area.

Pumping

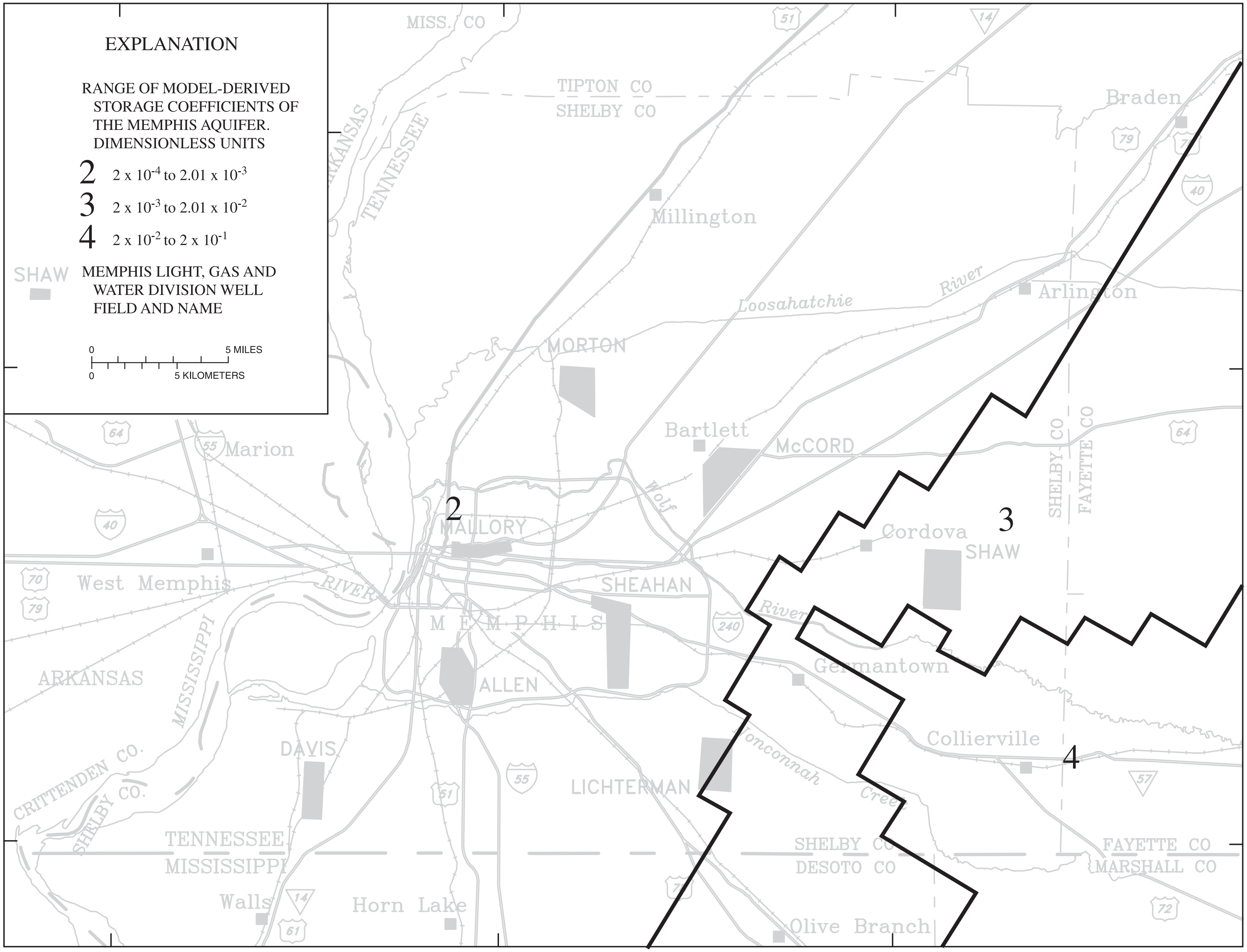
Pumping from the Memphis aquifer began in 1886, and pumping from the Fort Pillow aquifer began in 1924. Withdrawals from these two major aquifers have occurred at varying rates and with a changing areal distribution. Because of variation with time, pumping data were introduced in the model in nine discrete stress periods. The total modeled pumpage and the corresponding total reported pumpage for the nine periods are shown in figure 24. The length of the stress periods ranged from 5 to 39 years. Seasonal variations in pumping were not simulated. Mean annual pumping was used to calculate average stress at each node for each of the stress periods.

Delineation of stress periods was based on abrupt changes in pumpage rates, variations in the areal distribution of pumping centers, and on availability of water-level maps. The number of well nodes simulating pumping in the Memphis area increased from 18 in stress period 1 to 88 in stress period 9. Total pumping from the Memphis and Fort Pillow aquifers increased from 0 in 1885 to about 190 Mgal/d in 1985.

Pumpage data for the Memphis and Fort Pillow aquifers in the Memphis area are based on the published reports of Criner and Parks (1976) and Graham (1982). Areal distribution was assigned based on extensive unpublished documents of water use reported to the U.S. Geological Survey in Memphis (W.S. Parks, U.S. Geological Survey, written commun., 1984).

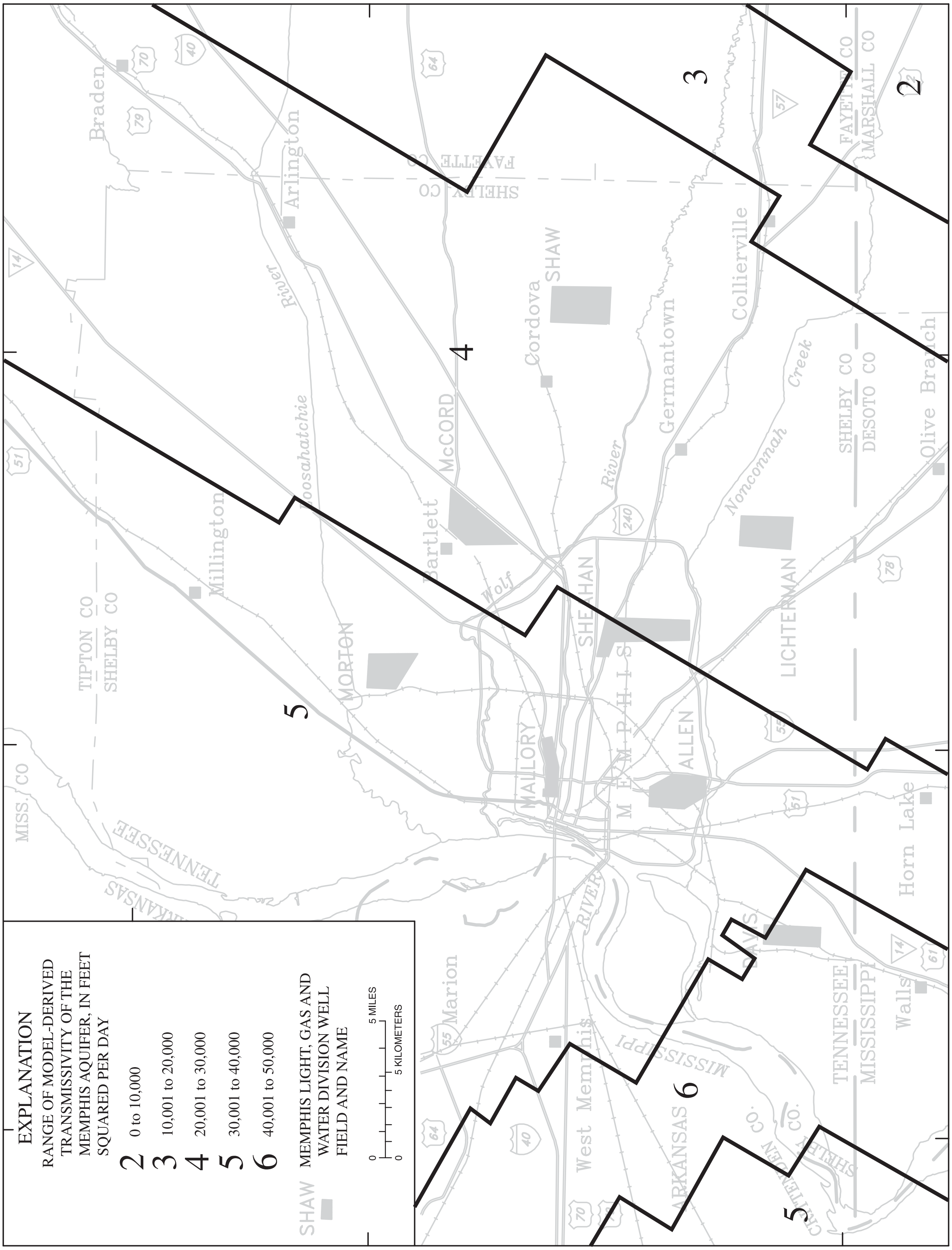
Model Calibration

Calibration of the flow model is the process of adjusting the input data to produce the best match between simulated and observed water levels. The



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

Figure 18. Model-derived storage coefficient of the Memphis aquifer.



Base from U.S. Geological Survey
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Figure 19. Model-derived transmissivity of the Memphis aquifer.

