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QUALITY OF WATER FROM FRESHWATER AQUIFERS AND PRINCIPAL WELL FIELDS IN THE MEMPHIS AREA, TENNESSEE

J.V. Brahana, W.S. Parks, and M.W. Gaydos

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DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
A-413 Federal Building
U.S. Courthouse
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CONVERSION FACTORS

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

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

Temperature in degrees Celcius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$°F = 1.8\ °C + 32$$

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 Mean Sea Level of 1929.

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ABSTRACT

Water from the freshwater aquifers in the Memphis area is suitable for most uses. Freshwater aquifers are the alluvium and fluvial (terrace) deposits of Quaternary age, the Memphis Sand and Fort Pillow Sand of Tertiary age, and the Ripley Formation and McNairy Sand of Cretaceous age. About 180 million gallons per day of freshwater are withdrawn from the Memphis Sand, primarily for municipal and industrial use; the Memphis Sand is the principal aquifer supplying the City of Memphis. The alluvium provides water for irrigation and some industrial uses, and the fluvial deposits provide water for domestic use in rural areas. The Fort Pillow Sand supplies water for some municipal and industrial uses. The Ripley-McNairy aquifer is not used as a source of water.

Water from the alluvium, fluvial deposits, and Memphis Sand is a calcium bicarbonate type, and water from the Fort Pillow Sand and Ripley-McNairy aquifer is a sodium bicarbonate type. Dissolved-solids concentrations are low in the Memphis Sand, with a median value of 83 milligrams per liter, and are high in the Ripley-McNairy aquifer with a value of about 1,000 milligrams per liter. Water is very soft in the Fort Pillow Sand with a median hardness value of 9 milligrams per liter as $CaCO_3$ and is very hard in the alluvium with a median value of 285 milligrams per liter. Iron concentrations are low in the fluvial deposits with a median value of 50 micrograms per liter and are high in the alluvium with a median value of 5,200 micrograms per liter. Temperature of the water generally increases with depth, ranging from 16.0 degrees Celsius in the alluvium and fluvial deposits to about 32.0 degrees Celsius in the Ripley-McNairy aquifer.

Water from the Memphis Sand at Memphis Light, Gas and Water Division well fields has very low mineralization. Median values are 79 milligrams per liter dissolved-solids concentrations, 56 milligrams per liter alkalinity as $CaCO_3$, 46 milligrams per liter hardness as $CaCO_3$, 4 milligrams per liter chloride, 3.5 milligrams per liter sulfate, and 600 micrograms per liter iron.

INTRODUCTION

The quality of water from the freshwater aquifers in the Memphis area varies between different aquifers and within the same aquifer. Freshwater aquifers, defined as having water with dissolved-solids concentrations of 1,000 milligrams per liter (mg/L) or less, include the alluvium, fluvial deposits, Memphis Sand, Fort Pillow Sand, and Ripley Formation and McNairy Sand. Of these freshwater units, the Memphis Sand is the most important.

Assessing water-quality changes in the Memphis Sand is important to anticipate increased treatment costs and to detect contamination. An increase in the current rate of withdrawal from the Memphis Sand could accelerate recharge by downward leakage from the near surface water-table aquifers--the alluvium and the fluvial deposits. In much of the area, hardness and concentrations of dissolved solids and iron are significantly higher in water from the water-table aquifers than from the Memphis

Sand. If significant amounts of water from the water-table aquifers enter the Memphis Sand, local water-quality degradation could occur. Additionally, a potential for contamination of water from the Memphis Sand exists in the vicinity of waste-disposal sites. Contaminants are present in the water-table aquifers at several abandoned dump sites that are known to contain hazardous waste (Parks and others, 1982; Graham, 1982).

Water-quality data used in this report have been obtained during a 55-year period. Some data, which are available but which were not considered "representative" of natural or uncontaminated water from the various aquifers, were not used in the compilation of tables 2 and 3. Consequently, the deletion of "nonrepresentative" data has introduced differences in ranges of constituent concentrations in this report as compared to those given in previous reports.

This investigation was conducted as a part of the continuing cooperative program between the City of Memphis, Memphis Light, Gas and Water Division (MLGW) and the U.S. Geological Survey to collect information concerning the ground-water hydrology and geology of the aquifers in the Memphis area. This program includes special studies to aid in the development, conservation, and protection of the ground-water resource.

Purpose and Scope

The purposes of this report are (1) to summarize data from U.S. Geological Survey and MLGW files to show the general water-quality characteristics of the natural, uncontaminated water in freshwater aquifers in the Memphis area, and (2) to summarize the range and median of selected constituents in water from the Memphis Sand at MLGW well fields.

Water samples were collected by the Survey and analyzed by MLGW for about 60 wells for this investigation. The tables and graphs were compiled from a data base of more than 1,000 analyses from several hundred wells. Most quality of ground-water data for the Memphis area are limited to the major constituents. Relatively few trace-constituent data have been collected. Concentrations of organic compounds in water have been determined mostly at or near waste-disposal sites.

Acknowledgments

Acknowledgments are due Messrs. P.P. Schuyler, Charles H. Pickel, and Billy C. Grimm, for their support of this study and for making available MLGW laboratory staff and facilities for performing water-quality analyses ; Messrs. James W. Murphrey and James H. Webb, who provided analyses of water from wells in the Memphis area and for analyses of water from MLGW well fields; and Mr. Fred P. Von Hofe, who was responsible for providing a tabulation of the many analyses from MLGW laboratory reports and for assisting in a review of MLGW and Survey analyses to detect changes in water quality or evidence of contamination.

Location and Size

The Memphis study area comprises about 1,500 square miles, measuring approximately 44 miles by 34 miles (fig. 1). It includes all of metropolitan Memphis and other urban and rural areas affected by pumping at Memphis. The area includes all of Shelby County and parts of Fayette and Tipton Counties, Tenn., DeSoto and Marshall Counties, Miss., and Crittenden and Mississippi Counties, Ark.

Previous Investigations

The hydrogeology of the aquifer systems in the Memphis area is described in reports by Safford (1890), Glenn (1906), Wells (1931, 1933), Kazmann (1944), Schneider and Cushing (1948), Criner and Armstrong (1958), Plebuch (1961), Criner and others (1964), Nyman (1965), and Bell and Nyman (1968). A series of potentiometric maps and a description of historic water-level changes and pumpage from the Memphis Sand and Fort Pillow Sand are included in Criner and Parks (1976). The configurations of the potentiometric surface in the Memphis Sand for 1978 and 1980 are shown in Graham (1979, 1982).

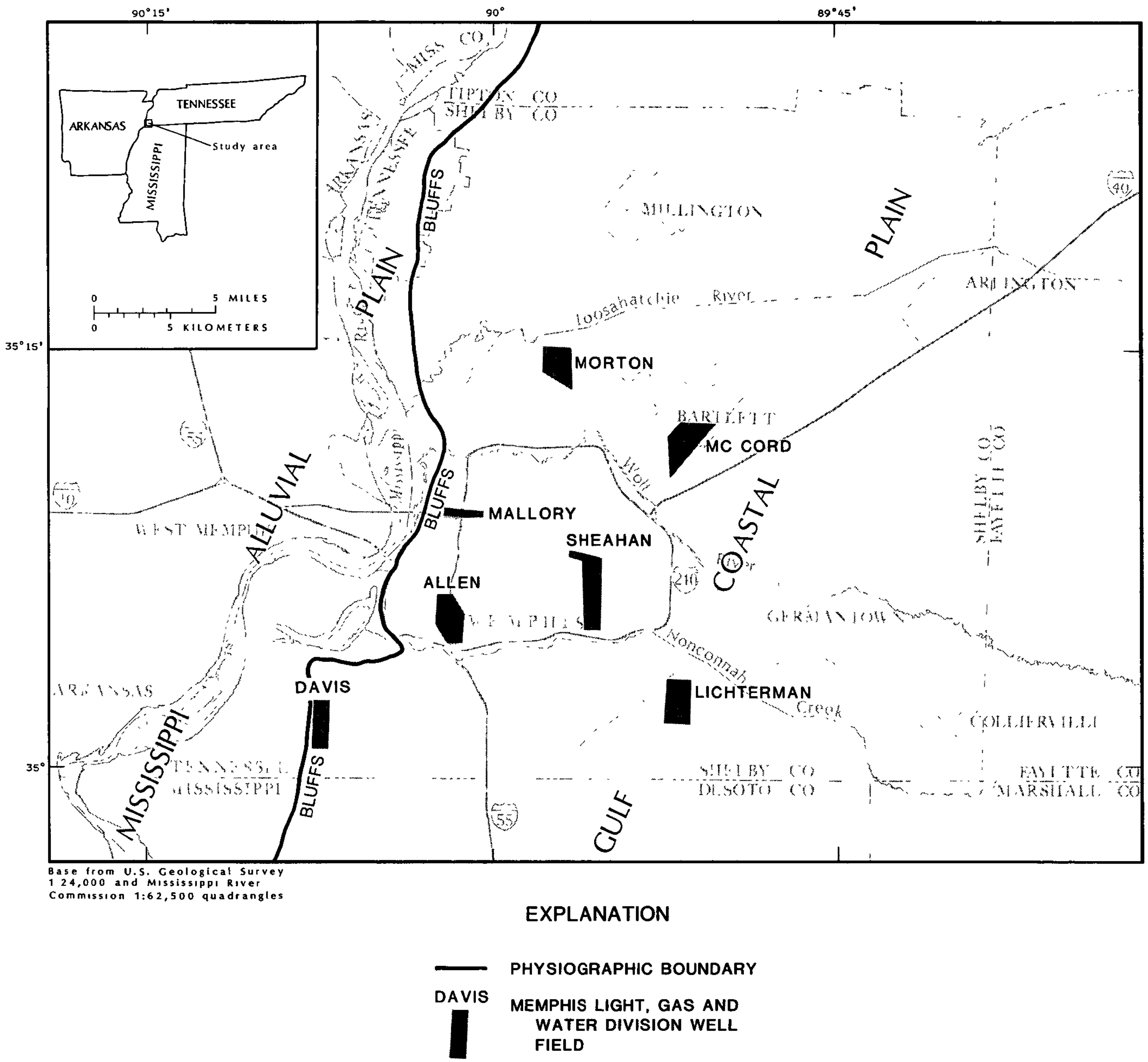


Figure 1.--Major physiographic subdivisions in the Memphis area and locations of Memphis Light, Gas and Water Division well fields.

