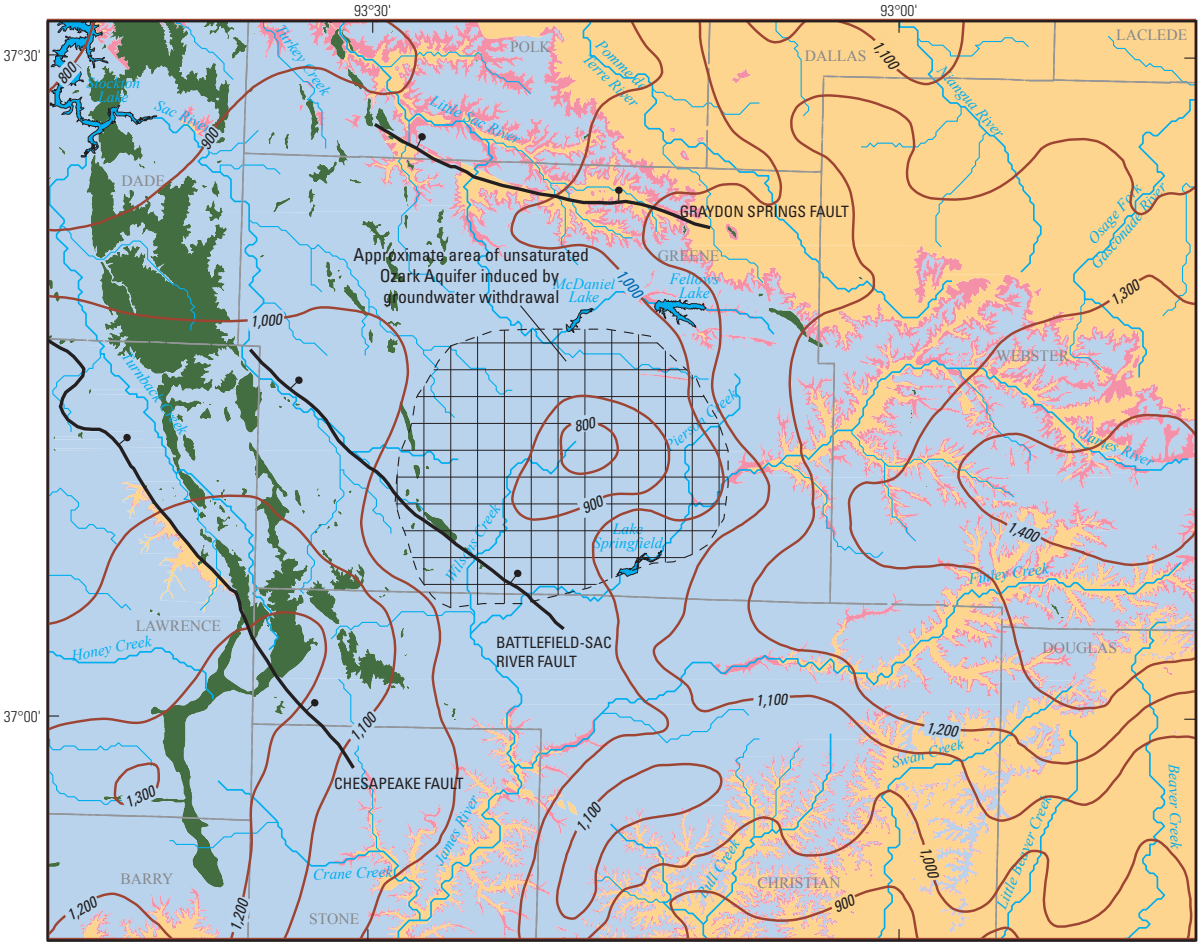
In cooperation with Greene County, Missouri, the U.S. Army Corps of Engineers, and the Missouri Department of Natural Resources

Groundwater-Flow Model and Effects of Projected Groundwater Use in the Ozark Plateaus Aquifer System in the Vicinity of Greene County, Missouri—1907-2030



Scientific Investigations Report 2010–5227

U.S. Department of the Interior
U.S. Geological Survey

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By Joseph M. Richards

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U.S. Department of the Interior
U.S. Geological Survey

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch	2.54	centimeter (cm)
inch	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Groundwater-Flow Model and Effects of Projected Groundwater Use in the Ozark Plateaus Aquifer System in the Vicinity of Greene County, Missouri—1907–2030

By Joseph M. Richards

Abstract

Recent and historical periods of rapid growth have increased the stress on the groundwater resources in the Ozark aquifer in the Greene County, Missouri area. Historical pumpage from the Ozark aquifer has caused a cone of depression beneath Springfield, Missouri. In an effort to ease its dependence on groundwater for supply, the city of Springfield built a pipeline in 1996 to bring water from Stockton Lake to the city. Rapid population growth in the area coupled with the expanding cone of depression raised concern about the sustainability of groundwater as a resource for future use. A groundwater-flow model was developed by the U.S. Geological Survey in cooperation with Greene County, Missouri, the U. S. Army Corps of Engineers, and the Missouri Department of Natural Resources to assess the effect that increased groundwater demand is having on the long-term availability of groundwater in and around Greene County, Missouri.

Three hydrogeologic units were represented in the groundwater-flow model: the Springfield Plateau aquifer, the Ozark confining unit, and the Ozark aquifer. The Springfield Plateau aquifer is less than 350 feet thick in the model area and generally is a low yield aquifer suitable only for domestic use. The Ozark aquifer is composed of a more than 900-foot thick sequence of dolomite and sandstone in the model area and is the primary aquifer throughout most of southern Missouri. Wells open to the entire thickness of the Ozark aquifer typically yield 1,000 gallons per minute or more. Between the two aquifers is the Ozark confining unit composed of as much as 98 feet of shale and limestone. Karst features such as sinkholes, springs, caves, and losing streams are present in both aquifers, but the majority of these features occur in the Springfield Plateau aquifer. The solution-enlarged fracture and bedding plane conduits in the karst system, particularly in the Springfield Plateau aquifer, are capable of moving large quantities of groundwater through the aquifer in relatively short periods of time.

Pumpage rates in the model area increased from 1,093,268 cubic feet per day in 1962 to 2,693,423 cubic feet per day in 1987 to 4,330,177 cubic feet per day in 2006. Annual precipitation ranged from 25.21 inches in 1953 to 62.45 inches in 1927 from 1915 to 2006 in the model area. Recharge to the model was calculated as 2.53 percent of the annual precipitation and was varied annually. Recharge was distributed over the model area based on land slope and was adjusted in the city limits of Springfield to account for the impervious surface.

A groundwater model with annual stress periods from 1907 to 2030 was developed using a transient calibration period from 1987 to 2006 and a prediction period from 2007 to 2030 to simulate flow in the Springfield Plateau aquifer and the Ozark aquifer. For the model area of approximately 2,870 square miles, the model hydrogeologic units and hydraulic properties were discretized into 253 rows, 316 columns, and 3 layers with the layer boundaries crossing hydrogeologic unit boundaries in some areas. The horizontal cell spacing was 1,000 feet by 1,000 feet. The model was calibrated by minimizing the difference between simulated head and observed water levels and simulated and observed flows in rivers and springs.

Population and the associated groundwater use were estimated for 12 communities and the unincorporated area of Greene County based on past growth. Each was analyzed individually, and a low and high annual rate of growth relative to the 2006 population was computed for each community or group. Low growth rates ranged from 0.215 percent per year in Springfield to 6.997 percent per year in Rogersville. Total growth from 2006 to 2030 at the low growth rate ranged from 5.2 percent in Springfield to 167.9 percent in Rogersville. High growth rates ranged from 0.236 percent per year in Springfield to 7.345 percent per year in Rogersville. Total growth from 2006 to 2030 at the high growth rate ranged from 5.7 percent in Springfield to 176.3 percent in Rogersville.

Response of the flow system to selected hypothetical pumping stresses and recharge conditions was simulated

using the calibrated model. Seven hypothetical scenarios were simulated from 2007 to 2030 to test the effects of various stresses on the head in the Ozark aquifer. Hypothetical scenario 1 continued the 2006 pumping rates without change to the end of 2030. Scenario 2 assumed a low population growth rate with a 4-year drought at the beginning of the prediction period. Scenario 3 assumed a low population growth rate with a 4-year drought at the end of the prediction period. Scenario 4 assumed a high population growth rate with a 4-year drought at the beginning of the prediction period. Scenario 5 assumed a high population growth rate with a 4-year drought at the end of the prediction period. Scenario 6 and 7 had one new industrial well installed within the city limits of Springfield and one new industrial well installed about 3.5 miles east of Rogersville. Scenario 6 assumed a low population growth rate and scenario 7 assumed a high population growth rate.

Results were compared by examining differences in head at the end of the simulation period. All scenarios examined resulted in potentiometric-surface declines from 2006 levels. Results from scenario 1 indicated that even with no increase in pumping, the potentiometric surface in the Springfield area continued to decline. The maximum decline of approximately 62 feet from the 2006 potentiometric surface occurred in Springfield. The maximum decline from the 2006 potentiometric surface in scenarios 2 and 3 was approximately 203 feet and in scenarios 4 and 5 was approximately 207 feet. The drought occurring at the end of the simulation period tended to broaden the drawdown area relative to the drought at the beginning. Drought timing did not substantially affect the potentiometric surface in the Ozark aquifer except for where the Ozark aquifer was exposed. Although not a substantial difference, the high population growth rate scenarios tended to have larger declines than the low population growth rate scenarios. As in the previous scenarios, little difference was noted between the low and high growth rate in scenario 6 and 7. Scenarios 6 and 7 showed declines of more than 640 feet from the 2006 potentiometric surface at the new well located in Springfield. The drawdown at the new wells decreased relatively quickly with increased distance from the well. Simulated head in the nearby cities of Nixa, Ozark, and Republic was nearly the same for scenarios 2 through 7 and was lower than the head predicted for scenario 1. Results from scenarios 2 through 7 indicate that the potentiometric surface in 2030 near these cities could decline 100 feet or more from the 2006 levels. Because model layers 2 and 3, representing the Ozark confining unit and most of the thickness of the Ozark aquifer, were simulated as confined, drawdown in the wells in the area of the Ozark aquifer that is unconfined or becomes unconfined during the simulation period will likely be under predicted.

Introduction

The demand for commercial, industrial, and residential water from the Ozark aquifer in Greene County, Missouri (fig. 1) and the surrounding area has increased steadily since the first deep wells were drilled for drinking water as early as 1907. Springfield (fig. 2), the third largest city in Missouri, was incorporated in 1838 (City Utilities of Springfield, 2009) and had an estimated 2007 population of 154,770 (Greene County Resource Management Department, written commun., 2009). Greene County had an estimated 2007 population of 263,793 (Greene County Resource Management Department, written commun., 2009). Historical population growth in Springfield and surrounding communities has increased local demand on the aquifer. The population of Springfield nearly doubled between 1950 and 1980, with the majority of growth occurring from 1950 to 1970 (Imes, 1989). The population of Springfield increased approximately 11 percent, from 1970 to 1980 (Imes, 1989). Population growth from 1970 to 1980 in some surrounding communities exceeded 24 percent (Imes, 1989). By the 1970s, groundwater pumpage from the Ozark aquifer in the Springfield area caused a cone of depression in the potentiometric surface (Emmett and others, 1978), which continued to grow during the 1980s (Imes, 1989). Projected rapid population growth coupled with a growing cone of depression in the Ozark aquifer, and the fact that the existing surface-water supply was operating near its maximum capacity, led Springfield water managers to look for alternative sources to supply their water needs. In the late 1980s, the city of Springfield began the process of supplementing their water supply with water from Stockton Lake (fig. 2). The project, completed in 1996, consisted of building a pump station and a 30-mile pipeline from Stockton Lake to Fellows Lake located 5 miles north of Springfield (Burns and McDonald, 2009).

The population of Springfield had increased by about 16 percent from 1980 to 2007, whereas Dintelmann and others (2006) reported that from 1990 to 2000, population growth in the nearby cities of Nixa, Ozark, and Republic (fig. 2) was 158 percent, 128 percent, and 34 percent, respectively. Commercial, industrial, and residential water use in these cities has continued to increase in proportion to the population growth, and between 1990 and 2003, these cities increased their groundwater pumpage by an estimated 139 percent over that same period (Dintelmann and others, 2006). Even though Springfield has reduced its dependence on groundwater after building the pipeline to Stockton Lake, all other municipal, industrial, and residential use in the area is entirely dependent on groundwater (Dintelmann and others, 2006). Groundwater level measurements made in 2006 and 2007 indicated that the

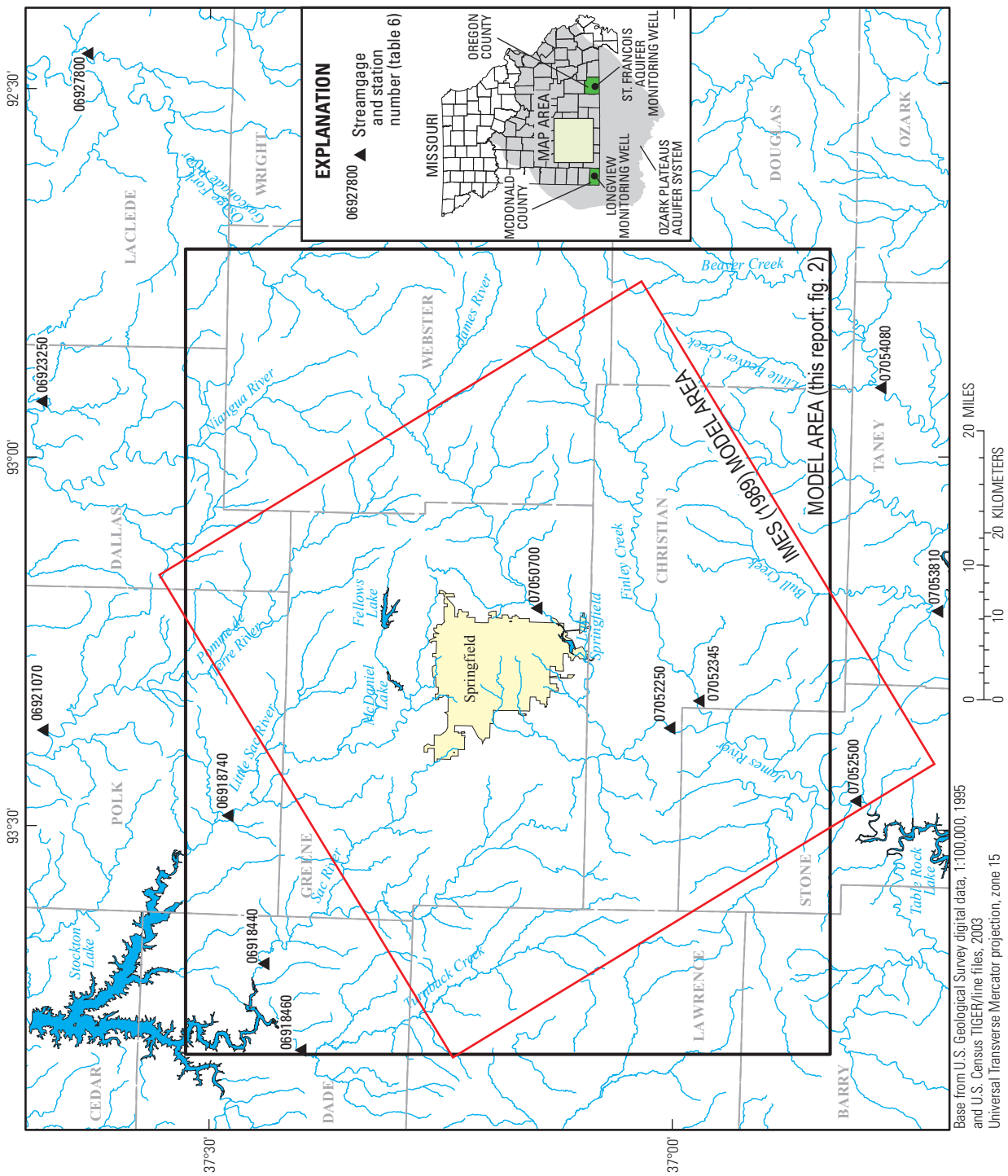


Figure 1. Location of current and previous model areas.

