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

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

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

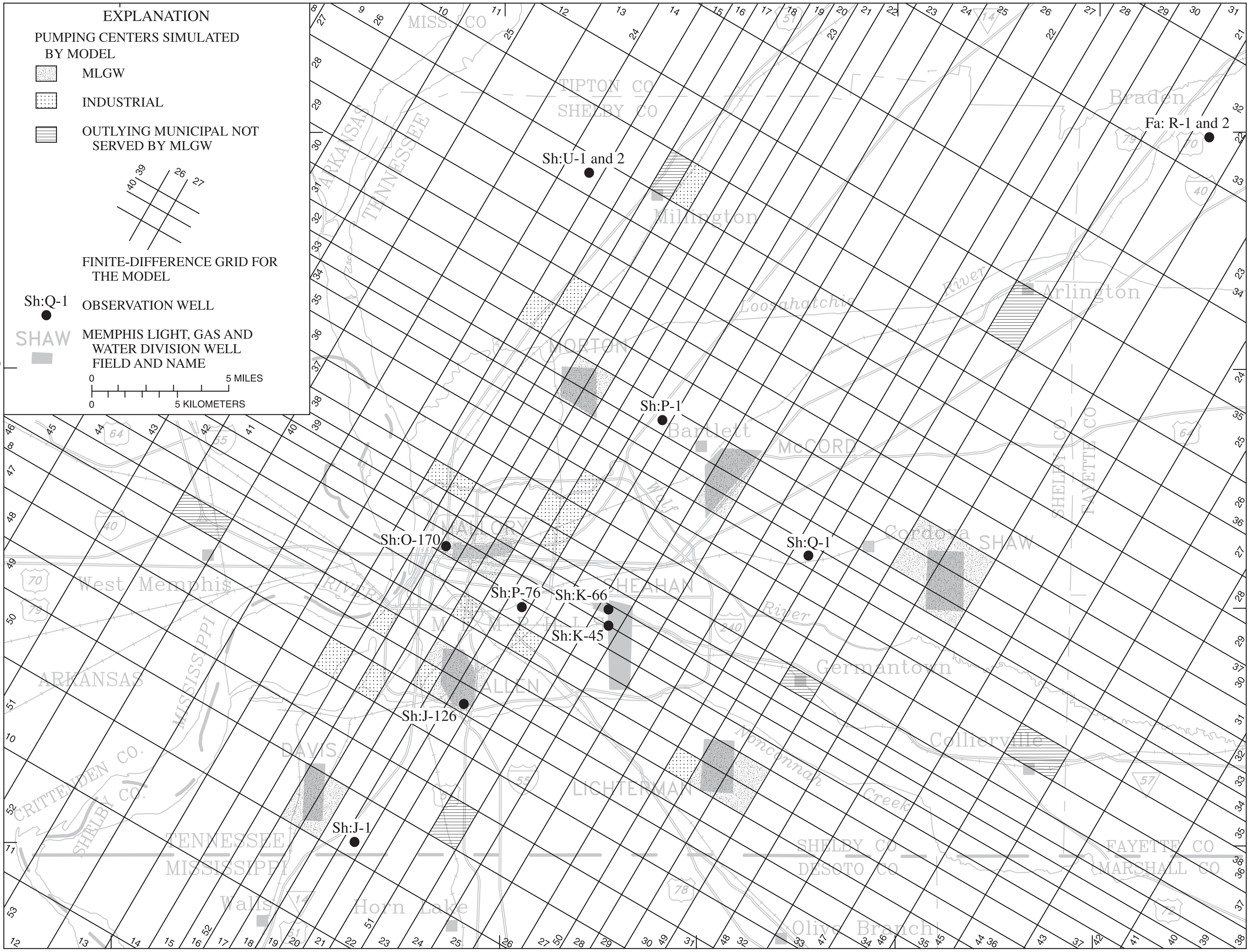
For example, the prepumping (1886) potentiometric surface of the Memphis aquifer is based on four data points (Criner and Parks, 1976), all of which were extrapolated (fig. 16). Data points for the Fort Pillow aquifer in the Memphis area likewise are lacking for this period. Because of this data, no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