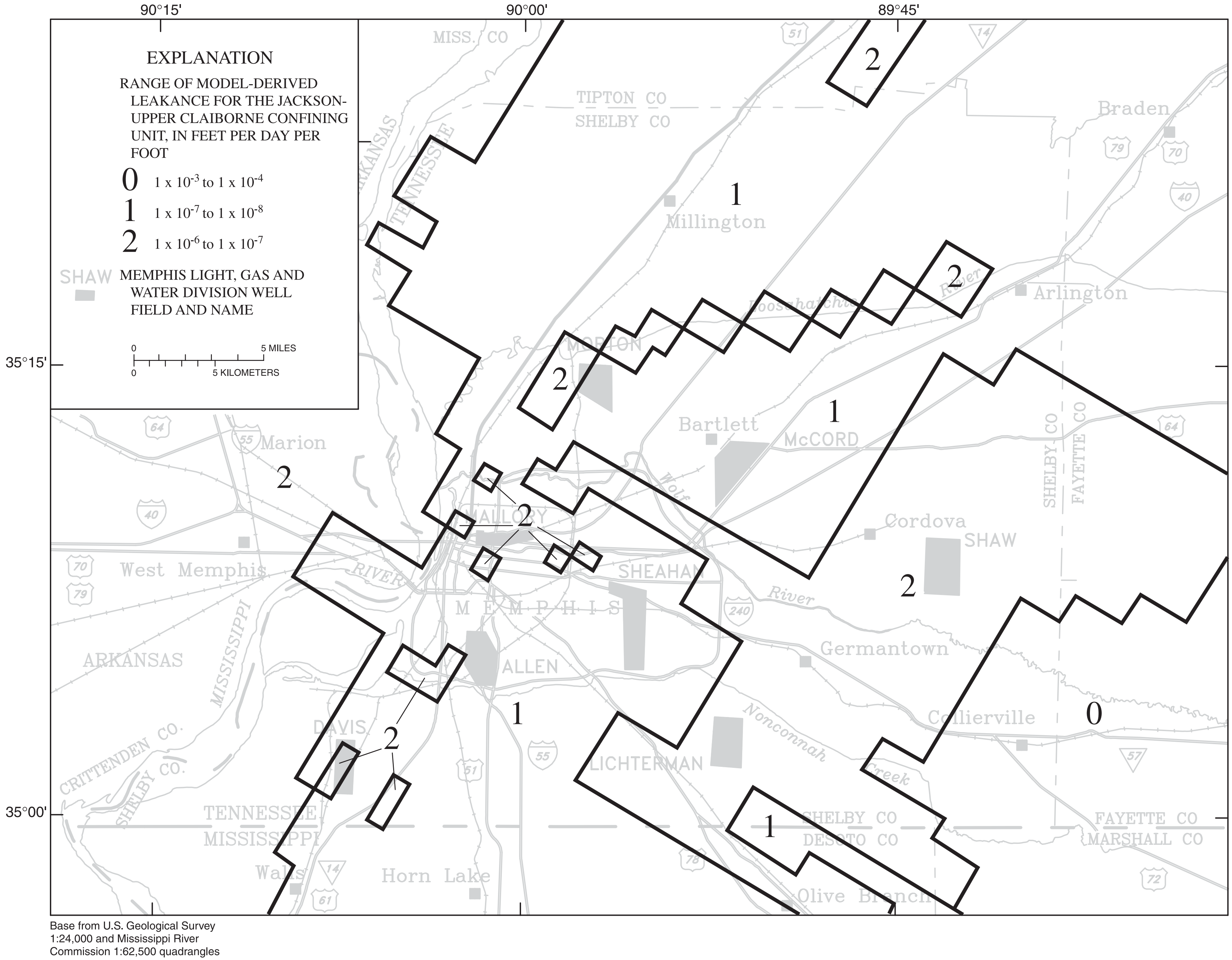
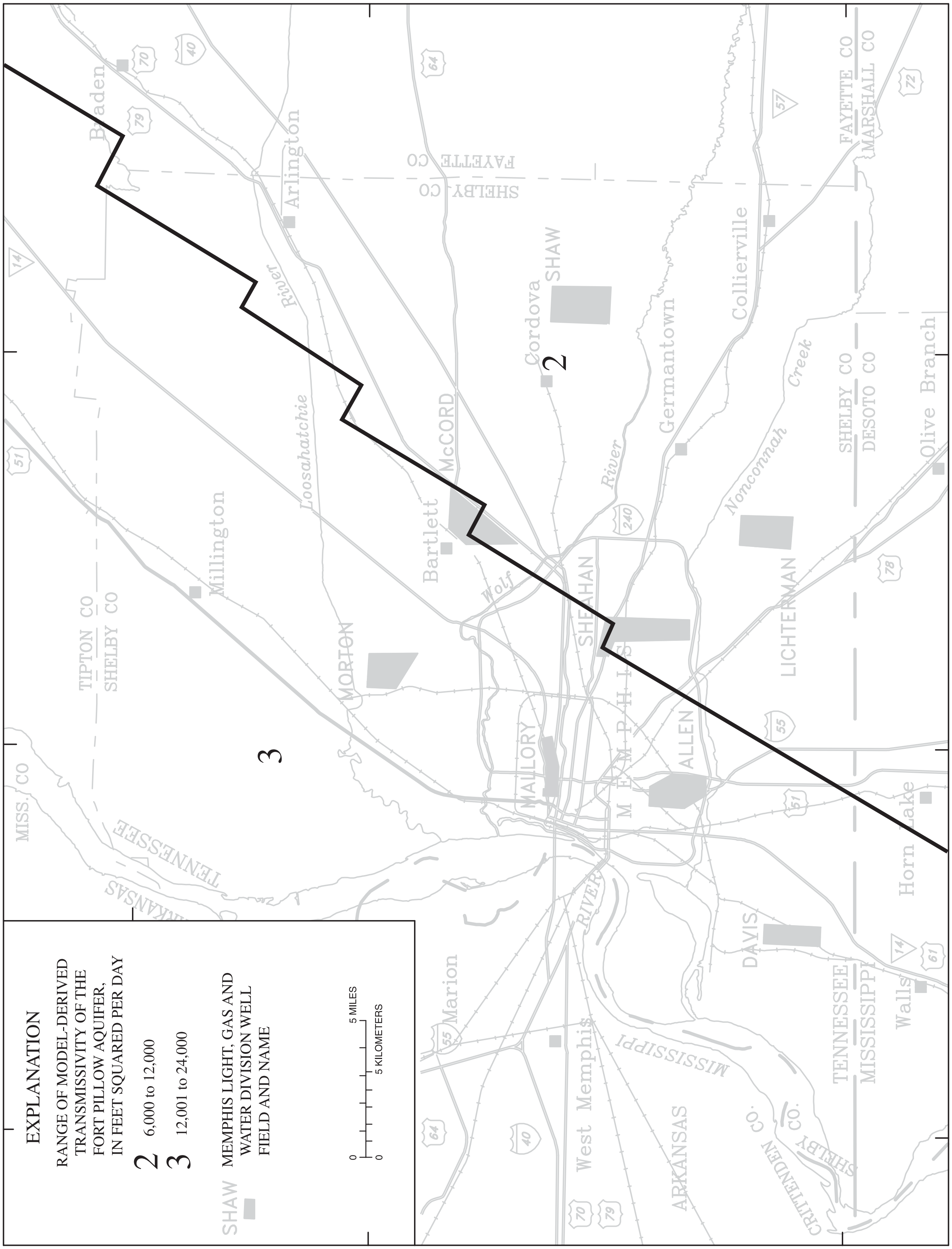
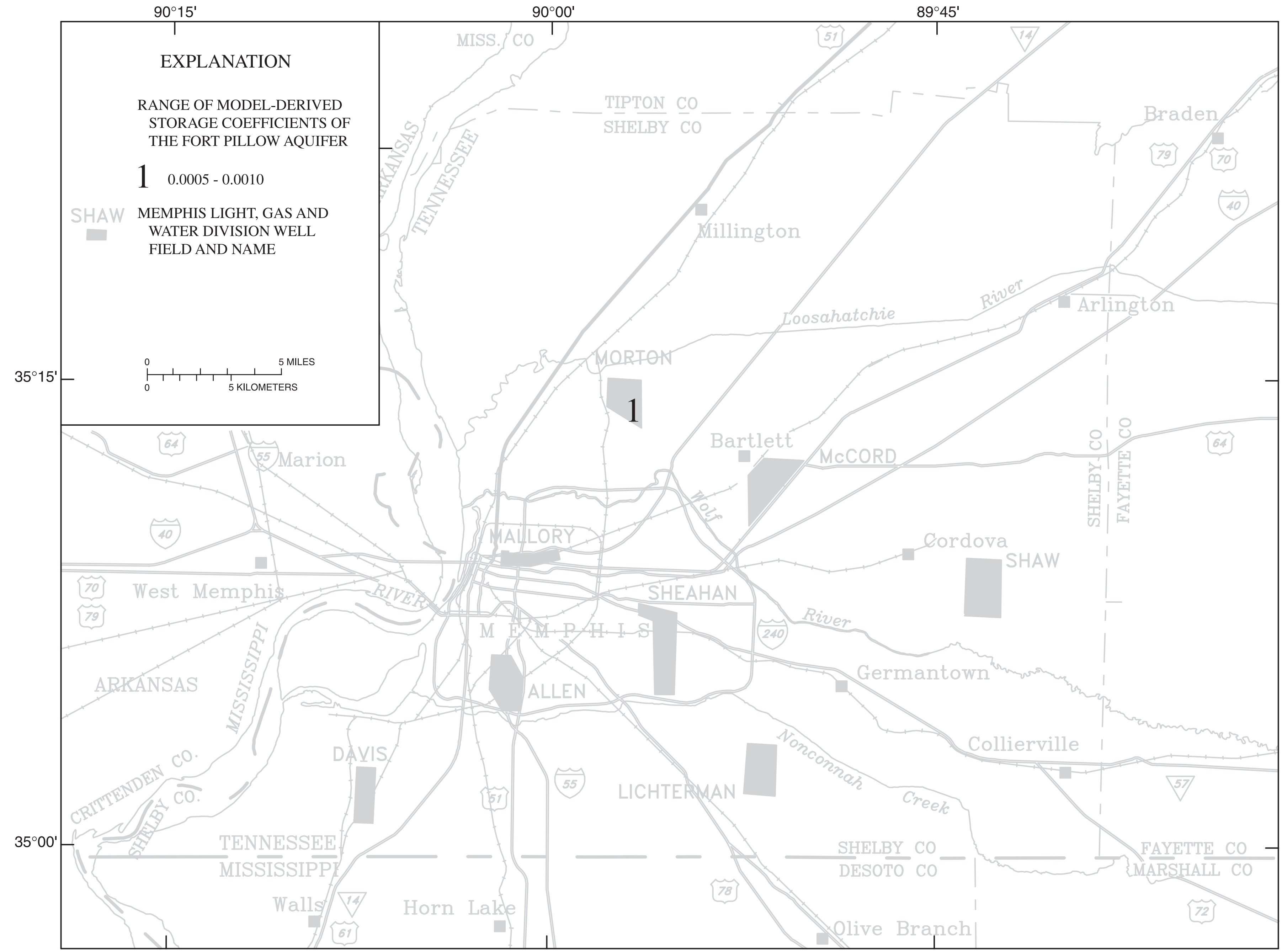


Figure 20. Model-derived leakance of the Jackson-upper Claiborne confining unit.