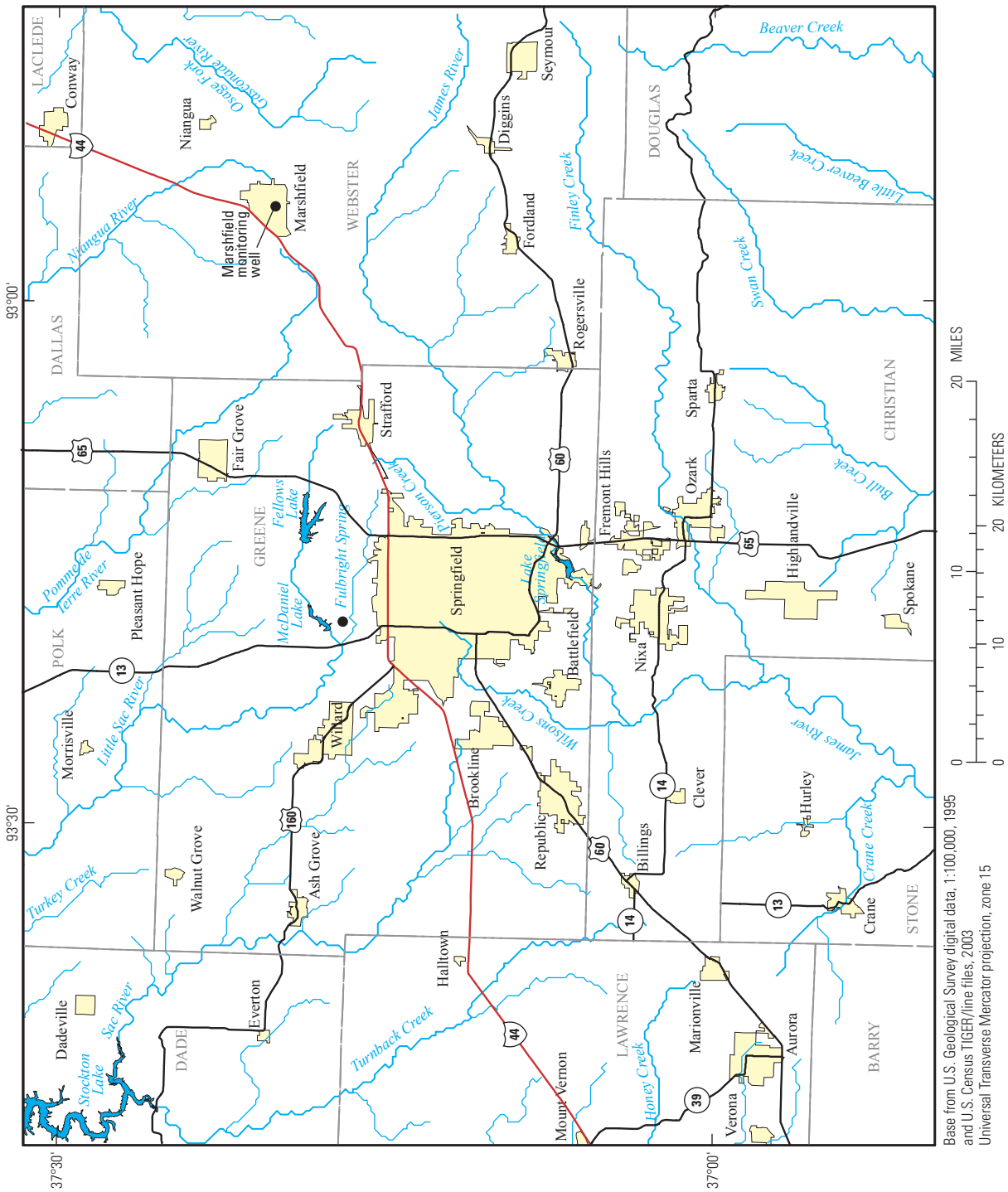


Figure 2. Location of communities in study area, which corresponds to the model area for the model described in this report.

cone of depression identified in the Ozark aquifer in the 1970s and 1980s continued to expand and deepen (Richards and Mugel, 2008).

The increasing stress on the Ozark aquifer and its continuing potentiometric-surface decline has raised new concerns about the future groundwater availability and the sustainability of current (2006) groundwater use. To assess the effect that increased groundwater demand might have on the long-term availability of groundwater in Greene County and the surrounding area, the U.S. Geological Survey (USGS), in cooperation with Greene County, the U.S. Army Corps of Engineers, and the Missouri Department of Natural Resources, developed and applied a groundwater-flow model to a model area covering a part of the Ozark Plateaus aquifer system (figs. 1 and 2).

Purpose and Scope

The purpose of this report is to document a groundwater-flow model that characterizes groundwater flow within a part of the Ozark Plateaus aquifer system in the vicinity of Greene County, Missouri. A description is presented of the development and calibration of the groundwater-flow model used to simulate groundwater flow within the Springfield Plateau and Ozark aquifers and followed by a description of the simulated effects of hypothetical pumping scenarios using the calibrated model. The scope of the model is limited to the part of the Springfield Plateau aquifer and Ozark aquifer within a 2,870 square mile (mi^2) area centered on Springfield, Missouri.

Previous Investigations

Numerous investigations have been made of the geology, hydrology, and water resources in the model area with particular emphasis on the city of Springfield and Greene County. Because of rapid growth and water-supply concerns, Emmett and others (1978) made a comprehensive assessment of the water resources and geology of the Springfield area, and identified and mapped a cone of depression in the potentiometric surface of the Ozark aquifer. By 1974, a potentiometric-surface decline from predevelopment conditions of nearly 300 feet (ft) in the center of the cone of depression was indicated (Emmett and others, 1978). Mapping historical water-level data at 10-year intervals, Steinkamp (1987) concluded that the cone of depression was present beneath Springfield in the late 1930s and that it continued to develop over time. In the late 1980s, the USGS completed a hydrologic study for the city of Springfield, Missouri. The study included the collection of groundwater-use data, the collection of historical and current water-level data, and the preparation of a groundwater-flow model (Imes, 1989). Imes (1989) reported that by 1987, the potentiometric surface in the Ozark aquifer had declined 350 ft from predevelopment conditions and that the cone of depression was expanding in area. The Imes (1989) groundwater-model area included most of Greene and Christian Counties, and parts of eight adjacent counties. The model that is described in this report covers a larger area than the Imes (1989) model and contains nearly all of the Imes (1989) model area (fig. 1). The Imes (1989) groundwater model was composed of two layers with variably spaced cells having the smallest cells, approximately 0.5 mile (mi) on a side, concentrated in the Springfield area and the largest cells, approximately 2 mi on a side, located at the lateral model boundaries. Using projected growth, the groundwater model simulated 150 ft of additional decline in water levels at large pumping centers by the year 2010.

Imes and Emmett (1994) discussed the regional geohydrology and presented a regional groundwater model in their Central Midwest Regional Aquifer-Systems Analysis (CMRASA) study. The model cells of the CMRASA groundwater model had an area of 195.3 mi^2. The CMRASA model only simulated predevelopment conditions and did not simulate effects of pumping.

Miller and Vandike (1997) reported that by 1996, water levels in the center of the cone of depression had dropped approximately 500 ft from predevelopment levels. At the lowest measured point in the cone of depression in 1996, the water level in the Ozark aquifer was approximately 259 ft below the top of the Ozark aquifer, and approximately 1,067 ft of the Ozark aquifer remained saturated. Using water-level data and geographic information system (GIS) software to map the cone of depression in the Springfield area, Dintelmann and others (2006) concluded that the cone had expanded to the south. During 2006 and 2007, the USGS collected water-level measurements in 115 wells located within this model area and produced a potentiometric-surface map of the Ozark aquifer (fig. 3; Richards and Mugel, 2008).

To the west of this study area, Gillip and others (2008) presented potentiometric-surface maps of the Springfield Plateau and Ozark aquifer constructed from 285 water levels measured in 2006. A groundwater model of southwestern Missouri, southeastern Kansas, and northeastern Oklahoma was developed by the USGS to assess the sustainability of the groundwater resources in that area (Czarnecki and others, 2009). That study incorporated several hypothetical pumpage scenarios ranging from a fixed pumping rate equivalent to the groundwater use in 2006, and a 1-, 2-, and 4-percent per year annual increase until 2057. Groundwater declines for the fixed pumping rate resulted in moderate drawdown and pumpage could be maintained until 2057. For any of the other hypothetical scenarios specifying pumpage increases, the model of Czarnecki and others (2009) showed large declines in the potentiometric surface within the Ozark aquifer around the major pumping centers by the year 2057 or earlier, and that pumpage increases of 1-, 2-, and 4-percent per year could not be maintained in some parts of the model area.

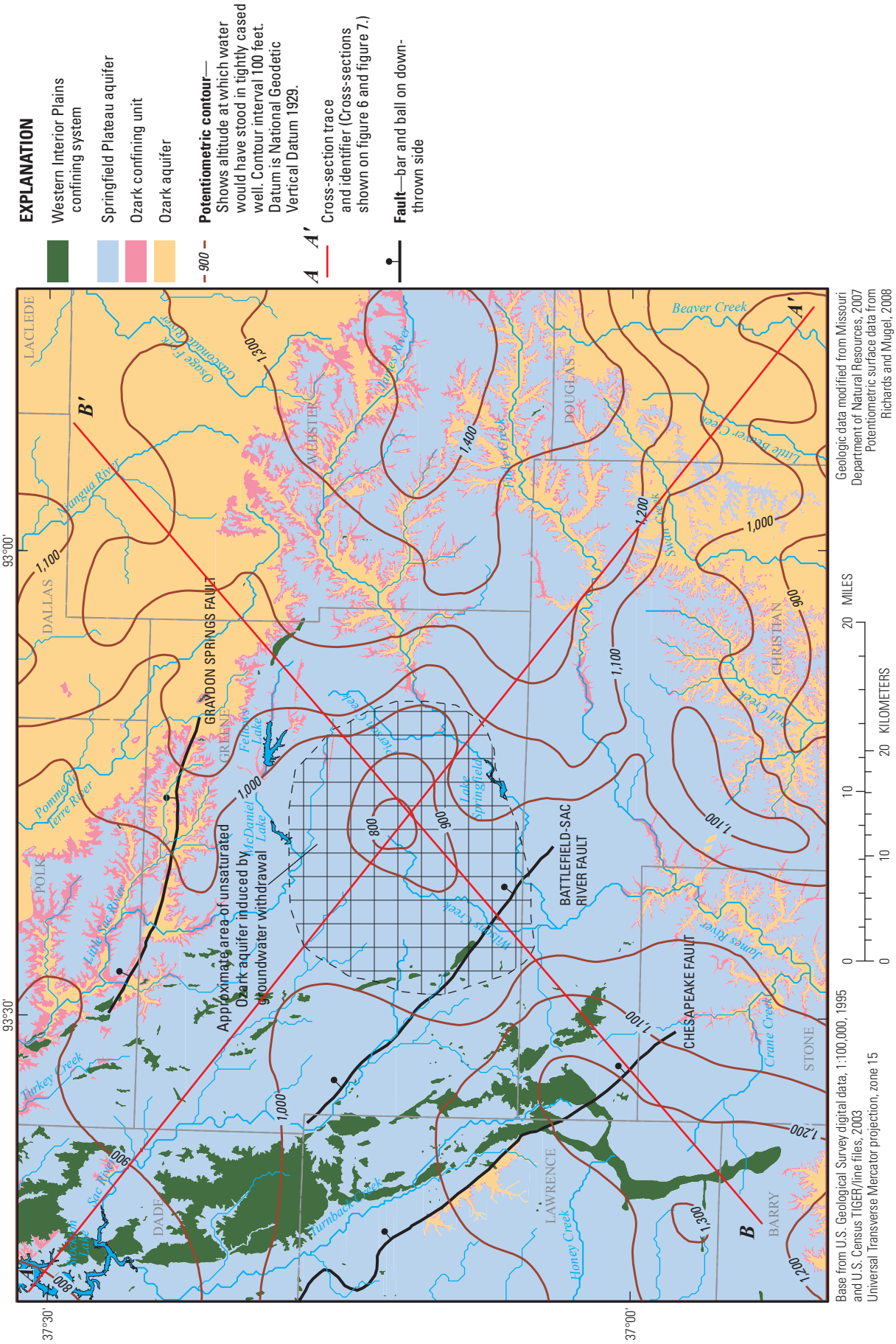


Figure 3. Potentiometric surface of the Ozark aquifer 2006–07 and outcrop areas of the hydrogeologic units in the study area.

Approach

Hydrologic data such as the configuration of the hydrogeologic units and their hydraulic properties, transient water-level measurements in the aquifers, the spatial distribution and the observed flows of the rivers and springs, the location and level of lakes, transient groundwater use from wells, and areal recharge estimates were compiled for the study area, which is the same as the model area. These data are used in the construction and calibration of a groundwater-flow model.

The configuration of the tops and bottoms of the hydrogeologic units were constructed from well logs obtained from the Missouri Department of Natural Resources (DNR; Missouri Department of Natural Resources, 2007) logged wells database. Locations of major faults were obtained from the digital geologic map (Missouri Department of Natural Resources, 2007). Land-surface elevations for top of the model were developed by computing the mean elevation for each model cell from the 10-meter USGS Digital Elevation Model (DEM) data (http://ned.usgs.gov/).

Hydraulic properties of hydrogeologic units were compiled from available sources and computed, in the case of hydraulic conductivity, from specific-capacity data where available. These values were used as initial estimates in the model and were subsequently modified during model calibration to improve the agreement between simulated head and observed water-level altitudes and river flows.

Water levels measured in wells in the model area in 2006–07 were compared to historical water levels to evaluate water-level trends, determine groundwater-flow direction, and provide water-level observation data used in the model calibration. After construction data for the wells were evaluated to determine their suitability, additional water-level observation points were selected from the USGS National Water Information System (http://water.data.usgs.gov/nwis) database and the Missouri Department of Natural Resources (2007) certified well and well log databases.

Locations of surface-water bodies were obtained from the national hydrography dataset for major rivers and lakes in the model area (http://nhd.usgs.gov/). Low-flow seepage-run data, collected as a series of stream-discharge measurements at intervals along a stream reach, assembled by the USGS in 2006 for this study, and 7-day annual low-flow discharge values for the 2-year recurrence interval ($7Q_2$) computed at USGS gaged sites were used to estimate base-flow rates at selected sites. Altitudes of rivers represented in the model were obtained from DEM data. Locations, orifice altitudes, and base-flow estimates of major springs in the model area were obtained from the Missouri Department of Natural Resources (2007) spring location database.

Groundwater-use data prior to 1962 was estimated. Groundwater-use data were compiled for the period 1962 to 2006 from USGS records, the Missouri DNR major water-user database (data on file at the Missouri Department of Natural Resources Division of Geology and Land Survey in Rolla, Missouri), census of Missouri public-supply reports (Missouri Department of Natural Resources, 1962–2006), and field reconnaissance by Greene County personnel. Water suppliers in the model area also were contacted and most supplied daily, weekly, monthly, or annual groundwater-use records that were assembled for use in the groundwater model.

Areal recharge estimates within the model area were compiled from available reported values and estimated using the water-table fluctuation method described in Risser and others (2005). Recharge estimates were modified in zones during model calibration.