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

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

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

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



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

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

The root mean square error is described by the equation:

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

where

RMSE is the root mean square error;

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

H^O is observed head, in feet;

n is the number of comparison points;

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

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

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

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

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

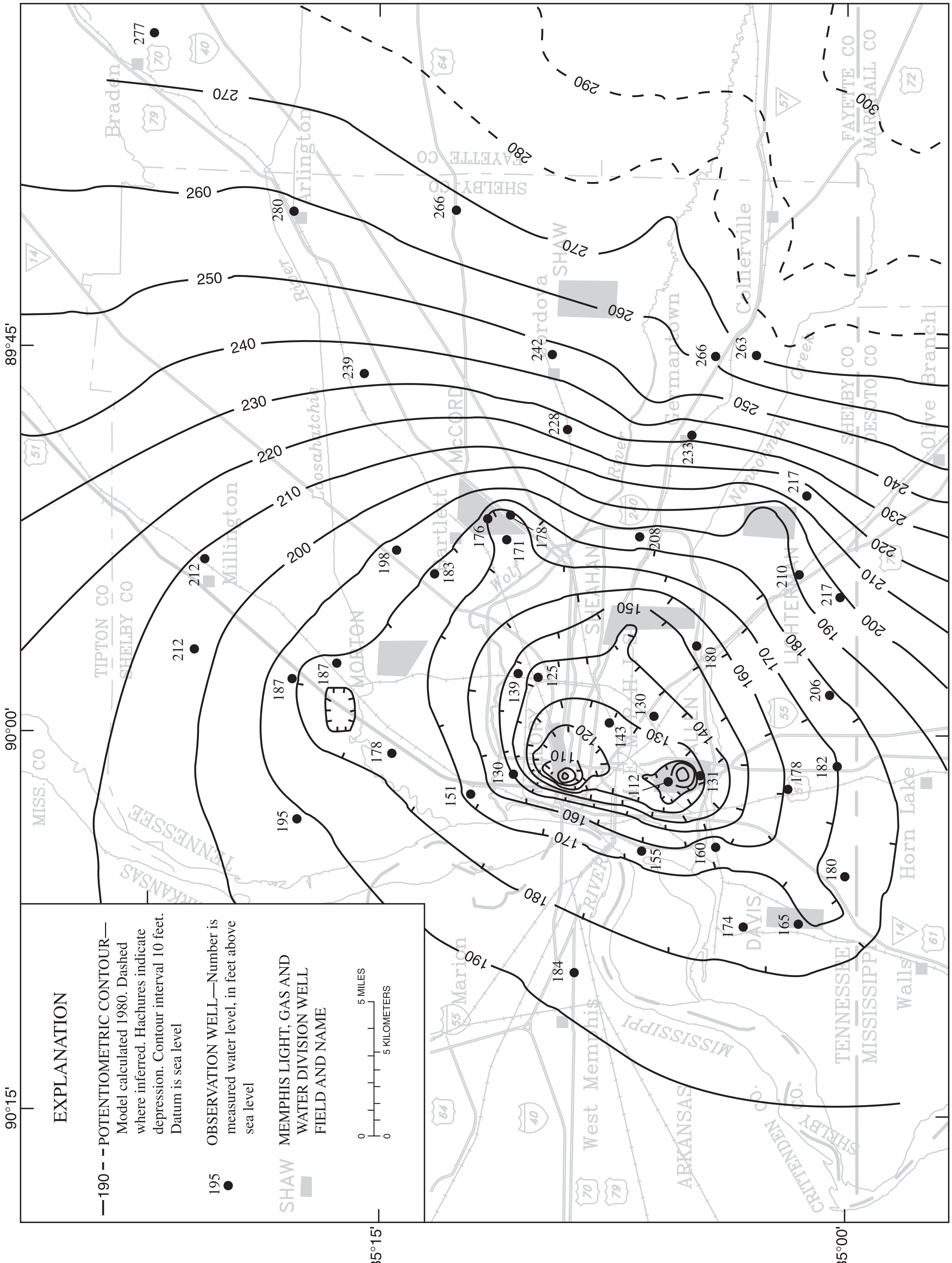
Although the overall simulation of heads in the Memphis aquifer is considered to be good, heads matched poorly in one subarea lying near Nonconnah Creek and the Tennessee-Mississippi border in south Memphis (figs. 26 and 7). Many alternative representations of transmissivity, leakage, and recharge were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

