ANALYSIS OF THE EFFECT OF PUMPING ON GROUND-WATER FLOW IN THE SPRINGFIELD PLATEAU AND OZARK AQUIFERS NEAR SPRINGFIELD, MISSOURI

By Jeffrey L. Imes

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CONVERSION FACTORS

For readers who prefer to use metric (International System) units, conversion factors for terms used in this report are listed below:

Multiply inch-pound unit	By	To obtain metric unit
foot (ft)	0.3048	meter (m)
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
gallons per minute per foot (gal/min-ft)	0.207	liter per second (L/S-m)

ANALYSIS OF THE EFFECT OF PUMPING ON GROUND-WATER FLOW IN THE SPRINGFIELD PLATEAU AND OZARK AQUIFERS NEAR SPRINGFIELD, MISSOURI

By Jeffrey L. Imes

ABSTRACT

Pumpage of water from the Ozark aquifer for public supply and industrial use in the city of Springfield and surrounding communities in southwestern Missouri has substantially altered ground-water flow patterns in the aquifer. Springfield is located on a former regional ground-water divide that trends east and west across southern Missouri. Ground water that once flowed north and south from the divide now moves toward Springfield. Drawdown in the Ozark aquifer beneath Springfield has increased 42 feet near the center of the city since 1974. The area of head decline also has increased, most notably to the south and southwest, because of increased pumpage of water-supply wells in the city and new ground-water withdrawals in communities with rapidly increasing populations, such as Republic and Nixa.

A finite-difference model of ground-water flow in a 42 by 42 mile area centered on Springfield was calibrated under predevelopment and transient pumping conditions. Estimates of the lateral hydraulic conductivity of the Springfield Plateau aquifer range from 5.0×10^{-5} to 5.0×10^{-4} feet per second, depending on the analysis used. An estimate of the lateral hydraulic conductivity of the Ozark aquifer areally ranges from 8.0×10^{-6} to 3.0×10^{-5} feet per second. An estimate of the vertical hydraulic conductivity of the Ozark confining unit areally ranges from 9.0×10^{-11} to 1.1×10^{-10} feet per second, and an estimate of the vertical hydraulic conductivity of the St. Francois confining unit is 4.5×10^{-11} feet per second.

Changes in the potentiometric surface of the Ozark aquifer, and to a lesser extent the Springfield Plateau aquifer, resulting from pumpage of water-supply wells has altered the hydrologic budget of the Springfield area. Of the approximately 17.6 cubic feet per second of water pumped from the Ozark aquifer in 1986, about 50 percent was supplied by increased downward leakage through the Ozark confining unit, about 10 percent came from storage within the Ozark aquifer, and about 40 percent was supplied by lateral flow in the Ozark aquifer. Downward leakage of ground water through the Ozark confining unit has increased from about 10 cubic feet per second before development of the area to about 18 cubic feet per second after development because drawdown in the Ozark aquifer has resulted in an increased vertical hydraulic gradient across the confining unit. Minimal quantities of water are supplied by increased upward leakage through the St. Francois confining unit. The hydraulic head in the shallow Springfield Plateau aquifer is affected by pumpage in the underlying Ozark aquifer. Model simulations indicate substantial quantities of water are still (1987) being removed from storage within the Ozark and Springfield Plateau aquifers and, thus, the hydrologic system is not in equilibrium at this time. An analysis of the response of water levels to a pumping rate increase of 20 percent every 10 years to the year 2010 indicates water levels in the Ozark aquifer may decline an additional 100 to 150 feet near Springfield, and water levels in the Springfield Plateau aquifer may decline an additional 20 to 30 feet near Springfield.

INTRODUCTION

The city of Springfield, Missouri, third largest city in the State, is the center of an area of rapidly increasing population in southwestern Missouri (fig. 1). The population of Springfield, which has increased from 29,000 in 1890 to 133,116 in 1980, nearly doubled between 1950 and 1980 (state of Missouri, 1890-1988). Much of the 1950 to 1980 increase occurred from 1950 to 1970. From 1970 to 1980, the population of Springfield increased by about 11 percent. Rapid increases in population also have been experienced by many of the smaller communities around Springfield. From 1970 to 1980, 9 of the 10 larger communities around Springfield had population increases that exceeded 24 percent. To supply the current (1988) demand for drinking water, City Utilities of Springfield operates surface-water intake and treatment stations at McDaniel Lake, Fellows Lake, and Fulbright Spring north of the city, and at the James River southeast of the city. Estimates of the dependable yield of the surface-water sources differ (Emmett and others, 1978, p. 104; U.S. Army Corps of Engineers, 1984) but are about 23 Mgal/d (million gallons per day). To supplement surface-water supplies during periods of dry weather, City Utilities also maintains a network of 10 water-supply wells. Presently (1988), four wells are active and six wells are in reserve. The estimated dependable yield of the four active wells is 3.9 Mgal/d. Emmett and others (1978, p. 104) estimated the yield of nine City Utilities wells at 6.2 Mgal/d. Ground-water use is small compared to the quantity of surface water used, because current (1988) water demand can be supplied from surface-water sources.

Current water demand for public supply in the city of Springfield is approaching the quantity that can be dependably supplied from existing surface-water sources during droughts. Estimated use of surface water for public supply increased from 15.4 Mgal/d during 1974 to 19.4 Mgal/d during 1983 (Steinkamp, 1987, p. 53). During the same interval, ground-water pumpage for public supply increased from 1.3 Mgal/d to 2.4 Mgal/d. Projections of water supplies needed by 1990 have declined from 28.5 Mgal/d (Burns and McDonnell Engineering Co., Inc., 1971) to 24.7 Mgal/d (Steinkamp, 1987; U.S. Army Corps of Engineers, 1984). However, even the lower estimate is greater that the estimated dependable yield of surface-water supplies; surface-water supplies may need to be increased or supplemented in the future.

Because of concern for the adequacy of future water supplies a cooperative effort was begun between the U.S. Geological Survey and City Utilities of Springfield to analyze the ground-water resources of the Springfield area. A detailed analysis of the ground-water resources near Springfield is needed to develop a conceptual model of ground-water flow and to estimate probable changes in flow caused by changes in rates of ground-water withdrawal.

The study area (fig. 1) encompasses more area than the large area of influence of the cone of depression, because of the possibility of a cumulative drawdown effect from interaction between wells in the city and surrounding communities, and the requirements of a digital model used to simulate ground-water flow near Springfield. The study area is 42 by 42 mi (miles), 1,764 mi^2 (square miles), and includes parts of 10 counties. Greene and Christian counties are represented almost entirely. Smaller parts of Dade, Polk, Dallas, Webster, Douglas, Taney, Stone, and Lawrence Counties are included in the study area.

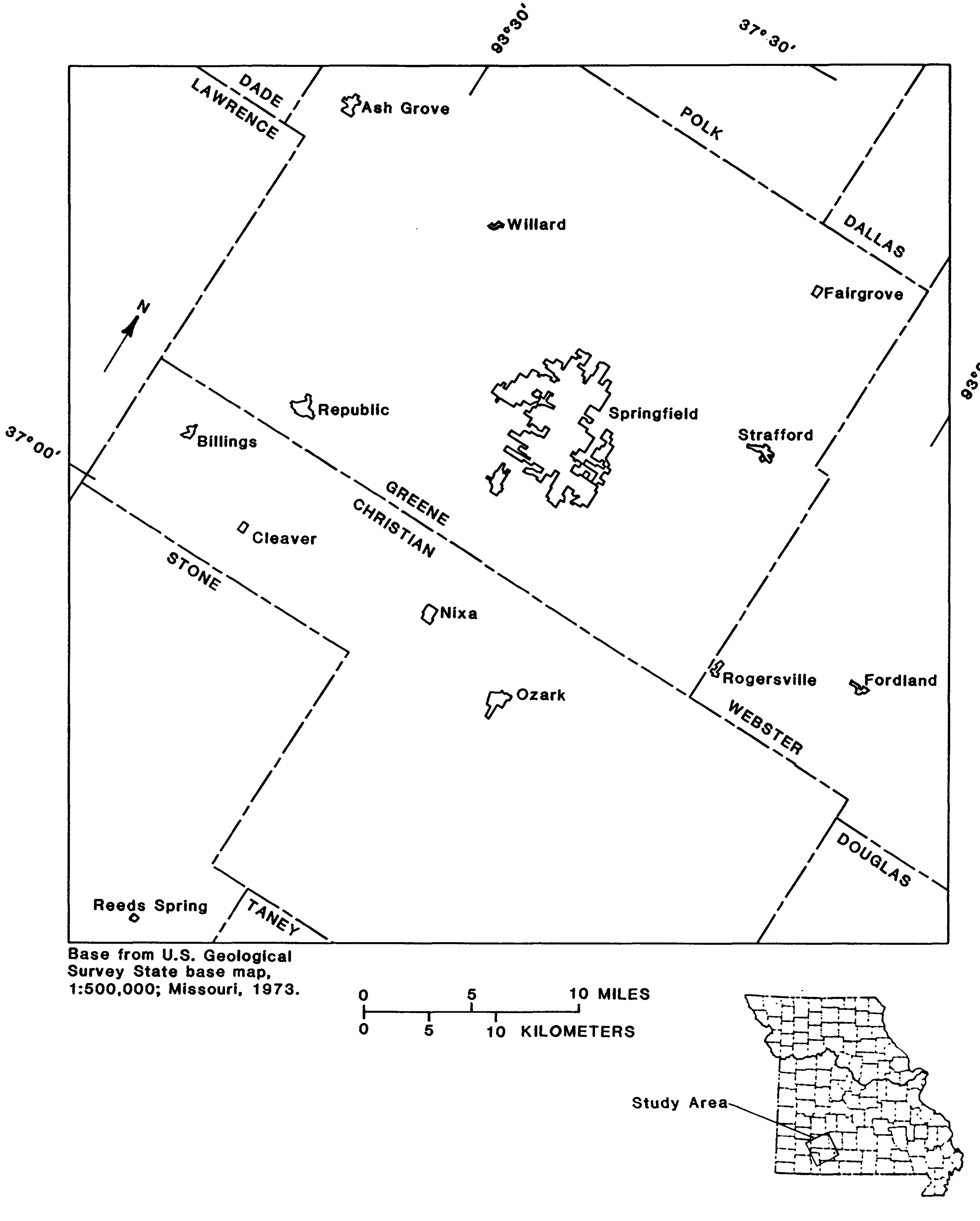


Figure 1.--Study area showing county boundaries and cities.

Purpose and Scope

This report describes the results of a study to qualitatively describe the ground-water flow system in the study area, to determine the magnitude of drawdown in the aquifers, and to assess the availability of future ground-water supplies and the effect of future development on the water levels in the aquifers. One goal of the study was to estimate the rate of ground-water leakage from the shallow aquifer, which is vulnerable to contamination, to the deep aquifer, which is the source of almost all ground-water supplies in the area. Part of the study included developing a three-dimensional digital model to simulate ground-water flow. The model was used to quantify the hydraulic properties of the aquifers and confining units and the hydrologic budget. The orientation and boundaries of the square study area were chosen to coincide with cell boundaries of a regional ground-water flow model of the Ozark Plateaus aquifer system (Imes and Emmett, in press). It was thought that the large study area would ensure that model boundaries would be sufficiently distant from areas affected by drawdown so that no time-dependent effects would be encountered at the boundaries. During this study it was noted that this condition, for the most part, was maintained. However, the size of the study area has proven to be minimal, as drawdown of water levels has occurred throughout most of the study area.

Acknowledgments

The author thanks Lise Scheuch and Roddy Rogers of City Utilities of Springfield for contributing substantial time and energy to this project. Many of the water-level measurements used to construct the current potentiometric map and pumpage data used to calibrate the ground-water flow model were available because of their field work. The author also thanks communities, industries, and residents in the study area that provided pumpage data and permitted access to their wells for water-level measurements, and the city of Springfield and the Missouri Department of Natural Resources for their assistance and access to their files.

TOPOGRAPHY AND DRAINAGE

Springfield is located near the eastern edge of the Springfield Plateau physiographic section (fig. 2; Fenneman, 1938). Mississippian cherty limestone forms the bedrock in most of this part of the Springfield Plateau, except where erosional remnants of Pennsylvanian sandstone and shale are present as elongated mounds that usually are less than 100 ft (feet) high. The plateau dips slightly to the west from the Eureka Springs Escarpment. The escarpment divides the Springfield Plateau from the Salem Plateau. Bedrock in the Salem Plateau predominately is Ordovician dolostone and sandstone. Land-surface altitude in the study area ranges from near 1,000 ft to more than 1,600 ft (fig. 3). The main drainage divide is formed by a topographic ridge that trends from east-central Greene County to western Christian County and passes through Springfield. Elevations along the broad ridge range from slightly less than 1,300 ft to slightly more than 1,500 ft and are about 1,300 to 1,350 ft in Springfield. Because existing topographic maps were either too detailed (1:100,000 scale) or too general (1:500,000 scale) for use in this study, the topographic map used and shown as fig. 3 was developed by contouring land-surface elevations of water wells.

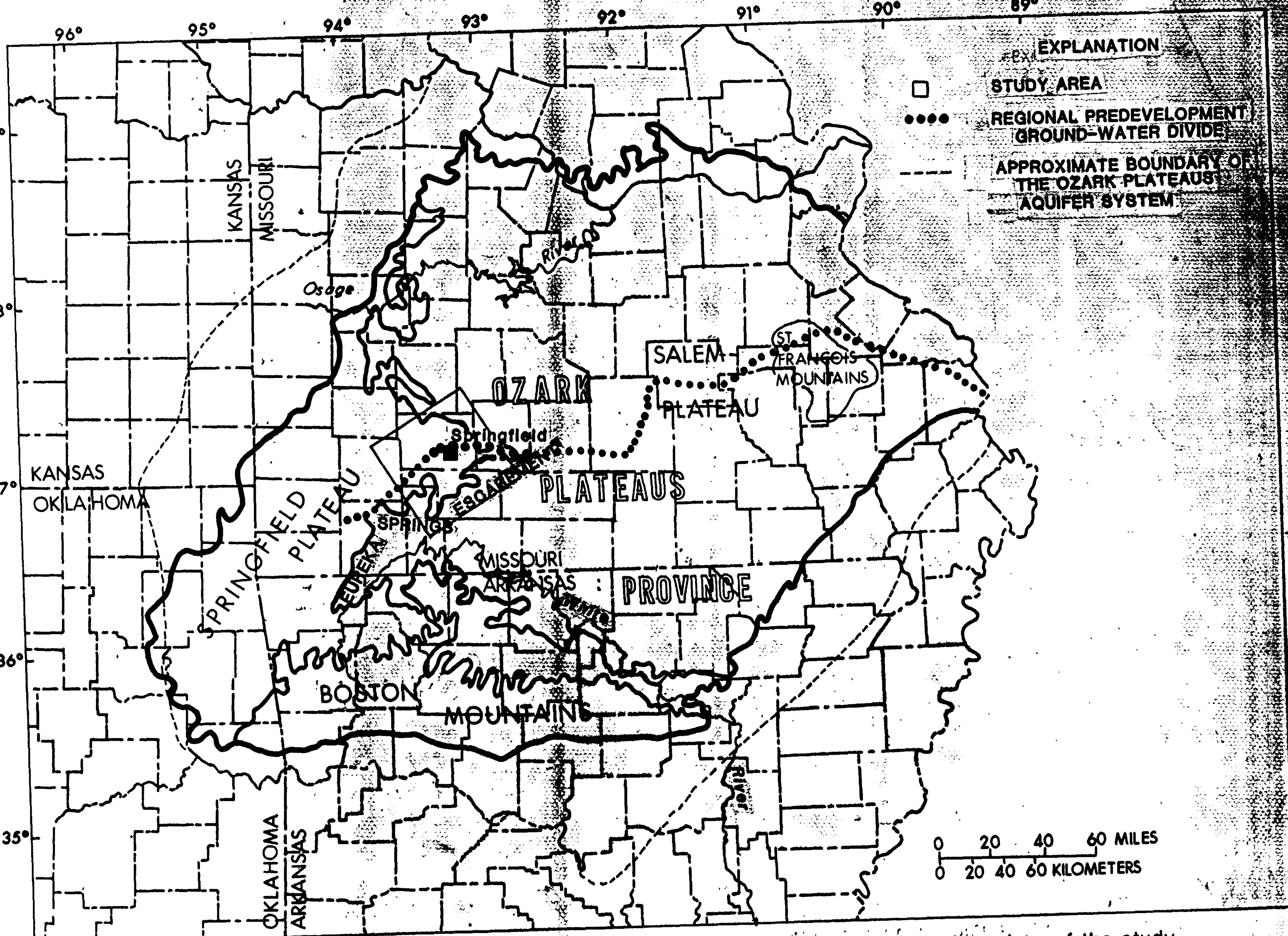
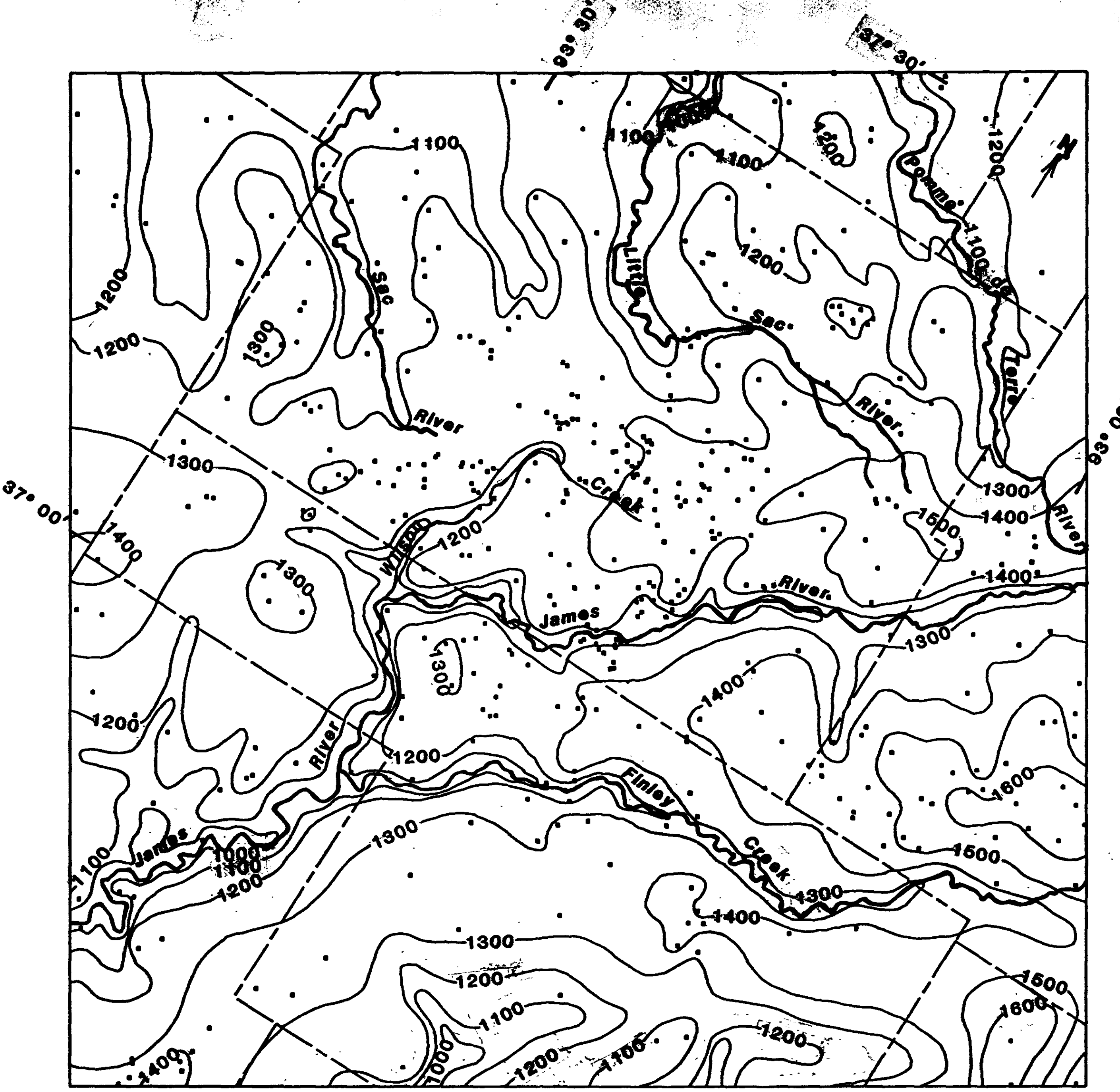


Figure 2.--Approximate boundary of the Ozark Plateaus aquifer system and boundary of the study area (physiography from Fenneman, 1938).



Base from U.S. Geological Survey State base map, 1:500,000; Missouri, 1973.

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

-1300- TOPOGRAPHIC CONTOUR--Shows altitude of land surface. Contour interval is 100 feet. Datum is sea level.

• CONTROL POINT

Figure 3.--Altitude of land surface.

Streams in the study area generally follow courses that trend northwest or southwest (fig. 4). A series of near parallel streams (Turnback Creek, the Sac River, Clear Creek, the Little Sac River, and the Pomme de Terre River) begin in the upland area along the main surface water divide and flow northwest out of the study area. Two major streams (the James River and Finley Creek) have their headwaters near the Eureka Springs Escarpment east of Springfield and flow west and southwest. Two of the larger tributaries of the James River are Crane Creek and Wilson Creek. The headwaters of Wilson Creek are within Springfield. The area south of the James River and Finley Creek is drained by Bull Creek and Swan Creek. Three large lakes are in the study area. McDaniel Lake and Fellows Lake are impoundments on the Little Sac River north of Springfield. The third, Lake Springfield, is on the James River south of Springfield.

The slightly rolling hills of the Springfield Plateau contain numerous sinkholes, especially northwest and south of Springfield, (Thomson, 1986a) that transport surface water to an extensive karst terrane that has evolved in the upper part of the surficial aquifer. One consequence of rapid flow through the solution enlarged joints and fractures is the convergence of ground water into the larger channels and emergence of the water as springs where the channels intersect land surface. The springs were a valuable source of drinking water and were a refrigerant for early settlers of the area. Even today, Fulbright Spring (fig. 4) is a source of public-water supply for Springfield.

GEOHYDROLOGY

Geohydrologic units in the study area previously were identified and mapped as part of a regional study of the Ozark Plateaus aquifer system (Imes and Emmett, in press). The units were defined on the basis of regional geohydrologic properties. The lateral and vertical hydraulic conductivity of each unit may vary considerably from one location to another within the boundaries of the aquifer system. Seven units are present in the Springfield area (figs. 5 and 6). From the stratigraphically youngest to oldest, the units are (1) the Western Interior Plains confining system, (2) the Springfield Plateau aquifer, (3) the Ozark confining unit, (4) the Ozark aquifer, (5) the St. Francois confining unit, (6) the St. Francois aquifer, and (7) the Basement confining unit. The sequence of geohydrologic units from the Springfield Plateau aquifer to the St. Francois aquifer comprise the Ozark Plateaus aquifer system. The relation between geohydrologic units and stratigraphic units within the study area and the water-bearing properties of each geohydrologic unit are summarized in table 1. The Western Interior Plains confining system is present only as isolated channel-sand deposits too permeable and too small to form an effective barrier to the percolation of water from land surface to the underlying Springfield Plateau aquifer. The Springfield Plateau aquifer, Ozark confining unit, and Ozark aquifer are most important to this study. The St. Francois confining unit separates the Ozark aquifer from the deeper St. Francois aquifer. The top of the St. Francois aquifer, the lowermost aquifer in the Ozark Plateaus aquifer system, is about 1,900 ft below Springfield. Because of the depth of the St. Francois aquifer and because adequate quantities of ground water for municipal and industrial supply exist in the overlying Ozark aquifer, water-supply wells in the study area are not open to the St. Francois aquifer. One conclusion of an Packer-test analysis of yield in an observation well at the Southwest Power Plant (fig. 6) location was that geologic formations below the Potosi Dolomite (St. Francois confining unit and St. Francois aquifer) are not productive (Layne-Western Company, 1972).

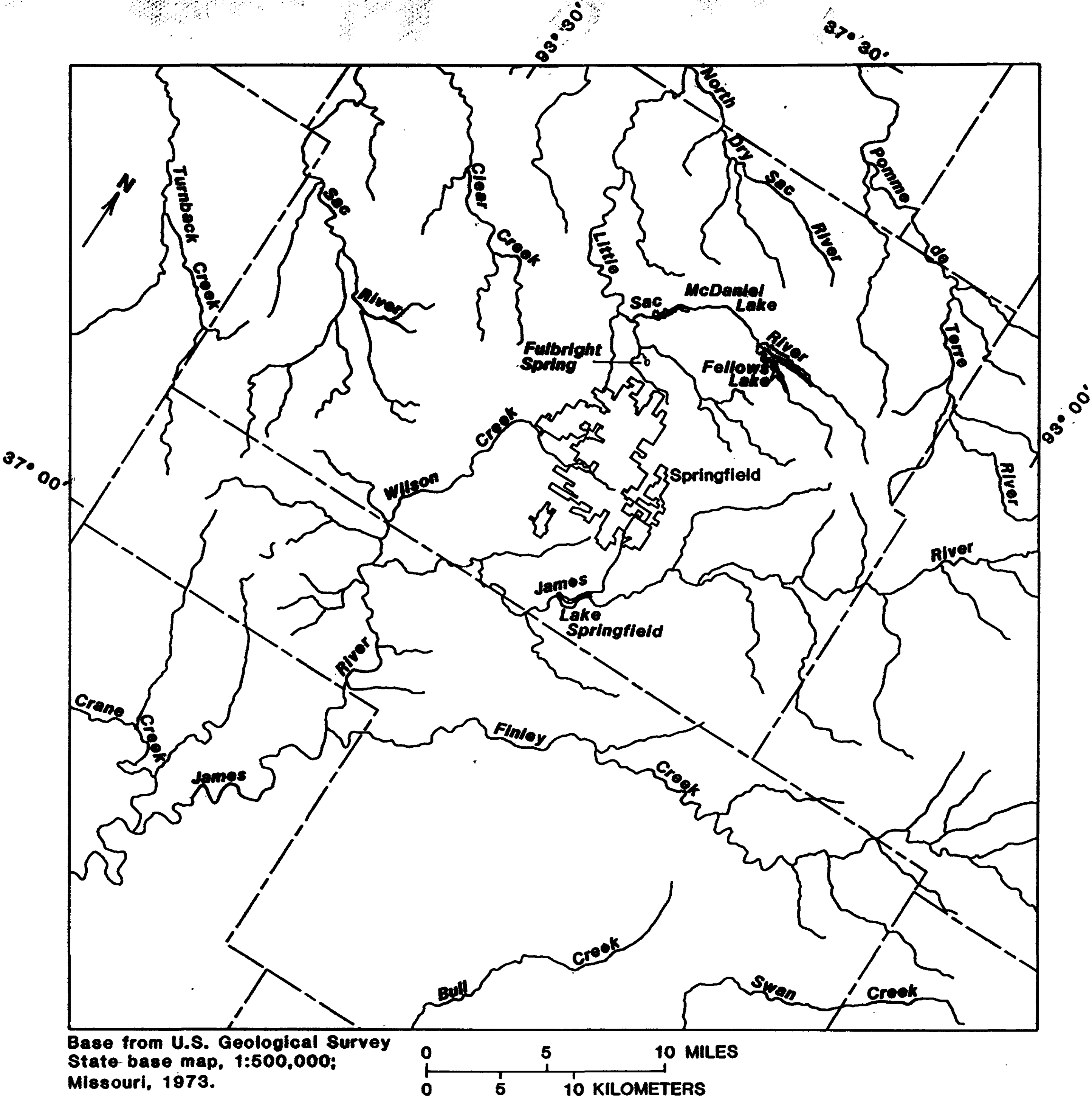


Figure 4.--Surface drainage of the Springfield area.

