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Hydrology of the Jackson, Tennessee, Area and Delineation of Areas Contributing Ground Water to the Jackson Well Fields

United States Geological Survey

Water-Resources Investigations
Report 92-4146

Prepared in cooperation with the
Jackson Utility Division

U.S. DEPARTMENT OF THE INTERIOR
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By ZELDA CHAPMAN BAILEY

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Nashville, Tennessee
1993

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTOR, VERTICAL DATUM, AND TRANSMISSIVITY

Multiply	By	To obtain
inch (in)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
acre	0.4047	hectare
foot per day (ft/d)	0.3048	meter per day
inch per year (in/yr)	2.54	centimeter per day
foot squared per day (ft^2/d)	0.0929	meter squared per day
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallon per day (gal/d)	3.785	liter per day
million gallons per day (Mgal/d)	0.04381	cubic meter per second

Temperature in degrees Fahrenheit (°F) can be converted to degree Celsius (°C) as follows: °C = 5/9(°F-32)

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

Transmissivity: In this report transmissivity is expressed as foot squared per day (ft^2/d)--The standard unit for transmissivity (T) is cubic foot per day per square foot times foot of aquifer thickness $[(ft^3/d)/ft^2]ft$ of cubic meter per day per square meter times meter of aquifer thickness $[(m^3/d)/m^2]m$. These mathematical expressions reduce to foot squared per day (ft^2/d) or meter squared per day (m^2/d).

Hydrology of the Jackson, Tennessee, Area and Delineation of Areas Contributing Ground Water to the Jackson Well Fields

By Zelda Chapman Bailey

Abstract

A comprehensive hydrologic investigation of the Jackson area in Madison County, Tennessee, was conducted to provide information for the development of a wellhead-protection program for two municipal well fields. The 136-square-mile study area is between the Middle Fork Forked Deer and South Fork Forked Deer Rivers and includes the city of Jackson.

The formations that underlie and crop out in the study area, in descending order, are the Memphis Sand, Fort Pillow Sand, and Porters Creek Clay. The saturated thickness of the Memphis Sand ranges from 0 to 270 feet; the Fort Pillow Sand, from 0 to 180 feet. The Porters Creek Clay, which ranges from 130 to 320 feet thick, separates a deeper formation, the McNairy Sand, from the shallower units. Estimates by other investigators of hydraulic conductivity for the Memphis Sand range from 80 to 202 feet per day. Estimates of transmissivity of the Memphis Sand range from 2,700 to 33,000 feet squared per day. Estimates of hydraulic conductivity for the Fort Pillow Sand range from 68 to 167 feet per day, and estimates of transmissivity of that unit range from 6,700 to 10,050 feet squared per day.

A finite-difference, ground-water flow model was calibrated to steady-state hydrologic conditions of April 1989, and was used to simulate hypothetical pumping plans for the North and South Well Fields. The aquifers were represented as three layers in the model to simulate the ground-water flow system. Layer 1 is the saturated part of the Memphis Sand; layer 2 is the upper half of the Fort Pillow Sand; and layer 3 is the lower half of the Fort Pillow Sand.

The steady-state water budget of the simulated system showed that more than half of the inflow to the ground-water system is underflow from the model boundaries. Most of this inflow is discharged as seepage to the rivers and to pumping wells. Slightly less than half of the inflow is from areal recharge and recharge from streams. About 75 percent of the discharge from the system is into the streams, lakes, and out of the model area through a small quantity of ground-water underflow. The remaining 25 percent is discharge to pumping wells.

The calibrated model was modified to simulate the effects on the ground-water system of three hypothetical pumping plans that increased pumping from the North Well Field to up to 20 million gallons per day, and from the South Well Field, to up to 15 million gallons per day. Maximum drawdown resulting from the 20 million-gallons-per-day rate of simulated pumping was 44.7 feet in a node containing a pumping well, and maximum drawdown over an extended area was about 38 feet. Up to 34 percent of ground-water seepage to streams in the calibrated model was intercepted by pumping in the simulations. A maximum of 9 percent more water was induced through model boundaries.

A particle-tracking program, MODPATH, was used to delineate areas contributing water to the North and South Well Fields for the calibrated model and the three pumping simulations, and to estimate distances for different times-of-travel to the wells. The size of the area contributing water to the North Well Field, defined by the 5-year time-of-travel capture zone, is about 0.8 by 1.8 miles for the calibrated model and pumping plan 1. The size of the area for pumping plan 2 is 1.1 by 2.0 miles and, for pumping plan 3, 1.6 by 2.2 miles. The range of distance for 1-year time-of-travel to individual wells is 200 to 800 feet for the calibrated model and plan 1, and 350 to 950 feet for plans 2 and 3.

The size of the area contributing water to the South Well Field, defined by the 5-year time-of-travel capture zone, is about 0.8 by 1.4 miles for the calibrated model. The size of the area for pumping plans 1 and 3 is 1.6 by 2.2 miles and, for pumping plan 2, 1.1 by 1.7 miles. The range of distance for 1-year time-of-travel to individual wells is 120 to 530 feet for the calibrated model, 670 to 1,300 feet for pumping plans 1 and 3, and 260 to 850 feet for pumping plan 2.

INTRODUCTION

The U.S. Geological Survey (USGS), in cooperation with the Jackson Utility Division (JUD), conducted a comprehensive investigation of the hydrogeology of the Jackson area in Madison County, Tennessee. This cooperative effort is a continuation of a pilot investigation of the Jackson area that provided preliminary information and analyses for the development of a wellhead-protection program for two municipal well fields (Broshears and others, 1991). The pilot investigation included a preliminary assessment of the local hydrogeology, ground-water quality, and potential sources of contamination. The purpose of the comprehensive investigation was to describe the hydrology of the Jackson area to the extent that the JUD can identify potential short- and long-term threats to the quality of ground water, and can use this information in the development of appropriate and timely strategies to protect municipal supplies. This information will assist JUD in making decisions about the protection and management of ground-water resources.

The 136-mi^2 study area (fig. 1) is oriented northeast to southwest, parallel to the outcrops of major aquifers, and includes most of the area of the pilot investigation. The northeastern extent of the study area is the Middle Fork Forked Deer River, and the southwestern extent is about 1 mile south of the South Fork Forked Deer River. A short segment of the North Fork of the South Fork is included in the study area. These tributaries of the Forked Deer River will be referred to for brevity in this report as the Middle, North, and South Forks. The northwestern boundary of the area is 3.5 miles from the North Well Field, and the southeastern boundary approximates the eastern edge of the outcrop of a major aquifer, the Fort Pillow Sand.

Purpose and Scope

This report describes the results of a comprehensive hydrologic investigation that was completed in 1990. The objectives were to (1) map the lithology and geometry of the aquifers and confining units in greater detail than previously available, (2) map the configurations of the water table and potentiometric surfaces, (3) determine directions of ground-water flow, (4) delineate areas of ground-water recharge and discharge, (5) evaluate effects of hypothetical increases in pumping from the well fields, (6) delineate areas contributing ground water to municipal wells, and (7) estimate times-of-travel for advective transport of solutes to municipal wells. Data collection for stratigraphic and water-level information was limited to existing well logs and wells.

Approach

Subsurface geometry and lithology of the major geologic units have been mapped on a regional scale by other investigators (Parks and Carmichael, 1989, 1990c). Local refinements for the study area were made by using 126 drillers' logs and borehole geophysical logs. The drillers' logs were selected from records in the State files on the basis of complete stratigraphic information. The geophysical

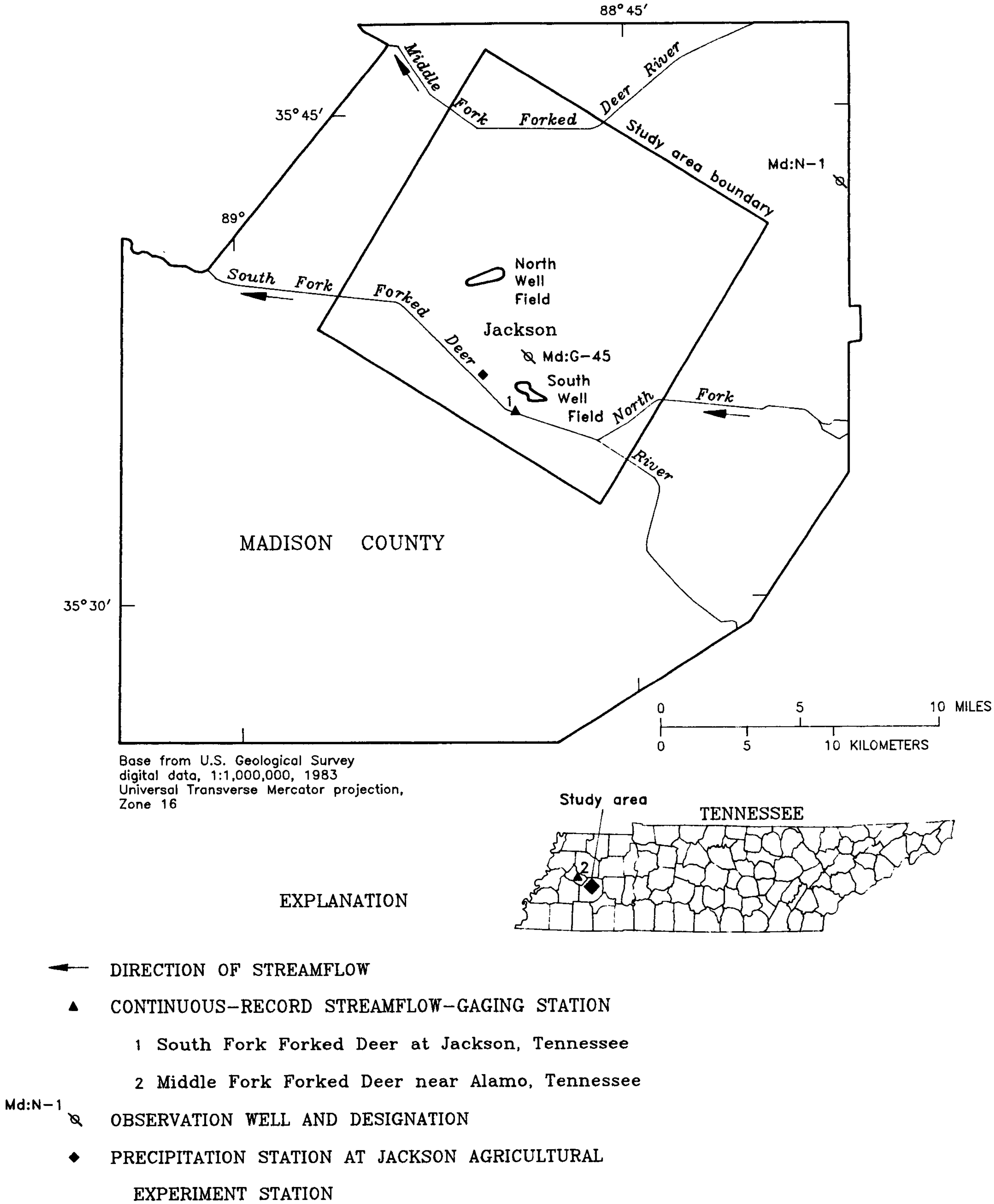


Figure 1. Study area.

logs were collected from deep wells by the USGS during previous investigations.

Locations and quantities of water discharged to streams by industries or sewage treatment plants, and locations and rates of commercial, industrial, and municipal pumping were identified (fig. 2). Water levels were measured in 53 domestic, commercial, and municipal wells from April 24 through 25, 1989, and elevations of the wells were estimated from topographic contours. Stream discharge was measured or estimated at the same time at 79 sites along all the forks of the Forked Deer River and their tributaries (fig. 2).

A finite-difference, ground-water flow model was calibrated to hydrologic conditions of April 1989 and was used to simulate hypothetical pumping plans. A particle-tracking analysis was used to delineate areas contributing water to wells in the municipal well fields and to estimate distances for different times-of-travel to the wells.

Acknowledgments

The author thanks the Tennessee Department of Environment and Conservation (TDEC), Division of Systems and Procedures, for providing extensive drillers' log data. Appreciation also is expressed to the staff of the Jackson Utility Division who located wells for water-level measurement and assisted in the field data collection, and to the businesses and homeowners who graciously allowed their wells to be measured. Without their support, much of the data needed for this investigation could not have been collected.

DESCRIPTION OF STUDY AREA

Geography and Climate

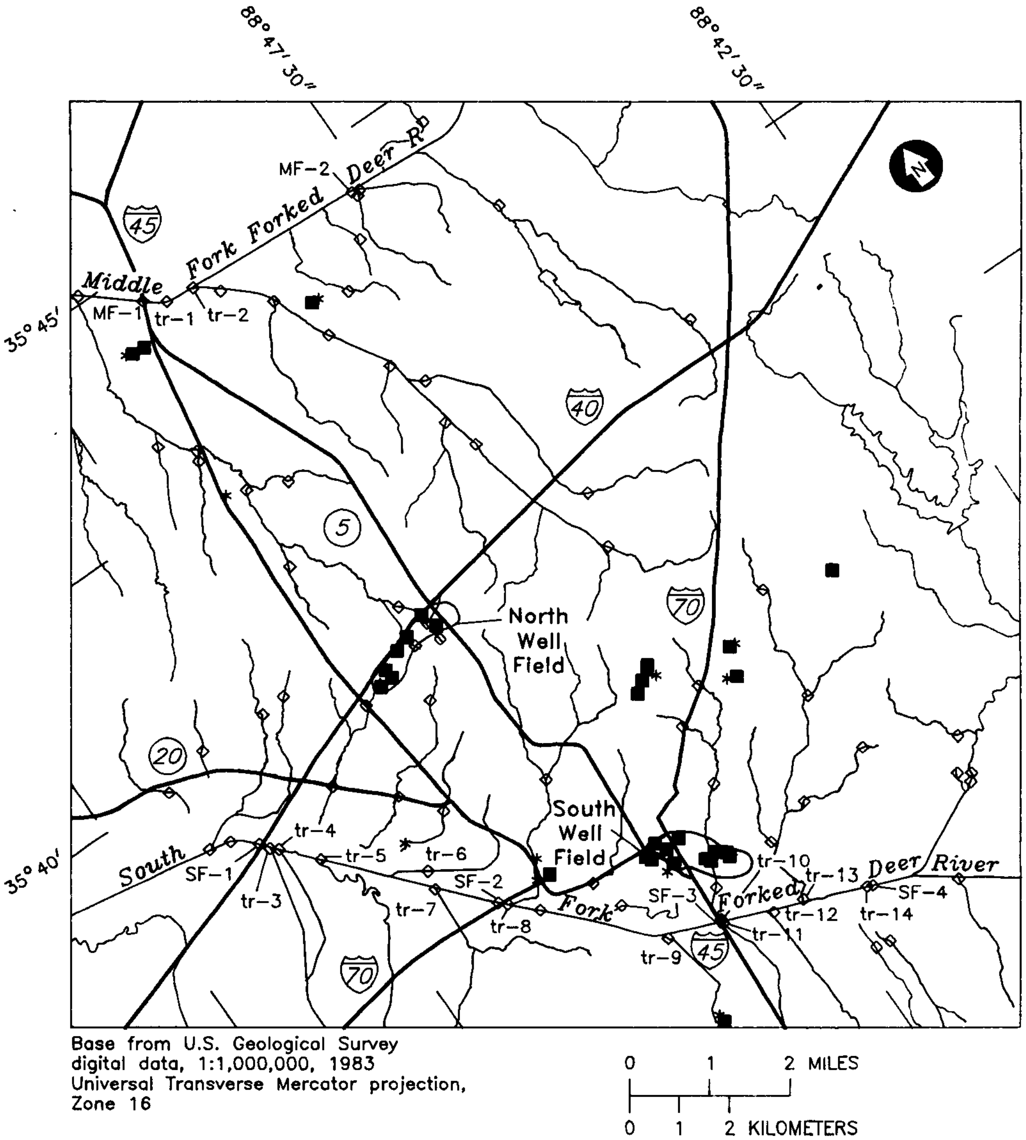
The area of investigation is in the West Tennessee Plain of the Coastal Plain physiographic province (Miller, 1974, p. 7). Total relief is about 280 feet. The lowest elevation, 320 feet above sea level, is where the South Fork leaves the study area and the highest elevation, about 540 feet, is along the drainage divide between the Middle and South Forks. The summit of one hill along the divide stands at nearly 600 feet above sea level.

Mean annual precipitation for the period 1941 to 1980 was 49.9 inches (National Climatic Data Center, National Oceanic and Atmospheric Administration, written commun., 1988). Rain characteristically falls throughout the year. Mean monthly precipitation ranges from about 2.5 inches in October to about 5.4 inches in April.

Geology

The geologic units that are of hydrologic interest in the study area include, from youngest to oldest, the Memphis Sand, Fort Pillow Sand (fig. 3), and Porters Creek Clay. In the northwestern part, comprising about half the study area, the Memphis Sand is overlain by loess, and in most of the remaining area, by Pleistocene fluvial deposits (fig. 3); however, these deposits are not saturated. The principal aquifers, the Memphis and Fort Pillow Sands, contain clay lenses of considerable thickness and areal extent. The Memphis Sand consists primarily of fine to very coarse sand and silt and clay. The Fort Pillow Sand consists primarily of fine to very coarse sand and minor clay. The saturated thickness of the Memphis Sand ranges from 0 to 270 feet (fig. 4). The Fort Pillow Sand in most of the area ranges from 0 to 180 feet thick, although the thickness in an area in the southern part of the study area, near the boundary of the model, is as much as 230 feet (fig. 5). Erosional remnants of the Flour Island Formation, which confines the Fort Pillow Sand to the west, may be present in the western part of the study area, but no evidence was found on drillers logs. The Porters Creek Clay, which ranges from 130 to 320 feet thick, separates a deeper formation, the McNairy Sand, from the shallower units. The bottom of the Porters Creek Clay was not mapped, but was estimated on the hydrogeologic sections (fig. 6) using an average thickness of 225 feet. All units thin from northwest to southeast and dip to the northwest at 20 to 50 ft/mi.

TDEC and USGS files and records were searched for stratigraphic information on existing wells. More than 900 wells in the study area were inventoried by the USGS prior to 1960; however, no stratigraphic data were collected. Few of the more than 3,100 wells in the TDEC files provided stratigraphic information. Data for all deep wells for



EXPLANATION

◇ DISCHARGE-MEASUREMENT SITE--Sites designated with numbers are listed in table 4

■ COMMERCIAL OR MUNICIPAL WELL

* INDUSTRIAL OR MUNICIPAL DISCHARGE POINT

Figure 2. Location of data-collection sites and pumped wells.

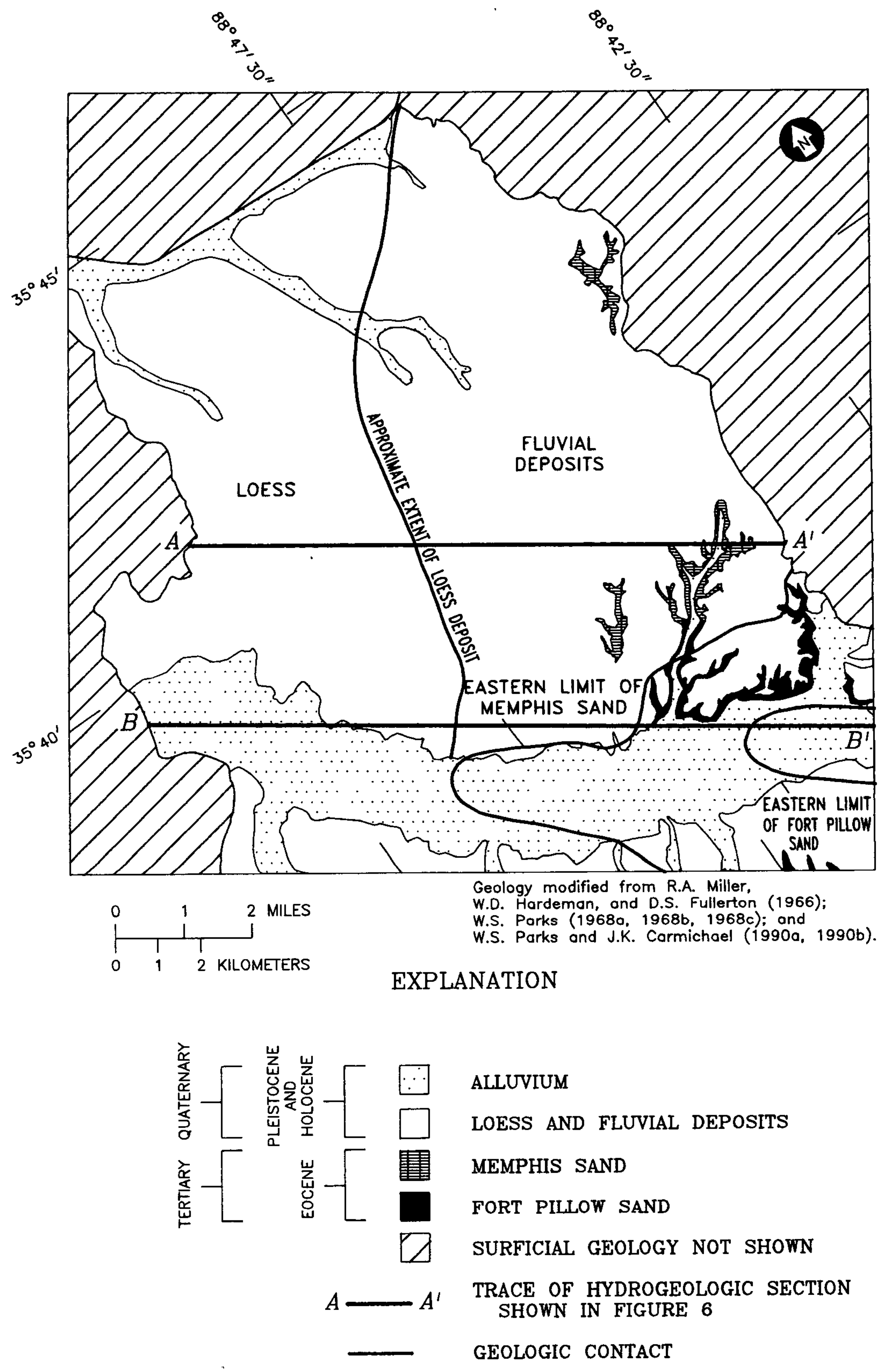
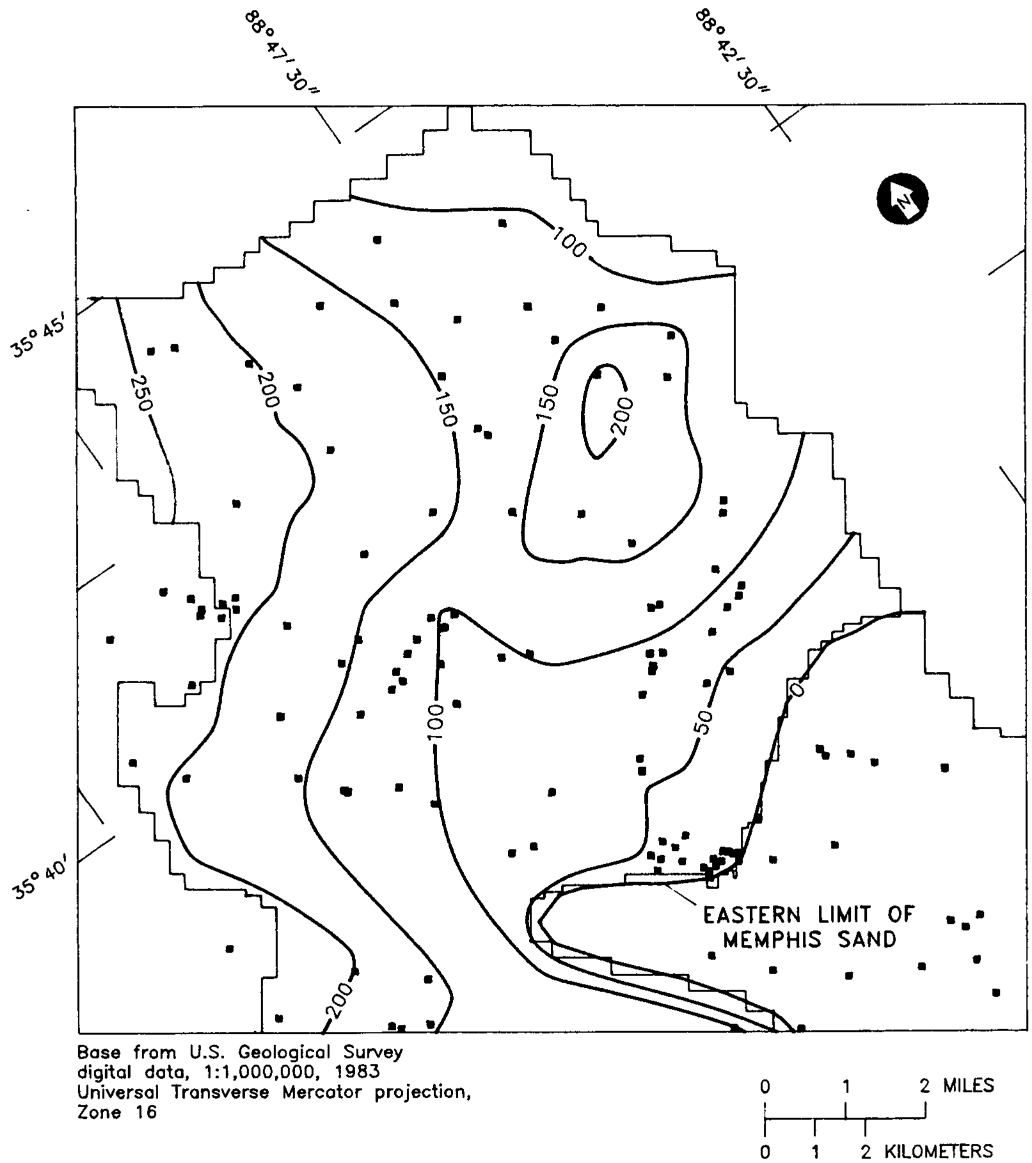


Figure 3. Surficial geology.