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

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

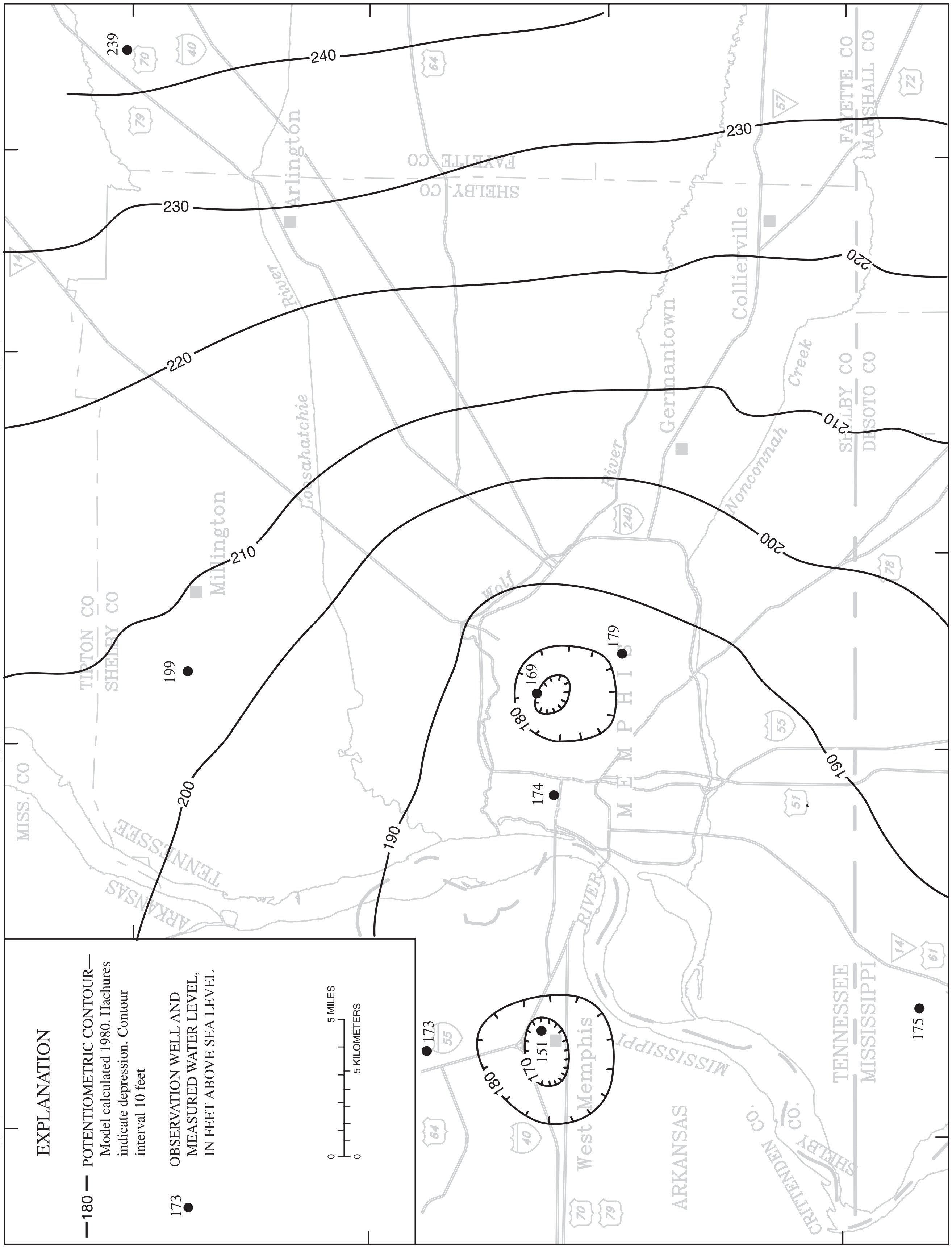
Model Testing

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



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

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