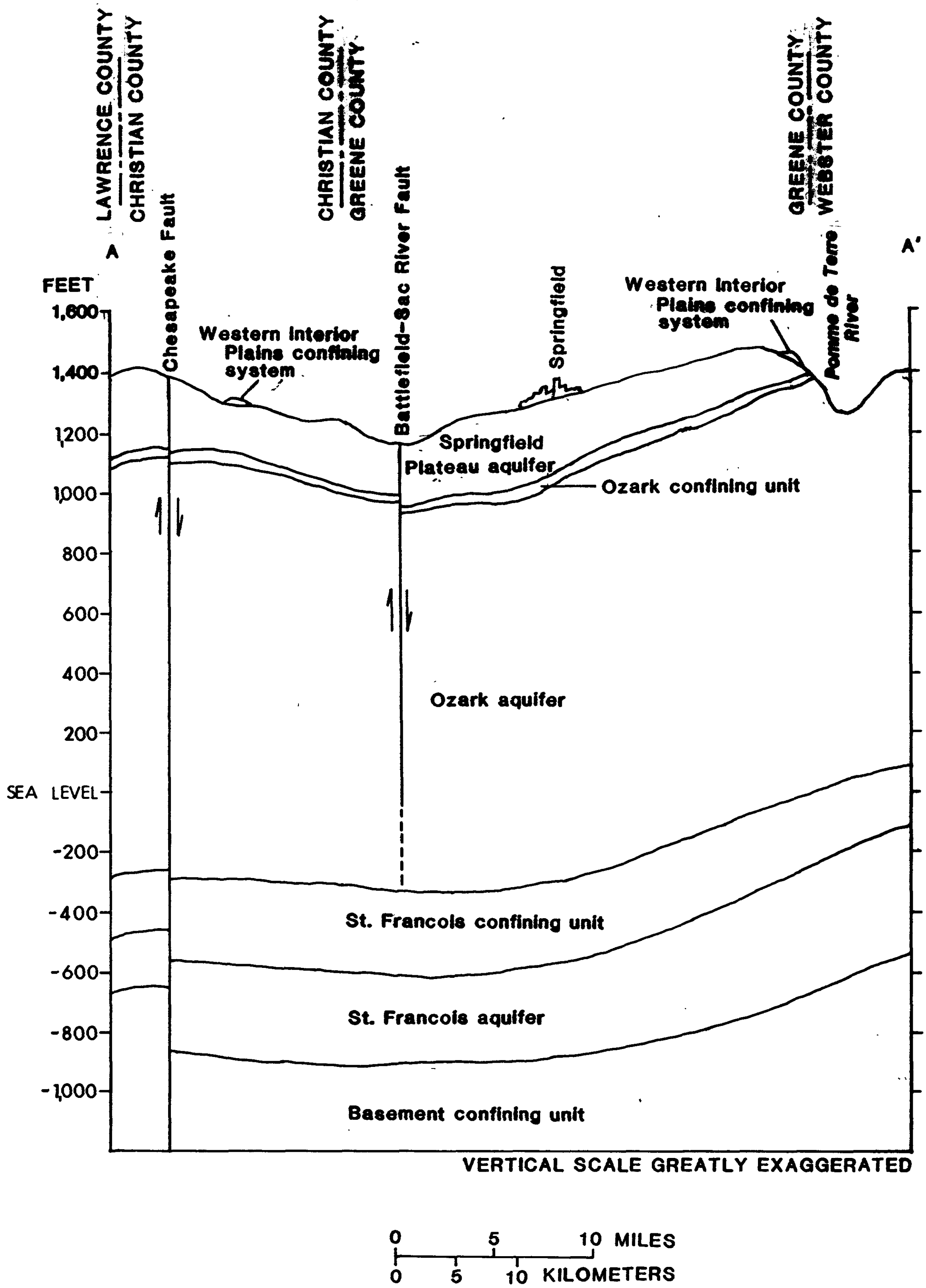
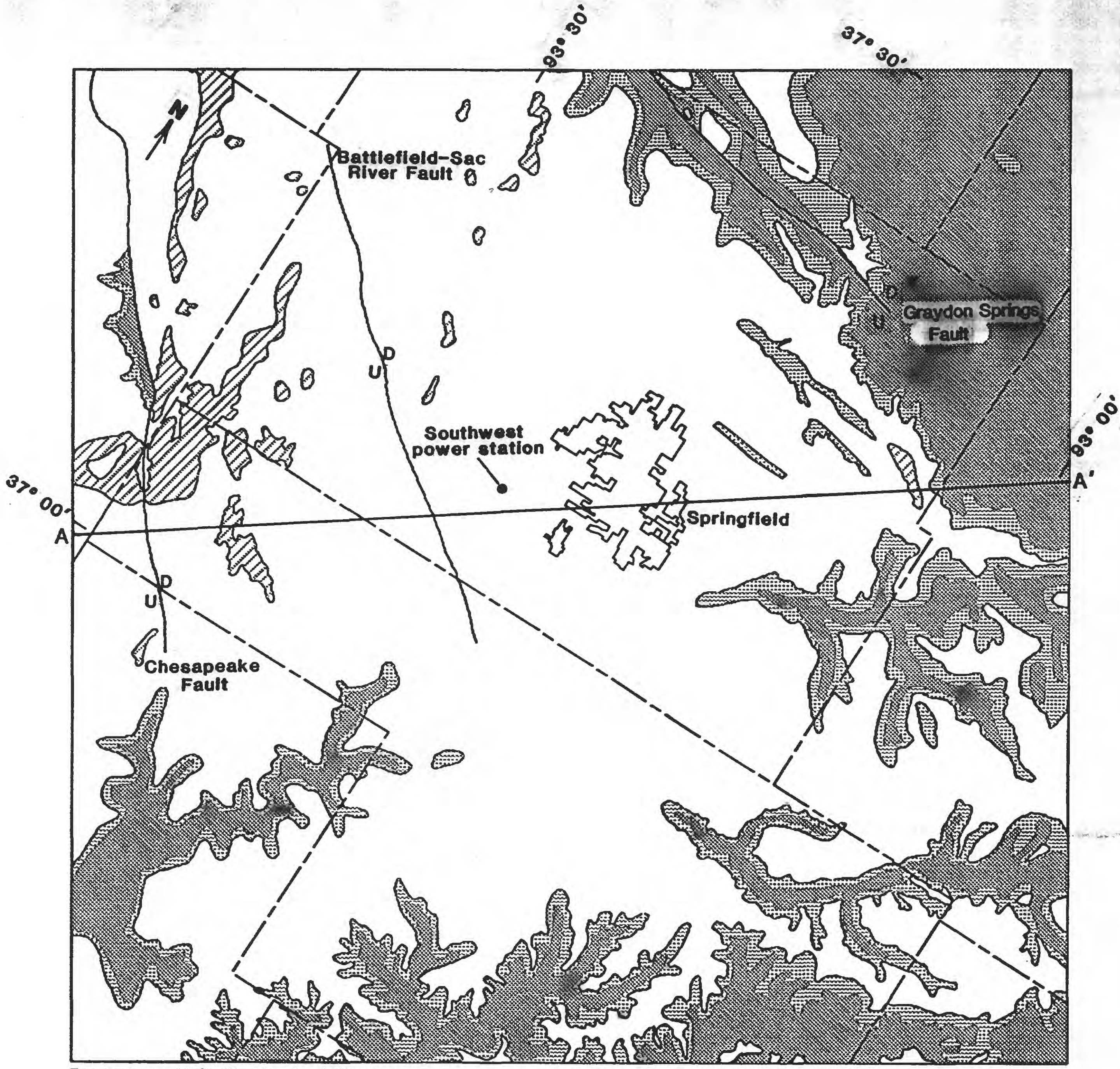


Figure 5.--Regional geohydrologic units near Springfield (trace of section in figure 6).



Base from U.S. Geological Survey
State base map, 1:500,000;
Missouri, 1973.

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

- OUTCROP AREA OF THE WESTERN INTERIOR PLAINS CONFINING SYSTEM
- OUTCROP AREA OF THE SPRINGFIELD PLATEAU AQUIFER
- OUTCROP AREA OF THE OZARK CONFINING UNIT
- OUTCROP AREA OF THE OZARK AQUIFER
- A—A' TRACE OF GEOHYDROLOGIC SECTION (shown on figure 5)
- U/D FAULT--U, upthrown side; D, downthrown side

Figure 6.--Outcrop areas of regional geohydrologic units.

Table 1.--Correlation of geohydrologic units and stratigraphic units in the Springfield area

Geohydrologic Unit	Stratigraphic Unit	Lithology	Water-bearing Properties
Western Interior Plains confining system	Pennsylvanian channel-sand deposits	Sand and clay	Hydraulic properties are unknown. Presumably, most of these localized, thin deposits are unsaturated.
Springfield Plateau aquifer	St. Louis Limestone Salem Limestone Warsaw Limestone Keokuk Limestone Burlington Limestone Elsey Formation Reeds Spring Formation Pierson Formation	Limestone and chert	Aquifer with karst zone in upper part. Yield to wells usually is less than 20 gallons per minute.. Adequate for domestic and stock use only. Contamination potential large because of extensive network of solution enlarged joints and fractures in karst terrane.
Ozark confining unit	Northview Shale Sedalia Limestone Compton Limestone Chattanooga Shale	Shale, silt, and limestone	Confining unit with confining material primarily in the Northview Shale.
Ozark aquifer	Smithville Formation Cotter Dolomite Jefferson City Formation Roubidoux Formation Gasconade Dolomite Gunter Sandstone Member Eminence Dolomite Potosi Dolomite	Dolostone and sandstone	Productive aquifer yielding about 1,000 gallons per minute to wells open to the entire sequence of rock units. Upper part of aquifer generally is less productive. Most productive rock units are the Roubidoux Formation, Gunter Sandstone Member of the Gasconade Dolomite, and the Potosi Dolomite.
St. Francois confining unit	Doe Run Dolomite Derby Dolomite Davis Formation	Dolostone, silt, and shale	Confining unit with confining material primarily in the Davis Formation, which contains the larger fraction of shale.
St. Francois aquifer	Bonneterre Dolomite Reagan Sandstone Lamotte Sandstone	Dolostone and sandstone	Insignificant as a source of water supply in the Springfield area because of small yield and large depth of aquifer.
Basement confining unit	Precambrian igneous and metamorphic rocks	Igneous and metamorphic rocks	Insignificant as a source of water.

Four geohydrologic units are exposed in the Springfield area (fig. 6). The Springfield Plateau aquifer is exposed over most of the study area. The aquifer is covered by scattered areas of Pennsylvanian channel-sand deposits of the Western Interior Plains confining system in the western part of the study area. The Ozark aquifer is exposed near the northeastern, southeastern, and southern boundaries of the study area, and generally is separated from the Springfield Plateau aquifer by relatively narrow exposures of the Ozark confining unit. The convoluted outline of many of the outcrop areas results from erosion and entrenchment of streams. Springfield is situated entirely on the Springfield Plateau aquifer (fig. 6). Because the Western Interior Plains confining system is localized and not hydrologically significant at the scale of this study, no additional information about the unit is given herein.

Springfield Plateau Aquifer

The Springfield Plateau aquifer is a sequence of permeable, partially saturated rocks of Mississippian age. Geologic formations that comprise this aquifer are limestone and cherty limestone rock units from the stratigraphically highest St. Louis Limestone to the stratigraphically lowest Pierson Formation (table 1). The Keokuk Limestone and Burlington Limestone are the two most permeable rock units in the aquifer and, where saturated, probably are capable of yielding larger quantities of water to wells than other rocks in the aquifer. The hydraulic conductivity of the aquifer within this study area, estimated from a previously calibrated steady-state model of regional ground-water flow in the Ozark Plateaus aquifer system (Imes and Emmett, in press), is 2.5×10^{-4} ft/s (feet per second). The corresponding transmissivity of the aquifer within the study area ranges from about 1.0×10^{-2} ft^2/s to about 5.0×10^{-2} ft^2/s. No attempt was made during calibration of the regional model to adjust the value of transmissivity of the aquifer to account for the unsaturated part of the aquifer; however, results of this study indicate that a significant thickness of the aquifer is unsaturated. Water wells open only to the Springfield Plateau aquifer yield insufficient water for any use except domestic and stock supply. Most new domestic wells are drilled into the deeper Ozark aquifer to ensure adequate quantities of water and less opportunity for well contamination. This is especially true of wells in the eastern part of the study area where the aquifer is thinner.

The top of the Springfield Plateau aquifer is coincident with land surface (fig. 3) throughout most of the study area except where the Western Interior Plains confining system exists. The higher altitude of the top of the aquifer (about 1,300 ft) occurs along the topographic ridge that trends nearly east and west through Springfield. The altitude generally decreases to the north and south of the ridge because of erosion and entrenchment of streams. The near-surface rocks of the aquifer contain numerous channels created by the dissolution of carbonate rock along the faces of joints, fractures, and bedding planes. The dissolution occurs as infiltrating precipitation, rich in carbon dioxide from the soil zone, percolates through the unsaturated zone to the water table. Many of the larger channels are cavernous and much of the area contains a large number of sinkholes caused by the collapse of dissolution-enlarged joints and subsurface caverns because of the inability of the weakened rock matrix to support the weight of overburden. Sinkhole density in the study area exceeds 10 sinkholes per 100 mi^2 (Harvey, 1980; Thomson, 1986a).

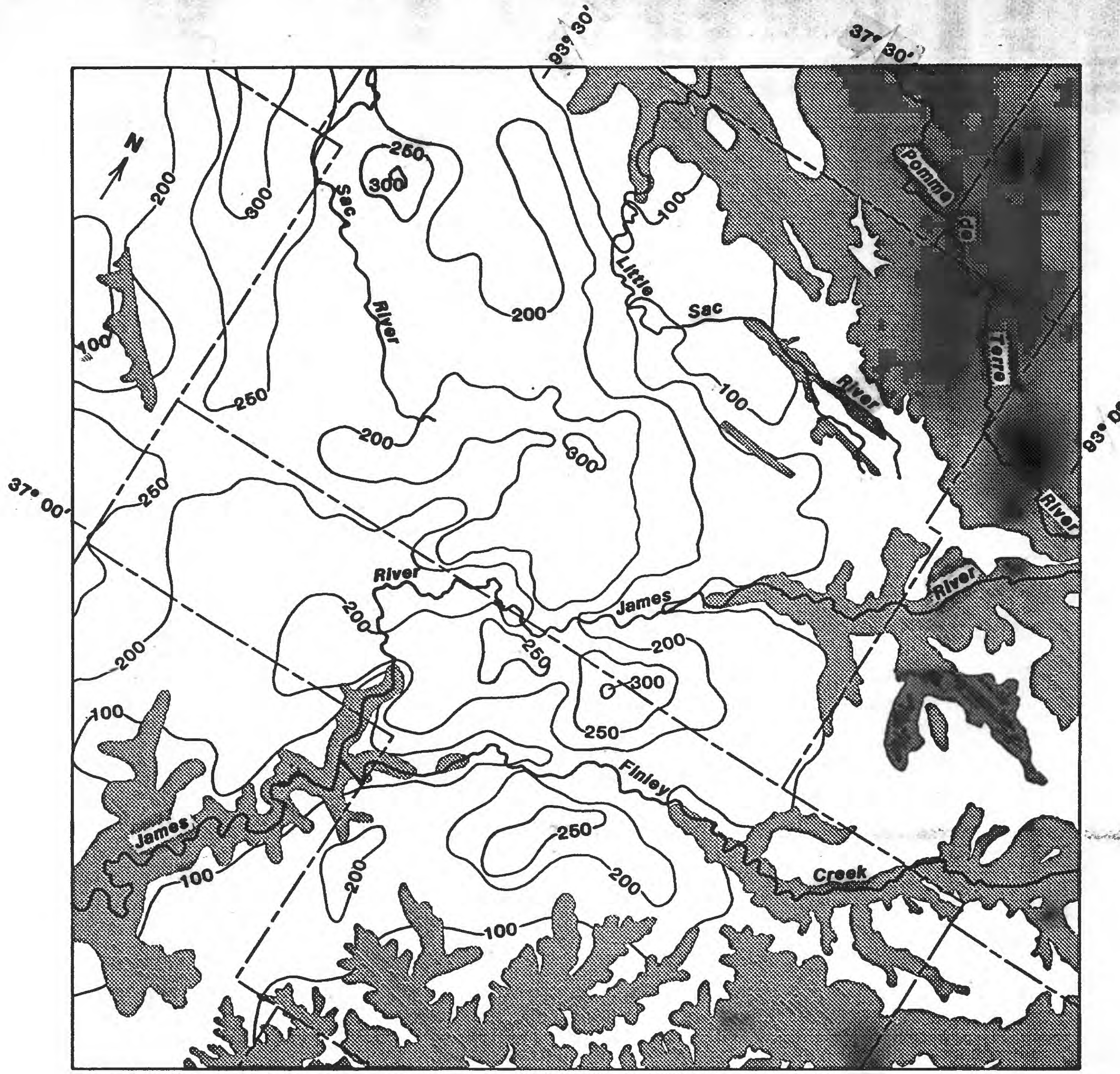
The thickness of the aquifer ranges from near zero to more than 300 ft in the study area (fig. 7). The area of largest thickness is in southern Greene County. Generally, the unit thickens to the west. Near Springfield the aquifer ranges from about 100 to more that 300 ft thick. Most of the abrupt variations in thickness can be attributed to the irregularity of land surface.

Water-level measurements for the Springfield Plateau aquifer are sparse. More historical water level measurements are available than recent water-level measurements. Many older, shallow wells have been destroyed or are difficult to locate; improved drilling methods and uncertainty about the quality of water in the aquifer has encouraged drilling new wells deeper and excluding water from the Springfield Plateau aquifer. Prior to ground-water development, water levels in the aquifer reflected the influence of local topography (fig. 8). The water table was about 100 ft below land surface beneath recharge areas of higher elevation and is at land surface in the larger valleys where ground water discharges to streams. Generally, ground water flows from areas of higher water-table altitude in eastern Greene County and southwestern Webster County toward the northwest to primarily discharge into the Sac and Little Sac Rivers and toward the southwest to discharge into the James River, Wilson Creek, and Finley Creek. Ground water also flows from a water-table mound in southwestern Greene County and the panhandle of Christian County eastward and southeastward to Wilson Creek and the James River. Smaller quantities of water flow from a ground-water divide that trends southwestward across central Christian County and discharges into the James River to the northwest or into Bull Creek to the southeast.

Because the surficial aquifer generally is less than about 300 ft thick and the depth to water in many areas may exceed 100 ft, the Springfield Plateau aquifer is partly unsaturated in all areas except the larger valleys that contain perennial streams. The aquifer is completely unsaturated in several areas near the eastern and southern margins where the water table is lower than the bottom of the aquifer. The saturated thickness of the aquifer (fig. 9), assuming predevelopment water table conditions as shown in figure 8, ranges from near zero to about 250 ft. Areas shown to be totally unsaturated in figure 9 may contain lenses of perched water above the Ozark confining unit and less permeable beds within the Springfield Plateau aquifer. In some areas, the volume of perched water may be adequate to supply domestic wells.

Ozark Confining Unit

The Ozark confining unit, the geohydrologic unit that separates and impedes the flow of ground water between the Springfield Plateau aquifer and Ozark aquifer, primarily is composed of limestone, silt, and shale of the Kinderhookian Series of Mississippian age (Northview Shale, Sedalia Limestone, and Compton Limestone) within the study area (table 1). Smaller thicknesses of Devonian Chattanooga Shale are present locally. The uppermost geologic formation in the confining unit is the Northview Shale. The Northview Shale usually is the thickest formation of the confining unit and contains substantial quantities of shale and silt. Other formations in the unit are either limestone and dolostone with little shale or silt content and are more permeable than the Northview Shale, or are shale formations that are too thin or too localized to form an effective barrier to the regional movement of ground water. Thus, of the several geologic formations in the Ozark confining unit, the Northview Shale is the most effective in impeding the flow of water between the aquifers. The estimated vertical hydraulic conductivity of the confining unit from the steady-state model of regional ground-water flow in the Ozark Plateaus aquifer system ranges from 1.0×10^{-8} to 5.0×10^{-8} ft/s (Imes and Emmett, in press).



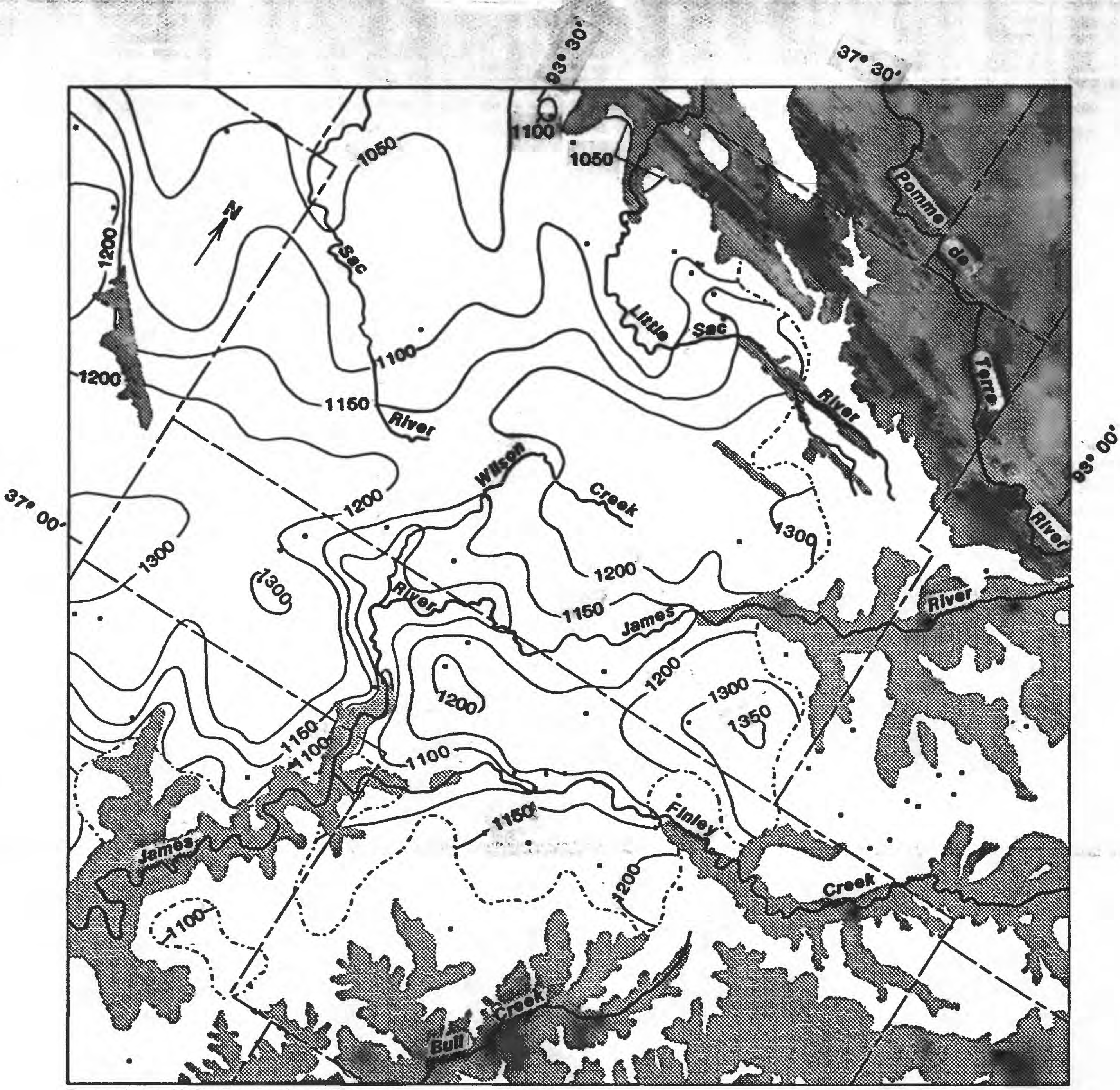
Base from U.S. Geological Survey
State base map, 1:500,000;
Missouri, 1973.

0 5 10 MILES
0 5 10 KILOMETERS

COMBINED OUTCROP AREA OF THE OZARK AQUIFER AND OZARK CONFINING UNIT

–100– LINE OF EQUAL THICKNESS--Interval, in feet, is variable.

Figure 7.--Thickness of the Springfield Plateau aquifer.



Base from U.S. Geological Survey
State base map, 1:500,000;
Missouri, 1973.