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

Figure 21. Model-derived transmissivity of the Fort Pillow aquifer.



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

Figure 22. Model-derived storage coefficient of the Fort Pillow aquifer.

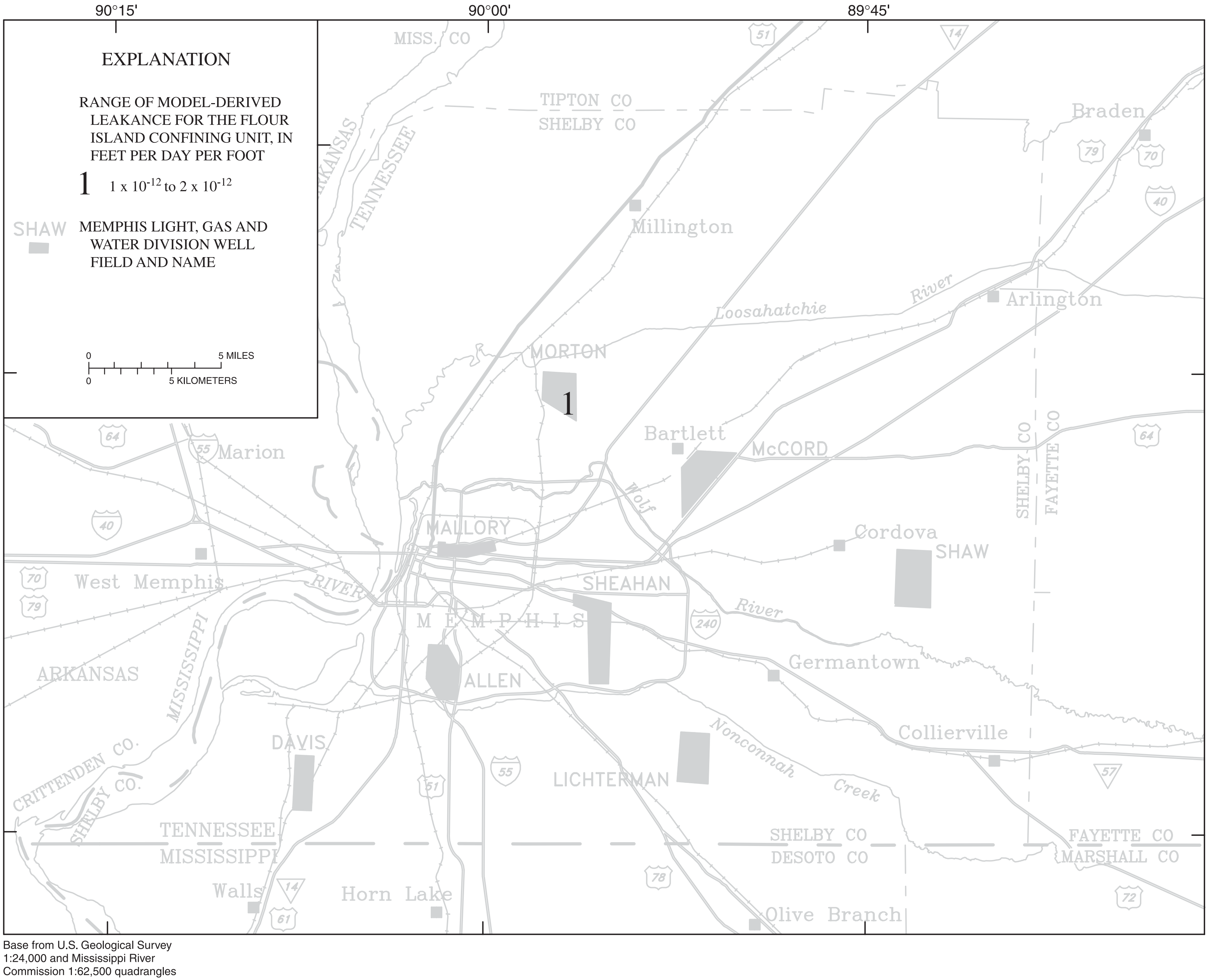


Figure 23. Model-derived leakance of the Flour Island confining unit.

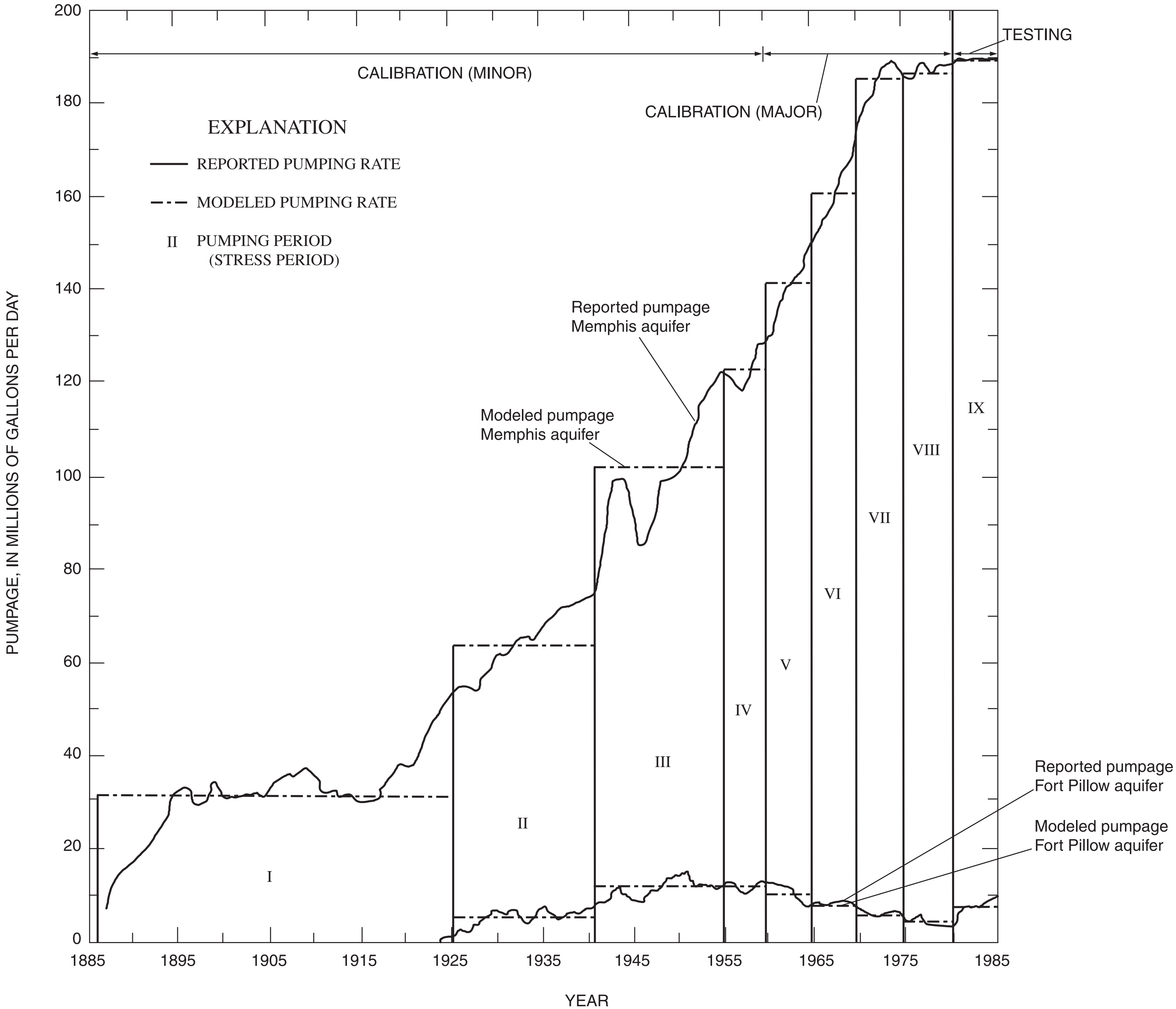


Figure 24. Actual and modeled pumpage from the Memphis aquifer and Fort Pillow aquifer in the Memphis area, 1886-1985.

model was calibrated by simulating the stress periods from 1886-1980, a time interval during which flow in both the Memphis and Fort Pillow aquifers was thought to be transient. Calibration was concentrated on stress periods from 1961 to 1980. Ground-water conditions were transient in both the Fort Pillow and the Memphis aquifers during the period 1961 to 1980, whereas conditions in the shallow aquifer were thought to be at steady state. It should be noted that water-level and pumping data exist for the entire period of development of the Memphis aquifers; the early data are sparse, however, and are less well documented than data collected after 1960.

An enlarged view of part of the model grid in the Memphis study area, including locations simulated as major centers of pumping, is shown in figure 25.

The strategy for calibration was dictated by the availability of data, and in partcular, by availability of detailed water levels and pumping information for specified wells. In general, there is a wealth of water-level and pumpage data for the Memphis and Fort Pillow aquifers since 1960. There are many records that are adequate for general interpretation for the period 1924 to 1960, but prior to 1924, there are few reliable records at all.

