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

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

SIMULATION OF THE GROUND-WATER FLOW SYSTEM

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

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

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

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

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

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

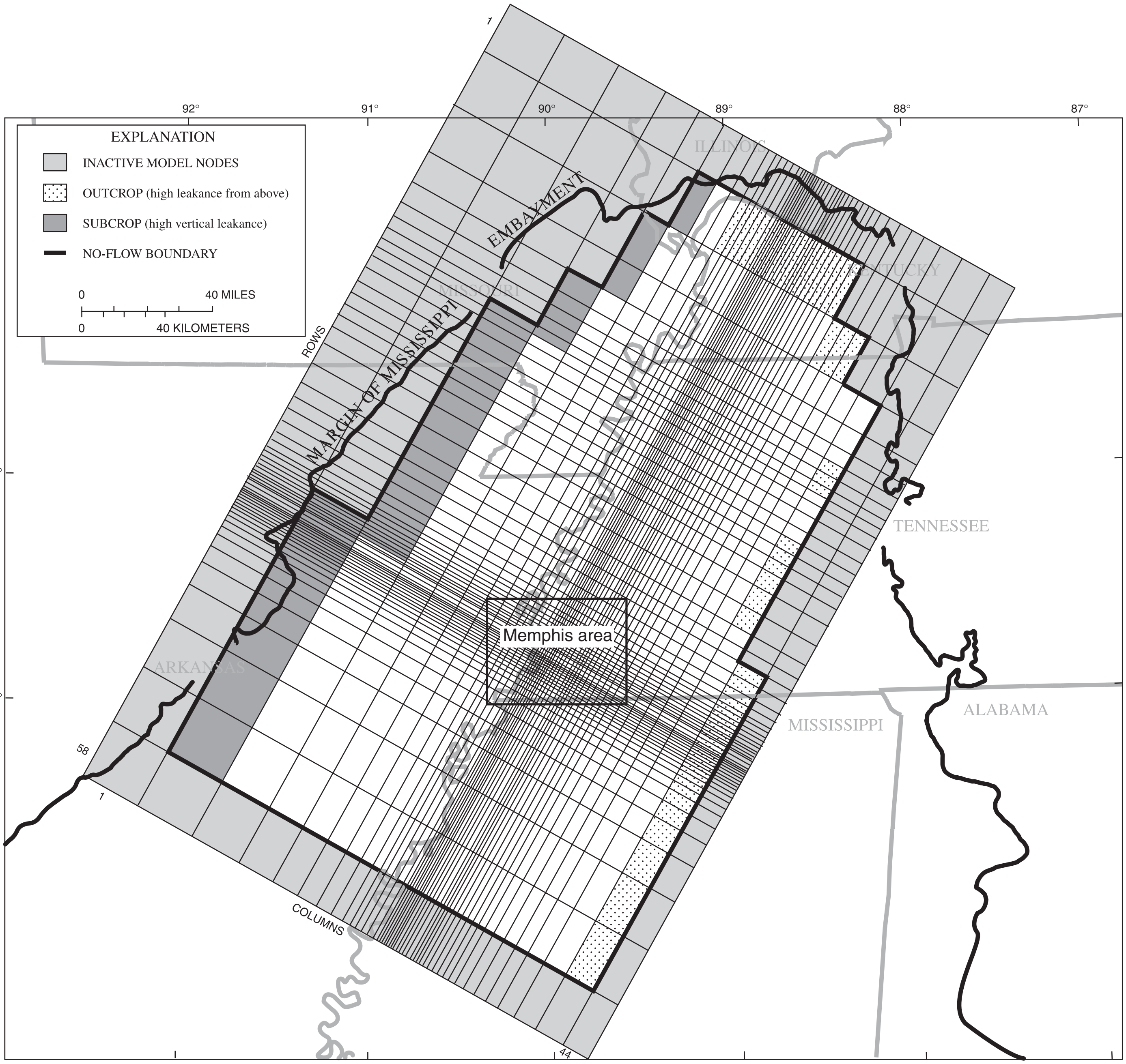
Finite-Difference Grid

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

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

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

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