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

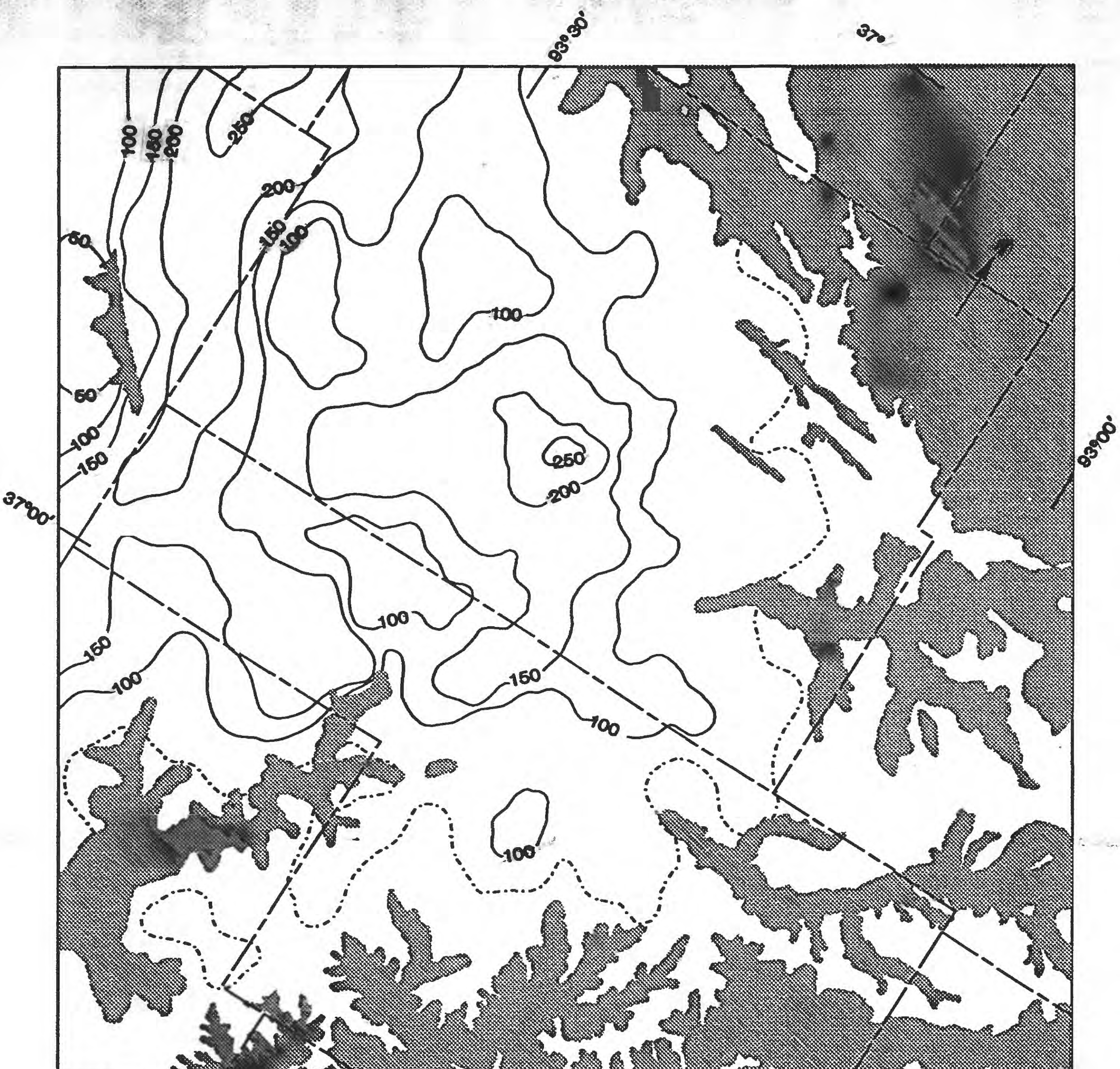
COMBINED OUTCROP AREA OF THE OZARK AQUIFER AND OZARK CONFINING UNIT

—1000— WATER TABLE CONTOUR—Shows altitude of water table. Contour interval, in feet, is variable. Datum is sea level.

—·—·— LIMIT OF SATURATED AREA

• CONTROL POINT

Figure 8.--Water table in the Springfield Plateau aquifer prior to development.



Base from U.S Geological Survey
State base map, 1:500,000;
Missouri, 1973.

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

COMBINED OUTCROP AREA OF THE OZARK AQUIFER AND OZARK CONFINING UNIT

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

-·-·-·-· LIMIT OF SATURATED AREA

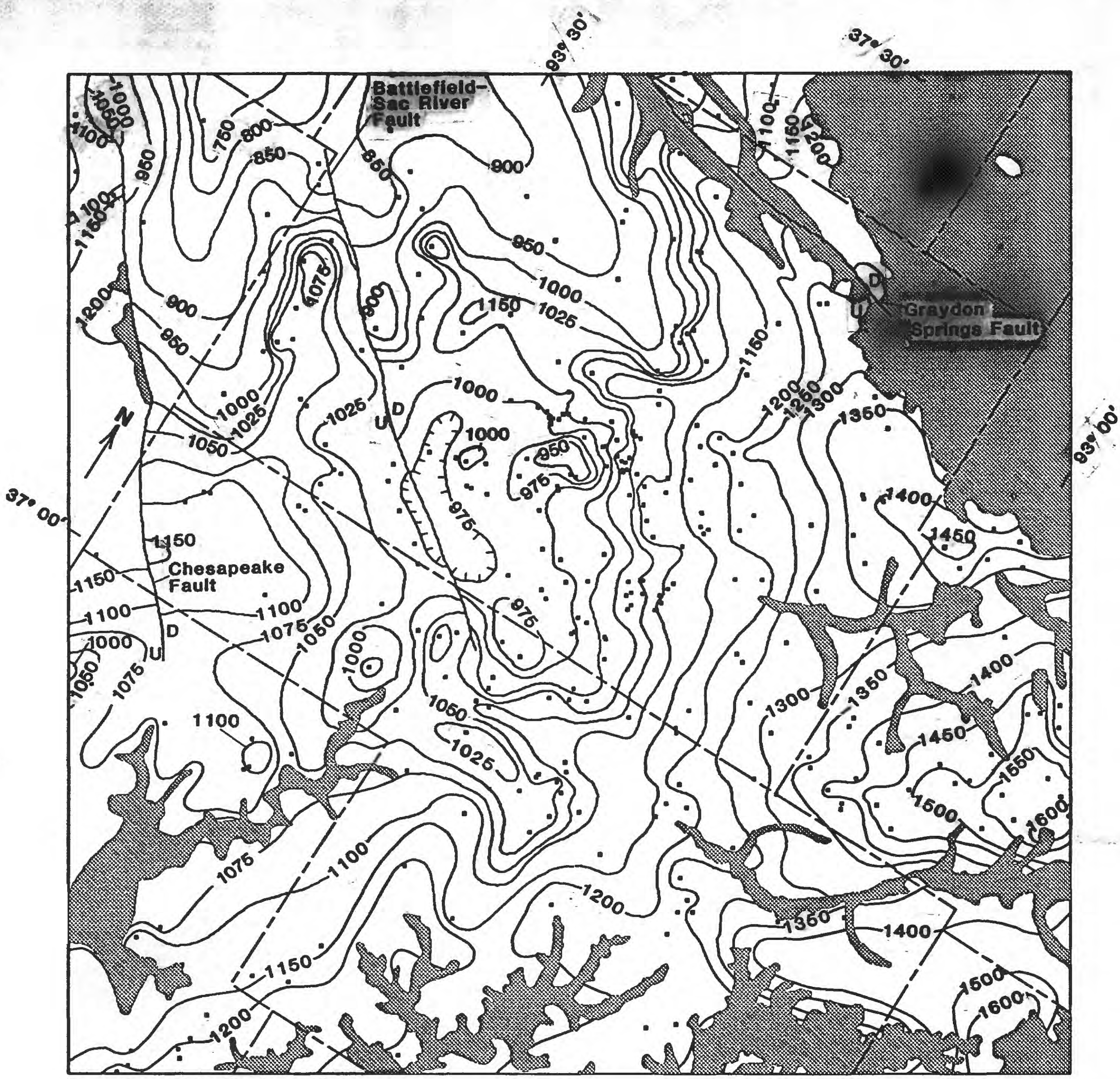
Figure 9.--Saturated thickness of the Springfield Plateau aquifer.

Regionally, the top of the Ozark confining unit forms a shallow syncline that dips to the northwest (fig. 10). The axis of the syncline is nearly coincident with the Battlefield-Sac River Fault. The area of higher altitude is in southwestern Webster County. The altitude of the top slopes away from this area and is lowest near the extreme southeastern corner of Dade County. Many smaller variations of altitude, both areally and in magnitude of relief, are superimposed on the regional dip. Three large faults pass through the confining unit. The Chesapeake Fault trends through western Christian County and northeastern Lawrence County. The offset of the top of the confining unit is nearly zero ft at the southern end of the fault and increases to about 125 ft at the northernmost location of the fault within the study area. The Battlefield-Sac River Fault in southwestern Greene County separates the top of the unit by as much as 100 ft along the northern one-third of the fault to near zero ft at the ends of the fault. The Graydon Springs Fault in northern Greene County is in an area of convoluted geohydrologic-unit contacts and itself forms some of the contacts. Other faults are present in the study area (Thomson, 1986a, b) and some of them undoubtedly intersect the Ozark confining unit. Only those faults whose presence are clearly indicated by the lithologic log data used to define the configuration of the top of the confining unit are shown in figure 10.

The Ozark confining unit is more than 90 ft thick in southern Polk County and generally decreases in thickness to the southeast along the edge of the contact that defines the northeastern limit of the confining unit (fig. 11). The unit is about 20 to 40 ft thick in southwestern Webster County. The thickness of the unit generally decreases to the west and is about 20 to 30 ft thick along the western edge of the study area. Beneath Springfield, the thickness of the unit ranges from about 20 to about 70 ft. Variations in the thickness of the Northview Shale (fig. 12) are distributed in a similar pattern to variations in thickness of the Ozark confining unit. The Northview Shale comprises about 50 to 100 percent of the thickness of the Ozark confining unit, the larger percentages occurring in the northern part of the study area. Beneath Springfield the thickness of the Northview Shale ranges from less than 10 to about 40 ft.

Ozark Aquifer

The Ozark aquifer is much thicker than the Springfield Plateau aquifer and is composed of rocks of several Cambrian and Ordovician geologic formations of varying permeability. The Ozark aquifer can be divided into five distinct zones (Imes and Emmett, in press) based on lithologic differences and degrees of secondary permeability development. The lowermost zone, the only zone represented in the Springfield area, contains geologic formations between the top of the Smithville Formation and the base of the Potosi Dolomite (table 1), and includes the most permeable and porous rocks in the Ozark aquifer. The predominant lithologies of rocks that form the aquifer are dolostone and sandstone. Formations within the Ozark aquifer that may yield large quantities of water to wells are the Roubidoux Formation, Gunter Sandstone Member of the Gasconade Dolomite, and the Potosi Dolomite. Water wells open to the entire thickness of the Ozark aquifer generally yield more than 1,000 gallons per minute, sufficient water to supply municipal and industrial needs.



Base from U.S. Geological Survey State base map, 1:500,000; Missouri, 1973.

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

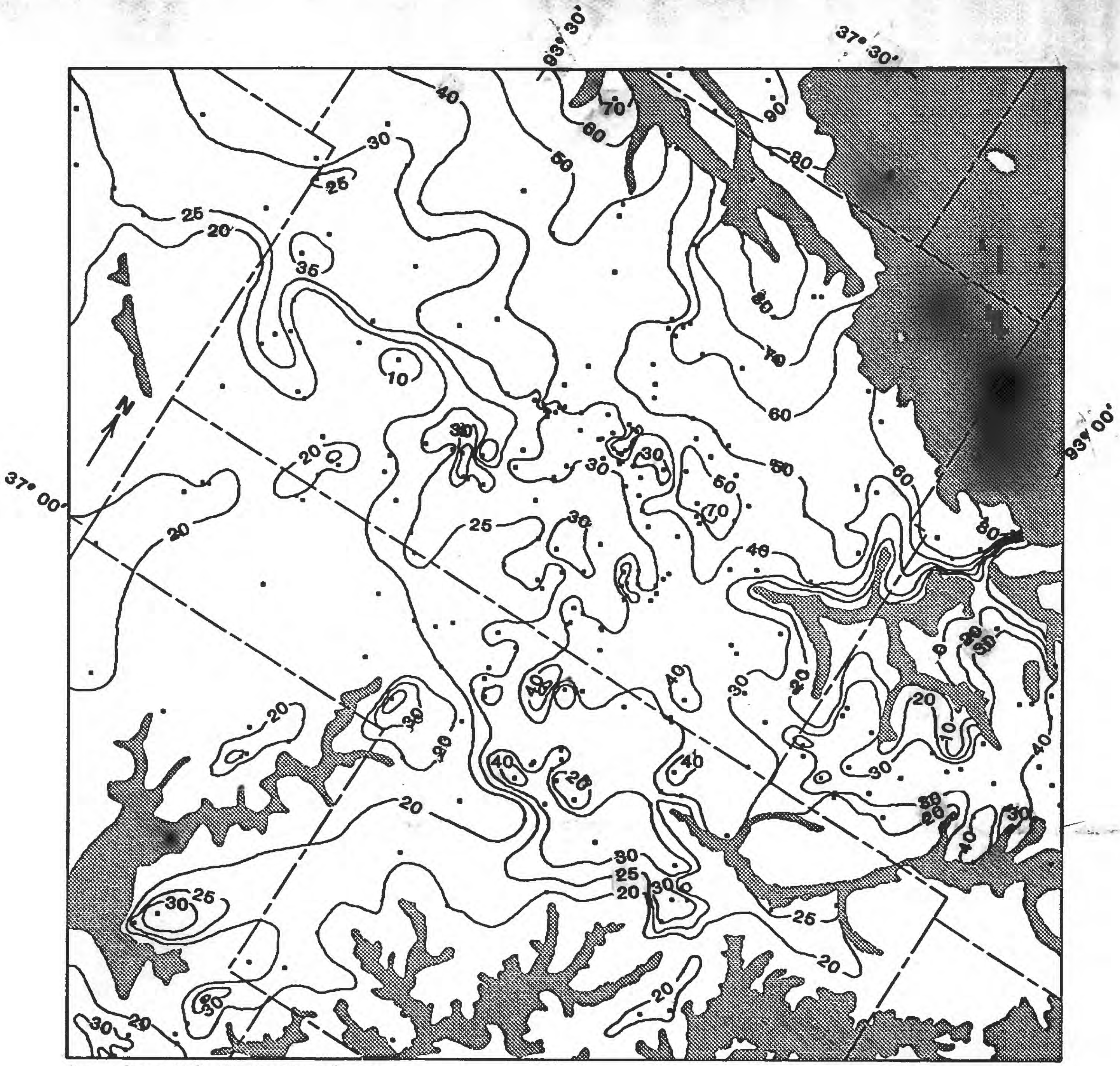
OUTCROP AREA OF THE OZARK AQUIFER

-1000- TOP OF OZARK CONFINING UNIT.--Shows altitude of top of Ozark confining unit. Interval, in feet, is variable. Datum is sea level.

U/D FAULT--U, upthrown side, D, downthrown side

• CONTROL POINT

Figure 10.--Configuration of the top of the Ozark confining unit.



Base from U.S. Geological Survey
State base map, 1:500,000;
Missouri, 1973.

0 5 10 MILES

0 5 10 KILOMETERS

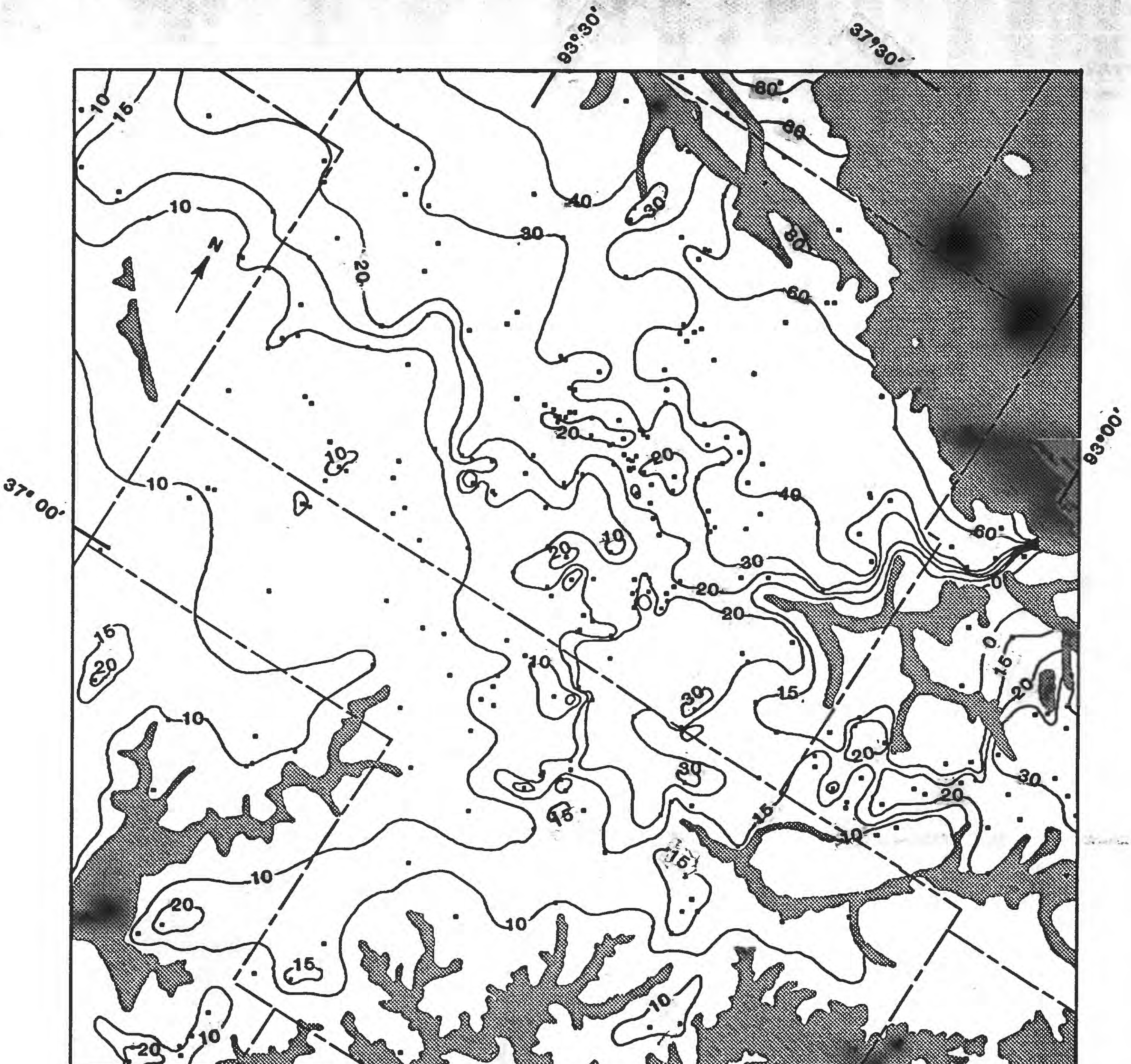
EXPLANATION

OUTCROP AREA OF THE OZARK AQUIFER

-20- LINE OF EQUAL THICKNESS--Interval, in feet, is variable.

• CONTROL POINT

Figure 11.--Thickness of the Ozark confining unit.



Base from U.S. Geological Survey State base map, 1:500,000; Missouri, 1973.

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

OUTCROP AREA OF THE OZARK AQUIFER

—10— LINE OF EQUAL THICKNESS--Interval, in feet, is variable.

• CONTROL POINT

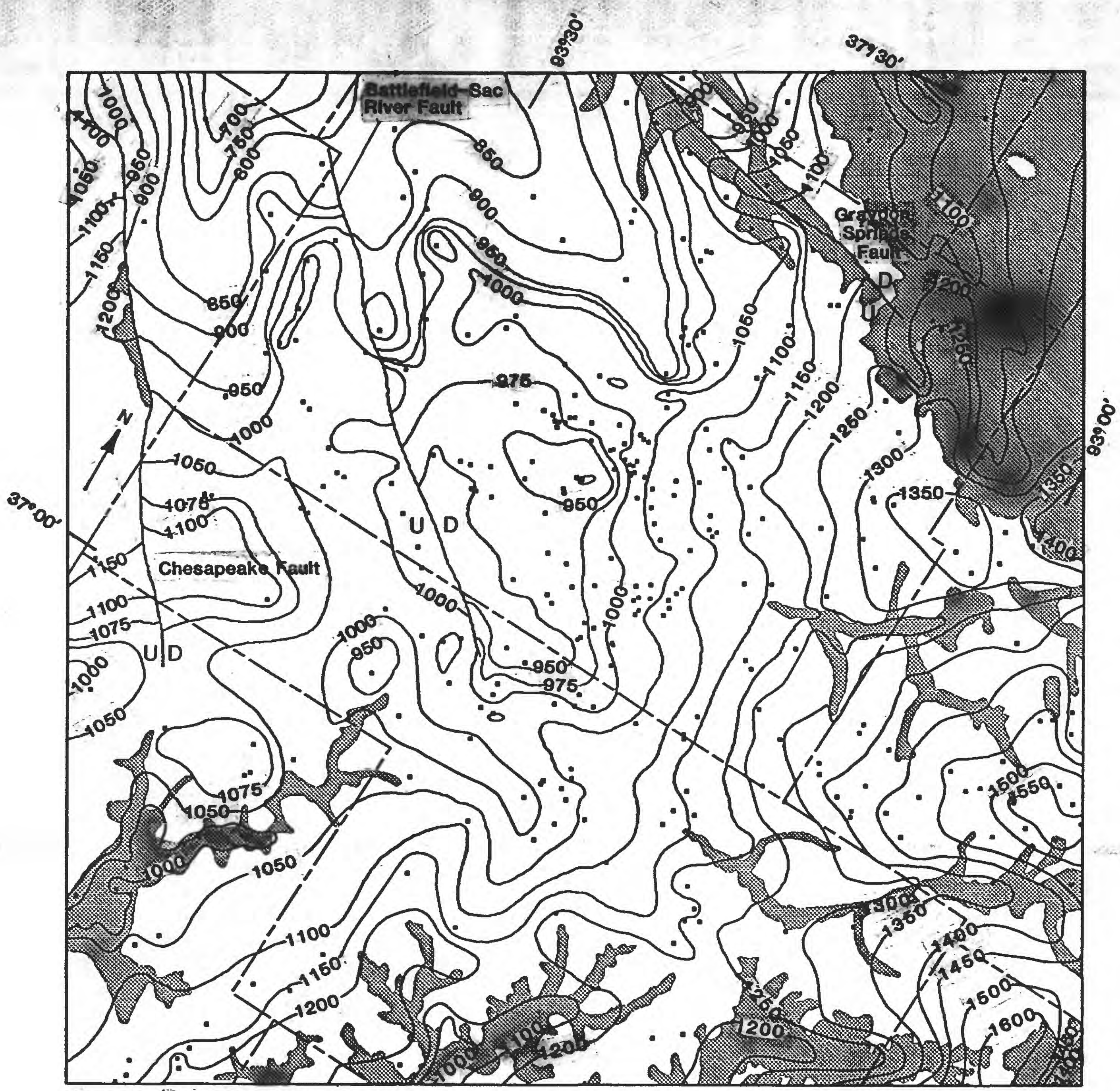
Figure 12.--Thickness of the Northview Shale.

The lateral hydraulic conductivity of the Ozark aquifer derived from the steady-state regional ground-water flow model for the part of the Ozark Plateaus aquifer system within this study area ranges from about 8.0 x 10^{-5} to about 1.3 x 10^{-4} ft/s (Imes and Emmett, in press). The corresponding range of aquifer transmissivity is from about 1.0 x 10^{-1} ft^2/s to about 1.7 x 10^{-1} ft/s. Emmett and others (1978, p. 30) report an apparent transmissivity of 4.6 x 10^{-2} ft^2/s for the Ozark aquifer based on two short-term aquifer tests. However, the authors indicate that their tests do not appear to yield estimates of regional transmissivity, but only anomalously large local values of transmissivity. The authors subsequently used a closed-contour method (Emmett and others, 1978, p. 112) to determine a regional transmissivity of 7.74 x 10^{-3} ft^2/s.

The Ozark aquifer is exposed near the northern, eastern, and southern boundaries of the study area (fig. 6). Most of the narrow, elongated outcrop areas are the result of erosion of overlying geohydrologic units by streams and subsequent exposure of the Ozark aquifer. Although some karst features, such as caves and sinkholes, are present in the Ozark aquifer, karst terrane is not nearly as well developed in the Ozark aquifer as it is in the Springfield Plateau aquifer. The altitude of the top of the aquifer in the outcrop areas ranges from near 1,000 ft in the James River valley of northeastern Stone County to more than 1,600 ft in southwestern Webster County (fig. 13). The top of the aquifer surface slopes to the west from the high in southwestern Webster County to less than 950 ft in a small depression or basin along the northeastern edge of the Battlefield-Sac River Fault southwest of Springfield. Similarly, the surface of the top of the aquifer slopes from a higher area at the western edge of Christian County eastward to the basin and northwestward to less than 700 ft at the boundary of the study area.

The Ozark aquifer is thickest (about 1,450 ft) in east-central Greene County northeast of Springfield (fig. 14). The thickness of the unit exceeds 1,400 ft in northwest Douglas County, central Stone County, and western Christian County. Between these areas of larger thickness, the aquifer thins to the northwest.

Before pumping began in the Ozark aquifer (mid 1800's), the configuration of the potentiometric surface of the aquifer resulted from the rate at which water was naturally recharged to and discharged from the saturated zone, and by the hydraulic properties of the aquifer and adjacent confining units. Hydraulic heads in the Ozark aquifer were lower that heads in the Springfield Plateau aquifer but higher than the top of the Ozark aquifer. Thus, the Ozark aquifer was confined and recharged from the overlying Springfield Plateau aquifer. Regional ground-water flow in the Ozark aquifer produced a ground-water divide (fig. 15) that generally paralleled the major topographic ridge. The divide trended through western Christian County, southern Greene County, and southern Webster County. Ground water north of the divide flowed to the northwest and discharged at the Osage River and ground water south of the divide flowed south and southwest and discharged at the White River (fig. 2). With the advent of ground-water withdrawals from the Ozark aquifer by municipal and industrial wells in Springfield and the surrounding communities, the potentiometric surface has been altered in the vicinity of Springfield. During the study an assumption was made that water levels generally have not risen since predevelopment conditions.



Base from U.S. Geological Survey State base map, 1:500,000; Missouri, 1973.

0 5 10 MILES

0 5 10 KILOMETERS

EXPLANATION

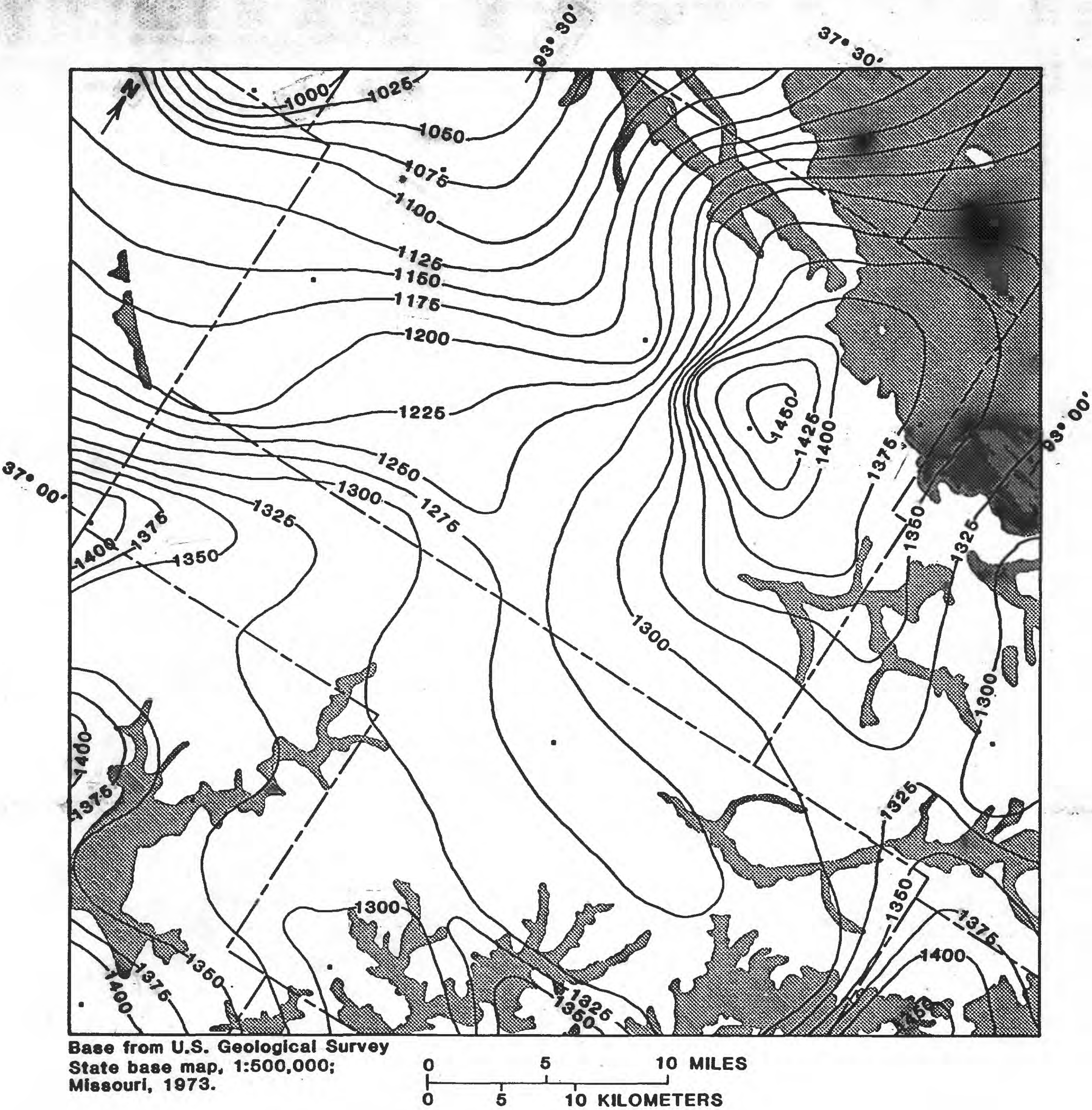
OUTCROP AREA OF THE OZARK AQUIFER

—1000— TOP OF OZARK AQUIFER--Shows altitude of Ozark aquifer. Interval, in feet, is variable. Datum is sea level.

