TWO-DIMENSIONAL DIGITAL GROUND-WATER MODEL OF THE MEMPHIS SAND AND EQUIVALENT UNITS, TENNESSEE-ARKANSAS-MISSISSIPPI

by

J. V. Brahana

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Prepared by
U.S. Geological Survey
for
U.S. Army Corps of Engineers
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Nashville, Tennessee

1982

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

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Nashville, Tennessee 37203

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CONVERSION FACTORS

The following report uses inch-pound units for consistency with U.S. Army Corps of Engineers requirements. The units are frequently abbreviated using the notations shown below. The inch-pound units can be converted to SI units by multiplying by the factors given in the following list.

Inch-pound unit to convert	Multiply by	To obtain SI unit
Foot (ft)	0.3048	Meter (m)
Foot per second (ft/s)	0.3048	Meter per second (m/s)
Foot per day (ft/d)	$3.528 \times 10^{-}$	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)	2.832×10^{-2}	Cubic meter per second (m^3/s)
Mile (mi)	1.609	Kilometer (km)
Square mile (mi^2)	2.59	Square kilometer (km^2)
Gallon per day (gal/d)	4.384×10^{-8}	Cubic meter per second (m^3/s)
Million gallons per day (Mgal/d)	4.384×10^{-2}	Cubic meters 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)	.0254	Meter per year (m/a)

TWO-DIMENSIONAL DIGITAL GROUND-WATER MODEL OF THE MEMPHIS SAND AND EQUIVALENT UNITS, TENNESSEE-ARKANSAS-MISSISSIPPI

ABSTRACT

A digital model simulating ground-water flow in the Memphis Sand and equivalent units underlying the Memphis metropolitan area was constructed and tested and found to simulate historic water levels within 5 feet of observed for 75 percent of the control points. Split-sample testing verified that the model could reproduce water levels for pumping configurations other than those for which it was developed.

Utilization of the model for predictive purposes requires input for pumping locations, pumping rates, and duration. Output includes a tabled computation of water level for each grid node and a contoured potentiometric map for the area.

The modeling effort refined the concepts of flow in the aquifer which at one time was considered to be essentially homogenous. Zones of less transmissivity were determined during the model testing phase to provide the best overall calculated response. These zones, which closely match the locations of fault zones hypothesized by previous researchers, appear to restrict flow between the aquifer in the Memphis area and to the west in Arkansas. Calibration also indicated that leakage was nonhomogeneous throughout the area. Zones of high leakage along the upper reaches of the Wolf and Loosahatchie Rivers; upper reaches of Nonconnah Creek, and the alluvial aquifer of the Mississippi River alluvial plain were essential in simulating observed water levels. Electric logs from these suspected zones of leakage commonly show thinner confining clays or sandier zones within the confining layer as compared with areas where leakage is low.

INTRODUCTION

The Memphis area has experienced a continuing increase in ground-water withdrawals with resulting water-level declines since 1886, when the first well was completed in the major aquifer, the Memphis Sand. Although the aquifer is capable of supplying the present pumping demand of almost 195 Mgal/d, its importance as an intensively utilized resource requires that it be effectively managed and protected, particularly in light of anticipated growth in the area.

In response to this requirement, a digital ground-water model that simulated two-dimensional flow in the leaky, artesian Memphis Sand and equivalent units was constructed by the U.S. Geological Survey at the request of the Memphis District, U.S. Army Corps of Engineers, as part of the Memphis Metropolitan Area Urban Study. This model, described herein, can be used to determine resource adequacy and to help establish a general management plan for usage of ground water from the aquifer.

Previous Studies

Memphis and the surrounding area have been intensively studied with respect to water resources. Some of the more notable works include Wells (1931 and 1933), Kazmann (1944), Schneider and Cushing (1948), Criner and Armstrong (1958), Criner and others (1964), Moore (1965), Nyman (1965), and Bell and Nyman (1968). Particularly helpful was the compilation by Criner and Parks (1976) which summarized pumpage and water-level data for the Memphis area, and the water-level map by Graham (1979). Records of water levels from 1936 through 1973 have been issued periodically in U.S. Geological Survey Water-Supply Papers 817, 840, 845, 886, 907, 937, 945, 987, 1017, 1024, 1072, 1097, 1127, 1157, 1166, 1192, 1222, 1266, 1322, 1405, 1538, 1803, 1978, and 2171.

Ryling (1960), Plebuch (1961), Halberg and Reed (1964), and Halberg (1972) included data describing historic water levels and pumpage from Arkansas; Davis and others (1971) include the same for Kentucky; and Callahan (1973), Dalsin and Bettandorff (1976), and Newcome (1976) provide these data for Mississippi.

Regional and local studies relating to the geology of the Memphis area have been made by Fisk (1944), Caplan (1954), Stearns and Armstrong (1955), Stearns (1957), Cushing and others (1964 and 1970), Boswell and others (1968), Hosman and others (1968), Payne (1968), and Stearns and Zurawski (1976). Krinitzsky and Wire (1964) described the Mississippi River alluvium and its hydrology, and Reed (1972) summarized the results of an analog simulation of the Sparta Sand in the Mississippi embayment. Parks (1973a, 1973b, 1974, 1975, 1977a, 1977b) has mapped the geology of selected quadrangles within the Memphis area.

Data used in this study that have not been published include electric logs, well completion data, driller's records, geologic logs, summaries of pumping tests, inventories of pumpage, and individual records and maps of historic water levels. These records are primarily in the files of the U.S. Geological Survey, Water Resources Division; Tennessee Division of Geology; Tennessee Division of Water Resources; and Memphis Light, Gas and Water Division (MLGW). Table 1 shows the addresses and phone numbers of these and other agencies that are the primary sources of ground-water and geologic information. Additional sources of unpublished information exist, but they are generally not the primary repository of the data. Table 2 contains a summary of the published reports of the area.

Description of the Study Area

The study area is centered within the Memphis metropolitan area, and includes approximately 1,000 square miles in Shelby County, Tenn., and parts of adjacent counties. Figure 1 shows the general location of the study area; county boundaries and identification are given in figure 6. This area approximately coincides with the Corps of Engineers' metropolitan study area. Although a much larger area simulating the natural boundaries of the regional aquifer system was incorporated in the model, it is described in this report only in its hydrologic relation to the Memphis area.

Table 1.--Primary agencies that maintain ground-water information of the Memphis area

U.S. Geological Survey, Water Resources Division (ground-water occurrence, water use, and two-dimensional ground-water flow model)

Memphis Office
204 Federal Office Building
167 N. Main Street
Memphis, TN 38103
phone (901) 521-3229

Nashville Office
A-413 Federal Building
U.S. Courthouse
Nashville, TN 37203
phone (615) 251-5424

Little Rock Office
Room 2301 Federal Office Building
700 W. Capitol Avenue
Little Rock, AR 72201
phone (501) 378-6391

Jackson Office
Suite 710 Federal Building
100 West Capitol Street
Jackson, MS 39201
phone (601) 960-4600

Tennessee Department of Conservation, Division of Geology (geologic data)

Memphis Office
c/o Earthquake Information Center
Memphis State University
Memphis, TN 38152
phone (901) 454-2779

Nashville Office
G5 State Office Building
Nashville, TN 37219
phone (615) 741-2726

Tennessee Department of Conservation, Division of Water Resources (well-completion data, water use, ground-water data)

Memphis Office
1109 A State Office Building
Memphis, TN 38103
phone (901) 529-7294

Nashville Office
4721 Trousdale Drive
Nashville, TN 37219
phone (615) 741-6860

Memphis Light, Gas, and Water Division
(drilling information, pumping, water-level data)

P.O. Box 430
Memphis TN 38101
phone (901) 528-4011

U.S. Army Corps of Engineers
(well-drilling information; stratigraphy; lithology, primarily concentrated in alluvial plain of Mississippi River; two-dimensional ground-water flow model)

Memphis District
U.S. Army Engineer District, Memphis
Corps of Engineers
668 Clifford Davis Federal Building
Memphis, TN 38103
phone (901) 521-3635

Table 2.--A SUMMARY OF PUBLISHED GROUND-WATER AND GEOLOGIC REPORTS OF THE MEMPHIS AREA

Subject Area	General Hydrology	Water Levels	Pumpage	General Geology	Water Quality	Modeling Studies
Regional-Mississippi Embayment	Cushing & Others, 1970 Hosman & Others, 1968 Payne, 1968 Boswell & Others, 1968 Krinitsky & Wire, 1964	General Hydrology references contain water levels	General Hydrology references contain pumpage	Fisk, 1944 Stearns, 1957 Cushing & Others, 1964	General Hydrology references contain water quality	Reed, 1972
West Tennessee	Wells, 1933 Moore, 1965	General Hydrology references contain water levels	General Hydrology references contain pumpage	Stearns & Arm-strong, 1955 Stearns & Zurawski, 1976	Wells, 1933 Moore, 1965	
Shelby County, Tennessee and Memphis	Wells, 1931 Kazmann, 1944 Schneider & Cushing, 1948 Criner & Armstrong, 1958 Criner, Sun & Nyman, 1964 Nyman, 1965 Bell & Nyman, 1968	USGS WSP 817, 840, 845, 886, 907, 937, 945, 987, 1017, 1024, 1072, 1097, 1127, 1157, 1166, 1192, 1222, 1266, 1322, 1405, 1538, 1803, 1978, 2171 Criner & Parks, 1976 Graham, 1978	Criner & Parks, 1976	Parks, 1973a; 1973b; 1974; 1975; 1977a; 1977b	Bell & Nyman, 1968 Criner, Sun & Nyman, 1964 Parks & Lounsbury, 1976 Waste Age, 1979 Parks, Graham & Lowery, 1981	
North Mississippi	Dalsin & Bettandorff, 1976 Newcome, 1976 Boswell, 1976 Dalsin, 1978	General Hydrology references contain water levels	Callahan, 1973		General Hydrology references contain water quality	
East Arkansas	Plebuch, 1961 Ryling, 1960 Halberg & Reed, 1964	General Hydrology references contain water levels	Halberg, 1972 Halberg, 1977			

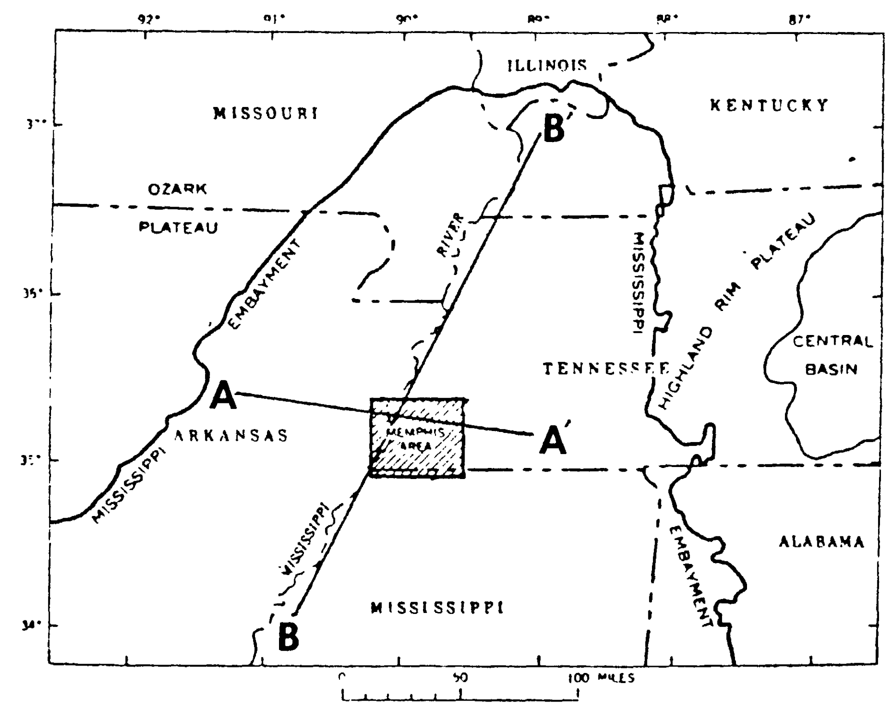

Figure 1.--Location of the study area showing generalized lines of sections A-A' and B-B'.

Geologic Setting

The study area is near the center of the northern half of the Mississippi embayment, a structural trough that at Memphis has been filled by about 3,000 feet of unconsolidated gravel, sand, silt, and clay. The trough axis strikes N. 30° E., with the present course of the Mississippi River approximately marking the axis. Near Memphis, the axis of the embayment plunges southwestward at about 10 feet per mile.

Fisk (1944), Criner and others (1964), and Stearns and Zurawski (1976) are among researchers who feel there is evidence for faulting in the study area. However, abrupt facies changes, lack of marker beds, and vertical lithologic similarity of sediments make positive fault definition difficult.

Stratigraphically, the study is limited to the Memphis Sand, and to those geologic units that may have a direct hydrologic relation to the Memphis Sand (table 3). This formation, which ranges from 500 to 880 feet thick in the Memphis area (Criner and Parks, 1976), is made up of fine- to coarse-grained sand and subordinate lenses of clay and lignite. Geophysical logs of many wells indicate that the lower part of the Memphis Sand may contain clay beds that are areally more extensive than those in the upper part of the formation. Even the thickest of the clay beds is discontinuous, however, and the Memphis Sand is considered a single hydrologic unit (Criner and others, 1964).

At most places in the study area, the Memphis Sand is overlain by beds of clay, sandy clay, fine-grained sand, and lignite that are assigned to the undifferentiated upper part of the Claiborne Group and the Jackson Formation. Within the Memphis area this sequence of beds forms a zone that varies in thickness from 350 feet at Mallory well field to a feather edge where it pinches out in southeastern Shelby County. Where present, these fine-grained sediments retard the downward movement of water from the overlying formations and form the upper confining bed for the Memphis Sand. Geophysical logs of wells throughout the area show that both the thickness and nature of the confining bed are variable.

South of the study area, the Memphis Sand and its equivalent units thicken along the axis of the Mississippi embayment. The units crop out on the east side of the embayment; on the west side they have been extensively eroded and truncated, and younger Mississippi River alluvial sediments have been deposited directly on top of them. This relationship of the Memphis Sand and overlying alluvium is called a subcrop, and occurs throughout the subsurface in the Mississippi River alluvial plain except where a segment crops out at the surface as part of Crowleys Ridge in Arkansas (Hosman and others, 1968). These generalized relationships are shown in figure 2.

South of Memphis, approximately along lat 35° N., a zone of transition (facies change) occurs in the Memphis Sand. The middle sand units become increasingly clayey, and effectively separate the top sand unit from the bottom sand unit. In Arkansas, the interval equivalent to the Memphis Sand includes the Carrizo Sand, the Cane River Formation, and the

Table 3.--Post-Midway geologic units underlying the Memphis area and their hydrologic significance.