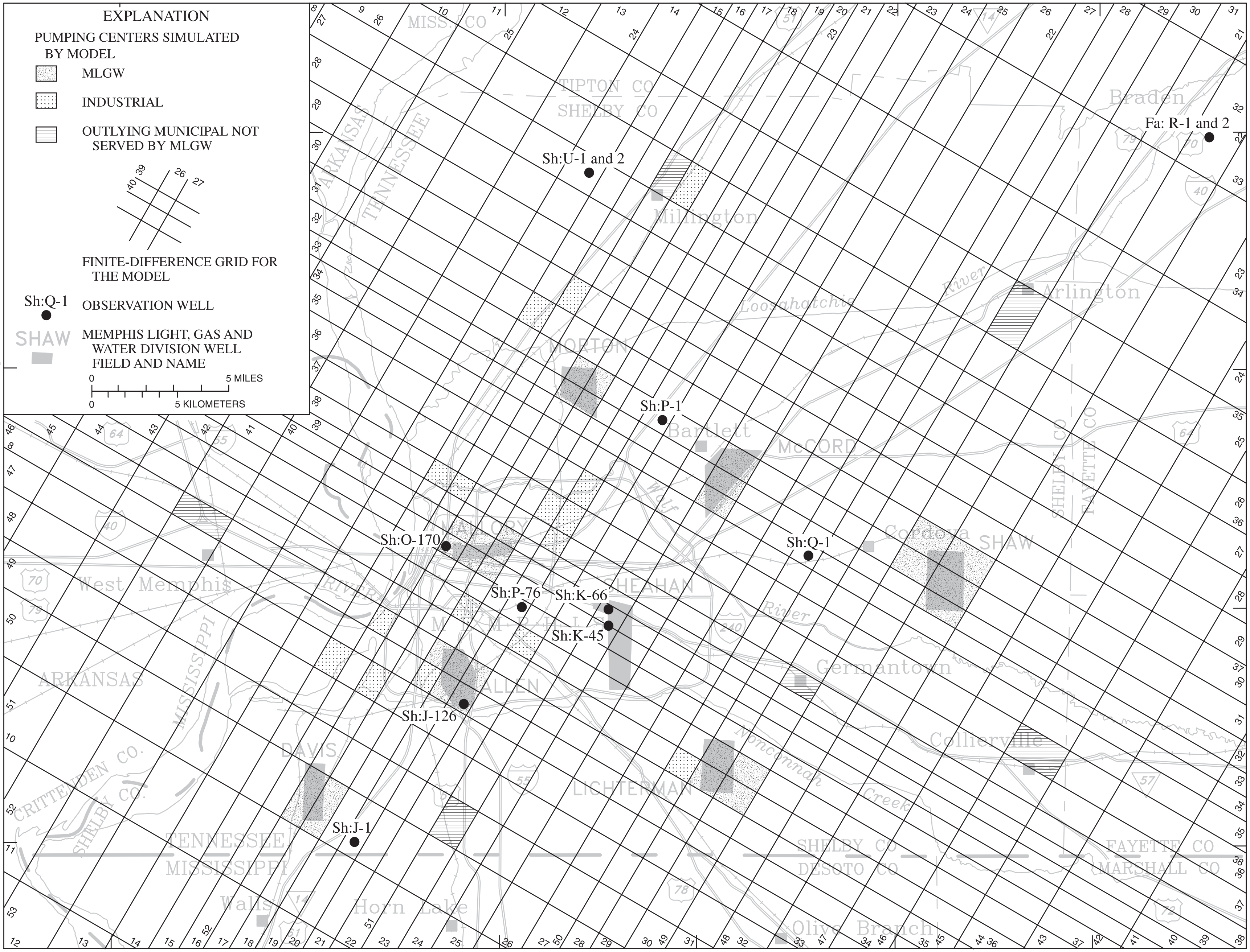
For example, the prepumping (1886) potentiometric surface of the Memphis aquifer is based on four data points (Criner and Parks, 1976), all of which were extrapolated (fig. 16). Data points for the Fort Pillow aquifer in the Memphis area likewise are lacking for this period. Because of this data, no formal steady-state calibration to these few prepumping data was attempted, although the match of prepumping conditions by removing pumping from the calibrated model (transient) provided a reasonable match with the estimated maps.

The completeness and documentation of the data base for conditions after 1960 justified using this data as the major tool of calibration. The transient simulation from 1961 to 1980 was completed using four 5-year pumping periods (fig. 24) of 10 time-steps each. Seasonal fluctuations in water levels were averaged to give a single annual value. The model was calibrated by minimizing the difference between model simulated heads and measured heads (Criner and Parks, 1976; Graham, 1982). In addition, differences between hydrographs of observed and simulated water levels at long-term observation wells were minimized.

Calibration was continued by adjusting the global multiplier of transmissivity, vertical conductance, and storage coefficients of the Memphis and Fort Pillow aquifers and their confining units until the sum of the squared differences between observed and calculated heads was minimized. Individual hydraulic data for nodes was adjusted only if geologic or hydrologic justification warranted such a change. Calibrated values for hydraulic properties were within the range determined by aquifer tests (table 2) and those estimated from published values of similar geologic materials (Schneider and Cushing, 1948; Criner, Sun, and Nyman, 1964; Halberg and Reed, 1964; Bell and Nyman, 1968; Boswell and others, 1968; Hosman and others, 1968; Cushing and others, 1970; Newcome, 1971; Reed, 1972; Parks and Carmichael, 1989a and b).

Data collected from the period 1886 to 1960 were used to make minor adjustments to parameters during calibration (fig. 24). These data were less well defined than post-1960 data, and in some instances, were essentially undocumented. As an example, major uncertainty exists about water levels and discharge from the Auction Avenue "tunnel," a major source of municipal supply that was used from about 1906 to about 1924. The Auction Avenue "tunnel" was a collector tunnel for some early wells screened in the Memphis aquifer (Criner and Parks, 1976, p. 13). According to Criner and Parks (1976): "...little is known about the tunnel (Auction Avenue "tunnel"), but it is reported to have been constructed in a clay layer, about 85 feet below land surface and below the potentiometric surface of the Memphis aquifer. The tunnel was reported to be brick-lined, about 5 feet in diameter, and about one-quarter mile in length. Several wells were completed along the tunnel and constructed so that water would flow into the tunnel through underground outlets. Water was pumped into the city supply system from a large well, 40 feet in diameter, at the end of the tunnel at Auction Avenue Station." Inasmuch as this and other dominant withdrawals during the period 1886-1924 were not well defined, little emphasis was given to calibrating the model using older data.

An important model calibration and testing criterion was an error analysis of simulated and observed water levels at the nodes representing the control points. The root mean square error (RMSE) was used to judge how closely the simulation matched "reality," which was defined by a network of observation wells (Criner and Parks, 1976, fig. 1). The root mean square error was calculated as a measure of the difference between model-calculated heads and observed heads.



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

Figure 25. Finite-difference grid in the Memphis study area showing location of pumping nodes and selected observation wells.

The root mean square error is described by the equation:

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{\langle H_i^C - H_i^O \rangle^2}{n}}$$

where

RMSE is the root mean square error;

H^C is calculated head, in feet, at a model node;

H^O is observed head, in feet;

n is the number of comparison points;

i is a subscript that defines any specific comparison point, varying between 1 and *n*.

Another criterion was the comparison made between observed and simulated hydrographs. Records from four wells from the Memphis aquifer and two wells from the Fort Pillow aquifer were of sufficient duration to provide reasonable comparisons (fig. 28). Locations of the wells from which the comparisons were made are shown on figure 25. For the most part, the observed and simulated hydrographs agree closely.

The results of the calibration are shown in figures 26, 27, and 28. A comparison of observed data points and simulated potentiometric surface of the Memphis aquifer is shown in figure 26; a similar map for the Fort Pillow aquifer is shown in figure 27. Hydrographs of observed and simulated water levels for selected wells are compared in figure 28.

The simulated potentiometric surfaces match the observed data points reasonably well for both aquifers at the end of the calibration period, stress period 8 (figs. 26 and 27). Likewise, interpretive maps contoured from the observed data (figs. 7 and 9) are similar to simulated potentiometric surfaces. Stress periods 4 through 7 simulated observed water levels as well or better than stress period 8, but because of their similarities to one another, have not been included as figures.

In addition to the areal match of water-level data, simulated and observed water levels agree closely through time for selected hydrographs (fig. 28). Variations are thought to be due to errors in the amount and distribution of pumping, particularly prior to 1960, when pumping was not accurately monitored.