U/D FAULT--U, upthrown side, D, downthrown side

• CONTROL POINT

Figure 13.--Configuration of the top of the Ozark aquifer.



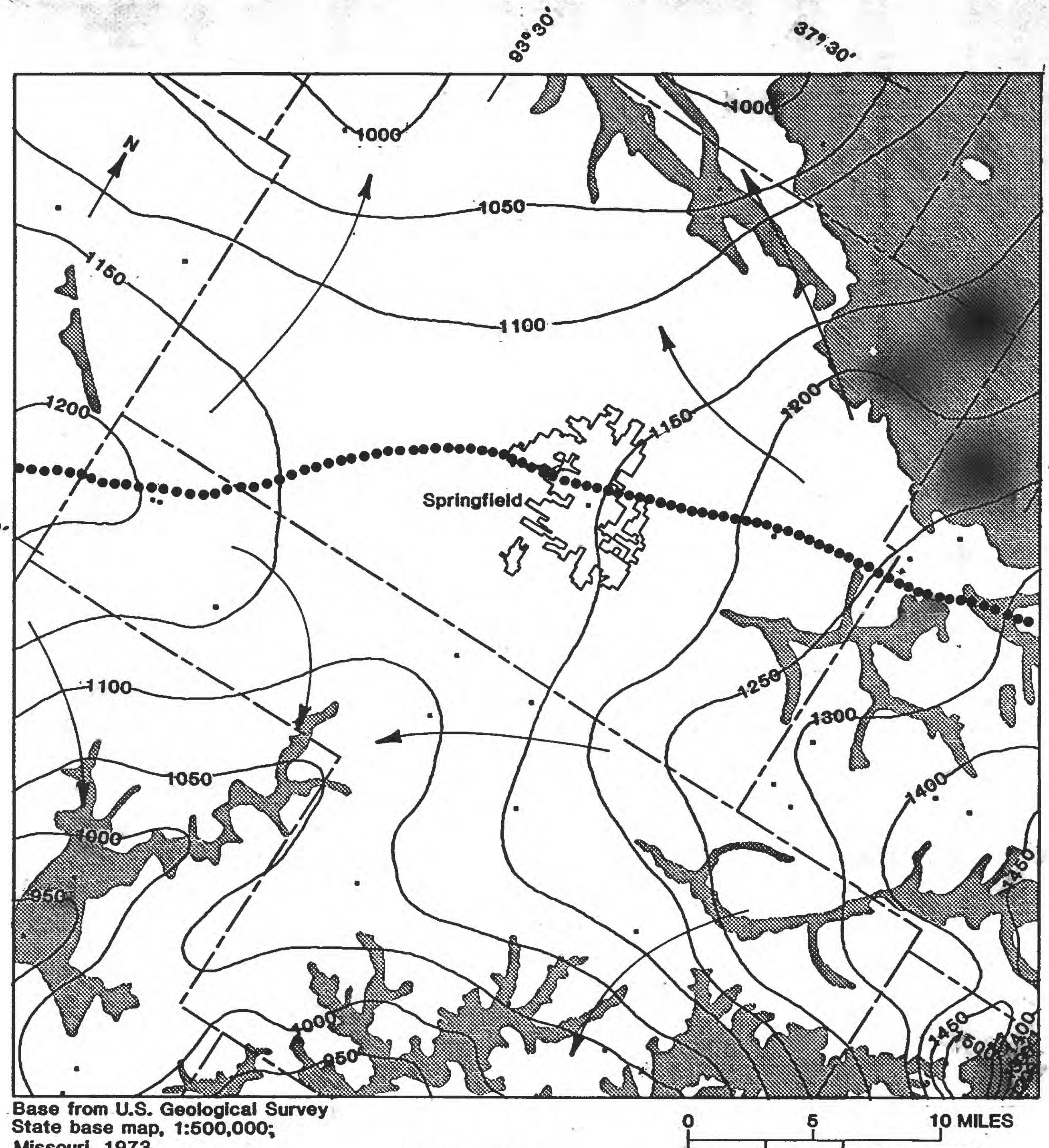
EXPLANATION

OUTCROP AREA OF THE OZARK AQUIFER

-1000- LINE OF EQUAL THICKNESS--Interval, in feet, is variable.

• CONTROL POINT

Figure 14.--Thickness of the Ozark aquifer (modified from Imes, in press, a).



EXPLANATION

OUTCROP AREA OF THE OZARK AQUIFER

--1100-- POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval, in feet, is variable. Datum is sea level.

DIRECTION OF GROUND-WATER FLOW

REGIONAL GROUND-WATER DIVIDE

CONTROL POINT

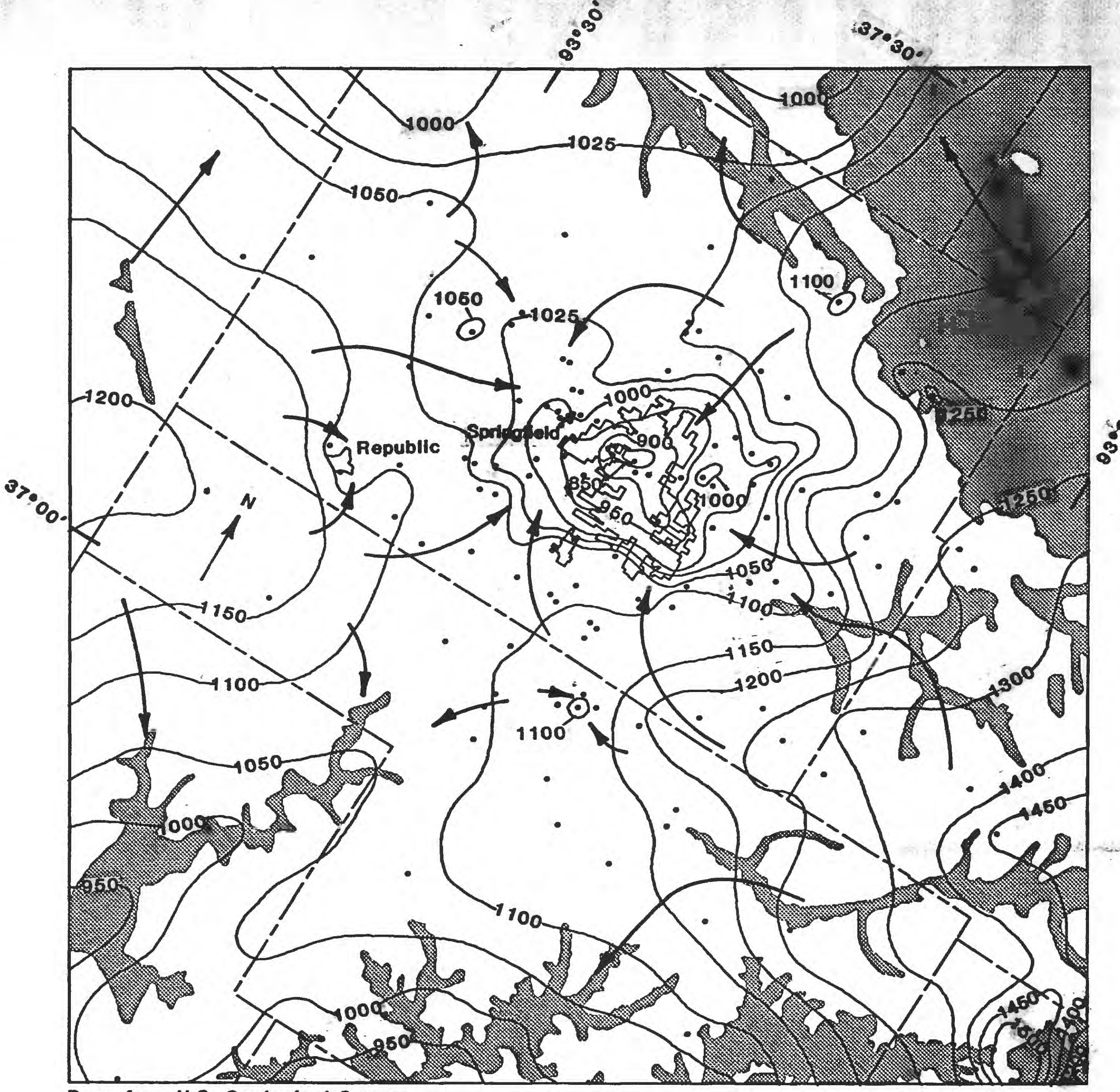
Figure 15.--Potentiometric surface of the Ozark aquifer prior to development.

By 1974, a large cone of depression more than 11 mi in diameter at the 1,050 altitude contour and less than 850 ft in altitude near the center had developed around Springfield in response to ground-water withdrawals (fig. 16). Hydraulic heads dropped by nearly 300 ft at the center of the drawdown cone and the ground-water divide was no longer present around Springfield. Ground water that once flowed north and south away from the divide was captured and diverted toward Springfield. By this time, a small cone also was developing around Republic, 12 mi southwest of Springfield.

Continued ground water withdrawals from the Ozark aquifer from 1974 to 1987 have lowered heads in the aquifer nearly an additional 50 ft (altitude of 800 ft) at the center of the cone of depression. The diameter of the cone at the 1,050 altitude contour has expanded to about 15 mi (fig. 17). Further changes are evident that potentially could affect future ground-water supplies in the area. Many communities surrounding Springfield that have experienced population growth in the previous 13 years have drilled new water-supply wells or increased the pumping rate of existing wells to meet the increased demand for water. As a result, in addition to the cone of depression around Republic, cones are now developing around the cities of Nixa, Fordland, and Willard, and around wells belonging to Greene County Public Water-Supply District 5 at Fairgrove. Hydraulic head data indicate areas of head decline are forming around Clever and Ozark. These cones are still small compared to the large cone caused by pumping in Springfield. Drawdown around Republic and Nixa probably is of the most immediate concern to Springfield because water-supply wells at Republic and Nixa are close to Springfield and have produced larger drawdowns than other communities in the area. If present (1988) growth rates and patterns of water use continue it is likely, in the near future, that cones of depression around Republic and Nixa will expand and merge with the large cone around Springfield. If this occurs, it is possible that resulting well interference will contribute to an increased rate of drawdown.

One factor that may mitigate the rapidly declining water levels is that the potentiometric surface of the Ozark aquifer in the central and eastern part of the principal cone of depression declined beneath the Ozark confining unit. The effect is to increase the quantity of water that can be withdrawn from storage per unit drop in head. Before the upper part of the aquifer was dewatered, water could only be released from storage in response to declining hydraulic head by the compression of the aquifer rock matrix and expansion of the water (this quantity is controlled by the storage coefficient of the confined aquifer). The volume of water that can be removed from the aquifer by these processes commonly is several orders of magnitude less than the volume of water that can be drained from the aquifer by gravity (controlled by the specific yield of the aquifer) as water levels drop below the top of the aquifer.

The approximately 500 mi^2 area in which the hydraulic gradient in the Ozark aquifer is toward wells in and near Springfield and Republic is shown by a dashed line in figure 17. The capture area extends from northwestern Christian County into central Webster County. Most of the area is overlain by the Ozark confining unit and leakage through the unit provides part of the water that supplies municipal and industrial wells. Where the Springfield Plateau aquifer is partially saturated and the Ozark aquifer is fully saturated, the leakage rate increased as the potentiometric surface of the Ozark aquifer declined. The Ozark aquifer is exposed in the James River valley in east-central Greene County. The James River in this reach is a gaining stream that receives water



Base from U.S. Geological Survey State base map, 1:500,000; Missouri, 1973.

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

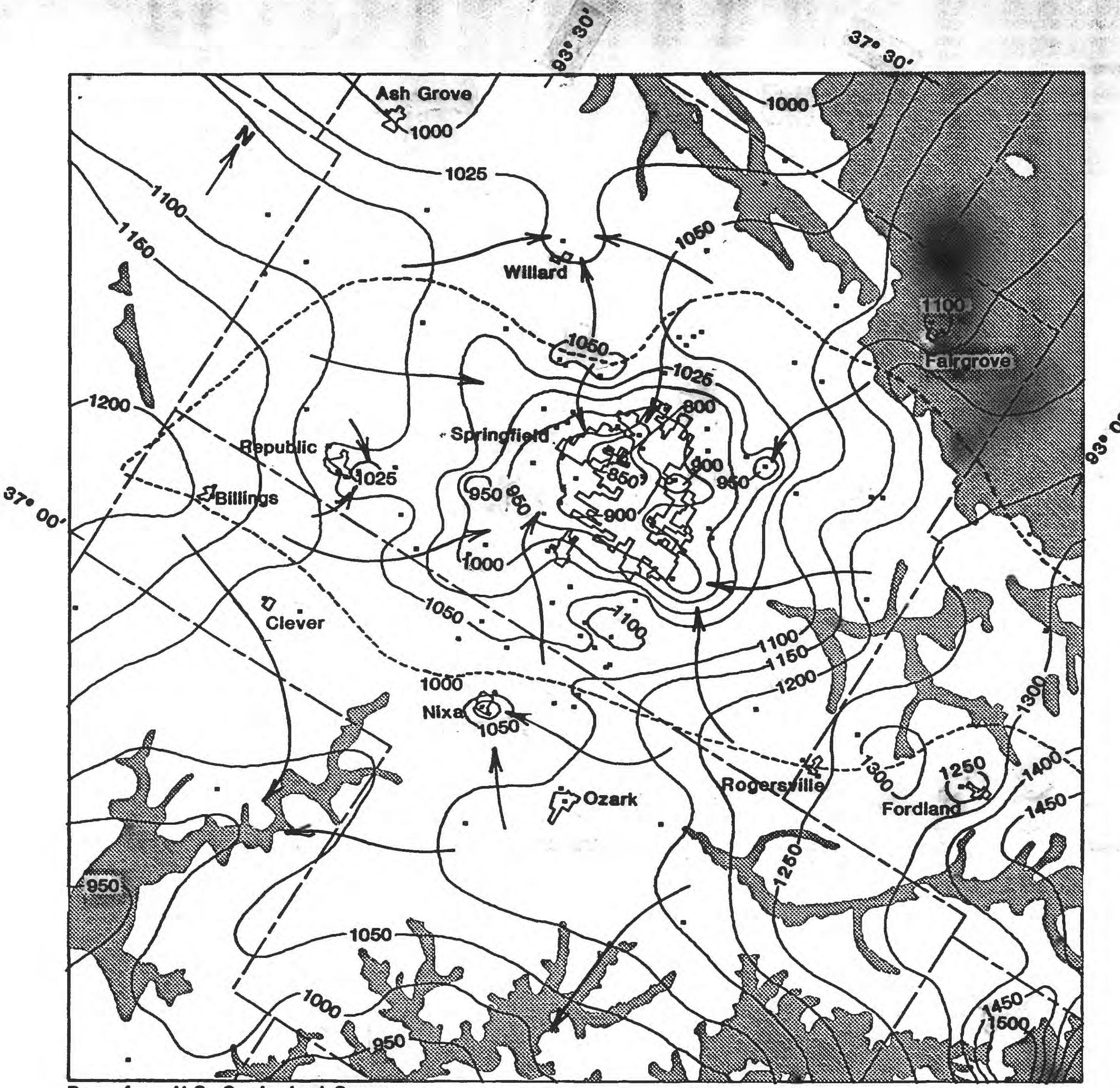
OUTCROP AREA OF THE OZARK AQUIFER

—1000— POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval, in feet, is variable. Datum is sea level.

DIRECTION OF GROUND-WATER FLOW

• CONTROL POINT

Figure 16.--Potentiometric surface of the Ozark aquifer, June 1974. (Modified from Emmett and others, 1978).



Base from U.S. Geological Survey
State base map, 1:500,000;
Missouri, 1973.

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

OUTCROP AREA OF THE OZARK AQUIFER

-1100- POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval, in feet, is variable. Datum is sea level.

------ LIMIT OF AREA IN WHICH LEAKAGE THROUGH OZARK CONFINING UNIT AND DEEP RECHARGE TO OZARK AQUIFER IS CAPTURED BY WELLS NEAR SPRINGFIELD

→ DIRECTION OF GROUND-WATER FLOW

• CONTROL POINT

Figure 17.--Potentiometric surface of the Ozark aquifer, July-August 1987.

discharged from the upper part of the aquifer. Continued expansion of the drawdown cone around Springfield and Fordland may eventually result in streamflow depletion of the James River. However, the depletion rate will likely be minimal because the Cotter Dolomite and Jefferson City Dolomite, the bedrock in which the stream is incised, are considerably less permeable than stratigraphically lower formations in the aquifer.

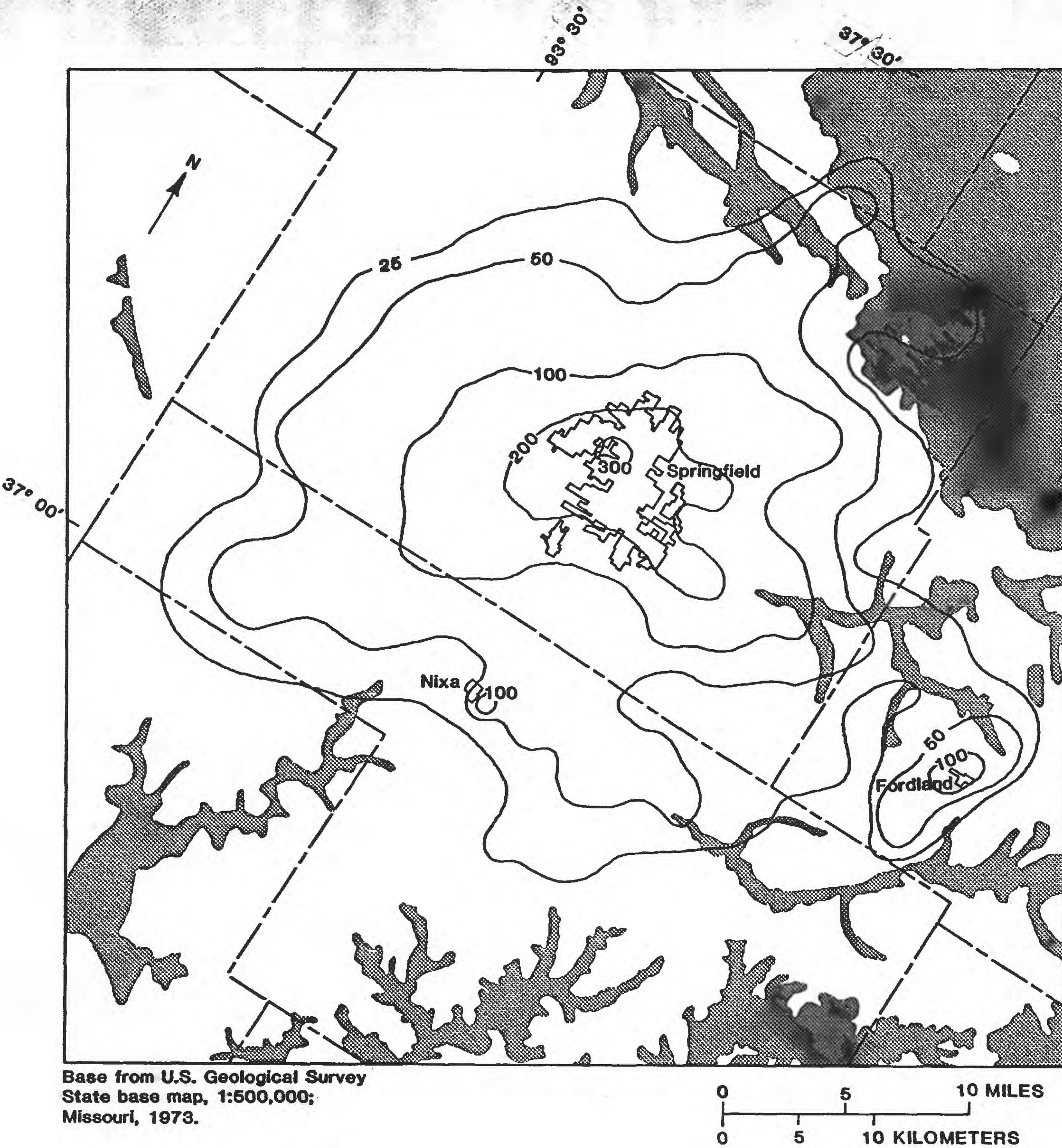
The capture area (fig. 17) does not represent an equivalent area at land surface where recharge to the water table is directed to wells in the Ozark aquifer. Most of the recharge to the Springfield Plateau aquifer discharges to the many streams that incise the aquifer, providing their base flow. Only a small fraction of the recharge to the Springfield Plateau aquifer leaks through the Ozark confining unit into the Ozark aquifer; most of this leakage probably originates as recharge in upland areas of higher altitude within the capture areas and some may originate in areas outside the capture area. Despite these assumptions, the boundary does approximate the area through which water can leak through the Ozark confining unit and flow to wells near Springfield.

The maximum drawdown in the Ozark aquifer as of July-August 1987 is about 300 ft (fig. 18) and is centered near the western edge of the city limits of Springfield. The 100-foot drawdown contour encloses an area surrounding Springfield equal to about one-fourth of Greene County. Two smaller areas having at least 100 ft of drawdown are around Fordland and near Nixa. The drawdown cones around Springfield and Fordland merge at the 25-foot contour.

A perspective drawing of the predevelopment potentiometric surface is given in figure 19. The view is slightly to the east of north from an angle of 45 degrees from the horizon. The direction of view is nearly parallel to the James River valley in northern Stone County, facing upstream. Comparison of figure 19 with figure 20, a view of the 1987 potentiometric surface from the same vantage point, shows the changes in the potentiometric surface caused by ground-water pumpage and the relative size of drawdown cones around the pumping wells.

SURFACE- AND GROUND-WATER INTERACTION

Streams in the study area usually are dry in the headwater reach where the streambed is higher than the water table. Streamflow in this upper reach occurs only when rainfall exceeds the rate of infiltration through the streambed and the storage capacity of the streambed. Streamflow usually is continuous, and increases, downstream from the point where the streambed intersects the water table. Streamflow on the Springfield Plateau aquifer, and the exchange of surface and ground water through streambeds, is substantially affected by the karst that has developed in the upper part of the aquifers. Abrupt changes in rock permeability and porosity, characteristic of karst terrane, can induce different streamflow characteristics. Headwater reaches of streams in karst areas may remain dry during rainfall, under conditions that create streamflow in nonkarst areas, because of the increased capacity of the aquifer to store and transport infiltrated water. Downstream from the point where the streambed first intersects the water table, the stream may not flow continuously along the entire stream reach, or stream discharge may decrease downstream along some stream reaches where the water table slopes away from the stream or lies below the stream. The part of the stream where flow is lost to the aquifer because of increased streambed and aquifer permeability and porosity is a losing-stream reach.



OUTCROP AREA OF THE OZARK AQUIFER

-100- LINE OF EQUAL DRAWDOWN--Contour interval, in feet is variable.

Figure 18.--Drawdown induced by pumping from the Ozark aquifer; predevelopment to July-August 1987.

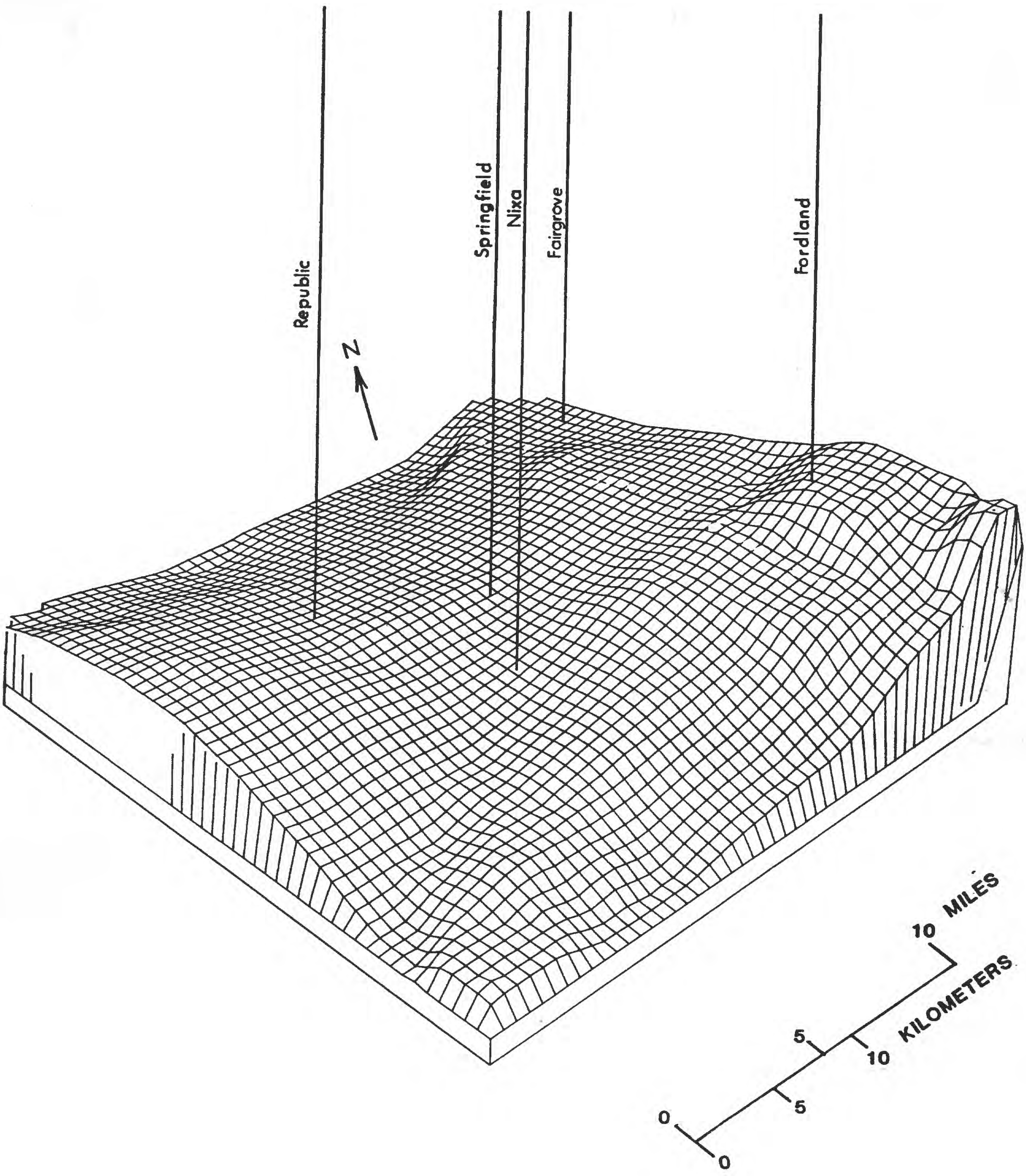


Figure 19.--Perspective drawing of the predevelopment potentiometric surface.