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

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

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

Hydrologic Parameters

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

Initial Head Distributions

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

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

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

Boundary Conditions

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

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

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

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

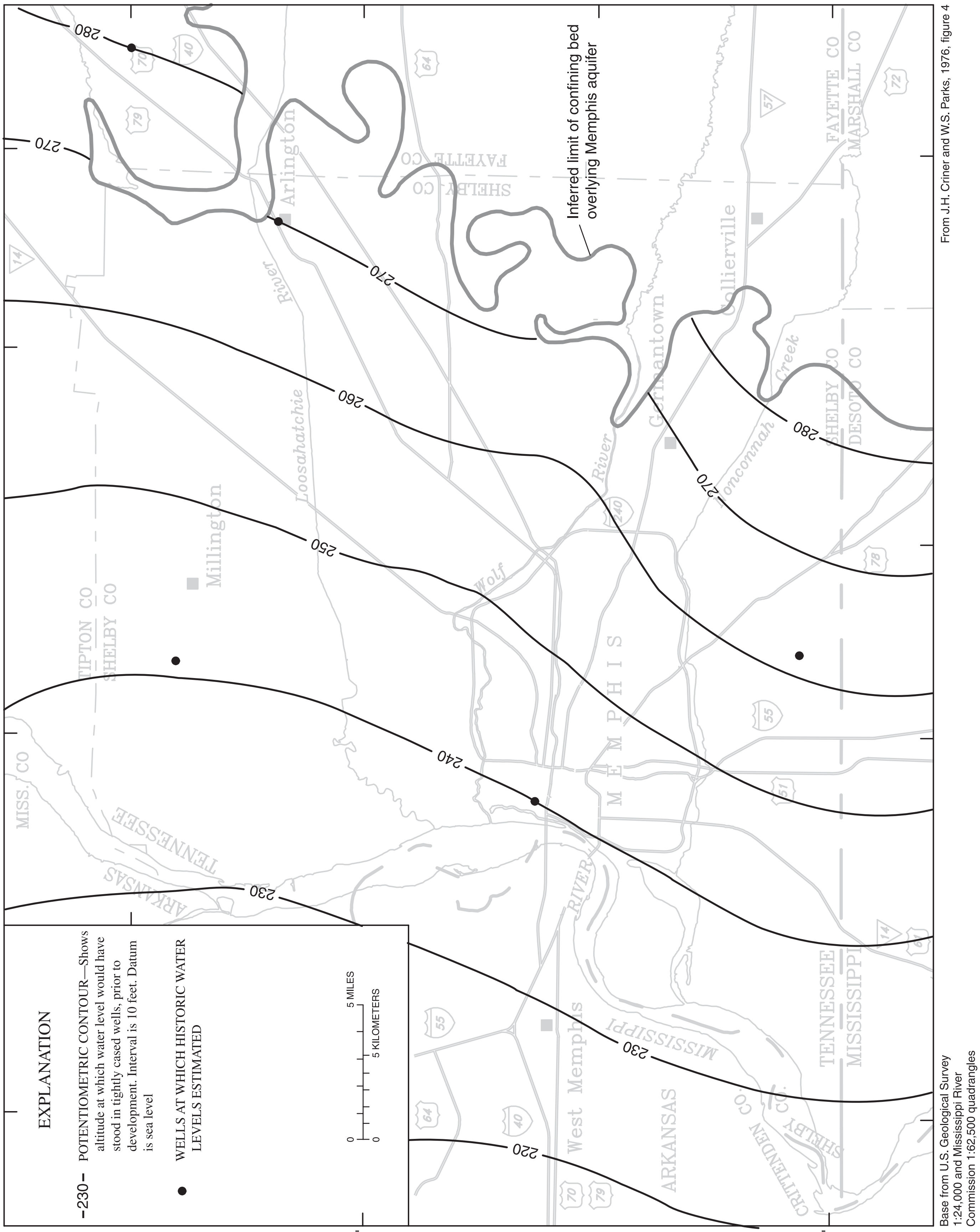
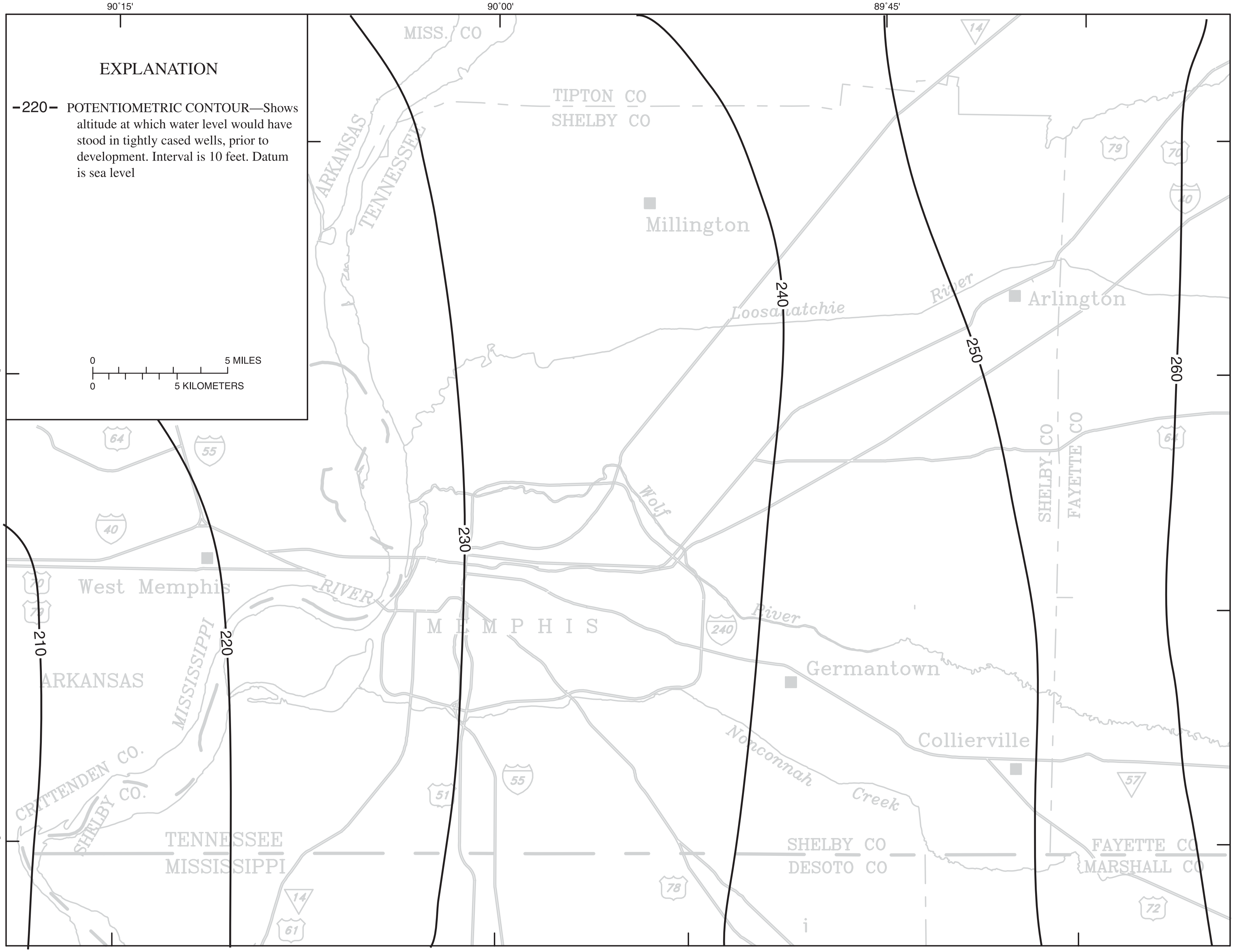