Information concerning water quality in the aquifers in the Memphis area is in Wells (1933), Schneider and Cushing (1948), Lanphere (1955), Criner and Armstrong (1958), Plebuch (1961), Moore (1962), Criner and others (1964), and Bell and Nyman (1968). Parks (1973, 1974, 1975, 1977, 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. Graham and Parks (1986) made a detailed investigation of the potential for leakage among the principal aquifers in the Memphis area.

A two-dimemsional digital computer flow model of the Memphis Sand was described by Brahana (1982). The application of this model as a predictive tool to estimate aquifer response to various hypothetical pumpage projections was described by Brahana and included in the U.S. Army Corps of Engineers, Memphis Metropolitan Urban Area Water Resources Study (1981).

Regional reports concerning 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).

Physiographic Setting

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

The Gulf Coastal Plain in the Memphis area is characterized by gently rolling to steep topography formed as a result of the erosion of geologic formations of Tertiary and Quaternary age. During the later stages of Pleistocene glaciation, this topography was covered by a relatively thick blanket of loess that makes up the present land surface. Gently rolling to steep topography is broken at many places by the flat-lying alluvial plains of the streams that cross the area. Perhaps the most distinctive feature of the Gulf Coastal Plain is the loess-covered bluffs that rise abruptly above the Mississippi Alluvial Plain at its eastern boundary. Land-surface altitudes in the Gulf Coastal Plain are as low as 190 feet above National Geodetic Vertical Datum of 1929 (NGVD of 1929) at the mouth of Nonconnah Creek in southwestern Shelby County, Tenn., and are as high as 470 feet above NGVD of 1929 in southwestern Fayette County, Tenn. Maximum local relief between the Gulf Coastal Plain and the Mississippi Alluvial Plain is about 200 feet on the bluffs in northwestern Shelby County.

The Mississippi Alluvial Plain in the Memphis area is flat-lying and is characterized by features of fluvial deposition--point bars, abandoned channels, and natural levees. Land-surface altitudes are as low as 180 feet above NGVD of 1929 on the banks of the Mississippi River in extreme northwestern DeSoto County, Miss., and as high as 230 feet above NGVD of 1929 adjacent to the bluffs in southwestern Tipton County, Tenn. Maximum local relief is probably no more than 10 or 20 feet, except where the alluvial plain has been built up above flood levels by man-emplaced fill.

Hydrogeology

The Memphis area is located near the axis of the Mississippi embayment (fig. 2), a regionally downwarped trough of Paleozoic rock that is filled with as much as 3,000 feet of unconsolidated sediments--primarily sand, clay, silt, chalk, gravel, and lignite. A description of the post-Paleozoic geologic units in the Memphis area is given in table 1.

On a regional scale, the sediments occur in a sequence of nearly parallel layers that reflect

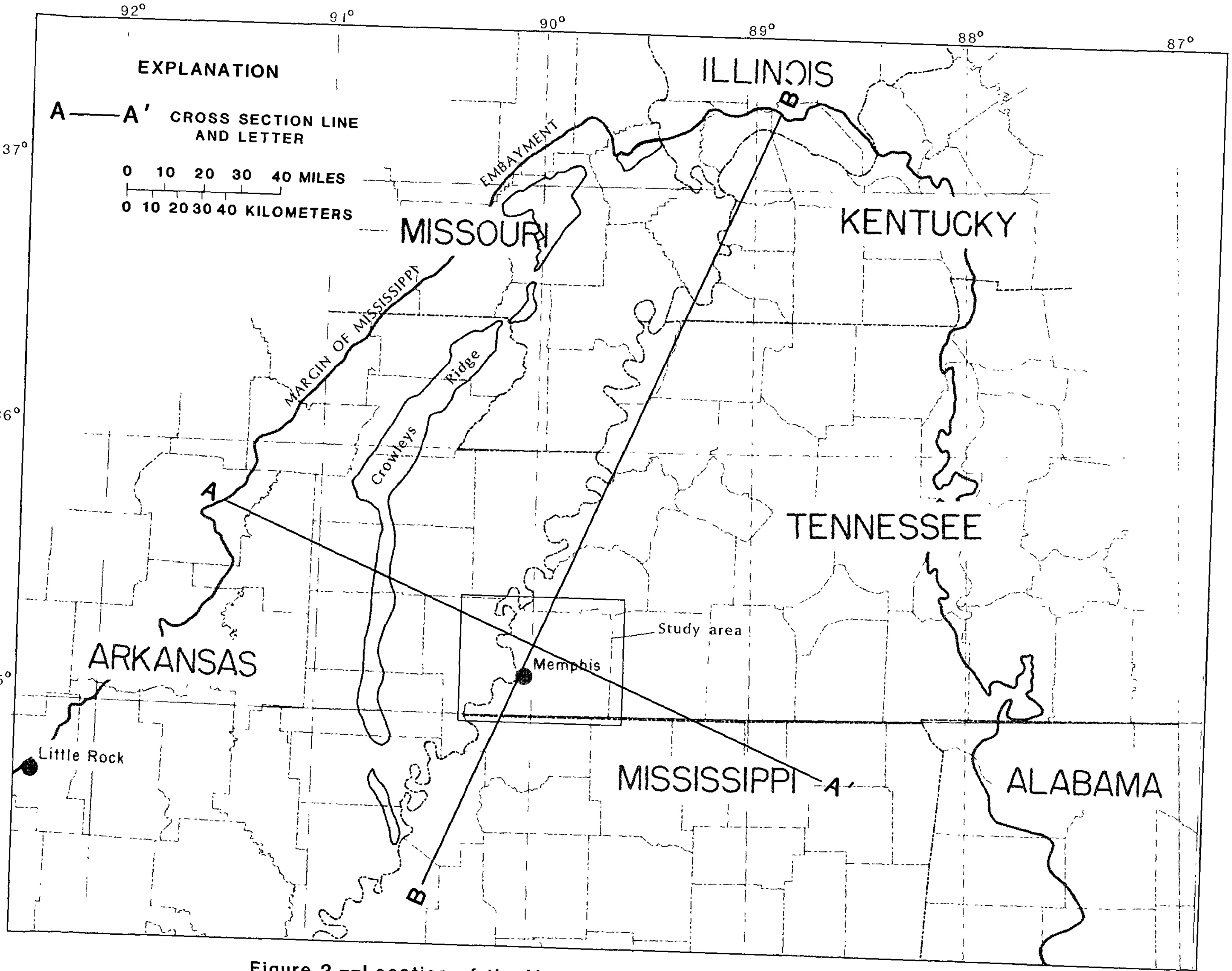


Figure 2.--Location of the Memphis area and hydrogeologic sections along lines A-A′ and B-B′ in the Mississippi embayment.

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

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

System	Series	Group	Stratigraphic unit	Thickness	Lithology and hydrologic significance
Quaternary	Holocene and Pleistocene		Alluvium	0-175	Sand, gravel, silt, and clay. Underlies the Mississippi Alluvial Plain and alluvial plains of streams in the Gulf Coastal Plain. Thickest beneath the Alluvial Plain, where commonly between 100 and 150 feet thick; generally less than 50 feet thick elsewhere. Provides water to farm, industrial, and irrigation wells in the Mississippi Alluvial Plain.
Quaternary	Pleistocene		Loess	0-65	Silt, silty clay, and minor sand. Principal unit at the surface in upland areas of the Gulf Coastal Plain. Thickest on the bluffs that border the Mississippi Alluvial Plain; thinner eastward from the bluffs. Tends to retard downward movement of water providing recharge to the fluvial deposits.
Quaternary and Tertiary(?)	Pleistocene and Pliocene(?)		Fluvial deposits (terrace deposits)	0-100	Sand, gravel, minor clay and ferruginous sandstone. Generally underlie the loess in upland areas, but are locally absent. Thickness varies greatly because of erosional surfaces at top and base. Provides water to many domestic and farm wells in rural areas.
Tertiary	Eocene	? / Claiborne	Jackson Formation and upper part of Claiborne Group ("capping clay")	0-370	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 Cockfield Formations, but locally the Cockfield may be overlain by the Jackson Formation. Serves as the upper confining unit for the Memphis Sand.
Tertiary	Eocene	Claiborne	Memphis Sand ("500-foot" sand)	500-890	Sand, clay, and minor lignite. Thick body of sand with lenses of clay at various stratigraphic horizons and minor lignite. Thickest in the southwestern part of the Memphis area; thinnest in the northeastern part. Principal aquifer providing water for municipal and industrial supplies east of the Mississippi River; sole source of water for the City of Memphis.
Tertiary	Eocene / ? / Paleocene	Wilcox	Flour Island Formation	190-310	Clay, silt, sand, and lignite. Consists primarily of silty clays and sandy silts with lenses and interbeds of fine sand and lignite. Serves as the lower confining unit for the Memphis Sand and the upper confining unit for the Fort Pillow Sand.
Tertiary	Paleocene	Wilcox	Fort Pillow Sand ("1400-foot" sand)	125-305	Sand with minor clay and lignite. Sand is fine to medium. Thickest in the southwestern part of the the Memphis area; thinnest in the northern and northeastern parts. Once the second principal aquifer supplying the City of Memphis; still used by an industry. Principal aquifer providing water for municipal and industrial supplies west of the Mississippi River.
Tertiary	Paleocene	Wilcox	Old Breastworks Formation	180-350	Clay, silt, sand, and lignite. Consists primarily of silty clays and clayey silts with lenses and interbeds of fine sand and lignite. Serves as the lower confining unit for the Fort Pillow Sand, along with the underlying Porters Creek Clay, Clayton Formation, and Owl Creek Formation.
Tertiary	Paleocene	Midway	Porters Creek Clay / ?	250-320	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.
Tertiary	Paleocene	Midway	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.
Cretaceous	Upper Cretaceous		Ripley Formation and McNairy Sand	360-570	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 noncalcareous 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.
Cretaceous	Upper Cretaceous		Coon Creek Formation	0-60	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.
Cretaceous	Upper Cretaceous		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 McNairy Sand and Coffee Sand.
Cretaceous	Upper Cretaceous		Coffee Sand	0-120	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.