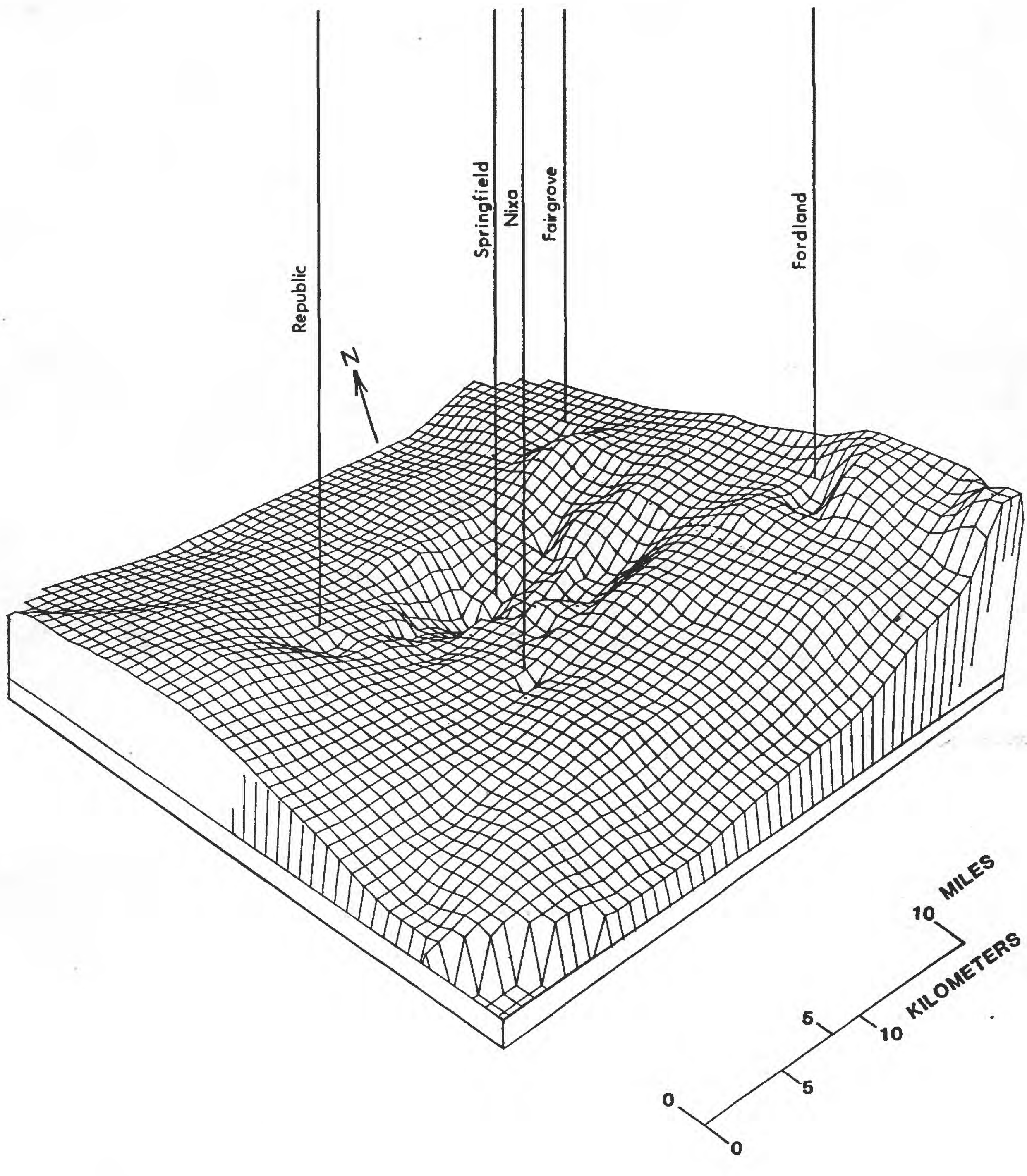


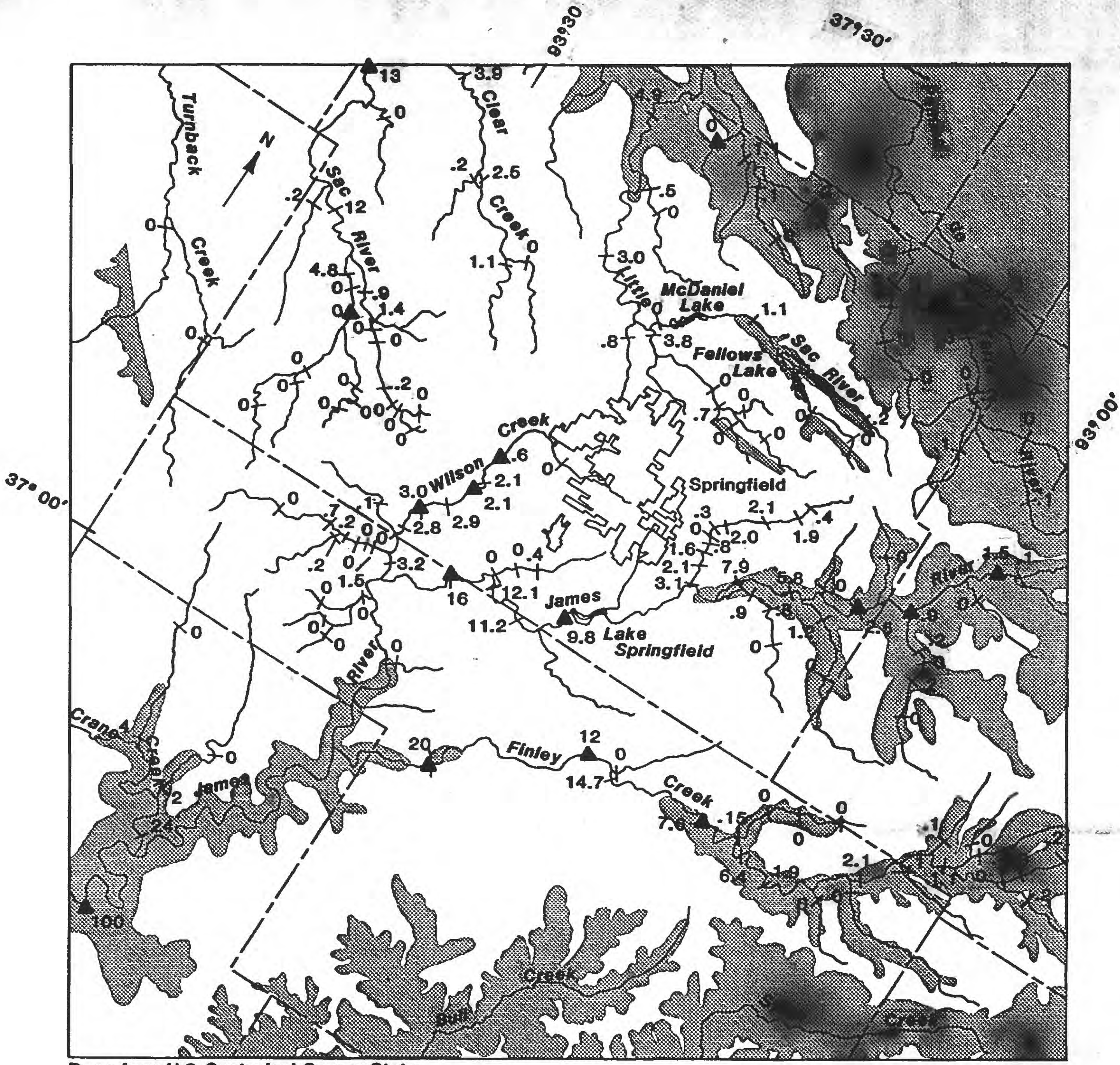
Figure 20.--Perspective drawing of the 1987 potentiometric surface.

Seepage-run data, collected as a series of stream discharge measurements at intervals along a stream reach, can indicate the magnitude and distribution of streamflow. Low-flow seepage-run data can provide information on the exchange of surface and ground water, including the location of losing-stream reaches. Existing streamflow data were compiled for this study to determine the quantity of water that discharges or recharges the surficial aquifer through streambed leakage. The purpose was to estimate land-surface boundary conditions, specifically, recharge and discharge rates and locations for incorporation into a ground-water flow model of the Springfield area. Considerable low-flow stream data are available for the study area in the form of 7-day Q_2 low-flow frequency data for continuous record and partial record gaging stations (Skelton, 1970, 1976) and seepage-run data obtained during or near low-flow conditions (Emmett and others, 1978).

To provide a common basis for analyzing stream-aquifer interaction, seepage-run data collected during low-flow conditions was adjusted by the ratio of 7-day Q_2 at a gaged station to the discharge measured at the gaged station during the collection of each set of seepage-run measurements (fig. 21). Low-flow data for the tributaries of Turnback Creek and Crane Creek were estimated from notes of field observations. Data for Wilson Creek were corrected to exclude the large quantity of treated wastewater that discharges into the creek from a sewage treatment plant southwest of Springfield (Harvey and Skelton, 1968). Low flows in the study area varied from zero ft^3/s (cubic feet per second) in many headwater areas and in small tributaries, to 100 ft^3/s near where the James River flows out of the study area. Within the study area, Crane Creek, Finley Creek, and the James River receive the largest quantities of ground water, most of which is discharged from the Ozark aquifer. Apparently, both Finley Creek and the James River gain water primarily in their upper reaches where they flow on outcrops of the Ozark aquifer, lose water shortly after they flow onto the Springfield Plateau aquifer, and then gain water as they near and flow onto the Ozark aquifer once again. Finley Creek loses a small quantity of water in its headwater area in the northeastern corner of Christian County. Throughout a relatively large area of extreme western Christian County and southwestern Greene County, most smaller streams are dry during low-flow conditions.

NATURAL AND INDUCED LEAKAGE THROUGH THE OZARK CONFINING UNIT

There are several mechanisms, both natural and manmade, by which water can be exchanged between the Springfield Plateau aquifer and the Ozark aquifer. The rate of ground-water leakage through the Ozark confining unit is controlled by the vertical hydraulic conductivity of the unit and the hydraulic gradient across the unit. The vertical hydraulic gradient in the natural flow system varies considerably depending on whether it is measured beneath an upland area or larger valley. The hydraulic head difference between the aquifers ranges from about -130 ft (downward gradient) in upland areas to about 30 ft (upward gradient) in valley areas under predevelopment conditions. The fact that the predevelopment potentiometric surface of the Ozark aquifer does not mirror local variations in water levels in the Springfield Plateaus aquifer indicates that the vertical permeability of the Ozark confining unit is small. When large quantities of ground water are pumped from the Ozark aquifer, as is the case for large capacity public-supply and industrial wells, the aquifer is unable to replenish the water being removed at the same rate it is being pumped. In this



Base from U.S Geological Survey State base map, 1:500,000; Missouri, 1973

0 5 10 MILES

0 5 10 KILOMETERS

EXPLANATION

COMBINED OUTCROP AREA OF THE OZARK AQUIFER AND OZARK CONFINING UNIT

20 MEASURING SITE-- Number indicates estimated 7-day annual low-flow for 2 year recurrance interval, in cubic feet per second

▲ GAGING STATION

Figure 21.--Location and magnitude of estimated 7-day Q2 low-flow data for streams.

situation, water levels around the well decline until the vertical gradient across the confining unit and the lateral gradient in the aquifer near the well have been increased sufficiently to replenish the water removed by pumping. The large drawdown cone around Springfield is evidence that this situation exists in the Ozark aquifer. As the downward hydraulic gradient across the Ozark confining unit increases, a larger quantity of water leaks through the confining unit than would occur naturally. The induced vertical hydraulic gradient attains a maximum when the top of the Ozark aquifer becomes unsaturated. The increased rate of leakage increases the possibility that potentially contaminated water from the Springfield Plateau aquifer can enter the Ozark aquifer and ultimately flows to water-supply wells.

By use of digital representations of confining unit thickness and aquifer potentiometric surfaces, the vertical volumetric leakage rate between the Springfield Plateau and Ozark aquifer within the capture area under predevelopment conditions can be estimated at [$5.2 \times 10^{10} K_v$] ft^3/s, where K_v is the vertical hydraulic conductivity, in ft/s, of the Ozark confining unit. The vertical hydraulic conductivity is assumed constant for this calculation and the leakage is downward. A similar calculation under 1987 drawdown conditions, assuming the potentiometric surface of the Springfield Plateau aquifer has remained unchanged, yields [$11.6 \times 10^{10} K_v$] ft^3/s for the leakage rate. Therefore, the increased downward leakage because of ground-water pumpage is about 100 percent of the predevelopment leakage rate.

The leakage coefficient (vertical hydraulic conductivity divided by confining unit thickness) of the Ozark confining unit varies spatially for several reasons. Permeability changes result from lithologic and thickness variations and development of secondary porosity and permeability. There are caverns that penetrate the Ozark confining unit that provide a hydraulic connection between the Springfield Plateau and Ozark aquifers. Near the Eureka Springs Escarpment and along the major river valleys, where the confining unit is not deeply buried or is exposed, it is probable that the vertical permeability of the confining unit has increased because of weathering processes.

Many faults are evident at land surface throughout the study area. Most of the faults probably extend through the confining unit and are paths of greater permeability. Many faults are associated with networks of joints and fractures that also provide more permeable routes for ground-water flow. A diagram of the altitude of the northeastern and southwestern faces of the Battlefield-Sac River Fault is given in figure 22. Where the fault displacement is greater than the thickness of the Ozark confining unit, the Springfield Plateau and Ozark aquifers are in direct contact. Two areas are shown in figure 22 where contact occurs. The larger contact area is west of Springfield along the northern one-third of the fault. The contact area is estimated at 1.9×10^6 ft^2 (square feet). A second, much smaller contact area is southwest of Springfield near the northeastern edge of Republic. The contact area, a short distance southeast of the fault center, is estimated at about 2.7×10^5 ft^2. Because of the much smaller thickness of the second contact (about 20 ft), there is a possibility that it is an artifact of the contouring and not an actual contact area.

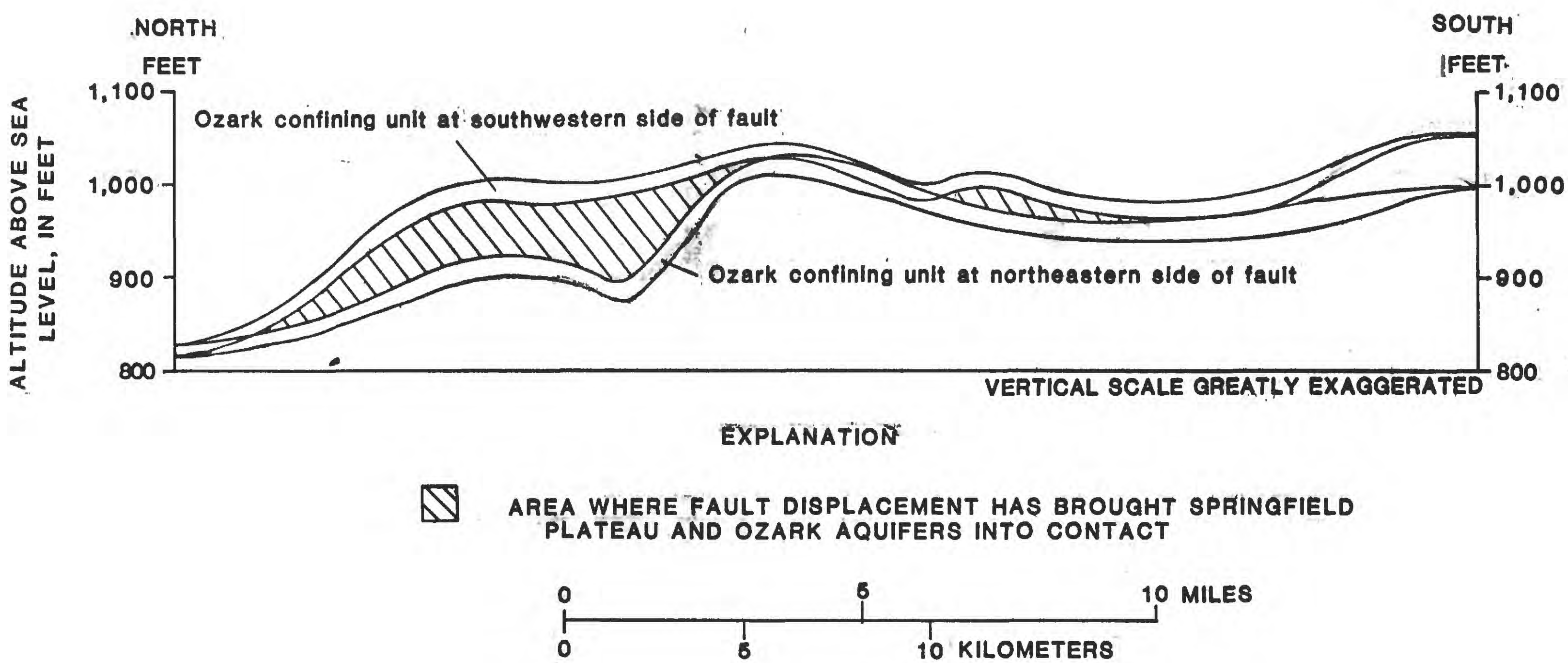


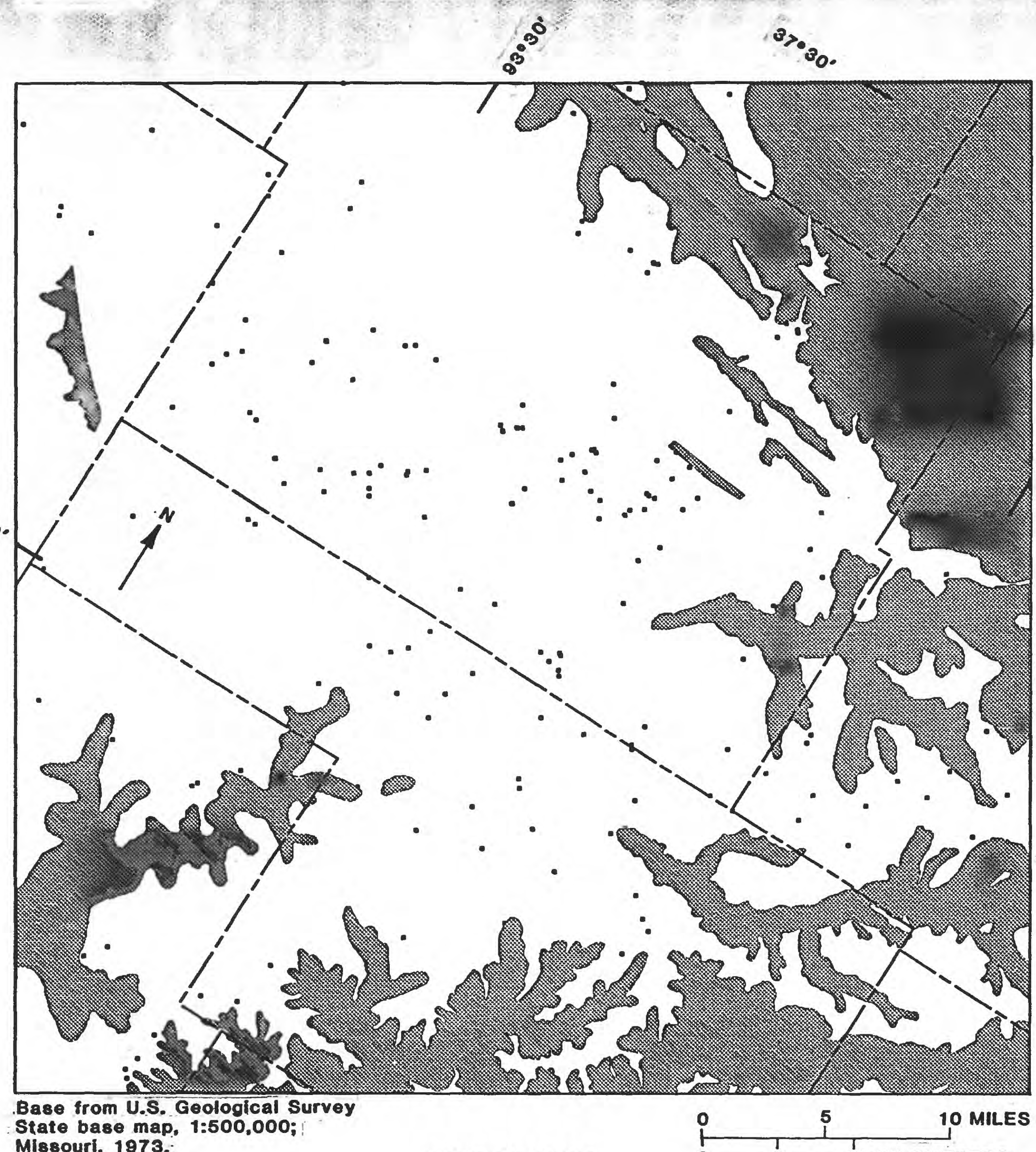
Figure 22.--Contact areas between the Springfield Plateau and Ozark aquifers resulting from displacement of the Battlefield-Sac River fault. Location of fault is shown in figure 10.

From the data available for this study, it is difficult to identify any anomalies or correlations in the potentiometric maps that definitely can be attributed to a permeable connection between the aquifers at the contact areas. One observation can be made that under predevelopment conditions the heads in the Springfield Plateau and Ozark aquifers near the larger contact area are both about 1,100 ft. This near equality is consistent with the existance of a permeable connection between the aquifers. Additional evidence for ground-water flow through this contact may be found if water levels around Springfield decline; water levels in the Ozark aquifer should remain somewhat higher near the contact area as water withdrawn by pumping is replenished by flow across the contact. There is some evidence that this is occurring, but it is difficult to verify at this time.

Another condition that effectively increases the permeability of the confining unit, and may allow contamination of the Ozark aquifer, is the presence of many wells in the area that are either open to both the Springfield Plateau aquifer and the Ozark aquifer (fig. 23), or are constructed (uncemented annulus) to allow easy exchange of water between the aquifers. Of the approximate 500 well logs in the sample log files of the Missouri Division of Geology and Land Survey (from which geologic information, well-construction data, and water-level measurements were tabulated for this study) about 200 well logs, or about 40 percent of the total, indicated wells open to both aquifers. These wells, especially the older abandoned wells and domestic wells from which only small quantities of water are pumped, provide direct avenues for the transport of contaminants into the Ozark aquifer. Emmett and others (1978) present the results of Ca/Mg (calcium-magnesium) ratio analyses on several wells in the Springfield area as an indication that the Ozark aquifer is recharged by leakage through a relatively permeable part of the Ozark confining unit. Although downward recharge also is occurring, 31 of the 62 wells for which analyses are given are open to both aquifers. Thus, many of the higher Ca/Mg ratios probably are indicative of ground-water mixing in the well bores. Other analyses may be affected by flow through the annulus around the casing of the wells from which the samples were collected.

GROUND-WATER USE

Water-use data are necessary to a study of ground-water resources, especially when modeling flow. Water-use data, however, sometimes are difficult to collect or estimate. Water-use estimates for this study generally were available for city wells, self-supplied subdivisions, mobile home parks, and institutions from approximately biannual publications of the Missouri Department of Natural Resources (1962-1987). It was often difficult to know the year for which the estimates were made because the published data may have been collected at any time after the previous publication. Water-use data for smaller cities, most of the self-supplied subdivisions, mobile home parks, and institutions in the study area are listed in table 2. Total water use for the categories municipalities and public water-supply districts, subdivisions and mobile home parks, and institutions for each year reported also is shown. Generally, water for public supply and industry is obtained from the Ozark aquifer. Water use by the smaller towns for public supply has increased markedly since the first compilation in 1962. Reported total water use for these smaller municipalities and public water-supply districts has increased four-fold in the years from 1961 to 1987. More than 43 percent of the ground water supplied to these towns, as published in 1987, was withdrawn by Republic, Nixa, and Ozark. Increases in ground-water pumpage by subdivisions and mobile home parks also has increased considerably, although the total use is not large compared to pumpage by the smaller communities.



EXPLANATION

COMBINED OUTCROP AREA OF THE OZARK AQUIFER AND OZARK CONFINING UNIT

• WELL LOCATION

Figure 23.--Location of wells open to both the Springfield Plateau aquifer and the Ozark aquifer.