System	Series	Group	Stratigraphic unit	Thickness (feet)	Lithology and hydrologic significance
Quaternary	Holocene and Pleistocene		Alluvium	0-175	Sand, gravel, silt, and clay. Underlies the Mississippi River alluvial plain and the flood plains of other streams in the area. Supplies water to a few domestic and industrial wells. Could be an important source of water for irrigation and some industrial uses.
	Pleistocene		Loess	0-65	Wind-deposited silt; silty clay and minor sand. Forms a blanket over the fluvial deposits in upland areas; topographically higher than alluvium. Thickest on the bluffs that border the Mississippi River alluvial plain; generally thinner towards the east. Not a source of ground-water.
Quaternary and Tertiary	Pleistocene and Pliocene		Fluvial deposits (terrace deposits)	0-100	Sand and gravel; minor ferruginous sandstone. Underlies the upland areas in a broad, irregular belt east of the Mississippi River alluvial plain; may be locally absent. Supplies water to many shallow, small-capacity wells in suburban and county areas.
Tertiary	Eocene	?	Jackson Formation and upper part of Claiborne Group ("capping clay")	0-350	Gray, bluish-gray, greenish-gray, and tan clay; subordinate beds of fine-grained sand and lignite. Supplies water to some small-capacity wells. Generally considered to be of low permeability and to confine water in Memphis Sand.. Absent in southeastern part of Memphis area.
		Claiborne	Memphis Sand ("500-foot" sand)	500-880	Fine- to coarse-grained sand; subordinate lenses of clay and minor amounts of lignite. Thick clay bed locally in lower part; coarse sand lenses locally at base. Very good aquifer supplying 95 percent of water used in Memphis area.
		Wilcox	Flour Island Formation	160-350	Gray, greenish-gray, and brown carbonaceous clay. Locally contains fine-grained sand lenses and some lignite. Serves as lower confining bed for Memphis Sand and upper confining bed for Fort Pillow Sand.
	?		Fort Pillow Sand ("1,400-foot" sand)	210-280	Fine- to medium-grained sand; minor amounts of lignite and some clay lenses. Second principal aquifer supplying about 3 percent of water used in Memphis area.
	Paleocene		Old Breastworks Formation	200-250	Gray, greenish-gray, and brown carbonaceous clay. Contains some lignite and is sandy near top. Lower confining bed for water in Fort Pillow Sand.

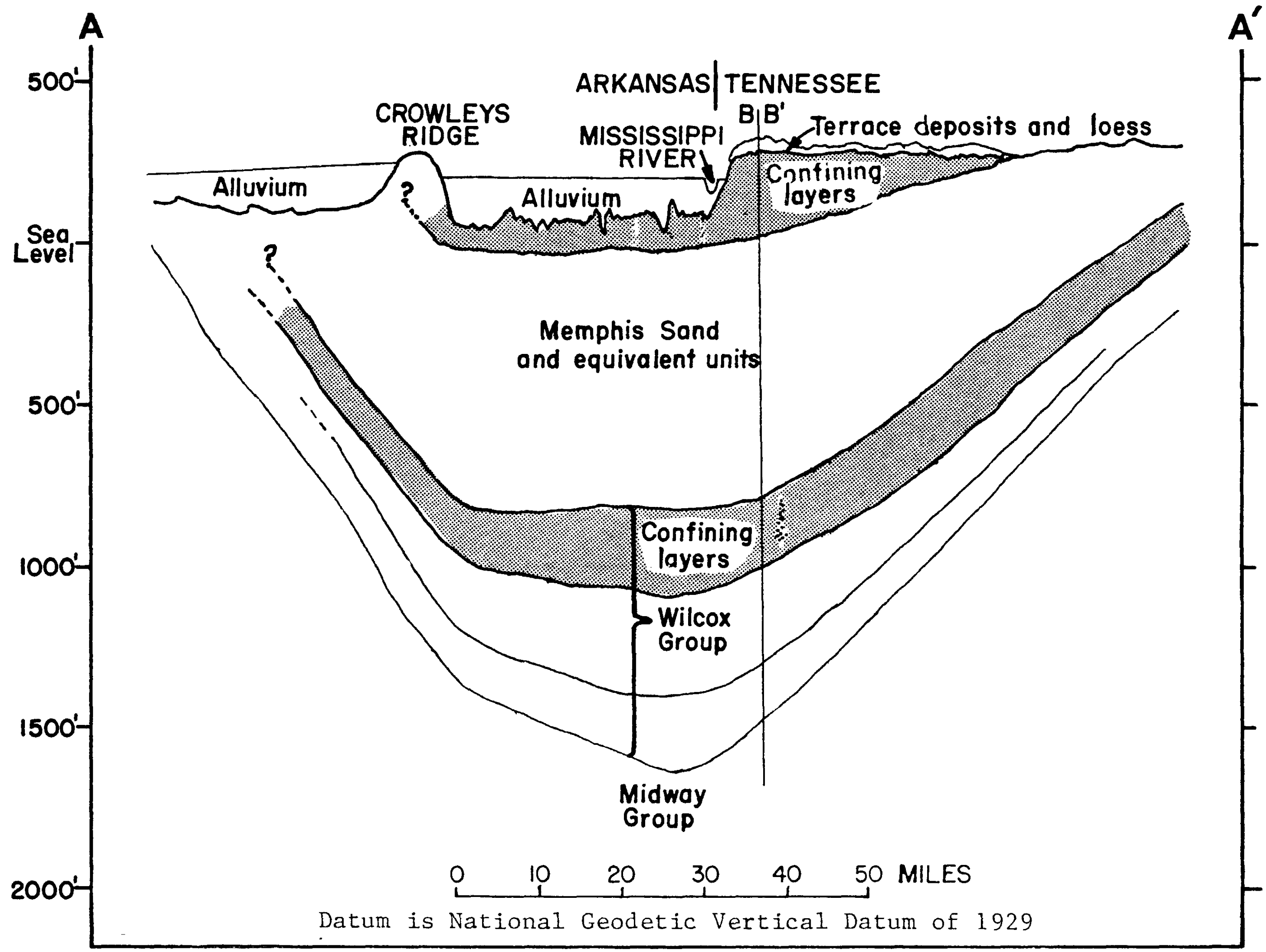

Figure 2.--Generalized geohydrologic section from west to east along line A-A'.

Sparta Sand; and in Mississippi, the Tallahatta Formation, Winona Sand, Zilpha Clay, and Sparta Sand (Hosman and others, 1968). For the purposes of this report, the Memphis Sand and its equivalent units in Arkansas and Mississippi are herein called the Memphis Sand. In the area of Memphis, the entire section of sand from the top of the Wilcox Group to the bottom of the "capping clay" of the Jackson Formation and upper part of the Claiborne Group constitutes a single aquifer hundreds of feet thick (Hosman and others, 1968). Figure 3 is a generalized geohydrologic section along the SW-NE trending line B-B' (fig. 1) that illustrates the above-mentioned relation.

Precipitation, Runoff, and Recharge

Precipitation serves as the ultimate source of recharge to the Memphis Sand. Mean annual precipitation is more than 48 inches per year in the Memphis area, and most occurs during the winter and spring. Droughts and low-flow conditions in streams are common during the late summer and fall. Low-flow studies in the area (Gold, 1978) have indicated that from 5 to 7 inches per year recharge the shallow aquifers where they outcrop north and east of the study area; most of this follows a fairly shallow ground-water path and reemerges as base flow of streams during the drier parts of the year. A small percentage of this recharge becomes part of the deep circulation pattern.

Hydrographs of wells tapping the Memphis Sand are characteristically sinusoidal: high during periods of recharge in the winter and spring, and low during the periods of greatest stress, during summer and fall. On a long-term basis, such as employed by the model, the effects of the seasonal variations cancel each other leaving the general water-level decline due to pumping as the dominant feature on the hydrograph.

Flow data from streams that drain the outcrop area of the Memphis Sand suggest that, during most of the year, the Wolf and Loosahatchie Rivers and Nonconnah Creek derive flow from ground-water discharge. Total discharge including storm runoff averages about 20 inches per year for these three streams. The upper Wolf, the upper Loosahatchie, and Nonconnah above the confluence with Johns Creek, lose flow to the Memphis Sand during the dry season at points along their reaches where the confining beds are absent.

Shallow ground-water aquifers likewise interact with the Memphis Sand in the area where it is confined. The confining beds that separate the shallow aquifers from the Memphis Sand vary in thickness and permeability (hydraulic conductivity). Where the confining beds are thinner and more permeable and head conditions are favorable, a significant amount of water may leak into or out of the Memphis Sand.

Water levels and water quality in the alluvium and Memphis Sand directly west of Memphis in eastern Arkansas are consistent with water being transmitted from the alluvium into the Memphis Sand. Likewise in the Memphis metropolitan area, similar water-level responses in the shallow terrace aquifers and the Memphis Sand suggest that leakage is recharging the confined aquifer here as well.

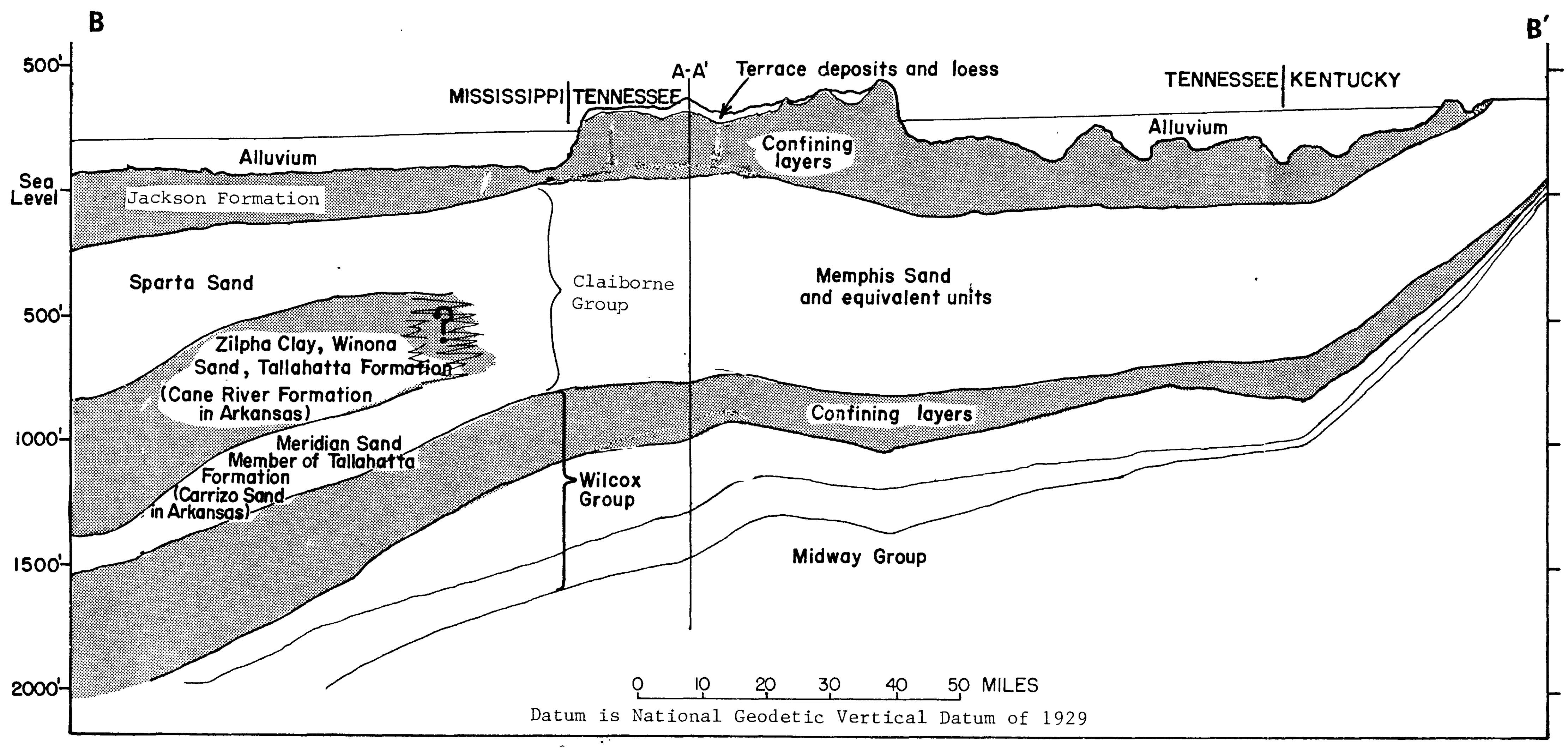

Figure 3.--Generalized geohydrologic section from southwest to northeast along line B-B'.

Discharge from the Memphis Sand into the alluvium occurs when head is greater in the Memphis Sand than in the alluvium. The Memphis Sand is thought to be discharging into the alluvium along much of the area where the Memphis Sand subcrops beneath the alluvium in Arkansas and Missouri (fig. 2).

BASIC MODELING CONCEPTS

The model of the Memphis Sand described in this report is based on the numerical approximations of the two-dimensional differential equation describing ground-water flow. The boundaries, aquifer properties, initial conditions, and pumping are input to the equations, and resulting drawdowns and heads are calculated. Adjustment of the input parameters in the calibration phase of the study optimizes the response calculated by the model to the response actually observed in the field. Split-sample testing and a sensitivity analysis of the model as a final step verified it as a tool capable of predicting water levels for pumping stresses different from those for which it was developed.

From Pinder and Bredehoeft (1968), the equation for transient two-dimensional flow of a homogeneous compressible fluid through a nonhomogeneous, anisotropic aquifer may be written as equation 1:

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial x}\left(T_{xy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial y}\left(T_{yx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right)=S\frac{\partial h}{\partial t}+W(x,y,t) \qquad (1)$$

in which

Txx, Txy, Tyx, Tyy are the components of the transmissivity tensor (L^2t^{-1});

h is hydraulic head (L);

S is the storage coefficient (dimensionless); and

W(x,y,t) is the volumetric flux of recharge or withdrawal per unit surface area of the aquifer (Lt^{-1}).

Considering only fluxes of (1) direct withdrawal of recharge, such as well pumpage, well injection, or evapotranspiration, and (2) steady leakage into or out of the aquifer through a confining layer or streambed, then W(x,y,t) may be expressed as:

$$W(x,y,t) = Q(x,y,t) - \frac{K_z}{m}(H_s - h)$$

where Q is the rate of withdrawal (positive sign) or recharge (negative sign), L/t;

K_z is the vertical hydraulic conductivity of the confining layer or streambed, L/t;

m is the thickness of the confining layer or streambed; L; and

H_s is the hydraulic head in the source bed or stream, L.

In the simulation model, equation 1 is simplified by assuming that the Cartesian coordinate axes x and y are alined with the principal components of the transmissivity tensor, Txx and Tyy, giving

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right) = S\ \frac{\partial h}{\partial t} = W(x,y,t) \qquad (2)$$

An exact solution to equation 1 is not possible mathematically because of the variable aquifer properties and variable boundary conditions, but a numerical solution of high accuracy offers an alternative that is practical for use on a digital computer. In this numerical method, the aquifer system parameters and boundaries, which are continuous in the field and are represented by equation 2, are replaced with a set of discrete values for each of the parameters and for the boundary. Determination of the values for these sets is accomplished by dividing the area into small rectangular subareas by means of a orthogonal grid, and taking the average value of each parameter in each block of the grid.

Equation 3 (Pinder and Bredehoeft, 1968) is the general form of the numerical method into which the appropriate discrete values are substituted and solved for each block in the grid. The equation yields head values calculated as finite-difference approximations to the continuous derivatives at a point (the node at the center of the block). Input values of appropriate hydrologic parameters represent average values for the entire block. Equation 2 may be approximated by equation 3, which is given as:

$$\begin{aligned}
& T_{xx}[i-(1/2),j]\left[\frac{h_{i-1,j,k}-h_{i,j,k}}{(\Delta x)^2}\right] \\
& \quad + T_{xx}[i+(1/2),j]\left[\frac{h_{i+1,j,k}-h_{i,j,k}}{(\Delta x)^2}\right] \\
& \quad + T_{xx}[i,j-(1/2)]\left[\frac{h_{i,j-1,k}-h_{i,j,k}}{(\Delta y)^2}\right] \\
& \quad + T_{yy}[i,j+(1/2)]\left[\frac{h_{i,j+1,k}-h_{i,j,k}}{(\Delta y)^2}\right] \\
& = S\left[\frac{h_{i,j,k}-h_{i,j,k-1}}{\Delta t}\right] \\
& \quad + \frac{q_w(i,j)}{\Delta x \Delta y} - \frac{k_z}{m}\left[H_s(i,j) - h_{i,j,k-1}\right] \qquad (3)
\end{aligned}$$

where i,j,k are indices in the x-, y-, and time-dimensions, respectively;

$\Delta x, \Delta y, \Delta t$ are increments in the x-, y-, and time-dimensions, respectively; and

q_w is the volumetric rate of withdrawal or recharge at the (i,j) node, L^3/t.