A conceptual model of the flow system was developed based on the assembled hydrogeologic data. The conceptual model describes the general inflow and outflow mechanisms, flow direction, material properties, and boundary conditions of the groundwater-flow system within the model area. After a conceptual model of the flow system was developed, a digital model of groundwater flow was constructed using MODFLOW-2005 (Harbaugh, 2005). Hydrogeologic data were specified within the model through use of GIS software, and hydrologic-boundary conditions were specified in accordance with the conceptual model. The model was calibrated by minimizing the difference between simulated head and observed water levels and simulated and observed flows in rivers and springs. Response of the flow system to selected hypothetical future pumping and recharge stresses was then simulated using the calibrated model. Results from the simulations were compared primarily by examining differences in head.

Description of Model Area

The model area is located on the eastern edge of the Springfield Plateau physiographic section (Fenneman, 1938) and is roughly centered on the city of Springfield, Missouri. The model area encompasses approximately 2,870 mi^2 and contains parts of 11 counties (fig. 2). Greene County is represented in its entirety in the model area, and nearly all of Webster and Christian Counties are included. Additionally, smaller areas of Barry, Dade, Dallas, Douglas, Laclede, Lawrence, Polk, and Stone Counties are included in the model area.

The land surface (fig. 4) is characterized by gently rolling hills in the central and western part of the model area where the Springfield Plateau aquifer is present at the surface (fig. 3). The land surface has steeper slopes in the northeastern and southeastern part of the model area where the Ozark aquifer is present at the surface (fig. 3). Numerous karst features such as sinkholes, losing streams, springs, caves, and solution-enlarged fractures are present in the model area at the land surface (fig. 5). The density of karst features is higher in the Springfield Plateau aquifer compared to the Ozark aquifer. A consequence of the existence of the karst features is the rapid flow of groundwater through the solution-enlarged joints and fractures and the emergence of the water as springs where the channels intersect the land surface. Historically, springs were a valuable source of drinking water, and their cool water was used for refrigeration by early settlers of the area (Bullard and others, 2001; City Utilities of Springfield, 2009). Even today, Fulbright Spring is a source of public-water supply for Springfield (fig. 2; Watershed Committee of the Ozarks, 2009).

The maximum land-surface altitude, 1,740 ft, occurs in the east-central part of the model area and the minimum land-surface altitude, 805 ft, occurs in the northwestern part of the model area (fig. 4). A topographic drainage divide crosses the model area approximately west to east with surface-water drainage to the north of this divide flowing to tributaries of the Spring River Basin (Honey Creek), the Sac River Basin, the Niangua River Basin, and the Gasconade River Basin. Surface-water drainage to the south of the topographic divide flows to tributaries of the James River Basin and the White River Basin (Bull Creek, Swan Creek, Little Beaver Creek, and Beaver Creek). There are four large lakes are in the model area. McDaniel Lake and Fellows Lake are impoundments on the Little Sac River north of Springfield, Lake Springfield is on the James River south of Springfield, and Stockton Lake is on the Sac River in the northwestern corner of the model area.

Mean annual precipitation in the region during 1971–2000 was 44.97 inches (National Climatic Data Center, 2008). Annual precipitation ranged from 25.21 inches in 1953 to 62.45 inches in 1927 from 1915 to 2006 in the model area. For the 20-year transient model-calibration period between 1987 and 2006, annual precipitation ranged from 34.07 inches in 1989 to 61.29 inches in 1990 and was less than the mean value 12 times.

Hydrogeologic Setting of the Ozark Plateaus Aquifer System

Groundwater recharge to the Springfield Plateau and Ozark aquifers occurs from precipitation that infiltrates directly into the aquifer where the aquifer is exposed at the land surface. Groundwater generally flows away from groundwater highs that roughly coincide with the topographic divides and discharges to rivers, lakes, or springs; is captured by pumping wells; or flows out of the model area. Groundwater can also flow into the model area from outside the model area.

Imes and Emmett (1994) identified and described the hydrogeologic units in the model area as part of a regional study of the Ozark Plateaus aquifer system (fig. 1). Each hydrogeologic unit consists of rocks with similar hydraulic properties, and the boundaries of hydrogeologic units coincide with geologic formation boundaries. Seven units from stratigraphically youngest to oldest include (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 hydrogeologic units from the Springfield Plateau aquifer through the St. Francois aquifer composes the Ozark Plateaus aquifer system. Erosion in the model area has exposed the Western Interior Plains confining system, the Springfield Plateau aquifer, the Ozark confining unit, and the Ozark aquifer hydrogeologic units (figs. 3, 6, 7, and table 1). Geologic formations that compose the Ozark Plateaus aquifer system dip to the northwest and range from Mississippian to Cambrian in age. The less permeable Western Interior Plains confining system overlies the Ozark Plateaus aquifer system and consists of Pennsylvanian- to Mississippian-age rocks. Igneous rocks of Precambrian age underlie the Ozark Plateaus aquifer system and make up the Basement confining unit. Detailed discussion of the hydrogeologic units can be found in Imes and Emmett (1994), Imes (1989), and Czarnecki and others (2009). Detailed discussion of the rocks that constitute the geologic formations can be found in Thompson (1995). The Western Interior Plains confining unit is present only as isolated channel-sand deposits (fig. 3) too permeable and too thin to form an effective barrier to the percolation of water from the land surface to the underlying Springfield Plateau aquifer. Because the Western Interior Plains confining unit is localized and not hydrologically significant in the model area, its thickness was added to the Springfield Plateau aquifer in the model. No additional information about the Western Interior Plains confining unit will be presented in this report. The St. Francois aquifer is hydrologically separated from the Ozark aquifer by the St. Francois confining unit. In the model area, there is no significant use of groundwater from the St. Francois aquifer because it is too deep and has a low yield (Imes, 1989). The Basement confining unit is an insignificant source of water. The St. Francois confining unit, the St. Francois aquifer, and the Basement confining unit are not included in the groundwater model. Figure 8 shows a map of the distribution of hydrogeologic units that were used in the model. A brief discussion of the remaining hydrogeologic units in the model area follows.

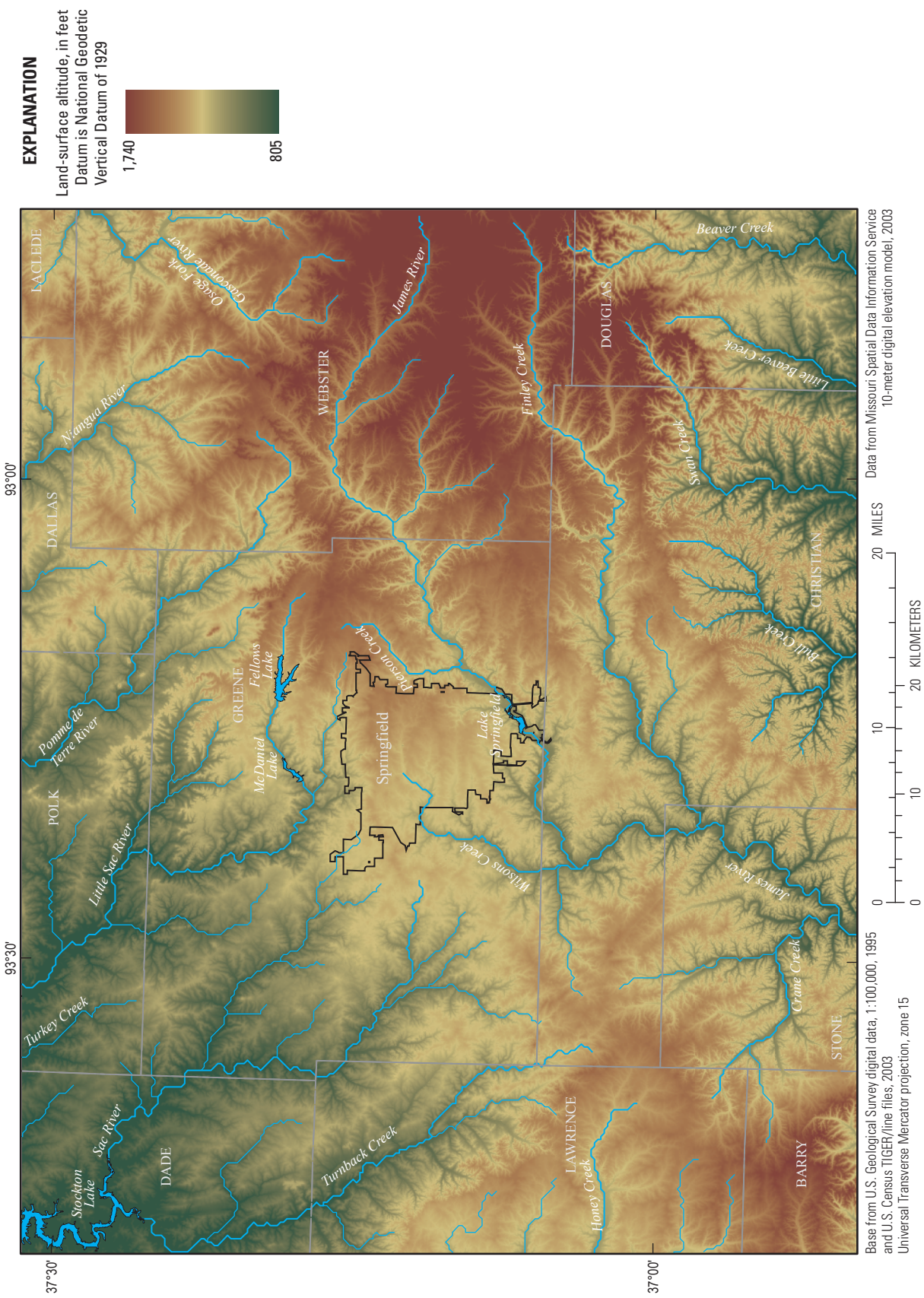


Figure 4. Altitude of the land surface in the model area.

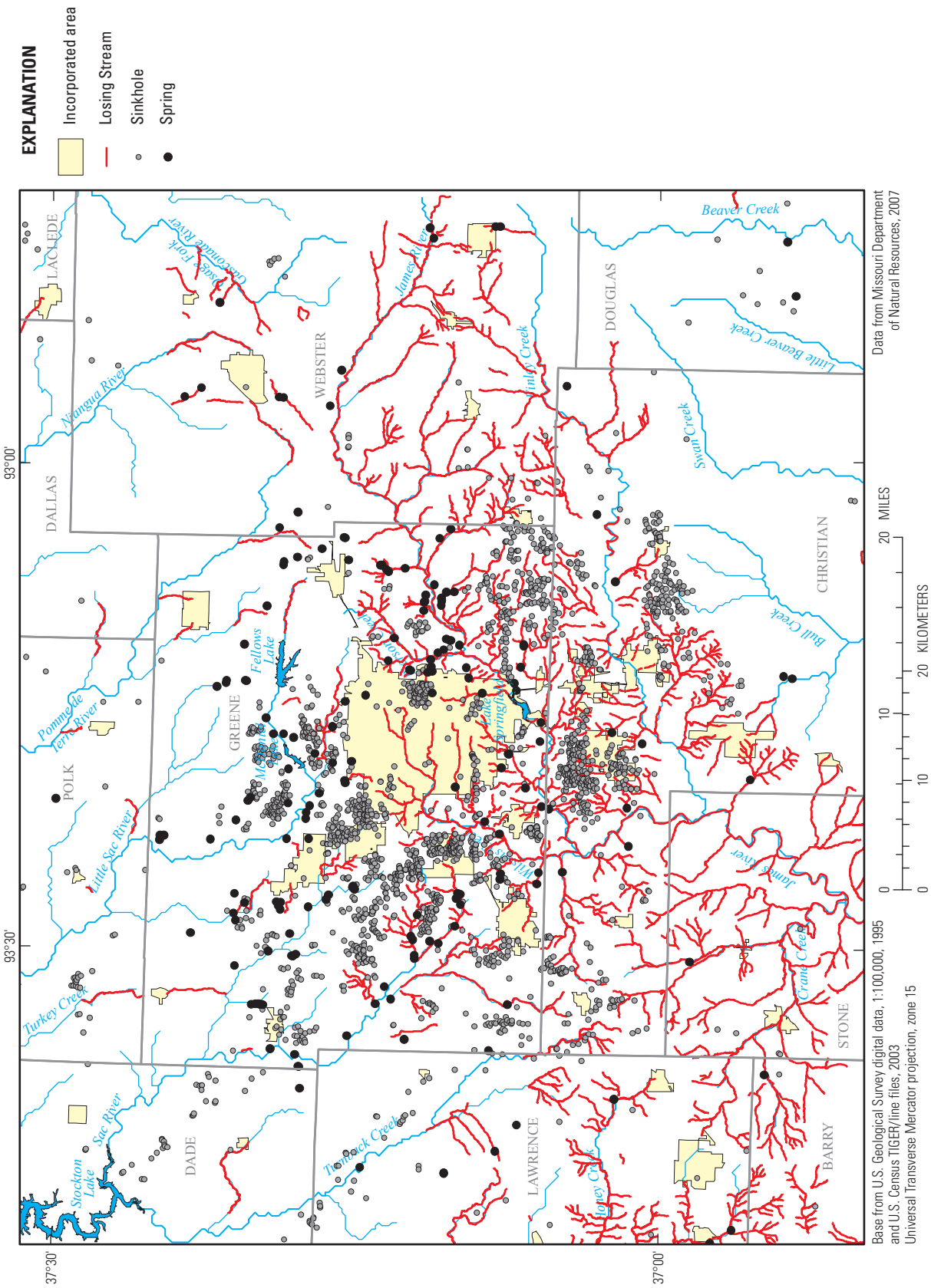


Figure 5. Distribution of karst features at the land surface in the model area.

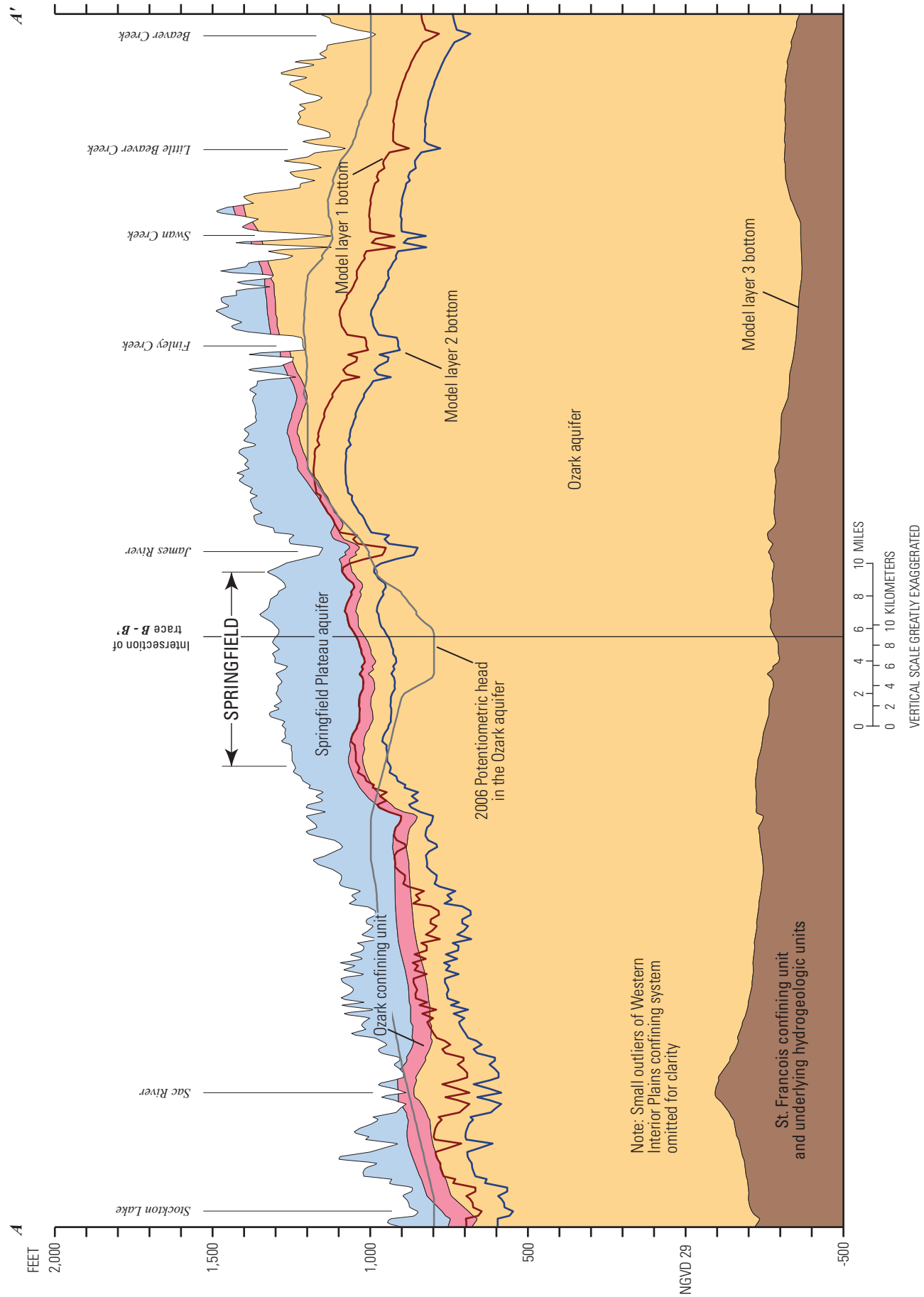


Figure 6. Northwest to southeast cross section from *A* to *A'* (on fig. 3) of the hydrogeologic units in the model area with model layers indicated.