the trough-like shape of the underlying Paleozoic rock. These layers of sediment, dipping slightly, about 10 to 35 feet per mile toward the axis of the embayment, are thicker in the south and southwest than in the outcrop areas to the north, west, and east (figs. 3-4).

Locally, lateral and vertical gradations (facies changes) occur within the sand and clay layers. These gradations along with variations in thickness and percentage of sand in the major clay layers (confining beds) are important because the clay layers control the interchange of ground water between the sand layers (aquifers). Areas where the confining beds are thin or sandy have high potential for vertical leakage and are possible pathways for contaminant migration.

WATER QUALITY IN THE FRESHWATER AQUIFERS

The freshwater aquifers in the Memphis area, from youngest to oldest, are: (1) alluvium, (2) fluvial deposits, (3) Memphis Sand, (4) Fort Pillow Sand, and (5) Ripley Formation and McNairy Sand (table 1) (figs. 3 and 4). Water supplies are obtained from each of these principal aquifers, except the Ripley and McNairy aquifer, although the amounts vary greatly.

Alluvium

Billions of gallons of water per day are provided to irrigation and industrial wells in Arkansas, Louisiana, Mississippi, and Missouri by the Mississippi River Valley alluvial aquifer. This aquifer is one of the largest sources of readily available ground water in the Mississippi embayment (Boswell and others, 1968).

Alluvium beneath the Mississippi Alluvial Plain supplies many irrigation and farm wells in the Arkansas and Mississippi parts of the Memphis area. The alluvium, however, is not used as a major source of ground water in the Tennessee part because of its limited area of occurrence, and the availibility of water of better quality from other aquifers. In Tennessee, the alluvium presently supplies a few industrial and some farm wells. The alluvium in the valleys of the Wolf River, Loosahatchie River, and Nonconnah Creek, is not a major source of water in the Memphis area; however, it does provide a source of recharge to the Memphis Sand.

The alluvium consists primarily of gravel, sand, silt, and clay. The clay is commonly rich in organic matter. In general, the upper part of the alluvium consists of fine sand, silt, and clay, and the lower part consists of sand and gravel. Beneath the Mississippi Alluvial Plain, the alluvium is commonly about 100 to 150 feet thick, but it is generally less than 50 feet thick beneath the alluvial plains of Wolf River, Loosahatchie River, and Nonconnah Creek.

Based on data from 11 wells in the alluvium of the Mississippi Alluvial Plain (fig. 1), water is a very hard (median--285 mg/L as $CaCO_3$), calcium bicarbonate type (table 2). In addition to hardness, high concentrations of iron, median--5,200 micrograms per liter (μg/L), limit the usefulness of the water for most purposes. Dissolved-solids concentrations were relatively low (median--314 mg/L); median water temperature observed was 16.5 degrees Celsius (°C). Trace-constituent data, available for only two of the 11 wells (table 3), show concentrations were below the Environmental Protection Agency (EPA) criteria for drinking-water supplies (U.S. Environmental Protection Agency, 1986b).

Water in the alluvium is susceptible to contamination. Several abandoned dumps, located on the alluvial plains of the Wolf River, Nonconnah Creek, and Big Creek, are known to contain hazardous waste (Parks and others, 1982). Dissolved-solids concentrations in water at the dump sites exceeded 500 mg/L; the maximum concentration was 2,620 mg/L. The median iron concentration of 15,000 μg/L at the dump sites was about three times the median concentration in natural water from the alluvium in the Mississippi River Alluvial Plain. Concentrations of arsenic, barium, and cadmium exceeded the EPA maximum contaminant levels for drinking-water standards at several sites. Pesticides detected included endrin, chlordane, DDT, heptachlor, and heptachlor epoxide (Parks and others, 1982).

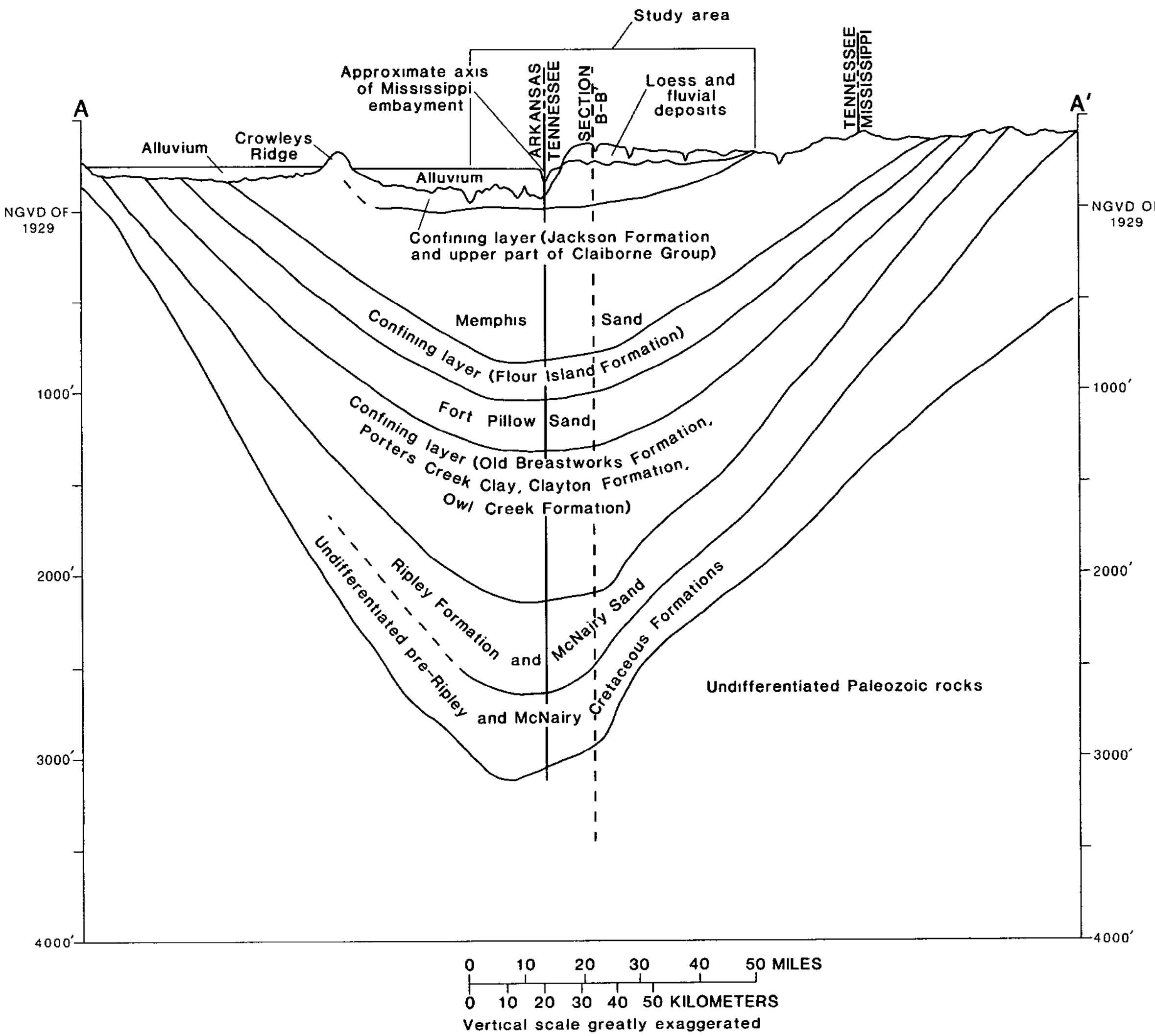


Figure 3.--Principal aquifers and confining layers, west to east, through the Mississippi embayment along line A-A'.