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

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

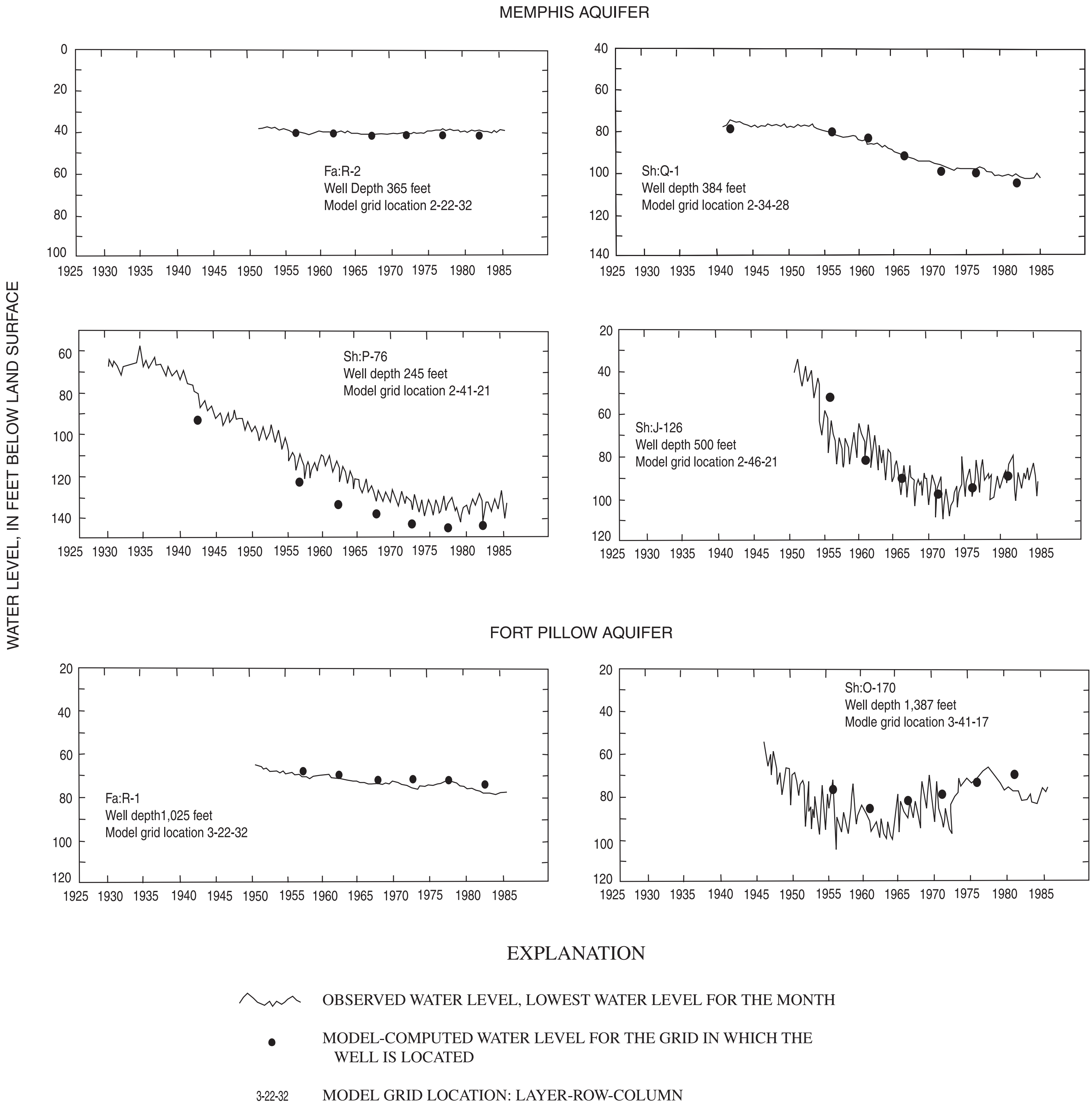


Figure 28. Selected hydrographs of observed and model-computed water levels for wells in the Memphis and Fort Pillow aquifers in the Memphis area.