Table 2.--Ground-water pumpage by municipalities[1], public water-supply districts, subdivisions, mobile home parks, and institutions in the Springfield area

[CCPWSD, Christian County Public Water-Supply District; GCPWSD, Greene County Public Water-Supply District; Sub., subdivision; MHP, mobile home park]

Owner	1962	1966	1969	1971	1973	1975	1977	1980	1982	1985	1987
	Year of data publication (Missouri Department of Natural Resources)										
	Pumpage in million gallons per day										
	Municipalities										
Ash Grove	0.0900	0.1400	0.1250	0.1400	0.1500	0.1500	0.1500	0.1500	0.1500	0.1600	0.1600
Billings	.0000	.0500	.0030	.0500	.0550	.0550	.0650	.0650	.0650	.1000	.1000
Clever	.0200	.0120	.0200	.0200	.0200	.0200	.0380	.0380	.0400	.0400	.0500
Crane	.1000	.0530	.0720	.0750	.0750	.0750	.0750	.0750	.0800	.0800	.1200
Diggins	.0000	.0050	.0090	.0090	.0100	.0090	.0090	.0120	.0170	.0200	.0200
Fordland	.0150	.0200	.0130	.0200	.0370	.0370	.0370	.0370	.0100	.0350	.0970
Galena	.0400	.0400	.0450	.0500	.0600	.0600	.0600	.0600	.0550	.0550	.0550
Halltown	.0000	.0000	.0000	.0000	.0000	.0080	.0080	.0080	.0080	.0100	.0100
Marionville	.1000	.2000	.1410	.1800	.1600	.2000	.1850	.1800	.1800	.1900	.2140
Miller	.0350	.0400	.0600	.0600	.0600	.0650	.0650	.0650	.0900	.0800	.0800
Nixa	.0400	.0400	.1100	.1750	.2000	.2000	.1900	.1900	.1900	.3000	.3000
Ozark	.0550	.1000	.4000	.4000	.3000	.5400	.4500	.4700	.5500	.5000	.5000
Pleasant Hope	.0000	.0100	.0110	.0120	.0120	.0120	.0120	.0220	.0200	.0220	.0220
Reeds Spring	.0500	.0500	.0500	.0500	.0500	.0500	.0500	.0500	.0500	.0500	.0750
Republic	.0650	.0100	.2000	.2500	.3250	.4000	.5000	.5600	.6000	.5600	.5600
Rogersville	.0180	.0180	.0250	.0250	.0350	.0350	.0350	.0450	.0300	.0500	.0600
Sparta	.0150	.0150	.0150	.0160	.0350	.0350	.0350	.0350	.0400	.0400	.0400
Strafford	.0000	.0000	.0300	.0300	.0400	.0850	.0600	.0600	.0800	.1300	.0850
Walnut Grove	.0500	.0300	.0500	.0450	.0530	.0530	.0750	.0750	.0550	.0500	.0400
Willard	.0350	.0350	.0350	.0500	.0580	.0600	.1000	.1250	.1500	.1000	.1500
	Public water-supply districts										
CCPWSD 1	0.0000	0.0090	0.0250	0.0260	0.0300	0.0300	0.0300	0.0300	0.0300	0.0250	0.0200
CCPWSD 2	.0000	.0000	.0000	.0000	.0200	.0200	.0200	.0200	.0200	.0500	.0580
GCPWSD 1	.0000	.0210	.0300	.0500	.0560	.0750	.0750	.1500	.2250	.2600	.2600
GCPWSD 5	.0000	.0000	.0200	.0200	.0250	.0300	.0350	.0350	.0350	.0350	.0350
GCPWSD 6	.0000	.0000	.0120	.0120	.0120	.0120	.0130	.0125	.0125	.0125	.0125

Table 2.--Ground-water pumpage by municipalities[1], public water-supply districts, subdivisions, mobile home parks, and institutions[2] in the Springfield area--Continued

Owner	1962	1966	1969	1971	1973	1975	1977	1980	1982	1985	1987
	Year of data publication (Missouri Department of Natural Resources)										
	Pumpage in million gallons per day										
Subdivisions											
Campbell City Sub.	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0020	0.0020	0.0030	0.0030	0.0030
Cassidy Water Co.	.0000	.0000	.0000	.0000	.0100	.0100	.0250	.0350	.0350	.0470	.0470
Cedar Hills Sub.	.0000	.0000	.0000	.0000	.0020	.0030	.0030	.0030	.0030	.0030	.0030
Cross Roads Acres	.0000	.0000	.0000	.0000	.0000	.0000	.0020	.0040	.0040	.0050	.0050
Eastbourough Sub.	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0070	.0099
Green Hills Addition	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0030	.0030	.0040	.0040
Heatherwoods Homeowners	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0020	.0020
Hickory Village Sub.	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0030	.0020	.0030	.0030
James River Addition	.0000	.0000	.0000	.0000	.0040	.0080	.0080	.0100	.0150	.0150	.0150
Orchard Crest Addition	.0000	.0000	.0240	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
Park Crest Addition	.0000	.0000	.1100	.1100	.0000	.0000	.0000	.0000	.0000	.0000	.0000
Peace of Mind Estates	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0050	.0050	.0050	.0050
Rankin Acres	.0000	.0000	.0000	.0000	.0100	.0100	.0100	.0100	.0100	.0100	.0100
Ridgeview Terrace Sub.	.0000	.0000	.0000	.0000	.0000	.0000	.0020	.0030	.0030	.0000	.0000
Sequiota Water Co.	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0050	.0050	.0050
Southwest Village	.0000	.0000	.0000	.0000	.0010	.0100	.0130	.0130	.0130	.0150	.0150
Spring Valley Estates Sub.	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0060	.0060	.0060
Stoneshire Water Co.	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0050	.0050
Sunset Heights Second Addition	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0025	.0040	.0040	.0040
Sunset Heights Sub.	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0020	.0020	.0020
Sussex Park Sub.	.0000	.0000	.0000	.0000	.0050	.0050	.0030	.0070	.0070	.0070	.0070
Valley Park Sub.	.0000	.0000	.0000	.0030	.0030	.0030	.0050	.0050	.0050	.0050	.0050
Villa Park Heights	.0000	.0000	.0000	.0000	.0630	.0500	.0650	.0650	.0780	.1300	.1620
Wadsworth Park Unit 4 and 5	.0000	.0000	.0000	.0000	.0000	.0000	.0080	.0100	.0100	.0100	.0100
Walter Schmitt Sub.	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0030	.0030
Wilden Heights Sub.	.0000	.0000	.0000	.0000	.0000	.0000	.0020	.0040	.0040	.0040	.0040
Mobile home parks											
Acres of Shade MHP	0.0000	0.0000	0.0000	0.0050	0.0080	0.0010	0.0010	0.0010	0.0010	0.0080	0.0060
Air Park South MHP	.0000	.0000	.0000	.0000	.0000	.0000	.0010	.0025	.0040	.0000	.0000
Bakers Acres MHP	.0000	.0000	.0000	.0000	.0000	.0000	.0010	.0012	.0000	.0000	.0012
Briarwood MHP	.0000	.0000	.0000	.0000	.0000	.0050	.0050	.0050	.0050	.0050	.0050
Candle Light MHP	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0060	.0220	.0220	.0200
Chalet City MHP	.0000	.0000	.0000	.0000	.0000	.0000	.0190	.0000	.0000	.0000	.0000
Chalet City South	.0000	.0000	.0000	.0000	.0150	.0150	.0000	.0000	.0000	.0000	.0000
Colony Cove MHP	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0070
Coronado MHP	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0070	.0070	.0000
Country Estates MHP	.0000	.0000	.0000	.0000	.0000	.0000	.0050	.0000	.0070	.0070	.0070
Country Squire Village	.0000	.0000	.0000	.0080	.0100	.0100	.0100	.0080	.0080	.0080	.0080
Countryside Manor MHP	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0020	.0020	.0030	.0030

Table 2.--Ground-water pumpage by municipalities, public water-supply districts, subdivisions, mobile home parks, and institutions in the Springfield area--Continued

Owner	Year of data publication (Missouri Department of Natural Resources)										
	1962	1966	1969	1971	1973	1975	1977	1980	1982	1985	1987
	Pumpage in million gallons per day										
	Mobile home parks										
English Village MHP	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0150	0.0260	0.0260	0.0660	0.0660
Hi View MHP	.0000	.0000	.0000	.0000	.0000	.0100	.0100	.0100	.0380	.0380	.0380
Homestead MHP	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0090
Lakewood MHP	.0000	.0000	.0000	.0000	.0000	.0000	.0100	.0100	.0100	.0100	.0000
Mobile Gardens Trailer Park	.0000	.0000	.0000	.0000	.0020	.0020	.0020	.0030	.0030	.0000	.0000
Oak Crest MHP	.0000	.0000	.0000	.0000	.0000	.0000	.0050	.0120	.0120	.0150	.0210
Oak Hill MHP	.0000	.0000	.0000	.0000	.0000	.0000	.0030	.0030	.0090	.0050	.0000
Oak Shade Mobile Villa	.0000	.0000	.0000	.0000	.0000	.0000	.0030	.0030	.0030	.0020	.0020
Ozark Highlands MHP	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0300	.0300
Ozark Park A Home	.0000	.0000	.0000	.0000	.0000	.0000	.0250	.0250	.0380	.0000	.0000
Pine Haven MHP	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0050	.0050	.0050	.0050
Rolling Acres MHP	.0000	.0000	.0000	.0000	.0000	.0000	.0030	.0030	.0040	.0040	.0040
Shady Acres MHP	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0040	.0060
Silver Bell Trailer Park	.0000	.0000	.0000	.0000	.0060	.0060	.0060	.0060	.0060	.0060	.0060
Sparta MHP	.0000	.0000	.0000	.0000	.0050	.0050	.0050	.0050	.0050	.0050	.0050
The Willows	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0015	.0100	.0200
Travelers Park, Inc.	.0000	.0000	.0000	.0000	.0000	.0150	.0010	.0020	.0020	.0020	.0020
Twin Ridges MHP	.0000	.0000	.0000	.0000	.0000	.0000	.0030	.0030	.0020	.0020	.0020
West Town Chalet	.0000	.0000	.0000	.0000	.0000	.0200	.0200	.0010	.0000	.0000	.0000
Whispering Lane MHP	.0000	.0000	.0000	.0060	.0080	.0080	.0080	.0080	.0100	.0100	.0100
White Pine Village MHP	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0030	.0030
	Institutions										
Central Bible College	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2880	0.0850	0.0000
General Council, Assembly of God	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.2600	.2600
Happy Acres Health Care	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0020	.0000	.0000
Republic Group Residence	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0020	.0020
	Summary of total pumpage										
Municipalities and public water-supply districts	0.7280	0.8980	1.5010	1.7650	1.8780	2.3160	2.3720	2.5695	2.7825	2.9545	3.1235
Subdivisions and mobile home parks	.0000	.0000	.1340	.1320	.1520	.1960	.3090	.3352	.4475	.5770	.6211
Institutions	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.2900	.3470	.2620

[1]Does not include City of Springfield.
[2]Does not include U.S. Medical Center.

Total ground-water pumpage by City Utilities of Springfield for public-drinking supply and power plant cooling has increased from an estimated 0.30 Mgal/d during 1961 to 2.43 Mgal/d during 1986; pumpage was substantially larger, 5.46 and 7.76 Mgal/d, during 1976 and 1980, respectively. The largest volume of ground water pumped by City Utilities is for use at the Southwest Power Station. Water use by City Utilities of Springfield is tabulated in table 3. Industrial water use probably has been the largest use category historically and is the category for which the least and most inaccurate data are available. Industrial pumpage in Springfield has been continuous since the turn of the century. Unpublished estimates of industrial ground-water pumpage in 1973 (L.F. Emmett, U.S. Geological Survey, 1988, written commun.) were collected during a previous study of ground-water resources near Springfield. Additional data were collected during the summer of 1987 by City Utilities of Springfield personnel. Neither set of data is complete and the accuracy of the data can not be determined. No data are available for other years. The lack of accurate historical industrial pumpage data makes it difficult to correlate changes in the potentiometric surface of the Ozark aquifer with historical ground-water pumpage rates. Pumpage data for individual industries are not published in this report.

A comparison of reported and estimated average annual ground-water pumpage in the study area for all categories of users is shown in figure 24. The large increase in pumpage by the City Utilities of Springfield in 1976 is coincident with the first year of operation of the Southwest Power Station. The second peak withdrawal rate occurred in 1980, a year with severe drought conditions. Much of the increase in pumpage probably resulted from ground water being used to supplement surface-water sources. Municipalities and public water-supply districts other than Springfield also show a continuing pattern of increasing water use, as do subdivisions and mobile home parks. Water use by the U.S. Medical Center in Springfield declined from about 0.4 Mgal/d to about 0.2 Mgal/d from 1970 to 1986.

Rural water use for domestic and stock supply in Green County was estimated for 1970 and 1980 using census statistics from State of Missouri (1890-1988) and an assumed per capita daily rate of 50 gallons. Wells that supply rural use may be open to either the Springfield Plateau or Ozark aquifer, or both aquifers. Few data are available on rural well construction. Estimates of rural water use in Greene County for 1974 and 1983, also based on an assumed per capita daily rate of 50 gallons, are given in Steinkamp (1987). The estimated rural use for Greene County increased from 1.3 Mgal/d during 1970 to 2.3 Mgal/d during 1983 (fig. 24).

Table 3.--Ground-water pumpage by City Utilities of Springfield, James River and Southwest Power Stations, and the U.S. Medical Center

Year	Springfield City Utilities Well 1	4	5	6	7	8	10	11	12	13	James River Power Station	Southwest Power Station	U.S. Medical Center
	Pumpage in million gallons per day												
1961	0.1813	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1184	0.0000	0.3945
1962	.1813	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.1184	.0000	.4044
1963	.8339	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0674	.0000	.4143
1964	.7981	.0001	.0001	.0001	.0001	.0001	.0000	.0000	.0000	.0000	.0816	.0000	.4239
1965	.2181	.0063	.0063	.0063	.0063	.0063	.0000	.0000	.0000	.0000	.0746	.0000	.4338
1966	.4745	.0001	.0001	.0001	.0001	.0001	.0000	.0000	.0000	.0000	.0696	.0000	.4437
1967	.0797	.0001	.0001	.0001	.0001	.0001	.0000	.0000	.0000	.0000	.0920	.0000	.4338
1968	.3082	.0001	.0001	.0001	.0001	.0001	.0000	.0000	.0000	.0000	.0816	.0000	.4239
1969	.4608	.0001	.0001	.0001	.0001	.0001	.0000	.0000	.0000	.0000	.0920	.0000	.4134
1970	.8219	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.1266	.0000	.4035
1971	.8219	.0001	.0001	.0001	.0001	.0001	.0000	.0000	.0000	.0000	.1458	.0000	.3939
1972	.6466	.0002	.0002	.0002	.0002	.0002	.0200	.0003	.0142	.0000	.1720	.0000	.3840
1973	.7808	.0006	.0006	.0006	.0006	.0006	.0003	.0010	.0019	.0000	.1468	.0000	.3576
1974	.1937	.0822	.0822	.0822	.0822	.0822	.0345	.2625	.9891	.0000	.1496	.0000	.3312
1975	.0000	.0737	.0737	.0737	.0737	.0737	.0041	.1978	.3836	.0000	.1562	.0000	.3057
1976	1.1096	.2474	.2474	.2474	.2474	.2474	.0103	.3863	1.0959	.0000	.4390	1.1811	.2793
1977	.1203	.0023	.0023	.0023	.0023	.0023	.1061	.1795	.5096	.0000	.1644	1.7670	.2532
1978	.3644	.0018	.0018	.0018	.0018	.0018	.1748	.3343	.2688	.0000	.2728	1.9233	.2270
1979	.9891	.0019	.0019	.0019	.0019	.0019	.1879	.4713	.6959	.0000	.2542	2.5455	.2376
1980	1.2685	.0017	.0017	.0017	.0017	.0017	.3480	.6548	.5425	1.4646	.8070	2.6688	.2481
1981	.8109	.0000	.0000	.0000	.0000	.0000	.1457	.2065	.2422	.0234	.2476	2.5011	.2580
1982	.9151	.0000	.0000	.0000	.0000	.0000	.1266	.1781	.2592	.0000	.2410	1.8963	.2688
1983	1.5260	.0000	.0000	.0000	.0000	.0000	.1543	.1510	.3491	.0000	.3112	1.3866	.2556
1984	.3206	.0000	.0000	.0000	.0000	.0000	.1304	.0469	.0885	.0000	.4164	2.2932	.2424
1985	.0000	.0000	.0000	.0000	.0000	.0000	.0931	.0611	.1216	.0000	.2016	2.0631	.2295
1986	.3370	.0000	.0000	.0000	.0000	.0000	.1375	.0000	.0000	.0000	.2680	1.6851	.2163

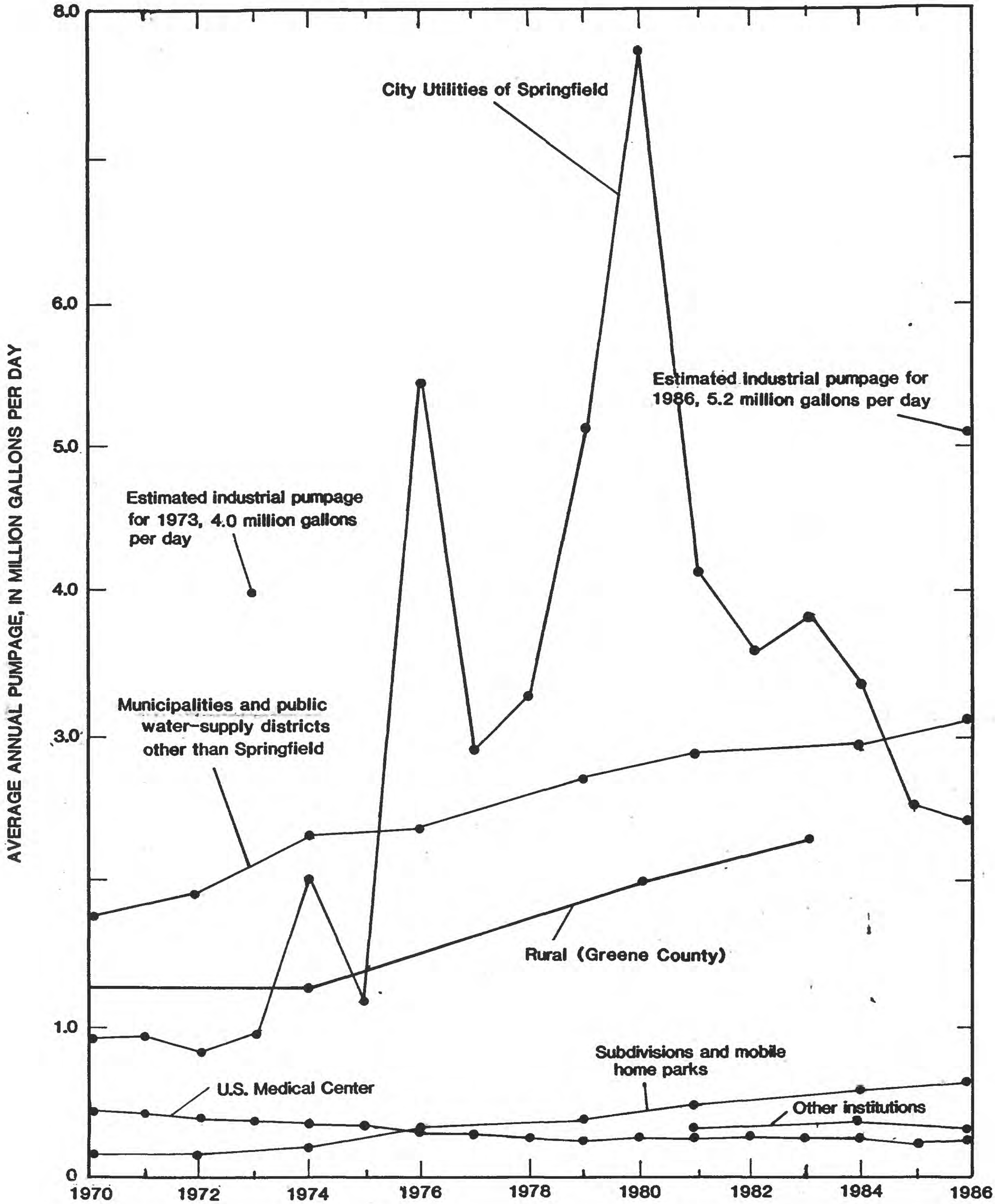


Figure 24.--Reported and estimated average annual ground-water pumping rates from 1970-86.

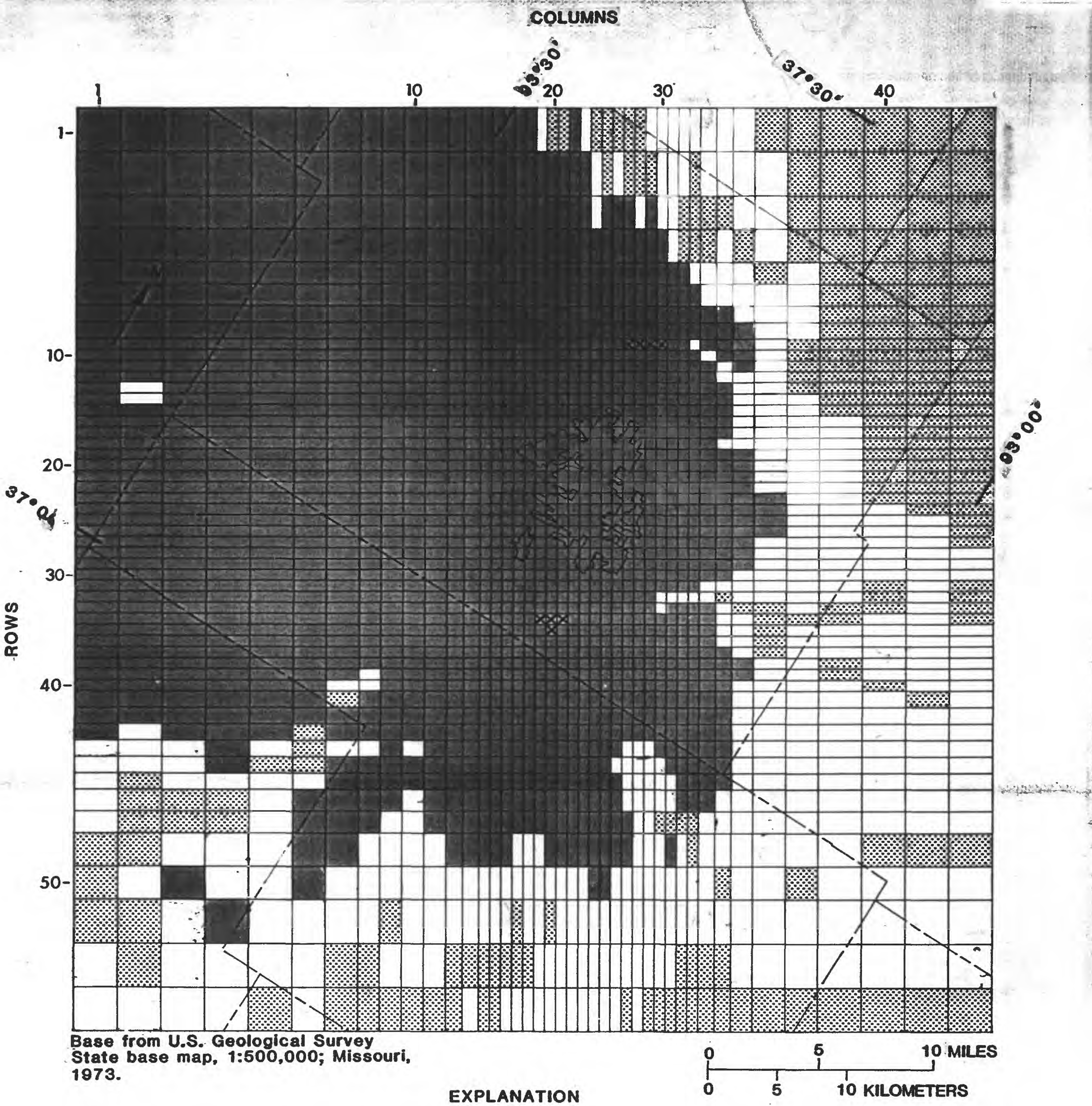
SIMULATION OF THE EFFECT OF PUMPING ON GROUND-WATER FLOW

A three-dimensional finite-difference model of ground-water flow in the Springfield area was constructed and calibrated. The U.S. Geological Survey modular model developed by McDonald and Harbaugh (1984) was used to test concepts of ground-water flow in the Springfield Plateau and Ozark aquifers by comparing the hydrologic budget and the rate of ground-water leakage across the Ozark confining unit.

The variable-grid model contains 53 rows and 42 columns of cells (fig. 25) oriented northeast and southeast to correspond with the orientation of model cells in a previously constructed model of regional ground-water flow in the Ozark Plateaus aquifer system (Imes and Emmett, in press). This orientation of the regional model originally was chosen to coincide with the general direction of the larger faults and joints that developed during erosional unloading of the Ozark Plateaus. It was expected that the transmissivity of aquifers in the Ozark Plateaus aquifer system would exhibit regional anisotropy because of the nearly orthogonal distribution of large faults in the area. Anisotropy was not evident at the regional scale, and apparently also is not a significant factor in ground-water flow in the Springfield area. Based on the hydraulic data collected during this study, no evidence was noted to indicate that the potentiometric surface of the Springfield Plateau or Ozark aquifer is substantially affected or distorted by faults. The orientation of the Springfield area model, however, was adjusted to match the regional model so intercell flow volumes of the regional model could be used as specified-flow boundaries for the Springfield area model.

The grid, with variable dimensions, was designed so that a more detailed analysis is provided near Springfield, and a less detailed analysis is provided away from the city, near the model boundaries. The smaller model cells near Springfield represent .5 mi by .5 mi areas and the largest cells at the corners of the square study area represent areas of 2 mi by 2 mi. The two-layer model simulates hydraulic head in the Springfield Plateau aquifer (model layer 1) and Ozark aquifer (model layer 2). For this modeling analysis, the Springfield Plateau aquifer and the small isolated areas where the Western Interior Plains confining system is present are modeled as one layer. Layer 1 is treated as an unconfined layer and receives recharge wherever the layer is present. Model layer 2 receives recharge where the Ozark aquifer is exposed and a specified constant leakage where the Springfield Plateau aquifer is unsaturated (fig. 25). Elsewhere, layer 2 is treated as a confined layer. The transmissivity of layer 2 is constant throughout the stress period because the saturated thickness of the Ozark aquifer remains nearly equal to the total thickness of the unit.

Model leakage coefficients were calculated using the thickness of the Northview Shale (not the entire thickness of the Ozark confining unit) because most of the confining material in the Ozark confining unit is concentrated in the Northview Shale. The leakage coefficients, therefore, more accurately represent the less permeable material that controls flow through the confining unit. Hydraulic heads are not simulated in the intervening Ozark confining unit and, consequently, storage of ground water in the confining unit is neglected. Computation of the leakage coefficient between the aquifers was accomplished independent of the model and included the effect of restrictive aquifer material between the centerline of each aquifer and the top (or bottom) of the intervening confining unit.



EXPLANATION

AREA WHERE ACTIVE CELLS IN LAYER 1 (SPRINGFIELD PLATEAU AQUIFER) ARE EXPOSED AT LAND SURFACE, ARE PARTIALLY SATURATED, AND RECEIVE RECHARGE

SPECIFIED HEAD CELL IN LAYER 1 (LAKE LEVEL)

AREA WHERE LAYER 2 (OZARK AQUIFER) IS EXPOSED AT LAND SURFACE AND RECEIVES RECHARGE

AREA WHERE LAYER 2 IS OVERLAIN BY THE UNSATURATED PART OF LAYER 1 OR OZARK CONFINING UNIT AND RECEIVES SPECIFIED CONSTANT LEAKAGE

Figure 25.--Model grid showing orientation, numbering system, and distribution of recharge.