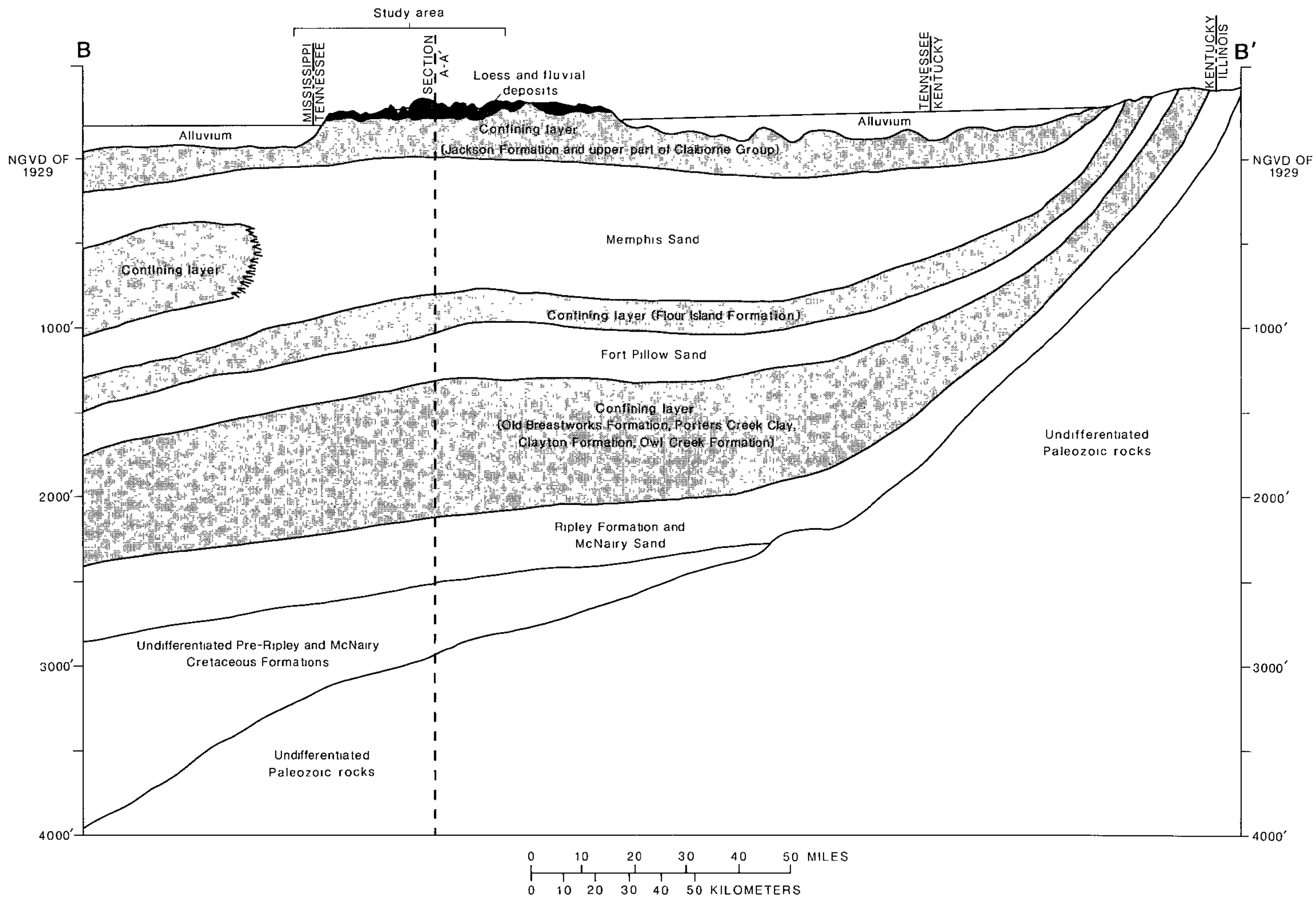


Figure 4.--Principal aquifers and confining layers, south to north, through the Mississippi embayment along line B-B′.

Table 2.--Minimum, median, and maximum values for selected major constituents and properties of water from the aquifers in the Memphis area

[mg/L, milligrams per liter; µg/L, micrograms per liter; °C, degrees Celsius; µS/cm, microsiemens per centimeter]

	Specific conductance (µS/cm at 25°C)	pH (units)	Temperature (°C)	Color (platinum-cobalt units)	Hardness (mg/L as $CaCO_3$)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)	Alkalinity (mg/L as $CaCO_3$)	Sulfate, dissolved (mg/L as SO_4)	Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO_2)	Solids, residue at 180°C (mg/L)	Iron, (µg/L as Fe)
Alluvium																
Minimum	288	6.5	16.0	0	120	30	11	5.9	1.0	99	6.8	3.0	.3	12	197	200
Median	500	6.8	16.5	6	285	65	27	11	2.8	292	23	8.0	.4	26	314	5,200
Maximum	989	7.5	17.0	10	408	112	43	13	7.7	572	33	12	.7	37	652	24,000
Number of wells	11	6	11	5	11	11	11	11	11	11	11	11	6	7	11	11
Fluvial deposits																
Minimum	100	5.7	16.0	0	20	3.7	1.6	7.0	.3	20	.4	1.2	.0	11	76	0
Median	305	7.0	16.5	3	100	32	10	13	.7	120	5.6	8.5	.2	23	170	50
Maximum	740	8.2	20.5	7	400	140	49	36	5.5	414	140	22	.7	45	440	1,100
Number of wells	32	34	32	29	35	35	35	36	36	35	36	36	35	34	35	33
Memphis Sand																
Minimum	33	5.8	16.0	0	9	2.0	.8	3.3	.1	14	.2	.6	.0	1.3	32	0
Median	125	6.4	17.0	5	46	11	4.3	8.0	.8	57	3.1	3.5	.1	13	83	540
Maximum	412	7.9	20.5	18	306	65	35	22	5.1	317	30	26	.7	31	333	16,000
Number of wells	98	96	78	83	105	105	105	101	96	96	105	104	91	92	101	82
Fort Pillow Sand																
Minimum	145	6.8	21.0	10	3	1.1	.1	31	1.0	79	1.8	.5	.0	8.0	99	170
Median	179	7.4	21.5	25	9	2.2	.9	40	1.3	90	4.9	1.8	.1	9.8	115	550
Maximum	280	8.0	25.0	60	17	4.0	1.9	59	3.0	150	10	3.5	.3	13	165	1,700
Number of wells	20	25	22	11	25	25	24	25	15	25	25	24	11	16	23	19

Table 3.--Minimum, median, and maximum values for selected trace constituents, in micrograms per liter, in water from aquifers in the Memphis area

[Values given as 0 (zero) or < (less than) indicate that the concentration was below the level of detection for the analytical method used at the time of analysis and do not indicate the presence or absence of a constituent; a = U.S. Environmental Protection Agency, 1986b; b = U.S. Environmental Protection Agency, 1986c]

	Arsenic, dissolved (as As)	Barium, dissolved (as Ba)	Cadmium, dissolved (as Cd)	Chromium, dissolved (as Cr)	Copper, dissolved (as Cu)	Lead, dissolved (as Pb)	Mercury, dissolved (as Hg)	Zinc dissolved (as Zn)
National drinking water regulations	a50	a1,000	a10	a50	b1,000	a50	a2	b5,000
				Alluvium				
Minimum	<5	284	<1	<2	10	--	--	<10
Median	--	--	--	--	--	--	--	--
Maximum	5	356	<1	<2	20	--	--	140
Number of wells	2	2	2	2	2	0	0	2
				Fluvial deposits				
Minimum	<5	32	0	0	<10	0	.0	10
Median	<5	60	0	0	10	3	.1	50
Maximum	<10	150	1	4	30	10	1.0	990
Number of wells	19	10	12	17	5	9	13	13
				Memphis Sand				
Minimum	0	0	0	0	0	0	<.1	0
Median	<5	44	<1	<2	9	3	.1	10
Maximum	4	644	4	20	20	20	.3	170
Number of wells	34	33	26	32	28	17	25	32
				Fort Pillow Sand				
Minimum	5	31	--	--	--	--	--	--
Median	5	40	--	--	--	--	--	--
Maximum	5	47	--	--	--	--	--	--
Number of wells	3	3	0	0	0	0	0	0

Fluvial Deposits

Fluvial (terrace) deposits are not a major aquifer but provide a source of water for many domestic and farm wells in rural parts of the Memphis area in Tennessee and Mississippi. Because thick, saturated sections of the fluvial deposits occur only locally, this aquifer generally is not used as a source of water for municipal, industrial, or irrigation wells. Nevertheless, the fluvial deposits were important to this investigation because they form the water-table aquifer in the upland areas and may provide a source of recharge to the Memphis Sand.

Fluvial deposits in the uplands and beneath the valley slopes are remnants of ancient alluvial deposits of either present streams or an earlier drainage system (Russell and Parks, 1975). These fluvial deposits consist primarily of sand and gravel with minor lenses of clay and thin, iron-oxide cemented (ferruginous) layers of sandstone or conglomerate. The thickness of the fluvial deposits is highly variable because of erosional surfaces at both the top and the base. Locally fluvial deposits are as much as 100 feet thick but are absent at some places.

Water-quality data from 36 wells in the fluvial deposits are summarized in table 2. Water from the fluvial deposits is a moderately hard (median--100 mg/L as $CaCO_3$), calcium bicarbonate type. Dissolved-solids concentrations are generally less than 250 mg/L (fig. 5); the maximum concentration is 440 mg/L. Iron concentrations are also low (median--50 µg/L). Temperature of water from the fluvial deposits is generally about 16.5 °C, which is the same as water from the alluvium. Trace-constituent data are available from 19 of the wells ; concentrations of trace constituents are all less than the EPA criteria for drinking water.

Areal differences exist in the quality of water from the fluvial deposits (fig. 5). Water in the fluvial deposits in the western part of the Gulf Coastal Plain near the bluffs is more mineralized than in the other parts of the study area. In this area, dissolved-solids concentrations range from about 200 to 450 mg/L in water from wells, and hardness ranges from about 100 to 400 mg/L as $CaCO_3$. The greater hardness and larger dissolved-solids concentrations are probably related to the thickness of the carbonate-rich loess. The loess overlies the fluvial deposits and is thickest near the bluffs in the west ; its thickness decreases from west to east, as does the dissolved-solids concentration in water from the fluvial deposits (fig. 5).