Figure 16. Estimated potentiometric surface of the Memphis aquifer prior to development in 1886.



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

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

Aquifer Hydraulic Properties

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

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

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

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

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

Pumping

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

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

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

Model Calibration

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

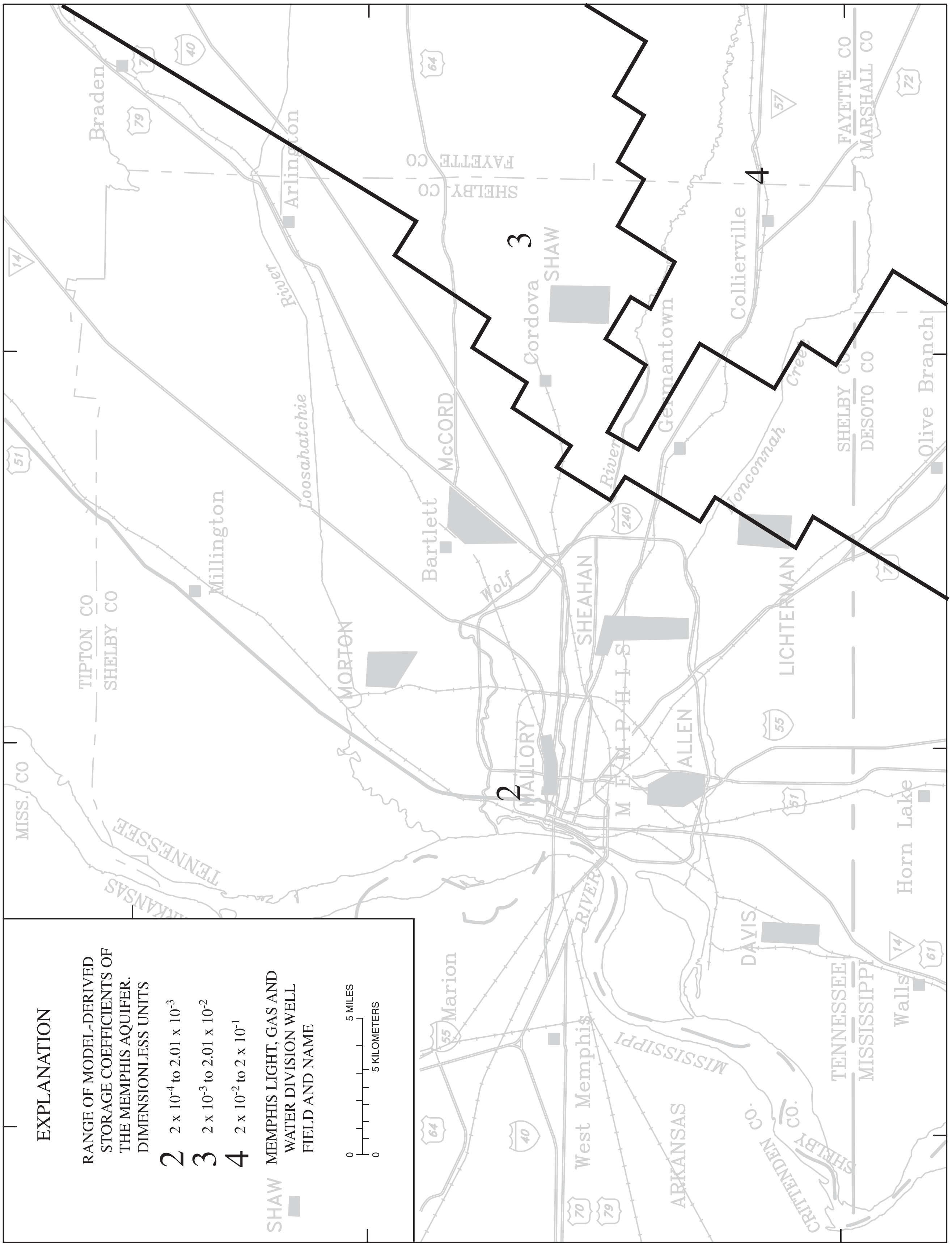
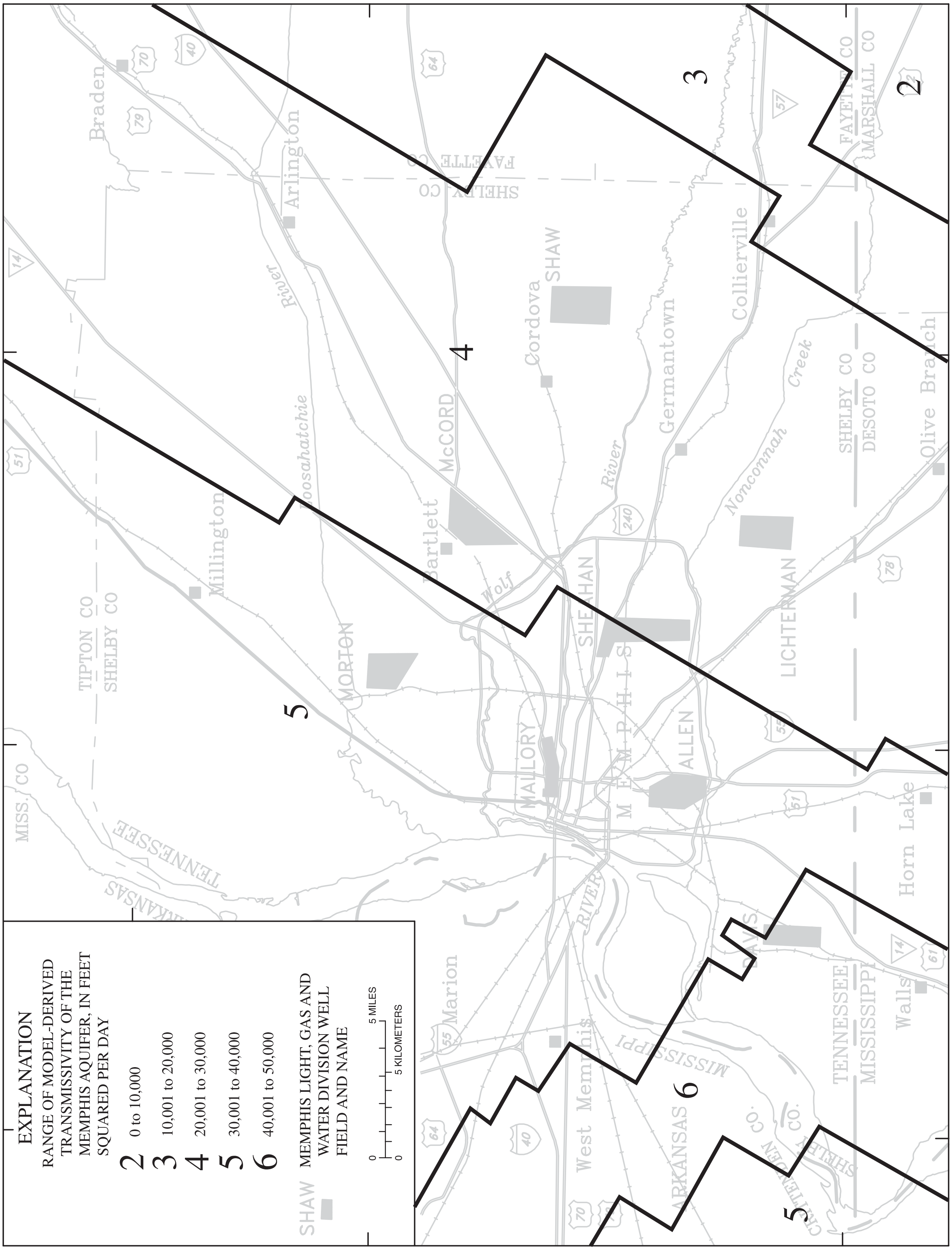
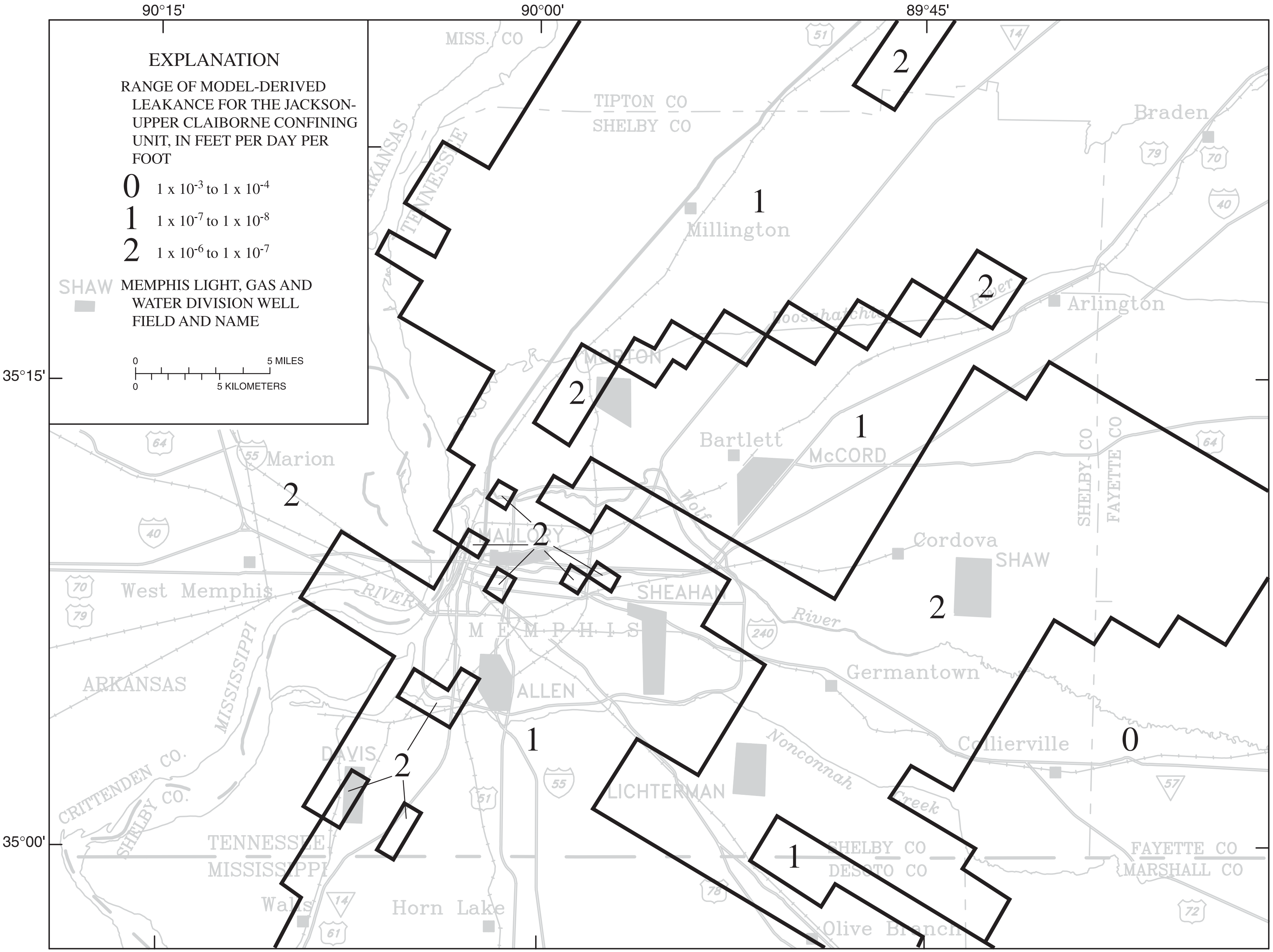