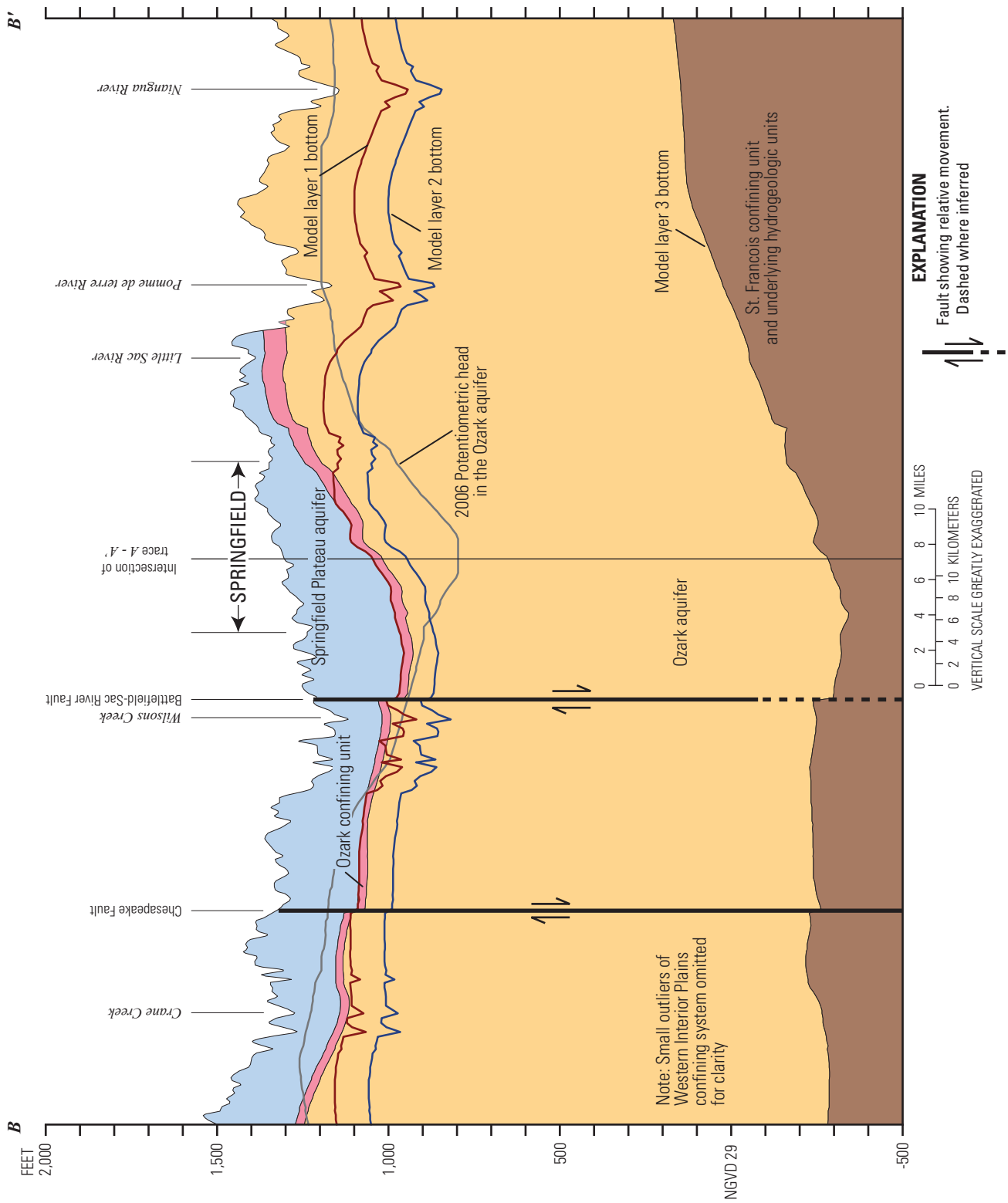


Figure 7. Southwest to northeast cross section from *B* to *B′* (on fig. 3) of the hydrogeologic units in the model area with model layers indicated.

Table 1. Correlation of hydrogeologic units and stratigraphic units in the model area (modified from Imes, 1989).

System	Hydrogeologic system	Hydrogeologic unit	Stratigraphic unit	Lithology	Water-bearing properties
Pennsylvanian	Western Interior Plains confining system	Western Interior Plains confining unit	Pennsylvanian channel-sand deposits	Sandstone and shale	Hydraulic properties are unknown. Presumably, most of these localized, thin deposits are unsaturated.
Mississippian	Ozark Plateaus aquifer system	Springfield Plateau aquifer	St. Louis Limestone Salem Formation Warsaw Formation Keokuk Limestone Burlington Limestone Elsey Formation Reeds Spring Formation Pierson Limestone	Limestone and chert	Karst aquifer. 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 karst features and surficial position.
		Ozark confining unit	Northview Shale Compton Limestone Bachelor Formation	Shale, siltstone, and limestone	Confining unit with confining material primarily in the Northview Shale.
Devonian			Chattanooga Shale		
Ordovician		Ozark aquifer	Smithville Dolomite Cotter Dolomite Jefferson City Dolomite Roubidoux Formation Gasconade Dolomite Eminence Dolomite Potosi Dolomite	Dolomite 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, Gasconade Dolomite, and the Potosi Dolomite.
Cambrian		St. Francois confining unit	Doe Run Dolomite Derby Dolomite Davis Formation	Shale, siltstone, dolomite, and limestone	Confining unit with confining material primarily in the Davis Formation.
		St. Francois aquifer	Bonneterre Formation Reagan Sandstone Lamotte Sandstone	Sandstone and dolomite	Aquifer not used in model area because of aquifer depth and small yield
Precambrian	No system recognized	Basement confining unit	Igneous and metamorphic rocks	Igneous and metamorphic rocks	Insignificant as a source of water

Springfield Plateau Aquifer

The Springfield Plateau aquifer is present in most of the model area (figs. 3 and 8) and ranges in thickness from 0 where it has been removed by erosion to 350 ft (fig. 9). It is a sequence of permeable, partially saturated rocks of Mississippian age. The stratigraphic units, from youngest to oldest, that comprise the Springfield Plateau aquifer include the St. Louis Limestone, Salem Formation, Warsaw Formation, Keokuk Limestone, Burlington Limestone, Elsey Formation, Reeds Spring Formation, and Pierson Limestone (table 1). These rock units are dominantly coarse crystalline and cherty limestone. The Keokuk Limestone and Burlington Limestone are the most permeable rock units and, where saturated, probably yield more water to wells than the other rock units (Miller and Vandike, 1997). Wells open only to the Springfield Plateau aquifer typically yield less than 20 gallons per minute (gal/min) and are only suitable for domestic and stock use (Imes, 1989). The water table in the Springfield aquifer is about 100 ft below the land surface in the recharge areas and is at the land surface in the larger stream valleys where the groundwater discharges to streams (Imes, 1989).

Because the Springfield Plateau aquifer occurs at the surface, the altitude of the top of the Springfield Plateau aquifer is the land-surface altitude. The thickness of the Springfield Plateau aquifer (fig. 9) was determined by subtracting the land-surface altitude from the altitude of the top of the Ozark confining unit. Occurrence of the Western Interior Plains confining unit in the model area (fig. 3) was assumed to be hydrologically unimportant, and its thickness was added to the thickness of the underlying Springfield Plateau aquifer in those areas.

Karst features such as solution-enlarged fractures, caves, sinkholes, losing streams, and springs are present in the Springfield Plateau aquifer (fig. 5). These karst features are formed by dissolution of the limestone by groundwater, rich in carbonic acid, as it percolates through the unsaturated zone to the water table. Locally, these features are hydrologically important because they can quickly move water and contaminants into and through the groundwater system and can move groundwater between surface-water drainage basins. Sinkhole density in the Springfield Plateau aquifer is greater than 10 sinkholes per 100 mi^2 throughout much of the model area (Harvey, 1980).

Estimates of hydraulic properties of the Springfield Plateau aquifer in the model area are sparse. Previously published values are presented in table 2 and will be discussed in greater detail in the Hydraulic Property Estimation section of the report.

Ozark Confining Unit

The Ozark confining unit is present in most of the model area (figs. 3, 8, and 10). It ranges in thickness from 0 ft, where it has been removed by erosion, to about 98 ft, and is thickest in the northern part of the model area (fig. 11). The Ozark confining unit retards groundwater flow between the Springfield Plateau aquifer and the Ozark aquifer. It is primarily composed of fine-grained limestone, siltstone, and shale of the Kinderhookian Series of Mississippian age and locally present shale of Devonian age. The stratigraphic units, from the youngest to the oldest, that compose the Ozark confining unit are the Northview Shale, Compton Limestone, Bachelor Formation, and Chattanooga Shale (table 1). The Northview Shale is the primary confining bed in the Ozark confining unit although the limestone formations can act as confining beds where secondary porosity is absent (Imes, 1989). The Northview Shale generally thins from a maximum thickness of about 80 ft in the northern and northeastern part of the model area to less than 10 ft in the southwestern part of the model area (Imes, 1989). The Ozark confining unit is exposed along streams and rivers where the Springfield Plateau aquifer has been eroded away.

The configuration of the top (fig. 10) and bottom of the Ozark confining unit was mapped from 1,042 well logs obtained from the Missouri DNR. Only well logs that intersected both the top and the bottom of the Ozark confining unit were used. The thickness map of the Ozark confining unit (fig. 11) was constructed by contouring the thicknesses obtained from the 1,042 well logs. In areas of overlap between the two model areas, these maps of the Ozark confining unit were similar to the maps of Imes (1989). Differences were noted in some areas but were largely the result of new data not available to Imes (1989).

Estimated values of the hydraulic properties for the Ozark confining unit in the model area are scarce. Previously published values are presented in table 2 and will be discussed in greater detail in the Hydraulic Property Estimation section of the report.

Ozark Aquifer

The Ozark aquifer is the primary bedrock aquifer in southern Missouri, providing most of the private and public water supplies in the region. It is present across the model area and is much thicker than the Springfield Plateau aquifer (figs. 6 and 7). It is composed of dolomite and sandstone of Cambrian and Ordovician age (table 1). The stratigraphic

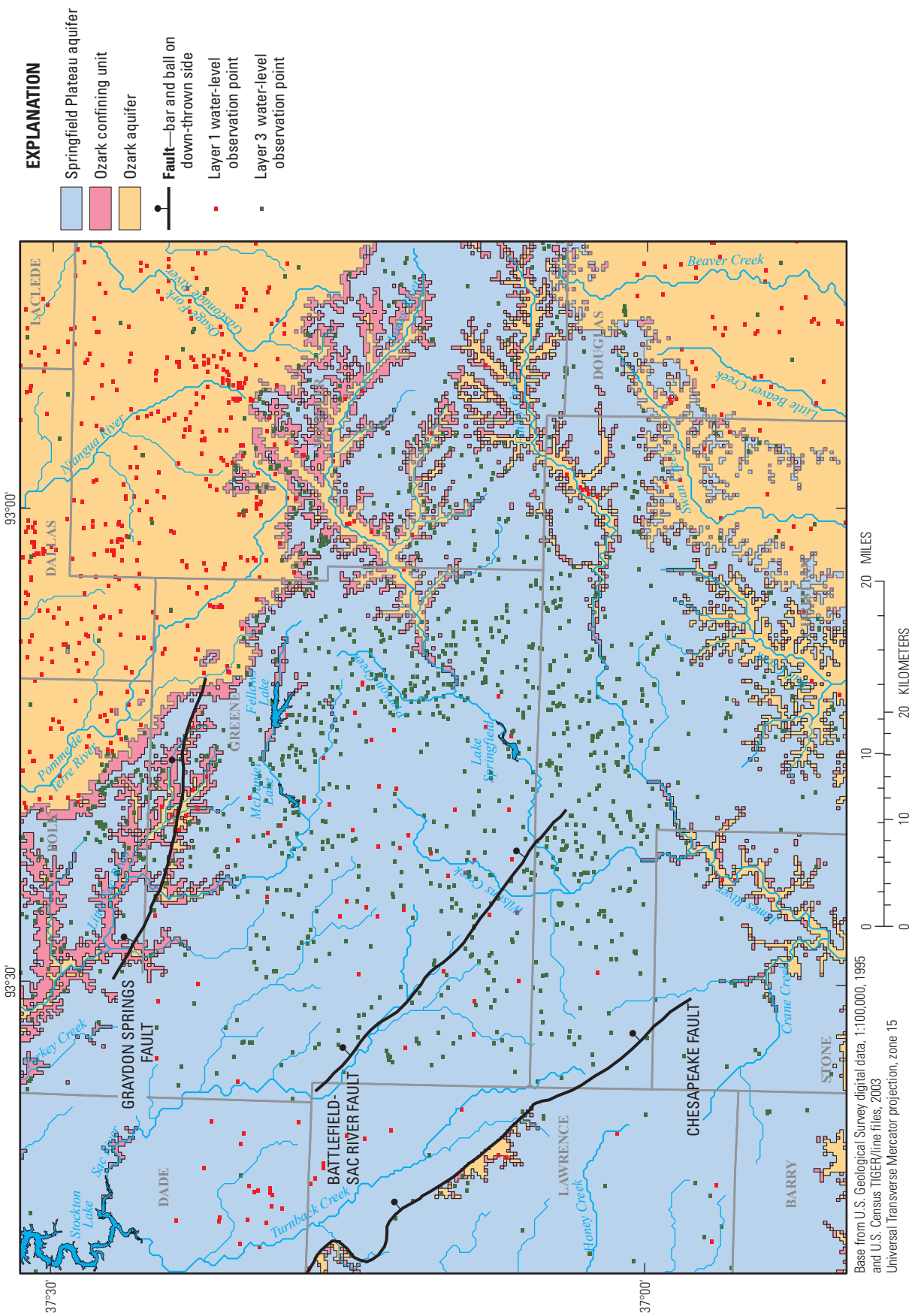


Figure 8. Distribution of the hydrogeologic units at the upper surface of the cells in layer 1 and water-level observations used for calibration in the model.