Water in the fluvial deposits is susceptible to contamination at waste-disposal sites. Abandoned gravel pits in the fluvial deposits have been used for waste disposal at many places in the Gulf Coastal Plain part of the Memphis area. At least one of these dumps is known to contain hazardous waste. Limited water-quality data from two wells at this dump indicate traces of phenols and some common pesticides, including chlordane, diazinon, and heptachlor (Parks and others, 1982).

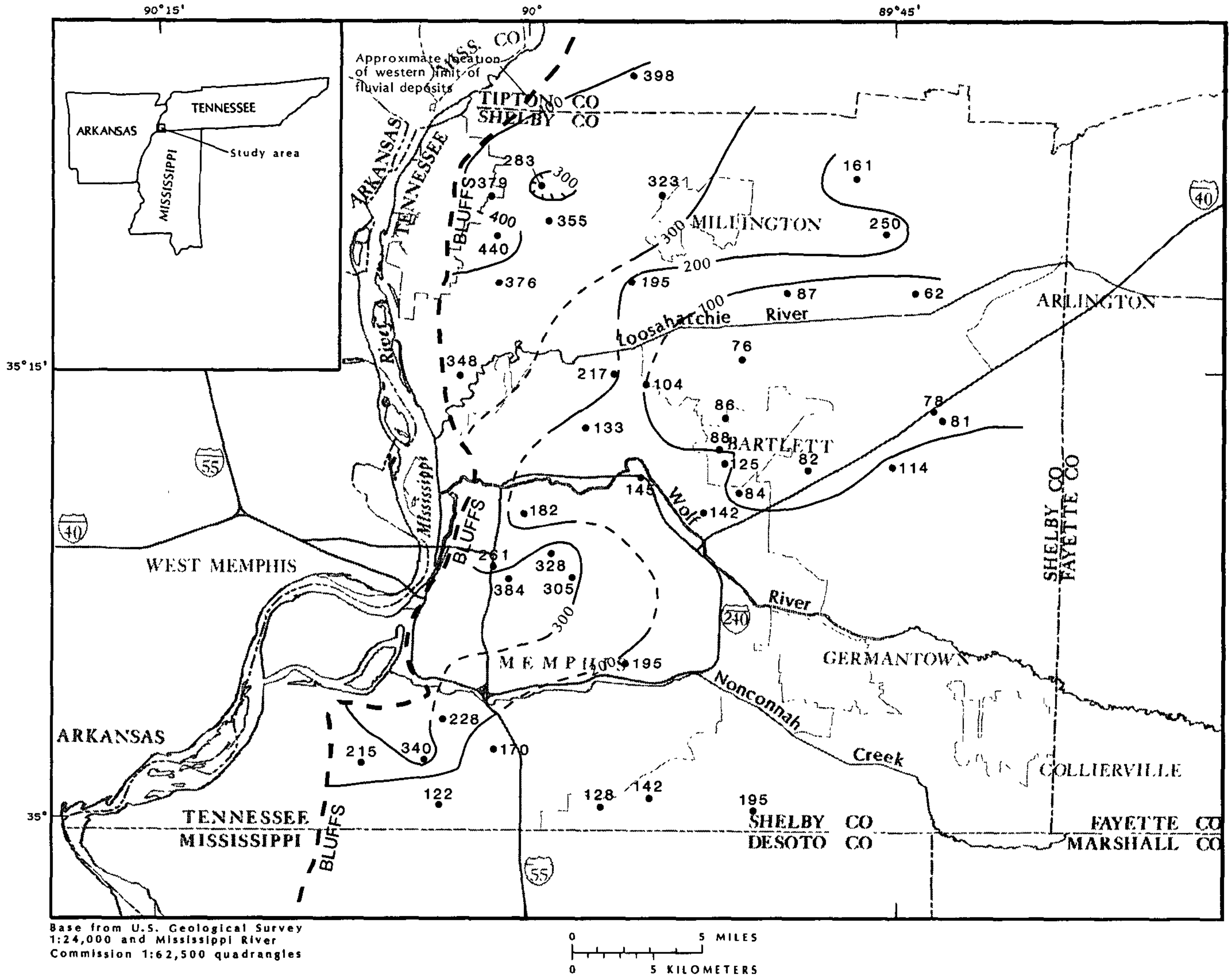
Memphis Sand

The Memphis Sand (and equivalents that comprise the Memphis aquifer) is a major aquifer in the northern part of the Mississippi embayment and is the source of ground water for the City of Memphis. Although now largely unused west of the Mississippi River, this aquifer provides water for municipal, industrial, farm, and domestic supplies in western Tennessee, southwestern Kentucky, and northwestern Mississippi (Hosman and others, 1968).

In the the Memphis area, pumpage from the Memphis Sand ("500-foot" sand) was about 180 Mgal/d in 1984 (Graham and Parks, 1986). The Memphis Sand generally is not used as an aquifer in Arkansas.

The Memphis Sand is in the subsurface throughout the Memphis area. This aquifer consists primarily of a thick body of fine to very coarse sand with clay lenses at various horizons. Some lignite occurs locally. Thickness ranges from 500 to 890 feet but probably averages about 750 feet at Memphis. The Memphis Sand is thinnest in northwestern Fayette County, Tenn., and thickest in southwestern Shelby County, Tenn.

The upper part of the Memphis Sand is equivalent to the Sparta aquifer (Newcome, 1976), and the lower part is equivalent to the



EXPLANATION

– –200— LINE OF EQUAL DISSOLVED SOLIDS IN 1980--Dashed where approximately located. Interval is 100 milligrams per liter

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Figure 5.--Dissolved-solids concentrations in water from the fluvial deposits in the Memphis area.

Winona-Tallahatta aquifer (Spiers, 1977) and the Meridian-upper Wilcox aquifer (Boswell, 1976). The Sparta, Winona-Tallahatta, and Meridian-upper Wilcox are separate aquifers in Mississippi, but in northern Mississippi near the Tennessee State line, these aquifers merge into the thick body of sand that makes up the Memphis Sand. Most wells in the Memphis area are in the upper part of the Memphis Sand, although in recent years MLGW has installed some wells in the lower part.

Water-quality data from 105 wells in the Memphis Sand are summarized in table 2. Based on these data, water from this aquifer is a soft (median hardness--46 mg/L), calcium bicarbonate type in most of the Memphis area. Dissolved-solids concentrations range from 32 to 333 mg/L. The median dissolved-solids concentration, 83 mg/L, in water from the Memphis Sand is lower than in any of the other four principal aquifers.

In much of the Memphis area, iron concentrations exceed 300 µg/L. Locally, high iron concentration is the most troublesome characteristic to water users. Water from the Memphis Sand generally is not used for drinking purposes west of the Mississippi River where iron concentrations greater than 5,000 µg/L have been determined. Median water temperature is 17.0 °C, but ranges from 16.0 to 20.5 °C. Trace-constituent data for 34 of the 105 selected wells show that no concentrations are in excess of maximum contaminant levels for drinking-water (table 3).

Areal variation exists in the quality of water in the Memphis Sand. Water changes from very dilute in the southeast to more mineralized in the northwest (fig. 6). Similarly, hardness is least in the southeast and increases toward the northwest.

Because of its importance as the major source of drinking water in the Memphis area, any potential for contamination of the Memphis Sand is of concern to water managers and consumers. In much of the area, the Memphis Sand is separated from the alluvium and fluvial deposits by a relatively thick confining bed. Locally, however, the confining bed may be thin or absent or may contain sand lenses that could provide a pathway for the movement of contaminated water from the shallower aquifers to the Memphis Sand (Criner and others, 1964; Bell and Nyman, 1968; Parks and Lounsbury, 1976, Graham, 1982; Graham and Parks, 1986).