A modified version of a computer program written and documented by Trescott and others (1976) was used for the analysis of the Memphis Sand. The Trescott, Pinder, and Larson model offers several solutional schemes to solve the system of equations that results from writing a finite-difference equation (equation 3) for each block in the grid. The strongly implicit procedure (Stone, 1968) was used because of its computational efficiency.

DEVELOPMENT OF THE MEMPHIS SAND GROUND-WATER MODEL

Conceptual Model

A conceptual model serves as the basic framework for developing a digital ground-water model. The conceptual model possesses the significant hydrologic features essential to define accurately ground-water flow within an aquifer, yet at the same time it is much less complex than the real aquifer.

The conceptual model of regional flow prior to pumping in the Memphis Sand is shown in figure 4. Historical water-level maps were used to determine original flow directions and to locate sources of recharge and discharge (Hosman and others, 1968; Reed, 1972; Criner and Parks, 1976). The regional flow system was characterized by movement from the outcrop area of the aquifer in western Kentucky and Tennessee toward the axis of the embayment and from there to areas of discharge. The initial discharge areas were the area of the subcrop in Missouri and Arkansas, and upward leakage where the overlying confining beds were thin and sandy. Some flow is presumed to have continued across the southwestern boundary of the model area.

Transient conditions associated with pumping are thought to have dominated the system since 1886, when the first wells were drilled and pumped. From 1886 to 1975 pumpage at Memphis had lowered the original potentiometric surface by as much as 150 feet in the major pumping center and reversed the original gradient, which was to the west (Criner and Parks, 1976). Much of the flow that moved through the area toward natural discharge points to the south and west before 1886 is now diverted and captured by pumpage at Memphis.

Leakage to and from the Memphis Sand is thought to occur at locations where head differences, confining bed thicknesses, and confining-bed permeabilities (hydraulic conductivities) are favorable. Leakage is assumed to occur primarily through the upper confining layer (capping clay), and three-dimensional modeling has confirmed this assumption. No accommodation was made in this model for leakage from the Flour Island Formation, which is the lower confining layer to the Memphis Sand. Evidence for

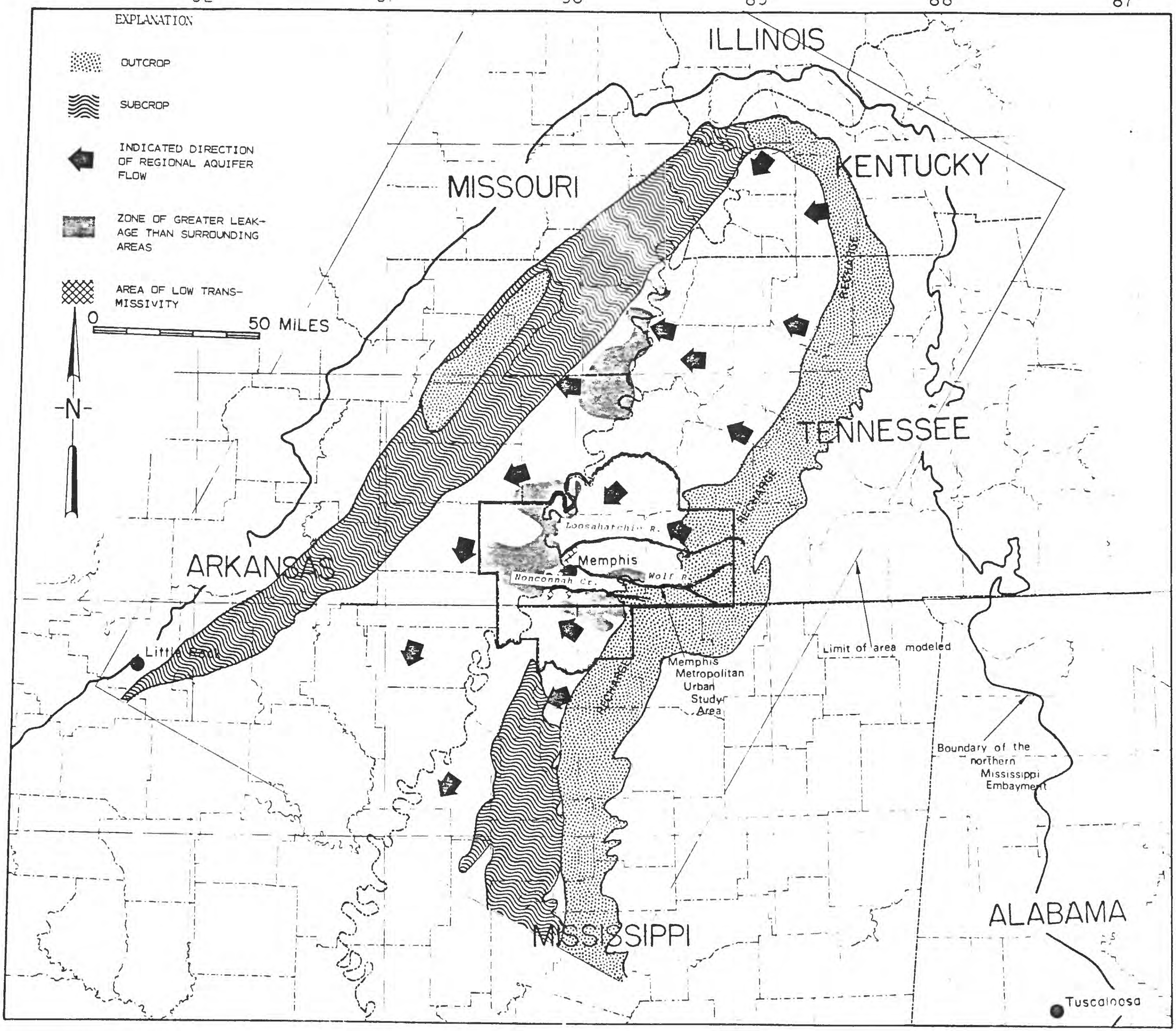

Figure 4.--Regional conceptual flow model of the Memphis Sand.

leakage includes greater than expected vertical hydraulic conductivity calculations from aquifer tests, observed water levels at altitudes higher than expected for known pumping rates and transmissivities, assymmetric water level response to pumping, and similarity of water levels and water chemistry between parts of the Memphis Sand and the alluvium (Ryling, 1960; Plebuch, 1961). Drilling records from exploration wells made by the Corps of Engineers in the Mississippi River alluvial valley and from electric logs from water and oil wells indicate a highly variable thickness of the confining bed and record its complete absence in some places (Krinitsky and Wire, 1964).

Evidence from pumping tests and grain size analyses of core samples (Criner and others, 1964; Moore, 1965; Bell and Nyman, 1968) as well as drilling records and the combined drawdown-pumping history records from Memphis indicate that the aquifer has a large hydraulic conductivity but is not homogeneous. Faulting, which is suspected (Fisk, 1944; Criner and others, 1964; Stearns and Zurawski, 1976), may contribute to the nonhomogeniety.

Digital Model

In the case of the Memphis Sand, the area was divided into discrete blocks and a form of equation 3 was solved at each block for specified boundaries, initial conditions, aquifer hydraulic properties, and pumping stresses.

Characteristics of the Model

The Model Grid

The rectangular grid that defines the arrangement of blocks in the model is alined parallel and perpendicular to the axis of the Mississippi embayment, and divides an area of almost 47,000 mi^2 into a 44 x 58 matrix (fig. 5, located at back of report). Spacing of the grid lines varies from 100,000 feet at the margins of the area to 3,200 feet within metropolitan Memphis.

The grid is closely spaced throughout the primary area of interest and is shown in figure 6 along with the location of pumping centers and control wells. The closer spacing allows a more refined input of pumping stresses to be placed on the model as well as more precise prediction of the resulting water levels in the aquifer. The grid spacing is adequate to define the response of major pumping centers as required by this study, but it is not suitable for defining individual wells within a well field. Pumping is input as the total of all wells represented as a single well for the block, and it is centered in the middle of the block. By convention, centers of the blocks are called nodes. Any specific node may be located by designating its row (i) and column (j) location. For example, Davis well field (fig. 6) in southwest Memphis is located in node (50, 17).

All the aquifer parameters and head values of each block represent an average value over the entire block. This approximation requires that precise well location be known, especially in the areas of steep water-level gradients and intensive pumping.

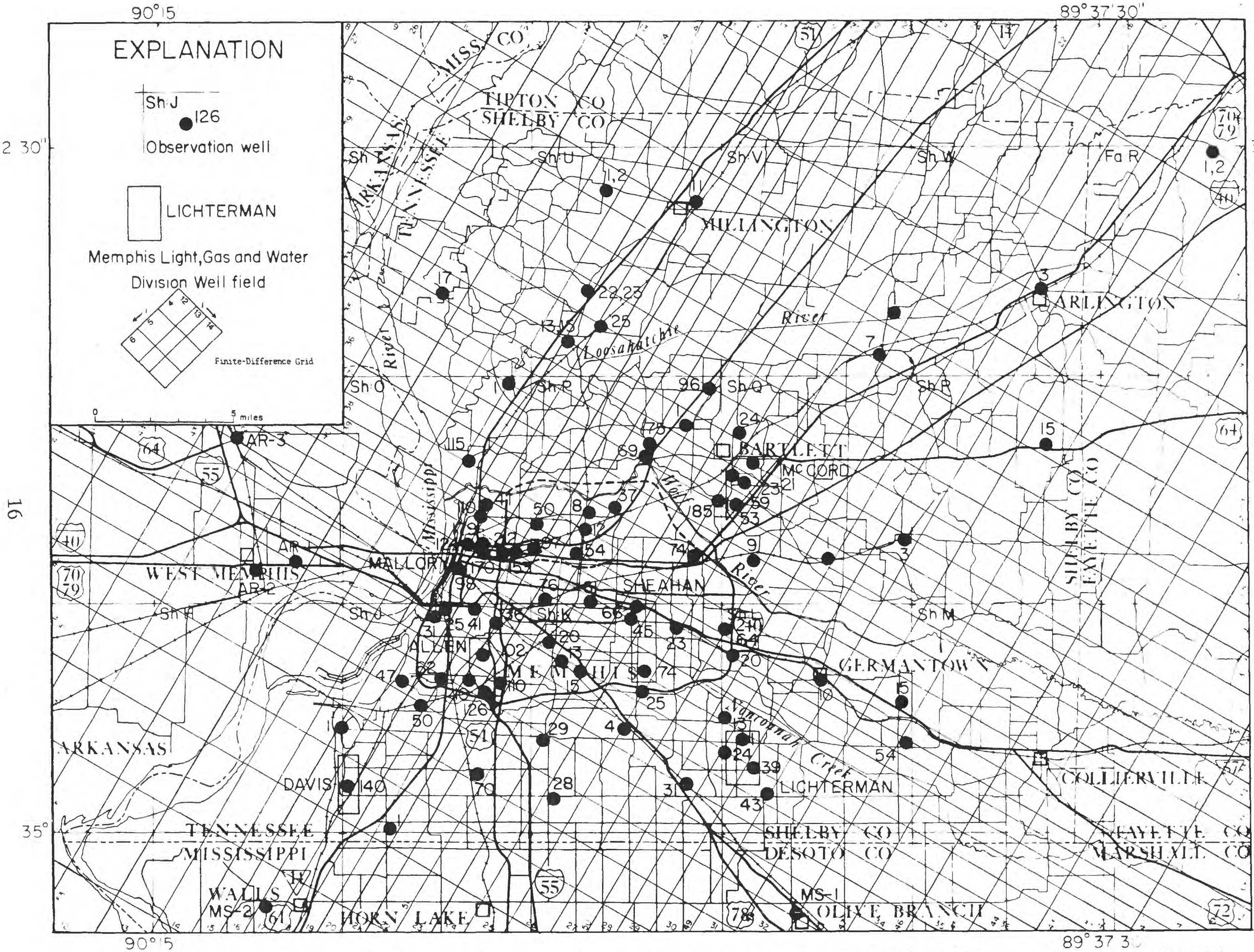

Figure 6.--Location of municipal well fields and control wells within the finite-difference grid in Memphis.

Boundaries of the model

The model is bounded on the north, east, and west by a representation of the natural boundary of the Memphis Sand and the overlying confining bed (fig. 5). The southern boundary has no geologic significance; it was chosen because (1) it was greater than 50 miles from Memphis, and (2) its position did not influence calculated water levels in the Memphis area.

The outcrop area of the Memphis Sand is represented in the model by two conditions. For one condition, where major streams flow year-round in the outcrop area, the corresponding block of the model grid is represented by a constant head. For the second condition, those blocks that have intermittent streams or no streams are modeled as recharge zones with constant flux. This flux represents precipitation that infiltrates and recharges the aquifer. The constant head conditions of the streams in nearby blocks divert excess recharge (representing base flow) and prevent excessive head build up in the constant flux blocks.

In those blocks modeled with constant flux conditions, head may vary with different pumping periods. This phenomenon has been observed in the field in southeast Shelby County along the upper reaches of Nonconnah Creek.

The outcrop area is modeled as an unconfined ground-water aquifer, with storage coefficients in the range of 0.2. In locations near the outcrop area where the upper confining bed is discontinuous, there is a transitional zone of semiconfined conditions. Vertical leakage occurs where the confining bed is thin or absent. The remainder of the aquifer has confined ground-water conditions, and has been modeled as such.

The subcrop of the Memphis Sand beneath the alluvium along the western boundary and also in the southeastern part of the area is modeled as a zone of high leakage. This simulates natural recharge and discharge between the Memphis Sand and overlying alluvium. At Crowleys Ridge, the aquifer crops out and is recharged; blocks corresponding to this feature are modeled as constant flux recharge.

The southern boundary of the Memphis Sand is modeled as a zone of high leakage to simulate under flow out of the area. It should be stressed that this boundary does not represent a physical boundary of the aquifer, but rather it is an areal boundary beyond the range of effect of any pumpage at Memphis. Choice of this boundary was necessitated by economics and computer storage limitations; results from the modeling computations indicate the representation is valid.

Aquifer Characteristics Modeled

Data used in the model were derived from numerous published and unpublished investigations made in the area (table 4). Because parts of the area have been studied by different researchers, disagreement as to the validity of certain data and conclusions exists. After evaluation, these data were plotted and contoured on a base map of the study area. The grid was superimposed and values were assigned by interpolation and weighted mean methods for each grid block.