Boundary conditions at land surface were derived from a previous analysis of recharge to the water table (Dugan and Peckenpaugh, 1986) and an analysis of stream low-flow data undertaken as part of this study. Estimated average annual recharge to the water table in the study area has been determined from results of a soil-moisture water-balance analysis for the Midwest by Dugan and Peckenpaugh (1986). Recharge, taking into account 1978 land-use conditions, ranges from 7.9 to 9.5 in/yr (inches per year). The recharge was reduced by a uniform percentage throughout the model area to adjust the total volume of recharge to a value consistent with estimated discharge to streams and other discharge components as appropriate for the particular simulation. Discharge to streams in the study area was estimated by adjusting low-flow seepage-run data available for the area to 7-day Q_2 low flow. Several nodes in layer 1 were set as specified-head cells to simulate the levels of McDaniel Lake (fig. 25, row 9, columns 27-30) and Lake Springfield (fig. 25, row 34, columns 19-21, and row 35, column 20) because it is likely that these lakes are hydraulically connected with the Springfield Plateau aquifer and lake levels probably represent the water table. Nodes representing the area containing Fellows Lake were not simulated as specified heads because the lake bed primarily is on an outcrop of the Ozark confining unit at the edge of the unsaturated part of the Springfield Plateau aquifer.

Boundary conditions representing lateral flow in the Springfield Plateau and Ozark aquifers and vertical flow through the bottom of the Ozark aquifer were initially derived from cell-to-cell flow terms in the calibrated regional model. This choice of model boundaries, or a similar choice, is necessary because of the lack of natural boundaries within a reasonable distance of the area of interest. To extend the model to natural discharge areas for the deeper flowing ground water in the study area would require that the study area be much larger; this increase in area would mask the detail needed for interpretating model results for this study. In the method initially used for this model, flow between adjacent cells in the regional model that crossed the boundaries of the local model were prorated among the smaller local model cells on the basis of the proportion of the local cell cross-sectional area at the boundary relative to the cross-sectional area of the regional model cell. Thus, fluxes resulting from these boundaries were comparable to the fluxes calculated for the regional model. The specified-flux boundary condition derived in this manner was adequate, although not as accurate as desired, for the steady-state predevelopment calibration of the model; it was inadequate for the transient calibration because of the necessity of decreasing considerably the value of hydraulic conductivity to achieve calibration. Therefore, the boundary conditions for the model were modified to general-head boundaries to make boundary fluxes more consistent with the smaller values of hydraulic conductivity of the local model.

General-head boundaries (McDonald and Harbaugh, 1984, p. 343) are defined by assigning a fixed head and hydraulic conductance to each boundary cell for which the general-head boundary condition is appropriate. During the simulation process, water is removed or added to the boundary cell in a quantity proportional to the difference between the simulated head at the cell and the fixed boundary head. These boundary conditions represent water supplied to the model area by increases in inflow or decreases in outflow that represent water derived from the water table and surface-water sources where the lower part of the Ozark aquifer is exposed to the north and east, and from storage and leakage outside the model boundaries to the west and south. Because detailed water-level information was not needed near the boundaries, a more thorough definition of the boundary conditions were not necessary. The fixed boundary heads for lateral flow to the Springfield Plateau and Ozark aquifers were set equal to the hydraulic head interpolated from potentiometric contour maps at the midpoint of the boundary face of each boundary cell. The hydraulic conductance at each general-head boundary was calculated in a preprocessor stage before each model simulation using the lateral hydraulic conductivity and the geometry of the cell. Because the effect of drawdown at the model boundaries was slight throughout the transient simulation, it was not necessary to adjust the boundary conditions with time. The effect on the boundary flux of small changes in hydraulic head at model boundary cells is approximated because boundary flows are a function of hydraulic-head differences at the boundary.

The St. Francois aquifer is not represented by the model; however, leakage between the Ozark aquifer and the underlying St. Francois aquifer through the intervening St. Francois confining unit is represented as a general-head boundary condition. The boundary flow is determined by the vertical hydraulic conductivity of the St. Francois confining unit and an approximate average thickness (Imes, in press, b) of 250 ft for the unit. Values of the vertical hydraulic conductivity of the St. Francois confining unit were made approximately equal to the values used for the Ozark confining unit because no independent estimate of conductivity was available for the St. Francois confining unit. The similar lithologies of the two confining units (limestone grading to shale and silt and dolostone grading to shale and silt) indicate that the permeabilities of the units probably are similar. The greater depth of burial of the St. Francois confining unit, however, may decrease the permeability of the lower unit. The flux of ground water through the St. Francois confining unit probably is much less than the flux through the Ozark confining unit because of the larger thickness of the St. Francois confining unit (250 ft rather than about 30 ft for the Ozark confining unit near Springfield.

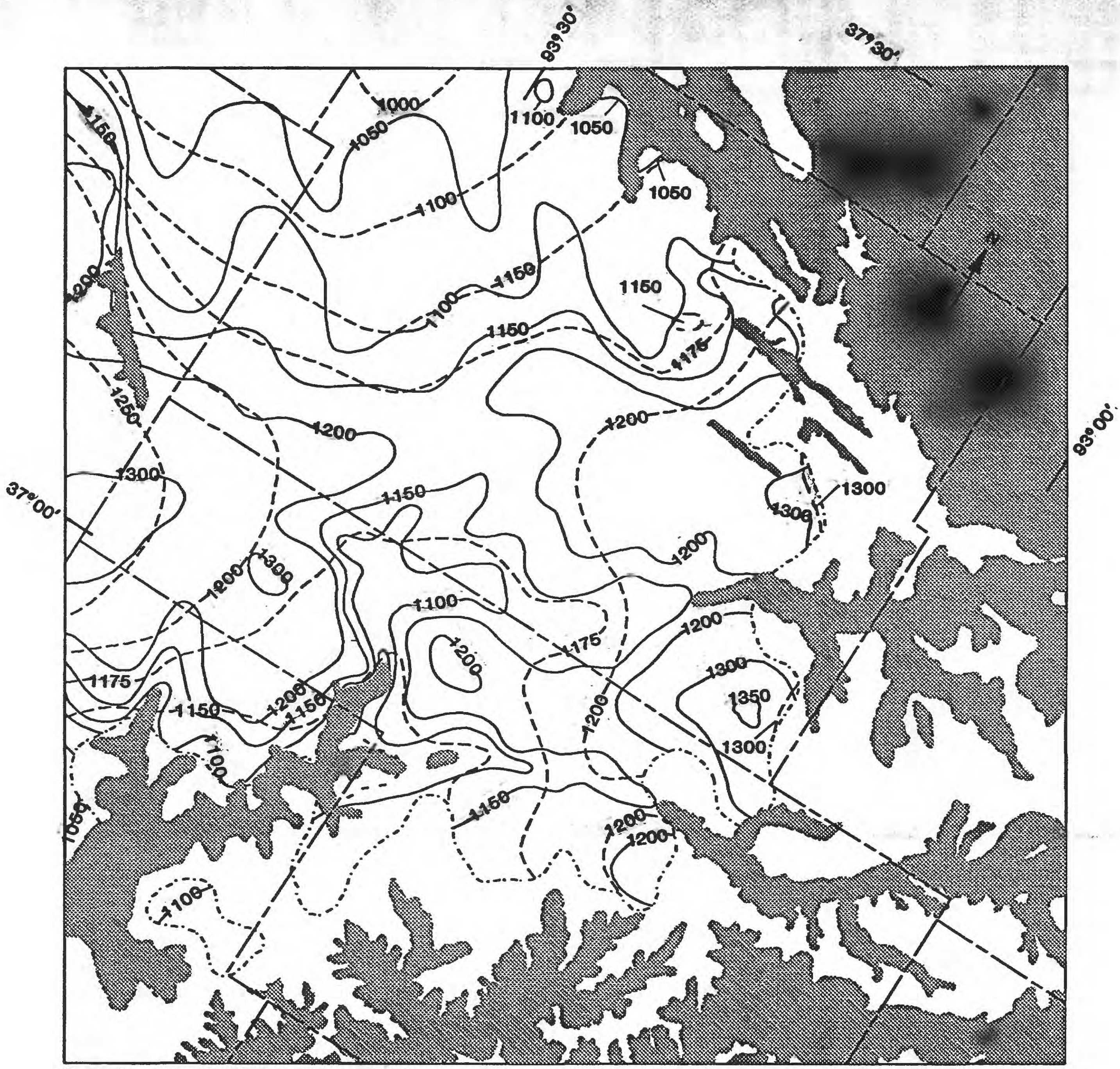
MODEL CALIBRATION AND THE HYDROLOGIC BUDGET

Steady-State Calibration: Predevelopment Conditions

The ground-water flow model was initially calibrated to the predevelopment potentiometric surfaces of the Springfield Plateau and Ozark aquifers. Preliminary estimates of the lateral hydraulic conductivity of the aquifers and vertical hydraulic conductivity of the confining units were obtained from the steady-state predevelopment calibration values determined from a regional model of the Ozark Plateaus aquifer system (Imes and Emmett, in press). Although a reasonably accurate predevelopment calibration was obtained, the introduction of ground-water pumpage into the model for transient calibration quickly indicated that the predevelopment calibration values of hydraulic conductivity were not adequate for this model. The volume of water flowing to the wells during simulation was too great to permit a sufficiently deep drawdown cone to develop around Springfield. Subsequently, the model was recalibrated using smaller values of hydraulic conductivity. One result of using smaller values of hydraulic conductivity was that the net flux of water from land surface (recharge) to the aquifers had to be decreased considerably and the relation between the model and the actual field situation had to be reevaluated and modified.

Reevaluation was necessary because it was determined that a single layer representation of the Ozark aquifer was not sufficient to simulate both discharge to streams and flow to deep pumping wells, a direct consequence of vertical variations in the lateral hydraulic conductivity of the Ozark aquifer. Even with 7-day Q_2 low-flow discharge conditions, the smaller values of hydraulic conductivity required to simulate the measured drawdown around Springfield were too small to simulate the flow of the larger quantities of ground water in the shallow part of the aquifer to streams. When values of conductivity and recharge were small enough to simulate drawdown at pumping wells, stream reaches having considerable discharge were modeled as dry. Conversely, when values of conductivity were large enough to simulate movement of ground water to streams almost no drawdown was simulated at pumping wells. Because the focus of this study was on the effect of ground-water withdrawals on water levels in the Ozark aquifer, stream discharge was removed from the part of the model representing outcrop areas of the Ozark aquifer, and the recharge to the water table in this area was decreased to more closely represent recharge to the deeper parts of the aquifer. Therefore, the model only simulates the lateral flow of ground water deep within the Ozark aquifer and does not simulate the interaction between streams and the aquifer. Evidence for the validity of assuming that the shallow part of the Ozark aquifer forms a leaky confining unit above the deeper part of the aquifer can be seen in northeastern Greene County where two Greene County Public Water-Supply District 5 wells, in the outcrop area of the Ozark aquifer and pumping at a combined rate of only 0.035 Mgal/d, have produced 50 to 60 ft of drawdown.

The average square error between the measured and simulated hydraulic heads in the Springfield Plateau aquifer is 1,392 ft squared with an average difference of 4 ft. A comparison between contour maps of measured and simulated predevelopment water table (fig. 26) indicates that the simulated hydraulic heads generally are slightly lower than measured heads in upland recharge areas and slightly higher than measured heads in lowland discharge areas. Some of this discrepancy probably can be eliminated by decreasing the value of lateral hydraulic conductivity of layer 1; however, because of model limitations it is difficult to determine how accurately the simulated lateral hydraulic conductivity of layer 1 (5.0×10^{-5} ft/s) represents the actual effective lateral hydraulic conductivity of the saturated thickness of the Springfield Plateau aquifer. The simulated hydraulic conductivity may more accurately represent the lateral hydraulic conductivity of the lower part of the aquifer where karst has not developed. The limitation occurs because of the manner in which layer 1 is simulated by the model. To more closely approximate actual field conditions, the value of transmissivity of layer 1 is calculated before each iteration as the product of the saturated thickness and the lateral hydraulic conductivity of the layer. From hydrologic budget calculations it can be determined that the Springfield Plateau aquifer can be simulated using estimated 7-day Q_2 discharge to streams, and an appropriately revised recharge to the water table, if the lateral hydraulic conductivity of layer 1 is about 5.0×10^{-4} ft/s, or 10 times the value of the lateral hydraulic conductivity used in the calibration. Using these larger values in the model is problematic; as the model solution oscillates during the first several iterations, layer 1 becomes dewatered at several nodes near the edge of the saturated area where the saturated thickness is small. The model handles this situation by removing the dewatered node from the calculations. When a node simulating discharge to a stream is dewatered, a large volume of water is removed relative to the quantity of recharge in the area surrounding the dewatered node and the water budget is altered. Hydraulic heads are subsequently changed during the simulation to



Base from U.S Geological Survey State base map, 1:500,000; Missouri, 1973.

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

COMBINED OUTCROP AREA OF THE OZARK AQUIFER AND OZARK CONFINING UNIT

—1000— WATER-TABLE CONTOUR--Shows altitude of measured water table. Contour interval, in feet, is variable.

--1000-- SIMULATED WATER-TABLE CONTOUR--Shows altitude of simulated water table. Contour interval, in feet, is variable.

-·-·-·- LIMIT OF SATURATED AREA

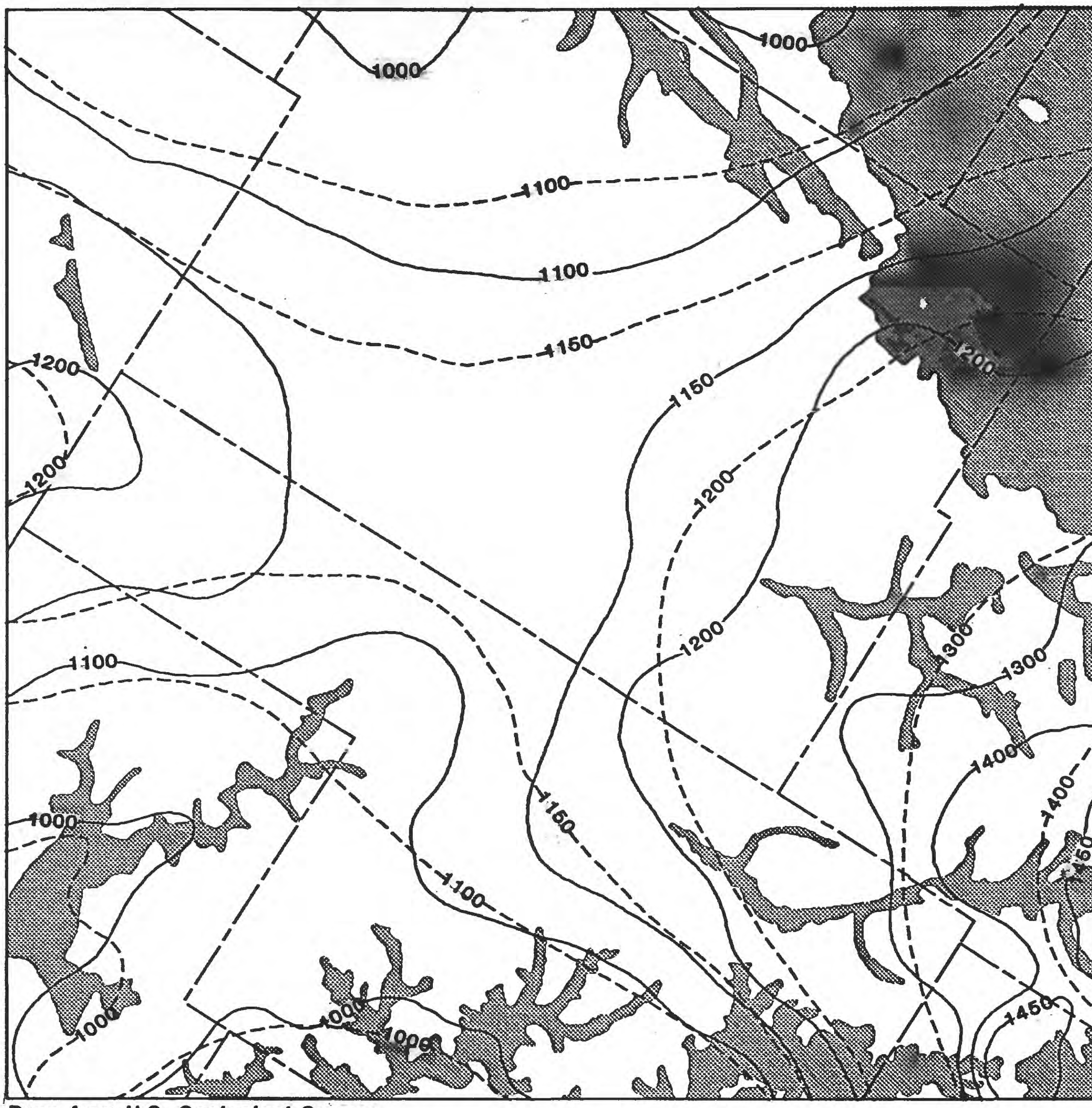
Figure 26.--Comparison of the measured and simulated predevelopment water table for the Springfield plateau aquifer.

reflect the modified water budget and, consequently, the model-derived heads for layer 1 no longer correctly simulate the measured heads. Use of the smaller values of lateral hydraulic conductivity and recharge to stabilize the model solution should not greatly affect the response of water levels in layer 1 to withdrawal of water in layer 2. Thus, the model can still be used to estimate the possible effect of ground-water pumpage in the Ozark aquifer on the shallow Springfield Plateau aquifer.

To test the hypothesis that it is possible to obtain an accurate simulation under 7-day Q_2 discharge conditions in the absence of the effect of dewatering nodes, an alternative model was constructed. A constant value of transmissivity throughout the stress period equal to the product of the saturated thickness, as determined from the difference between the predevelopment potentiometric surface and top of the confining unit, and the simulation lateral hydraulic conductivity, was used in the model. Using a lateral hydraulic conductivity of 5.0×10^{-4} ft/s and 17 percent of Dugan and Peckenpaugh's (1986) estimated recharge to the water table, the average squared error of the simulated heads for layer 1 is 3,594 feet squared (average difference of 11 ft) and the distribution of errors was nearly identical to the original model.

Thus, both models yield sufficiently accurate representations of the predevelopment potentiometric surface of the Springfield Plateau aquifer. However, the smaller calibration value of 5×10^{-5} ft/s, calculated using variable transmissivity and a smaller discharge to streams, probably is more representative of the deeper non-karstic parts of the aquifer; whereas, the larger calibration value of 5×10^{-4} ft/s, calculated using a fixed transmissivity and larger discharge to streams, probably is more representative of the upper karstic parts of the aquifer. The smaller value of hydraulic conductivity also is consistent with specific-capacity data from wells open only to the Springfield Plateau aquifer. The specific capacity of such wells generally is less than 1.0 gal/min-ft (gallons per minute per foot). Assuming a specific capacity of 1.0 gal/min-ft after 1 hour of pumping, a fully penetrating well of radius .25 ft open to 200 ft of aquifer, and an aquifer specific yield of .02, the aquifer hydraulic conductivity can be estimated, using the Jacob approximation to the Theis equation (Lohman, 1979), at 8×10^{-6} ft/s.

The predevelopment measured and simulated hydraulic heads in the Ozark aquifer are compared in figure 27. The average squared error between the heads is 605 ft squared with an average difference of -15 ft. The simulated heads generally are within 20 to 30 ft of the measured heads, except in the southwestern corner of Webster County where the difference is as much as 60 ft. This increased error probably is due to the difficulty of accurately simulating the complex outcrop patterns with relatively large square model cells. Because the model is not designed to distribute recharge at a particular node between two layers, all recharge to nodes that include outcrop areas of both aquifers is assigned to the aquifer having the larger outcrop area in the cell, generally layer 1. Also, most of the areas upgradient from the cells having large errors in simulated hydraulic head are treated as unsaturated. It is probable that the lack of accurate predevelopment head data in this area has contributed to inaccuracies in the identification of the extent of the unsaturated area. The leakage to the Ozark aquifer where the Springfield Plateau aquifer is unsaturated is limited in magnitude to the value of the vertical hydraulic conductivity of the Ozark confining unit. The hydraulic gradient across the confining unit is assumed to be equal to unity. The leakage would be greater if a larger gradient is responsible for the flow. The thickness of the Springfield Plateau aquifer, throughout the extent identified as unsaturated area, ranges from 40 to 100 ft and, therefore, may actually be partially saturated.



Base from U.S. Geological Survey
State base map, 1:500,000;
Missouri, 1973.

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

OUTCROP AREA OF THE OZARK AQUIFER

—1100— POTENTIOMETRIC CONTOUR--Shows altitude at which measured water levels would have stood in tightly cased wells. Contour interval, in feet, is variable. Datum is sea level.

--1100-- SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude of simulated water levels. Contour interval, in feet, is variable. Datum is sea level.

Figure 27.--Comparison of the measured and simulated predevelopment potentiometric suface of the Ozark aquifer.

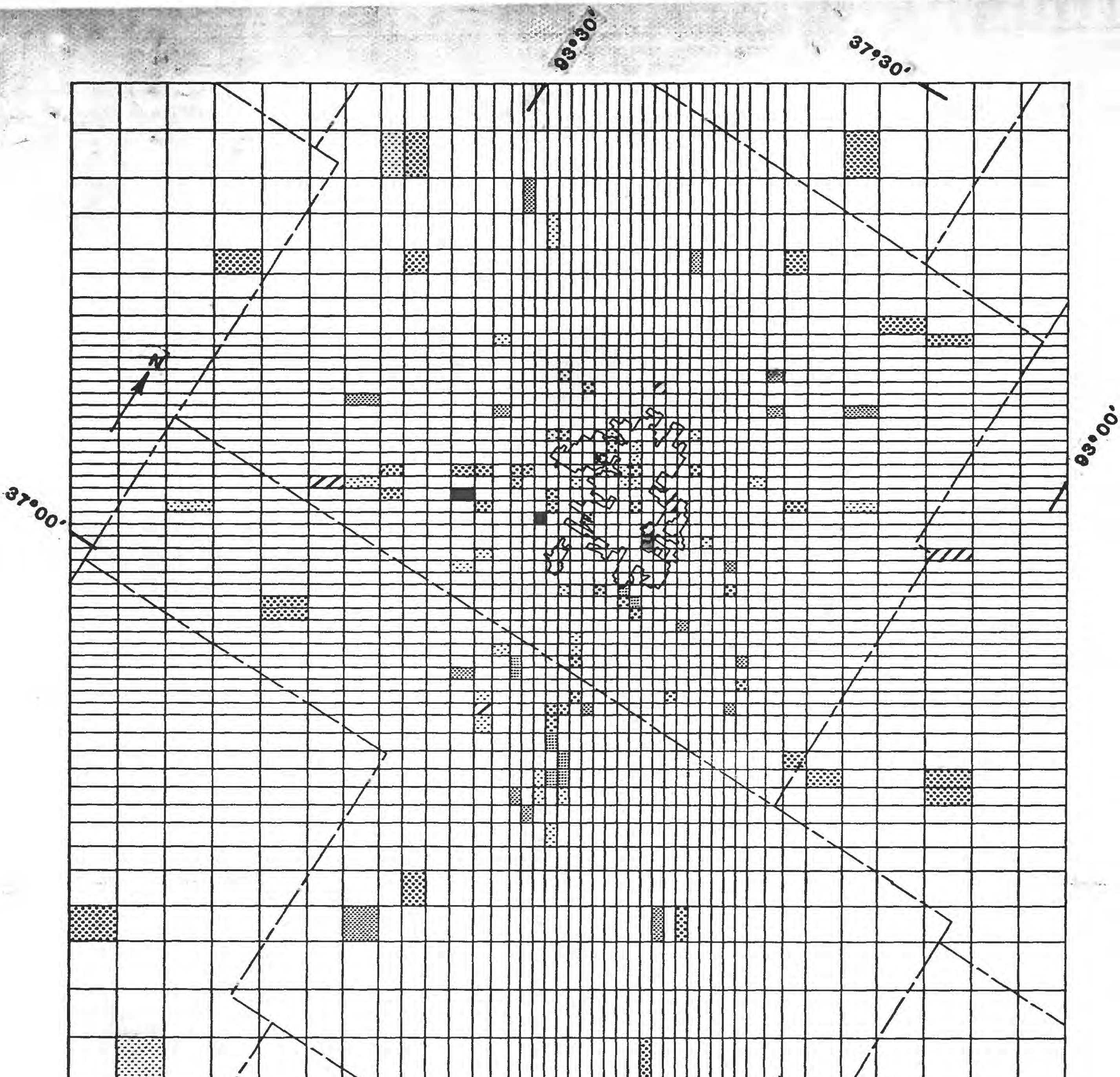
The best simulation of the predevelopment potentiometric surface is not represented by either figure 26 or 27. Both surfaces can be simulated with smaller average square errors and near zero average differences in hydraulic head. However, some accuracy in these simulations was sacrificed to more accurately simulate the pumping modified potentiometric surface measured in July and August 1987.

Transient Calibration: Pumping Conditions

Estimated ground-water withdrawals for the Springfield area, excluding water use for domestic and stock supply, were used to calibrate the ground-water flow model under transient conditions. Rural water use estimates were not used because the distribution of rural water use is unknown. Excluding the rural water use data should not greatly affect the accuracy of the model calibration because estimated rural water use is only about 10 percent of total water use. The simulated hydraulic heads were calibrated to the June 1974 and July-August 1987 potentiometric surface of the Ozark aquifer. Annual pumpage for this model calibration was initiated at 1961 estimated rates and terminated with 1986 estimated rates. Pumping rates for years for which measured or estimated rates are not available were derived by linear interpolation of estimated values or extrapolation of a value forward or backward in time. Because there is more uncertainty regarding the accuracy of pumping rates estimated for the earlier times, only a comparison between July-August 1987 measured hydraulic heads and simulated hydraulic heads at the end of 1986 was used to assess the accuracy of the transient calibration. Pumping-rate data published by the Missouri Department of Natural Resources (1962-1987) are assumed to represent withdrawal rates for the year previous to the publication year. The distribution of ground-water pumping rates for 1986 is shown in figure 28. There is more ground-water pumpage in and near Springfield, where the larger industries are located, than elsewhere. The pumpage data, although probably not complete, are believed to account for most of ground-water withdrawals in the Springfield area.

Values of lateral hydraulic conductivity for the Ozark aquifer range from 8.0×10^{-6} to 3.0×10^{-5} ft/s in the model. The simulated vertical hydraulic conductivity of the Ozark confining unit ranges from 9.0×10^{-11} to 1.1×10^{-10} ft/s. The simulated vertical hydraulic conductivity for the St. Francois confining unit is 4.5×10^{-11} ft/s. Calibration of the transient model also required that storage properties be simulated for the Springfield Plateau and Ozark aquifers. The simulated value of specific yield for the unconfined Springfield Plateau aquifer is constant at 0.02. The simulated value of specific yield for the Ozark aquifer ranges from 0.02 in areas where the aquifer is exposed at land surface to 0.001 in areas where the aquifer subcrops beneath the Ozark confining unit. The simulated value of storage coefficient for the confined part of the Ozark aquifer is 1.0×10^{-4}.

The estimate of lateral hydraulic conductivity of the Ozark aquifer is consistent with other estimates obtained from a previous, less detailed, transient model of ground-water flow in the Springfield area (Emmett and others, 1978), from a transient model of ground-water flow in northeastern Missouri (Imes, 1985), and from a transient model of ground-water flow in a 10 county area south and southeast of Audrain County, Missouri (Emmett and Imes, 1984). Although the boundaries of the Ozark aquifer do not extent north of the Missouri River, the lithologic and hydrologic characteristics of Cambrian and Ordovician rocks in northeastern Missouri are similar to the equivalent buried strata in



Base from U.S. Geological Survey State base map, 1:500,000; Missouri, 1973.