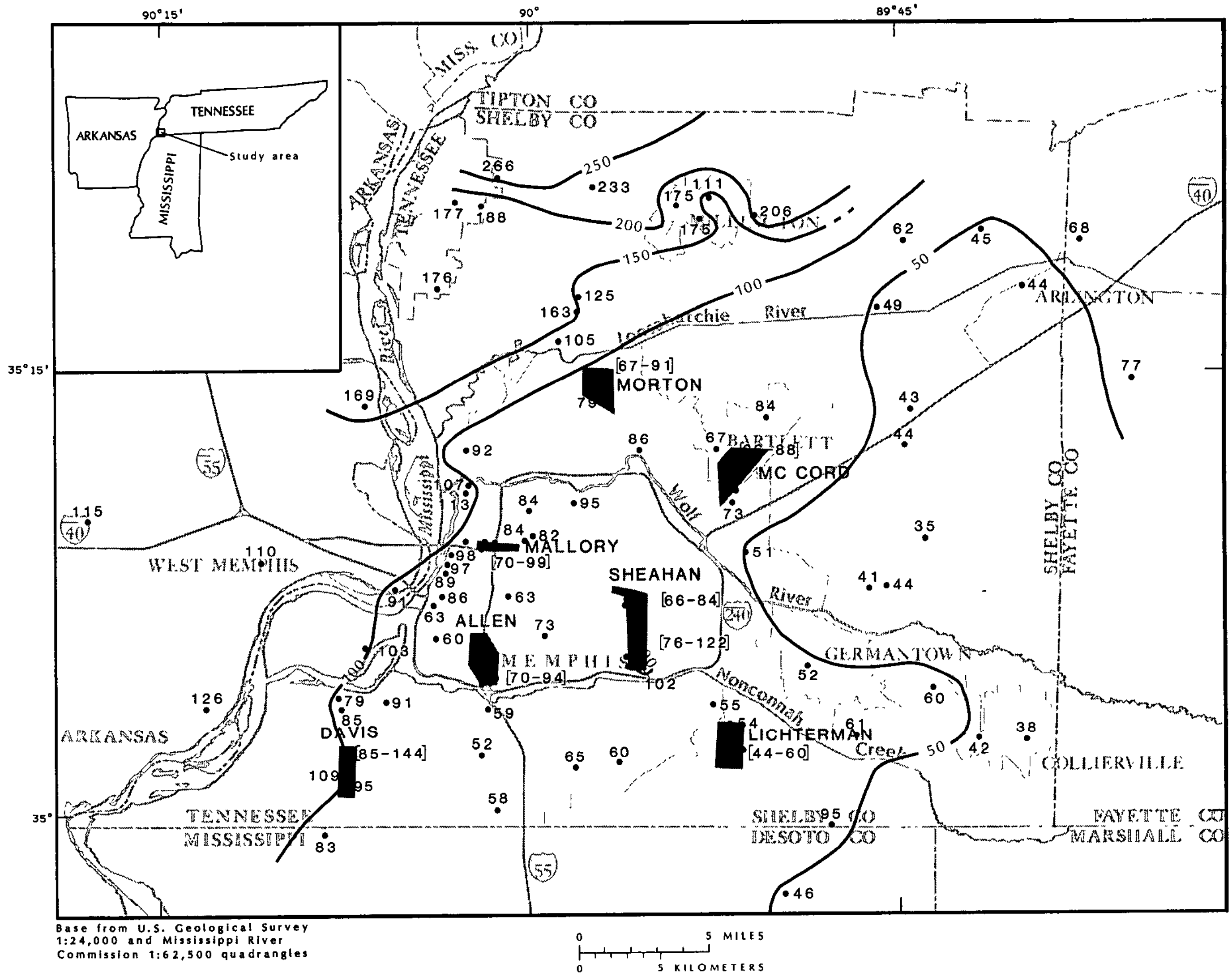
Fort Pillow Sand

The Fort Pillow Sand of the Wilcox Group (lower Wilcox aquifer) is one of the largest potential sources of ground water in the Mississippi embayment. In most of the embayment, however, this aquifer presently is not used extensively as a source of water because of the availability of water at shallower depths from the alluvium and Memphis Sand (Hosman and others, 1968).

In the Memphis study area, the Fort Pillow Sand ("1,400-foot" sand), once the second principal aquifer supplying the City of Memphis, now provides water to supplement supplies at Millington, the U.S. Naval Air Station near Millington, and one industrial user at Memphis in Tennessee. The Fort Pillow Sand (and equivalent) is the sole source of water for West Memphis, Marion, and Turrell in Arkansas and Walls in Mississippi. In 1984, pumpage from the Fort Pillow Sand averaged about 10 Mgal/d (Graham and Parks, 1986). Although the Fort Pillow Sand is much deeper than the Memphis Sand, the Fort Pillow Sand 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 Sand.

The Fort Pillow Sand is in the subsurface throughout the Memphis area and consists primarily of fine to medium sand with minor lenses of clay and some lignite. Thickness ranges from 125 to 305 feet and probably averages about 220 feet at Memphis. The aquifer is thinnest in northern Shelby and northwestern Fayette Counties, Tenn., and thickest in Crittenden County, Ark.

Based on data from 25 wells, water from the Fort Pillow Sand is a soft (median hardness--9 mg/L), sodium bicarbonate type (table 2). Concentrations of all major constituents are low; the maximum dissolved-solids concentration is 165 mg/L. Iron concentrations range from 170 to



EXPLANATION

—100— LINE OF EQUAL DISSOLVED SOLIDS IN 1980--Dashed where approximately located. Interval is 50 milligrams per liter

176 • DISSOLVED-SOLIDS ANALYSIS AND VALUE--Data collected from years other than 1980 were extrapolated based on no observed temporal variation of dissolved solids

[76-122] RANGE OF VALUES IN WELL FIELD

DAVIS ▮ MEMPHIS LIGHT, GAS AND WATER DIVISION WELL FIELD

Figure 6.--Dissolved-solids concentrations in water from the Memphis Sand in the Memphis area.

1,700 µg/L and have a median value of 550 µg/L. The temperature of the water ranges from 21.0 °C to 25.0 °C with a median value of 21.5 °C. Concentrations of arsenic and barium in water from three wells (table 3), the only trace-constituent data available, were less than drinking-water criteria.

Water quality in the Fort Pillow Sand is relatively consistent throughout the Memphis area and only small differences in hardness and concentrations of dissolved solids occur. The hardness of the water ranges from 3 to 10 mg/L in Arkansas and from 8 to 17 mg/L at Sheahan well field at Memphis; dissolved-solids concentrations range from 99 to 108 mg/L at Sheahan well field, and from 108 to 165 mg/L in Mississippi and Arkansas.

Ripley Formation and McNairy Sand

The Ripley Formation (and equivalent McNairy Sand) is a potential source of water in a large part of the northern Mississippi embayment. This aquifer presently is used in and downdip from the outcrop area in northern Mississippi, western Tennessee, southwestern Kentucky, southern Illinois, and southeastern Missouri, where shallower aquifers are not available or do not provide enough water to meet local demands (Boswell and others, 1965).

In the Memphis area, the Ripley-McNairy aquifer is not now used as a source of ground water, and it is doubtful that it will be used in the near future because of the availablity of water from the alluvium, Memphis Sand, and Fort Pillow Sand, which are at shallower depths. If a need arises for water from the Ripley-McNairy aquifer in the Memphis area, the greatest potential for use is in northeastern Shelby or northwestern Fayette Counties where the water may be less mineralized than at Memphis.

The Ripley-McNairy aquifer is in the subsurface throughout the Memphis area. Towards the northeast, this aquifer changes facies from sediments more characteristic of the Ripley Formation ("2,600-foot" sand) at Memphis to sediments more characteristic of the McNairy Sand in northwestern Fayette Counties. The Ripley Formation consists primarily of glauconitic sands and calcareous clays with thin interbeds of calcareous sandstone or sandy limestone; the McNairy Sand consists primarily of nonglauconitic sands with interbeds of noncalcareous clays and some lignite. The Ripley Formation and McNairy Sand combined ranges from 360 to 570 feet in thickness.

Water-quality data are available for the Ripley-McNairy aquifer in the Memphis area only from a 2,656-foot deep, unused well in the western part of Mallory well field. This well in the Ripley Formation has been sampled at least five times--in 1927, 1945, 1958, 1977, and 1983. No significant trends in water quality are evident from these analyses.

Water from this well is soft, with an average hardness of 8 mg/L; the water is a sodium bicarbonate type. Although the dissolved-solids concentration is relatively high with a median about 1,000 mg/L, concentrations of most major constituents, except sodium and bicarbonate, are low. Median concentration of fluoride is 4.4 mg/L, which exceeds the EPA maximum contaminant level for drinking-water (4.0 mg/L) for this area and climate (U.S. Environmental Protection Agency, 1986b). Median dissolved iron concentration from this aquifer is 46 µg/L. Water temperature, measured by geophysical methods at a depth of 2,627 feet is about 32.0 °C.

WATER QUALITY AT MEMPHIS LIGHT, GAS AND WATER DIVISION WELL FIELDS

Because of a need to detect water-quality changes at MLGW well fields and because of an awareness of the potential for contamination, MLGW and the Survey have collected data for 62 years in a continuing effort to monitor water quality. As shown in table 4, none of the parameters, with the exception of iron which is reduced in concentration by treatment, exceeds the EPA drinking-water criteria.

Summary statistics for each MLGW well field are illustrated as graphs for easy comparison (fig. 7). The range of values for a selected constituent is derived from water-quality data taken