TABLE 4.--DESCRIPTION OF INPUT PARAMETERS

PARAMETERS	RANGE OF PARAMETER	GENERALIZED SENSITIVITY OF MODEL TO RANGE OF PARAMETER	BASIS OF PARAMETER DEFINITION	SOURCE OF DATA	COMMENTS
Initial Head	125 to 400 (Feet above NGVD of 1929)	Low (drawdown) Highly sensitive (W.L. maps)	4 Points All Extrapolated	Criner & Parks, 1976 Reed, 1972 Chester & Fleming, 1920 Wells, 1931 & 1933	Maps are based on few data points, with none west of the Mississippi River in Arkansas. Water quality data and geology are used to reconstruct some flow directions.
Storage Coefficient	.00055 to .001	Low	Existing maps Unpublished pumping tests	Reed, 1972 Payne, 1968 Cushing, unpub. map Moore, 1965 Unpub. USGS records	Maps constructed by Cushing & Reed assumed to be proportional to thickness of the aquifer for confined areas.
Transmissivity	1,300 to 60,000 (ft^2/d)	Moderately sensitive	Existing maps Published and unpublished pumping tests	Reed, 1972 Reed, unpub. map Cushing, unpub. map Moore, 1965 Unpub. USGS records	Transmissivity maps based on thickness of sands and on scattered aquifer test results. Cushing's data used north of 35° N. lat.
Vertical Hydraulic Conductivity of Confining Bed	8.6×10^{-5} to 2×10^{-2} (ft/d)	Highly sensitive	Calibration Acceptable range from modeling literature No direct observation	Krinitzsky and Wire, 1964 Unpub. USGS records	This factor, as in most modeling studies, is poorly defined at best. Slight changes in input affect model results very markedly. With reasonable values input for the other parameters, this parameter can be obtained from the model.
Head in Overlying Aquifer	159 to 312 (feet)	Low	Maps - mean w. l. Published and unpublished water levels (>100 points)	Krinitzsky and Wire, 1964 Unpub. USGS records	Based on mean water levels, these values are fairly well defined but are subject to natural variation of as much as tens of feet.
Thickness of Confining Bed	45 to 180 (feet)	Low	Bore hole records E-log records (>100 points)	Krinitzsky and Wire, 1964 Unpub. USGS records	Original data from Corps of Engineers bore holes (in Mississippi River alluvial plain) and from unpublished USGS E-logs.
Boundary Flux	0.9×10^{-9} 1.0×10^{-6} (ft^3/s)	Moderately sensitive	Calibration Extrapolated from water budget studies No direct observations	Unpub. USGS records	Most of the precipitation that falls and infiltrates on the outcrop area reemerges as base flow of the streams draining the area. This parameter represents deep infiltration for the node. All data are indirect.
Pumpage Rates	50,000 to 25,000,000 (gal/d)	Highly sensitive	Empirical Water use inventories	Criner & Parks, 1976 Callahan, 1973 Unpub. USGS records	Data sources include, ongoing inventories in Shelby County & Mississippi & Arkansas. Rural Tennessee based on an updated study in 1976. Historic data is variable, with better records for the most part in the area of study.

The following parameters were input to the model as individual values for each grid block:

(1) initial head - the altitude of the water level in the Memphis Sand prior to pumping (1886),
(2) the storage coefficient of the aquifer,
(3) the transmissivity of the aquifer,
(4) the vertical hydraulic conductivity of the confining bed, and
(5) the head in the unconfined aquifers or rivers overlying the Memphis Sand,
(6) the thickness of the confining bed separating the unconfined alluvial aquifer from the Memphis Sand,
(7) the recharge to the aquifer from precipitation, simulated by constant flux cells and the discharge from the area, simulated by leakage out, and
(8) the discharge from pumping.

Table 4 defines the source of these input data and the range for each parameter used in the model.

Stresses on the System

Pumpage from the Memphis Sand began in 1886 when the Bohlen Huse Ice Co. drilled a well in downtown Memphis. Since that time, pumpage from the aquifer has occurred at varying rates and with a changing areal distribution of pumping centers. Because of variation with time, pumpage data were introduced in the model in seven discrete pumping periods. The modeled pumpage and the corresponding amount actually pumped for the seven periods are shown in figure 7.

The pumping periods were based on abrupt changes in pumpage rates, or variations in the areal distribution of pumping centers, and on availability of water-level maps. Pumping period duration, the historic amount pumped, in millions of gallons per day, and the pumpage simulated in the model are given in table 5. Variations between historic amount pumped and modeled amount pumped are less than 1 percent of total pumpage prior to 1965. Differences are due to round-off errors of simulated pumpage for which the withdrawal location was not known.

Although the exact pumping location was not always known, the centers of pumping were fairly well defined. The unlocated pumpage was assigned to nodes that fell within those pumping centers.

Actual pumpage generally increases throughout a pumping period, whereas the model maintains a constant pumping rate throughout a pumping period (fig. 7). The effect of different pumping rates may be observed by plotting computed hydrographs showing all time steps with observed hydrographs for selected wells in the area; the computed hydrographs show the computed water-level trends as steeper than actually observed at the beginning of the pumping period, and flatter than actually observed at the end of the period. Because the pumping rate modeled represents an average pumped during the interval, the rate for the model is greater than actual at the start, and less than actual at the finish. The water levels, however, should be similar at the end of a pumping period. Also

Table 5.--Summary of historic and simulated pumpage, in millions of gallons per day, used in the Memphis Sand ground-water model

Pumping period	Dates of occurrence	Historic pumpage *	Total simulated pumpage	Volume of simulated pumpage for which withdrawal location was not known
I	1886-1924	30.29	30.61	8.0
II	1925-1941	64.69	63.94	40.0
III	1942-1955	101.96	101.56	34.0
IV	1956-1960	122.50	122.15	17.8
V	1961-1965	141.26	141.59	14.9
VI	1966-1970	161.10	161.10	15.0
VII	1971-1975	184.80	184.80	0

* Criner and Parks, 1976.

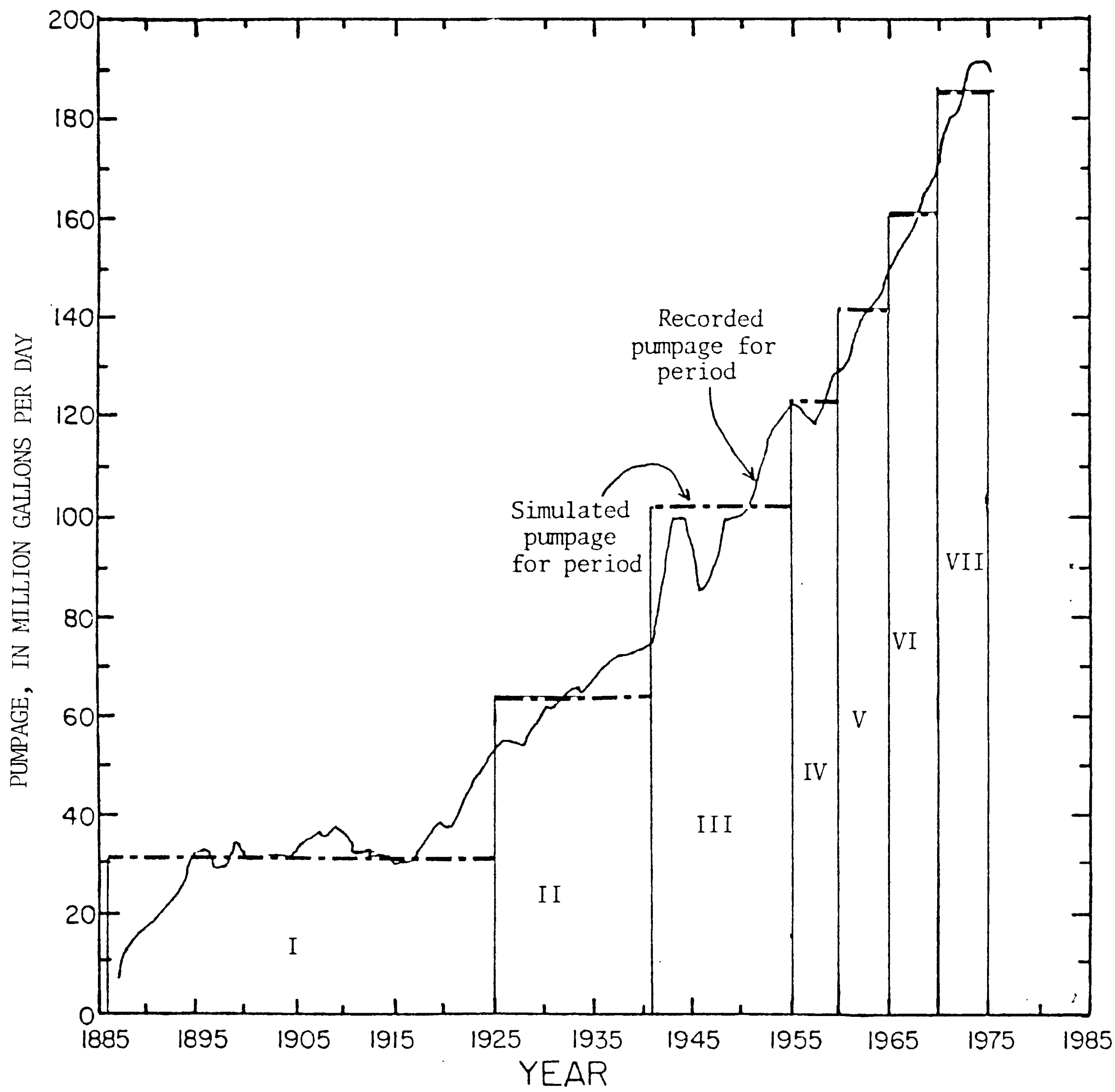

Figure 7.--Recorded and modeled pumpage for seven pumping periods from 1886 to 1975.

important is the fact that both the model and the actual hydrologic systems tend toward an equilibrium, which is observed in a stabilization of water-level trends after the abrupt initial decline.

Figure 8 shows calculated water levels at the end of pumping periods superimposed on observed hydrographs of six selected observation wells (Criner and Parks, 1976).

Calibration of the Model

Calibration of the model is the process in which differences between the observed and computed water levels are minimized by adjusting aquifer hydraulic properties and boundary conditions. As Konikow (1976) has pointed out, the large number of interrelated factors affecting ground-water flow makes calibration a highly subjective procedure, but one that can be simplified by evaluating the certainty of input parameters. Those values that are confidently known are not adjusted, which reduces the number of parameter combinations the modeler must evaluate.

Table 4 lists the input parameters and summarizes the significant features of each in the model. The parameter values used provide the "best fit" of the computed values of the model to the water levels observed in the field.

Initial calibration was conducted on a steady-state prepumping model using the input values and boundary conditions described previously. Water levels and ground-water discharge were computed and compared with observed data, and hydrologically reasonable adjustments were made to various parameters until an acceptable match of calculated and observed data occurred. The most significant adjustments were made on the vertical hydraulic conductivity of the confining bed separating the shallow aquifers from the Memphis Sand and on the constant flux nodes that simulated the recharging boundaries.

The results of the steady-state calibration are shown along with the 1886 water level as envisioned by Criner and Parks (1976) in figure 9. Criner and Parks (1976) based their map on four control points, which are simulated by the model within 5 feet. Part of the difference between the water-level maps is ascribed to the fact that control in the area is areally and temporally incomplete for water-level and pumping history.

An important result of the initial steady-state calibration was the refinement of the conceptual model of flow in the aquifer. Initial runs utilizing constant-head boundaries and the best estimate of aquifer characteristics resulted in a calculated water level map similar to that presented by Criner and Parks (1976).

Calibration of the pumping periods I, II, V, and VI was undertaken to refine the model further and test its ability to reproduce the observed water-level configurations under transient conditions. Input data that most nearly simulated Criner and Parks (1976) steady-state map resulted in a poor simulation of transient conditions. Modifications to input data were made in the same manner as for the steady-stage calibration until a best fit for the transient periods and steady state was

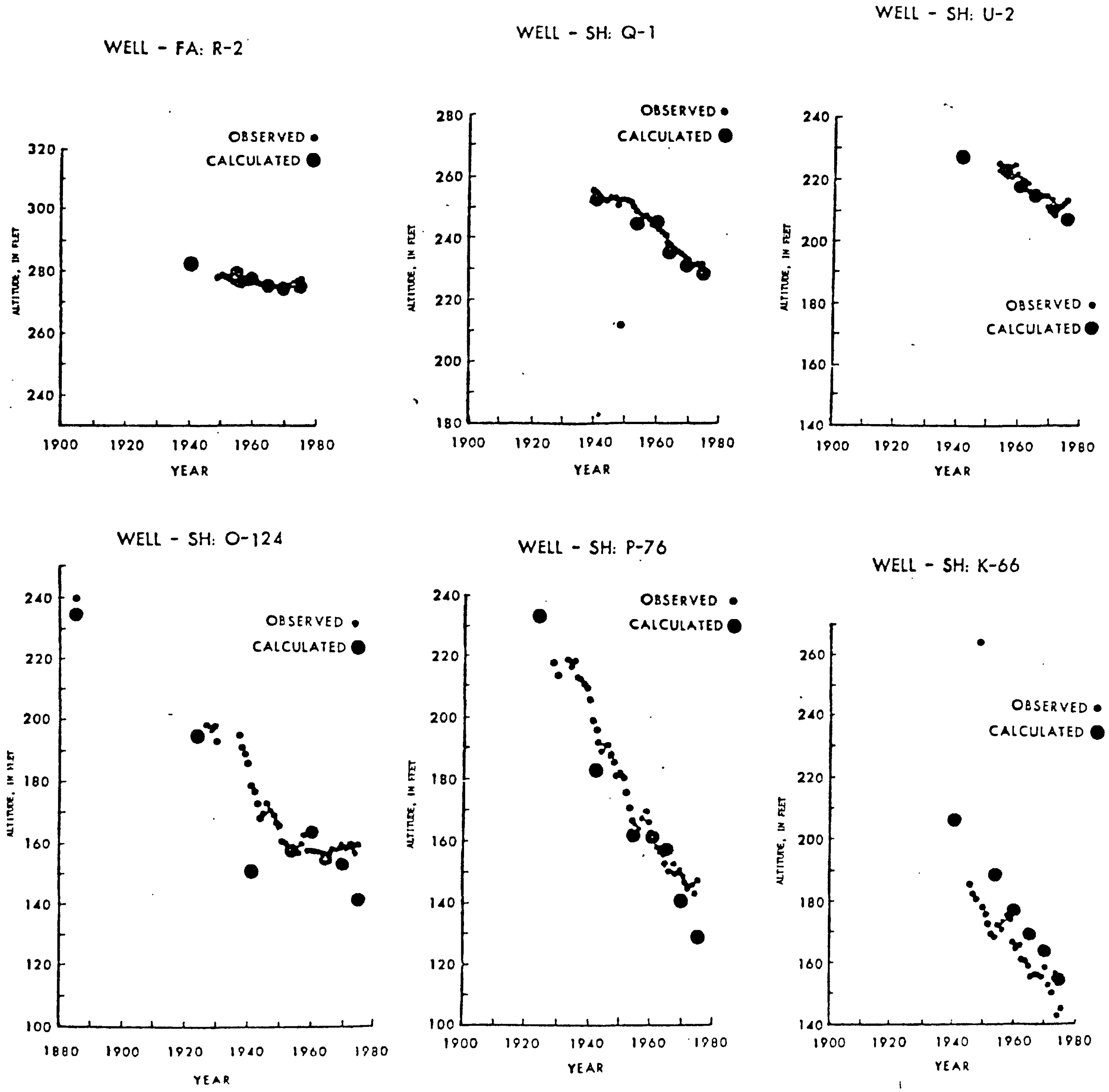

Figure 8.--Selected hydrographs of observed and computed water levels within the Memphis Sand.