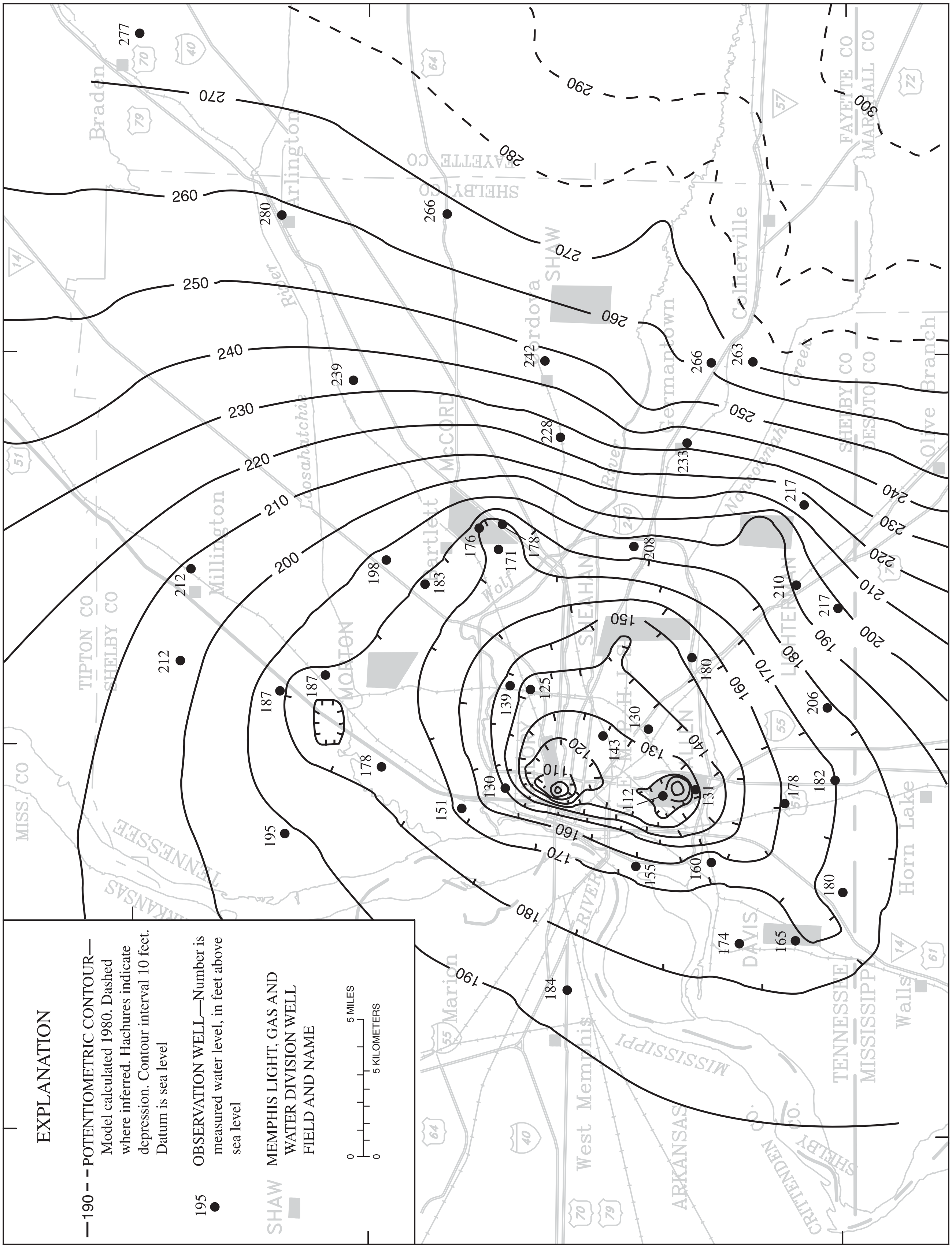
Although the overall simulation of heads in the Memphis aquifer is considered to be good, heads matched poorly in one subarea lying near Nonconnah Creek and the Tennessee-Mississippi border in south Memphis (figs. 26 and 7). Many alternative representations of transmissivity, leakage, and recharge were attempted, but their effect on heads outside the problem area created more problems with overall simulation than they solved with improved subarea simulation. Hydrogeologic data from this area suggest that the model does not contain all relevant hydraulic or boundary conditions; any model application to this subarea should be undertaken with extreme caution. There is no doubt that this subarea is a source of significant recharge to the Memphis aquifer. The quantity and location of the concentrated recharge in this area as indicated by the model may be subject to error and the descriptions of these factors in this report should be considered tentative at best.

It is common in reports documenting ground-water flow models to evaluate average ground-water discharge to streams with calculated flux from the model. Inasmuch as the Mississippi River and its tributaries dominated the ground-water flow, and inasmuch as simulation of the shallow aquifer was outside the scope of this report, no attempt was made to include this comparison. Discharge to streams was not undertaken in this study because:

1. Flow in the Mississippi River was four to five orders of magnitude greater than ground-water inflow rates to streams, thereby masking the inflow component;
2. Grid dimensions for the outcrop areas of the Memphis aquifer and Fort Pillow aquifer were large. Simulation of streams in these large blocks required estimations that were poorly quantified;
3. No aquifer hydraulic tests were reported for the fluvial deposits; and
4. Direct simulation of flow in the water-table aquifer was outside the scope of the investigation.

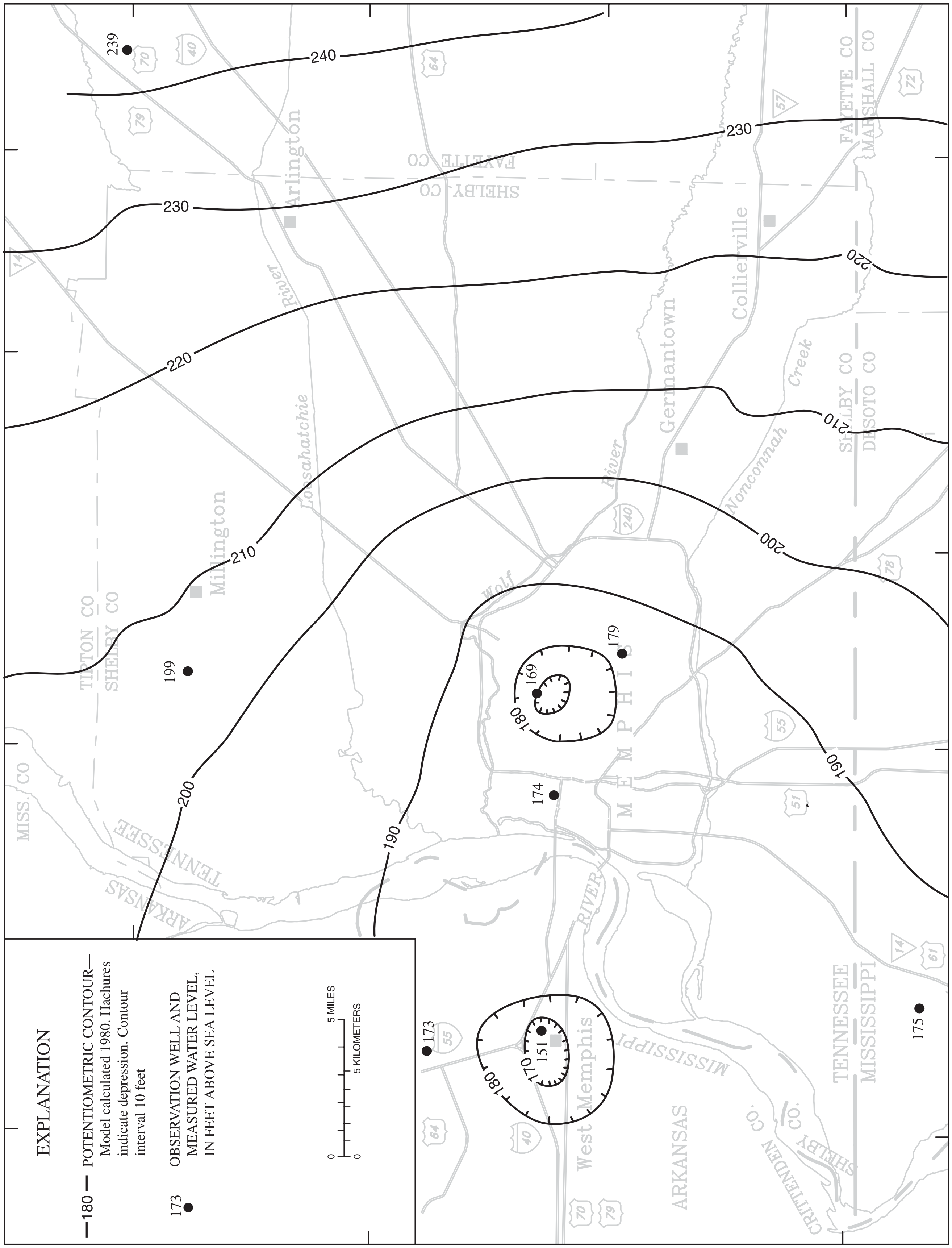
Model Testing

After calibration, the model was tested to determine its ability to simulate observed water levels for the period 1981-85 (fig. 24). For this testing phase, no modification of boundary conditions or calibrated data was made. In this testing phase, the flow model simulated heads in the Fort Pillow aquifer and Memphis aquifer within 5 feet of observed water levels for at least 75 percent of the observation wells (this comparison used interpolated values rather than root mean square error values). These results increase confidence that the model accurately simulates ground-water flow in the study area. The additional criteria used to evaluate the calibration phase also were used to judge the accuracy of the simulated results for this testing phase.



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

Figure 26. Comparison of observed water levels and model-computed potentiometric surface of the Memphis aquifer, Memphis area, 1980.



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

Figure 27. Comparison of observed water levels and model-computed potentiometric surface of the Fort Pillow aquifer, Memphis area, 1980.