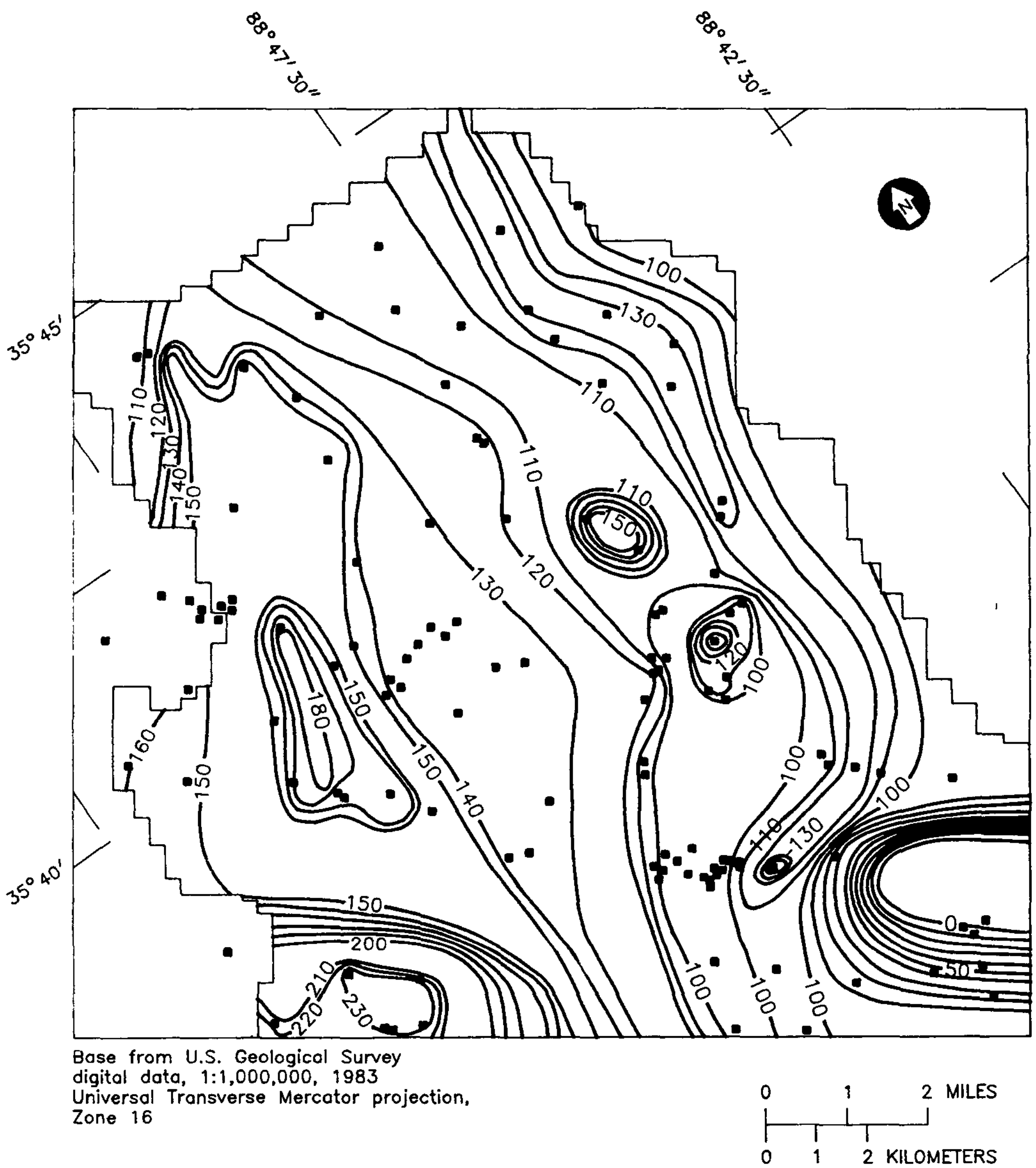
EXPLANATION

—100— LINE OF EQUAL SATURATED THICKNESS OF AQUIFER--Interval 50 feet

ACTIVE-NODE BOUNDARY

▪ TEST HOLE HAVING STRATIGRAPHIC DATA

Figure 4. Saturated thickness of the Memphis Sand, April 1989.



EXPLANATION

—100— LINE OF EQUAL THICKNESS OF AQUIFER--Interval 10 feet

ACTIVE-NODE BOUNDARY

■ TEST HOLE HAVING STRATIGRAPHIC DATA

Figure 5. Thickness of the Fort Pillow Sand.

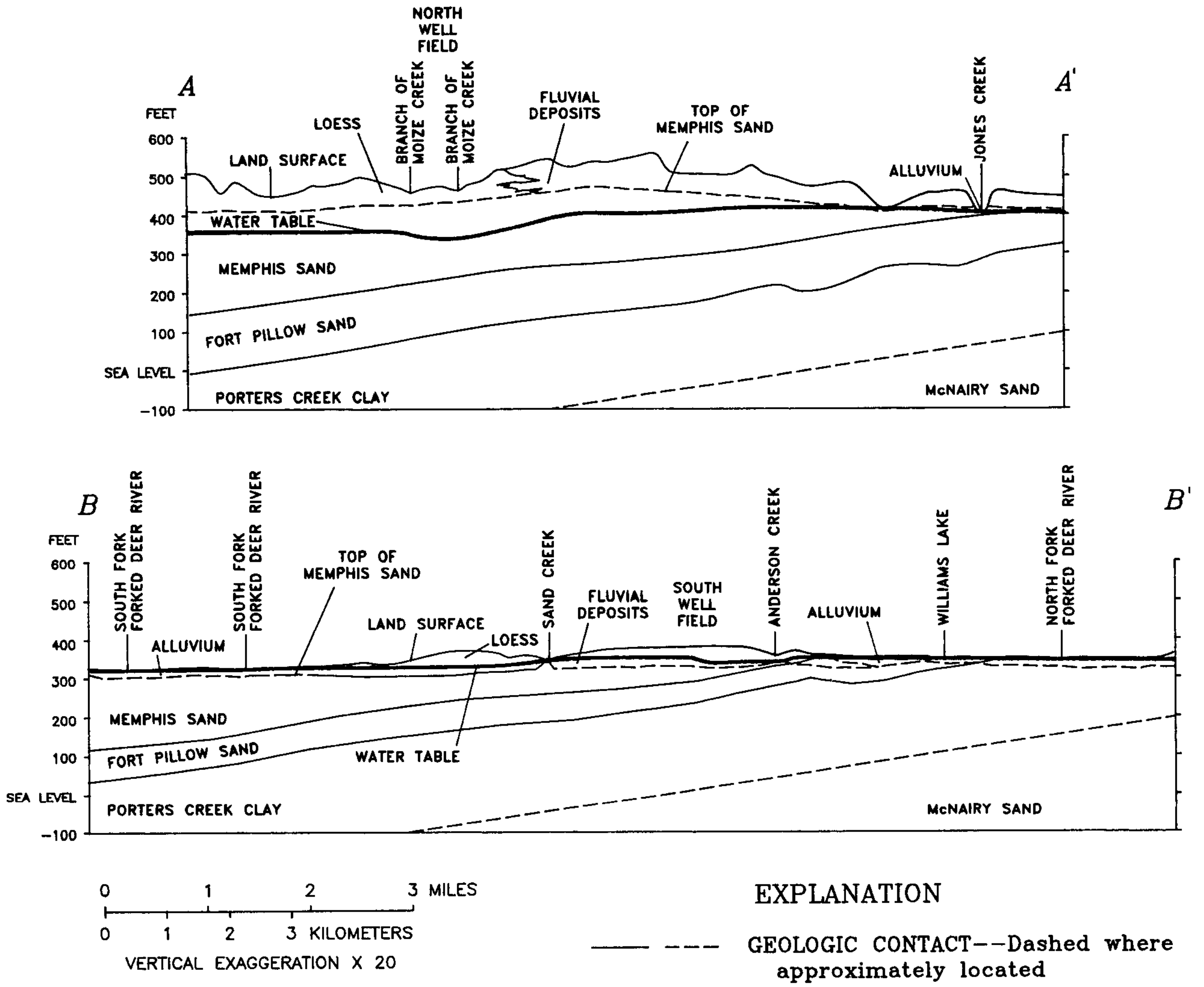


Figure 6. Hydrogeologic sections. (Traces of sections shown on figure 3.)

which stratigraphic data were available and data for selected shallow wells, a total of 129 wells, were used in this investigation to refine the larger scale geologic maps of other investigators (Miller and others, 1966; Parks, 1968a-c; Parks and Carmichael, 1989, 1990c).

Land Use

Land use is divided into five general categories: agricultural, urban, wetlands, forest, and disturbed (table 1). The distribution of these categories is shown on figure 7 only for the area included in the active-model area. The principal land use is agricultural. Urban areas include the city of Jackson and surrounding residential subdivisions, industrialized areas, and major highways. Wetlands include forested and nonforested wetlands and open water. Disturbed land includes land that has been cleared for construction, quarry operations, or landfills.

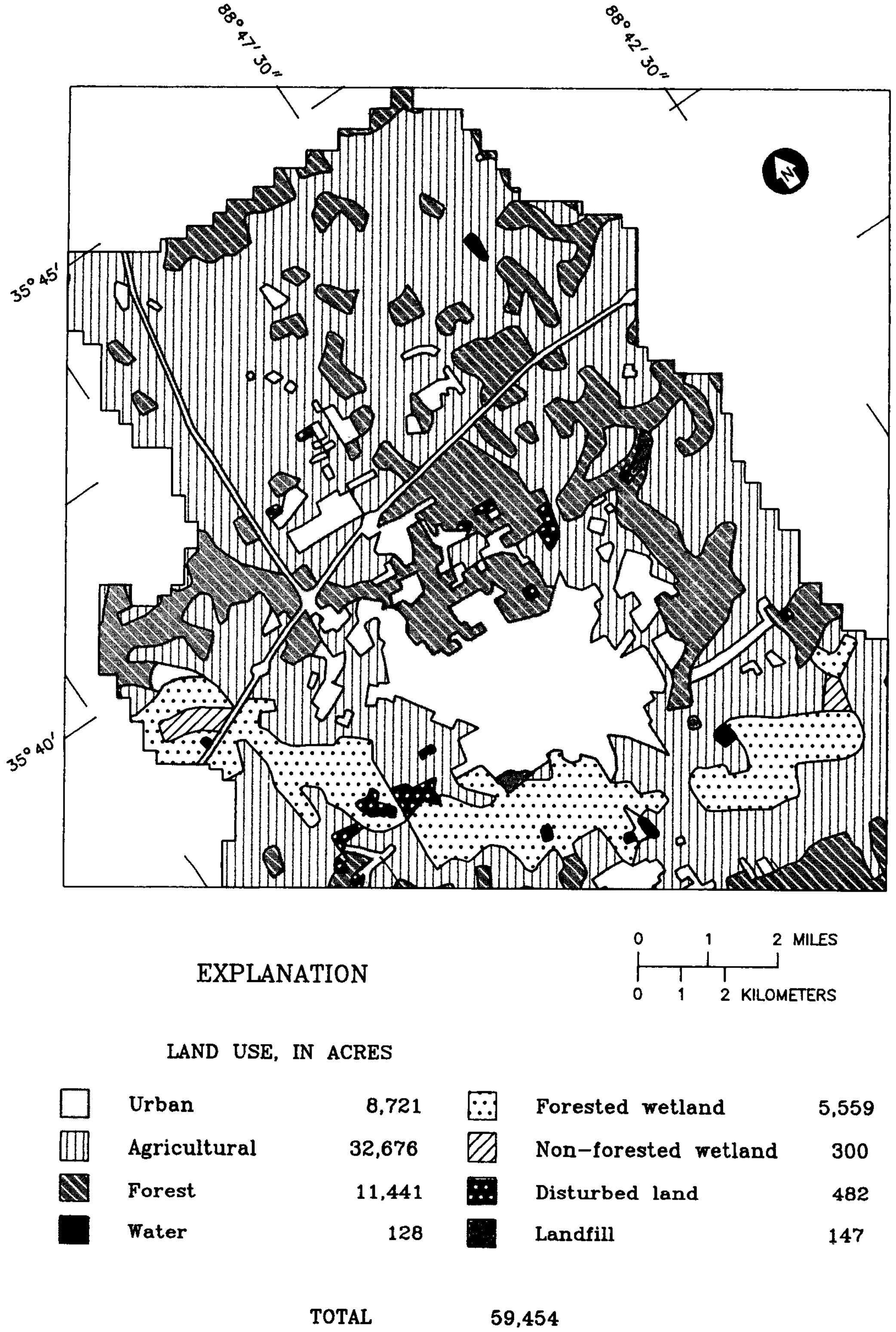


Figure 7. Land use.

Table 1. Land use

Land-use category	Area, in square miles	Percentage of total
Agricultural	51.0	55
Urban	13.6	15
Wetlands	9.4	10
Forested (8.7)		
Nonforested (0.5)		
Water (0.2)		
Forest	17.9	19
Disturbed	1.0	1
Total	92.9	100

Water Use

The primary sources of ground water in the area are the Memphis Sand and Fort Pillow Sand. A total of about 16.0 Mgal/d is pumped from these aquifers in the study area during 1989 (table 2). The McNairy Sand is not used extensively as a local source of water, but several flowing wells tap that aquifer. Some of these wells flow freely at a rate of about 300 gal/min.

Table 2. Average annual ground-water use from the Memphis and Fort Pillow Sands in the Jackson area, 1989

Source of pumpage	Pumping rate, in million gallons per day	Percentage of total water pumped	Year	Source of data
North Well Field	8.7	55	1989	Jackson Utility Division.
South Well Field	1.6	10	1989	Do.
Industrial	5.0	31	1988	Industry estimates.
Domestic and commercial.	.7	4	1985	Hutson, 1988.
Totals	16.0	100		

The JUD supplies water to customers in Madison County from two well fields in Jackson (figs. 1-2). Prior to 1980 all of the water, as much as 9 Mgal/d, was pumped from the South Well Field. Since 1980, as much as 85 percent of the municipal supply has been pumped from the North Well Field (fig. 8). Average annual withdrawal in 1989 was 8.7 Mgal/d from the North Well Field, and 1.6 Mgal/d from the South Well Field (table 2). Average pumpage for the week in April 1989 when water levels and stream discharges were measured was 9.2 Mgal/d for the North Well Field and 2.2 Mgal/d for the South Well Field (Danny Lester, JUD, written commun., 1989).

Average total industrial pumpage from 33 wells in the Jackson area is about 5 Mgal/d (table 2). Domestic wells provide water for many county residents and a few wells supply commercial enterprises; however, withdrawal from these wells, about 0.7 Mgal/d, is minor compared to withdrawals from municipal and industrial wells.

Streamflow Characteristics

The Middle, South, and North Forks are the major drains for most of Madison County (fig. 1), and their channels have been ditched and straightened. Wetlands predominate in the flood plains of the North and South Forks (fig. 7). The uplands between the rivers are dissected by tributaries that are dry most of the year.

A continuous-record streamflow-gaging station was operated on the South Fork at Jackson (fig. 1) from August 1929 through September 1973 and the station was reactivated in May 1988 (fig. 9). The drainage area of the stream upstream of the station is 495 mi^2. Average flow for 44 years of record (1929-73) was 705 ft^3/s or 19.34 in/yr (U.S. Geological Survey, 1974, p. 141). Maximum discharge for the period was 43,600 ft^3/s, and minimum was 67 ft^3/s.

A continuous-record streamflow-gaging station on the Middle Fork was operated near Alamo (fig. 1, location map), about 16 miles downstream from the study area, from August 1929 through September 1973. The drainage area of the stream upstream of the station is 369 mi^2. Average flow for 44 years of

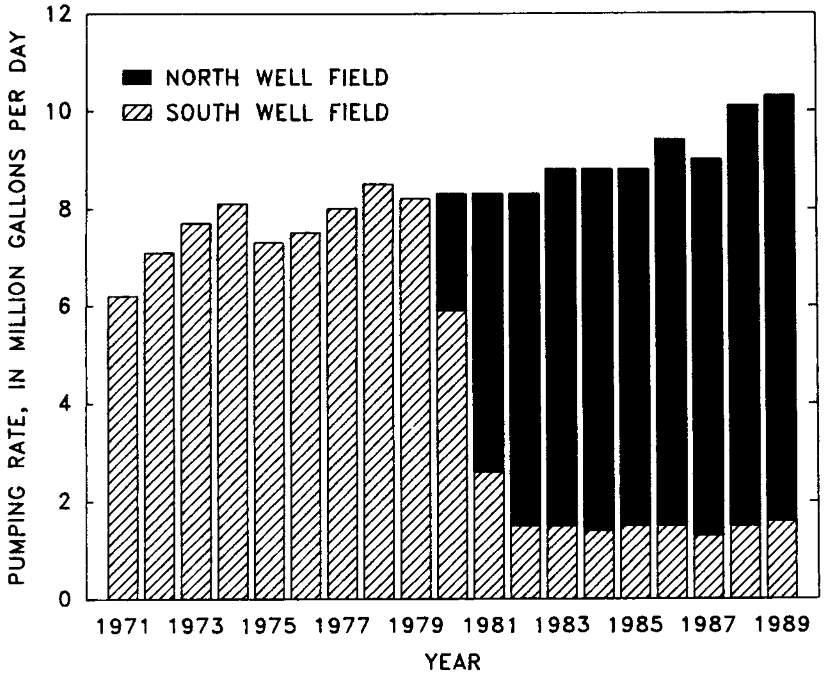


Figure 8. Average annual pumping rates from the well fields, 1971-89. (Danny Lester, Jackson Utility Division, written commun., 1989.)

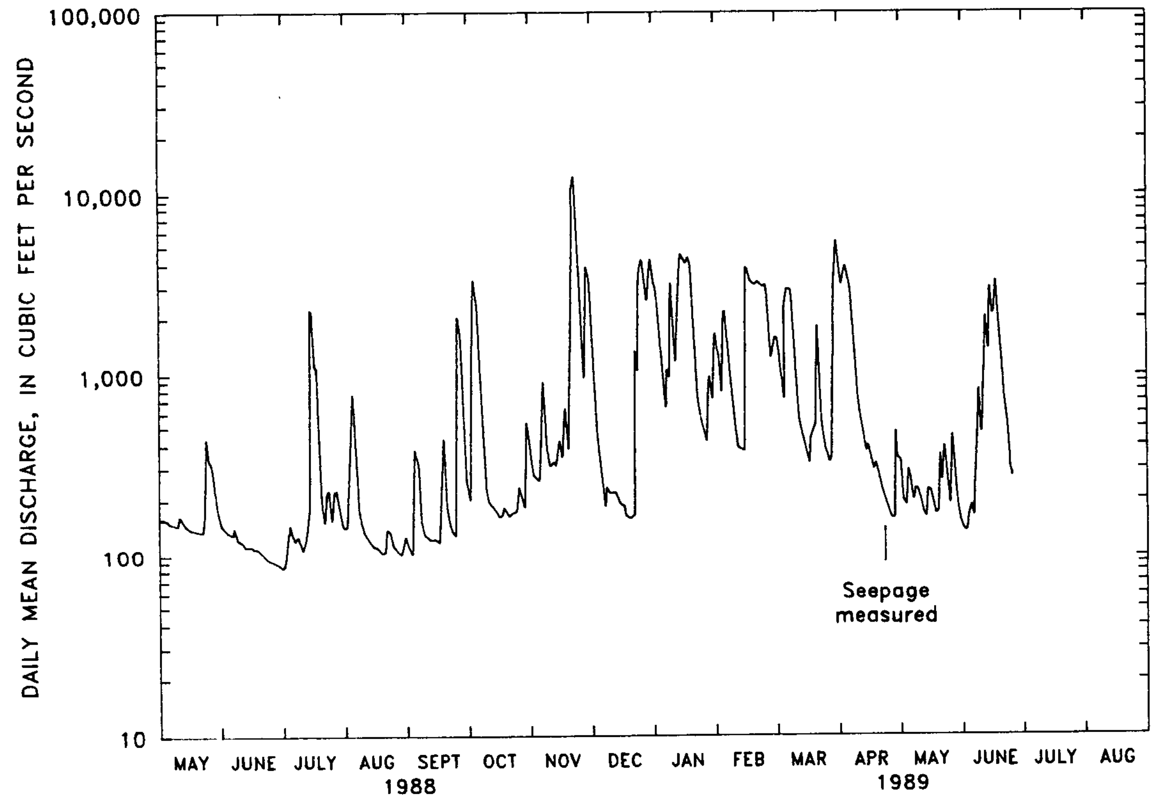


Figure 9. Discharge of the South Fork Forked Deer River at Jackson, Tennessee.

record (1929-73) was 521 ft³/s or 19.17 in/yr (U.S. Geological Survey, 1974, p. 142). Maximum discharge for the period was 34,300 ft³/s, and minimum was 68 ft³/s.

HYDROLOGIC SYSTEM

Hydraulic Characteristics of Aquifers

Average hydraulic conductivity, transmissivity, and storage coefficient of the Memphis Sand and Fort Pillow Sand in Madison County have been estimated (table 3) by Hosman and others (1968, p. 8, 9, and 21) and by Moore (1965, pl. 7). Parks and Carmichael (1990c) reported estimates of transmissivity and storage coefficient from a regional study of the Memphis Sand. The values were estimated from tests in a small number of wells and applied to large areas, so hydraulic characteristics of the aquifers in any specific location may vary considerably from these estimates. Previous investigations in the Jackson area provided estimates of hydraulic conductivity and transmissivity for both the Memphis Sand and the Fort Pillow Sand (Nuzman, C.E., consultant for Layne Central Company, Inc., written commun., 1977; Groundwater Management, Inc., written commun., 1987).

Estimates of hydraulic conductivity for the Memphis Sand range from 80 to 202 ft/d, transmissivity from 2,700 to 33,000 ft²/d, and storage coefficient from 0.0001 to 0.011. Two estimates of hydraulic conductivity for the Fort Pillow Sand are 68 and 167 ft/d, and estimates of transmissivity, 6,700 and 10,050 ft²/d. The only estimate of storage coefficient is 0.0015. The range of porosity for unconsolidated sand aquifers of the type found in the study area is between 20 and 50 percent (Freeze and Cherry, 1979, p. 37).

Table 3. Estimated hydraulic characteristics of the Memphis Sand and Fort Pillow Sand in or near Madison County

Aquifer	Transmissivity, in feet squared	Hydraulic conductivity	Storage coefficient	Source of data
Memphis Sand	[a]6,700		0.0003	Moore (1965)
	[b]13,400-20,100		.0004	Moore (1965)
	20,100	80	.011	Hosman and others (1968)
	[c]20,000-25,000			Nuzman, C.E., written commun., 1977[e]
	[d]11,000-33,000	202		Nuzman, C.E., written commun., 1977[e]
	2,700-29,400		.0001-.0006	Parks and Carmichael (1990c)
	[f]11,900			Parks and Carmichael (1990c)
Fort Pillow Sand	10,050	68	.0015	Hosman and others (1968)
	[g]6,700	167		Groundwater Management, Inc. written commun., 1987.

[a]Estimate is for a small area in west-central part of the county.
[b]Estimate is for the northwestern corner of the county.
[c]Calculated from a multiple-well aquifer test.
[d]Calculated from an estimated hydraulic conductivity of 202 feet per day and full aquifer thickness at a piezometer.
[e]Report for Layne-Central Company, Inc.
[f]Value for aquifer in Gibson County adjacent to northern Madison County line.
[g]Estimated from a specific-capacity test on a well in the South Well Field.

Ground- and Surface-Water Interaction

Base-flow measurements and flow-duration curves were used to study the hydraulic connection between ground water and surface water. Discharge measurements or estimates of streamflow were made at 79 sites (fig. 2) during base-flow conditions from April 24 through 26, 1989. During the discharge measurements, flow at the gage on the South Fork (fig. 1; fig. 2, site SF-3) was equivalent to about the 60-percent flow duration (figs. 9 and 10). A number of the smaller tributaries were dry, and are typically dry except for short periods after significant rainfall. Ground-water gains and losses were calculated for the segments of the Middle and South Forks within the study area (table 4), and overall, both streams were gaining ground water. The seepage rate for the Middle Fork was 7.6 ft^3/s per mile of stream channel, and for the South Fork, 2.8 ft^3/s per mile of stream channel. Seepage rates also were calculated for three segments of the South Fork (fig. 2, SF-4 to SF-3, SF-3 to SF-2, SF-2 to SF-1), and the rates were -2.4, 8.9, and 2.7 ft^3/s per mile of stream channel, respectively ("-" indicates loss of streamflow to the ground-water system).