EXPLANATION

AVERAGE ANNUAL GROUND-WATER WITHDRAWAL, IN CUBIC FEET PER SECOND

- Less than 0.0001
- 0.001 - 0.01
- 0.01 - 0.1
- 0.1 - 0.5
- 0.5 - 1.0
- More than 1.0

0 5 10 MILES
0 5 10 KILOMETERS

Figure 28.—Estimated average annual withdrawal of water from the Ozark aquifer during 1986.

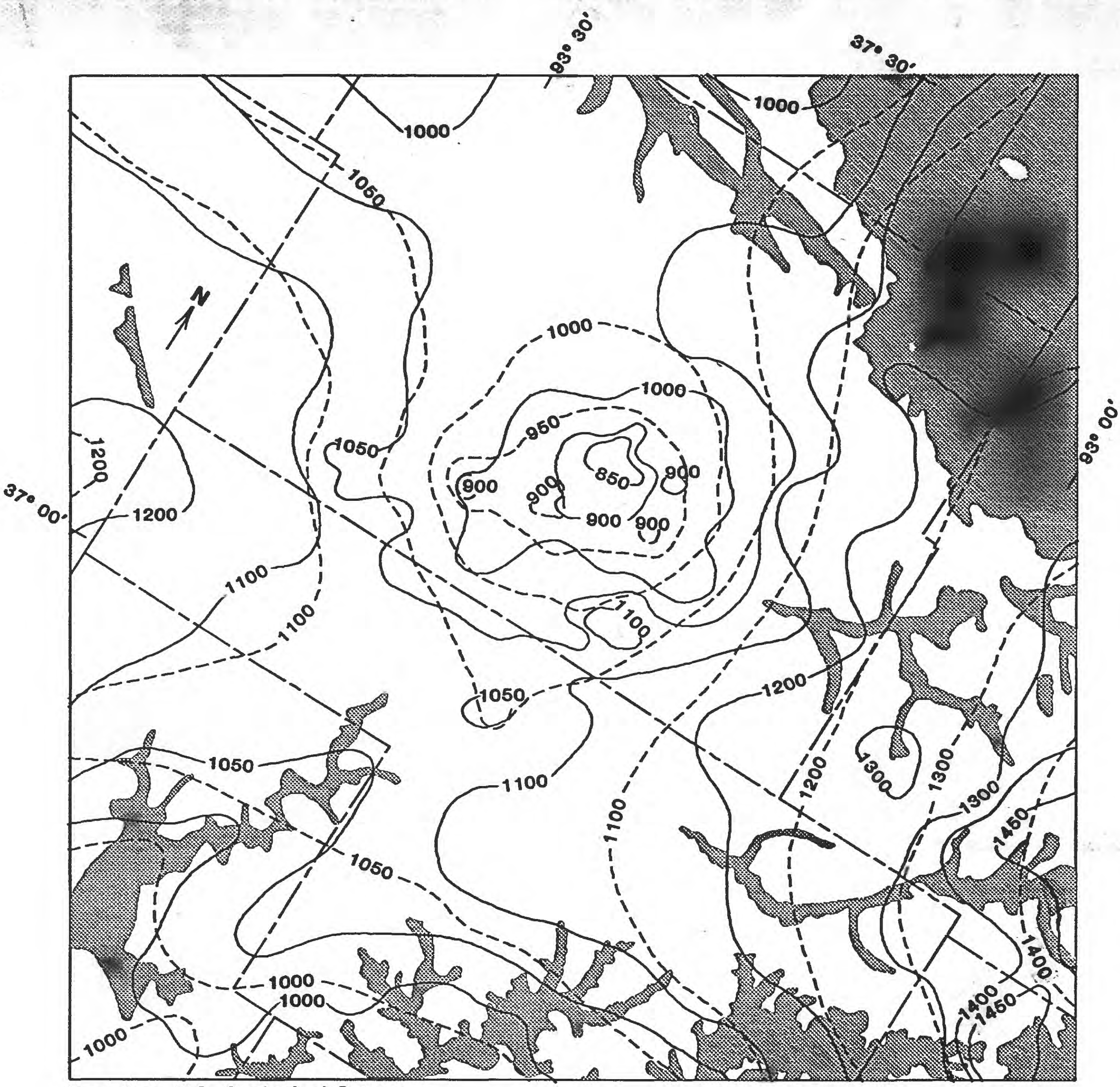
the western Ozark Plateaus. The estimate of lateral hydraulic conductivity also is consistent with a flow net analysis of the June 1974 drawdown pattern around Springfield reported by Emmett and others (1978, p. 31). As with the previous ground-water flow model of this area, the lateral hydraulic conductivity of the Ozark aquifer is less than the hydraulic conductivity derived from hydraulic testing of the aquifer (Emmett and others, 1978, p. 30).

The simulated vertical hydraulic conductivity of the Ozark confining unit is smaller than the value of 1.0×10^{-9} estimated by Emmett and others (1978, p. 109). However, there are valid reasons for this difference in estimates. The previous model did not include a representation of the outcrop area of the Ozark aquifer. Instead, the Ozark aquifer was assumed to be confined everywhere. Thus, recharge to the outcrop area of the aquifer was implicitly applied as additional leakage through the Ozark confining unit, which necessitated a larger effective vertical hydraulic conductivity.

A comparison of measured and simulated 1987 hydraulic heads in the Ozark aquifer (fig. 29) indicates a generally adequate representation of the actual heads by the model. The average squared error between measured and simulated heads is 898 ft squared and the average difference is 11 ft. One factor that may explain the larger differences between measured and simulated hydraulic heads near the center of the drawdown cone at Springfield is the possibility that some measured heads in this area show the effect of large localized drawdown in nearby pumping wells, not the average hydraulic head over the area of the model cell as is simulated by the model. To eliminate this error as much as possible, pumps in production wells were turned off for several minutes before a water level was measured within the well. Other factors include the possibility that pumping data are not accurate and that the model simulates the response of the potentiometric surface to average annual pumpage, and, therefore, does not simulate seasonal variations in pumpage. It is possible that some industrial pumpage is larger in the hotter summer months than in the cooler winter months.

Changes in the Hydrologic Budget Resulting from Pumping

A comparison of the model water budget under predevelopment conditions and after the effect of 1986 pumpage (referred to as the 1987 water budget) allows several conclusions about the effect of pumpage on the ground-water flow system (fig. 30). Net recharge to layer 1 increases slightly from 10.2 to 11.5 ft^3/s. Because both simulations use the same initial conditions to describe recharge to the water table and discharge to streams and these boundary conditions are independent of hydraulic head, the model cannot simulate changes in stream discharge. However, the change in net recharge does indicate that hydraulic heads in layer 1 decreased sufficiently to decrease discharge to the lakes represented as constant heads in the model (McDaniel Lake and Lake Springfield). Leakage from layer 1 to layer 2 increased from 9.3 to 18.5 ft^3/s because a larger hydraulic gradient is available to move water through the Ozark confining unit. The approximate doubling of downward leakage compares favorably with the increase estimated previously using contoured measured hydraulic head data. Most of the increased leakage of water from layer 1 to layer 2 is provided by the 7.4 ft^3/s of water released from storage as water levels in layer 1 decline. The decline, as computed by the model, is about 20 to 25 ft near the center of the drawdown cone. It is difficult to determine the accuracy of this estimated decline because of assumptions used during the model design, because of the manner in which the model simulation is affected as small areas in layer 1 are dewatered, and because data on water levels in layer 1 are lacking.



Base from U.S. Geological Survey State base map, 1:500,000; Missouri, 1973.

0 5 10 MILES
0 5 10 KILOMETERS

EXPLANATION

OUTCROP AREA OF THE OZARK AQUIFER

-1000- POTENTIOMETRIC CONTOUR--Shows altitude at which measured water level would have stood in tightly cased wells. Contour interval, in feet, is variable. Datum is sea level.

- -1000- - SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude of simulated water levels. Contour interval, in feet, is variable. Datum is sea level.

Figure 29.--Comparison of the measured and simulated 1987 potentiometric surface of the Ozark aquifer.

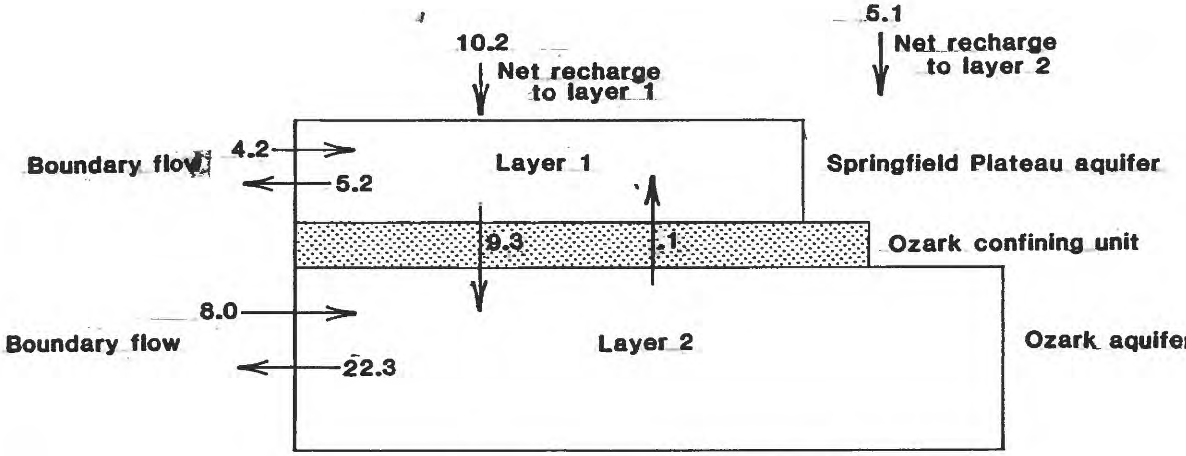
The hydrologic budget for model layer 2 is directly affected by the 17.6 ft^3/s of ground water removed by water-supply wells. Differences between the predevelopment and 1987 water budgets (fig. 30) reflect the response of the ground-water system to the pumping. Water removed by pumping is replaced by an increase in leakage through the Ozark confining unit (from 9.3 to 18.5 ft^3/s), by the removal of water from storage in the aquifer (1.2 ft^3/s), and by reduced flow out of the study area laterally through the Ozark aquifer and vertically through the St. Francois confining unit (from a net 14.3 ft^3/s to a net 7.1 ft^3/s). The increased flow of water into the Ozark aquifer from upward leakage through the St. Francois confining unit is about 0.4 ft^3/s. Thus, the St. Francois aquifer only provides a small fraction of the total water pumped from the Ozark aquifer.

Assuming a porosity of 10 percent for the Northview Shale and the model-derived vertical hydraulic conductivity, the rate of ground-water flow across the Northview Shale beneath Springfield can be estimated at 100 years. The traveltime estimate implicitly assumes a uniform, unfractured or unbreached, strata of shale. Fractures and cavernous breaches can increase vertical flow rates by several orders of magnitude.

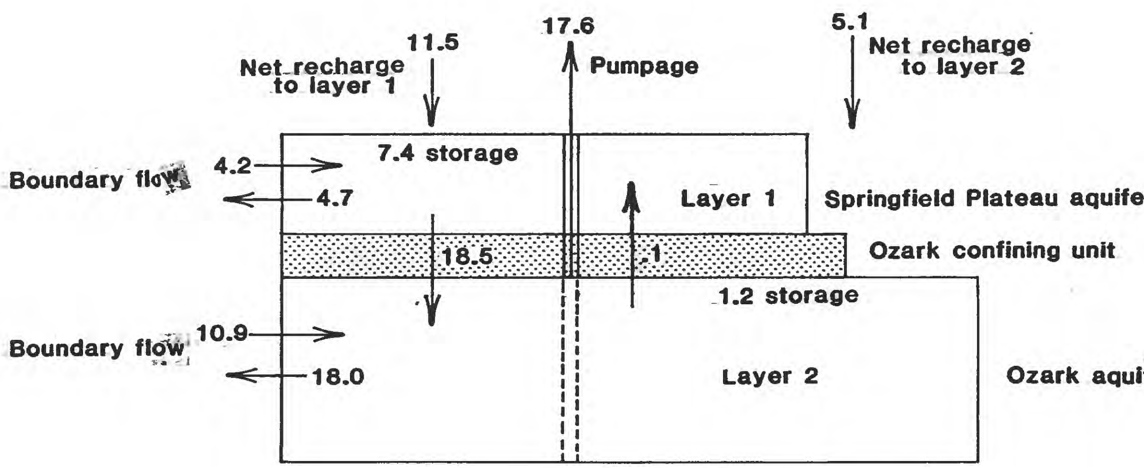
ESTIMATED EFFECTS OF CONTINUED DEVELOPMENT OF THE OZARK AQUIFER

To estimate the response of the Springfield Plateau and Ozark aquifers to continued withdrawals of ground water from the Ozark aquifer, estimated future pumping rates were applied to the calibrated model. Future pumping rates were assumed to increase annually by 1.84 percent from the pumping rate of the previous year, beginning with the 1986 estimated rate. This increase corresponds to a 20 percent increase in pumpage every 10 years and is consistent with conservative estimates of future water needs (Lise Scheuch, City Utilities of Springfield, 1988, oral commun.). The increase was assumed to apply equally to all wells in the model area that were pumping during 1986 and does not indicate water available only to City Utilities of Springfield.

This hypothesis was simulated for the period 1987 to 2010, when total pumpage is estimated to be 27.3 ft^3/s. For 2010, estimated water levels within the Ozark aquifer at the model boundaries declined a maximum of about 150 ft. The largest estimated declines were localized in a small area east of Springfield. Model simulated heads probably are not severely affected by the boundary conditions; however, the model should not be used to predict hydraulic head distributions beyond 2010. Additional drawdowns range from about 100 to 174 ft are predicted for the area that encompasses Springfield and a small region southwest of the city (fig. 31). Additional drawdowns of at least 50 ft are predicted for a nearly circular area centered southwest of Springfield and extending to Republic and Nixa. Tests of model sensitivity to changes in values of hydraulic variables indicate that the model is most sensitive to changes in hydraulic conductivity of the Ozark aquifer, and much less sensitive to changes in recharge and hydraulic conductivity of the Springfield Plateau aquifer. A ± 10 percent change in hydraulic conductivity of the Ozark aquifer causes a ± 7.6 percent or less change in simulated additional drawdown at 2010 for the area around Springfield where the maximum drawdown occurs. This percentage change translates into a ± 13 feet maximum uncertainty in simulated additional drawdown around Springfield. Although ground-water supplies to the study area should be adequate under the assumptions of this scenario for the next 20 years, some pumps may need to be lowered so that water levels do not decline below the



Predevelopment water budget



1987 water budget

VOLUMETRIC FLOW RATES ARE IN CUBIC FEET PER SECOND

Figure 30.--Model water budget under predevelopment conditions and under conditions at the end of 1986, shown as the 1987 water budget.

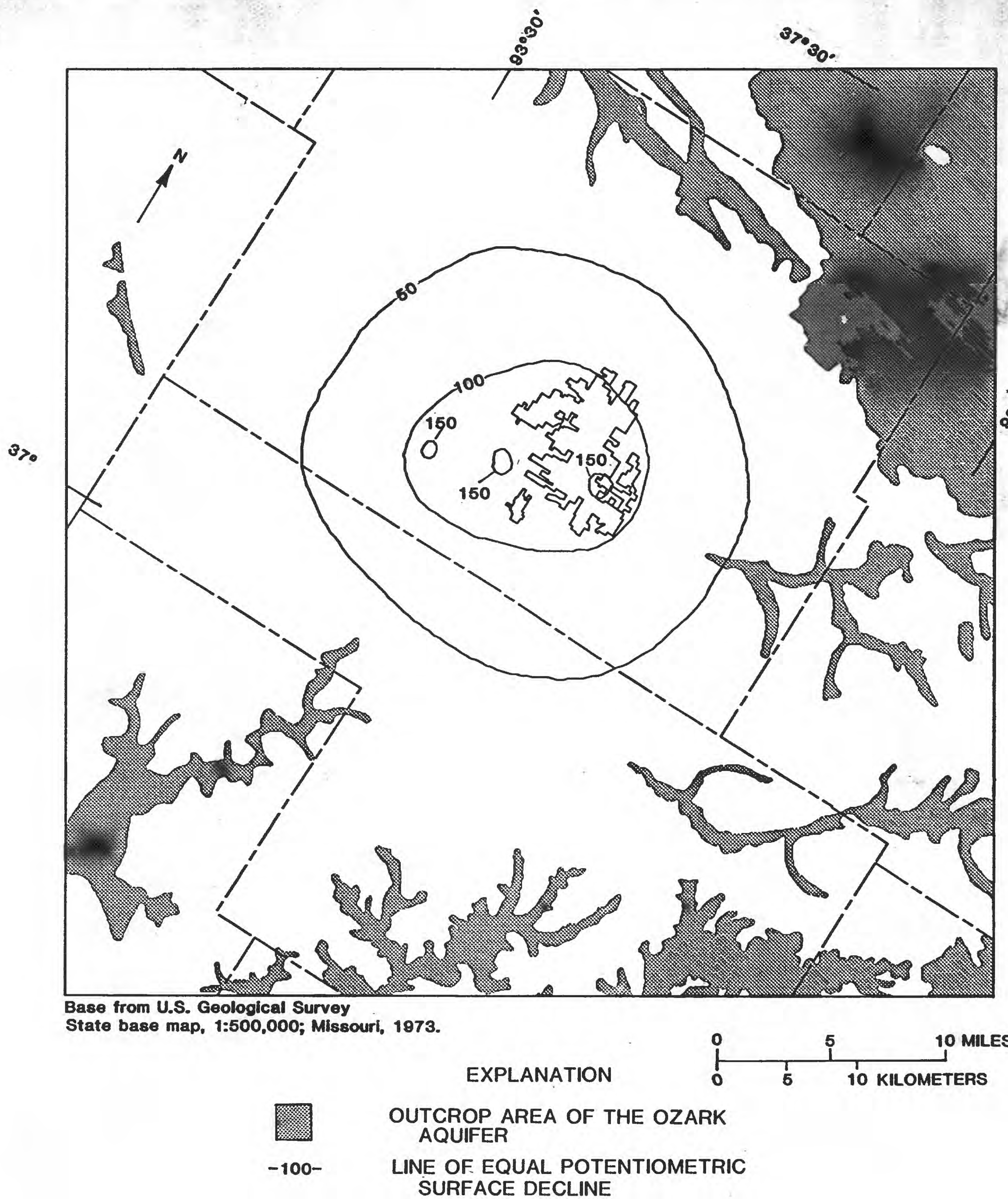


Figure 31.--Estimated decline of the potentiometric surface in the Ozark aquifer from 1987 to 2010.

pump intakes. Water levels in the Springfield Plateau aquifer may decline an additional 20 to 30 ft throughout much of the area west and south of Springfield. No new wells were introduced into the model during the simulation period. This pumping scenario does not represent the actual changes in pumping rates of individual wells but only represents one way of applying an estimate of future total water demand for the area to the flow model.

NEEDS FOR FUTURE STUDY OF GROUND-WATER FLOW AND WATER QUALITY NEAR SPRINGFIELD

The assumptions made in defining the hydrogeologic system in the study area are limited by the current level of understanding of ground-water flow and ground-water quality near Springfield. The effect of ground-water withdrawals from the Ozark aquifer on water levels in the overlying Springfield Plateau aquifer is not known. A network of shallow wells can be used to estimate this effect. Water levels in these monitoring wells may be correlated with variations in precipitation and changes in water levels in the Ozark aquifer. Sinkholes and solution channels are used to remove stormwater from Springfield; this practice may contribute to dissolution of carbonate rock in the study area. The fate of materials transported into the Springfield Plateau aquifer through solution channels and sinkholes is not known. The potential for contaminant migration into the Ozark aquifer through interaquifer exchange of water in abandoned or infrequently used wells that are open to both the Springfield Plateau and Ozark aquifers is not known, nor is the contribution to interaquifer flow through the annuli of poorly cased wells.

Future water-level declines in the Ozark aquifer west and southwest of Springfield may present an opportunity to study ground-water flow across the contact area created by displacement of the Battlefield-Sac River Fault. Flow from the Springfield Plateau aquifer to the Ozark aquifer may increase the risk of contamination of the Ozark aquifer.

SUMMARY

The ground-water flow system near Springfield was studied to provide a quantitative description of the system and determine the effect of continued ground-water pumpage. Three aquifers are present in the Springfield area; the Springfield Plateau aquifer, the Ozark aquifer, and the St. Francois aquifer. Rocks that comprise the Springfield Plateau aquifer form the bedrock surface beneath Springfield. Thickness of the unconfined aquifer ranges from near zero to about 300 ft in the 1,764 mi^2 study area. The small yield of wells open to the Springfield Plateau aquifer and its susceptibility to contamination because of karst development in the upper part of the aquifer limit its use to domestic and stock-water supply in rural areas. In contrast, the underlying Ozark aquifer is more than 1,000 ft thick and can yield large quantities of water to wells. The Ozark confining unit separates and partially isolates the Ozark aquifer from the Springfield Plateau aquifer. The Ozark aquifer is used as a source of water for municipalities and industries throughout the study area. Recently drilled domestic wells also usually are open to the Ozark aquifer. The St. Francois aquifer is the deepest of the three aquifers. Because well yield does not increase substantially from that obtained in the overlying Ozark aquifer, water-supply wells commonly are not drilled into the St. Francois aquifer.

Ground-water withdrawals from the Ozark aquifer for public supply and industrial use by Springfield and surrounding communities have substantially altered the potentiometric surface of the aquifer. Ground water that once flowed north and south from a regional divide (that trends east and west through southern Missouri and passes through Springfield) now is directed towards Springfield. From the time wells first penetrated the Ozark aquifer (late 1800's) to June 1974, water levels in the aquifer have declined a maximum of 293 ft near the western edge of Springfield. The maximum drawdown in July-August 1987 had increased to 335 ft, or 42 ft more than the 1974 maximum drawdown. The area of the cone of depression has increased, especially to the south and southwest, because of increased pumpage by Springfield, Republic, and Nixa. Estimates of the downward leakage of ground water through the Ozark confining unit based on historic and 1987 potentiometric surfaces indicate that downward leakage has approximately doubled because of the increased hydraulic gradient across the confining unit.

Calibration of a ground-water flow model for a 42 mi by 42 mi area centered on Springfield for predevelopment and transient conditions provided estimates of the lateral hydraulic conductivity of the Springfield Plateau aquifer that range from 5.0×10^{-5} to 5×10^{-4} ft/s, depending on the analysis used. The smaller value probably is more representative of the deeper, non-karstic parts of the Springfield Plateau aquifer. The lateral hydraulic conductivity of the Ozark aquifer is estimated to range from 8.0×10^{-6} to 3.0×10^{-5} ft/s. The vertical hydraulic conductivity of the Ozark confining unit ranges from 9.0×10^{-11} to 1.1×10^{-10} ft/s, and the vertical hydraulic conductivity of the St. Francois confining unit is estimated to be 4.5×10^{-11} ft/s. The magnitude of the calibration vertical hydraulic conductivity of the Ozark confining unit, and St. Francois aquifer, and the lateral hydraulic conductivity of the Ozark aquifer are less than initial estimates from a predevelopment steady-state model of regional ground-water flow in the Ozark Plateaus aquifer system. The estimates obtained during the calibration of the Springfield area model probably are more accurate because of additional transient calibration and smaller size of the model cells. However, the Springfield model does not represent the more conductive shallow part of the Ozark aquifer, but only the deeper part that transmits ground water to wells.

The estimated specific yield of the unconfined Springfield Plateau aquifer and unconfined part of the Ozark aquifer is 0.02. Where the Ozark aquifer is confined under natural conditions, a storage coefficient of 1.0×10^{-4} was estimated. A specific yield of 0.001 was assigned to the Ozark aquifer where the aquifer subcrops beneath the Ozark confining unit and 0.02 was assigned where the aquifer is exposed at land surface.

Changes in the hydraulic heads of the Ozark aquifer, and to a lesser extent the Springfield Plateau aquifer, because of pumpage have altered the hydrologic budget of the Springfield area. Of the approximately 17.6 ft^3/s of ground-water pumped from the Ozark aquifer in 1986, about 50 percent is supplied by increased downward leakage through the Ozark confining unit, about 10 percent comes from storage within the Ozark aquifer, and about 40 percent is supplied by lateral flow in the Ozark aquifer. Minimal quantities of water are supplied by increased leakage through the St. Francois confining unit. Previous studies of deep well production in this area have shown that well yields are not substantially increased by extending well openings to include the deeper St. Francois aquifer. Hydraulic heads in the shallow Springfield Plateau aquifer are lowered somewhat by pumping in the underlying Ozark aquifer, but the head decline seems to be only on the order of 25 ft or less. Because simulations indicate ground water is presently (1987) being removed from storage within the Springfield Plateau and Ozark aquifers, the hydrologic system apparently is not in equilibrium at this time.

An analysis of the response of water levels in the Springfield Plateau and Ozark aquifers to a pumping rate increase of 20 percent every 10 years to the year 2010 indicated water levels in the Ozark aquifer may decline an additional 100 to 150 ft near Springfield and at least an additional 50 ft in a nearly circular area centered near southwest Springfield and extending to Republic and Nixa. Water levels in the Springfield Plateau aquifer may decline an additional 20 to 30 ft. This analysis uses only one of many possible methods of applying a projected increase in water use for the region. The analysis does not attempt to proportion projected water requirements between ground water and potential new surface-water sources. The assumption is made that all future water needs are derived from ground-water withdrawals from the Ozark aquifer. Actual drawdowns may be smaller than predicted drawdowns if new surface-water sources are developed. Also, ground-water use can vary considerably from year to year depending on climatic conditions. Because of the rapid response of the ground-water system to changes in pumping rates, water levels can change substantially within a few years. As an example, water levels near Springfield rose considerably from 1980 to 1985 because of reduced ground-water use by City Utilities of Springfield after the drought of 1980. Because these situations cannot be predicted, they cannot be included in this analysis of the response of water levels to future ground-water withdrawals. However, ground-water supplies should be adequate for at least the next 20 years, assuming that water-use projections used in this report are correct. Estimated regional drawdown by 2010 is not large enough to necessitate excessive pump-lift requirements; however, the placement of new, large-capacity wells in close proximity to each other may result in substantially larger drawdowns near the wells than is predicted by this model.

Contaminant movement in the karst terrane of the Springfield Plateau aquifer cannot be modeled using the relatively small value of hydraulic conductivity used to model regional ground-water flow to wells in the Springfield area. This is because contaminants will move along solution-enlarged fractures and joints much more rapidly than through the non-karstic parts of the aquifer characterized by the small conductivity values. Because the Ozark confining unit is thin, the less conductive shale fraction even thinner, and because in places, the confining unit is breached by fractures and larger joints, faults, and uncased water wells, contamination of the Springfield Plateau aquifer could result in contamination of the Ozark aquifer.

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