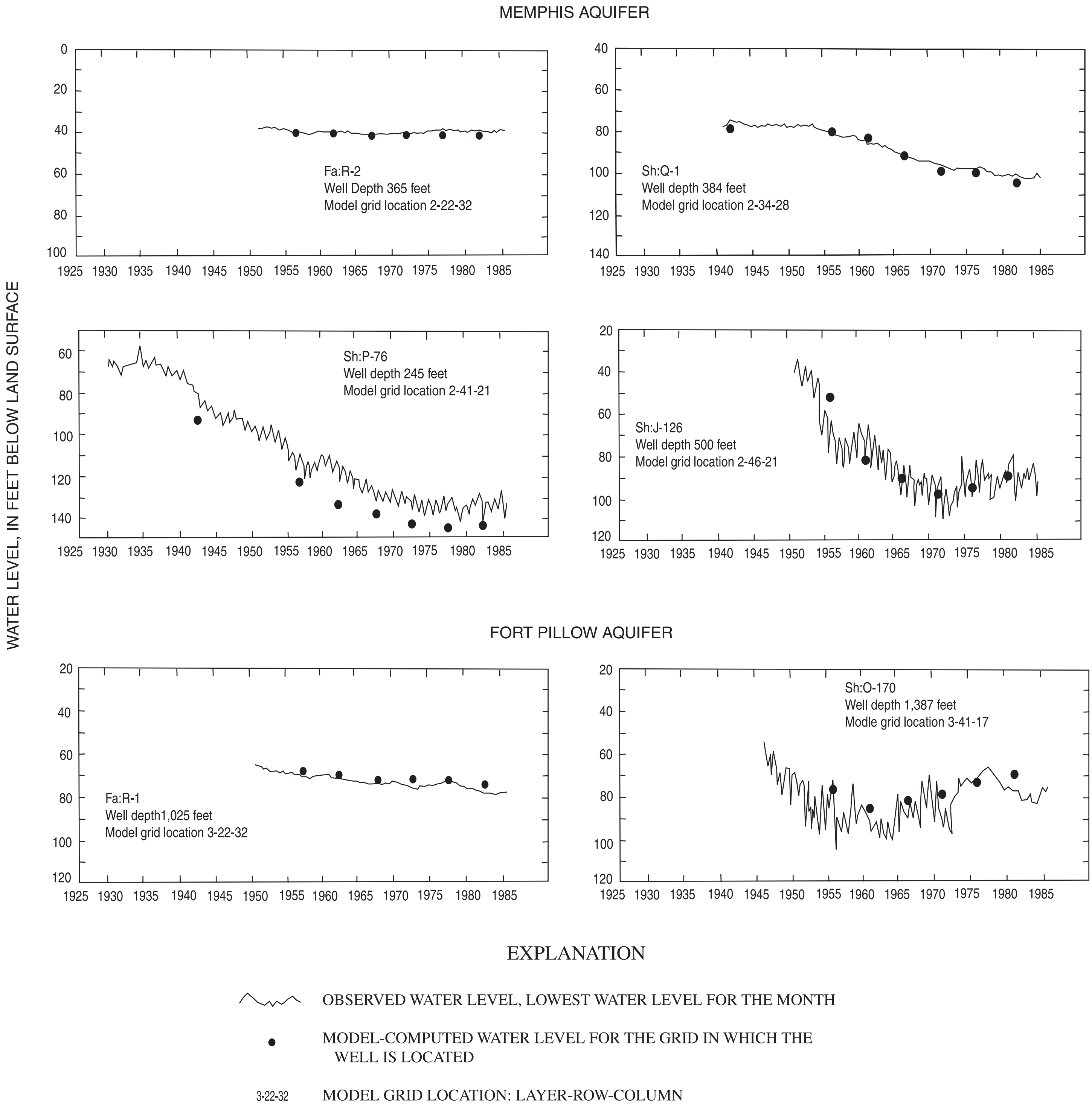


Figure 28. Selected hydrographs of observed and model-computed water levels for wells in the Memphis and Fort Pillow aquifers in the Memphis area.

Sensitivity Analysis

The response of the calibrated model to variations in model parameters, pumping, and boundary conditions was evaluated by sensitivity analysis. Transmissivity and storage of the Memphis and Fort Pillow aquifers, and leakance for the Jackson-upper Claiborne and Flour Island confining units were each varied uniformly in the model while the other parameters were kept constant. The subsequent effects of these variations on calculated water levels in the Memphis and Fort Pillow aquifers were evaluated by root mean square error (*RMSE*) comparison of observed and simulated water levels for 1980. Results of the sensitivity analyses are illustrated in figures 29 and 30 for the Memphis aquifer and the Fort Pillow aquifer, respectively.

The *RMSE* was 14 feet for the Memphis aquifer and about 10 feet for the Fort Pillow aquifer. These values, on initial evaluation, appear to define very poor simulation of a system. The data set that was used to generate the *RMSE* value, however, was treated in a nontraditional manner, and the values generated should be considered relative rankings rather than absolute measures of goodness-of-fit.

The data set for *RMSE* comparisons included all known observed water levels for the period of interest. Typically, for pumping periods 4 through 9 (fig. 24) occurring after 1955, the data set included more than 100 points. For pumping period 8, on which figures 29 and 30 are based, 129 comparison points were used. Many of the observation wells did not occur at the center of a model node, but fell near boundaries of adjacent nodes. Rather than interpolate an observed value to the nearest nodal center, the actual measurement was compared to the simulated head at the surrounding nodes typically either the two nearest if on a boundary, or the four nearest if on a corner. Because of the steep gradients associated with pumping, a large difference in head frequently occurred for such comparisons (one typically higher, one typically lower), giving rise to a large *RMSE* when in fact an interpolation of simulated conditions matched observed conditions closely.

Results of the sensitivity analysis showed that calculated heads in the Memphis aquifer were most sensitive to variations in aquifer transmissivity and leakance of confining unit A, and least sensitive to storativity (fig. 29). Calculated heads in the Memphis aquifer were not responsive to changes in the aquifer characteristics of the Fort Pillow aquifer. Calculated heads in the Fort Pillow aquifer were most sensitive to transmissivity, and least sensitive to leakance of the Flour Island confining unit and storativity (fig. 30). As a general rule, calculated heads in the Fort Pillow aquifer were insensitive to general changes in aquifer characteristics of the Memphis aquifer. Because of the dominating effect of the pumping stress in the Memphis aquifer, calculated heads in the Fort Pillow aquifer were sensitive to factors affecting recharge and leakage to the Memphis aquifer. Although not shown in the figures, variations in simulated pumping caused large variations in calculated heads in the aquifers. Changes in simulating the southern boundary of the model 20 miles closer and 20 miles farther from Memphis caused only very slight changes in calculated heads from calibrated values.

These results suggest that the values used in the calibrated model are reasonable approximations of actual conditions within the aquifer, particularly in light of the constraints made by the well-defined pumping data and the well-defined potentiometric surfaces. The high sensitivity of leakance of the Jackson-upper Claiborne confining unit with respect to simulated heads in the Memphis aquifer gives confidence that an otherwise poorly defined parameter is well approximated in the model.

Interpretation of Model Results

The underlying objective of ground-water flow modeling was to develop a tool to quantitatively assess the hydrogeology of the Memphis area, and thereby improve understanding of the factors affecting ground-water flow. Digital simulation of ground-water flow permitted a quantitative evaluation of flux across hydrogeologic boundaries and calculation of a hydrologic budget. Interpretation of these results promotes a more complete understanding of the flow system and often has direct implications for resource management.

Hydrologic Budget

One of the principal products of the digital model is a hydrologic budget for each layer in which ground-water flow is simulated. For a given stress period, the model calculates the simulated volume of water that was added to or removed from the layer. Flow rates are also calculated. Because pumpage was variable in space and time throughout the simulation, components of the hydrologic budget were not

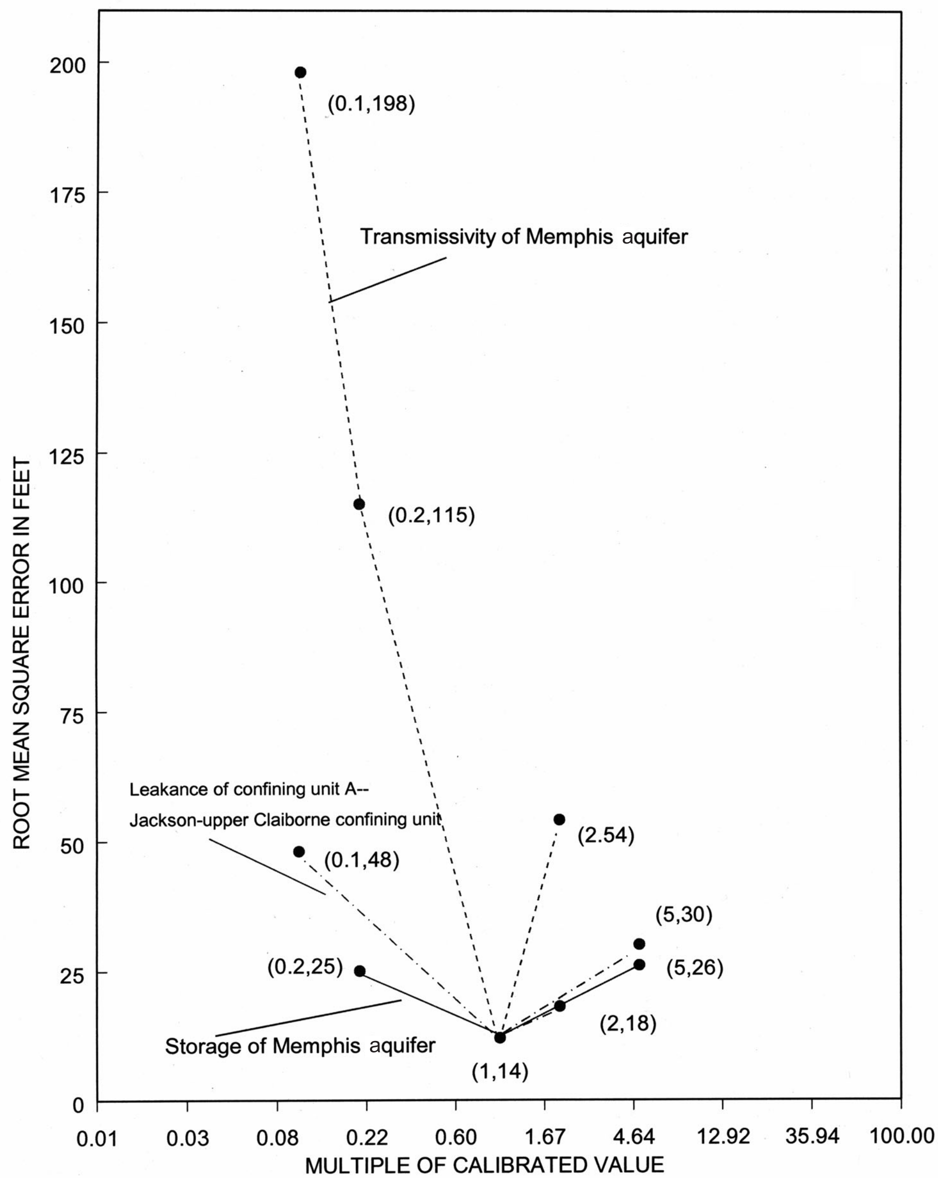


Figure 29. Relation between changes in magnitude of calibrated input (1980) parameters and root mean square error between observed and simulated water levels in the Memphis aquifer.