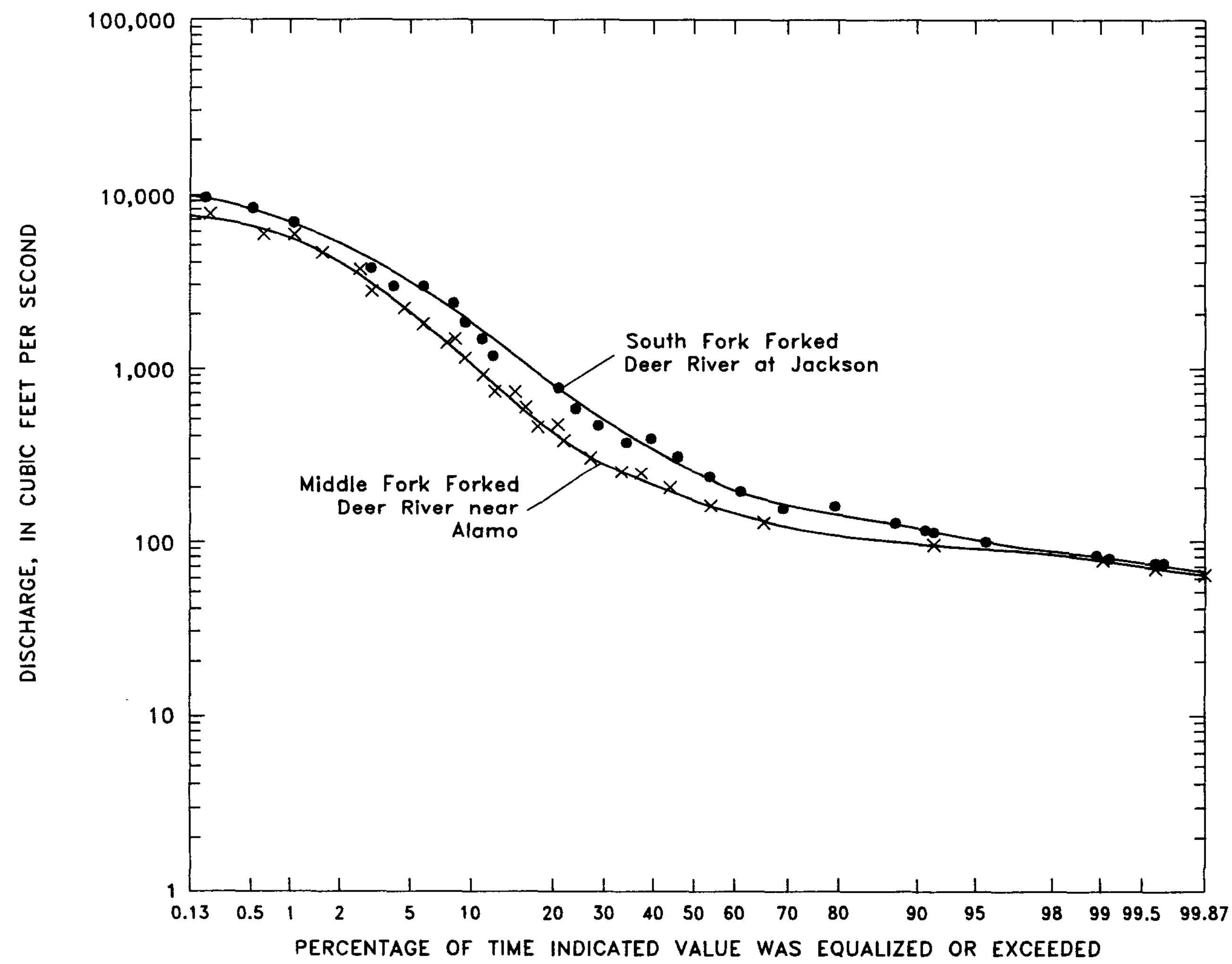


Figure 10. Flow duration of the Middle and South Forks Forked Deer River.

Table 4. Discharges and ground-water gains and losses along segments of the Middle and South Forks Forked Deer River, April 24 through 26, 1989

[MF, Middle Fork; SF, South Fork; tr, tributary]

Measurement site[1]	Discharge measured, in cubic feet per second[2]		Gain or loss, in cubic feet per second	Reach length, in miles
MF-1	150			
tr-1	0.74			
tr-2	1.59			
MF-2	125		22.7	3
		Total	22.7	
SF-1	337			
tr-3	16.3			
tr-4	.02			
tr-5	3.91			
tr-6	.01			
tr-7	.37			
SF-2	311		5.4	2
tr-8	.04			
tr-9	3.07			
SF-3	284			
tr-10	1.24		23.9	2.7
tr-11	6.65			
tr-12	16.2			
tr-13	4.16			
tr-14	.12			
SF-4	263		-17.4	3.1
		Total	21.9	7.8

[1]Locations shown in figure 2.
[2]Measurement accuracy within 5 to 8 percent.
[3]Negative number indicates loss to ground-water system.

Flow-duration curves were plotted for the Middle and South Forks (fig. 10). The shape of a flow-duration curve is determined by hydrologic and geologic characteristics of the drainage basin. A steep slope on the curve indicates a highly variable stream whose flow is mainly from direct runoff. A steep slope at the lower end of the curve indicates a negligible amount of perennial storage in the basin; a flat slope indicates a large amount of storage (Searcy, 1959, p. 22). The storage may be shallow ground water or in wetlands or ponds along the river channel.

The flow-duration curves for the Middle Fork near Alamo and the South Fork at Jackson (fig. 10) are relatively flat and are especially flattened on the lower end, which indicates a large amount of perennial storage capacity that allows slow drainage of water to the streams. This configuration is typical of low gradient streams having wide, marshy flood plains.

Areal Recharge

Nearly all areal recharge to the aquifers is from precipitation during November through April. During the growing season, May through October, nearly all precipitation is transpired and little, if any, recharge percolates to the ground-water system (Moore, 1965). A recharge rate of 9.5 in/yr to the Coastal Plain within the Tennessee River basin was estimated from the 1968 water year hydrograph at the Big Sandy River at Bruceton (Zurawski, 1978, p. 9). The drainage basin of that river is adjacent to Madison County, and recharge in that basin is probably representative of the recharge characteristics of the aquifers in the Jackson area. The two aquifers that crop out in the Big Sandy River basin are the Cretaceous McNairy and Coffee Sands. The McNairy Sand is the deep aquifer in Madison County.

Recharge rates can be estimated from seepage data, which would represent the period in which the data were collected, and from continuous-record streamflow data, which would represent average annual recharge. Areal recharge rates were calculated from seepage measured during the base-flow investigation in April 1989. Streamflow at the gage on the South Fork was at about 60-percent flow duration (fig. 10), which is slightly lower than average flow. Recharge rates over the areas drained by the stream segments were 8.1 in/yr for the Middle Fork (38-mi^2 drainage area) and 2.6 in/yr for the South Fork (116-mi^2 drainage area). The calculated rate for the South Fork is probably small because of ground-water interception by pumping wells. If these losses to pumping wells, about 17 Mgal/d, are added back into the seepage, calculated recharge would be at least 5.7 in/yr.

Graphical hydrograph-separation techniques (Pettijohn and Henning, 1979, and Ronald A. Sloto, U.S. Geological Survey, written commun., 1989) were applied to data from the continuous-record streamflow-gaging stations on the Middle Fork near Alamo and the South Fork at Jackson to determine average aquifer discharge, which can be equated to average annual recharge to the ground-water system. Although the station at Jackson is in the study area, the station near Alamo records data from an area more geologically similar to that of the study area. The average rates of recharge calculated for the gage at Jackson for the years 1966 through 1970, which represent years of average rainfall (fig. 11), range from 6.7 to 8.0 in/yr. The rate calculated for the station near Alamo for the same years ranges from 5.6 to 6.7 in/yr. The ranges of averages resulted from three different graphical techniques for both water years and calendar years. The range of areal recharge rates from all the estimating methods is 5.6 to 9.5 in/yr.

Water-Level Fluctuations

Seasonal ground-water fluctuations are related to recharge, natural discharge to streams, evapotranspiration, and the effects of pumping. Natural seasonal fluctuations are related to seasonal changes in precipitation, evapotranspiration, and thus, to changes in recharge. Fluctuations of about the same magnitude from year to year are indicative of a ground-water system at long-term steady state, in which recharge and discharge are about equal on an annual basis.

Long-term, water-level records are available for two observation wells in Madison County (fig. 1).

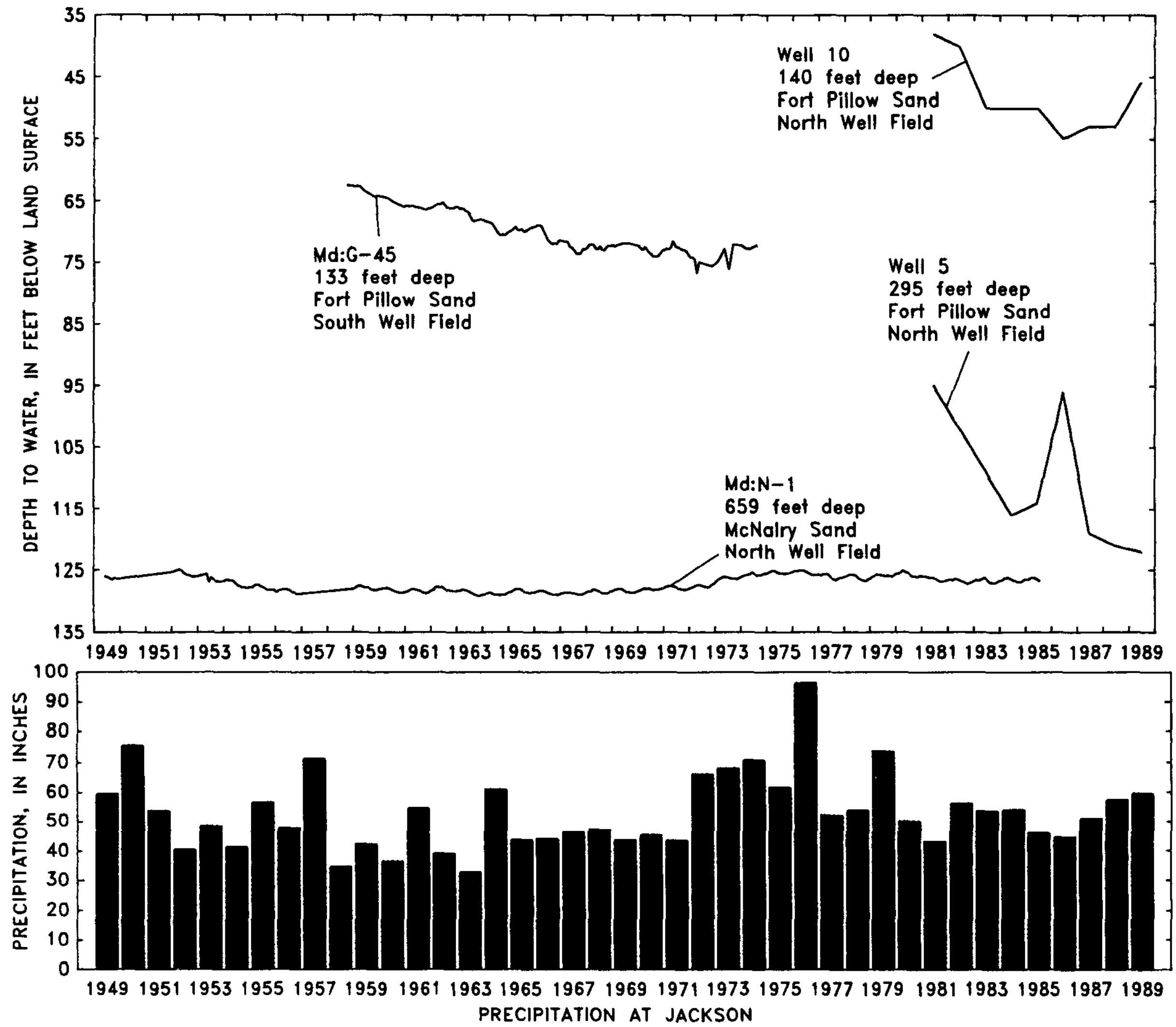


Figure 11. Water levels in observation wells and precipitation at the Jackson Agricultural Experiment Station (location of Md:N wells shown on figure 1).

Well Md:N-1 is in the McNairy Sand, and Md:G-45, near the South Well Field, is in the Fort Pillow Sand. The hydrograph of well Md:N-1 shows natural seasonal fluctuations (fig. 11), which indicates that the deep aquifer is at steady state and is unaffected by pumping. A downward trend in water levels, the effects of pumping, are superimposed on seasonal fluctuations in well Md:G-45. The slight leveling of the downward trend of the hydrograph of Md:G-45 in the late 1960's and early 1970's (fig. 11) may indicate that the aquifer was approaching equilibrium with the pumpage.

No continuous water-level records are available for either well field; however, JUD has measured each pumped well annually since 1981. Water levels from a representative pumped well in the South Well Field (fig. 11, well 10) show that water levels fluctuated from year to year after 1983, but show no significant sustained decline. Water levels from a representative pumped well in the North Well Field (fig. 11, well 5) show that water levels declined sharply from the onset of pumping through 1984, but the rate of decline after that year was less. Measurements from all the pumped wells in the North Well Field showed high water levels in 1986 (fig. 11), which may have been related to conditions at the time the wells were measured that were not representative of average conditions for 1986.

Water levels in the South Well Field may still be recovering and readjusting to an equilibrium as a result of decreased pumpage; however, the trend is slight. Pumpage from the South Well Field has remained relatively constant since 1982. Similarly, water levels in the North Well Field are probably still declining and equilibrating to pumpage; however, that trend also is believed to be slight. Therefore, the system is considered to be near steady state in the area of the well fields and at steady state in most of the study area.

Ground-Water Flow

The Memphis and Fort Pillow Sands function as a single aquifer, although clay lenses locally act as confining units. The McNairy Sand is hydraulically separated from this aquifer by the Porters Creek Clay.

Ground-water flow is generally from the east-northeast toward the major streams. Flow is diverted locally toward major pumping centers. The water table is generally below the tributaries in the central part of the area, and the tributaries have little effect on the ground-water system except to contribute recharge after rainfall events.

The natural ground-water divide would be expected to bisect the area between the Middle and South Forks, coinciding with the surface-water divide. However, pumping in the North Well Field and at a major industrial center along the divide, has caused the ground-water divide to move northward toward the Middle Fork (fig. 12).

GROUND-WATER FLOW MODEL

Model Assumptions

The finite-difference model of McDonald and Harbaugh (1988) was used to simulate three-dimensional ground-water flow in the sand aquifers. The following simplifications and assumptions were made to simulate the hydrologic system:

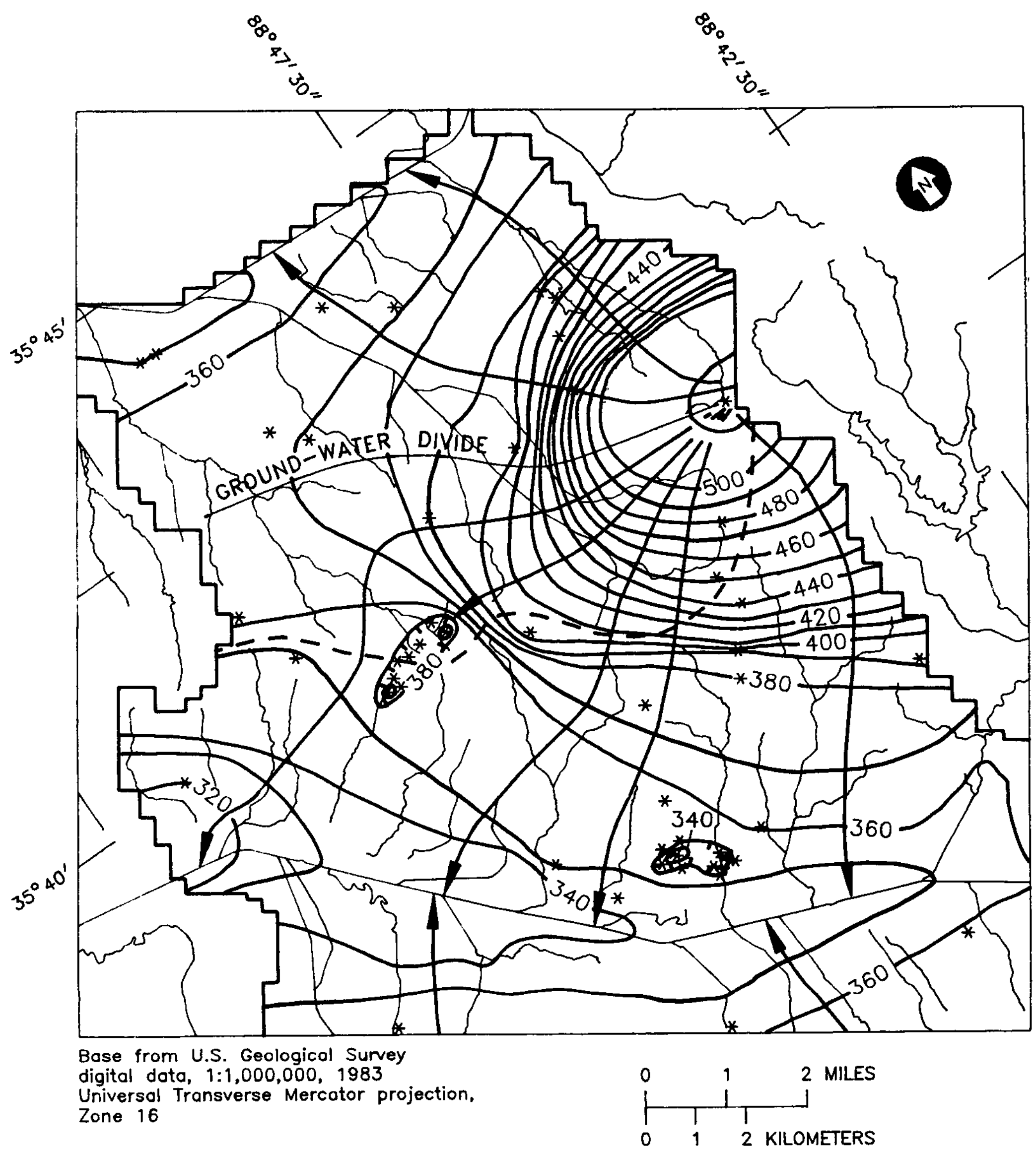
1. The Memphis Sand is unconfined; the Fort Pillow Sand is confined over most of the area, but is unconfined where it crops out.

2. The bottom of the model is specified as the top of the Porters Creek Clay, which is assumed to be a no-flow boundary.

3. On a regional scale, each aquifer is homogeneous.

4. Flow in the aquifers is horizontal; flow (leakage) between the aquifers, whether divided by clay or not, is vertical.

5. The regional ground-water system is at steady state; however, this assumption may not be valid in the area of the well fields.



EXPLANATION

—350—	WATER–TABLE CONTOUR––Contour interval 10 feet. Datum is sea level
◄——	DIRECTION OF GROUND–WATER FLOW
⌐___	ACTIVE NODE BOUNDARY
– – –	PREPUMPING GROUND–WATER DIVIDE
*	WATER–LEVEL MEASUREMENT SITE

Figure 12. Configuration of the water table in April 1989 and general directions of ground-water flow.

Conceptual Model

The aquifers were divided into three layers to simulate the ground-water flow system (fig. 13). Layer 1 is the saturated Memphis Sand; layer 2 is the upper half of the Fort Pillow Sand; and layer 3 is the lower half of the Fort Pillow Sand. The layers, particularly layers 2 and 3, are not necessarily hydraulically distinct aquifers, but were divided to allow greater accuracy in particle-tracking analysis. Layer 1, a water-table aquifer, does not extend to the southeastern part of the model, where the Memphis Sand pinches out. Layer 2 is simulated as confined beneath the Memphis Sand and as a water-table aquifer in the southeastern part of the modeled area where the upper part of the Fort Pillow Sand crops out. Layer 3 also is simulated as confined over most of the modeled area and unconfined in the outcrop area. Alluvium covering the outcrop area of the Porters Creek Clay is included in layer 3.

Model Grid and Boundaries

The model grid is an 11.8- by 11.5-mile rectangle and includes the entire study area; however, only 92.9 mi² are active in the model. The model is discretized into a matrix of 88 by 96 grid blocks (fig. 14). The grid blocks are variably dimensioned to accommodate more detail in the well fields and to separate pumped wells into individual grid blocks.

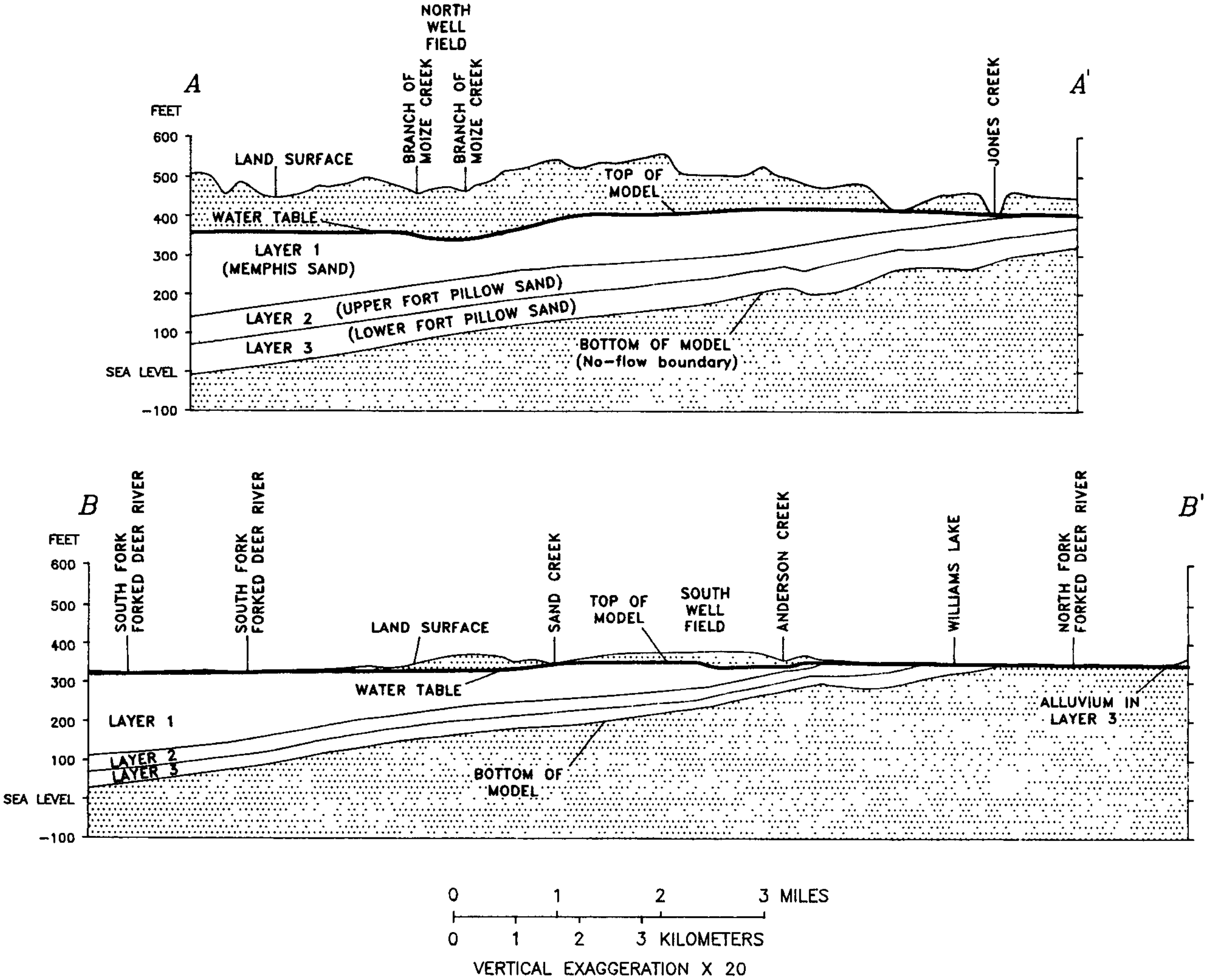


Figure 13. Representation of aquifer layers in the digital model (along rows 40 and 71, figure 14).