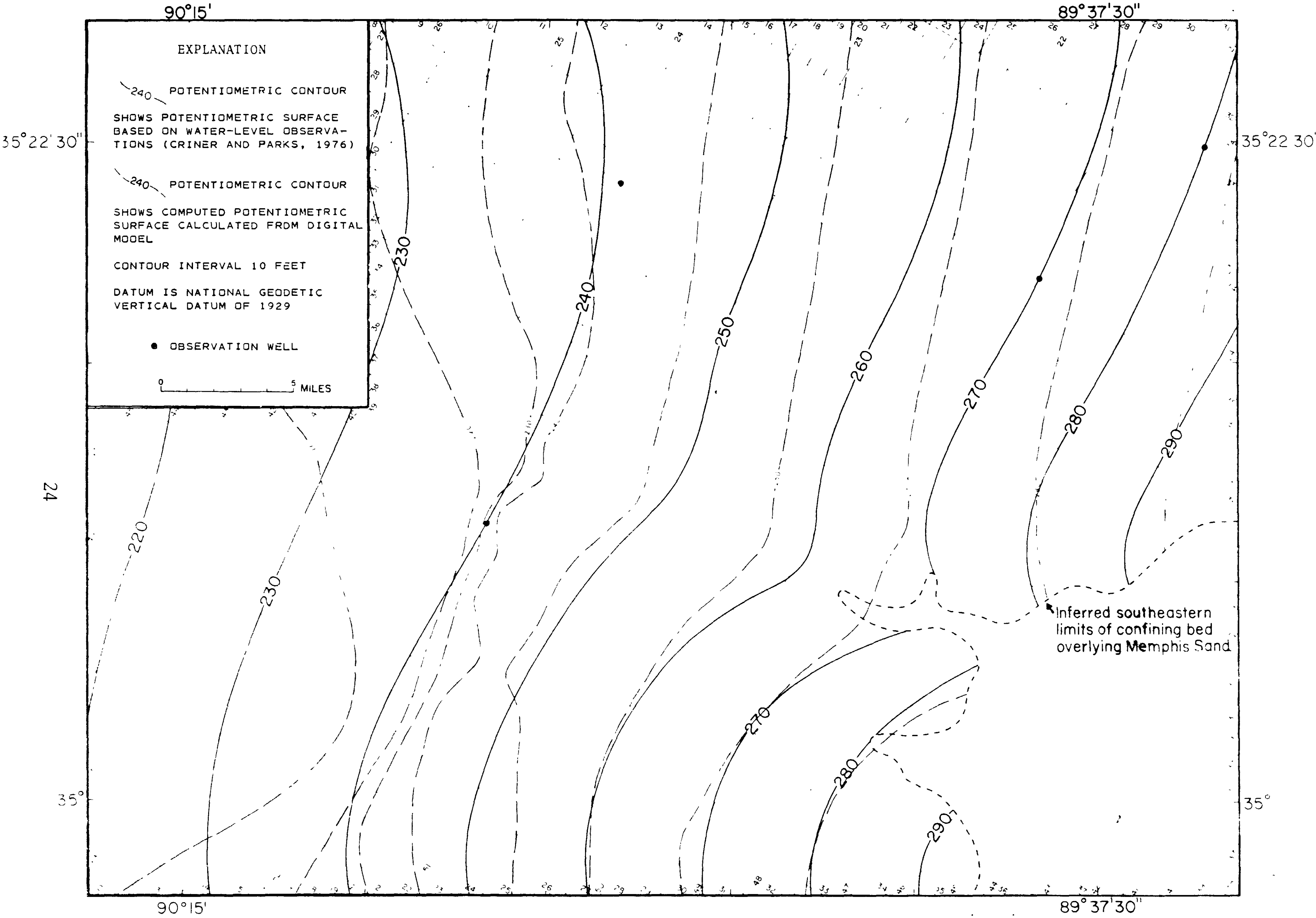

Figure 9.--Computed and observed steady-state water-level map of the Memphis Sand, 1886.

determined for one unique, specific set of input data. Inasmuch as data were sparse for the earlier pumping periods, more importance was attached to calibration of pumping periods V and VI.

Because calibration periods were split into several discrete intervals and not run as a continuous sequence, observed water level at the beginning of pumping period I and pumping period V were input. This had the effect of splitting the sample into four parts: a calibration (I-II), followed by a verification (III-IV); and another original calibration (V-VI), followed by a final verification (VII).

The two zones of low transmissivity (fig. 4), whose presence is consistent with other hydrologic and geologic evidence, were located in the calibration phase, as was a refinement in definition of the leaky zones of the confining layer.

Figure 10 shows the results of pumping at the end of pumping period VI, the final calibration period. Major features of the water-level surface are generally well reproduced by the model, particularly the asymmetric shape of the cone of depression in Memphis, details in the cone at the major points of pumpage, the steep slope of the cone to the west and the fairly flat potentiometric surface underlying the alluvium. Table 6 shows the rates computed for major elements of the hydrologic budget for pumping period VI (1966-1970).

More than 100 hydrologically possible configurations of aquifer properties, pumpage, and recharge were run and evaluated. Calibration runs that did not include high-leakage zones from parts of the Mississippi alluvial aquifer and near the recharge areas east and south of Memphis and the low-transmissivity zones as shown in the conceptual model did not simulate the observed water-level measurements as well as those that included these features.

Removal of the low-transmissivity zones shifted the effect of simulated pumping to the west and tended to reduce the calculated drawdown and diffuse it over a larger area. Exclusion of high leakage zones in the alluvial plain to the west resulted in greater than observed drawdowns during transient calculations and poorly matched water-level configurations during both steady-state and transient simulation.

The calibration of this model involved matching calculated and observed water levels with as many as 48 observation wells for a given pumping period. Throughout the calibration phase, close simulation of the observation well data was highest priority. In addition to these discrete point matches, the general symmetry of the calculated water-level surface was matched qualitatively to interpretive water-level maps that were based on more extensive although unverified data.

Historic pumping and water-level data collected prior to 1960 were commonly incomplete, and in some cases, were inaccurate. Calculations based on these data made matching water levels from individual observation wells difficult. The overall "goodness-of-fit" of calculated

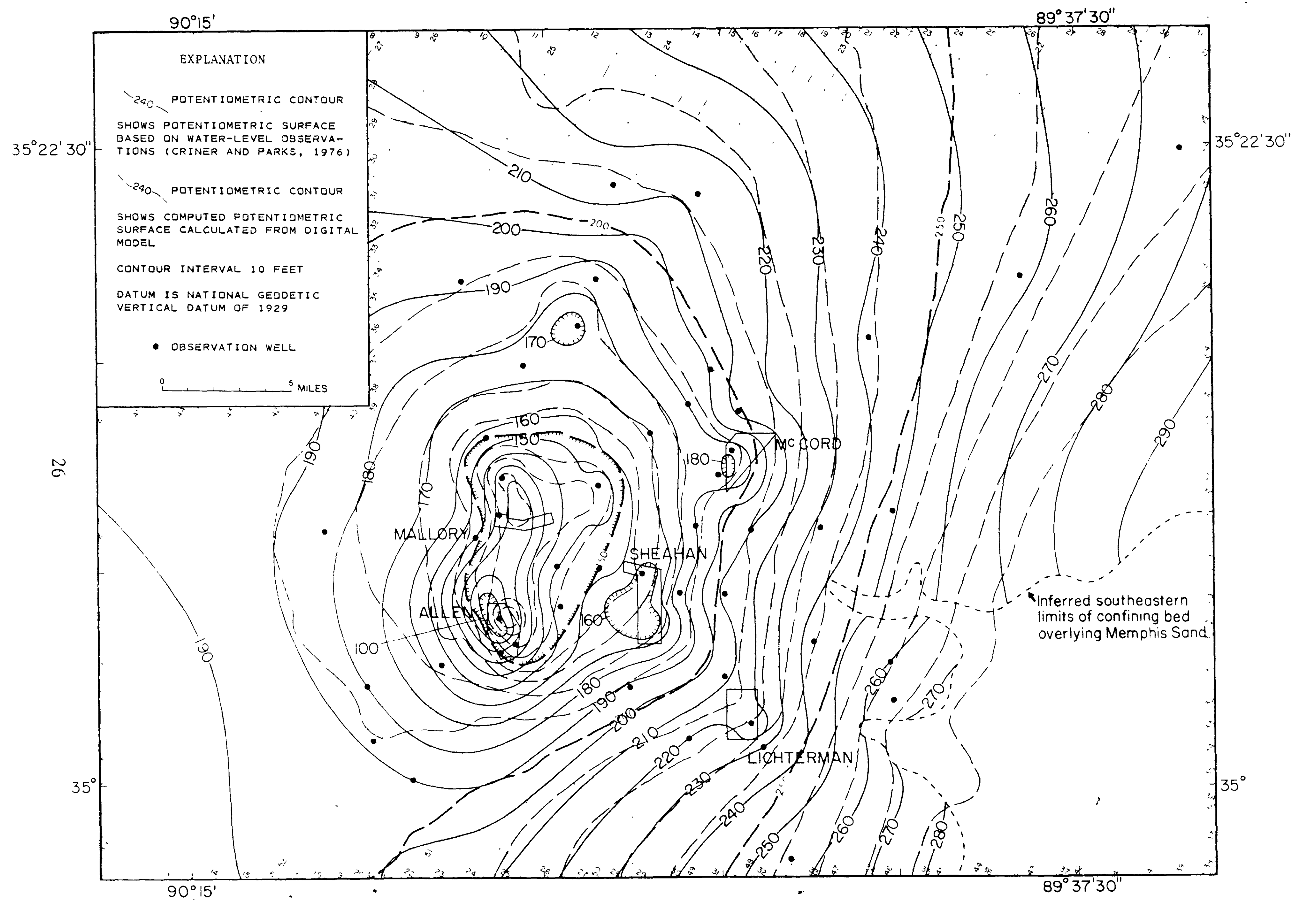

Figure 10.--Computed and observed transient water-level map of the Memphis Sand, 1970, (Period VI).

Table 6.--Generalized hydrologic budget computed by model for pumping period VI (1966-1970)

	Millions of gallons per day
Total pumpage from wells in Memphis metropolitan area	164.1
Recharge - simulated by recharge boundaries east and northeast of study area	91.6
Vertical leakage to aquifer - primarily from near outcrop area, Mississippi River alluvium, and zones along upper reaches of Wolf and Loosahatchie Rivers and Nonconnah Creek	61.2
Storage	11.3

water levels to observed water levels, however, gave confidence in the results calculated by the final model because it simulated conditions quite closely.

Reliability of the Model

Testing of model reliability was accomplished by split-sample testing. With this method, pumpage data, which were not used during any aspect of the calibration phase, were run in the calibrated model. No aquifer parameter changes were made during the verification. Water levels calculated by the model were within the predetermined range of accuracy of the water level as measured, and the model was judged acceptable. The acceptable accuracy limit was simulation to within 5 feet for 75 percent of the observation wells.

The Memphis Sand model was verified using data from pumping periods III, IV, and VII. The computed results of a single run from pumping period VII are shown in figure 11.

The model was successful in reproducing the general water-level configurations for pumping periods III and IV, and for qualitatively simulating the major features and most of the details of pumping period VII. Variations between the observed and calculated values of pumping periods III and IV can be accounted for in part by the fact that exact pumping locations for about 33 percent of total pumping were not known and thus assigned to known well fields for period III, and about 15 percent were similarly assigned to period IV.

During pumping period VII the location of all pumpage was known, and new heavy pumping began during this period. Because the new pumping could not be considered in earlier calibration runs to help determine recharge, the verification runs for this period did not meet the accuracy standards. They were, however, close to those standards (71 percent).

The verification procedure addresses the question of model capabilities and prediction reliability insofar as data exist, but it does not specify the source or cause of error, defined as the difference between calculated and observed data. In the Memphis Sand model, a qualitative estimate of reliability has been assigned to the general sources of error described below, and estimates for specific parameters are provided in table 4.

Four general sources of error are common with models; these limit the effect of the model as a predictive tool, and if not evaluated carefully, commonly lead to misapplication of the model. The errors are:

(1) poor choice and application of a numerical scheme to approximate the flow equations;

and lack of accuracy or completeness in definition of:

(2) aquifer boundary simulation;
(3) aquifer hydraulic properties; and
(4) historic records of stress (pumping) and response (water level).

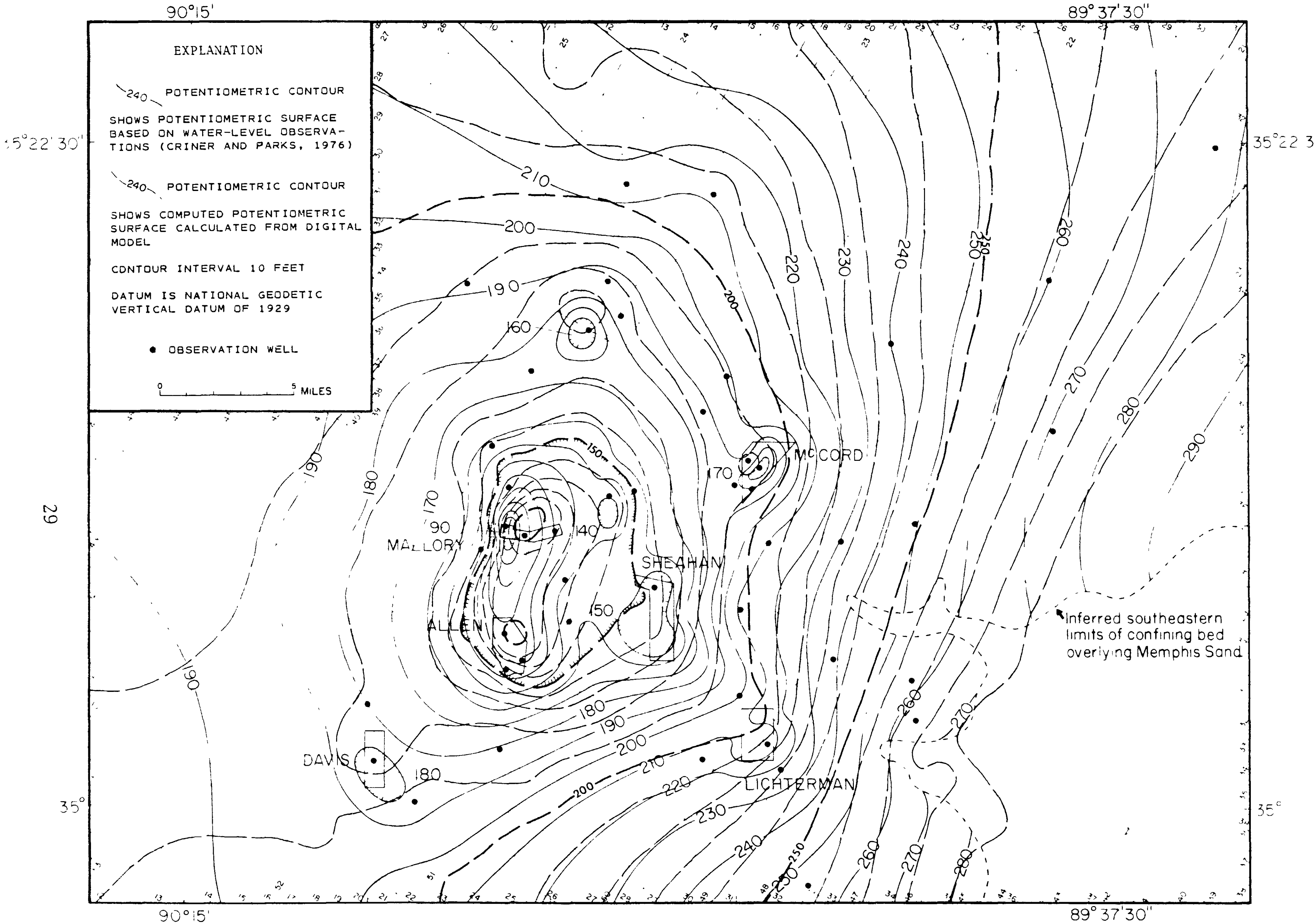

Figure 11.--Computed and observed transient water-level map of the Memphis Sand, 1975, (Period VII).