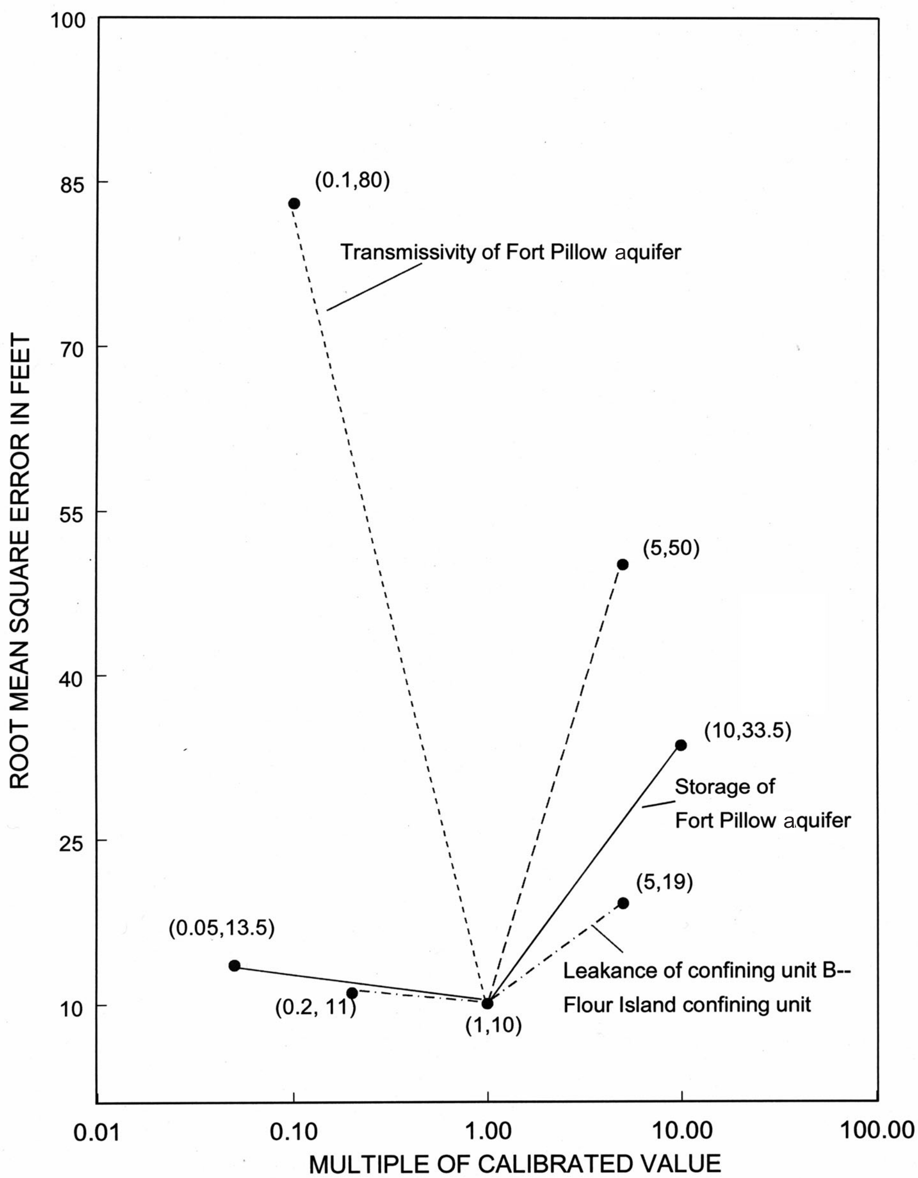


Figure 30. Relation between changes in magnitude of calibrated input (1980) parameters and root mean square error between observed and simulated water levels in the Fort Pillow aquifer.

constant. The budget figures for 1980 are presented in table 4.

Pumpage accounted for almost all of the total discharge from the Memphis aquifer (table 4). Model simulations indicated pumped water was replaced from three sources: recharge and lateral inflow (42 percent), leakage from the shallow aquifer (54 percent), leakage from the deep aquifer (1 percent), and storage (3 percent). Lateral inflow refers to the essentially horizontal movement of water within the aquifer; the ultimate source of this water is recharge in the outcrop area.

Leakage to the Memphis aquifer occurred both from the surficial aquifers and the Fort Pillow aquifer. As water-levels in the Memphis aquifer declined in response to pumpage, hydraulic gradients favored the flow of water across the overlying and underlying confining units. Approximately 98 percent of the simulated leakage to the Memphis aquifer was attributable to flow across the Jackson-upper Claiborne confining unit. In 1980, this leakage from water-table aquifers contributed more than 50 percent of the water pumped from the Memphis aquifer. Because water in the water-table aquifers is inferior in quality and more susceptible to contamination than water in the Memphis aquifer, this substantial contribution may be cause for concern. The third source of water pumped from the Memphis aquifer was storage, which refers to water made available by compression of the aquifer and expansion of the water column. Storage contributes a minor part (3 percent) of the budget of the Memphis aquifer, based on simulation of 1980 conditions.

The hydrologic budget for the Fort Pillow aquifer in 1980 also is defined in table 4. Water was removed from this aquifer both by pumpage (88 percent) and leakage to the Memphis aquifer (12 percent). Most of the water removed from this aquifer was derived from recharge and lateral inflow (87 percent). About 13 percent of the water was derived from storage.

Areal Distribution of Leakage

Downward leakage from the water-table aquifer through the Jackson-upper Claiborne confining unit to the Memphis aquifer poses a potential threat to the quality of water used for public supply in the Memphis area. To facilitate management and protection of this resource, it is important to identify those areas where leakage is most significant.

In the flow simulation, a small amount of downward leakage to the Memphis aquifer occurred throughout the study area. In certain zones, however, leakage was more pronounced (fig. 31). In most places leakage did not exceed 0.01 cubic feet per second per square mile, which is equivalent to an infiltration velocity of 0.14 inch per year (in/yr). Near the outcrop area and around Lichterman well field in southeastern Memphis, there was a zone in which leakage was greater than other areas. Near the outcrop area, leakage rates varied from 0.01 to 0.1 cubic feet per second per square mile, which is equivalent to an infiltration velocity of 0.14 to 1.4 in/yr. In this zone the confining unit is known to be relatively thin (fig. 5).

Simulated leakage rates were substantially higher in several other locations, as well. These locations included: (1) Johns Creek, Nonconnah Creek, and the South Sheahan area (fig. 31, area 1); (2) the Wolf River between Sheahan and McCord well fields (fig. 31, area 2); (3) along the Mississippi River near Mallory well field (fig. 31, area 3); and (4) a zone east of Lichterman well field (fig. 31, area 4). The large leakage rates indicated by the simulation agree with other evidence supporting substantial flow between the surficial aquifers and the Memphis aquifer at these locations. Other evidence includes isotopic data, water-level measurements, and thermal anomalies (Graham and Parks, 1986).