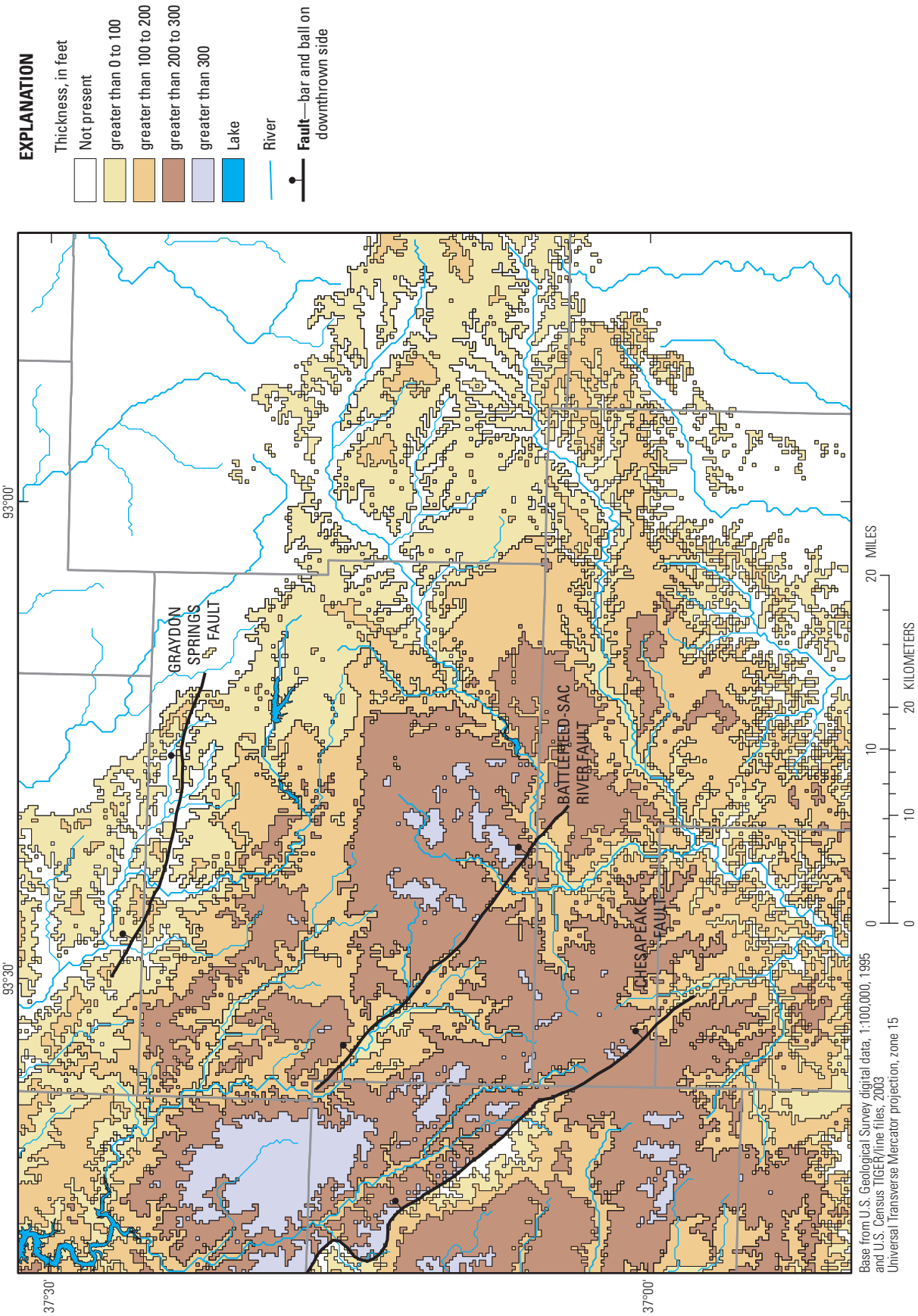


Figure 9. Thickness of the Springfield Plateau aquifer in the study area.

Table 2. Reported hydraulic property values for the model area and vicinity.

[ft, foot; ft^2/d, square foot per day; 1/ft, per foot; ft/d, foot per day; 1/d, per day; K, hydraulic conductivity; MO, Missouri; KS, Kansas; OK, Oklahoma; >, greater than; <, less than; —, no data]

Location	Thickness (ft)	Transmissivity (ft^2/d)	Storage coefficient (dimensionless)	Specific storage (1/ft)	Specific yield (dimensionless)	Horizontal K (ft/d)	Vertical K (ft/d)	Leakance (1/d)	Reference
Springfield Plateau aquifer									
Springfield, MO	0-300	860-4,320	—	—	$2.00x10^{-2}$	4.3-43	—	—	Imes, 1989, p. 1, 12
Greene County area	0-400	3,450-8,640	—	—	—	21.6	—	—	Imes and Emmett, 1994, p. 107, fig. 68
Ottawa County, OK	300	390-10,500	—	$1.0x10^{-5}$	$2.00x10^{-1}$	1.3-35	$2.6x10^{-2}$ - $7.0x10^{-1}$	—	Reed and Czarnecki, 2006, p. 14, fig. 8
Tristate area (MO, OK, KS)	0-400	—	—	$5.0x10^{-6}$ - $1.0x10^{-5}$	$1.00x10^{-2}$ - $1.00x10^{-1}$	0.89-35	$2.97x10^{-4}$ - 1.00	—	Czarnecki and others, 2009, p. 27
Ozark confining unit									
Springfield, MO	—	—	—	—	—	—	$8.6x10^{-5}$	—	Emmett and others, 1978
Springfield, MO	0-100	—	—	—	—	—	$7.8x10^{-6}$ and $9.5x10^{-6}$	—	Imes, 1989, p. 1, 52
Ottawa County, OK	—	—	—	—	—	—	—	$4.3x10^{-8}$ - $7.7x10^{-8}$	Christenson and others, 1994, p. 23
Greene County area	—	—	—	—	—	—	$1.7x10^{-3}$ - $4.3x10^{-3}$	$5.2x10^{-5}$ - $1.7x10^{-4}$	Imes and Emmett, 1994, p. 111, fig. 69
Tristate area (MO, OK, KS)	0-100		—	$5.0x10^{-6}$	$1.00x10^{-1}$	$1.0x10^{-5}$ - $4.0x10^{-5}$	$2.0x10^{-7}$ - $2.45x10^{-5}$		Czarnecki and others, 2009, p. 27
Ozark aquifer									
Springfield, MO	—	670-3,974	—	—	—	—	—	—	Emmett and others, 1978, p. 30, 112
Springfield, MO	<1,000 - >1,450	—	$1.0x10^{-4}$	—	$1.00x10^{-3}$ - $2.00x10^{-2}$	0.7-2.6	—	—	Imes, 1989, p. 1, 23, 52 Fig. 14
Springfield, MO	1,200	2,146 - 2,821	$1.6x10^{-4}$	—	—	2.11	—	—	Vandike and Sherman, 1994, p. 53-54
Greene County area	—	8,640 - 14,688	—	—	—	6.91 - 11.23	—	—	Imes and Emmett, 1994, p. 49
Tristate area (MO, OK, KS)	700-1,500	—	—	$1.00x10^{-7}$ - $3.97x10^{-5}$	$3.56x10^{-4}$ - $7.50x10^{-2}$	0.10 - 5.00	$5.00x10^{-3}$ - 1.81	—	Czarnecki and others, 2009, p. 27
St. Francois confining unit									
Springfield, MO	250	—	—	—	—	—	$3.8x10^{-6}$	—	Imes, 1989, p. 52
Springfield, MO	250	—	—	—	—	—	$8.6x10^{-4}$	—	Imes and Emmett, 1994, p. 114, fig. 71

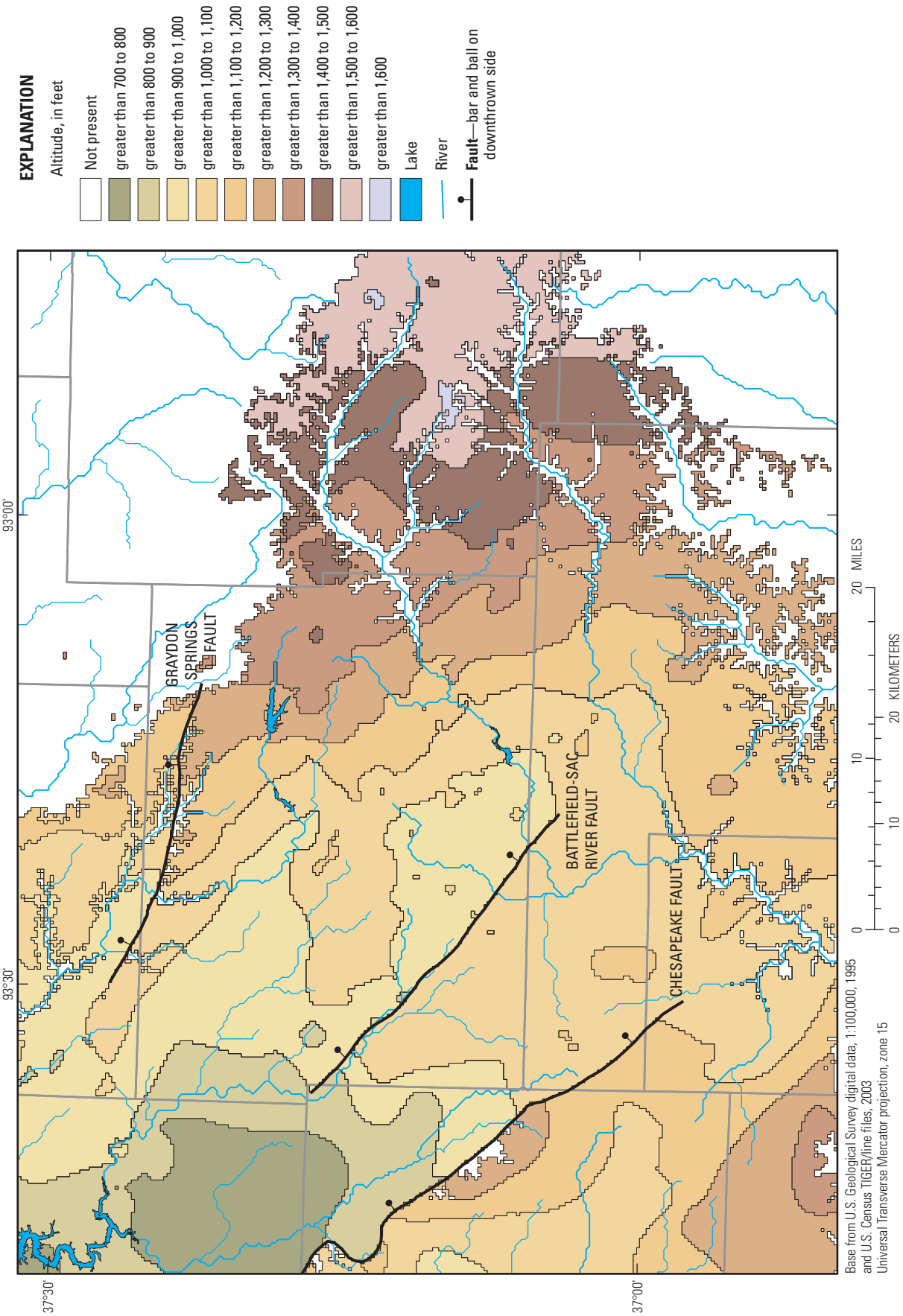


Figure 10. Configuration of the top of the Ozark confining unit in the study area.

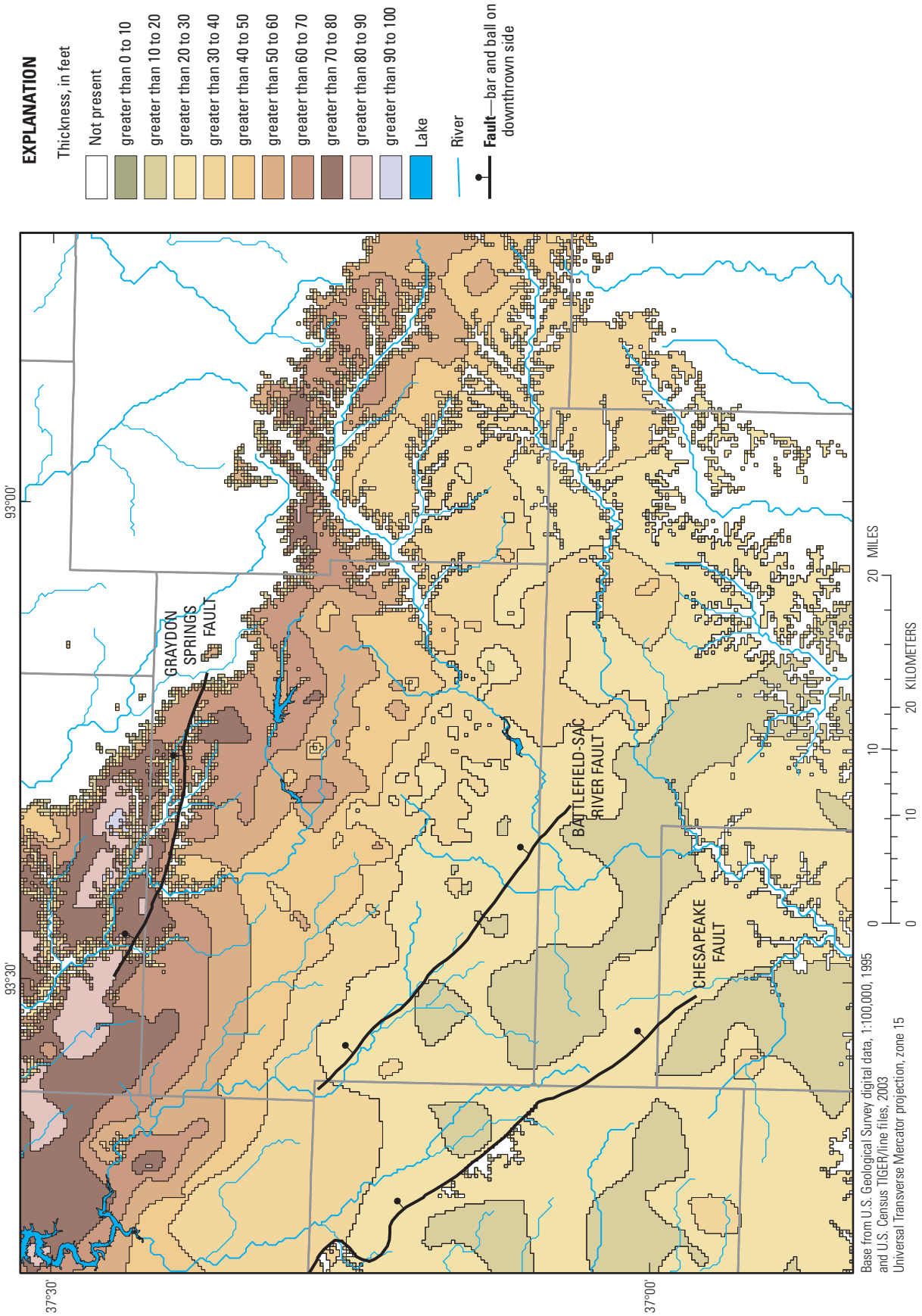


Figure 11. Thickness of the Ozark confining unit in the study area.

units, from the youngest to the oldest, that comprise the Ozark aquifer in the model area are the Smithville Dolomite, Cotter Dolomite, Jefferson City Dolomite, Roubidoux Formation, Gasconade Dolomite, Eminence Dolomite, and Potosi Dolomite (table 1).