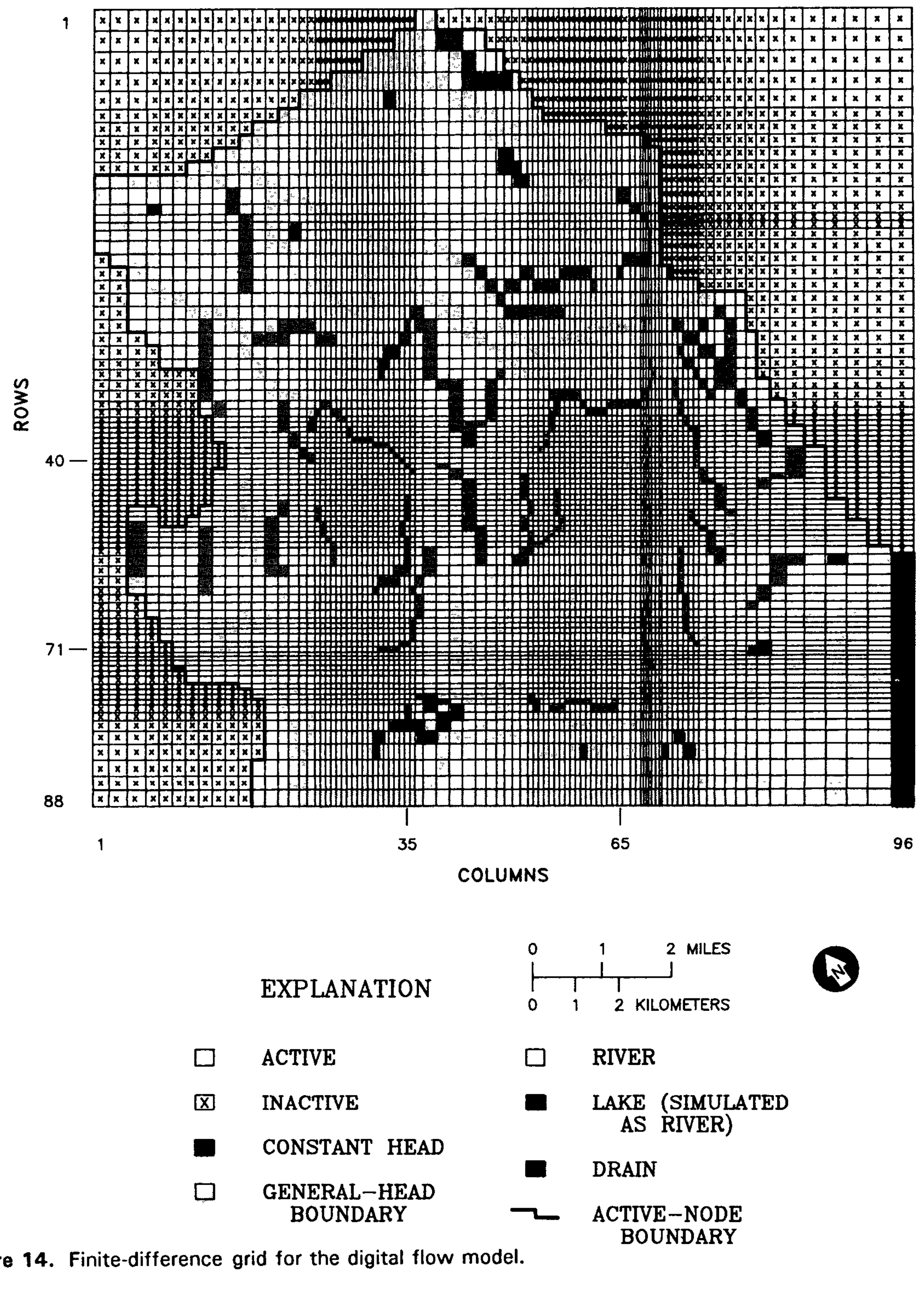


Figure 14. Finite-difference grid for the digital flow model.

The dimensions of the smallest grid blocks, located in the South Well Field, are 300 by 250 feet and the largest grid blocks, at the boundaries, are 1,200 by 1,800 feet.

The upper boundary of the model is the water table, and the lower boundary is the top of the Porters Creek Clay, which subcrops beneath the alluvium in the river valley of the North and South Forks (figs. 6 and 13). The northern boundary of the active model area follows the course of the Middle Fork, which is simulated as a head-dependent flux (river node) boundary in layer 1 (fig. 14). No ground water is assumed to flow beneath the river across this boundary, and the effects of simulated pumping, because of the distance to the pumping centers, should not extend beyond the Middle Fork. The northern boundary in layers 2 and 3 is a no-flow boundary.

The west-northwestern boundary (a surface-water divide) is assumed to correspond closely to a ground-water divide and is simulated as a no-flow boundary except where the South Fork flows out of the modeled area. Underflow in this area is simulated with a constant-head node (fig. 14) in each of the three layers.

The south-southwestern boundary was extended about a mile south of the South Fork to accommodate the potential effects of simulated pumping from the South Well Field and industrial pumping in the area. This boundary is a general-head boundary (fig. 14) in all three layers. The general-head boundary allows ground-water inflow or outflow to fluctuate based on the difference between a specified head outside the model and a model-calculated head at the model boundary (McDonald and Harbaugh, 1988, p. 11-1).

Conductances (C), in feet squared per day, between the specified heads and each general-head boundary node in the model were calculated by:

$$C=\frac{KA}{L},$$

where K is average hydraulic conductivity of the aquifer between the specified head and the model boundary, in feet per day;

A is the area of the vertical face of the boundary node (width X depth), in square feet; and

L is the distance from the specified head to the model boundary, in feet.

The distance between the boundary head and model boundary (L) was 3,000 feet. Hydraulic conductivity (K) was 200 ft/d for layer 1 and 170 ft/d for layers 2 and 3, which are the highest values estimated by other investigators (table 3). The head specified for the southern part of the south-southwestern boundary was 360 feet above sea level, which was derived from a projection outside the modeled area of the 360-foot water-level contour. Where the 360-foot contour is inside the model boundary, the specified head was 370 feet (fig. 12). This boundary condition was specified for all three layers.

The eastern boundary, a surface-water divide, is simulated as a no-flow boundary along the northern two-thirds, except for a small area of constant head to allow inflow to the modeled area (fig. 14). Although a surface-water divide can be assumed to be a ground-water divide, flow is probably induced (fig. 12) into the study area by pumping. The southern third of the eastern boundary, which cuts across the flood plain of the North and South Forks, is specified as a constant-head boundary, which allows simulations of underflow in this area.

Simulation of Sources and Sinks of Water

Average pumping rates for 18 municipal wells and 14 commercial or industrial wells were included in the model (fig. 2). Pumping rates for the JUD wells were calculated based on pumping rates during a week in April 1989: 9.2 Mgal/d for the North Well Field and 2.2 Mgal/d for the South Well Field. Not all wells are pumped every day, so the average pumping rate for some of the wells is lower than the actual withdrawal rate. However, for steady-state conditions, the lower rate (compared to wells pumped every day) is more representative of the average stress on the system than the actual pumping rate when a well is pumped intermittently. Pumping was applied to the layer in which most of the well screen is open.

The recharge rates calculated from seepage data and hydrograph-separation techniques represent areal averages, but local recharge is dependent on geology, topography, and land use. Local recharge rates were determined by assigning relative rankings to soil type (which is a product of geology and topography) and land use. Soils have been classified into hydrologic soil groupings that represent similar runoff potential from rainfall (U.S. Department of Agriculture, 1978, p. 35-40). Three groups are represented in the study area: soils having a moderate infiltration rate, a slow rate, and a very slow rate. Land use also was divided into three groups of similar runoff potential: urban and disturbed land having the highest runoff potential (and lowest recharge potential), forest and wetlands having intermediate runoff potential, and agriculture having the lowest runoff potential and highest recharge potential. The relative rankings of soil and land use were combined to create five categories of relative recharge rates (fig. 15). The volume of water resulting from average areal recharge of 8 in/yr was applied to the model area and the percent of recharge to each grid block was calculated based on the relative recharge for that block. The resulting recharge rates assigned to the grid blocks ranges from 3.4 to 10.3 in/yr. Recharge was applied to the uppermost active layer for any particular node. Recharge was not applied to nodes simulating rivers, lakes, or constant heads.

The rivers, tributaries, and lakes were simulated as river nodes connected to the water table (fig. 14). Conductance (C), in feet squared per day, used to simulate leakage to and from river nodes, was calculated by:

$$C=\frac{KA}{b},$$

where K is vertical hydraulic conductivity of the streambed, in feet per day;
A is the area of the river within the node, in square feet; and
b is the streambed thickness, in feet.

Thickness of the streambeds was assumed to be 1 foot to simplify calculations; a vertical hydraulic conductivity of 1 ft/d was used initially for all streams. These initial values could be changed during calibration if simulated seepage to the streams did not approximate measured seepage. The streambed bottom within each river node is the elevation of the stream on a topographic map, and stream stage was calculated for each node using depth of water measured in April 1989.

Dry stream reaches were simulated as drains (fig. 14) that can gain water from the ground-water system, but cannot contribute recharge to the ground water. Elevation of the drains is the elevation of the stream channel obtained from topographic maps. Conductance of the drain bottoms was calculated in the same manner as conductance for river nodes.

Conductance for lakebeds was calculated in the same manner as conductance for river nodes. Lake-surface elevations and depths were estimated from topographic maps.

Transmissivity for each layer was calculated from a uniform value of hydraulic conductivity and the variable thickness of the layer. The initial hydraulic conductivity of layer 1 was 200 ft/d, and of layers 2 and 3, 170 ft/d, which are the highest values estimated by other investigators (table 3). Initial transmissivity of layer 1 ranged from 2,000 to 54,000 ft^2/d; and for layers 2 and 3, from 1,700 to 19,550 ft^2/d.

Leakage between model layers was simulated by vertical conductance. Because the layers were assumed to be hydraulically well connected and not separated by confining material, vertical conductance between layers was calculated using the aquifer properties. Vertical conductance is calculated within the model using values of vertical leakance (McDonald and Harbaugh, 1988, p. 5-11). Vertical leakance, in feet per day per foot, between adjacent layers was calculated by:

$$Vertical\ leakance=\frac{2K_{La}K_{Lc}}{K_{La}b_{Lc}+K_{Lc}b_{La}},$$

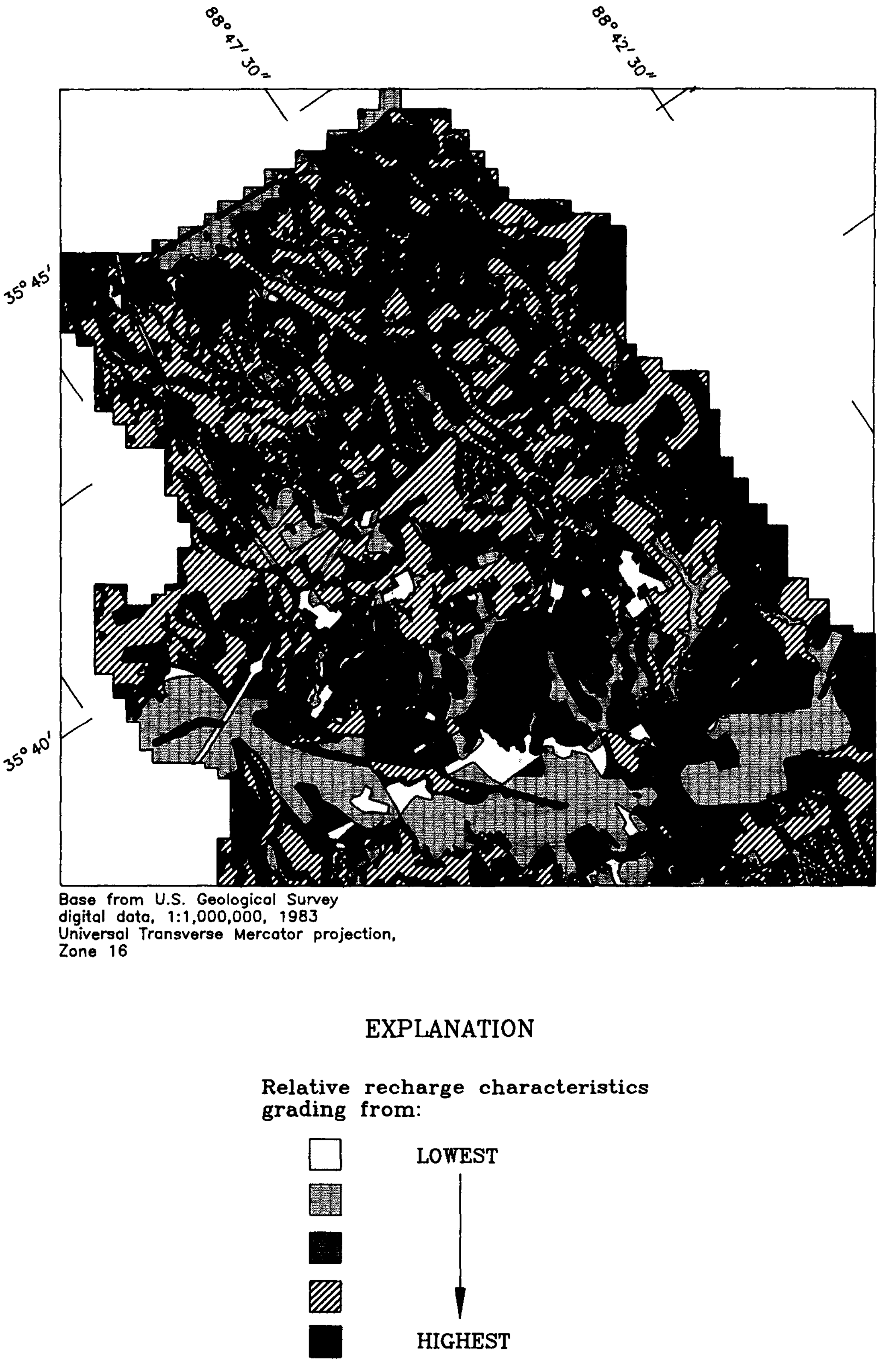


Figure 15. Categories of relative recharge rates.

where K is vertical hydraulic conductivity, in feet per day;
b is thickness, in feet;
La is the uppermost layer; and
Lc is the lowermost layer.

In order to calculate the largest reasonable vertical conductance between model layers for initial runs, the highest estimated hydraulic-conductivity values for the Memphis and Fort Pillow Sands (200 and 170 ft/d, respectively) were used to calculate leakance values at each grid block. Initial vertical-leakance values between layers 1 and 2 ranged from 0.9 to 58.1 (ft/d)/ft, and between layers 2 and 3, 1.6 to 6.8 (ft/d)/ft. Vertical conductance between layers varied areally because thickness of each layer varied (producing the ranges of vertical leakance) and because areas of grid blocks varied.

Model Calibration

The ground-water flow model was calibrated to water levels in 46 of the 53 wells measured in April 1989, and to ground-water seepage to streams measured at the same time. The overall system is assumed to be at steady state because long-term water levels seem to be approaching equilibrium, although the assumption of steady-state conditions in the area of the well fields may not be valid. Hydraulic conductivity for all layers, vertical leakance between layers, recharge, and conductivity of the streambeds were varied during the calibration process to maximize matches between simulated- and measured-head values and simulated and measured seepage to streams.

Initial values of aquifer hydraulic conductivity were reduced by 0.5 to 100 ft/d for the Memphis Sand and 85 ft/d for the Fort Pillow Sand. These reductions are reasonable because the initial values were the maximum estimated values. Initial vertical-conductance values were reduced by an order of magnitude. This reduction also is reasonable because the highest calculated values of aquifer hydraulic conductivity were used as initial values, and because vertical hydraulic conductivity of aquifers of this type is commonly one-tenth the horizontal conductivity (Freeze and Cherry, 1979, p. 32). Aquifer hydraulic conductivity, used to calculate initial conductance values for the general-head boundaries, also was reduced by one-half.

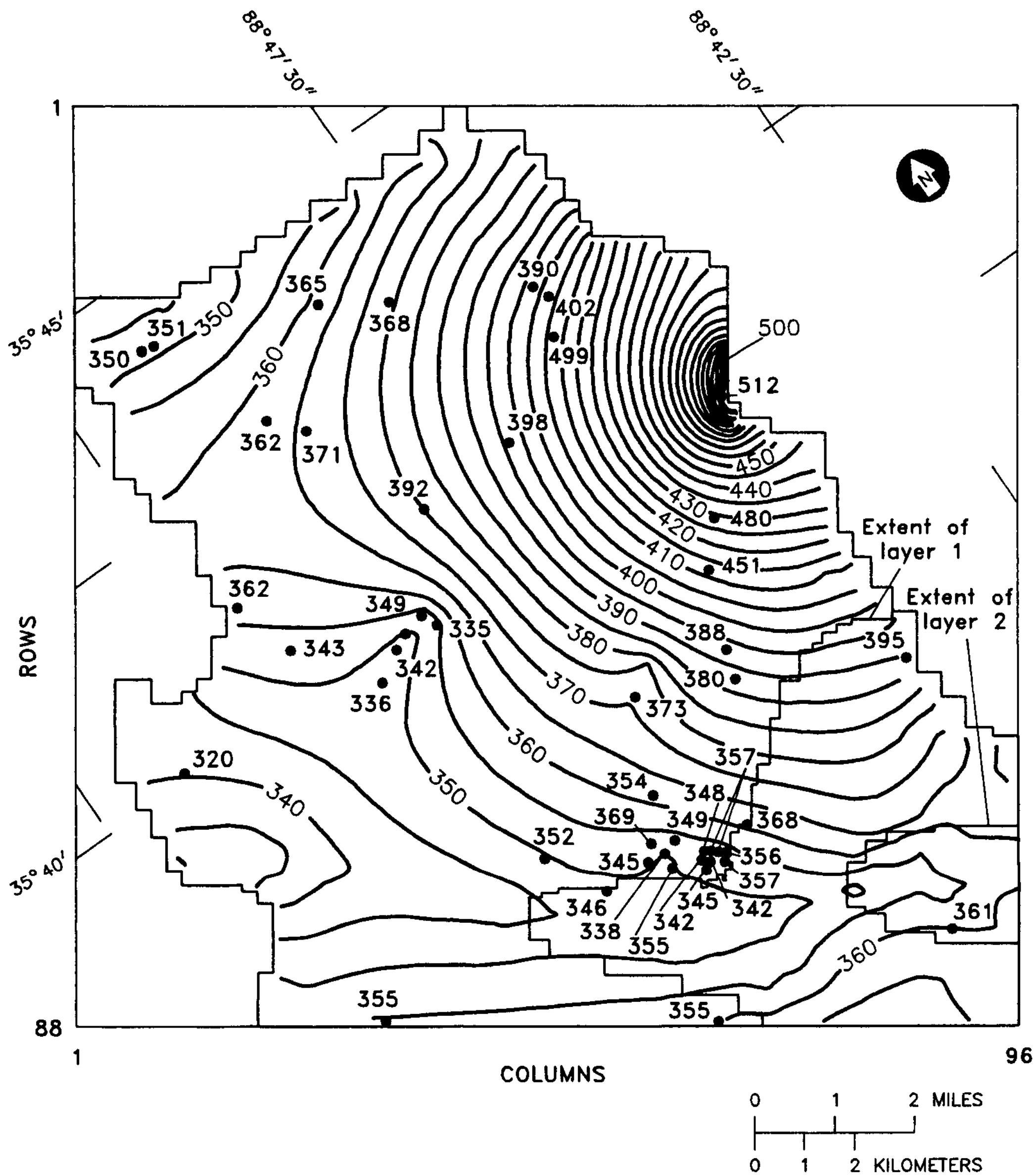
The initial value of hydraulic conductivity for all streambeds and lakes was 1 ft/d but the following changes were made during calibration: Conductivity of lakes was reduced to 0.0001 ft/d, which is a reasonable reduction because of siltation of lake bottoms. Conductivity of the Middle Fork was reduced to 0.5 ft/d, and of the South and North Forks, to 0.05 ft/d. Conductivity of all tributaries was increased to 5 ft/d, because fine sediment accumulation is less likely in the tributaries.

Measured heads and ground-water seepage to streams were relatively well matched. Sixty-three percent of the 46 comparison-head values were matched within ± 5 feet, and 87 percent within ± 10 feet. The model-calculated potentiometric surface is shown only for layer 3 (fig. 16) because layer 3 shows the full extent of the modeled area. Measured-head values are shown for the 46 comparison wells. Although these wells are distributed among all three layers, simulated vertical gradients between the layers are small, and water-level configurations are similar for layers 1 and 2.

Model simulated seepage to the Middle Fork was 10.9 ft^3/s compared to half of the measured seepage of 11.3 ft^3/s. The model simulated only half the measured seepage (table 4) because the river is a model boundary and simulated seepage is contributed from only one side. Simulated seepage to the measured reach of the South Fork was 22.0 ft^3/s compared to measured seepage of 21.9 ft^3/s (table 4).

Components of the steady-state water budget of the simulated system are summarized in table 5. More than half of the source of water to the ground-water system in the calibrated model is inflow through the boundaries. Most of this inflow is lost through seepage to the river and nearby pumping. Slightly less than half of the source of water is from areal recharge and recharge from streams. About 75 percent of the discharge from the system is into the streams, lakes, and out of the model area through a small quantity of ground-water underflow. The remaining 25 percent is discharge from pumping wells.

Net vertical leakage between model layers is nostly flow from layers 1 and 3 into layer 2, because most of the pumpage is from layer 2 (fig. 17). A total of 62 ft^3/s leaks into layer 2 and



EXPLANATION

—360— MODEL-CALCULATED WATER LEVEL CONTOUR-- Contour interval 5 feet. Datum is sea level

ACTIVE-NODE BOUNDARY

355 • WELL--Ground-water-level measurement, April 1989

Figure 16. Model-calculated water levels in layer 3 and measured water levels.

Table 5. Steady-state ground-water budget for the calibrated model and pumping plans for the Jackson area

[CH, constant head; CF, constant flux][1]

Sources and discharges	Model simulation, flow in cubic feet per second								
	Calibrated			Plan 1		Plan 2		Plan 3	
	CH	Percentage of total	CF	CH	CF	CH	CF	CH	CF
Sources:									
Boundary flux:		52							
Constant head/flux	33.0		33.0	33.7	33.0	33.9	33.0	34.8	33.0
Head dependent	19.2		19.2	20.0	20.2	19.7	20.0	20.8	21.1
Areal recharge	41.3	41	41.8	41.3	41.8	41.3	41.8	41.3	41.8
Leakage from streams and lake	7.4	7	7.4	7.7	7.8	8.0	8.1	8.2	8.5
Total	100.9	100	101.4	102.7	102.8	102.9	102.9	105.1	104.4
Discharges:									
Boundary flux:		3							
Constant head/flux	3.4	3.4	2.8	3.4	2.3	3.4	2.0	3.4	
Head dependent	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Ground-water seepage to streams/lakes	71.3	71	71.7	61.1	60.7	59.8	58.8	48.9	47.0
Ground-water seepage to drains	0.9	1	0.9	0.2	0.2	0.5	0.5	0.1	0.1
Pumpage	25.4	25	25.4	38.6	38.6	40.4	40.4	54.1	54.1
Total	101.0	100	101.4	102.7	102.9	103.0	103.1	105.1	104.6

[1]Each pumping plan was simulated with either constant-head or constant-flux conditions specified as boundaries. These conditions are end points and respectively maximize or minimize boundary fluxes calculated by the model.

45.1 ft^3/s leaks from layer 2 to the other two layers, leaving a net gain to layer 2 of 16.9 ft^3/s. The net flow of water through vertical leakage from layers 1 and 3 is 10.5 and 6.4 ft^3/s, respectively.

Model Limitations and Sensitivity Analysis

The accuracy of the calibrated model in simulating the ground-water flow system is limited by several factors:

1. Ground-water levels for calibration were accurately measured, but elevation above sea level of those water levels was estimated from topographic maps. The error could be in the range of ± 10 feet.
2. Water levels were measured primarily in pumped wells.
3. No piezometers were available to measure vertical gradients.
4. Few wells at hydrologic boundaries were available for measurement.
5. The assumption of steady-state conditions is probably valid regionally, but not necessarily in the areas of the well fields.
6. Several combinations of aquifer characteristics in the simulations produced similar matches to measured heads and seepage to streams. The combination accepted for the calibrated model is nonunique and the existing data do not provide adequate criteria for selecting the best solution.

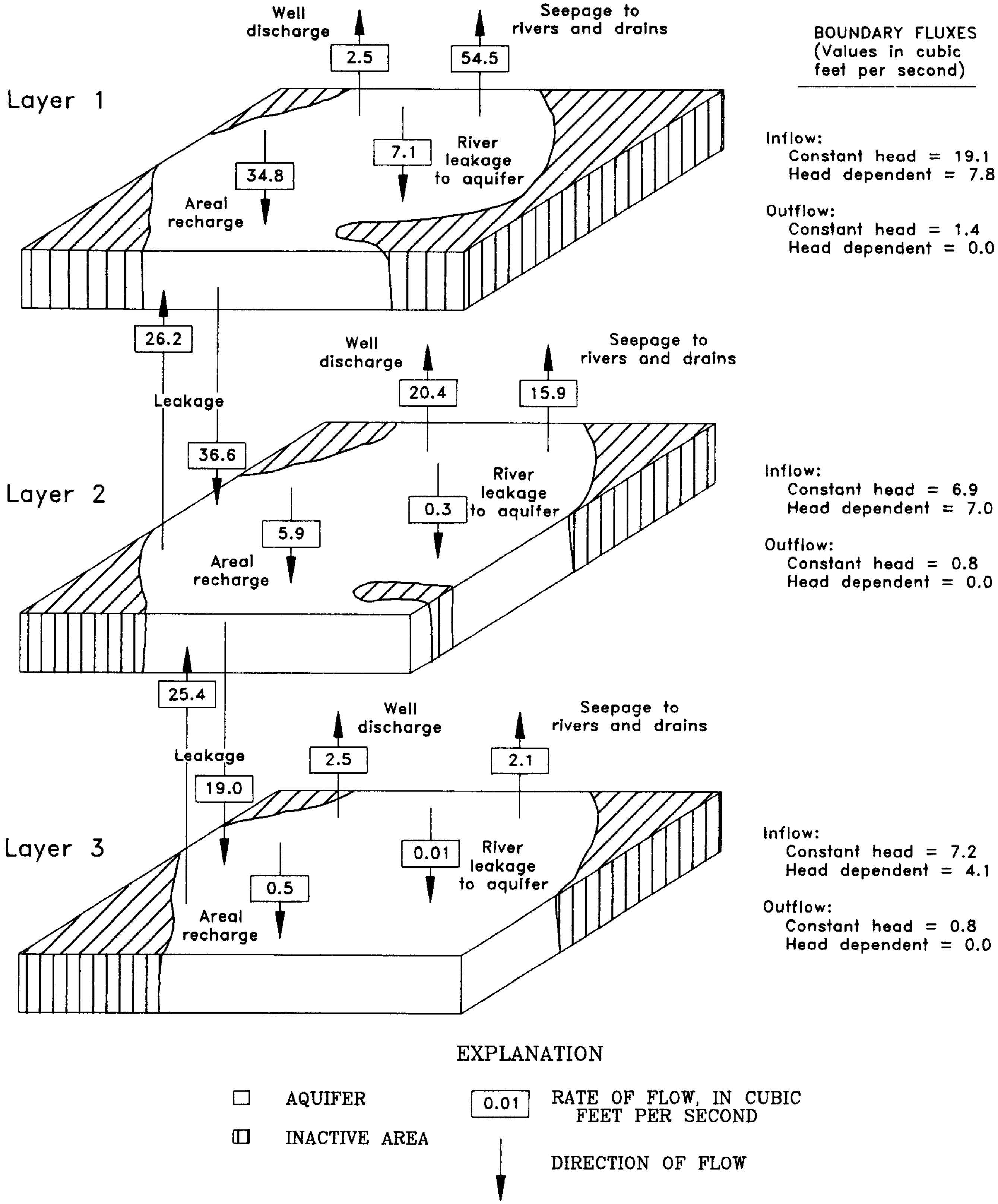


Figure 17. Distribution of water-budget components among the layers of the digital flow model.