Sensitivity Analysis

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

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

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

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

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

Interpretation of Model Results

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

Hydrologic Budget

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

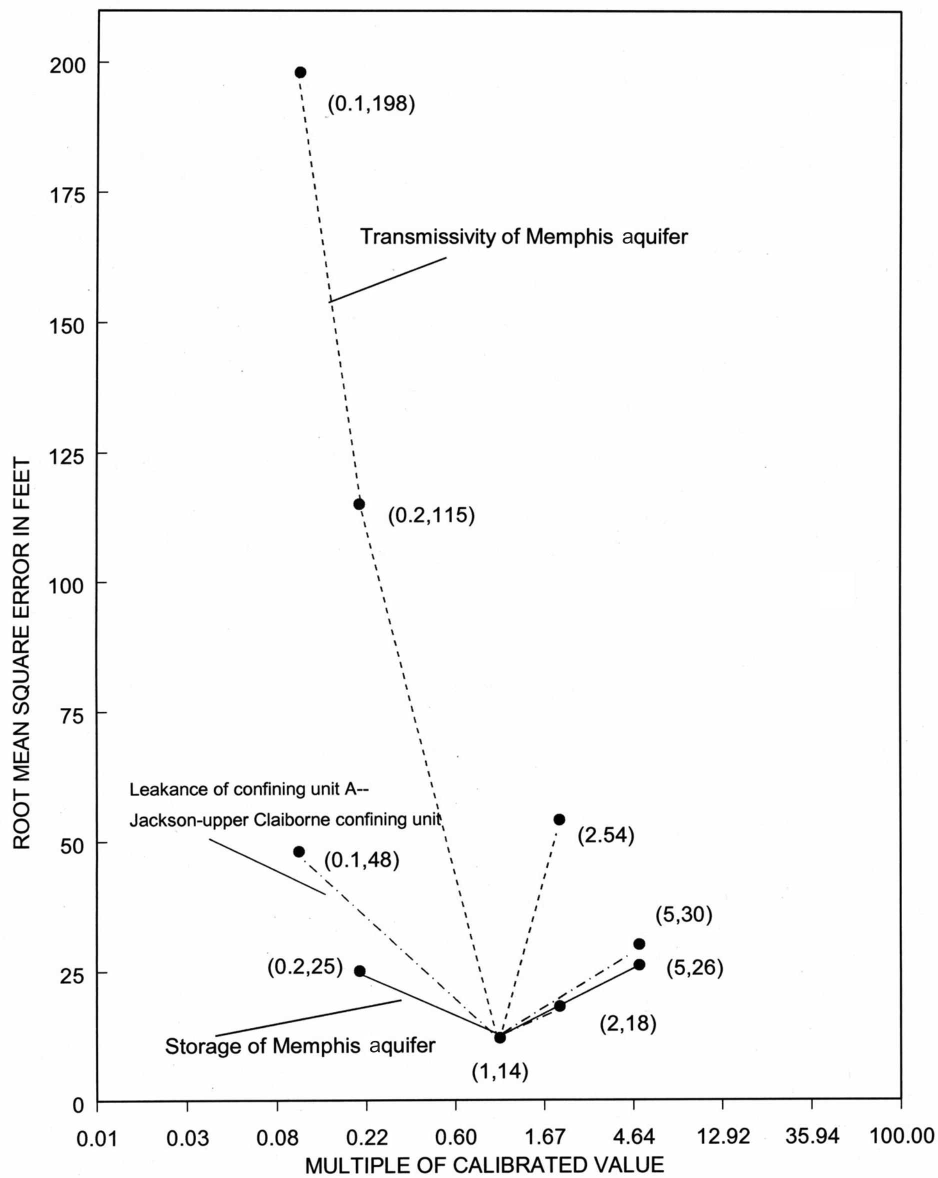


Figure 29. Relation between changes in magnitude of calibrated input (1980) parameters and root mean square error between observed and simulated water levels in the Memphis aquifer.