The altitude of the top of the Ozark aquifer (fig. 12) was obtained by subtracting the Ozark confining unit thickness map from the altitude of the top of the Ozark confining unit map. Land-surface altitudes were used where the Ozark aquifer is exposed at the surface. The thickness of the Ozark aquifer (fig. 13) was obtained by subtracting the altitude of the top of the Ozark aquifer map from the altitude of the top of the St. Francois confining unit map. In areas of overlap, these maps of the Ozark aquifer were similar to the maps of Imes (1989). Differences were noted in some areas but were largely the result of new data not available to Imes (1989).

The aquifer is about 900 ft thick in the northwestern part of the model area and thickens to about 1,780 ft in the southeastern part of the model area (fig. 13). In most of the model area, it is a confined aquifer with a potentiometric surface above the top of the aquifer. The aquifer is exposed and is unconfined in the northeastern and southeastern parts of the model area and along some streams. The aquifer is also unconfined where groundwater pumpage has lowered the potentiometric surface below the base of the Ozark confining unit (fig. 3). Although some karst features exist in the Ozark aquifer in the model area, karst terrane is not nearly as well developed in the Ozark aquifer as it is in the Springfield Plateau aquifer.

Wells that are open to the entire Ozark aquifer typically yield about 1,000 gal/min, which is sufficient to supply municipal and industrial needs (Vandike and Sherman, 1994). The formations within the Ozark aquifer that yield the greatest amount of water are the Roubidoux Formation, Gunter Sandstone Member of the Gasconade Dolomite, and the Potosi Dolomite (Imes, 1989; Vandike and Sherman, 1994). Wells completed in the Jefferson City and Cotter dolomites usually yield less than 50 gal/min.

Estimates of the hydraulic properties of the Ozark aquifer in the model area are sparse. Previously published values are presented in table 2 and will be discussed in greater detail in the Hydraulic Property Estimation section of the report.

St. Francois Confining Unit

Although the St. Francois confining unit is not represented as a specific layer in the model, this unit is used to define the bottom of the Ozark aquifer, and the hydraulic properties of this unit regulate flow through the bottom of the Ozark aquifer. The St. Francois confining unit is approximately 250 ft thick and retards groundwater flow between the overlying Ozark aquifer and the underlying St. Francois aquifer (Imes, 1989). It is composed of shale, siltstone, dolomite, and limestone of Cambrian age. The formations that make up the St. Francois confining unit are the Doe Run Dolomite, the Derby Dolomite, and the Davis Formation (table 1).

The Missouri DNR well-log data for the St. Francois confining unit were relatively sparse. The altitude of the top of the St. Francois confining unit was contoured from 51 wells that penetrated into or through the unit in the general model area (fig. 14). In areas of overlap, the map was similar to the map of Imes (1989). Differences were noted in some areas but were largely the result of new data not available to Imes (1989).

Conceptual Model of the Groundwater-Flow System

Part of a modeling process is to develop a conceptual model of the groundwater-flow system to explain flow within the study area by identifying sources and sinks of water. The conceptual model is the basis for developing the digital model and takes into account annual precipitation, topography, properties and distribution of the hydrogeologic units, hydrologic boundaries, current and past water-level data, pump-test data, water-quality data, and previously published interpretations of the flow system.

The two principal aquifers within the model area are the Springfield Plateau aquifer and the Ozark aquifer, with the Ozark aquifer being more important in terms of water supply. Recharge occurs in the model area through infiltration of precipitation that falls on the land surface. Groundwater can

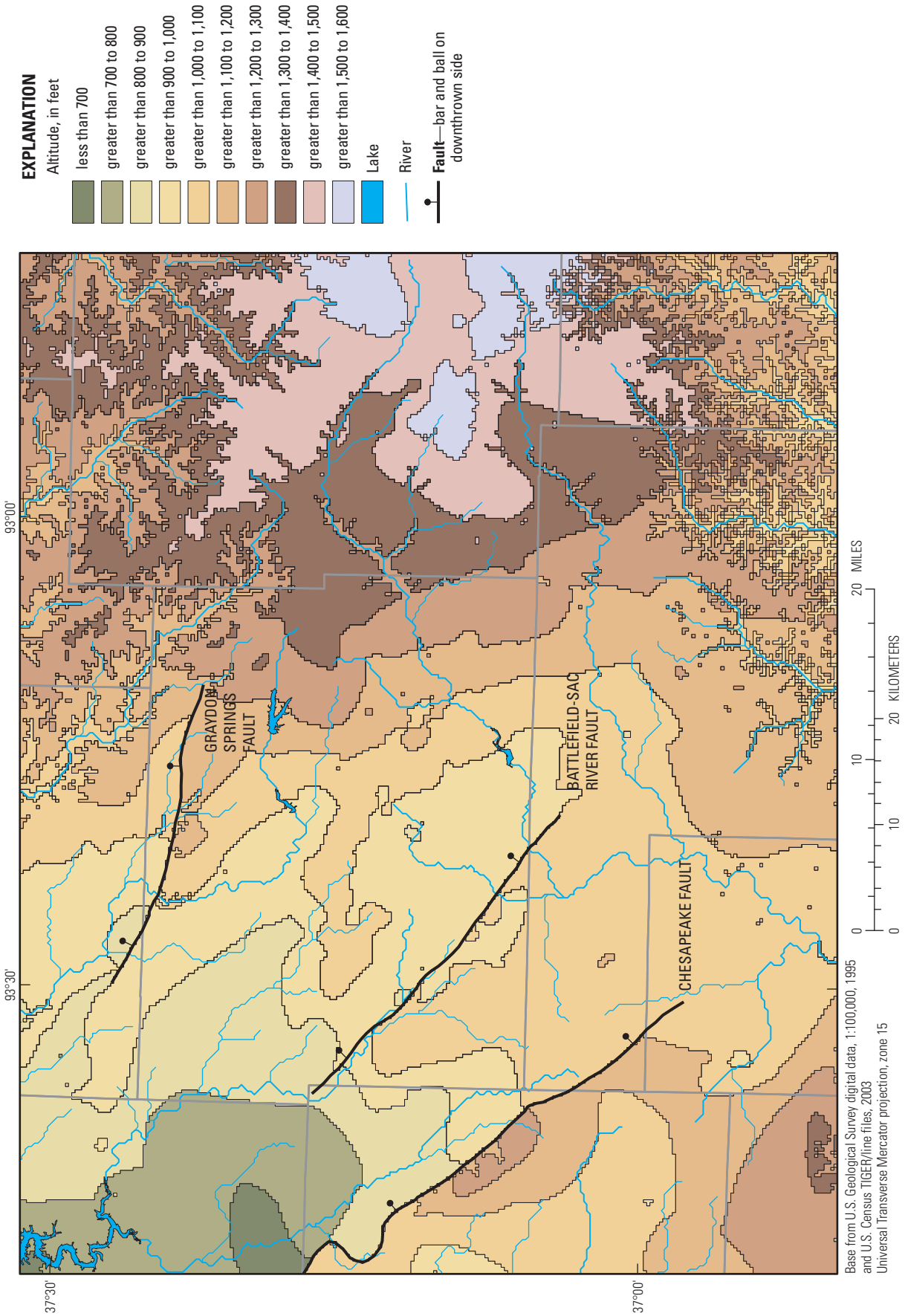


Figure 12. Configuration of the top of the Ozark aquifer in the study area.

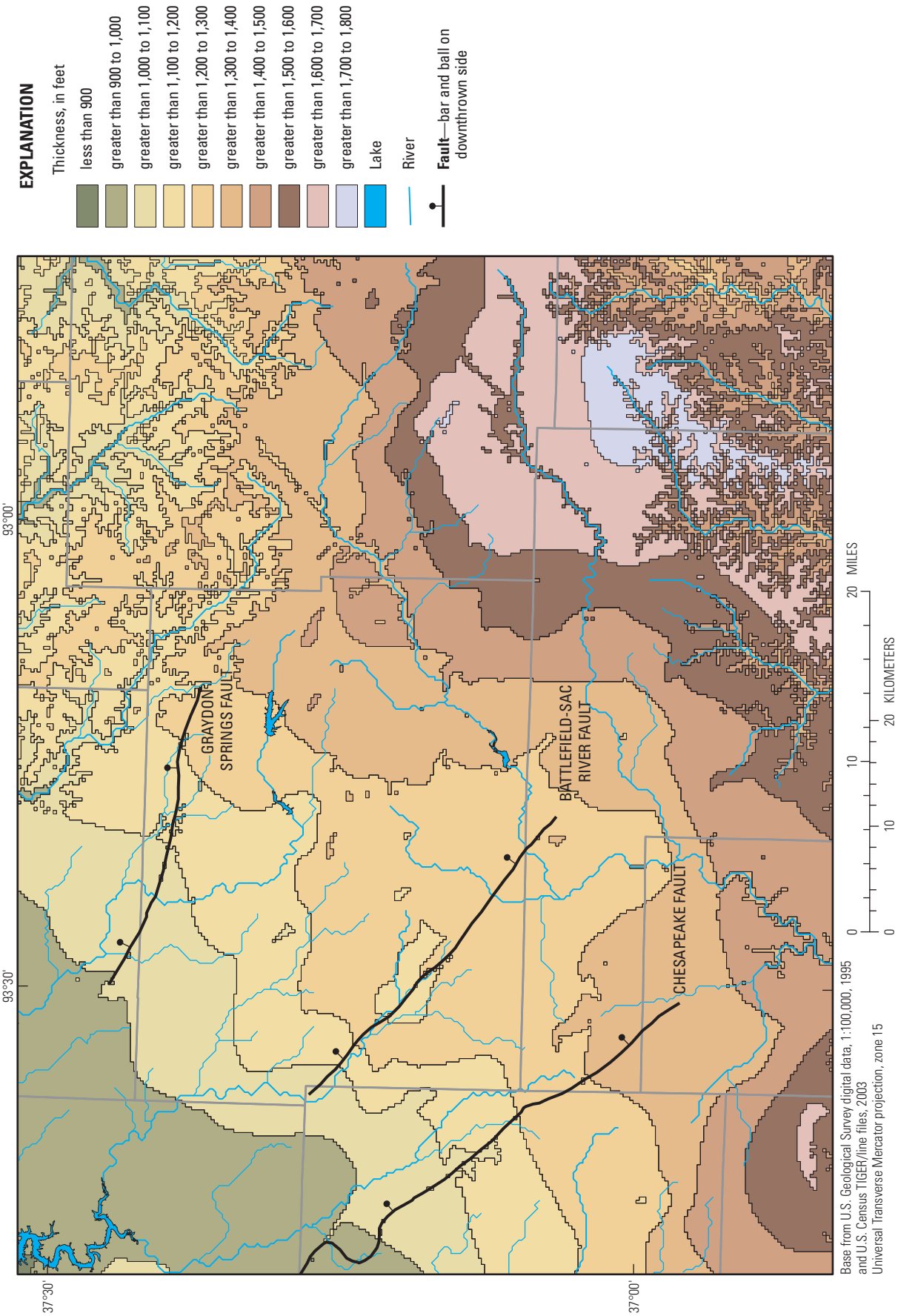


Figure 13. Thickness of the Ozark aquifer in the study area.

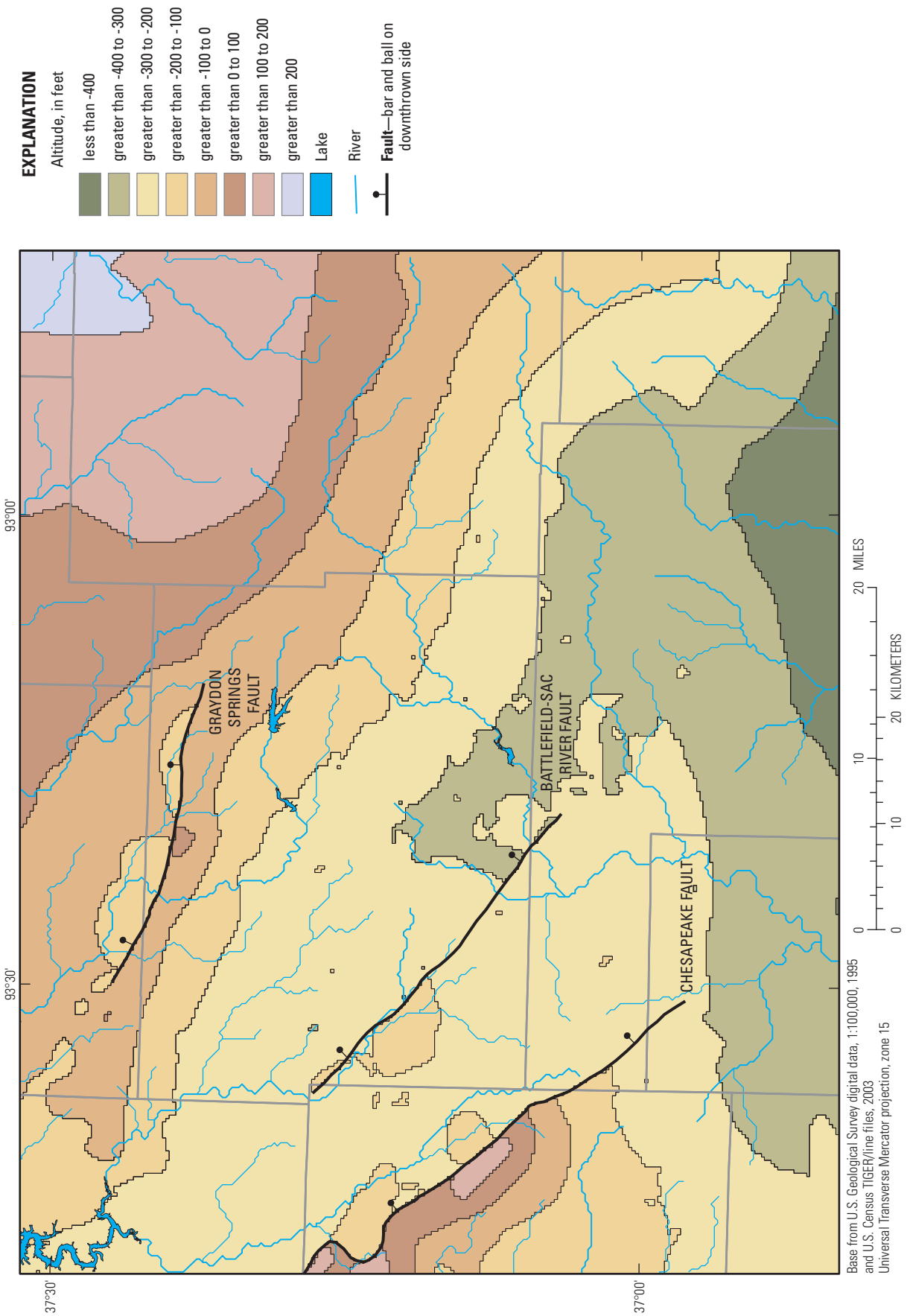


Figure 14. Configuration of the top of the St. Francois confining unit in the study area.

flow into the study area by lateral flow. Surface water can enter the groundwater system from rivers and lakes that have a stage that is higher than the head in the hydrogeologic unit underlying those features. Discharge from the groundwater system occurs at the land surface to rivers, lakes, and springs where the head in the hydrogeologic unit underlying those features is higher than the water level in those features. Groundwater can flow out of the study area by lateral flow. Groundwater also can be removed by pumping wells in the study area. Wells producing large amounts of water in the study area are typically open to almost the entire thickness of the Ozark aquifer (Missouri Department of Natural Resources, 2007; Jim Vandike, Missouri Department of Natural Resources, oral commun., 2008). Head gradients between hydrogeologic units induce vertical flow through the Ozark confining unit and the St. Francois confining unit.