The lack of adequate data to determine a more unique set of aquifer characteristics increases the possibility of inaccurate delineation of areas contributing water to the pumped wells and misleading results from simulation of hypothetical pumping. However, model sensitivity analyses can indicate the characteristics that are the most critical to an accurate simulation and assist in evaluating the reliability of model results.

The response of the model to adjustments in recharge, hydraulic conductivity of the layers, vertical conductance between layers, and hydraulic conductivity of the streambeds was evaluated using sensitivity analyses. Hydraulic conductivity of all layers was adjusted by the same multiple for each sensitivity test (rather than each layer being adjusted individually while the other two layers were held constant). Both leakage layers and hydraulic conductivity of all the streambeds were varied by the same multiple for each test. For each adjustment, a sensitivity test was made for both constant-head and constant-flux boundary conditions. The flux values were determined by model-calculated fluxes at the constant-head nodes.

Differences between measured and simulated water levels were used as indicators of the sensitivity of the model to adjustments of a variable. The root mean square error (RMSE) is a measure of the overall difference between measured and simulated water levels. Lower RMSE values indicate better matches to measured water levels. RMSE, in feet, was calculated for measured and simulated water levels using the equation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N} (h_i^m - h_i^c)^2}{N}},$$

where N is the number of observations (46);

h_i^m is the measured water level, in feet; and

h_i^c is the calculated water level, in feet.

RMSE was plotted for each adjustment in a variable to display the range of sensitivity.

The overall RMSE for all layers in the calibrated steady-state model is 11.6 feet because not all measured water levels were exactly matched. The RMSE of individual layers is: 15.6 feet for layer 1, 6.1 feet for layer 2, and 5.3 feet for layer 3. Average head difference between simulated and measured heads for the model was -0.2 foot and the standard deviation is 11.6 feet. Calibrated heads were slightly lower overall than measured heads. In the following discussions, references to RMSE are to the value for all layers.

Areal recharge was adjusted from 0.5 to 2 times (4 to 16 in/yr) the calibrated value. Adjustments between about 7 and 10 in/yr produced minor changes in RMSE (fig. 18) or in seepage. The RMSE was slightly lower using 9 in/yr. A range of recharge from 8 to 10 in/yr produced net seepage to the Middle and South Forks that was within ±5 percent of measured seepage. This range was within the measurement error of the disharge measurements.

The model was sensitive to adjustments in hydraulic conductivity of the layers (fig. 19), particularly for constant-flux boundary conditions. The range of conductivity tested was from 50 to 500 ft/d for the Memphis Sand and from 43 to 425 ft/d for the Fort Pillow Sand. Head matches were improved slightly by using 0.8 times (80 and 68 ft/d) the calibrated values, but the calibrated values were the only ones that produced seepage to the Middle and South Forks within ±5 percent of measured seepage.

When results of the sensitivity tests for recharge and hydraulic conductivity were compared (fig. 20), a narrow range of optimal values for the two parameters (within the 11-foot RMSE contour) was observed. Although measured heads could be matched better overall by using higher recharge and lower hydraulic conductivity values, seepage to streams did not match as well in that range (fig. 20). This comparison also showed that, although the model was not a unique combination of values for aquifer characteristics, the range of values that would produce a unique model is small.

The model was insensitive to the tested range of vertical conductance between model layers (fig. 21). Changes in the vertical conductance from 0.1 to 10 times the calibrated value resulted in only small changes in the RMSE. The model failed to reach a solution when values beyond the range of those

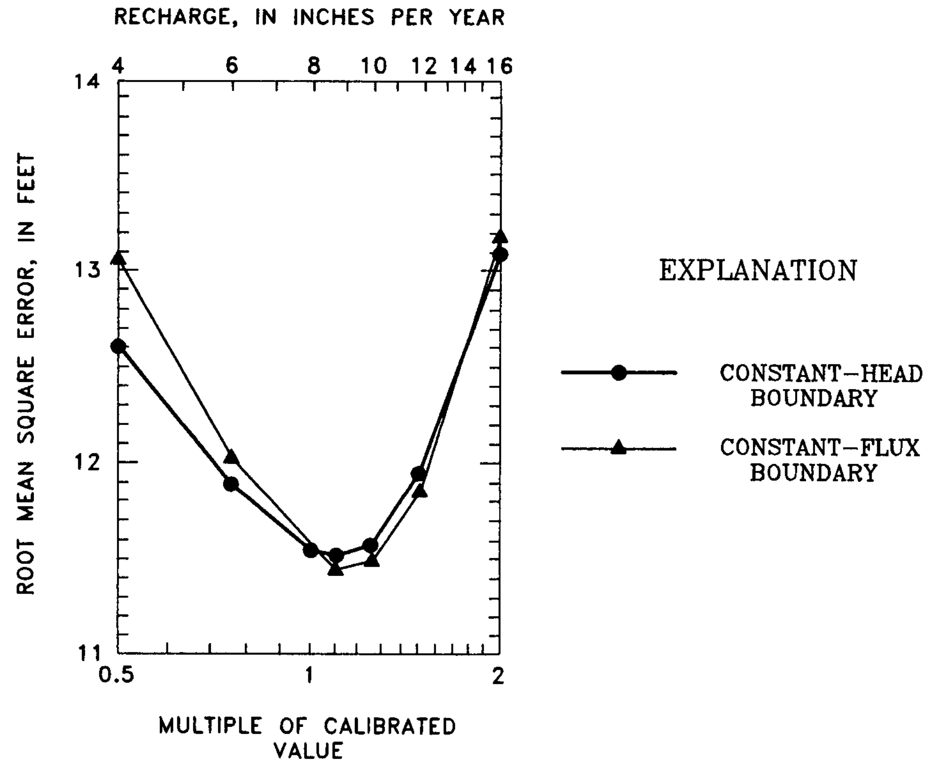


Figure 18. Sensitivity of the digital flow model to adjustments in recharge.

shown in figure 21 were tested. Seepage to streams was little affected by adjustments in vertical conductance.

Hydraulic conductivity of the streambeds was adjusted between 0.1 and 50 times the calibrated values (fig. 22). The model was insensitive to adjustments between 0.5 and 10 times the calibrated values. Conductivity values from about 2 to 5 times the calibrated values produced slightly lower RMSE, but the calibrated values were the only ones that produced seepage to the Middle and South Forks within ±5 percent of measured seepage.

Sensitivity analyses confirm that a range of values for all of the hydraulic characteristics of the aquifers would produce similar model results and that the calibrated model was a nonunique combination of aquifer characteristics. However, the acceptable ranges of areal recharge and hydraulic conductivity of the aquifers, the two hydraulic characteristics that the model is most sensitive to, were relatively small. The calibrated model was considered the best combination of hydraulic characteristics to produce reasonable results from pumping simulations and from particle-tracking analyses. No significant improvements were indicated by the sensitivity analyses.

Pumping Simulations

The calibrated model was modified to simulate the effects on the ground-water system of three hypothetical pumping plans suggested by JUD. Only steady-state conditions were simulated because the main consideration was the determination of a final water-level distribution under simulated stress, not the time to reach that point. Following are descriptions of the three plans:

1. Average pumping rates of 10 Mgal/d for the South Well Field and 10 Mgal/d for the North Well Field.

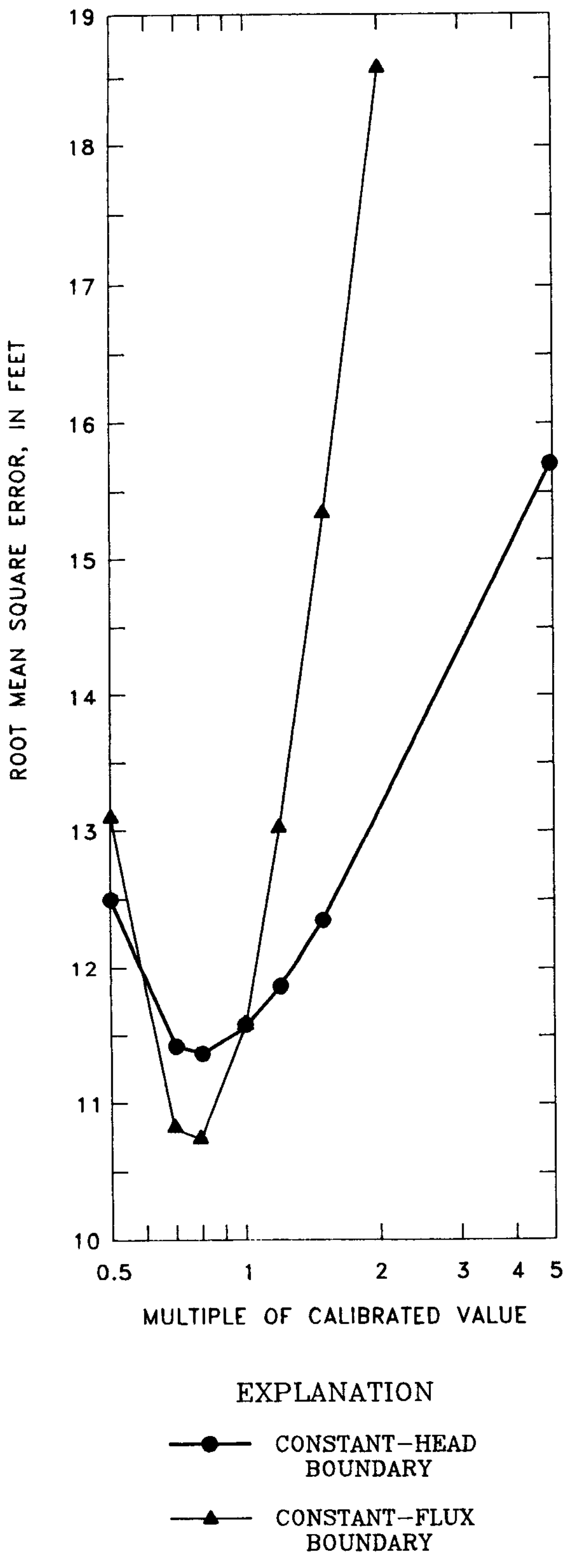


Figure 19. Sensitivity of the digital flow model to adjustments in hydraulic conductivity of aquifers.

2. Average pumping rates of 5 Mgal/d for the South Well Field and 15 Mgal/d for the North Well Field.

3. Average pumping rates of 10 Mgal/d for the South Well Field and 20 Mgal/d for the North Well Field.

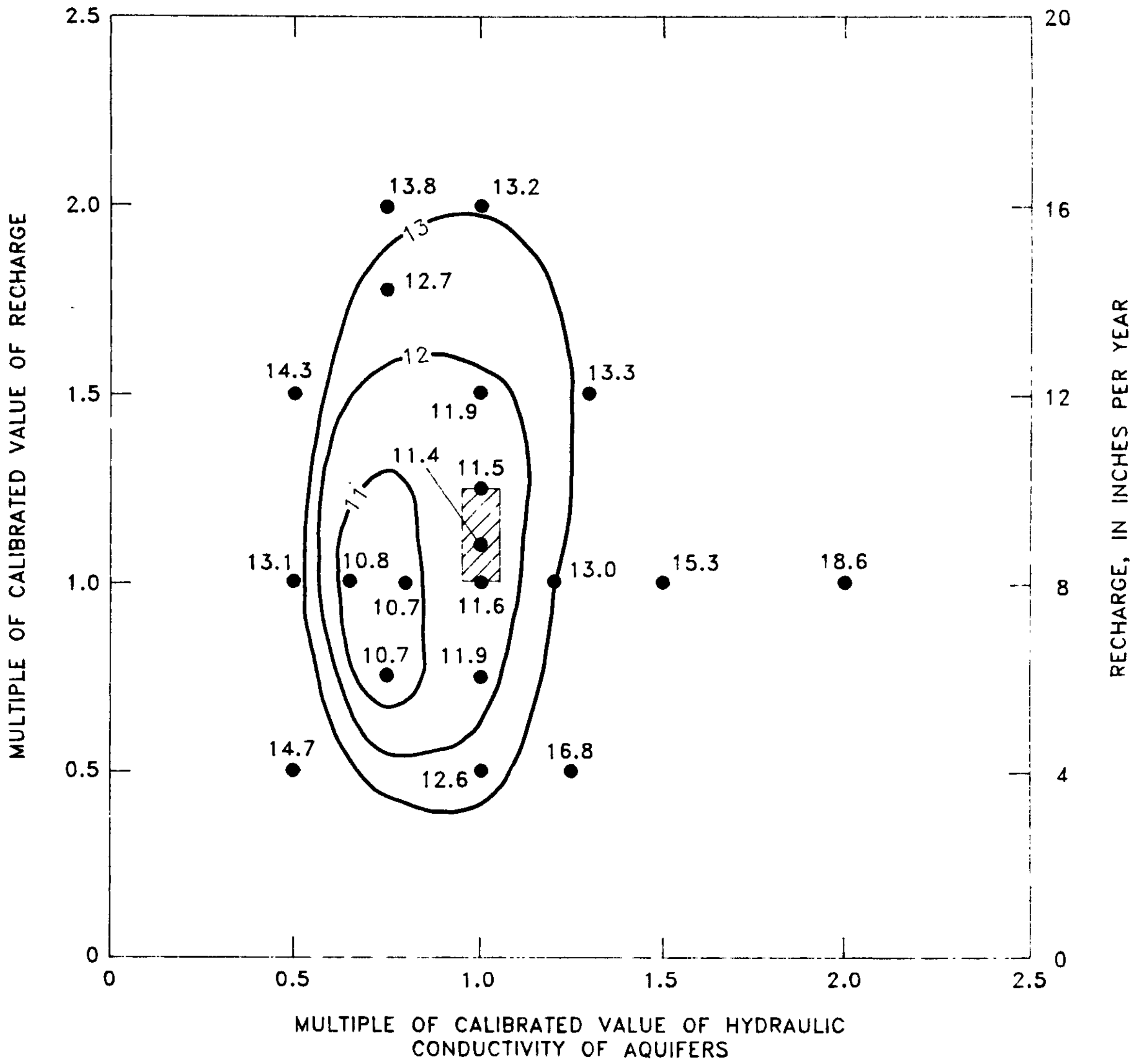
Each pumping plan was simulated with (1) constant-head boundary conditions, which maximize ground-water flow into the system and minimize drawdown, and (2) constant-flux boundary conditions, which limit ground-water flow into the system to the rate calculated by the calibrated model and maximize drawdown. These two extremes of boundary conditions represent endpoints for simulated model results, and reasonable results of the pumping schemes were within these endpoints. The constant-flux conditions produced the most conservative simulation results, and were, therefore, the conditions shown on the figures and discussed in this section.

Pumping in the calibrated model was increased for pumping plan 1 in some of the seven wells in the North Well Field to a total of 10 Mgal/d, and pumpage from each of the eleven wells in the South Well Field was increased by about 4.5 times the calibrated rate to a total of 10 Mgal/d.

Three hypothetical wells pumping from layer 2 were added to the seven existing wells of the North Well Field for pumping plan 2. Pumpage in the original seven wells was altered slightly to total 9.9 Mgal/d and each of the additional wells was pumped 1.7 Mgal/d. Total pumpage from the North Well Field was 15 Mgal/d. Pumpage from each well in the South Well Field was increased by about 2.2 times the calibrated pumping rate to a total of 5 Mgal/d.

Four more hypothetical wells pumping from layer 2 were added to the North Well Field for pumping plan 3. Total withdrawal for the original seven wells was adjusted to 9.2 Mgal/d, and each of the seven additional wells was pumped 1.54 Mgal/d. Total pumpage from the North Well Field was 20 Mgal/d. Pumpage from the South Well Field (10 Mgal/d) was the same as for pumping plan 1.

The water-level configuration in the calibrated model was the datum used for calculating drawdown. Configurations of drawdown for the three



EXPLANATION

—11—	LINE OF EQUAL ROOT MEAN SQUARE ERROR--Interval 1 foot
14.7 ●	ROOT MEAN SQUARE ERROR--Values in feet
▨	AREA OF ACCEPTABLE SIMULATED GROUND-WATER SEEPAGE TO STREAMS (± 5 PERCENT OF CALIBRATED SEEPAGE.)

Figure 20. Changes in root mean square error of simulated water levels with respect to simultaneous changes in recharge and aquifer hydraulic conductivity using constant-flux boundary conditions.

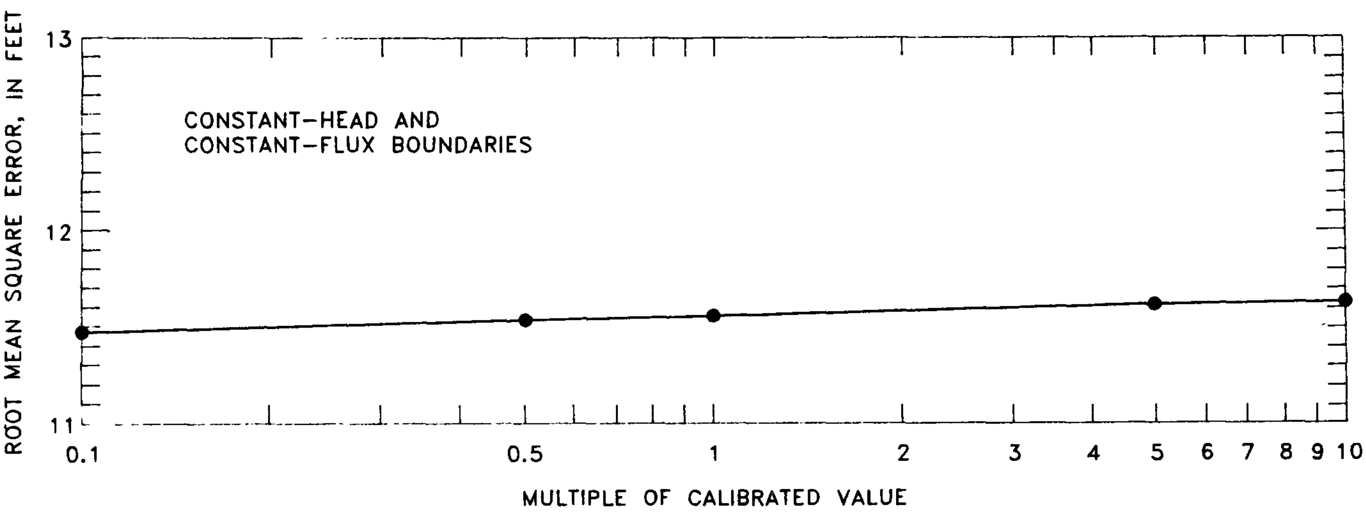


Figure 21. Sensitivity of the digital flow model to adjustments in vertical conductance between layers.

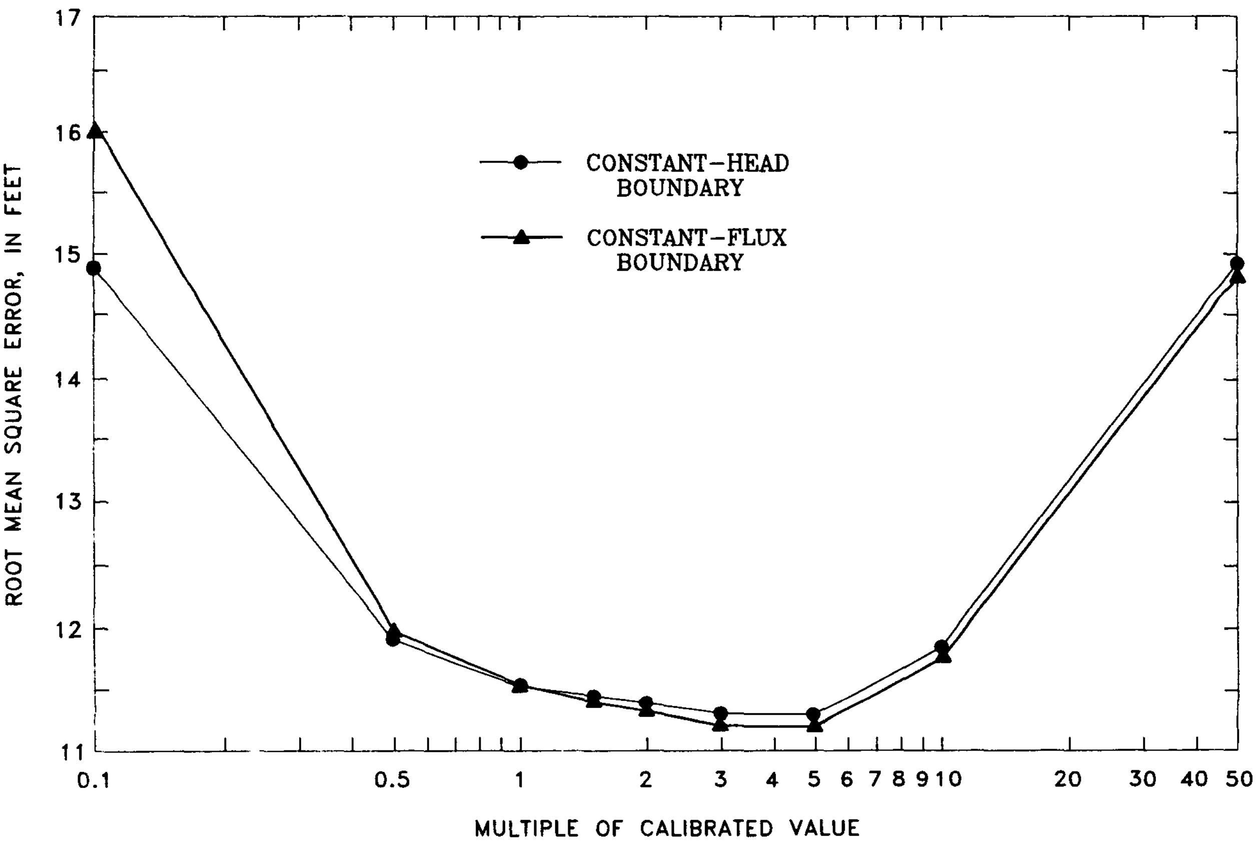


Figure 22. Sensitivity of the digital flow model to adjustments in hydraulic conductivity of streambeds.

pumping plans are shown (figs. 23-25) only for simulations with constant-flux boundary conditions, because these boundary conditions show the worst case and the configuration for constant-head boundaries was nearly the same as for constant-flux boundaries. Only layer 3 is shown on the figures because layers 1 and 2 do not cover the entire modeled area and because the configuration of drawdown was similar for all the layers. Drawdown in the nodes containing pumping wells is slightly greater for constant-flux boundary conditions than for constant head (table 6). Drawdown from pumping in the South Well Field dewaters the Memphis Sand (layer 1) in that area in all the pumping simulations. The Memphis Sand is thin in that area and the well field is at the edge of the outcrop of the Fort Pillow Sand.