Figure 18. Model-derived storage coefficient of the Memphis aquifer.



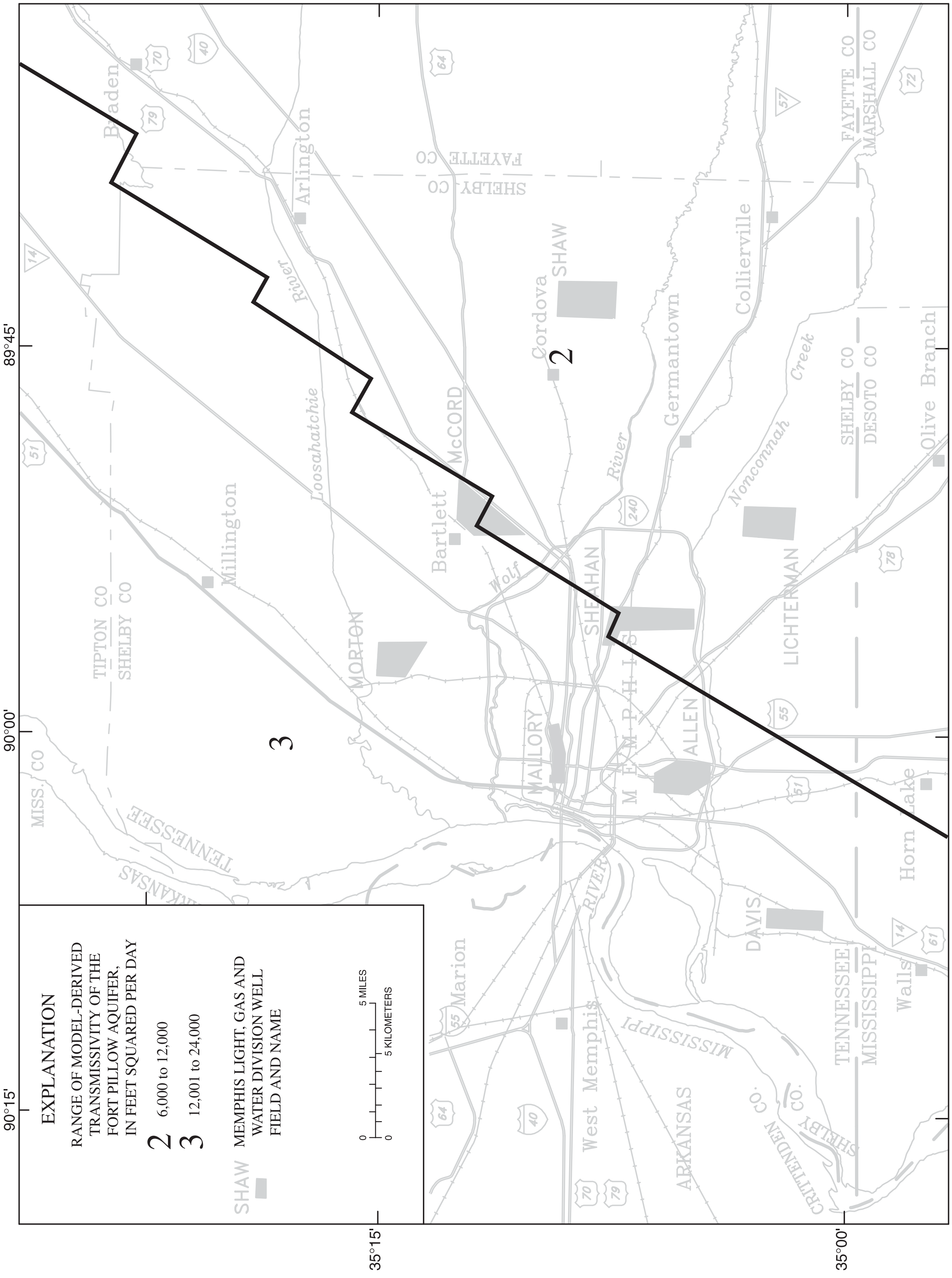
Base from U.S. Geological Survey
1:24,000 and Mississippi River
Commission 1:62,500 quadrangles