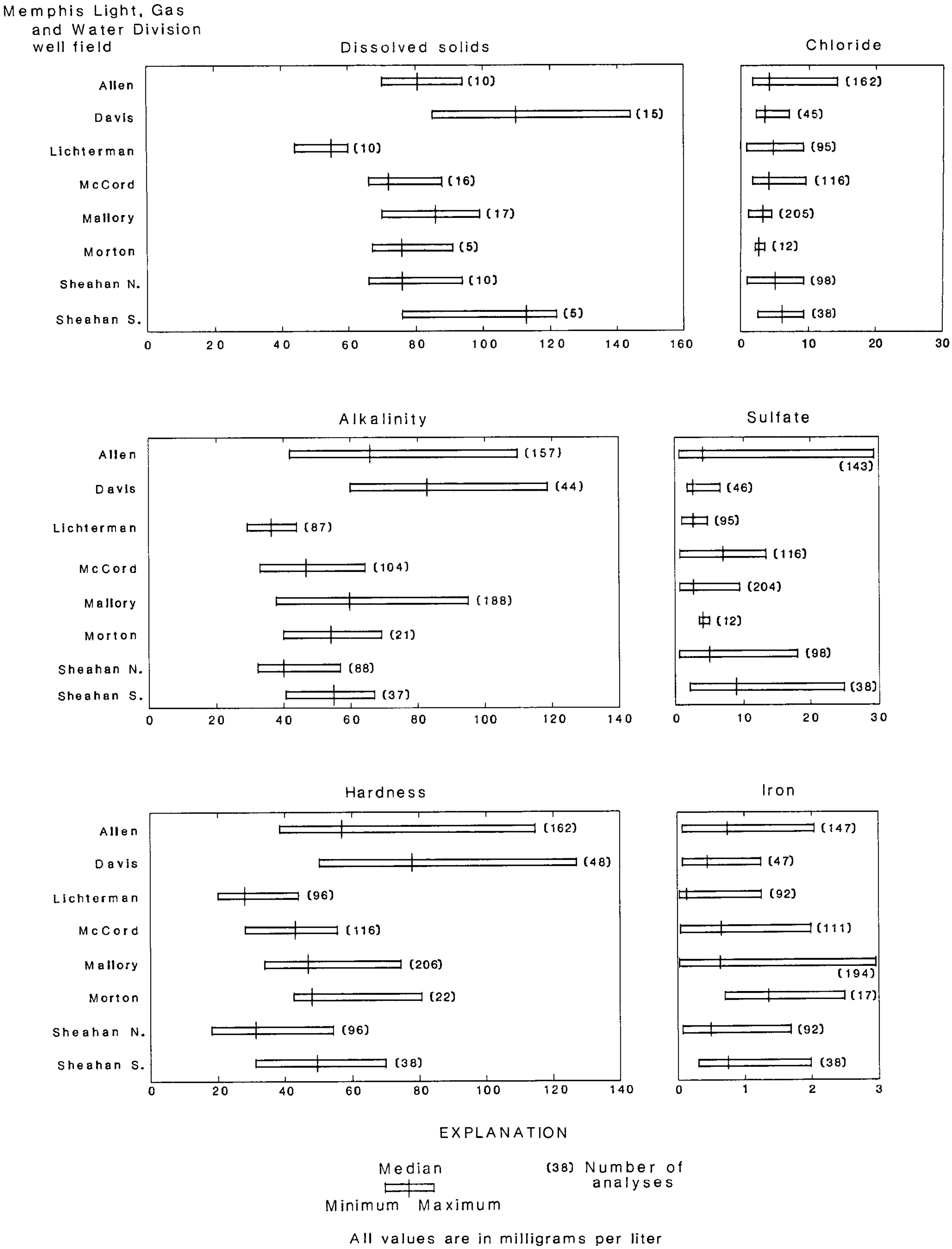


Figure 7.--Minimum, median, and maximum values for selected major constituents and properties of water from the Memphis Sand at Memphis Light, Gas and Water Division well fields.

Table 4.--Minimum, median, and maximum values for selected major constituents and properties of water from Memphis, Light, Gas and Water well fields and corresponding drinking water criteria

Constituent or property	Number of analyses	Minimum	Median	Maximum	EPA criteria (U.S. Environmental Protection Agency, 1986c)
Dissolved solids (mg/L)	91	44	79	144	500
Alkalinity (mg/L as $CaCO_3$)	732	29	56	119	--
Hardness (mg/L as $CaCO_3$)	791	18	46	127	--
Chloride (mg/L as Cl)	778	.8	4.0	14	250
Sulfate (mg/L as SO_4)	759	.2	3.5	30	250
Iron (µg/L as Fe)	744	0	600	3000	300

from widely spaced wells from each well field. The differences identified during this investigation are discussed for each property and constituent. Because water-quality differences occur between the widely separated northern and southern parts of Sheahan well field, those parts are distinguished as North Sheahan and South Sheahan in this discussion.

Dissolved-solids concentrations in water at all MLGW well fields range from 44 to 144 mg/L. Concentrations range about 60 to 100 mg/L from Allen, McCord, Mallory, Morton, and North Sheahan well fields, from about 44 to 60 mg/L in the Lichterman field, and from 76 to 122 mg/L in the South Sheahan. The median at South Sheahan is 113 mg/L, the highest of any well field. Davis well field shows the widest range--from 85 to 144 mg/L--with a median of 110 mg/L.

These data at the well fields reflect the general trend in western Tennessee that dissolved-solids concentrations increase from southeast to northwest (Moore, 1962). This trend, which in the Memphis area is from southeast to northwest (fig. 6), is generally consistent for all well fields except for South Sheahan. There is no apparent source of water from the Memphis Sand with dissolved-solids concentrations more than 122 mg/L within about 9 miles of South Sheahan well field (fig. 6). The overlying fluvial deposits, however, are characterized by water with dissolved-solids concentrations of about 200 mg/L (fig. 5).

Graham and Parks (1986) have shown evidence which indicates that water has been leaking downward from the water-table aquifer to the Memphis Sand in the area of South Sheahan well field. The evidence includes (1) thinness of the confining bed, (2) a depression in the surface of the fluvial deposits, (3) water-declines in the fluvial deposits, (4) carbon and hydrogen isotope concentrations indicating the presence of recent water in the Memphis Sand, (5) distorted temperature gradients indicating downward leakage of water, and (6) head differences between the aquifers with a gradient favoring downward movement of water. The anomaly of the high dissolved-solids concentrations is consistent with the conclusion of Graham and Parks (1986).

Alkalinity in water from wells in MLGW well fields ranges from 29 to 119 mg/L. Lichterman has the lowest median, 36 mg/L, and Davis has the highest, 83 mg/L. Allen has a range in alkalinity from about 42 to 110 mg/L, Davis has a range from 60 to about 119 mg/L, and Mallory has a range from 38 to 95 mg/L. The other well fields have alkalinity values with smaller ranges: Lichterman ranges from about 29 to 44 mg/L, McCord ranges from 33 to 64 mg/L, Morton ranges from 40 to 69 mg/L, Sheahan North ranges from 32 to 57 mg/L, and Sheahan South ranges from 41 to 67 mg/L.

The distribution of hardness of water from wells in MLGW well fields is very similar to the distribution for alkalinity. The range is from 18 to 127 mg/L for all well fields. Lichterman well field has the lowest median, 28 mg/L, and Davis has the highest, 78 mg/L. Allen ranges from about 38 to 114 mg/L, and Davis ranges from 50 to 127 mg/L; those two well fields have the widest range of hardness. Lichterman has the narrowest range, from 20 to 44 mg/L.

Dissolved chloride concentrations at MLGW well fields range from 0.8 to 14 mg/L. Median concentrations from all well fields fall in the narrow range from about 3 to 6 mg/L. It is significant to note that such low concentrations of chloride are attained only in an aquifer that is flushed with freshwater. Concentrations of chloride above 20 mg/L in MLGW well fields may indicate local contamination.

Dissolved sulfate concentrations at MLGW well fields range from 0.2 to 30 mg/L. The higher concentrations occur at well fields within the central part of the metropolitan Memphis area. South Sheahan well field has the highest median concentration of dissolved sulfate, 9 mg/L, and Davis, Lichterman, and Mallory well fields have the lowest, 2.5 mg/L. Allen well field has the widest range of sulfate concentration, 0.2 to 30 mg/L, and Morton the narrowest range, 3.5 to 5 mg/L.

Dissolved iron concentrations at MLGW well fields range from 0 to 3,000 µg/L. Iron is the only constituent in water from the Memphis Sand at these well fields that exceeds the EPA drinking-water criteria. Median concentrations of iron range from about 500 µg/L to 1,000 µg/L, with two exceptions--the median is 150 µg/L at Lichterman well field and is about 1,400 µg/L at Morton well field. Mallory well field has the greatest range, from 0 to 3,000 µg/L.

SUMMARY

Water from the freshwater aquifers in the Memphis area is suitable for most uses. Water from the alluvium, fluvial deposits, and Memphis Sand is a calcium bicarbonate type, and water from the Fort Pillow Sand and Ripley Formation and McNairy Sand is a sodium bicarbonate type. Dissolved-solids concentrations are highest in water from the Ripley-McNairy aquifer and lowest in water from the Memphis Sand.

Water from the alluvium is characteristically very hard, median--285 mg/L as $CaCO_3$; and has high concentrations of iron, median--5,200 µg/L; and relatively low concentrations of dissolved solids, median--314 mg/L. Water from the fluvial deposits generally is moderately hard, median--100 mg/L; and has low concentrations of iron, median--50 µg/L; and dissolved solids, median--170 mg/L.

Water from the Memphis Sand is soft, median--46 mg/L, and has moderate concentrations of iron, median--540 µg/L, and low concentrations of dissolved solids, median--83 mg/L. Water from the Fort Pillow Sand is soft, median--9 mg/L, and has moderate concentrations of iron, median--550 µg/L, and low concentrations of dissolved solids, median--115 mg/L.

The quality of water from the Ripley Formation and McNairy Sand in the Memphis area is known only at an unused well at Memphis, which has been sampled at least five times between 1927 and 1983. Water from this well is soft, average--about 8 mg/L, but dissolved-solids concentrations are relatively high, average--about 1,000 mg/L.

Temperature of water in the freshwater aquifers generally increases with depth. The medians are: alluvium, 16.5 °C; fluvial deposits, 16.5 °C; Memphis Sand, 17.0 °C; and Fort Pillow Sand, 21.5 °C. A temperature of about 32.0 °C was measured geophysically at a depth of 2,627 feet in the unused well in the Ripley Formation and McNairy Sand.

Summary statistics for MLGW well fields, which pump solely from the Memphis Sand, show that dissolved-solids concentrations range from 44 to 144 mg/L; alkalinity, as $CaCO_3$, ranges from 29 to 119 mg/L; hardness ranges from 18 to 127 mg/L; chloride ranges from 0.8 to 14 mg/L; sulfate ranges from 0.2 to 30 mg/L; and iron ranges from 0 to 3,000 µg/L.

SELECTED REFERENCES

Bell, E.A., and Nyman, D.J., 1968, Flow pattern and related chemical quality of ground water in the "500-foot" sand in the Memphis area, Tennessee: U.S. Geological Survey Water-Supply Paper 1853, 27 p.

Boswell, E.H., 1976, The Meridian-Upper Wilcox aquifer in Mississippi: U.S. Geological Survey Water-Resources Investigations Report 76-79, 3 sheets.

Boswell, E.H., Cushing, E.M., and Hosman, R.L., 1968, Quaternary aquifers in the Mississippi embayment, with a discussion of Quality of the water by H.G. Jeffery: U.S. Geological Survey Professional Paper 448-E, 15 p.