Table 6. Maximum simulated drawdown in the North and South Well Fields for constant-head and constant-flux boundary conditions

[CH, constant head; CF, constant flux]

Pumping plan	Layer	Maximum drawdown, in feet: North Well Field CH	North Well Field CF	South Well Field CH	South Well Field CF
1	1	4.7	5.1	36.2	36.5
	2	5.4	5.7	38.8	38.5
	3	5.6	6.0	40.7	40.7
2	1	23.2	24.3	12.9	12.9
	2	26.7	27.3	13.0	13.7
	3	24.8	25.2	13.9	14.1
3	1	25.9	37.0	41.4	40.1
	2	38.3	39.4	42.9	43.9
	3	35.6	36.8	44.7	44.2

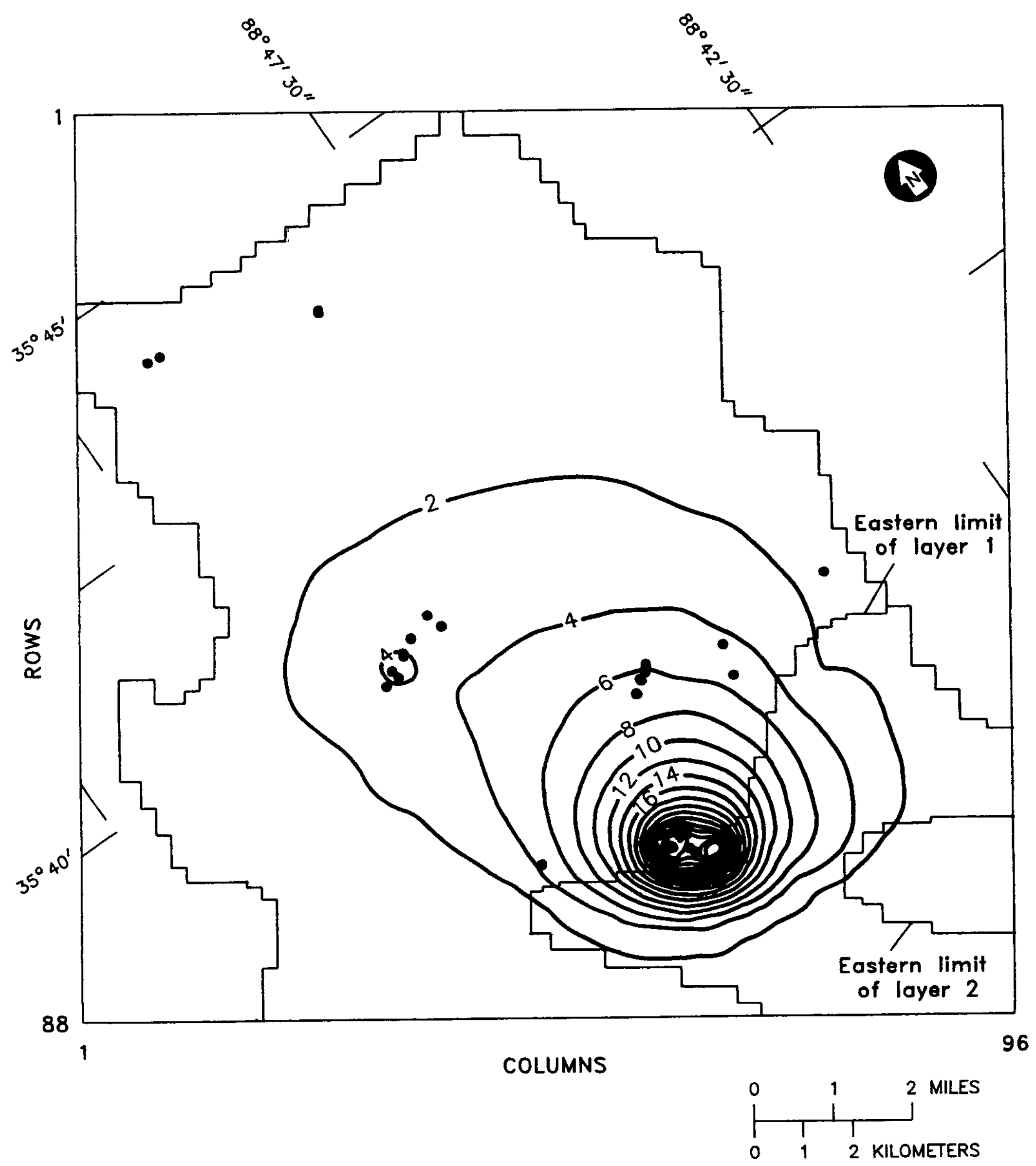
Drawdown resulting from simulated pumping in plan 1 (fig. 23) was concentrated around the South Well Field, because pumping there was increased by about 4.5 times the rate in the calibrated model. Maximum drawdown was 40.7 feet in a node containing a pumping well, but maximum drawdown over an extended area was about 32 feet. Pumping in the North Well Field was increased only slightly, and resulting simulated drawdown was small (up to 6 feet).

Drawdown in the South Well Field resulting from simulated pumping in plan 2 (fig. 24) was less, because pumping increases were more moderate. Pumping in the South Well Field was increased by 2.2 times the rate in the calibrated model, and pumpage in the North Well Field was increased by 1.6 times. Maximum drawdown is 27.3 feet in a node in the North Well Field containing a pumping well, and maximum drawdown over an extended area is about 22 feet. Maximum drawdown in the South Well Field is 14.1 feet.

Drawdown resulting from simulated pumping in plan 3 (fig. 25) was the greatest, both locally and in areal extent. Pumping in the South Well Field was increased by 4.5 times the rate in the calibrated model, and pumping in the North Well Field was increased by 2.2 times. Maximum drawdown in a node containing a pumping well in the North Well Field was 39.4 feet. Maximum drawdown was 44.7 feet in the South Well Field in a node containing a pumping well, and maximum drawdown over an extended area was about 38 feet.

Simulated drawdown in the pumping simulations, particularly plans 2 and 3 for the North Well Field, may be somewhat greater than actual drawdown would be because the extent of the cones of depression reaches the no-flow boundaries. In reality, some water would be induced across those boundaries. Simulated drawdown near the South Well Field for plans 1 and 3 may be somewhat underestimated because the model continues to simulate a source of water from the South Fork and the general-head boundary on the opposite side of the river.

The primary sources of water for additional pumping for the pumping plans were ground water intercepted before reaching the streams and additional water induced through the boundaries (table 5). Up to 34 percent of ground-water seepage to streams in the calibrated model was intercepted in the pumping simulations. In the constant-head simulations, up to 8 percent more water was induced through the general-head boundary and up to 5 percent more through the constant-head boundaries. In the constant-flux simulations, up to 9 percent more water was induced through the general-head boundaries, but no more could be induced through the constant-flux boundary.



EXPLANATION

—16— LINE OF EQUAL SIMULATED DRAWDOWN-- Interval 2 feet

ACTIVE-NODE BOUNDARY

• PUMPED WELL

Figure 23. Simulated drawdown in layer 3 for pumping plan 1 with constant-flux boundaries.

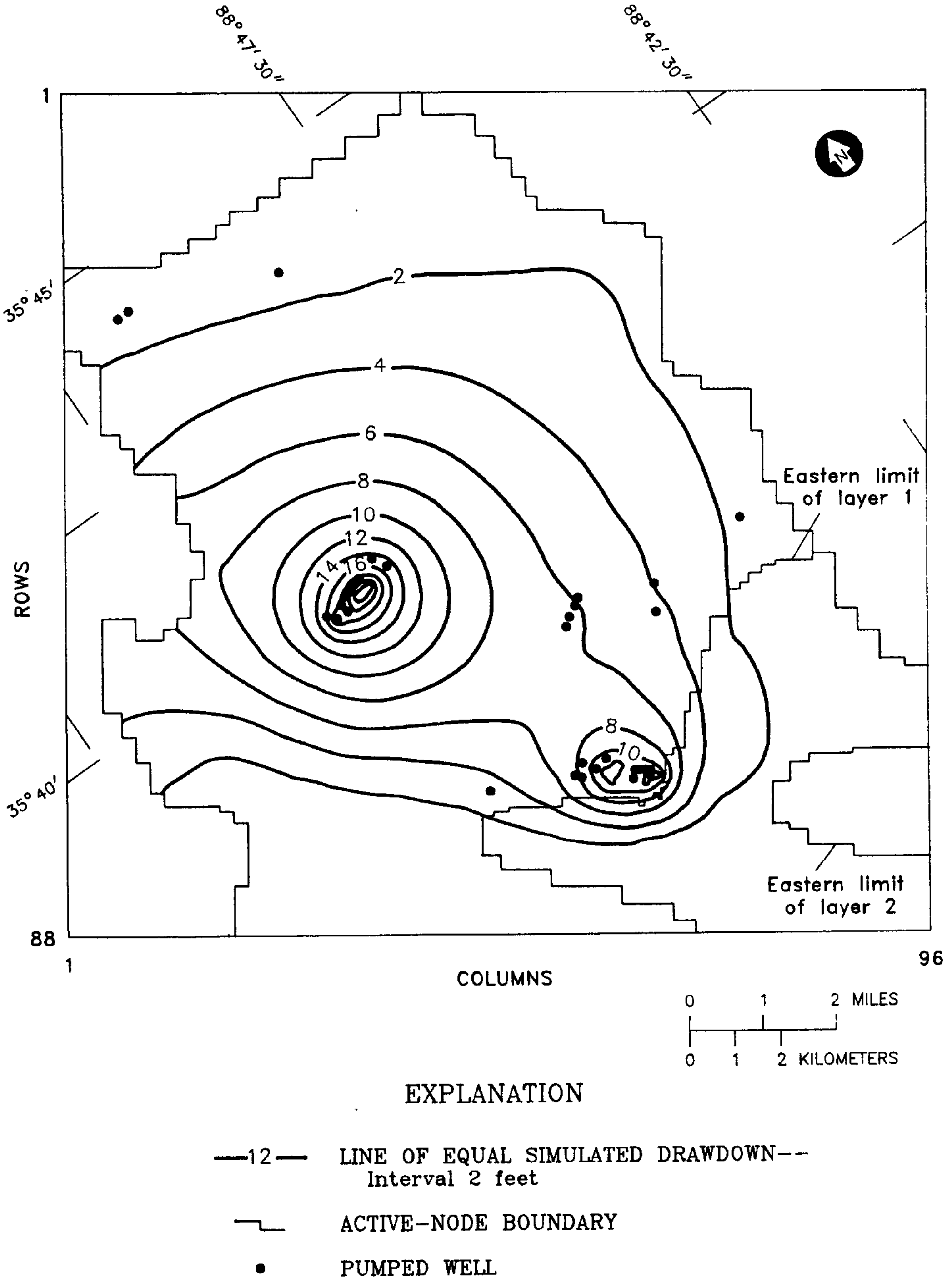


Figure 24. Simulated drawdown in layer 3 for pumping plan 2 with constant-flux boundaries.

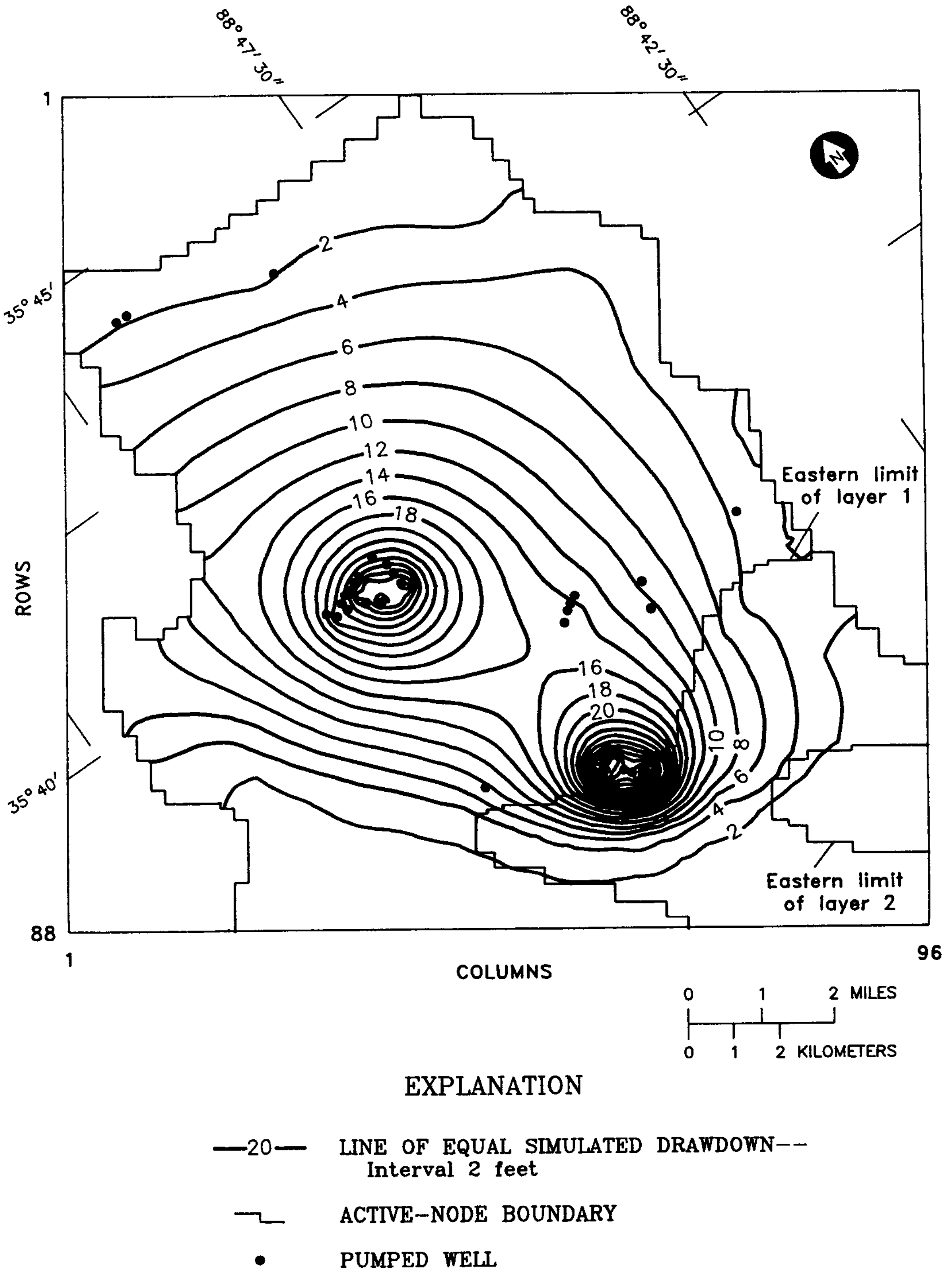


Figure 25. Simulated drawdown in layer 3 for pumping plan 3 with constant-flux boundaries.

AREAS CONTRIBUTING WATER TO THE WELL FIELDS

A particle-tracking program (Pollock, 1989) was used to delineate areas contributing water to the North and South Well Fields for prescribed pumping conditions, and to estimate distances for different times-of-travel to the wells. The particle-tracking program (MODPATH) uses the results from steady-state model simulations to delineate pathlines of ground-water flow and the position of particles at specified times. Particle tracking is based on advective transport only and cannot be used to compute solute concentrations in ground water.

Particle-tracking analyses were done for the calibrated model (April 1989 hydrologic conditions) and the three pumping plans using constant-flux boundary conditions. Particles were tracked backward from the well fields to delineate the configuration of areas contributing water to wells. Tracking was accomplished by placing a total of six particles on the cell faces of nodes containing each pumping well; that is, one particle was placed on each cell face. Travel times are based on velocities calculated in the model, assuming 30-percent porosity for the aquifers (Freeze and Cherry, 1979, p. 37). Use of a different porosity value would affect travel time, but would not affect the configuration of pathlines.

Results of the particle-tracking analyses are displayed for the calibrated model and the three pumping plans in two ways: (1) A general configuration of areas contributing water to the municipal well fields and other major pumping centers for the entire area and the definition of a 5-year time-of-travel capture zone (figs. 26-29), and (2) a detailed display of pathlines from individual wells in the North and South Well Fields showing increments of 1 year of travel time along each pathline for a total of 5 years (figs. 31-34). Flow lines along representative hydrologic sections through the well fields also were plotted for pumping plan 2 for increments of 1 year of travel time for 5 years (fig. 30).

Although details within the well fields are obscured by the density of pathlines on the figures showing the entire modeled area, the general configuration of contributing areas is evident. If fewer pathlines were shown, which would more clearly show the pumping center, or if the contributing areas were more generalized, then the configuration of the overall contributing areas would be less accurately displayed. Therefore, information shown on figures 26 through 29 is meant to display a generalized pattern, and the details of pathlines and travel times are shown on subsequent figures of each well field.

Configuration of Ground-Water Flow to the Well Fields

The area contributing water to the municipal well fields and to other major pumping centers (commercial and industrial) for the entire modeled area for the calibrated model (fig. 26) were generally separate and distinct. Flow pathlines, calculated by MODPATH, that emanate from the pumping wells define the contributing areas for each pumping center. Water was drawn to the wells primarily from upgradient source areas. As pumping in the North and South Well Fields was changed for each of the pumping plans (figs. 27-29), changes in the contributing areas occurred due to interactions between the pumping centers. A point along each flow line was calculated to delineate the distance from which water particles would take 5 years to reach the well fields. These points (figs. 26-29), if connected, would define a 5-year time-of-travel capture zone around each pumping center. Particles upgradient from the 5-year demarcation would take longer than 5 years to travel to the wells, and particles closer to the pumping centers would take a shorter time.

The configuration of the flow pathlines and resulting contributing areas for the calibrated model and pumping plan 1 probably are not affected by simulation of the western boundary as a no-flow boundary. However, the configuration for pumping plans 2 and 3 may be affected by the boundary condition. The boundary, as simulated, eliminated the capture of any ground water from the west and forced water into the contributing areas that may not be realistic. The configuration of the 5-year time-of-travel capture zone may not be as significantly affected as the western part of the contributing area (figs. 28-29).

Time-of-travel locations and pathlines that were used to delineate the contributing areas and capture

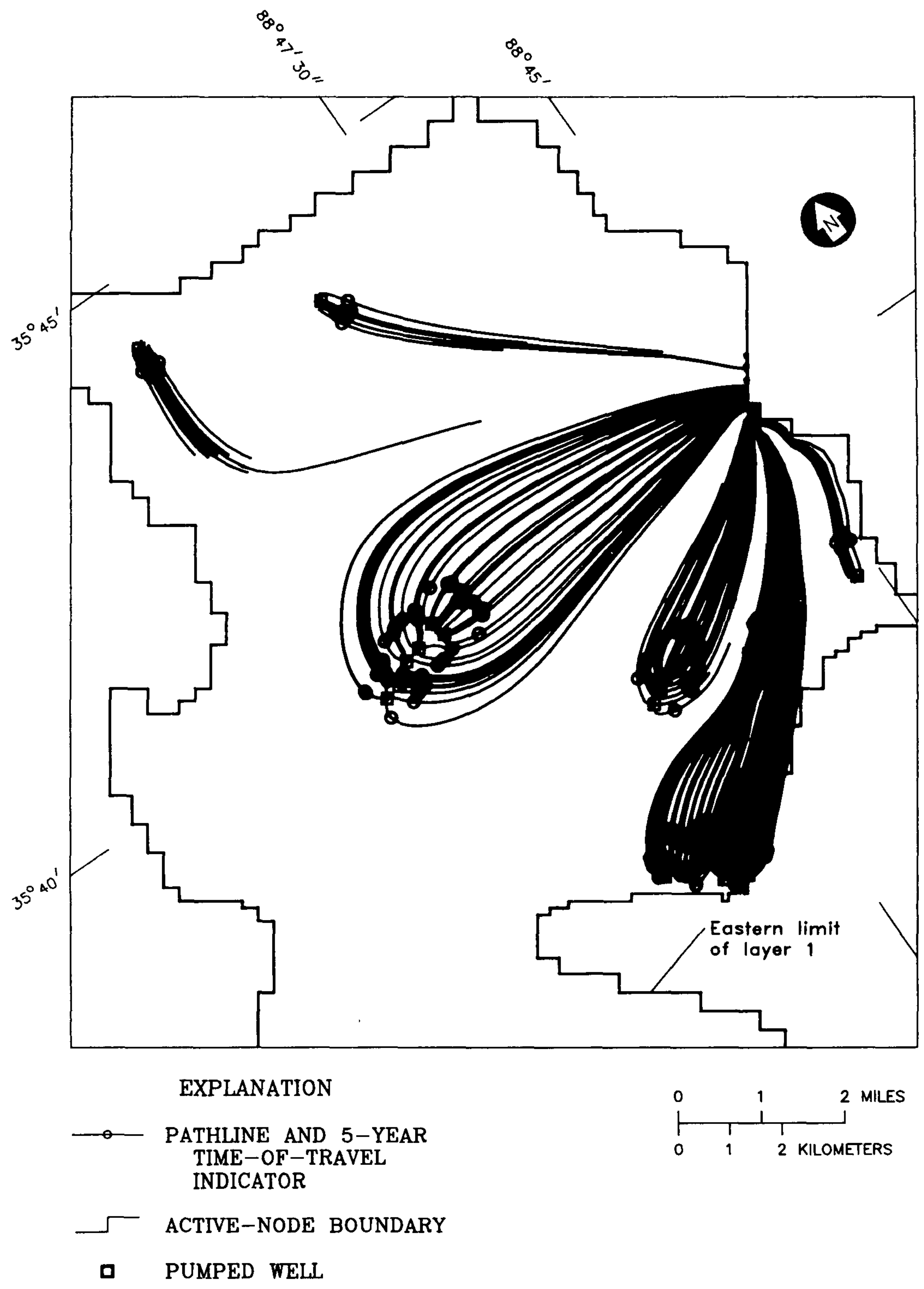


Figure 26. Simulated particle-flow pathlines and 5-year time-of-travel capture zones for the calibrated model.

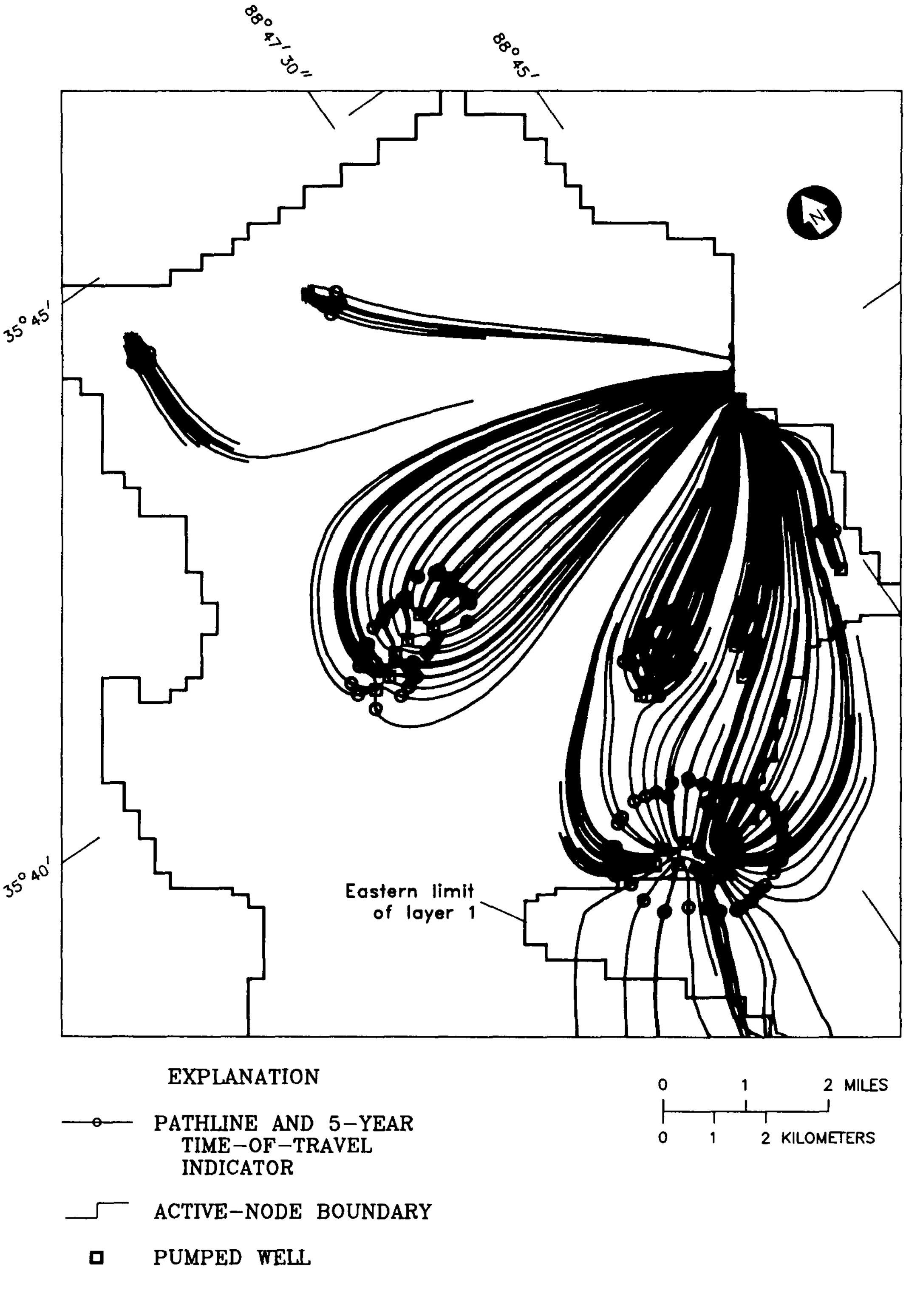


Figure 27. Simulated particle-flow pathlines and 5-year time-of-travel capture zones for pumping plan 1.