Figure 19. Model-derived transmissivity of the Memphis aquifer.



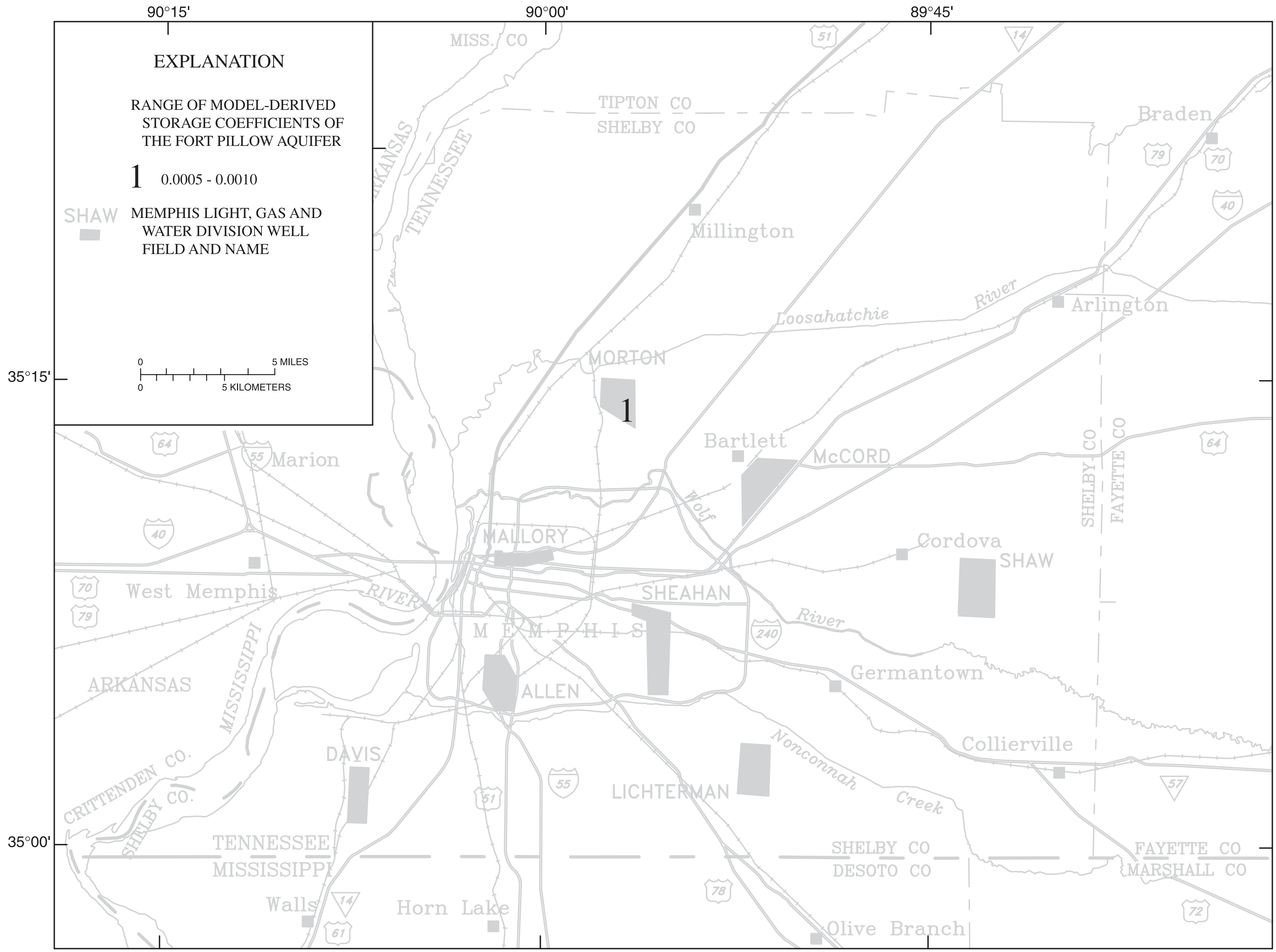
Base from U.S. Geological Survey
1:24,000 and Mississippi River
Commission 1:62,500 quadrangles