The Memphis Sand model used the SIP (strongly implicit procedure) solutional scheme, which has successfully been applied to studies in similar hydrologic terrains (Trescott and others, 1976). From the transferability of results from these similar studies, and from the evaluation of the mass balance error of 0.01 or less on the final runs of the Memphis Sand model, the numerical technique was not judged a major source of error.

The fact that this two-dimensional model represents a three-dimensional system probably accounts for error, but the magnitude is difficult to assess. Where initial assumptions concerning vertical flow are violated, errors will occur in the model. The three-dimensional model would provide the magnitude of this source of error.

Aquifer boundary simulation in the Memphis Sand model, while qualitatively correct, has not been defined by direct measurement. Indirect methods, which include water budget analyses, comparison of expected flow rates based on observed hydrologic characteristics and responses, and extreme examples of no-flow and constant-head configurations provide a range of possible flux across each boundary node. Recharge rates were chosen from within this range.

Confidence in aquifer hydraulic properties of the Memphis Sand model is variable areally for each of the different parameters. Table 4 contains a summary of the overall confidence of the data that comprise each parameter. All the input data are constrained by the requirement of being hydrologically reasonable both with regard to absolute value and to total range of values for the parameter. Error in the model due to poor aquifer hydraulic property definition is not significant on a regional scale, but could cause predicted water levels to be more than 10 feet in error in small localized areas, based on previous model calculations during calibration. A possible example would be a future large pumping center proximate to presently unknown zones of low transmissivity.

Model Capability and Reliability in Predicting

This study, which utilized a split-sample analysis for calibration and verification, suggests that the Memphis Sand model reliably simulated water levels to within ±5 feet for 75 percent of the observation wells using a range of recharge values. The model is suitable for quantitative prediction within the limits established by the calibration and verification and within the range of maximum and minimum values of parameters listed in table 4. The variations between calculated and observed water-level changes are thought to result primarily from (1) simplification of unknown aspects of a complex, nonhomogeneous hydrologic system, particularly variable transmissivity, recharge, and leakage, and (2) incomplete pumping records.

Continuing reassessment will be very important in the evolution of the model. As ongoing studies fill the gaps in the data base and improve our understanding of this complex flow system, the model can be modified to include these changes. Newly developed techniques of aquifer-parameter estimation would be particularly useful as an aid to understanding the system, as would development of a three-dimensional model, and an optimization model (Larson and others, 1977). The latter would be helpful in evaluating placement of future well fields and pumping configurations.

Historic records of pumping stress and water-level response in Memphis are more complete for the recent data. Unlocated pumping ranges from more than 60 percent for pumping period II to essentially zero percent for pumping period VII (table 5). Although ground-water withdrawal during the first four pumping periods was areally restricted to several specific pumping centers, the actual amount of pumping was generally not known and had to be estimated. For that reason, more emphasis was placed on the calibration of periods V and VI for which 90 percent or more of the pumpage locations were known.

The resulting response to pumpage may likewise be subject to error and misrepresentation. Prepumping conditions are based on extrapolations of early reported water levels. The maps presented are the best estimate based on all the available data, but data from the older historic records was sparse until the 1940's, during pumping period III. This was used as further justification to attach more importance to calibration of periods V and VI.

Although these potential sources of error may appear significant in a conservative evaluation of limitations, in actual application their combined effect has been minor. The calibration phase, particularly pumping period VI, showed that the model simulated the major components of the flow system of the Memphis Sand. Likewise, more than 100 variations of the calibration exercise confirmed that alternative configurations were poorer than the final model in simulating not only pumping periods V and VI, but the entire pumping record.

Significant changes introduced by resource development may render the present model inaccurate. Monitoring the study area so that important changes to the aquifer system can be programmed into the model will help maintain its accuracy. Development of new stresses or changing boundary conditions caused by pumping, lignite or other mineral mining, or changing land use could have a considerable effect at Memphis.

Sensitivity of Input Parameters

By varying one parameter and holding all others constant, it is possible to observe the relative sensitivity of the model to different input parameters. A column summarizing the sensitivity of each input parameter is given in table 4, and sections showing Criner and Parks' (1976) interpretation of the observed water level, and water levels calculated using a range of selected input values for single parameters are shown in figure 12.

Vertical hydraulic conductivity of the confining bed, pumpage, and transmissivity appear to be the most sensitive parameters; vertical hydraulic conductivity of the confining bed, and boundary fluxes are the parameters for which the least data exist. The sensitivities of leakage and transmissivity provide a fairly narrow range of acceptable input

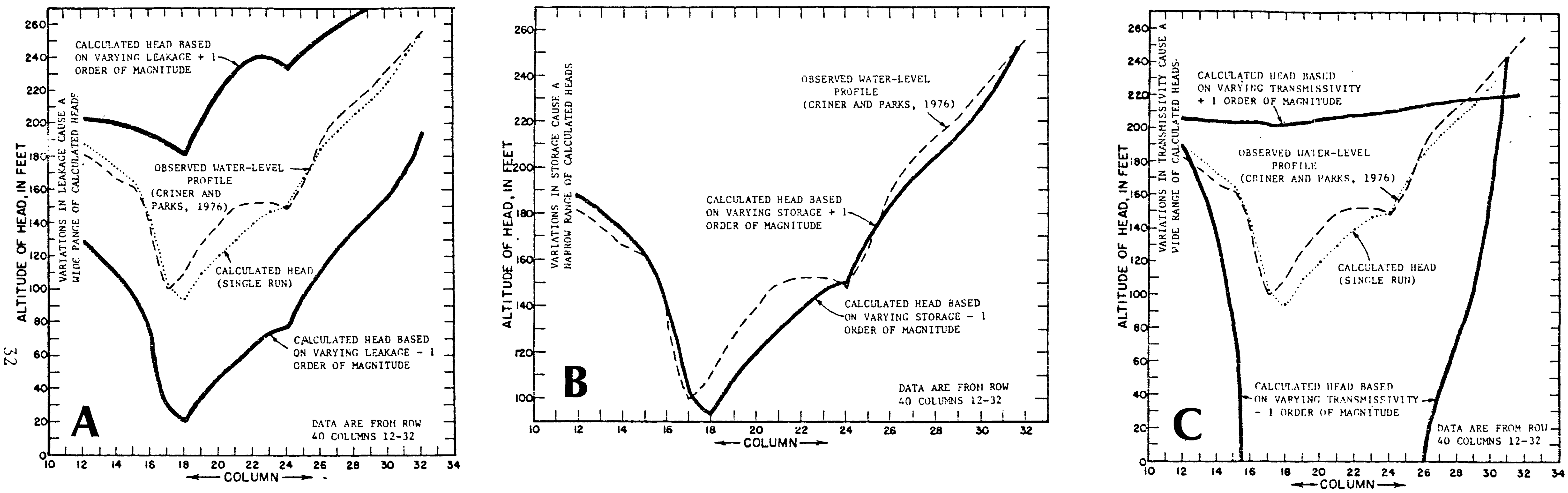

Figure 12.--Sensitivity analysis of selected input parameters to the model on calculated head of the Memphis Sand on the basis of: A, varying leakage one order of magnitude; B, varying storage one order of magnitude; and C, varying transmissivity one order of magnitude.

values for the parameters, but boundary fluxes are relatively unconstrained because most of the observation wells are far removed from the recharge area. The total mass input must be equal to a specified amount, but this can be accommodated by innumerable recharge configurations. The choice of recharge from the input cells was determined to provide the best compromise between efficiency and accuracy.

SUMMARY AND CONCLUSIONS

A digital model simulating ground-water flow in the Memphis Sand was constructed, tested, and found to simulate historic water levels for the Memphis metropolitan area and found to be within 5 feet of observed for 75 percent of the control points. The model is based on the two-dimensional Trescott-Pinder-Larson (1976) model using the SIP algorithm and pumping periods ranging from 5 to 39 years; the model has been used successfully in other areas of similar hydrologic setting.

Pumping and water-level data were split into two samples, one which was used to develop and adjust the model, and the other which was retained and used only as a final test of the model. This testing verified that the model could reproduce water levels for pumping configurations other than those for which it was developed. A sensitivity analysis of input parameters increased confidence that the model could predict water-level responses.

Use of the model for predictive purposes has been simplified to an essentially one-step process for the individual utilizing the model. Projected pumpage configurations and durations are located within the model grid, coded, and entered. The output from the model is a printed tabulation of water levels and flux calculations, and a contoured map showing the water-levels that would be expected from the specified pumping.

The construction of the model of the Memphis Sand provides not only a tool that will aid in evaluating the capabilities of the aquifer and in predicting responses to management alternatives of this aquifer, but also provides much insight into the flow system of the aquifer in the Memphis area.

Specifically, the regional homogeneity of transmissivity initially ascribed to the aquifer did not suitably simulate observed water levels. Several narrow zones of lower transmissivity, some as much as one order of magnitude less, were determined during the calibration phase to provide the best overall calculated response. These zones, which closely match the locations of fault zones hypothesized by Fisk (1944), Criner and others (1964), and A. Zurawski, U.S. Geological Survey (oral commun., 1978) appear to restrict flow between the aquifer in the Memphis area and to the west in Arkansas.

Placement of these zones of less transmissivity is also consistent with water quality differences observed in the aquifer (Plebuch, 1961; Criner and others, 1964; Halberg and Reed, 1964; Moore, 1965) and water-level variations (Halberg and Reed, 1964; Criner and Parks, 1976).

Figures 9, 10, and 11 show water-levels in the areas of restricted flow. Observed geometries in these diagrams are consistent with restriction of flow in the aquifer between western Tennessee and eastern Arkansas.

Comparing observed with calculated water levels also indicated that the inclusion of leakage along the upper reaches of Wolf and Loosahatchie Rivers, Nonconnah Creek, and the Mississippi River alluvium provided the closest simulation of observed water levels. Electric logs from these suspected zones of leakage commonly show thinning of confining clays or more sandy zones within the confining layer. Approximately 15 percent of the total leakage shown in the water budget in table 6 occurs near the subcrop area where the confining bed is thin, or in the western part of the study area where streams have breached the confining clay.

Resolving the intricacies of interaquifer movement of ground water between the Memphis Sand, the alluvium, and the Wilcox Group aquifers will require a three-dimensional model, as will any water-quality models, and any newly developed studies to evaluate total resource management alternatives. Parameter-estimation techniques (Cooley, 1977) should be helpful in quantitative studies of the hydrology of the area. An existing optimization model developed by Larson and others (1977) offers an attractive approach to evaluating placement of future well fields and pumping configurations.

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Attachment I

TECHNICAL DESCRIPTION OF GENERALIZED TWO-DIMENSIONAL DIGITAL MODEL FROM WHICH THE MODEL OF THE MEMPHIS SAND WAS DERIVED

The digital ground-water model presented in this report is based on the model developed by Trescott, Pinder, and Larson (1976) that has been used successfully to simulate a variety of aquifer systems in two dimensions. This report by Trescott, Pinder, and Larson (1976) provides a cogent description of the theory and capabilities of the generalized model, as well as giving detailed instruction in the general use and application of the model, and documentation of the model. Included in the documentation are flow charts, complete program listing, example simulations, and alternative data output techniques to the printout of calculations and contoured map generated by the Memphis Sand model.

Used in conjuction with Attachment II, the documentation in the Trescott, Pinder, Larson (1976) report will provide the practical basis for full utilization, including troubleshooting, of the model of the Memphis Sand.

Attachment II

INSTRUCTIONS AND EXAMPLES FOR CARD INPUT - GROUND-WATER MODEL OF THE MEMPHIS SAND

The digital model of the Memphis Sand has been simplified to facilitate use by personnel inexperienced in computer modeling. Although the Memphis Sand model follows the same format as described on pages 49-55 of Trescott, Pinder, and Larson (1976), most data are stored on the U.S. Geological Survey computer in Reston, Va., and do not need to be reentered.

Only the title, simulation options, problem dimensions, and parameters that change with the pumping period will require encoding and entry into the general Memphis Sand ground-water model. Other job control language and parameter cards will not change, and these are described at the back of Attachment II.

A flow chart (fig. 13) shows the sequential steps necessary for running the model. The sequence is defined in greater detail below:

1. Code Title -- Code any title that identifies the individual run in 120 spaces or less; 80 spaces on the first card, 40 spaces on the second card. Always include two cards; leave the last 40 spaces on the second card blank.

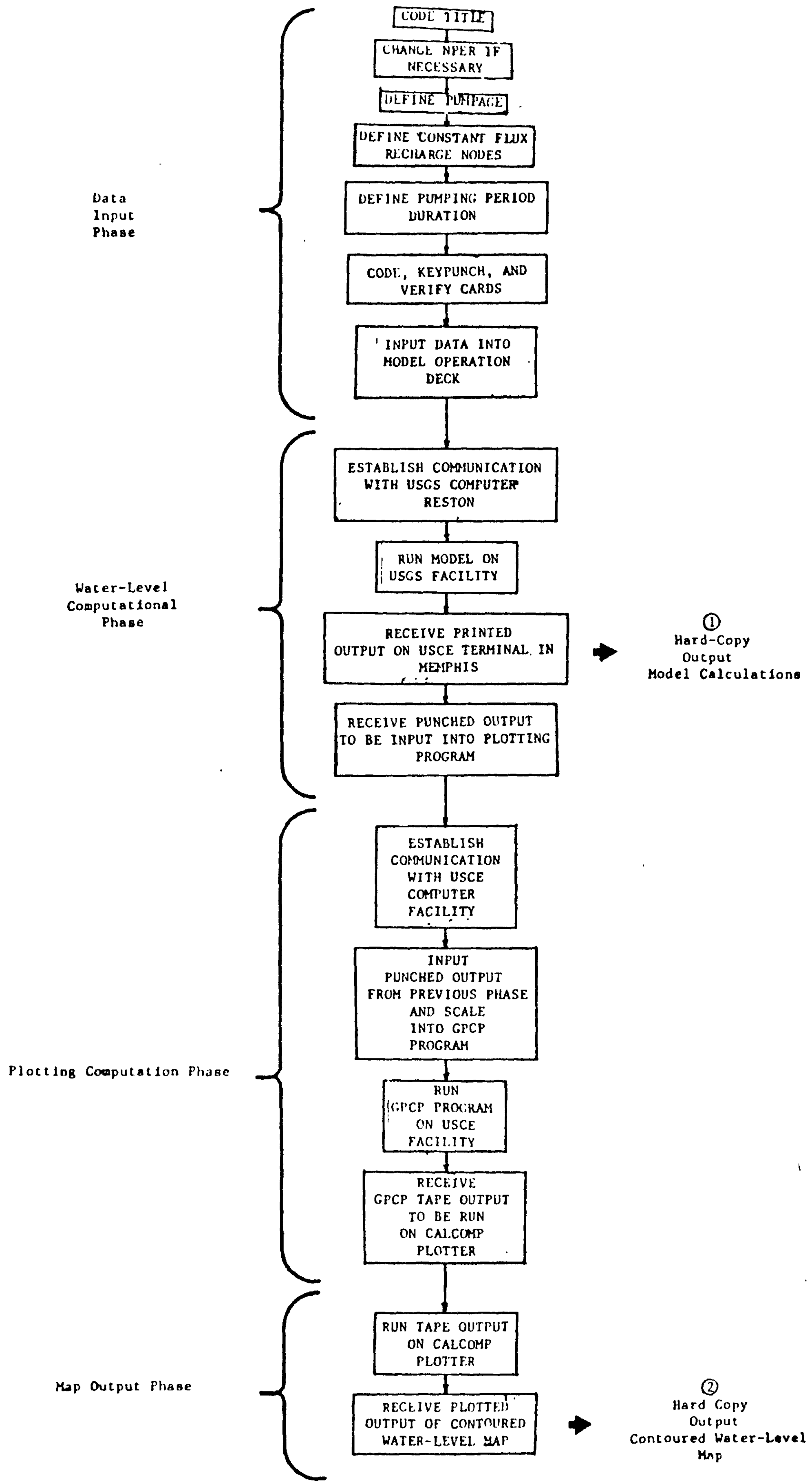
2. If simulation of more than one pumping period is desired, change variable NPER (group II, card 2, columns 9-10) to 7 plus the number of pumping periods simulated. Otherwise, leave NPER = 8. Note that this number should match the highest number given for variable KP (group IV, card 1, column 9-10).