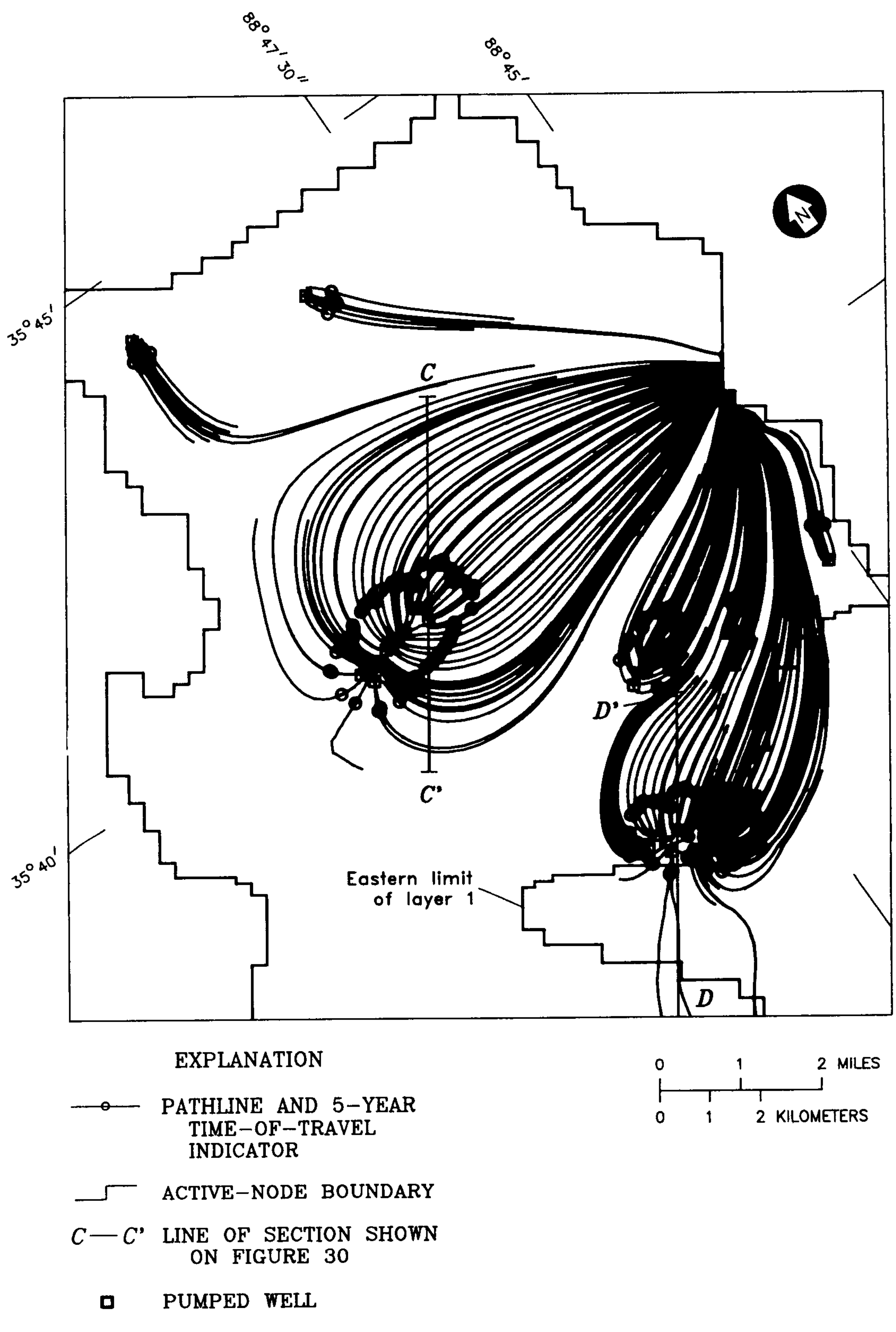


Figure 28. Simulated particle-flow pathlines and 5-year time-of-travel capture zones for pumping plan 2.

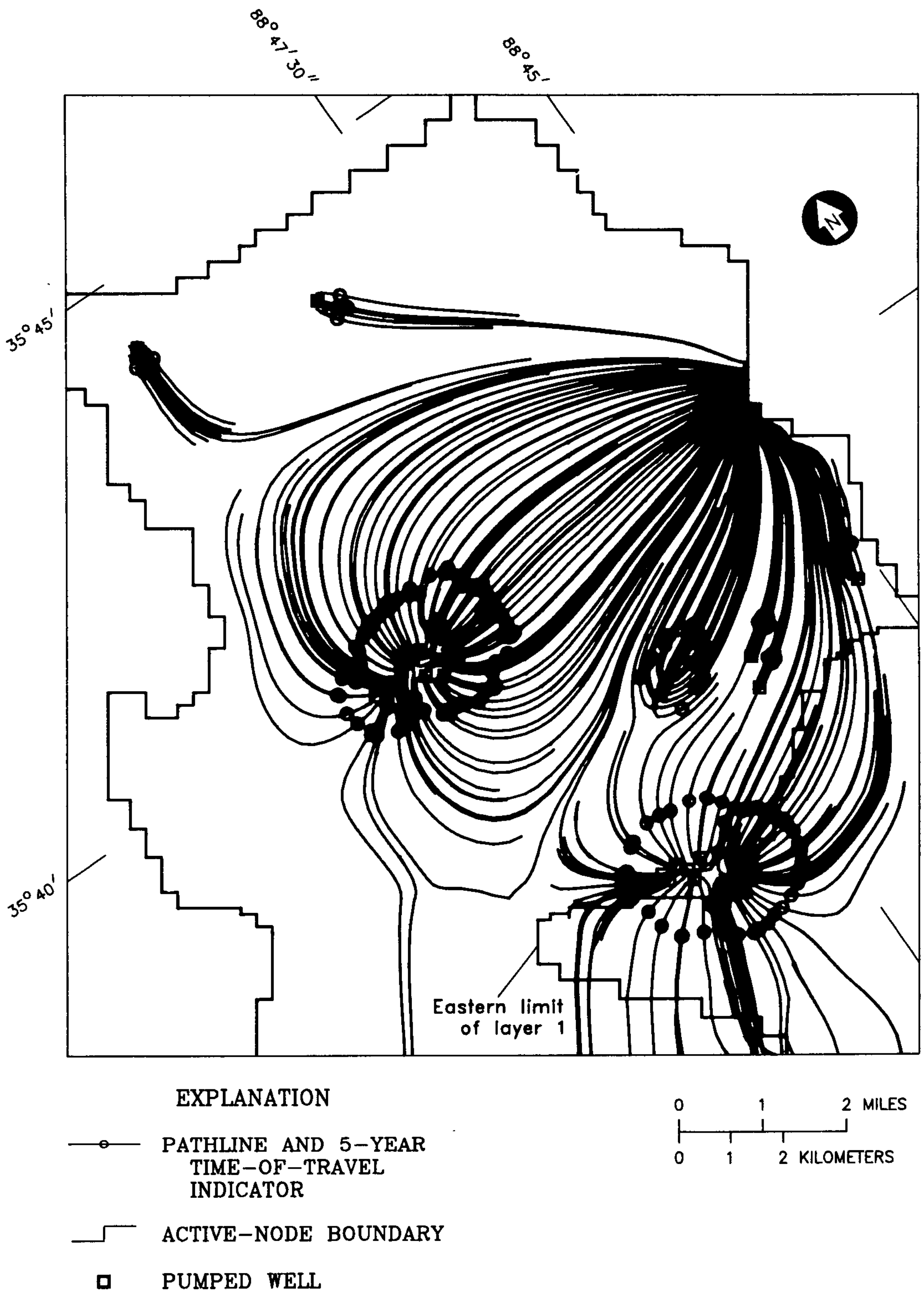
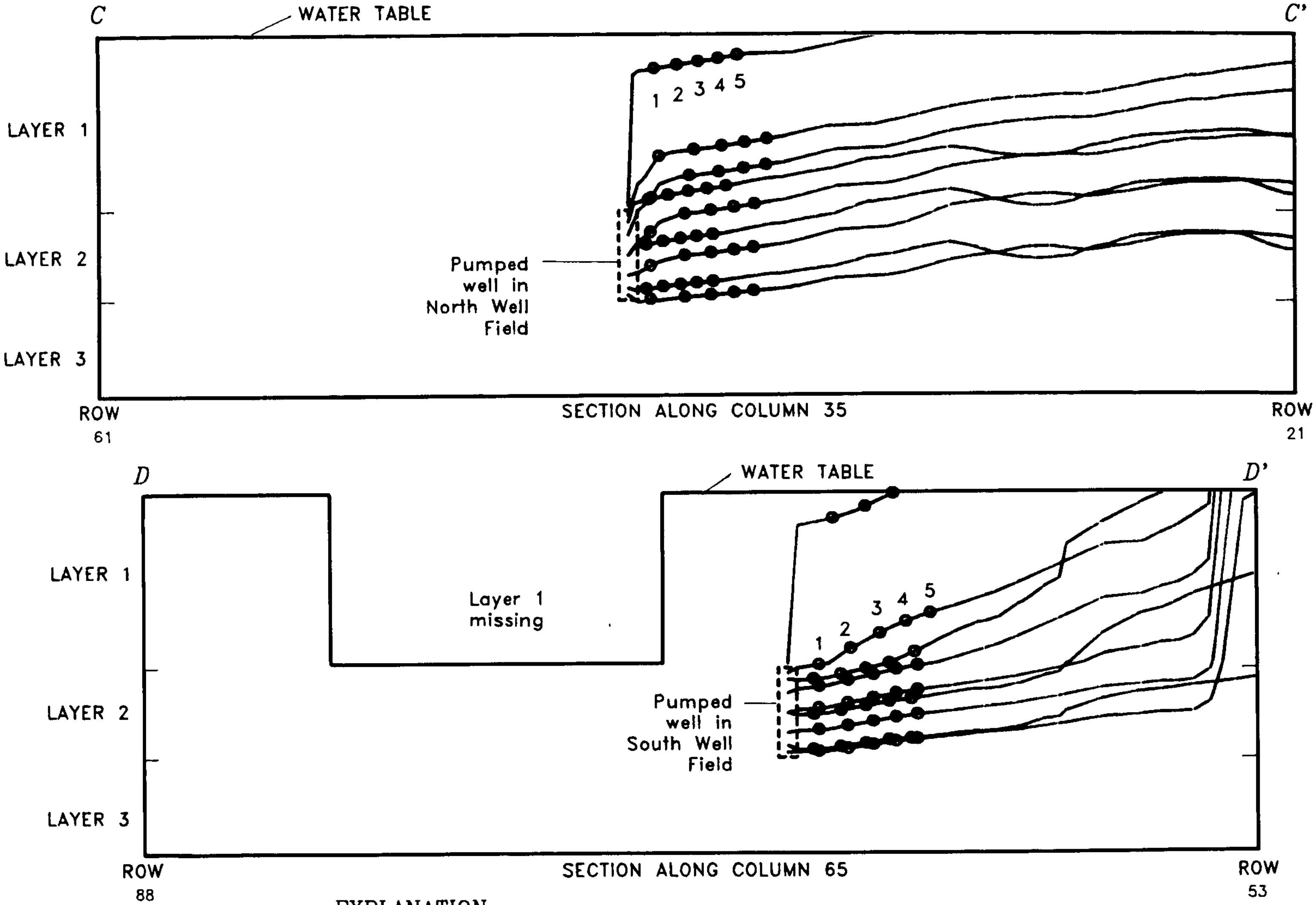


Figure 29. Simulated particle-flow pathlines and 5-year time-of-travel capture zones for pumping plan 3.



EXPLANATION

MODEL ROW AND COLUMN BOUNDARIES

1 PATHLINE AND 1-YEAR TIME-OF-TRAVEL INDICATOR--Numbers indicate years. Pathlines that cross are an artifact of the plane of section

0 2,000 4,000 FEET

0 500 1,000 METERS

VERTICAL EXAGGERATION X 30

Figure 30. Hydrologic sections through the North and South Well Fields showing increments of 1 year of travel time for 5 years along pathlines to a single pumped well for pumping plan 2. (Lines of section shown on figure 28.)

zones were projected to the surface of layer 1 to construct a map view. Therefore, the locations of the capture zone on the surface does not necessarily indicate that a particle reaching the well originated at that surface location. This concept is illustrated by showing the pathlines as they appear in a hydrologic section (fig. 30). The time-of-travel indicators (fig. 30) show the distance along the pathlines from which particles would, in increments of 1 year, reach the well. Particles introduced to a flowpath from a source at a great distance from the well might take many years to reach the well, but, if not attenuated, could eventually affect the well. The sections illustrate that, although any potential sources of contaminants particles near the wells should be of immediate concern, sources far from the wells along flow pathlines should not be ignored.

Pathlines that were used to delineate the contributing areas and capture zones for the calibrated model and pumping simulations for the whole modeled area (figs. 26-29) are shown on figures 31 through 38 to demonstrate flow to individual wells in more detail for the North and South Well Fields. Increments of travel time were increased to 1-year intervals to show the distances from which particles reach the wells. The following discussions focus on flow pathlines and times-of-travel to individual wells in each well field.

North Well Field

The configuration of flow pathlines and contributing areas for the North Well Field for the calibrated model and pumping plan 1 were nearly identical (figs. 31-32). Pumping in plan 1 was slightly greater than in the calibrated model, so water was drawn from slightly farther downgradient. The size of the 5-year time-of-travel capture zone is about 0.8 by 1.8 miles for the calibrated model and plan 1. The pathlines and contributing areas for pumping plans 2 and 3 are similar, but water was drawn from a farther distance to the east in plan 3 because of the locations of the four additional pumping wells (figs. 33-34). The 5-year time-of-travel capture zone for plan 2 was about 1.1 by 2.0 miles and for plan 3, about 1.6 by 2.2 miles.

The range of distance for 1-year time-of-travel to individual wells was 200 to 800 feet for the calibrated model and plan 1, and 350 to 950 feet for plans 2 and 3.

South Well Field

The configuration of flow pathlines and contributing area were different between the calibrated model and the three pumping plans for the South Well Field (figs. 35-38). Actual pumping was much less in the calibrated model than in the hypothetical pumping simulations. Nearly all the water to wells in the calibrated model came from upgradient, and flow to each of the two clusters of wells in the well field was separate (fig. 35). The size of the 5-year time-of-travel capture zone, for the eastern cluster, was 0.5 by 0.7 mile, and for the western cluster, 0.7 by 0.8 mile. The size of the capture zone for the entire well field, was about 0.8 by 1.4 miles.

The configurations for plans 1 and 3 were nearly identical because hypothetical pumping was the same for the South Well Field (figs. 36, 38). The slight differences were caused by different pumping rates in the North Well Field. The size of the 5-year time-of-travel capture zone around the well field was about 1.6 by 2.2 miles.

The size of the 5-year time-of-travel capture zone around the well field for pumping plan 2 was 1.1 by 1.7 miles (fig. 37). Pumping from all three plans draws water from the opposite side of the South Fork and would result in streamflow reduction. Simulated seepage to the measured segments of the South Fork was reduced by 5.1, 4.2, and 9.5 ft^3/s, for plans 1, 2, and 3, respectively, compared to calibrated seepage (22 ft^3/s).

The range of distance for 1-year time-of-travel to individual wells was 120 to 530 feet for the calibrated model, 670 to 1,300 feet for plans 1 and 3, and 260 to 850 feet for plan 2.

SUMMARY AND CONCLUSIONS

The Jackson Utility Division supplies water to customers in Madison County, Tennessee, from two well fields in Jackson. Prior to 1980 all of the water, as much as 8.5 Mgal/d, was pumped from the South Well Field. Since 1980, as much as 85 percent of the municipal supply has been pumped

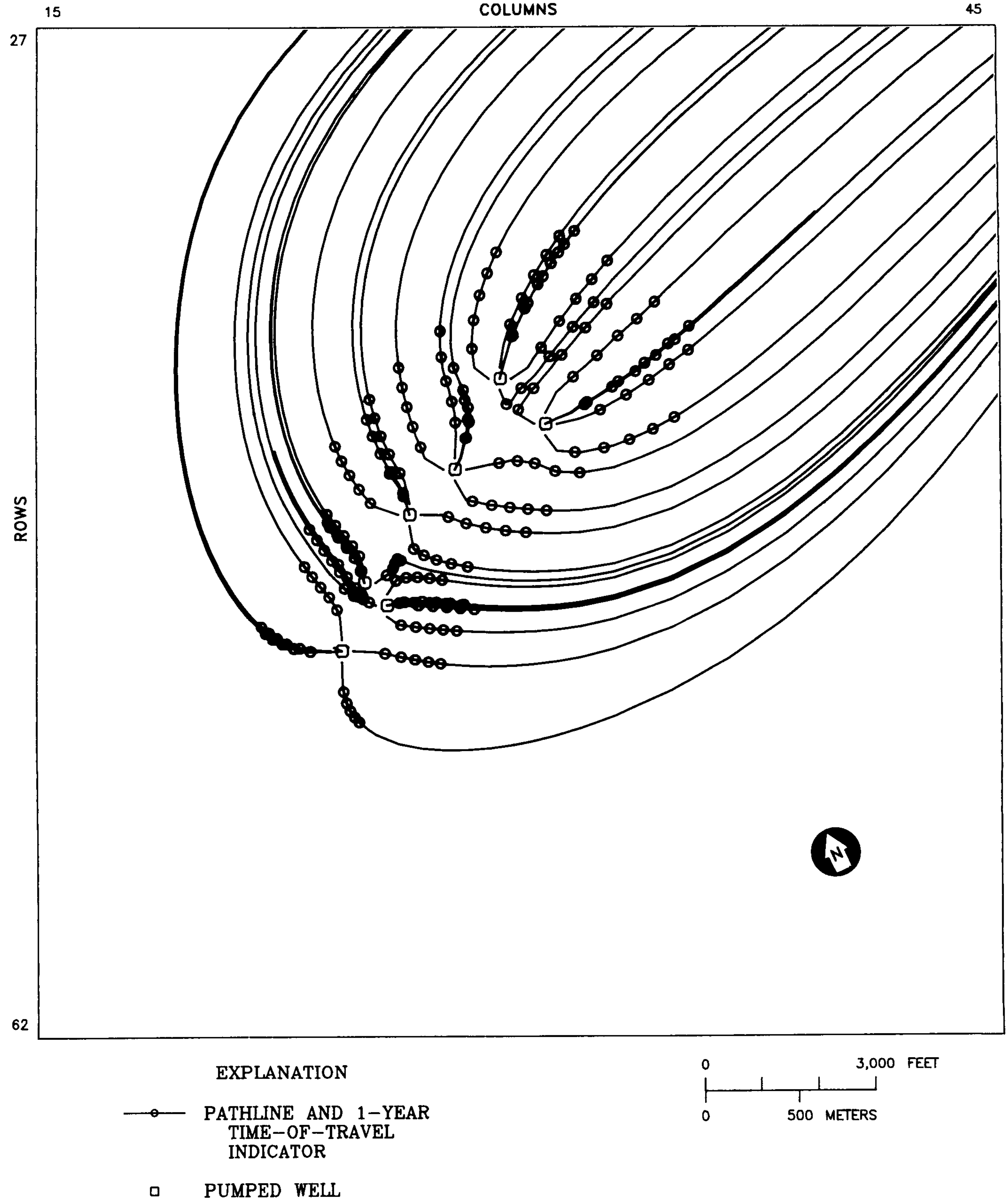
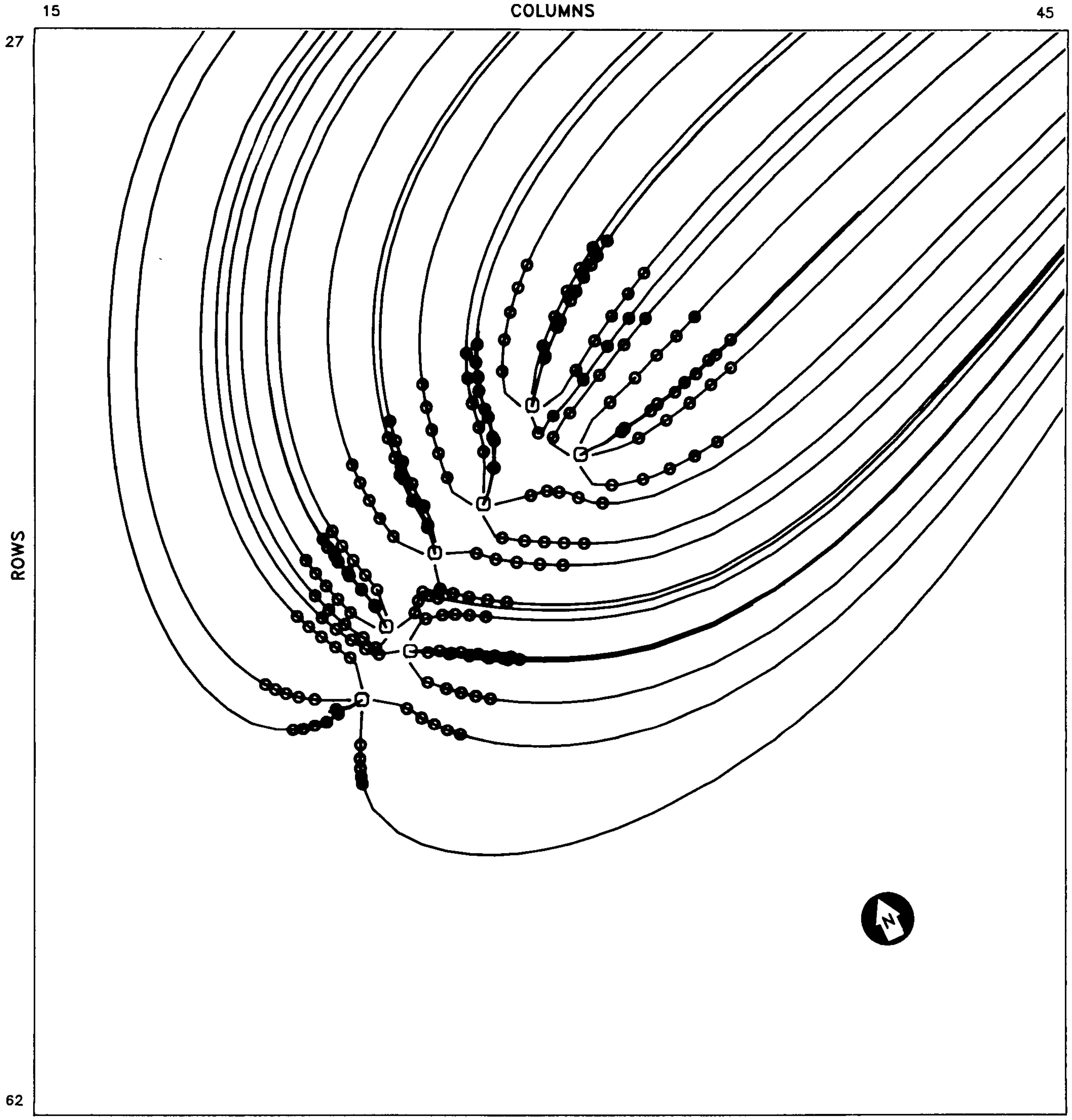


Figure 31. Increments of 1 year of travel time for 5 years along pathlines to individual wells in the North Well Field for the calibrated model.



EXPLANATION

PATHLINE AND 1-YEAR TIME-OF-TRAVEL INDICATOR

PUMPED WELL

0 3,000 FEET

0 500 METERS

Figure 32. Increments of 1 year of travel time for 5 years along pathlines to individual wells in the North Well Field *for pumping plan 1.*

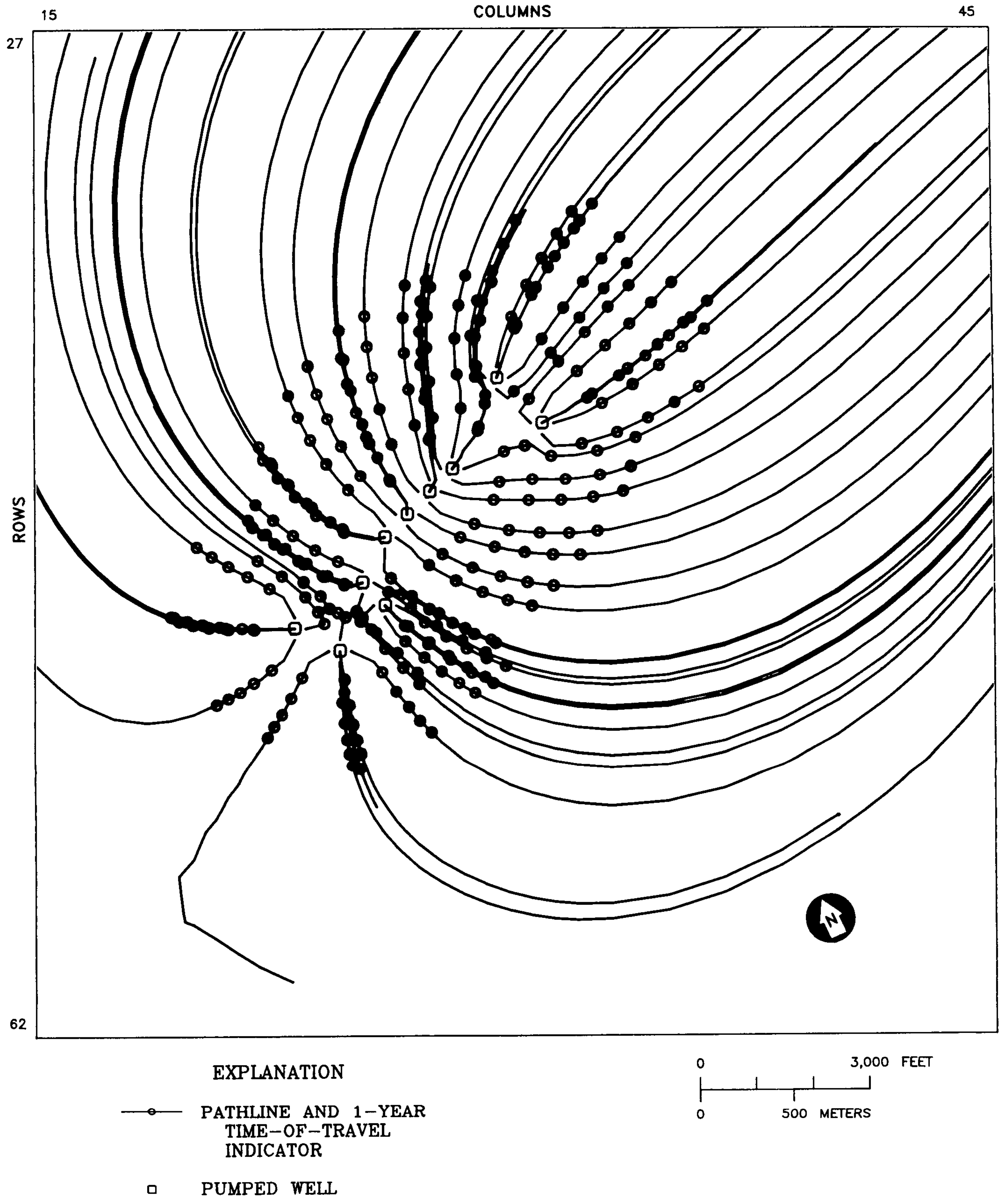


Figure 33. Increments of 1 year of travel time for 5 years along pathlines to individual wells in the North Well Field for pumping plan 2.