Boswell, E.H., Moore, G.K., MacCary, L.M., and others, 1965, Cretaceous aquifers in the Mississippi embayment, with discussions of Quality of water by H.G. Jeffery: U.S. Geological Survey Professional Paper 448-C, 37 p.

Brahana, J.V., 1982, Two-dimensional digital ground-water model of the Memphis Sand and equivalent units, Tennessee, Arkansas, Mississippi: U.S. Geological Survey Open-File Report 82-99, 55 p.

Caplan, W.M., 1954, Subsurface geology and related oil and gas possibilities of northeastern Arkanasas: Arkansas Resources and Development Commission, Division of Geology Bulletin 20, 124 p.

Criner, J.H., and Armstrong, C.A., 1958, Groundwater supply of the Memphis area: U.S. Geological Survey Circular 408, 20 p.

Criner, J.H., and Parks, W.S., 1976, Historic water-level changes and pumpage from the principal aquifers of the Memphis area, Tennessee: 1886-1975: U.S. Geological Survey Water-Resources Investigations 76-67, 45 p.

Criner, J.H., Sun, P-C.P., and Nyman, D.J., 1964, Hydrology of the aquifer systems in the Memphis area, Tennessee: U.S. Geological Survey Water-Supply Paper 1779-O, 54 p.

Cushing, E.M., Boswell, E.H., and Hosman, R.L., 1964, General geology of the Mississipppi embayment: U.S. Geological Survey Professional Paper 448-B, 28 p.

Cushing, E.M., Boswell, E.H., Speer, P.R., and Hosman, R.L., and others, 1970, Availability of water in the Mississippi embayment: U.S. Geological Survey Professional Paper 448-A, 13 p.

Fenneman, N.M., 1938, Physiography of eastern United States: New York, McGraw-Hill, 714 p.

Fisk, H.N., 1944, Geological investigation of the alluvial valley of the lower Mississipppi River: U.S. Department of the Army, Mississipppi River Commission, 78 p.

Glenn, L.C., 1906, Underground waters of Tennessee and Kentucky west of Tennessee River and of an adjacent area in Illinois: U.S. Geological Survey Water-Supply Paper 164, 173 p.

Graham, D.D., 1979, Potentiometric map of the Memphis Sand in the Memphis area, Tennessee, August 1978: U.S. Geological Survey Water-Resources Investigations Open-File Report 79-80, scale 1:125,000, 1 sheet.

----- 1982, Effects of urban development on the aquifers in the Memphis area Tennessee: U.S. Geological Survey Water-Resources Investigations Report 82-4024, 20 p.

----- 1985, Test well installation and water quality, Hollywood Dump area, Memphis, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 84-4214, 35 p.

Graham, D.D., and Parks, W.S., 1986, Potential for leakage among principal aquifers in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 85-4295, 46 p.

Hildenbrand, T.G., Kane, M.F., and Hendricks, J.D., 1982, Magnetic basement in the upper Mississippi embayment region - A Preliminary report, in Investigations of the New Madrid, Missouri, earthquake region: U.S. Geological Survey Professional Paper 1236-E, p. 39-53.

Hosman, R.L., Long, A.T., and Lambert, T.W., and others, 1968, Tertiary aquifers in the Mississippi embayment, with discussions of Quality of the water by H.G. Jeffery: U.S. Geological Survey Professional Paper 448-D, 29 p.

Kazmann, R.G., 1944, The water supply of the Memphis area, A progress report: U.S. Geological Survey, 66 p.

Krinitzsky, E.L., and Wire, J.C., 1964, Ground water in alluvium of the Lower Mississippi Valley (upper and central areas): U.S. Army Engineer Waterways Experiment Station Technical Report no. 3-658 (2 v.), 100 p.

Lanphere, C.R., 1955, Geologic source and chemical quality of public ground-water supplies in western Tennessee: Tennesssee Division of Geology Report of Investigations no. 1, 69 p.

McKeown, F.A., and Pakiser, L.C., eds., 1982, Investigations of the New Madrid, Missouri, earthquake region: U.S. Geological Survey Professional Paper 1236, 201 p.

Moore, G.K., 1962, Downdip changes in chemical quality of water in the "500-foot" sand of western Tennessee: U.S. Geological Survey Professional Paper 450-C, p. 133-134.

----- 1965, Geology and hydrology of the Claiborne Group in western Tennessee: U.S. Geological Survey Water-Supply Paper 1809-F, 44 p.

Moore, G.K., and Brown, D.L., 1969, Stratigraphy of the Fort Pillow test well, Lauderdale County, Tennessee: Tennessee Division of Geology Report of Investigation 26, 1 sheet.

Newcombe, Roy, Jr., 1976, The Sparta aquifer system in Mississippi: U.S. Geological Survey Water-Resources Investigations Report 76-7, 3 sheets.

Nyman, D.J., 1965, Predicted hydrologic effects of pumping from the Lichterman well field in the Memphis area, Tennessee: U.S. Geological Survey Water-Supply Paper 1819-B, 26 p.

Parks, W.S., 1973, Geologic map of the Southwest Memphis quadrangle, Tennessee: U.S. Geological Survey open-file report, scale 1:24,000.

----- 1974, Geologic map of the Southeast Memphis quadrangle, Tennessee: U.S. Geological Survey open-file report, scale 1:24,000.

----- 1975, Geologic map of the Germantown quadrangle, Tennessee: U.S. Geological Survey open-file report, scale 1:24,000.

----- 1977, Geologic map of the Ellendale quadrangle, Tennessee: U.S. Geological Survey Open-File Report 77-752, scale 1:24,000.

----- 1978, Geologic map of the Tennessee portion of the Fletcher Lake quadrangle, Tennessee (including portions of adjacent quadrangles to the north, west, and south): Tennessee Division of Geology GM 404-SW, scale 1:24,000.

----- 1979a, Geologic map of the Northeast Memphis quadrangle, Tennessee: U.S. Geological Survey Open-File Report 79-1268, scale 1:24,000.

----- 1979b, Geologic map of the Tennessee portion of the Northwest Memphis quadrangle, Tennessee: U.S. Geological Survey Open-File Report 79-1269, scale 1:24,000.

Parks, W.S., Graham, D.D., and Lowery, J.F., 1982, Installation and sampling of observation wells and analyses of water from the shallow aquifer at selected waste-disposal sites in the Memphis area, Tennessee: U.S. Geological Survey Open-File Report 82-266, 32 p.

Parks, W.S., and Lounsbury, R.W., 1976, Summary of some current and possible future environmental problems related to geology and hydrology at Memphis, Tennessee: U.S. Geological Survey Water-Resources Investigations 4-76, 34 p.

Plebuch, R.O., 1961, Fresh-water aquifers of Crittenden County, Arkansas: Arkansas Geology and Conservation Commission Water Resources Circular no. 8, 65 p.

Russell, E.E., and Parks, W.S., 1975, Stratigraphy of the outcropping Upper Cretaceous, Paleocene, and lower Eocene in western Tennessee (including descriptions of younger fluvial deposits): Tennessee Division of Geology Bulletin 75, 118 p.

Safford, J.M., 1890, The water supply of Memphis: Tennessee Board of Health Bulletin v. 5, 93 p.

Schneider, Robert, and Blankenship, R.R., 1950, Subsurface geologic cross section from Claybrook, Madison County, to Memphis, Shelby County, Tennessee: Tennessee Division of Geology Ground-Water Investigations, Preliminary Chart 1.

Schneider, Robert, and Cushing, E.M., 1948, Geology and water-bearing properties of the "1,400-foot" sand in the Memphis area: U.S. Geological Survey Circular 33, 13 p.

Spiers, C.A., 1977, The Winona-Tallahatta aquifer in Mississippi: U.S. Geological Survey Water-Resoureces Investigations Report 77-125, 2 sheets.

Stearns, R.G., 1957, Cretaceous, Paleocene, and lower Eocene geologic history of the northern Mississippi embayment: Geologic Society of America Bulletin, v. 68, p. 1077-1100.

Stearns, R.G., and Armstrong, C.A., 1955, Post-Paleozoic stratigraphy of western Tennessee and adjacent portions of the upper Mississippi embayment: Tennessee Division of Geology Report of Investigations no. 2, 29 p.

Stearns, R.G., and Zurawski, Ann, 1976, Post-Cretaceous faulting in the head of the Mississippi embayment: Southeastern Geology, v. 17, no. 4, p. 207-229.

U.S. Army Corps of Engineers, Memphis District, 1981, Memphis metropolitan urban area water resources study, 127 p.

U.S. Environmental Protection Agency, 1986a, Amendment to National Oil and Hazardous Substances Contingency Plan; National priorities list, final rule and proposed rule: Federal Register, v. 51, no. 111, June 10, 1986, p. 21053-21112.

----- 1986b, Maximum contaminant levels (subpart B of part 141, National interim primary drinking-water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100 to 149, revised July 1, 1986, p. 524-528.

----- 1986c, Secondary maximum contaminant levels (section 143.3 of part 143, National secondary drinking-water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100 to 149, revised July 1, 1986, p. 587-590.

Wells, F.G., 1931, A preliminary report on the artesian water supply of Memphis, Tennessee: U.S. Geological Survey Water-Supply Paper 638-A, 34 p.

----- 1933, Ground-water resources of western Tennessee, with a discussion of chemical character of the water by F. G. Wells and M. D. Foster: U.S. Geological Survey Water-Supply Paper 656, 319 p.

Zoback, M.D., Hamilton, R.M., Crone, A.J., Russ, D.P., McKeown, F.A., and Brockman, S.R., 1980, Recurrent intraplate tectonism in the New Madrid seismic zone: Science, v. 209, no. 4460, p. 971-976.

★ U.S GOVERNMENT PRINTING OFFICE; 1987 — 751-198