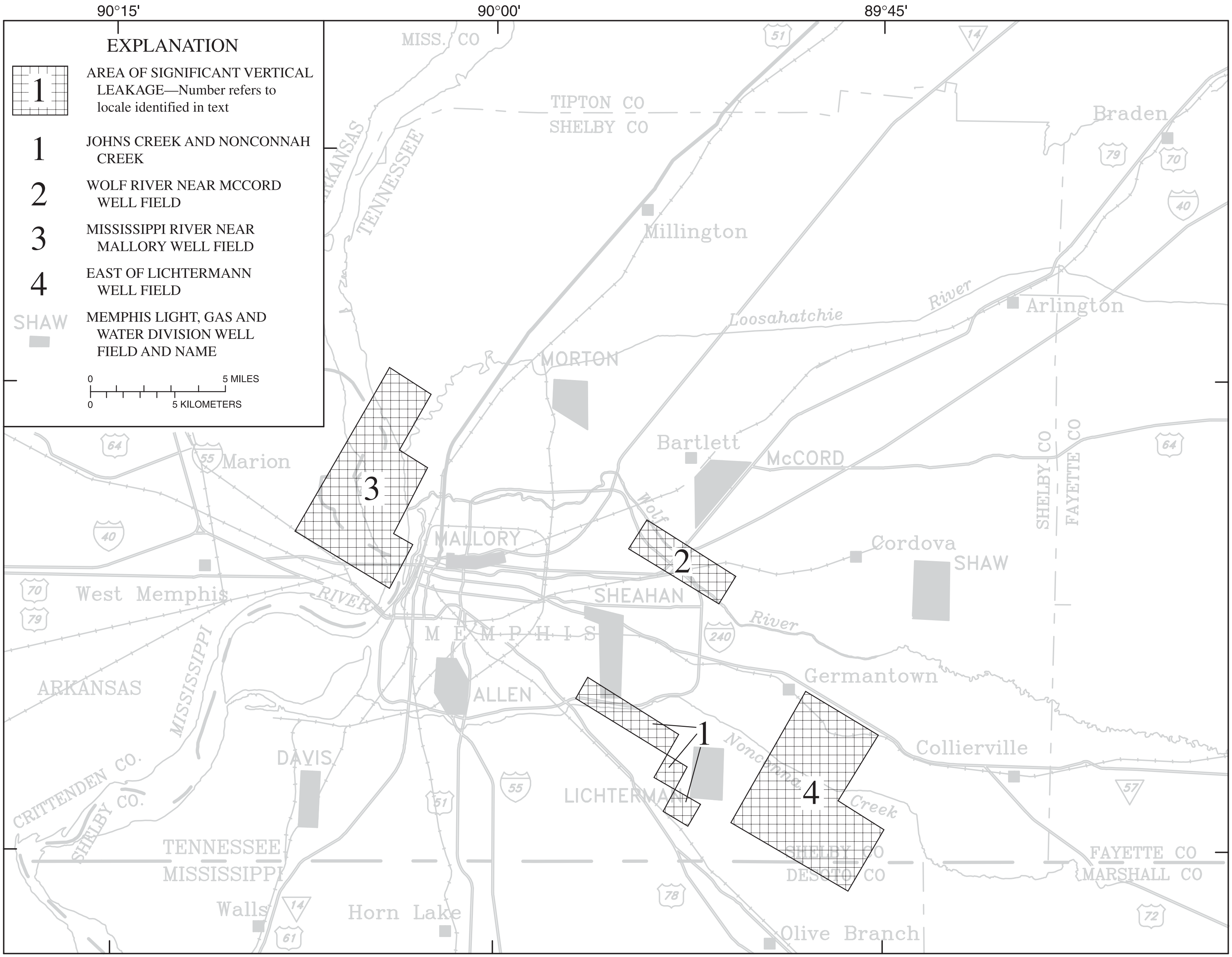
Model Limitations

Models by their very nature are only approximations, and are not exact replicas of natural systems. The success of a model in approximating the natural system is limited by such factors as scale, inaccuracies in estimating hydraulic characteristics and stresses, inaccurate or poorly defined boundary or initial conditions, and the degree of violation of flow-modeling assumptions (P. Tucci, U.S. Geological Survey, written commun., 1988).

For example, the minimum grid block size for this model is about 0.45 mi^2, an area much too large to simulate ground-water levels in individual wells. The model was neither designed for nor should it be used for site-specific applications. It was designed for intermediate to regional evaluation of "average" transient ground-water conditions within the Memphis area, and within this application, the model has been shown to simulate observed conditions to a reasonable degree of accuracy.

Table 4. Water budget calculated by the flow model, 1980, for the Memphis area

Sources and discharges	Flow, in cublc feet per second	Percentage of total
	Memphis Aquifer	
Sources:		
Recharge	106	36
Boundary flux	17	6
Leakage from shallow aquifer	157	54
Leakage from deep aquifer	2	1
Storage	10	3
Total	292	100
Discharge:		
Boundary flux out	3	1
Pumping	289	99
Leakage (net in)	0	0
Total	292	100
	Fort Pillow Aquifer	
Sources:		
Recharge	*5*	31
Boundary flux in	9	56
Leakage from Memphis aquifer	0	0
Storage	2	13
Total	16	100
Discharge:		
Boundary flux out	0	0
Pumping	14	88
Leakage to Memphis aquifer	2	12
Total	16	100



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

Figure 31. Areas of significant vertical leakage in the Memphis area as determined by model calculations.

Selection of model boundary conditions can greatly influence model results. Model boundaries should closely correspond to natural hydrologic boundaries whenever possible (E. Weeks, U.S. Geological Survey, written commun., 1975), and, with the exception of the southern boundary, this concept was a guiding approach that was followed in this (figs. 14 and 15) and previous models of the area (Brahana, 1982a, fig. 5). The variable spacing of the grid, however, has the potential of introducing "average" approximations within the larger grid cells (the largest are about 8 mi^2) that are significantly different than actual conditions. For example, representation of hydrologic features such as divides or drains is difficult in large grid cells, because the feature represents only a small percentage of the total area of the cell. For this reason, any but regional interpretations regarding head and flow in grid cells larger than several square miles should be avoided, and, as with the actual development of the model, emphasis should be limited to the Memphis study area.

Continuing reassessment will be very important in the evolution of the model. As ongoing studies fill the gaps in the data base and improve understanding of this complex flow system, the model can be modified and recalibrated to include those changes. Newly developed techniques of aquifer parameter estimation would be particularly useful as an aid to understanding the system, as would an optimization model (Larson and others, 1977; Lefkoff and Gorelick, 1987). Though the USGS does not develop them, an optimization model might be useful to resource managers in evaluating placement of future well fields and pumping configurations.

Despite the limitations discussed in this section, the model provided useful insights into the workings of the hydrologic system of the study area. Model results support the conceptual model of the ground-water flow system that the Memphis aquifer and Fort Pillow aquifer are partially isolated by the Flour Island confining unit. Leakage between aquifer layers represents a large component of the hydrologic budget (table 4), and if the model is to be used for predictive purposes using pumping configurations with locations significantly different than those tested for the calibration and validation phases, simulated results may vary from measured results. Extreme caution is recommended in interpreting results in such simulations.

SUMMARY AND CONCLUSIONS

The Memphis area has a plentiful supply of ground water suitable for most uses, but the resource may be vulnerable to contamination. Current withdrawals totalling about 200 million gallons per day have caused water-level declines in the major aquifers, increasing the potential for contaminated ground water in the surficial aquifer downward into the major aquifers. This study describes the hydrologic framework, simplifies and conceptualizes the hydrogeologic system to preserve and emphasize the major elements controlling ground-water flow, and quantitatively tests each of the major elements. The main tool for the investigation is a digital ground-water flow model; the ultimate objective of the study is an improved understanding of the factors affecting ground-water flow in the Memphis area.

The hydrogeologic framework of the area consists of approximately 3,000 feet of unconsolidated sediments that fill a regional downwarped trough, the Mississippi embayment. For the most part, the sediments are interbedded clays and sands, with varying amounts of silt, gravel, chalk, and lignite present. On a regional scale, the sediments form a sequence of nearly parallel, sheetlike layers of similar lithology. On a local scale, complex lateral and vertical gradations in lithology are common.

Clays of the Owl Creek Formation, Clayton Formation, Porters Creek Clay, and Old Breastworks Formation effectively define the base of freshwater aquifers. Overlying this base, the hydrogeologic framework includes the Fort Pillow Sand, the Flour Island Formation, the Memphis Sand, the Jackson Formation and upper part of the Claiborne Group, and alluvial and fluvial deposits.

Ground-water flow in this framework of aquifers (sands and gravels) and confining units (clays) is controlled by the altitude and location of sources of recharge and discharge, and by the hydraulic characteristics of the hydrogeologic units. Leakage between the Fort Pillow aquifer (Fort Pillow Sand) and Memphis aquifer (Memphis Sand), and between the Memphis aquifer and the shallow aquifer (alluvium and fluvial deposits) is a major component of the hydrologic budget. Pumping from the Fort Pillow and Memphis aquifers has significantly affected flow in these aquifers in the study area. Net discharge to the Mississippi River alluvial plain from the subcropping Fort Pillow and Memphis aquifers has decreased or ceased since predevelopment time; pumpage has captured most of present-day flow by lowering potentiometric surfaces. The shallow surficial aquifer has not been pumped intensively (<1 Mgal/d), and with the exception of one limited area, is thought to have remained at steady state throughout the period of evaluation.

A three-layer finite-difference flow model was constructed to simulate the regional flow system in the Memphis area. The model area was much larger than the area of immediate concern, so that natural boundaries of the aquifers could be incorporated. Initial conditions, boundary conditions, hydraulic characteristics, and stresses were input values into 58 row by 44 column matrices. The model calculated heads and hydrologic budgets. In the model, the uppermost aquifer layer represents the shallow aquifer. Flow within the shallow aquifer was not simulated; rather, the layer consisted of an array of constant-head nodes representing water levels at steady state during any given stress period. The second and third layers represent the Memphis aquifer and Fort Pillow aquifer, respectively, where horizontal flow was simulated. Layers of the model are separated by leaky confining units. These units are depicted by arrays of leakance terms. Leakance values are high in areas where confining units are thin or absent, and are low in areas where the confining units are thick and hydraulically tight. The model was calibrated and tested using standard accepted practices of the U.S. Geological Survey.

This study has provided an improved understanding of the hydrogeology and ground-water flow in the Memphis and the Fort Pillow aquifers in the Memphis area. Calibration and validation of a multilayer finite-difference flow model indicated that leakage through the upper confining layer was a significant part of the hydrologic budget of the Memphis aquifer. The model attributes more than 50 percent of water withdrawn from this aquifer in 1980 to leakage. Although a significant portion of this leakage occurs near the outcrop area where the confining unit is thin, the implications for the Memphis aquifer remain the same. The potential exists for contamination of the Memphis aquifer in areas where surficial aquifers are contaminated and head gradients favor downward leakage.

Leakage was not uniformly distributed. The assumption of zones of high leakage along the upper reaches of the Wolf and Loosahatchie Rivers, the upper reaches of Nonconnah Creek, and in the area of the surficial aquifer in the Mississippi River alluvial plain was essential in simulating observed water levels in the Memphis aquifer. Geologic and geophysical data from these suspected zones of leakage suggest relatively thin or sandy confining units. On a regional basis, simulated vertical leakage through the upper confining unit was almost an order of magnitude greater than leakage through the lower confining unit.

A significant component of flow (12 percent) from the Fort Pillow aquifer was calculated to occur in the form of upward leakage to the Memphis aquifer. This upward leakage generally was limited to areas near major pumping centers in the Memphis aquifer, where heads in the Memphis aquifer have been drawn significantly below heads in the Fort Pillow aquifer. Although the Fort Pillow aquifer is not capable of producing as much water as the Memphis aquifer for similar conditions, it is nonetheless a valuable resource throughout the area.

The multilayer finite-difference flow model is a valuable tool for hydrogeological research and resource management in the Memphis area. The model integrates boundary conditions as suggested by available information on the geology, hydrology, and water chemistry of the area; it can be updated as new data are collected.

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