Faults within the study area can be barriers or conduits to flow, but no information is available to determine which, if either, condition exists so the faults were ignored. Karst features such as sinkholes, caves, solution enlarged fractures, and springs exist in the study area. Groundwater flow in the karst area can be conceptualized as two separate but linked groundwater-flow systems: the karst quick-flow component and the slower porous-media flow component (Imes and others, 2007). The quick-flow component recharges rapidly from infiltration after precipitation events and discharges rapidly by flow from springs. The porous-media flow component slowly recharges from infiltration and from exchange with the groundwater in the karst system and slowly discharges to streams and by exchange with the karst system. The porous-media flow component is the part of groundwater flow that maintains the base flow to the streams and springs.

Description of the Groundwater-Flow Model

Converting the conceptual model of groundwater flow into a digital numerical model requires the use of computer software and simplifying assumptions. The following sections describes the software used, the assumptions made to develop the model, and the specifications of the various components applied in the model.

Groundwater-Modeling Software

Groundwater flow was simulated using MODFLOW-2005 (Harbaugh, 2005), which is the USGS finite-difference, three-dimensional numerical modeling software. The approximation for spatial distribution of head over time was solved with the Preconditioned-Conjugate-Gradient (PCG) solver in the MODFLOW-2005 software (Harbaugh, 2005). Three-dimensional simulation of groundwater flow was used to determine the head distribution around major pumping centers in the model area, to describe vertical flow between adjacent units, and to represent the three-dimensional geometry of the flow system. GIS software was used for processing input data to the model and for display of model results (Environmental Systems Research Institute, 2009).

Simplifying Assumptions

Darcy's law (Freeze and Cherry, 1979) for flow through a porous media was assumed to be applicable to this system. It was assumed that the stratigraphic rock units could be aggregated into the hydrogeologic units of the Springfield Plateau aquifer, Ozark confining unit, and the Ozark aquifer and that the groundwater-flow system could be represented by a three-layer model. Combining hydrogeologic units by computing composite hydraulic properties in some model cells was assumed to not adversely affect the distribution of head computed by the model. The assumption was made that there was flow through the lateral boundaries in the model and that there was vertical flow through the base of the Ozark aquifer. Reference head values at the lateral boundaries and at the base of the Ozark aquifer were assumed to be invariant throughout the simulation. Groundwater pumpage and recharge was assumed to be constant for each stress period but varied between stress periods. This assumption ignored seasonal precipitation changes or changes in pumpage within the stress period. It was assumed a linear relation exists between precipitation and recharge in the study area. Recharge was assumed to vary spatially based on land slope and to be less in Springfield because of the occurrence of impervious surface in the city. Hydraulic properties within a model cell were assumed to reflect the mean conditions over the volume of the cell, neglecting local variations in those properties. Horizontal anisotropy of the hydrogeologic units was unknown and was assumed to be negligible at the model scale. Assumptions were

made that faults in the model area do not alter groundwater flow and that the karst development in the Springfield Plateau aquifer and the Ozark aquifer was extensive enough that the hydrogeologic units could be represented as porous media for the model grid spacing. It also was assumed that the karst, quick-flow component of the groundwater-flow system occurred during a short enough period when compared to the stress period length that it would not substantially alter the longer-term porous-media flow system. All pumping wells were assumed to be open to the full thickness of the model.

Attempts to simulate all layers in the model as unconfined were unsuccessful because the model became unstable and the simulation failed to converge. By necessity, it was assumed that model layers 2 and 3 were confined and that simulating layers 2 and 3 as confined in the model would provide reasonable estimates of the head distributions in these layers.

Model Specifications

The numerical model has four main components: (1) the finite difference grid, (2) stress-period discretization, (3) model boundary conditions, and (4) groundwater use. Each of these components will be discussed in the following sections.

Finite-Difference Grid

The model was subdivided into a regularly spaced grid of 253 rows and 316 columns. Each model cell was 1,000 ft by 1,000 ft in size representing an area of 0.036 mi^2. The model grid was oriented north and south and all cells were active in the model.

Initial Hydrogeologic Unit Discretization

The initial unsuccessful discretization of the model area divided the model into three layers of variable thickness along the contacts between the Springfield Plateau aquifer, Ozark confining unit, and the Ozark aquifer. Land-surface altitude (fig. 4) for each model cell in layer 1 was determined by computing the mean of the 10-meter (32.8 ft) DEM values within each cell. Using the model grid as a base, altitudes of the tops of the hydrogeologic units were discretized for each cell from the maps shown in figure 10, 12, and 14. Because the rock units dip slightly and the topographic surface is an erosional surface, the hydrogeologic units of the Springfield Plateau aquifer and Ozark confining unit become thin along their contact areas. Natural groundwater fluctuation can allow the hydrogeologic units along this contact zone to become unsaturated. During the initial unsuccessful attempt of model calibration (see Model Calibration section), the model solution oscillated at several nodes in layer 1 where the Springfield Plateau aquifer was thin and the saturated thickness becomes small. This oscillation led to a numerical instability around cells that would alternately go wet and dry as the mathematical solver attempted to determine a solution, causing the model to fail to converge. This problem was also noted in the model of Imes (1989). Cells in this area of layer 1 were inactivated in an attempt to solve the numerical instability problem. The area of inactive cells grew to cover parts of the Springfield Plateau aquifer known to be saturated. In addition, recharge to the model was affected because nearly 25 percent of the cells in the Springfield Plateau aquifer were inactive. The model never became stable using this discretization.

Final Hydrogeologic Unit Discretization

To alleviate the numerical instability near the edge of the saturated area of the Springfield Plateau aquifer, the model was rediscretized so that the cells in layer 1 would always remain partially saturated and not go dry. This was accomplished by determining the approximate mean head for each surficial cell in the model then computing the estimated minimum head that could occur because of temporal fluctuation. The bottom elevation of the cell was assigned to be at or below the estimated minimum head in the cell.

The final discretization of the model area divided the model into three layers. Layers 1 and 3 were of variable thickness, and layer 2 was a constant 100-ft thickness. Land-surface altitude (fig. 4) for each model cell in layer 1 was determined by computing the mean of the 10-meter (32.8 ft) DEM values within each cell. A conceptual cross section of model layers is shown in figure 15 and helps illustrate in the following discussion how the model layers were determined. In areas where the Springfield Plateau aquifer is present and is of sufficient thickness, cells in layer 1 of the model are composed entirely of Springfield Plateau aquifer (fig. 15, cell A). Layer 1 can also be composed of a combination of Springfield Plateau aquifer and Ozark confining unit (fig. 15, cell B) or composed of a combination of Springfield Plateau aquifer, Ozark confining unit, and Ozark aquifer (fig. 15, cell C). Adjacent model cells with large

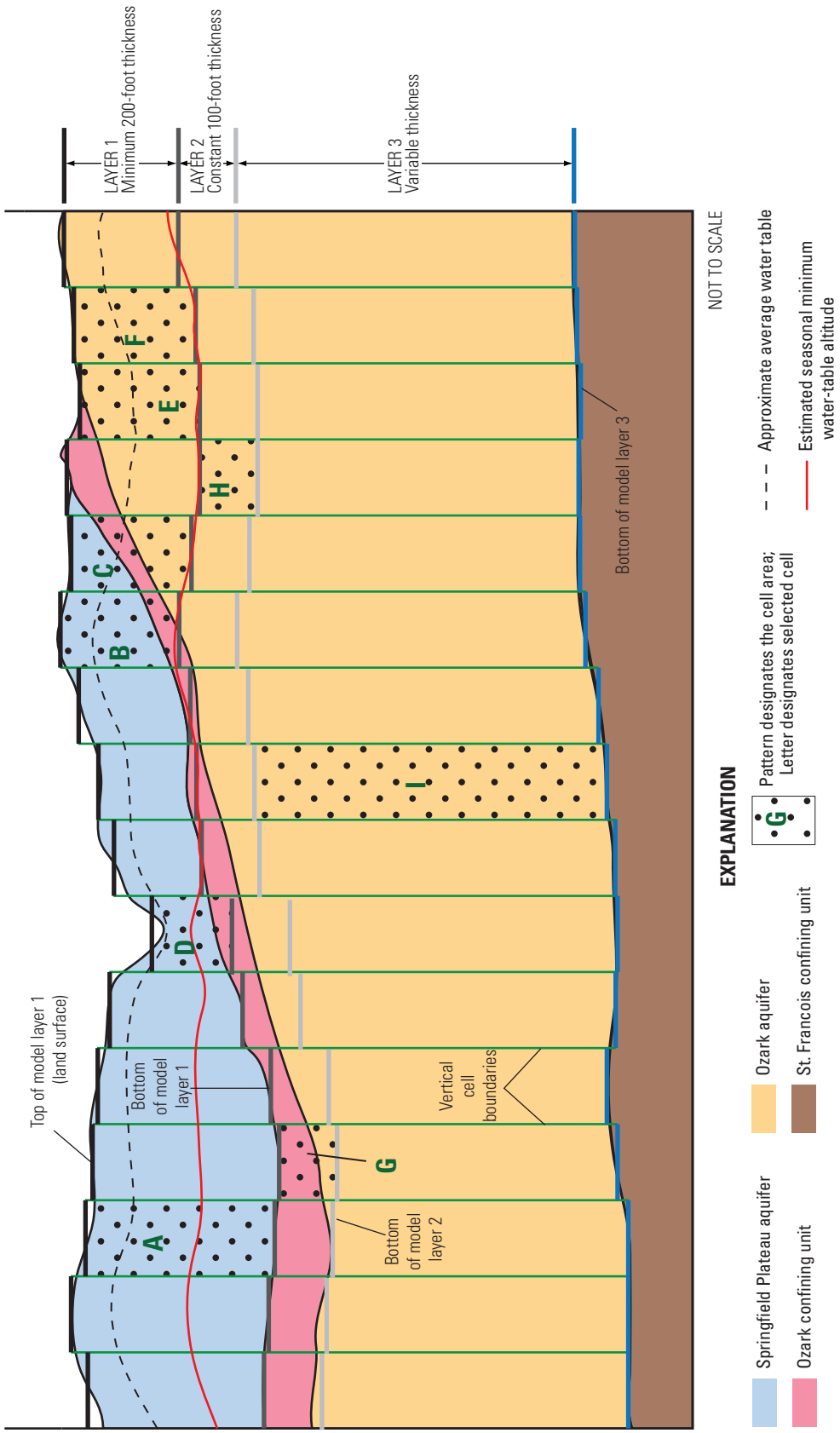


Figure 15. Conceptual cross section of model layers compared with the hydrogeologic units.

differences in thickness can cause numerical instability. A minimum thickness of 200 ft was specified for layer 1 so that adjacent model cells did not have large thickness differences (fig. 15, cell D). In areas where the Springfield Plateau aquifer is not present, layer 1 of the model is composed of a combination of Ozark confining unit and Ozark aquifer where the Ozark confining unit is present at the surface (fig. 15, cell E) or entirely Ozark aquifer where the Ozark aquifer is present at the surface (fig. 15, cell F). Layer 2 was assigned a constant thickness of 100 ft, which restricted the occurrence of the Ozark confining unit to layer 1 or layer 2. Layer 2 is composed of a combination of Ozark confining unit and Ozark aquifer (fig. 15, cell G) or composed entirely of Ozark aquifer (fig. 15, cell H). By definition, layer 2 does not contain any Springfield Plateau aquifer anywhere in the model. Layer 3 of the model is composed entirely of Ozark aquifer (fig. 15, cell I). Layer 1 and layer 3 vary in thickness.

Figure 6 and figure 7 show cross sections (trace shown on figs. 3, 16, and 17) from northwest to southeast and southwest to northeast across the model area with the bottoms of the layers of the model indicated. As can be seen on figure 6 and figure 7, model layers 1 and 2 can be composed of a combination of several hydrogeologic units. Figure 16 and figure 17 show the plan view distribution of the hydrogeologic units in layer 1 and layer 2 in the model.

Hydraulic Property Computation

Because model layers can comprise multiple hydrogeologic units (figs. 6, 7, 15, 16, and 17), composite hydraulic properties for each model layer were computed. The horizontal and vertical composite hydraulic conductivity for each cell was computed based on the concepts of “branch conductances” (McDonald and Harbaugh, 1988). Specific yield and specific storage were computed by calculating the thickness weighted mean in each cell. For each model run, hydraulic properties of the various hydrogeologic units were specified and converted into composite hydraulic properties for each cell prior to executing the groundwater model.

Stress Period Discretization

The first stress period simulated in the model was specified as steady state to allow the simulated head to come into equilibrium with the model boundary conditions. There was no pumping from the aquifers specified in stress period 1. The steady-state stress period was followed by 100 annual transient stress periods representing the period from 1907 to 2006. Annual stress periods were specified so that groundwater-pumping rates and recharge could be varied annually as groundwater demand and precipitation changed with time. Calibration of the model was focused on the predevelopment steady-state stress period and on the period from 1987 to 2006. Predevelopment water-level data were obtained from the Missouri DNR well-log database (Missouri Department of Natural Resources, 2007) and supplemented with interpolated values from predevelopment potentiometric surface maps developed by Imes (1990a, 1990b). The USGS collected four (1987, 1993, 1996, and 2006) sets of synoptic water-level measurements from wells between 1987 and 2006, and numerous random measurements were obtained from USGS databases and Missouri DNR databases for the calibration period. For the predictive simulation period from 2007 to 2030, annual stress periods were specified so that groundwater-pumping rates and recharge could be varied annually as groundwater demand and precipitation changed with time.

Model Boundary Conditions

Model boundary conditions were specified such that groundwater flow was consistent with the conceptual model. The flux boundary conditions were specified by using the RCH package of MODFLOW for areally distributed recharge, the RIV package of MODFLOW for flow to and from rivers, and the DRN package of MODFLOW for flow to springs (Harbaugh, 2005). The GHB package of MODFLOW (Harbaugh, 2005) was used for flow to and from lakes, for lateral flow through the boundary of the model, and for vertical flow through the bottom of the Ozark aquifer. Each of these specifications is discussed in the following sections.

Areally Distributed Recharge

Areally distributed recharge occurs at the land surface from infiltration resulting from atmospheric precipitation. Mean annual precipitation in the region for the period 1971–2000 was 44.97 inches (National Climatic Data Center, 2008). Some of this precipitation infiltrates into the Springfield Plateau aquifer and the Ozark aquifer where they are present at the land surface. It was assumed that there was no recharge to the groundwater where the Ozark confining unit is present at the land surface, which has a small area (fig. 8). Areal recharge can vary substantially and is an important model variable for simulating groundwater flow.