3. Define Pumpage -- Locate pumping centers on base map by alining grid overlay of same scale. Grid location should be given by row (down) in card space 9-10, by column (across) in card space 19-20, and pumpage, in units of negative feet per second in columns 21-30. Row and column are integer numbers, and pumpage is a decimal. All numbers should be right justified in their fields. Pumpage can be converted from millions of gallons per day to negative feet per second by multiplying the value in millions of gallons per day times (-1.547). If pumpage falls between two or more nodes, it should be divided proportionally between the nodes.

4. Define Pumping Period Duration -- The number of the pumping period should be coded in card space 9-10. Most simulations will use 8, because 7 were used in modeling through 1975. For simulations run with the model, the following pumping period designations were used. It is not necessary to conform to these, but other variations should be noted.

Pumping period	Interval
8	1976-1980
9	1981-1990
10	1991-2000
11	2001-2025

Figure 13.--Flow chart for operating the Memphis Sand digital ground-water model.



In card space 19-20, code 1 minus the value you have in columns 9-10. For example, if pumping period 8 were shown in card space 10, then (8-1) or 7 would be shown in space 20. In card spaces 28-30, show the total number of nodes in which pumping and recharge will occur during this period (count them on the grid). Right justify the number in the field. Right justified in card space 31-40, show the number of days the wells will be pumped. Days = 365 x number of years. Code 100 into spaces 48-50. Code 1.5 into spaces 58-60. Right justified into spaces 61-70, code the value = (number of days in period x 24)/170. This completes the pumping header card. This card, when punched, goes in front of the group of pumpage and recharge cards completed in step 3. For each pumping period a new set of pumpage (step 4) data by nodes preceded by a pumping period duration card (step 5) is required. Multiple periods should be placed directly in back of the preceding pumping period.

5. Code, keypunch, list on printer, and verify, -- check input values carefully; errors here are magnified in the program.

6. After inserting these data in the deck described in the attached listing (p. 69), this deck is now ready to be run on the USGS 370-195 computer in Reston, Va.

7. Run the program.

8. Upon successful completion, a printed record of the calculations will be received.

9. In addition, the card punch at the terminal will receive punched output which will be used to draw the water-level contour map.

10. Initiate communications with USCE INFØNET computing facility.

11. Read punched output or tape of card images into file GRD02 on INFØNET.

12. Run SPLØT on INFØNET. This is an interactive program that asks questions about map scales, titles, and plotting information.

13. Output from SPLØT will be a plot tape.

14. Have the tape plotted on CALCØMP plotter.

15. Output is a water-level map on paper or mylar contoured to the scale of the specified base (generally 1:10416). This represents the resulting water level in the Memphis Sand from pumping the configuration previously input in step 3.

Attachment III

Observed and computed water levels for selected wells in the Memphis Sand under transient pumping conditions

[Datum is National Geodetic Vertical Datum of 1929]

Well no.	Grid location	Observed altitude of water level (feet) Aug. 1960	Sept. 1970	Aug. 1975	Calculated altitude of water level (feet) 1960	1970	1975
Fa:R-2	22-23	276	275	277	277	275	275
Sh:H-1	49-15/16	188	180	180	188		180
Sh:J-1	50-20	200	190	184	197	197	189
Sh:J-10	46-19/20	139			140		
Sh:J-25	44-17	159			158		
Sh:J-31	44/45-17	158			155		
Sh:J-36	43/44-19/20	144			145		
Sh:J-41	43/44-18/19	146			144		
Sh:J-47	47-17	173			171		
Sh:J-50	47/48-18/19		157			178	
Sh:J-62	46/47-18/19	163			158		
Sh:J-70	48-22			181			180
Sh:J-102	45-20	130	99	124	130	104	87
Sh:J-110	45/46-21	145	123	129	150	128	120
Sh:J-126	46-20/21	151	122	135	147	139	132
Sh:J-140	50-17		188	171		188	171
Sh:K-4	44/45-25/26	211	192		209	189	
Sh:K-13	43/44-22/23	171			172		
Sh:K-15	43/44-23/24	184			183		
Sh:K-20	43-22	170	153	155	171	148	135
Sh:K-23	39/40-25/26	190	186		197	186	
Sh:K-25	43-25/26	201			261		
Sh:K-28	48-25	211			213		
Sh:K-29	46/47-23/24	199			197		
Sh:K-31	45-28		220	215		212	203
Sh:K-66	39/40-24	166	159	145	175	164	154
Sh:K-74	42/43-25	178			184		
Sh:L-1	42/43-29	241			243		
Sh:L-10	38-30	253	243	239	253	235	231
Sh:L-13	42-28		208	200		207	198
Sh:L-15	37-32	266	260	258	264	260	261
Sh:L-20	39/40-27	230			228		

Attachment III

Observed and computed water levels for selected wells in the Memphis Sand under transient pumping conditions--Continued

Well no.	Grid location	Observed altitude of water level (feet) Aug. 1960	Sept. 1970	Aug. 1975	Calculated altitude of water level (feet) 1960	1970	1975
Sh:L-24	43/44-28/29	238			237		
Sh:L-39	43/44-30	245	216	208	248	221	218
Sh:L-43	44-30/31	249	230	222	251	232	227
Sh:L-54	38/39-32/33		264	263		266	268
Sh:L-64	38/39-26/27	225	212	211	222	201	195
Sh:O-1	34/35-14/15	184	174	174	179	178	175
Sh:O-41	38/39-16/17	133	126	126	138	128	130
Sh:O-98	42/43-16/17		140	142		156	145
Sh:O-110	39/40-16/17	131			133		
Sh:O-115	37/38-14/15	161	157	157	162	159	152
Sh:O-124	41-16/17	158	159	160	165	154	142
Sh:O-153	40/41-18/19	130			134		
Sh:O-179	39/40-16/17	124	127	88	133	127	127
Sh:O-212	40/41-18			105			103
Sh:P-1	32-22/23	205	190	188	206	191	184
Sh:P-8	37-20/21	144	144	141	148	141	145
Sh:P-12	37/38-21	143			148		
Sh:P-37	36/37-21/22	162		157	165		153
Sh:P-50	38/39-18/19	145			144		
Sh:P-54	38/39-21	154			151		
Sh:P-61	40/41-22/23	168	157		168	153	
Sh:P-69	34/35-21/22		170			176	
Sh:P-74	36/37-25	202	190		203	191	
Sh:P-75	33/34-21/22	193			193		
Sh:P-76	41/42-21	163	149	148	162	141	129
Sh:P-85	34/35-24/25	200	183	182	201	188	184
Sh:P-96	30/31-22/23		201	198		201	193
Sh:P-97	39/40-19/20			131			116
Sh:Q-1	34-28/29	243	233	231	245	231	229
Sh:Q-3	31/32-30	257	249	249	255	247	246
Sh:Q-9	35/36-16		210	210		206	201
Sh:Q-21	32-25	217			219		
Sh:Q-23	33-24/25	209	184	188	212	190	180
Sh:Q-24	31-24	220	211		222	203	
Sh:Q-53	34-25			181			182
Sh:Q-59	33-25			168			178

Attachment III

Observed and computed water levels for selected wells in the Memphis Sand under transient pumping conditions--Continued

Well no.	Grid location	Observed altitude of water level (feet) Aug. 1960	Sept. 1970	Aug. 1975	Calculated altitude of water level (feet) 1960	1970	1975
Sh:R-15	27-32			271			273
Sh:T-17	32/33-12		192	192		195	193
Sh:U-2	27-14	221	214	214	219	211	207
Sh:U-11	26-17/18	223	213	212	223	214	210
Sh:U-13	31/32-15/16			157			170
Sh:U-15	31/32-15/16		168			178	
Sh:U-22	30-15/16	199			197		
Sh:U-23	30-15/16		186	187		188	179
Sh:U-25	30/31-16/17	187		183	187		180
Sh:V-1	26-26	246			244		
Sh:V-7	27/28-26/27	246	242	240	245	237	234
Sh:W-3	24/25-30	258	258	260	259	262	262
AR-1	45/46-12	186	183		188	188	
MS-1	47/28-32/33	263	256	254	262	258	256

ATTACHMENT IV

PROJECTIONS OF WATER USE

Future pumping demands are required input if the model is to be used for predictions of future water levels. Because water-use projection is affected by many variables, most of which are outside the domaine of the U.S. Geological Survey, it was decided to chose a range of values - maximum, intermediate, and minimum - that would bracket the probable pumpage and define its limits. These projected demands are summarized in table 7 by major use and figure 14 by major well field. The pumping demands are based on extrapolation of information provided by MLGW, and represent a "best estimate" at this time. They include the time period from 1980 to 2025.

Maximum conditions are based on the ultimate design capability of the MLGW distribution system for each municipal well field, as well as inclusion of all planned withdrawal demands for projects that have been proposed. Self-supplied industrial pumpage, industries that use their own wells, has remained relatively constant since about 1950, and on the basis of little variation during the last 30 years, it was assumed that all new industrial pumpage would be accommodated by MLGW. Pumping demands for existing self-supplied industries were projected as 20 percent greater than 1980 figures. Calculation of the maximum conditions yields a conservative pumping figure that is felt to be an extreme upper limit of ground-water use.

The intermediate pumpage figures are based on extrapolations of MLGW projections. These values are taken as one hypothetical situation only and were determined to show water-level effects in the middle of the range between maximum and minimum. No increase was assumed in self-supplied industrial pumpage.

Minimum pumpage was arbitrarily selected as the smaller of (a) the minimum 5 year demand that stabilized for each well field during the last 30 years or (b) the projected MLGW pumpage reduced by a factor of 40 percent.

Table 7.--Projection of maximum, intermediate, and minimum pumpage for three periods, in millions of gallons per day, from 1981 to 2025

MLGW well field	Time period	Pumpage projection Maximim	Intermediate	Minimum
Allen	1981-1990	25.49	22.08	15.00
	1991-2000	29.55	23.85	15.00
	2001-2025	33.80	25.34	15.00
Airport	1981-1990	10.97	6.49	3.80
	1991-2000	14.48	12.99	4.60
	2001-2025	15.00	14.74	5.00
Davis	1981-1990	22.20	17.32	10.00
	1991-2000	28.30	21.74	10.00
	2001-2025	30.00	27.35	10.00
Lichterman	1981-1990	27.46	25.91	19.52
	1991-2000	30.00	29.21	20.92
	2001-2025	30.00	30.00	22.48
Mallory	1981-1990	25.06	21.78	13.00
	1991-2000	29.72	23.94	13.00
	2001-2025	34.09	26.60	13.00
McCord	1981-1990	26.75	23.75	18.00
	1991-2000	28.00	26.79	18.00
	2001-2025	28.00	28.00	18.00
Morton	1981-1990	19.76	13.38	4.38
	1991-2000	28.26	21.27	9.99
	2001-2025	30.00	28.53	16.25
Sheahan	1981-1990	29.55	25.20	15.00
	1991-2000	34.10	28.99	15.00
	2001-2025	35.00	33.62	15.00
Municipal pumpage (Subtotal)	1981-1990	187.24	155.91	98.70
	1991-2000	222.41	188.78	106.51
	2001-2025	235.89	214.18	114.73
Industrial pumpage	1981-1990	75.00	74.00	72.5
	1991-2000	80.00	76.00	72.5
	2001-2025	87.00	80.00	72.5
Municipalities (outside MLGW) pumpage	1981-1990	10.00	9.00	8.21
	1991-2000	12.00	10.00	8.21
	2001-2025	15.00	12.00	8.21
Total pumpage	1981-1990	272.24	238.91	179.41
	1991-2000	314.41	274.78	187.22
	2001-2025	337.89	306.18	195.44

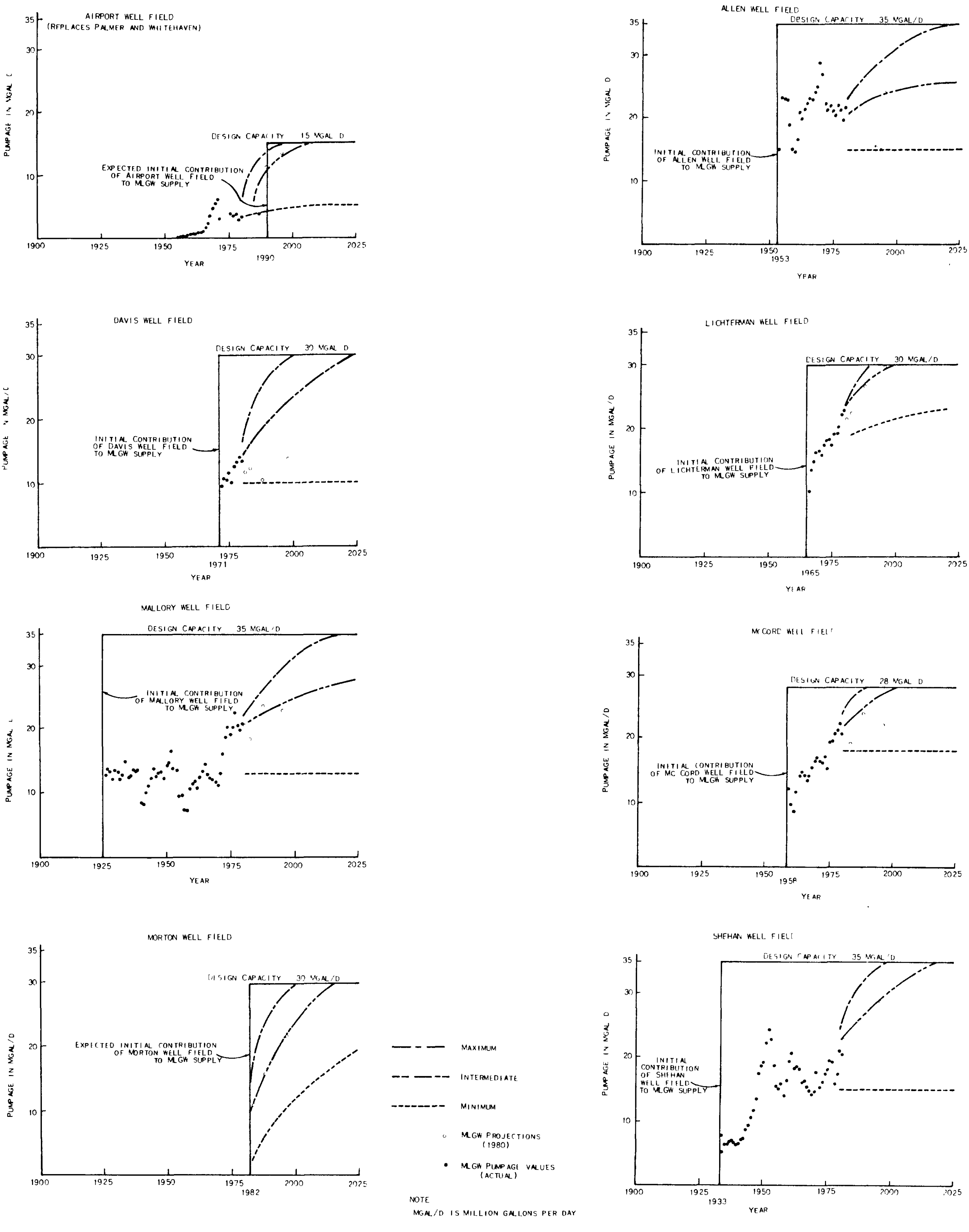


Figure 14.--Historic pumpage and the range of expected pumpage through 2025 for major MLGW well fields.