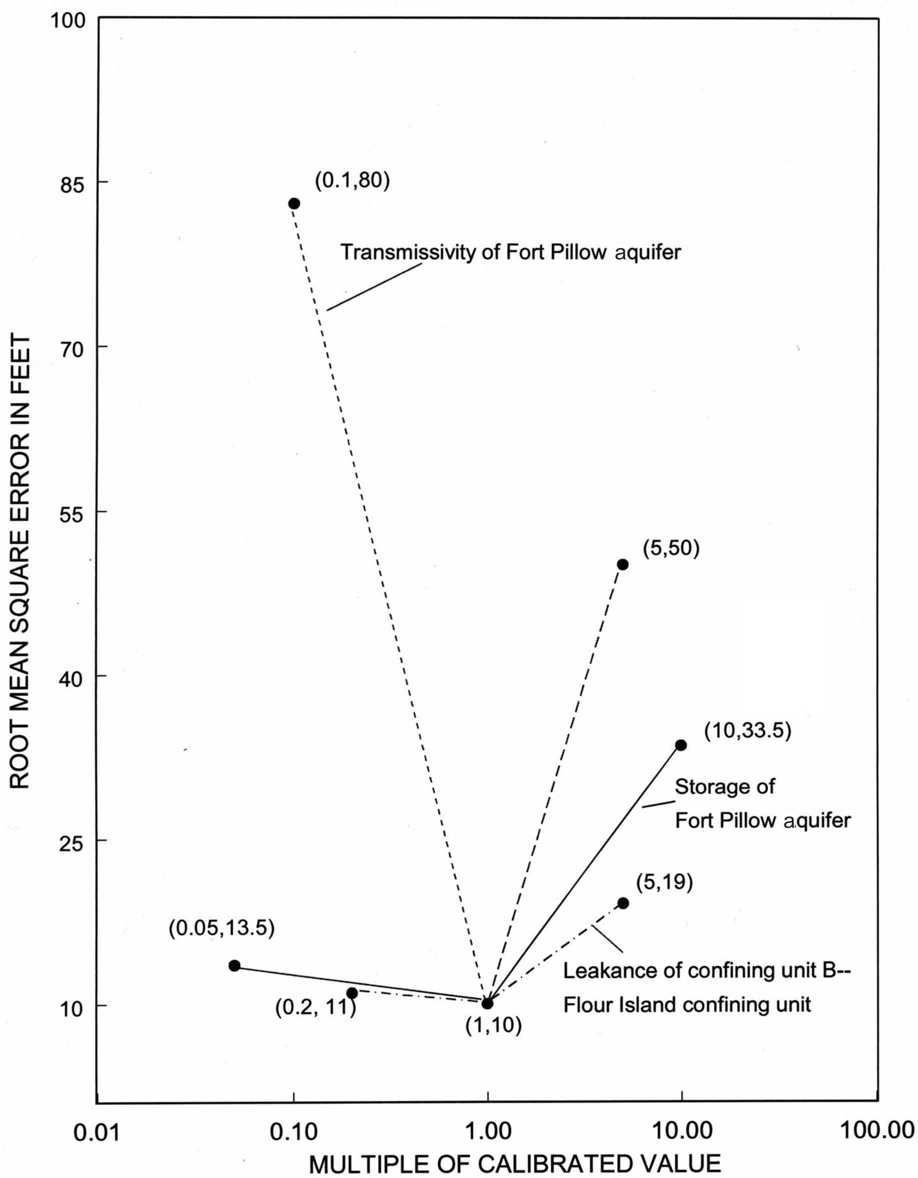


Figure 30. Relation between changes in magnitude of calibrated input (1980) parameters and root mean square error between observed and simulated water levels in the Fort Pillow aquifer.