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



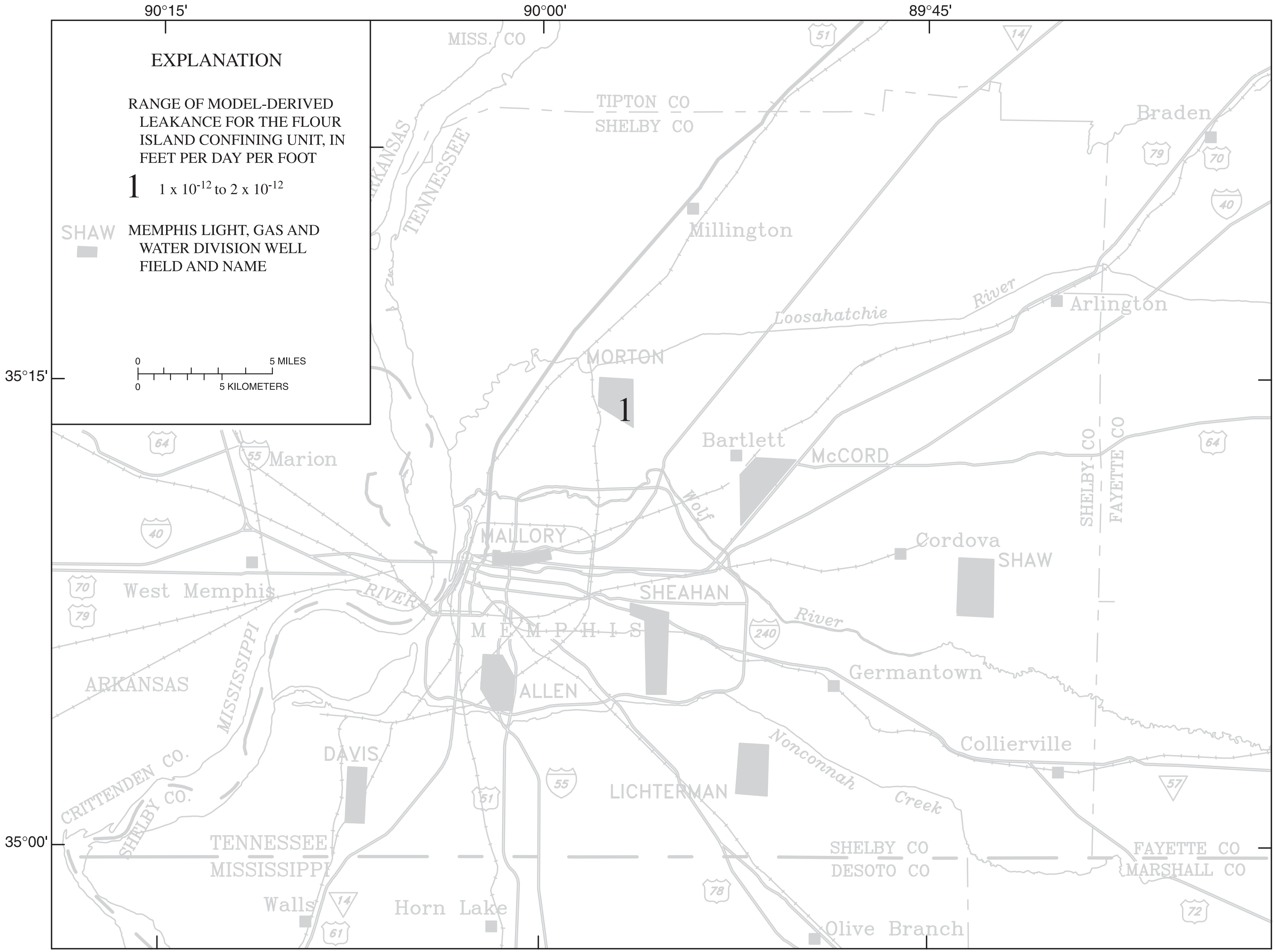
Base from U.S. Geological Survey
1:24,000 and Mississippi River
Commission 1:62,500 quadrangles