ATTACHMENT V

Selected Input Parameters

The input to the computer model is included in a 58 by 44 matrix for the following parameters:

1. transmissivity,
2. head in the overlying aquifer,
3. thickness of the confining layer, and
4. vertical hydraulic conductivity of the confining layer.

Each entry in a matrix represents the coded value of the appropriate parameter at the row and column location shown.

Parameter: Transmissivity

```
                         Column (j)

         5    10    15    20    25    30    35    40
      00000|00000|00000|00000|00000|00000|00000|00000|0000
      00000|00222|22222|22222|22333|35555|53300|00000|0000
      00001|16664|44444|44455|55555|66655|44333|11111|0000
      00001|16777|65544|44444|44444|44322|22211|11111|1000
      00011|17777|65553|33333|33333|33222|22211|11111|1000
  5   00011|56676|55533|32211|11111|11111|11111|11111|1000
      00011|55555|52333|21111|11111|11111|11111|11111|1100
      00011|55545|43321|11111|11223|27777|77777|77731|1100
      00011|55433|33211|11111|11127|77777|77777|77731|1100
      00011|55433|32111|11111|22777|77777|77777|77773|1100
 10   00011|66433|11111|22277|77777|77777|77777|77773|1100
      00011|66533|37777|77777|77777|77777|77777|77773|1100
      00011|76433|77777|77777|77777|77777|77777|77773|1100
      00011|64337|77777|77777|77777|77777|77777|77731|1000
      00115|54377|77777|77777|77777|77777|77777|77753|1000
 15   00113|53777|77777|77777|77667|77777|77777|77753|1000
      00235|45677|77777|77777|77777|77777|77777|77753|1100
      00233|33377|77777|77777|77777|77777|77777|77753|1100
      00133|33777|77777|77777|77777|77777|77777|77531|1000
      00133|33777|77777|77777|77777|77777|77777|75311|1000
 20   00233|33777|77655|55555|77777|77777|77777|77531|1000
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      00133|37777|77777|77777|77777|77777|77777|75311|1100
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 30   00333|37777|77777|71777|77777|77777|77777|54311|1100
      00445|57777|77777|17777|77777|77777|77775|43111|1100
      00445|57777|77777|17777|77777|77777|77775|43111|1100
      00445|57777|77777|17777|88888|88888|88775|43111|1100
      00445|57777|77777|17777|88888|88888|77775|43111|1100
 35   00445|57777|77777|17777|88888|88887|77775|43111|1100
      00445|57777|77777|17777|77777|77777|77775|43111|1100
      00774|57777|77777|71777|77777|77777|77775|43111|1100
      00774|57777|77777|17777|77777|77777|77775|43111|1100
      00774|57777|77777|17777|77777|77777|77765|43111|1100
 40   00774|57777|77777|17777|77777|77777|77775|43111|1000
      00774|57777|77777|71777|77777|77777|77777|53111|1000
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      00774|58877|77777|71777|77777|77777|77777|75311|1000
      00774|59977|77777|71117|77777|77777|77777|75311|1000
 45   00774|59987|77777|71771|77777|77777|77777|75311|0000
      11774|59998|77777|77177|77777|77777|77777|75311|0000
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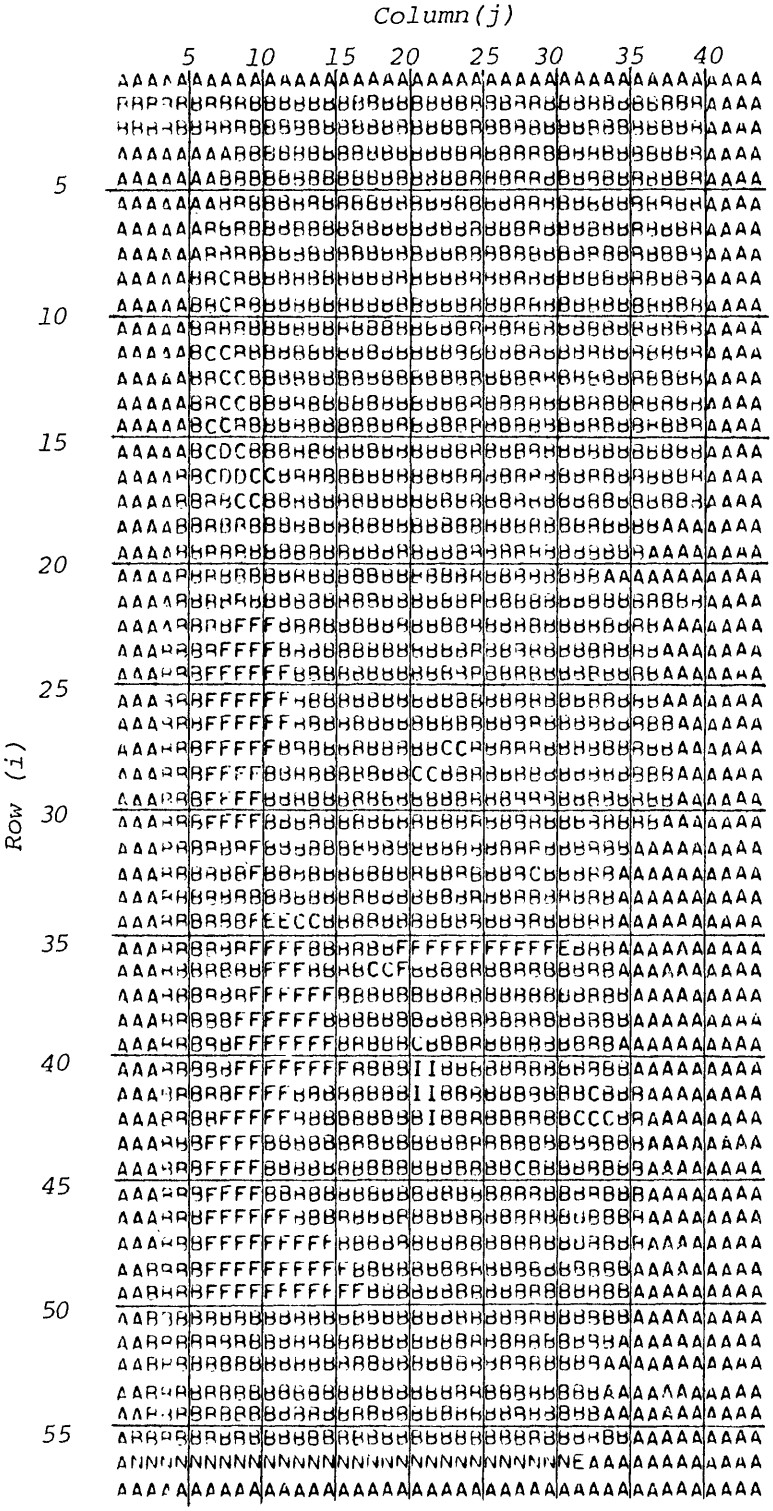
      00974|59999|87777|77177|77777|77777|77777|65310|0000
      00877|58999|99887|87177|77777|77777|77777|65310|0000
 50   00887|76778|99999|99199|77777|77777|77777|65310|0000
      00887|77777|77899|99999|77777|76333|22211|11111|0000
      00888|77777|74444|44444|44433|33222|23111|11111|0000
      00888|76666|66666|66655|44444|33111|11111|11111|0000
      00664|45755|43333|33333|33211|11111|11111|11111|0000
 55   05322|34755|55433|33333|33333|11111|11111|11111|1000
      03323|34444|44333|33333|33332|11111|11111|11111|1100
      00000|00000|00000|00000|00000|00000|00000|00000|0000

Row (i)
```

EXPLANATION

Code	Transmissivity ($x\ 10^3\ ft^2/d$)		
0	0		
1	>0	and	≤6.7
2	>6.7	and	≤13.4
3	>13.4	and	≤20.0
4	>20.0	and	≤26.7
5	>26.7	and	≤33.4
6	>33.4	and	≤40.1
7	>40.1	and	≤46.8
8	>46.8	and	≤53.5
9	>53.5		

Parameter: Vertical hydraulic conductivity of the confining layer



EXPLANATION

Code	Vertical hydraulic conductivity of confining bed (x 10^{-3} ft/d)		
A		0	
B	>0	and	≤1.7
C	>1.7	and	≤3.4
D	>3.4	and	≤5.2
E	>5.2	and	≤6.9
F	>6.9	and	≤13.8
G	>13.8	and	≤20.7
H	>20.7	and	≤27.6
I	>27.6	and	≤34.5
J	>34.5	and	≤41.4
K	>41.4	and	≤48.3
L	>48.3	and	≤55.2
M	>55.2	and	≤62.1
N	>62.1	and	≤69
O	>69		

Parameter: Thickness of the confining layer

Column (j)

Row (i)

```
     5    10   15   20   25   30   35   40
AAAAA|AAAAA|AAAAA|AAAAA|AAAAA|AAAAA|AAAAA|AAAAA|AAAA
AAAAA|AAAFF|DDGED|EEFFF|FEFFI|HIIIG|HGGAA|AAAAA|AAAA
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AAAAA|AABFG|HHIIL|KKIII|IHHGG|HIJIH|HGDFH|IBAAA|AAAA
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AABRR|RRPON|NMLLL|LKKJJ|JJIHH|HGGGF|FFEED|DAAAA|AAAA
AAAAA|AAAAA|AAAAA|AAAAA|AAAAA|AAAAA|AAAAA|AAAAA|AAAA
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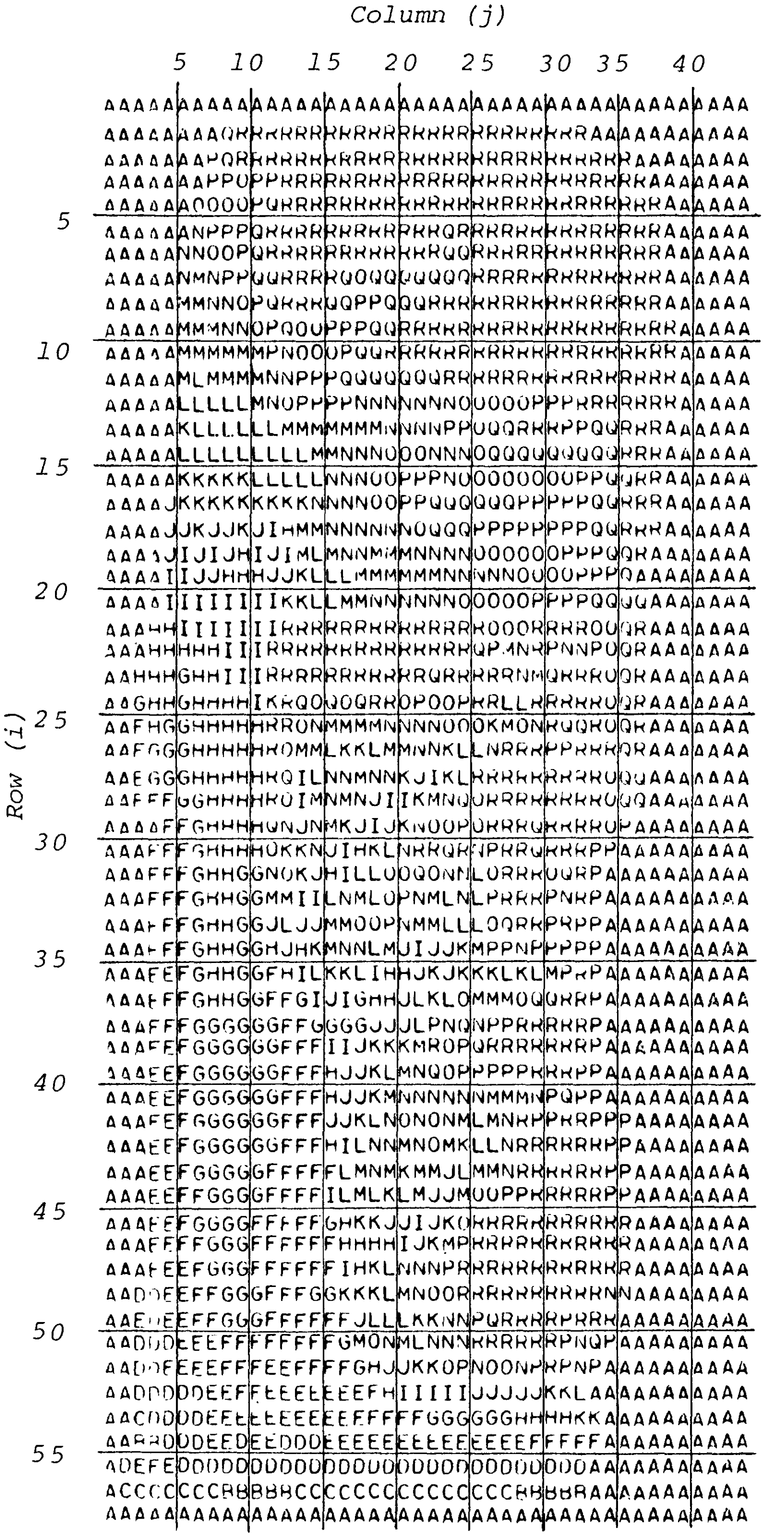
EXPLANATION

Code	Thickness of confining bed (feet)		
A		0	
B	>0	and	≤25
C	>25	and	≤50
D	>50	and	≤75
E	>75	and	≤100
F	>100	and	≤125
G	>125	and	≤150
H	>150	and	≤175
I	>175	and	≤200
J	>200	and	≤225
K	>225	and	≤250
L	>250	and	≤275
M	>275	and	≤300
N	>300	and	≤325
O	>325	and	≤350
P	>350	and	≤375
Q	>375	and	≤400
R	>400		

Parameter: Head in the overlying aquifer



EXPLANATION

Code	Head in overlying aquifer (feet)		
A		≤150	
B	>150	and	≤160
C	>160	and	≤170
D	>170	and	≤180
E	>180	and	≤190
F	>190	and	≤200
G	>200	and	≤210
H	>210	and	≤220
I	>220	and	≤230
J	>230	and	≤240
K	>240	and	≤250
L	>250	and	≤260
M	>260	and	≤270
N	>270	and	≤280
O	>280	and	≤290
P	>290	and	≤300
Q	>300	and	≤310
R	>310		