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

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

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

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

Areal Distribution of Leakage

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

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

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

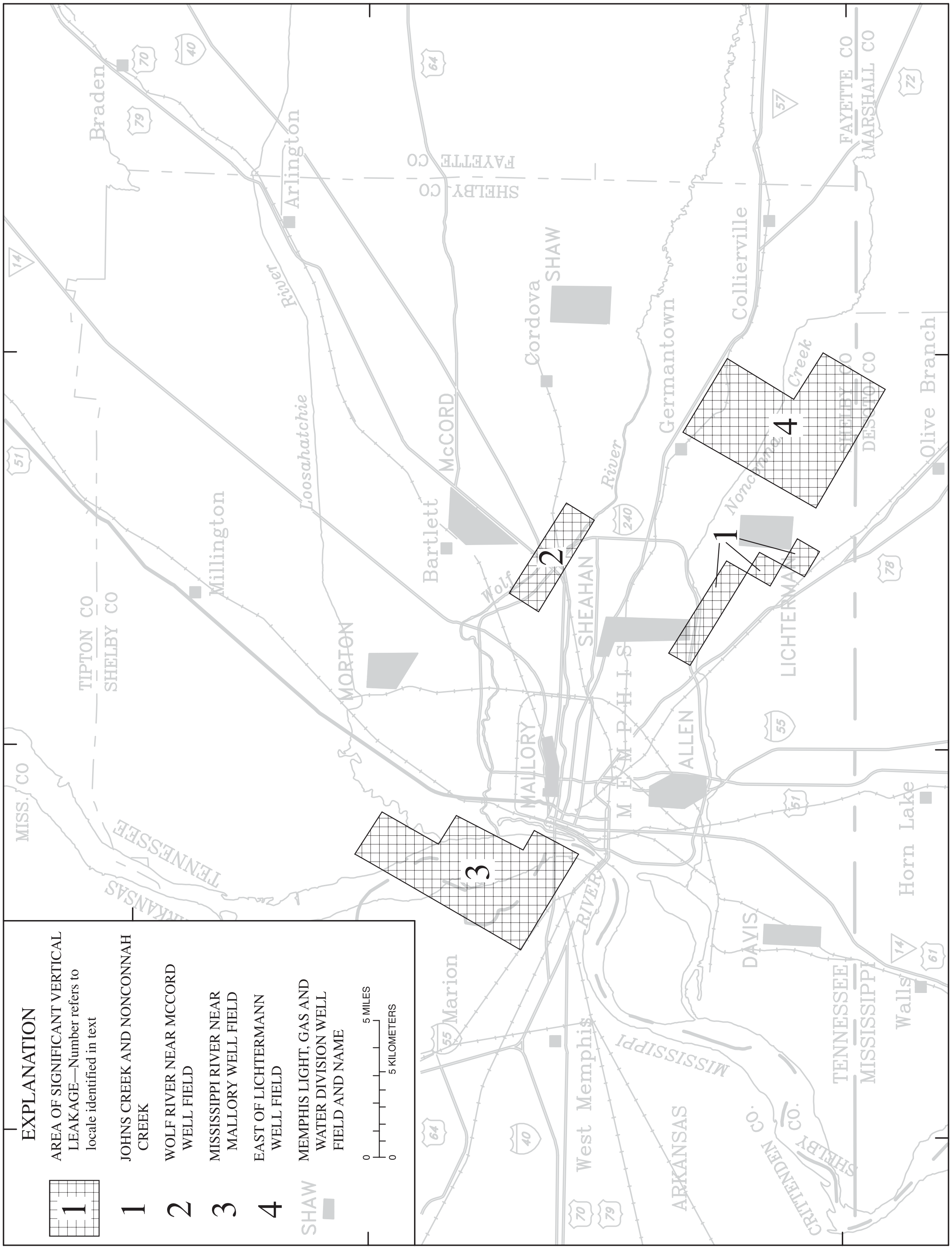
Model Limitations

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

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

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

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



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

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

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

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

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

SUMMARY AND CONCLUSIONS

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

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

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

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

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

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

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

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

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

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