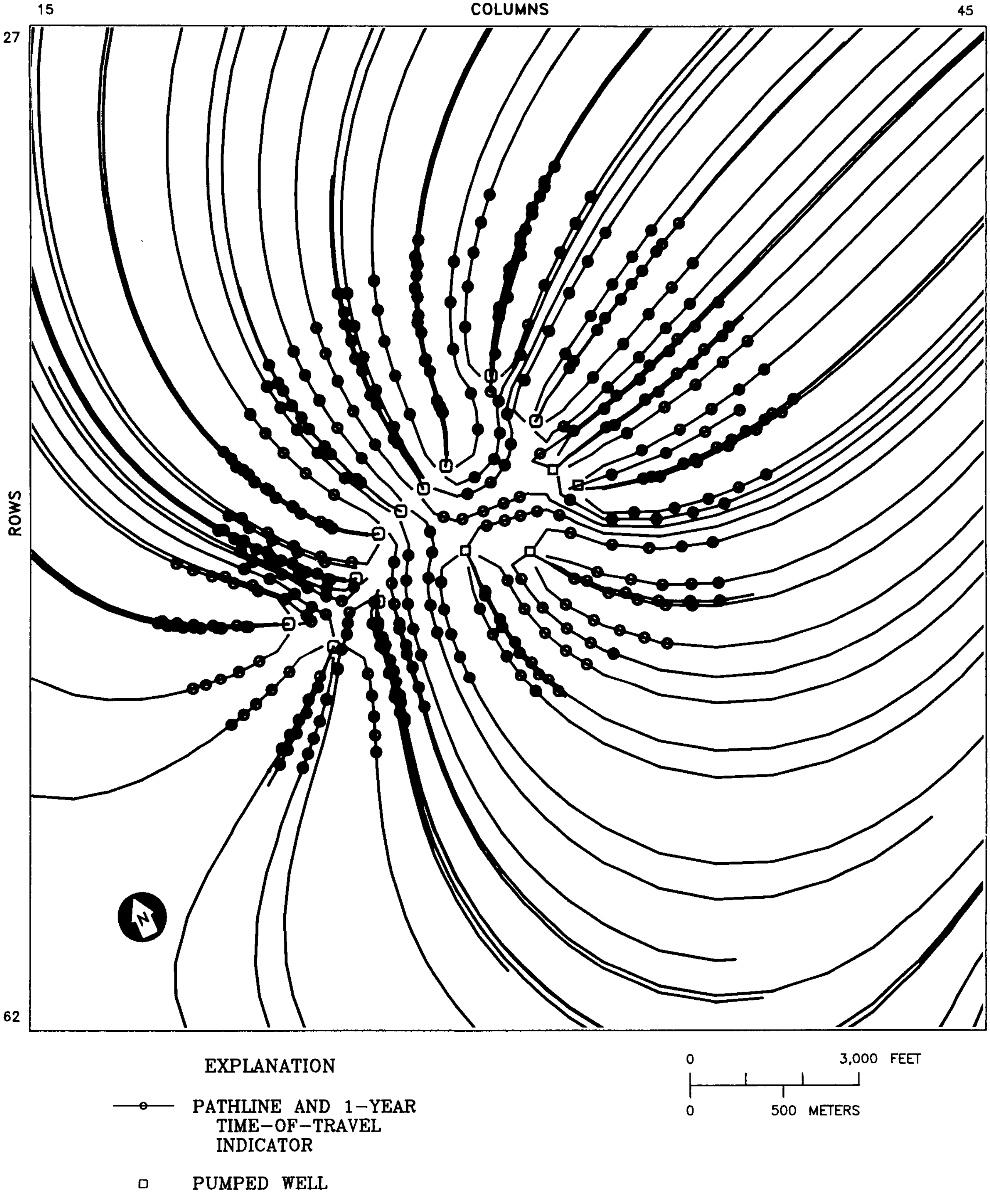
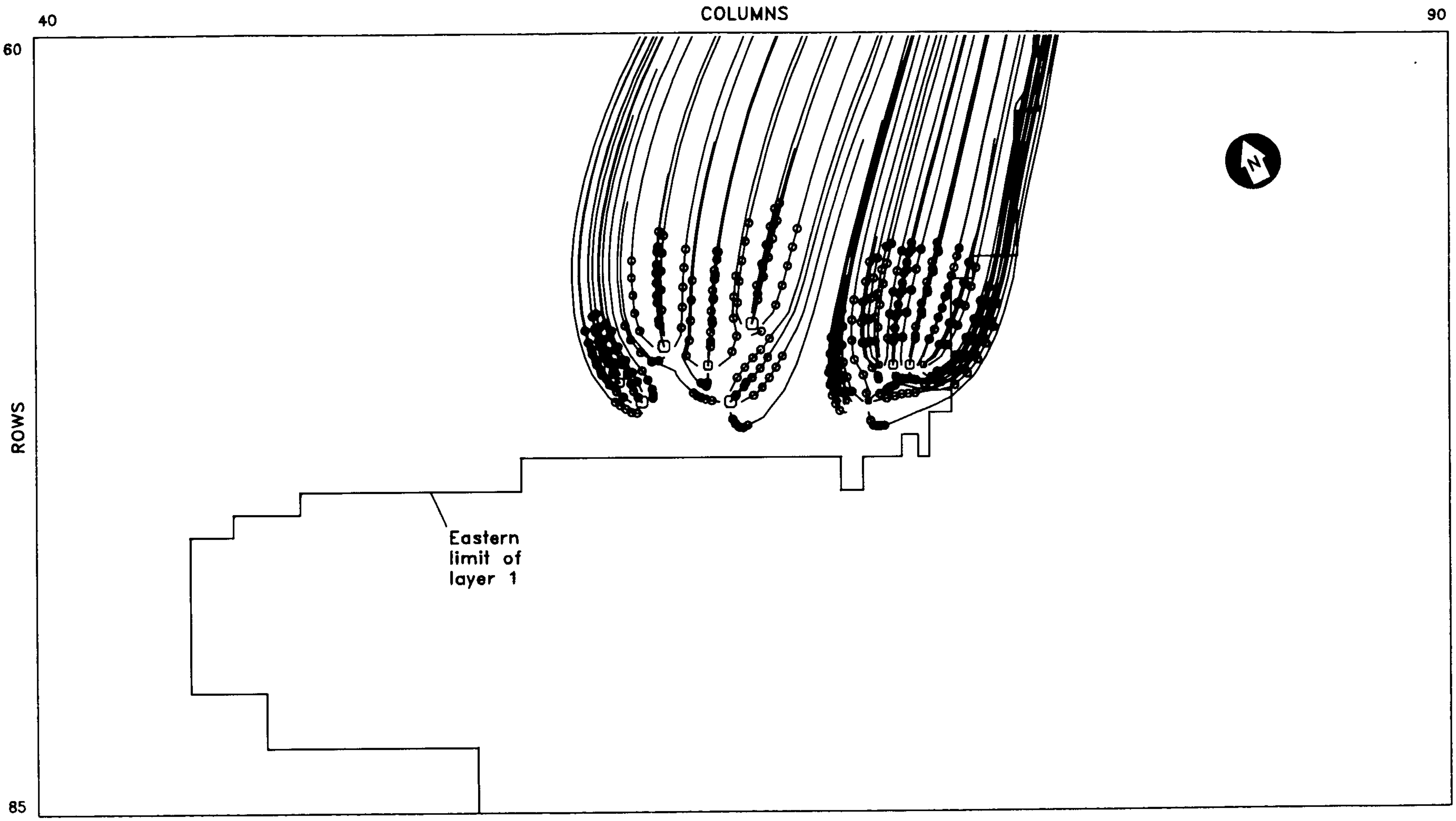


Figure 34. Increments of 1 year of travel time for 5 years along pathlines to individual wells in the North Well Field *for pumping plan 3.*



EXPLANATION

—o— PATHLINE AND 1-YEAR TIME-OF-TRAVEL INDICATOR

□ PUMPED WELL

0 3,000 FEET
0 500 METERS

Figure 35. Increments of 1 year of travel time for 5 years along pathlines to individual wells in the South Well Field for the calibrated model.

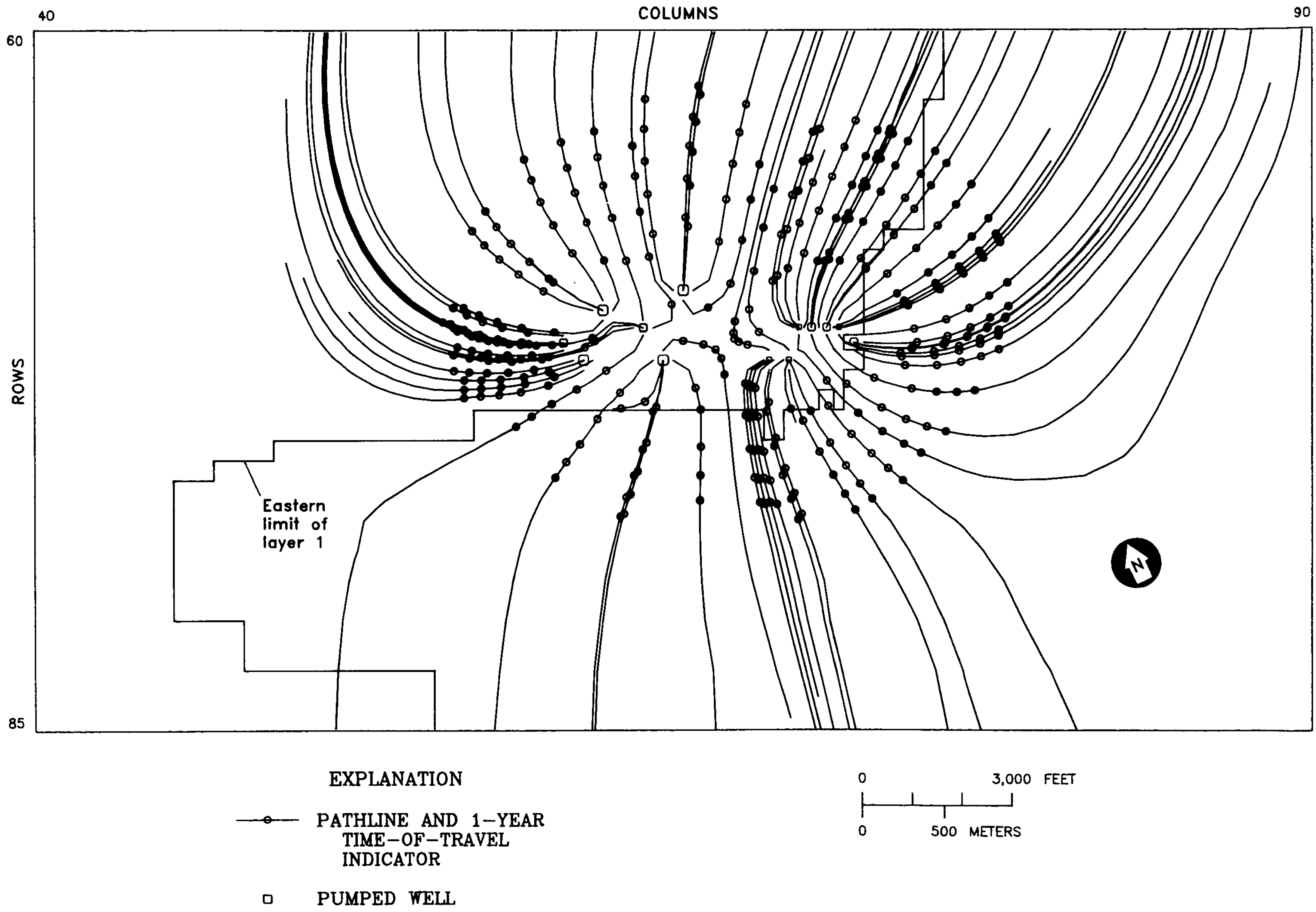


Figure 36. Increments of 1 year of travel time for 5 years along pathlines to individual wells in the South Well Field for pumping plan 1.

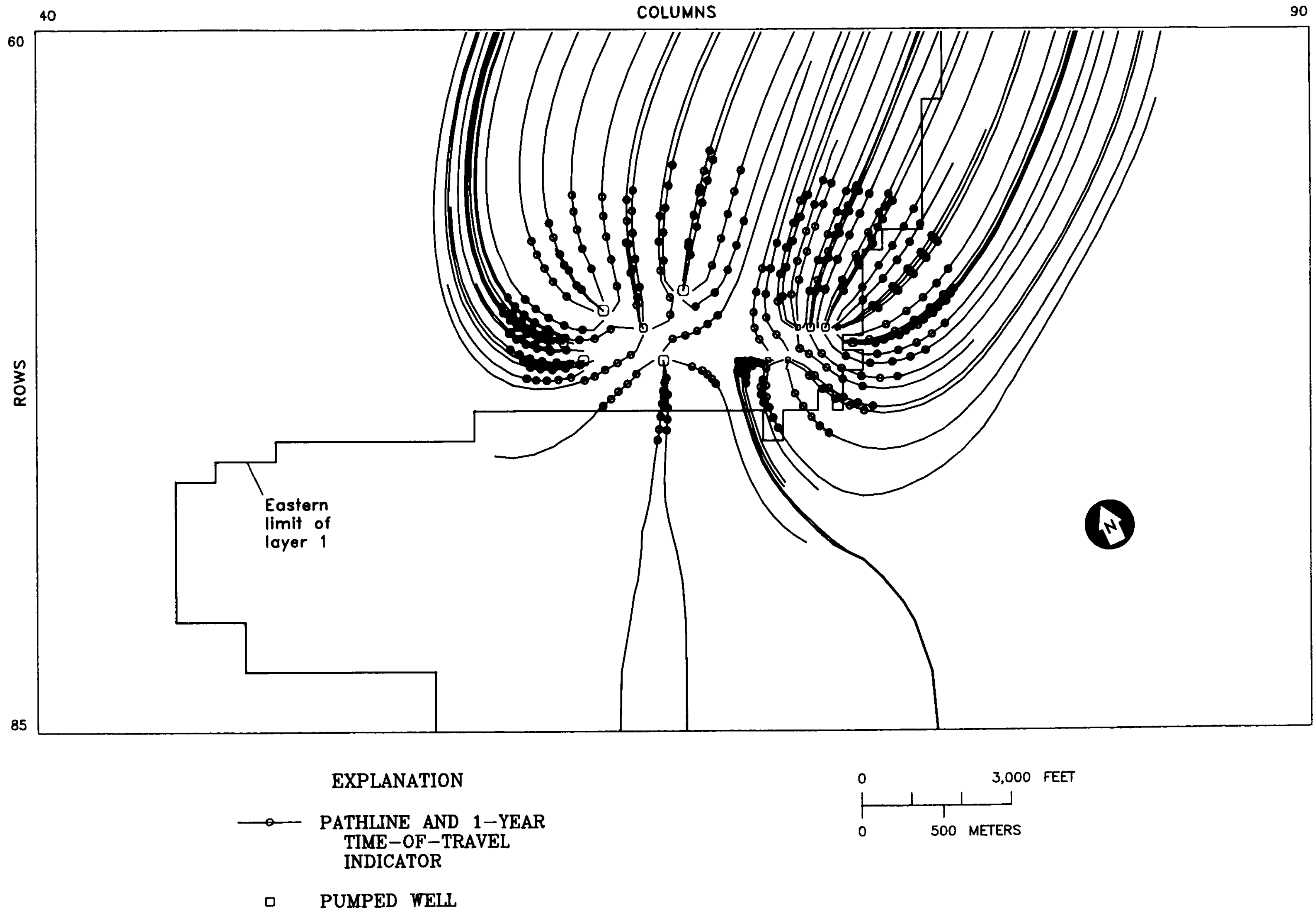


Figure 37. Increments of 1 year of travel time for 5 years along pathlines to individual wells in the South Well Field for pumping plan 2.

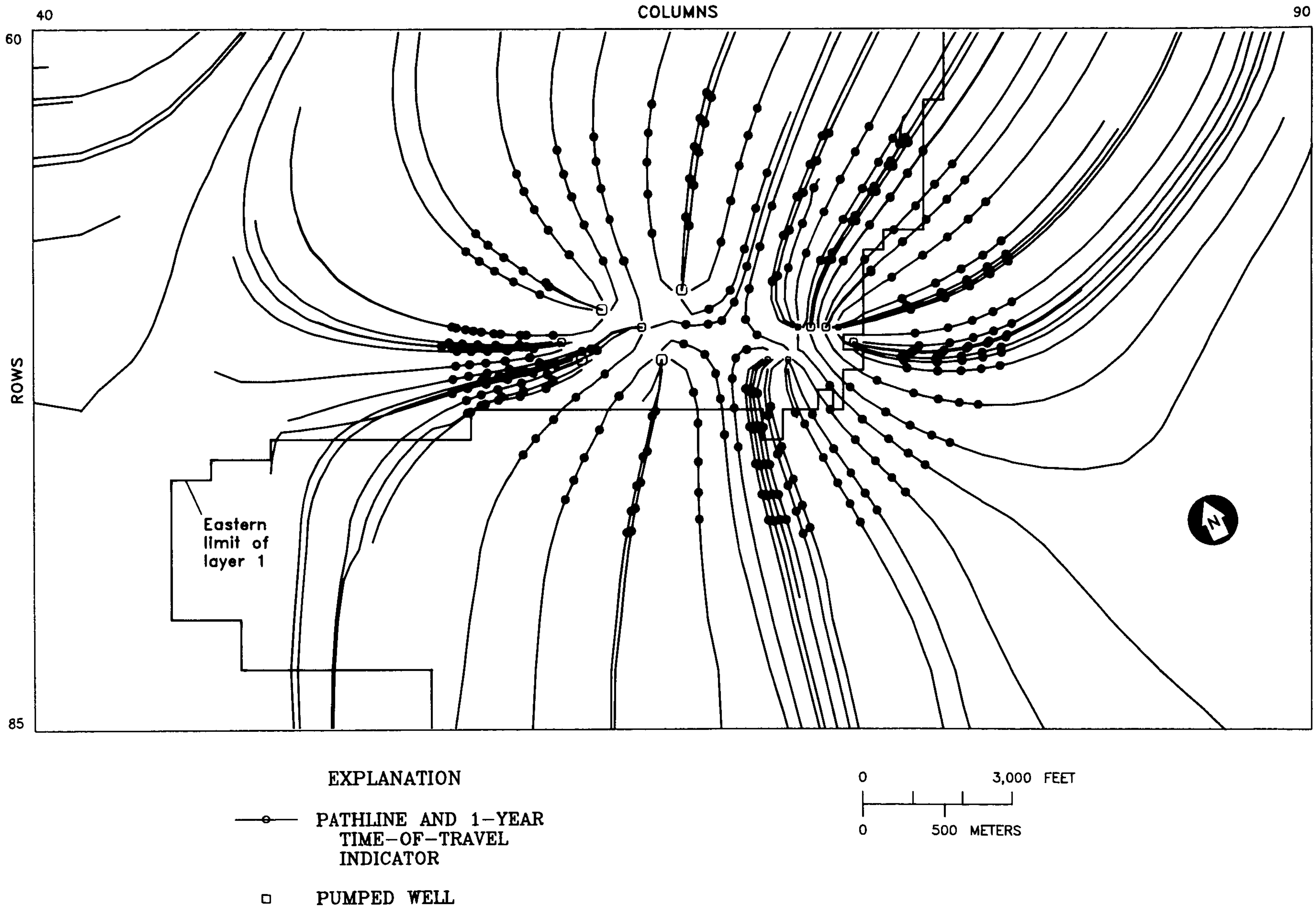


Figure 38. Increments of 1 year of travel time for 5 years along pathlines to individual wells in the South Well Field for pumping plan 3.

from the North Well Field. Average pumpage from the North Well Field for a week in April 1989 was 9.2 Mgal/d, and from the South Well Field, 2.2 Mgal/d.

The geologic units of interest that crop out in the Jackson area include the Memphis Sand and Fort Pillow Sand, the principal aquifers in the area, and the Porters Creek Clay, the underlying confining unit. The saturated thickness of the Memphis Sand ranges from 0 to 270 feet; the Fort Pillow Sand, from 0 to 180 feet. The Porters Creek Clay, which ranges from 130 to 320 feet thick, separates a deeper formation, the McNairy Sand, from the shallower units. All units thin from northwest to southeast and dip to the northwest at 20 to 50 ft/mi.

The Memphis and Fort Pillow Sands function as a single aquifer, although clay lenses are probably locally confining. The McNairy Sand is hydraulically separated from the shallow aquifers by the Porters Creek Clay. The natural ground-water divide would be expected to bisect the area between the Middle and South Forks Forked Deer River, but pumping in the North Well Field and at a major industrial center along the divide has caused the ground-water divide to move northward toward the Middle Fork. Ground-water flow is generally from the east-northeast and toward the major streams. Flow is diverted locally toward major pumping centers.

Previous investigations in the Jackson area produced estimates of hydraulic conductivity and transmissivity for the Memphis Sand and the Fort Pillow Sand. Estimates of hydraulic conductivity for the Memphis Sand ranged from 80 to 202 ft/d, transmissivity from 2,700 to 33,000 ft^2/d, and storage coefficient from 0.0001 to 0.011. Estimates of hydraulic conductivity for the Fort Pillow Sand range from 68 to 167 ft/d, transmissivity from 6,700 to 10,050 ft^2/d. The only estimate of storage coefficient is 0.0015.

Areal recharge rates were calculated from seepage measured during the base-flow investigation in April 1989 and from graphical hydrograph-separation techniques that were applied to data from two continuous-record streamflow-gaging stations. Calculated rates ranged from 5.6 to 8.1 in/yr. An estimate of areal recharge for an adjacent drainage basin was 9.5 in/yr.

A finite-difference ground-water flow model was used to simulate the three-dimensional, steady-state flow system in the sand aquifers. The model uses three layers to simulate the ground-water flow system. Layer 1 was the saturated Memphis Sand; layer 2 was the upper half of the Fort Pillow Sand; and layer 3 was the lower half of the Fort Pillow Sand. The model was calibrated to water levels in 46 wells measured in April 1989 and to ground-water seepage to streams measured at the same time. Simulated heads and ground-water seepage to streams matched measured values relatively well.

A nonunique combination of values for aquifer characteristics comprised the calibrated model; however, the ranges of the most sensitive characteristics were shown to be small. The calibrated model is considered the best combination of hydraulic characteristics for pumping simulations and for particle-tracking analyses because no significant improvements were indicated by the sensitivity analyses. The aquifer characteristics and boundary conditions in the calibrated model should produce reasonable results from hypothetical pumping simulations and from particle-tracking analyses.

The steady-state water budget of the simulated system showed that more than half of the inflow to the ground-water system was underflow into the valley of the South Fork Forked Deer River. Most of this inflow was discharged as seepage to the river and nearby pumping. Slightly less than half of the inflow was from areal recharge and recharge from streams. About 75 percent of the discharge from the system is into the streams, lakes, and out of the model area through a small quantity of ground-water underflow. The remaining 25 percent was discharged to pumping wells.

The calibrated model was modified to simulate the effects on the ground-water system of three hypothetical pumping plans. Pumpage in the calibrated model was increased for pumping plan 1 in the North Well Field to a total of 10 Mgal/d, and pumpage from the South Well Field was increased to a total of 10 Mgal/d. For pumping plan 2, pumpage in the North Well Field was 15 Mgal/d, and pumpage in the South Well Field was 5 Mgal/d. For pumping plan 3, total pumpage from the North Well Field was 20 Mgal/d, and from the South Well Field, 10 Mgal/d.

Drawdown resulting from simulated pumping in plan 1 was concentrated around the South Well Field. Maximum drawdown was 40.7 feet in a node containing a pumping well, but maximum drawdown over an extended area was about 32 feet. Drawdown resulting from simulated pumping in plan 2 was less, because pumping increases were more moderate. Maximum drawdown was 27.3 feet in a node containing a pumping well in the North Well Field, and maximum drawdown over an extended area was about 22 feet. Drawdown resulting from simulated pumping in plan 3 was the greatest, both locally and in areal extent. Maximum drawdown was 44.7 feet in a node containing a pumping well in the South Well Field, and maximum drawdown over an extended area was about 38 feet.

A particle-tracking post-processor program, MODPATH, was used to delineate areas contributing water (capture zone) to the North and South Well Fields for the calibrated model and the three pumping simulations, and to estimate times-of-travel from recharge areas to the wells. Flow paths to the well fields and to other pumping wells (commercial and industrial) for the entire area for the calibrated model were generally separate and distinct. Water to all the wells was drawn primarily from upgradient source areas.

The size of the 5-year time-of-travel capture zone for the North Well Field was about 0.8 by 1.8 miles for the calibrated model and plan 1. The size of the capture zone for plan 2 was 1.1 by 2.0 miles and for plan 3, 1.6 by 2.2 miles. The range of distance for 1-year time-of-travel to individual wells was 200 to 800 feet for the calibrated model and plan 1, and 350 to 950 feet for plans 2 and 3.

The size of the 5-year time-of-travel capture zone for the South Well Field, was about 0.78 by 1.4 miles for the calibrated model. The size of the capture zone for pumping plans 1 and 3 was 1.6 by 2.2 miles, and for pumping plan 2, 1.1 by 1.7 miles. The range of distance for 1-year time-of-travel to individual wells was 120 to 530 feet for the calibrated model, 670 to 1,300 feet for plans 1 and 3, and 260 to 850 feet for plan 2.

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