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



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

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



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

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

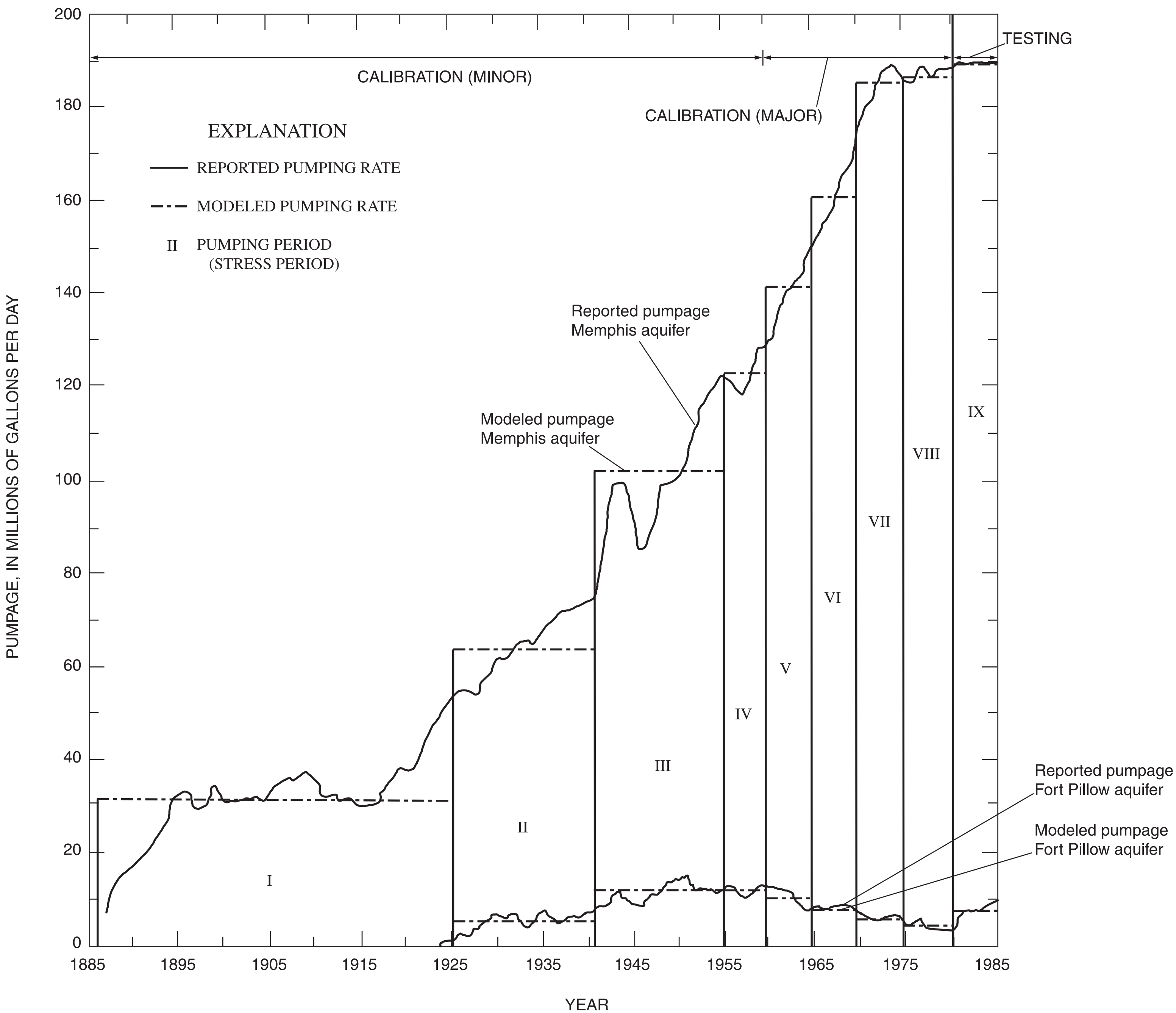


Figure 24. Actual and modeled pumpage from the Memphis aquifer and Fort Pillow aquifer in the Memphis area, 1886-1985.