Using a soil-moisture water-balance analysis, Dugan and Peckenpaugh (1986) provided estimates of potential recharge across the model area that ranged from 1.80×10^{-3} to 2.17×10^{-3} feet per day (ft/d) or 7.9 to 9.5 inches per year (in/yr). These estimates of recharge were used in this model as a starting point to begin the calibration process. Results from these initial attempts resulted in head distributions that were too high and flows to the rivers that were too large, even with commensurate changes

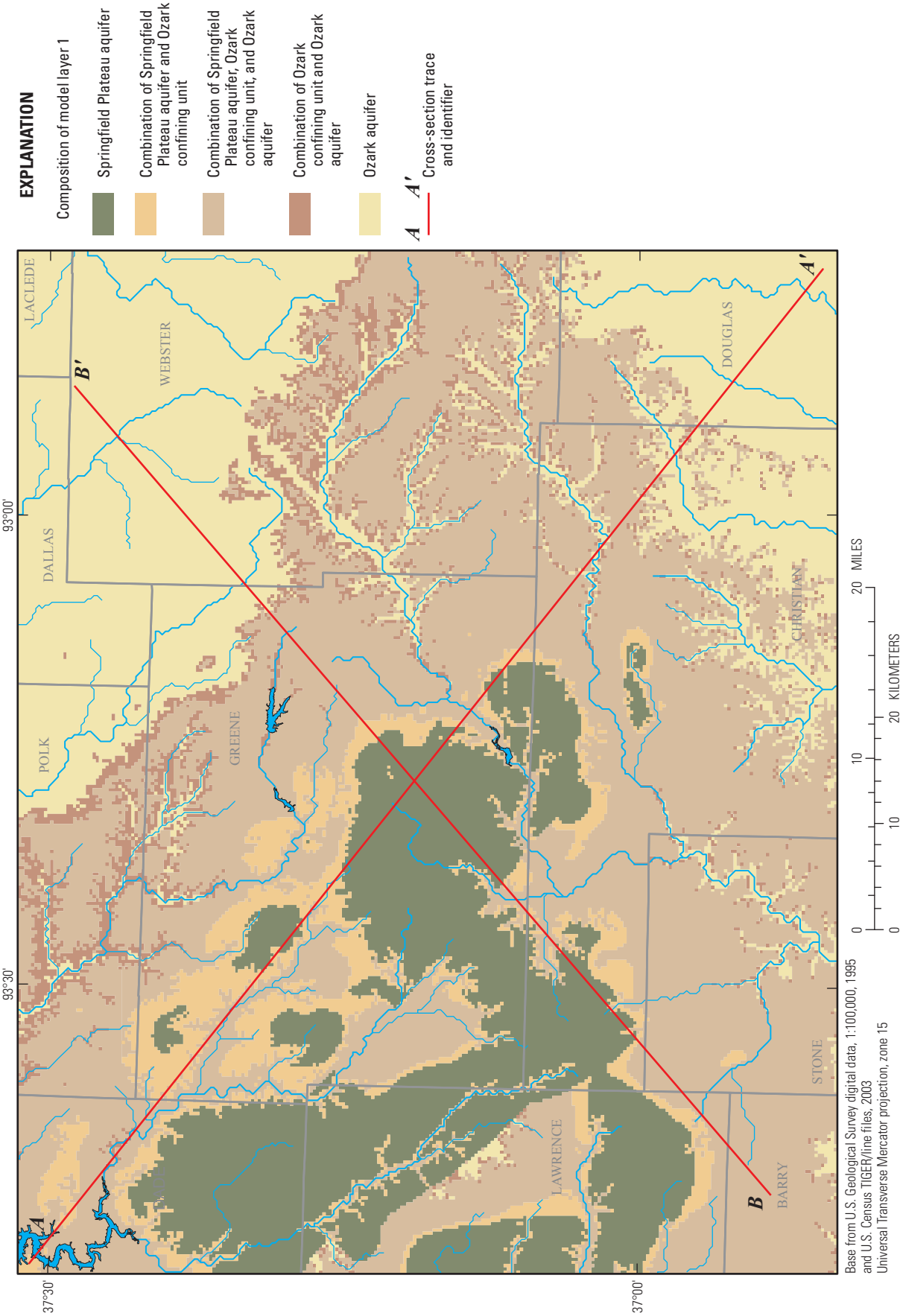


Figure 16. Distribution of hydrogeologic units in layer 1 of the model.

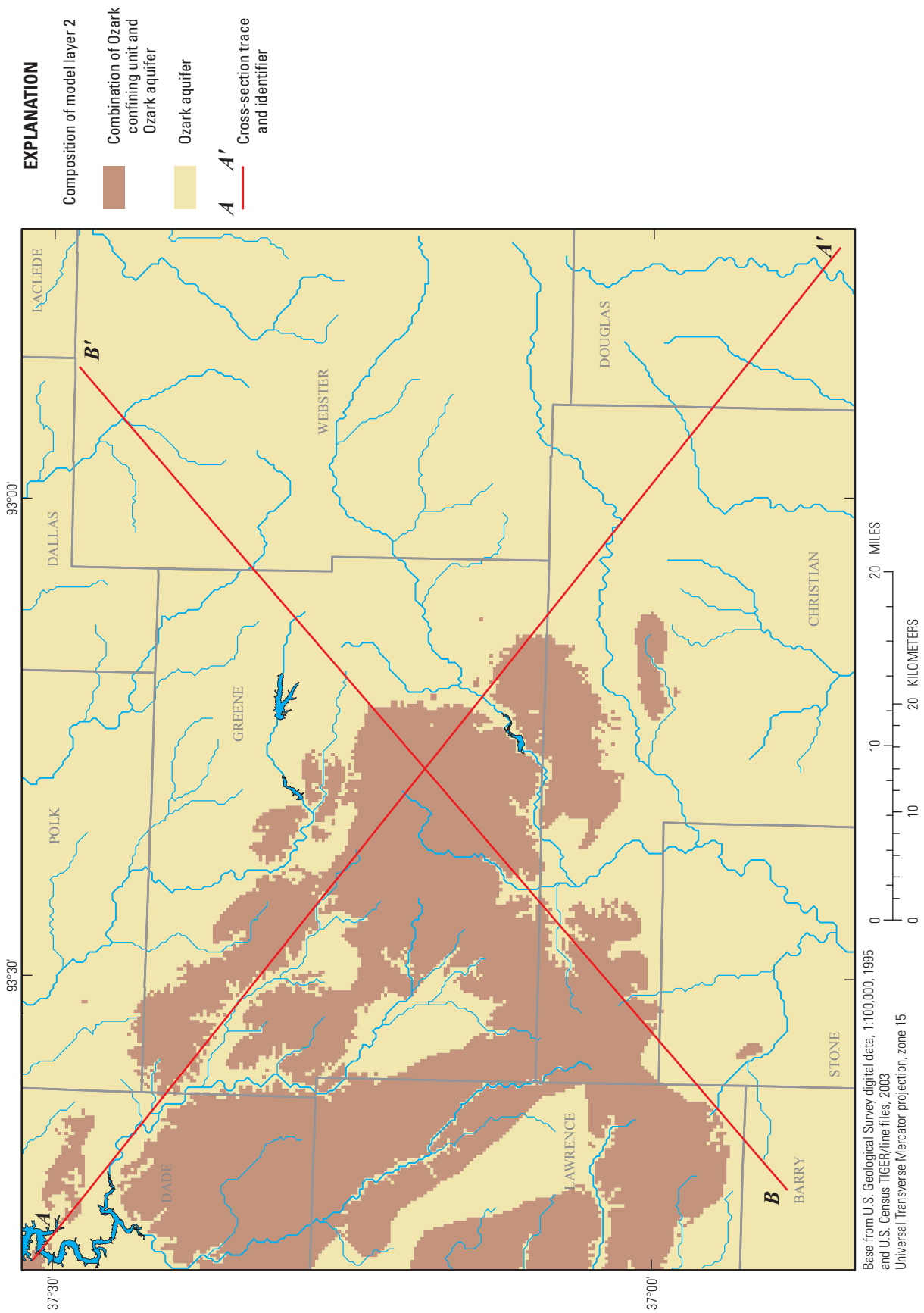


Figure 17. Distribution of hydrogeologic units in layer 2 of the model.

in hydraulic conductivity. These estimates of recharge were also found to be too large in previous models completed in the Springfield, Missouri, area (Imes, 1989), in the regional model of Imes and Emmett (1994), and in the model of Czarnecki and others (2009) in southwestern Missouri, southeastern Kansas, northeastern Oklahoma, and northwestern Arkansas.

The water-table fluctuations method (Risser and others, 2005) was used to estimate the minimum recharge to the groundwater in the Springfield Plateau aquifer at the Longview monitoring well in McDonald County, Missouri, southwest of this model area. The water-table fluctuations method measures the effect of recharge at the water table and requires that the value of specific yield for the aquifer be known to translate the measured water-level fluctuations into estimates of recharge. The method assumes that the water-level rise in the well is caused only by recharge arriving at the water table and that the specific yield of the aquifer is constant. Changes in the water levels were computed from the daily observations at the Longview monitoring well (fig. 18). Annual cumulative totals were obtained by summing the daily rise in the water level. Daily water levels that fell or that had no change did not change the cumulative total. The annual cumulative total then was multiplied by the specific yield value, 0.003, used in the model to determine the recharge value for the year. To ensure the greatest accuracy, only years with greater than 350 daily observations were used to compute the recharge value. Years with fewer data points, although useful for some applications, were not used in this analysis. Between 1984 and 2008, 8 years had greater than 350 daily observations resulting in calculated recharge ranging from 1.74×10^{-4} ft/d to 2.09×10^{-4} ft/d (0.762 and 0.915 in/yr) with a mean recharge of 1.94×10^{-4} ft/d (0.849 in/yr) (table 3). This range of recharge is similar to that specified by Imes (1989) of 3.01×10^{-4} to 3.69×10^{-4} ft/d and to values specified by Czarnecki and others (2009) of 2.00×10^{-5} to 8.00×10^{-4} ft/d.

In this model, it was assumed that recharge varied spatially based on land slope. It was also assumed that recharge was less in the city of Springfield because of the distribution of impervious surface in the city (fig. 19). Recharge was applied to all cells in layer 1 except cells where the Ozark confining unit is exposed at the surface. Land slope was determined from the DEM and then classified into three zones that were used to adjust the amount of recharge being applied to the land surface (table 4). Lower slope values tend to occur in the upland areas and near streams. It was assumed that greater infiltration would occur in areas with lower slope values. This assumption is supported by the greater number of sinkhole occurrences that are associated with the relatively flat uplands in the model area (fig. 5). The total recharge rate was computed as approximately 2.53 percent of the total annual precipitation observed in the region (table 5). It was assumed that areas covered by impervious surface in the city of Springfield do not contribute recharge to the aquifer; the city of Springfield is estimated to be covered by approximately 32 percent impervious surface (fig. 20). Within the city, the computed recharge based on land slope was reduced by 32 percent to account for the reduced potential for recharge to the aquifer (table 4). In areas where recharge was applied, the percentage of the total precipitation that became recharge to the model ranged between 1.44 and 3.00 percent (table 4). Recharge, in areas where recharge was applied, for the mean annual precipitation value of 44.97 in/yr ranged between 1.47×10^{-4} and 3.08×10^{-4} ft/d (0.645 in/yr and 1.35 in/yr; table 4). The total annual recharge to the model, from 1907 to 2006, ranged between 1.45×10^{-4} and 3.60×10^{-4} ft/d (0.637 in/yr and 1.58 in/yr) (table 5), and this range in recharge is similar to recharge values used in previous models and to the values obtained by the water-table fluctuation method.

The area is characterized by well-developed karst (fig. 5), which has the ability to move large volumes of water through the aquifer quickly by way of a complex network of conduits and fractures. The effect of this short residence time in the Springfield Plateau aquifer is that a large fraction of the recharge from precipitation ends up discharging to springs and streams before it can flow through the Ozark confining unit into the Ozark aquifer. Whereas the values of recharge used in the model are small relative to the Dugan and Peckenpaugh (1986) values, the majority of the recharge estimated by Dugan and Peckenpaugh (1986) moves through the karst system as fracture flow and cannot provide recharge to the regional groundwater-flow system. The value of recharge used in the model is consistent with the estimated discharge to streams and other discharge components of the model.

Table 3. Estimated recharge values of the Springfield Plateau aquifer computed from continuous water-level data collected at the Longview monitoring well in McDonald County, Missouri.

[ft/d, feet per day; in/yr, inches per year]

Year	Cumulative total rise (inches)	Recharge (ft/d)	Recharge (in/yr)	Number of observations
1984	23.68	1.95×10^{-4}	0.852	366
1985	25.25	2.08×10^{-4}	.909	365
1989	23.07	1.90×10^{-4}	.831	365
1990	25.43	2.09×10^{-4}	.915	365
1991	21.35	1.75×10^{-4}	.769	365
2001	21.16	1.74×10^{-4}	.762	365
2005	23.71	1.95×10^{-4}	.854	365
2007	24.93	2.05×10^{-4}	.897	351

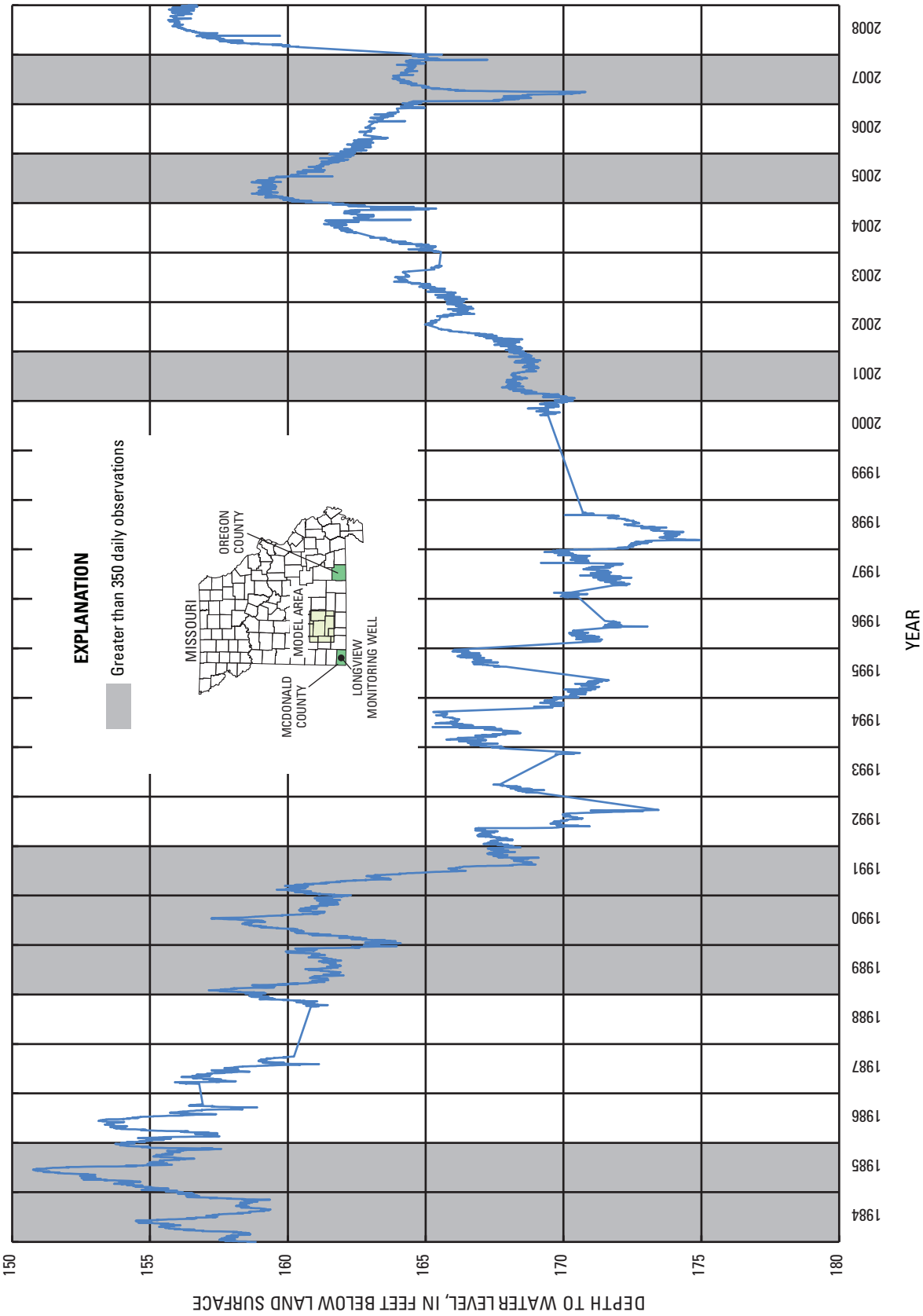


Figure 18. Hydrograph of the Longview monitoring well in McDonald County, Missouri.

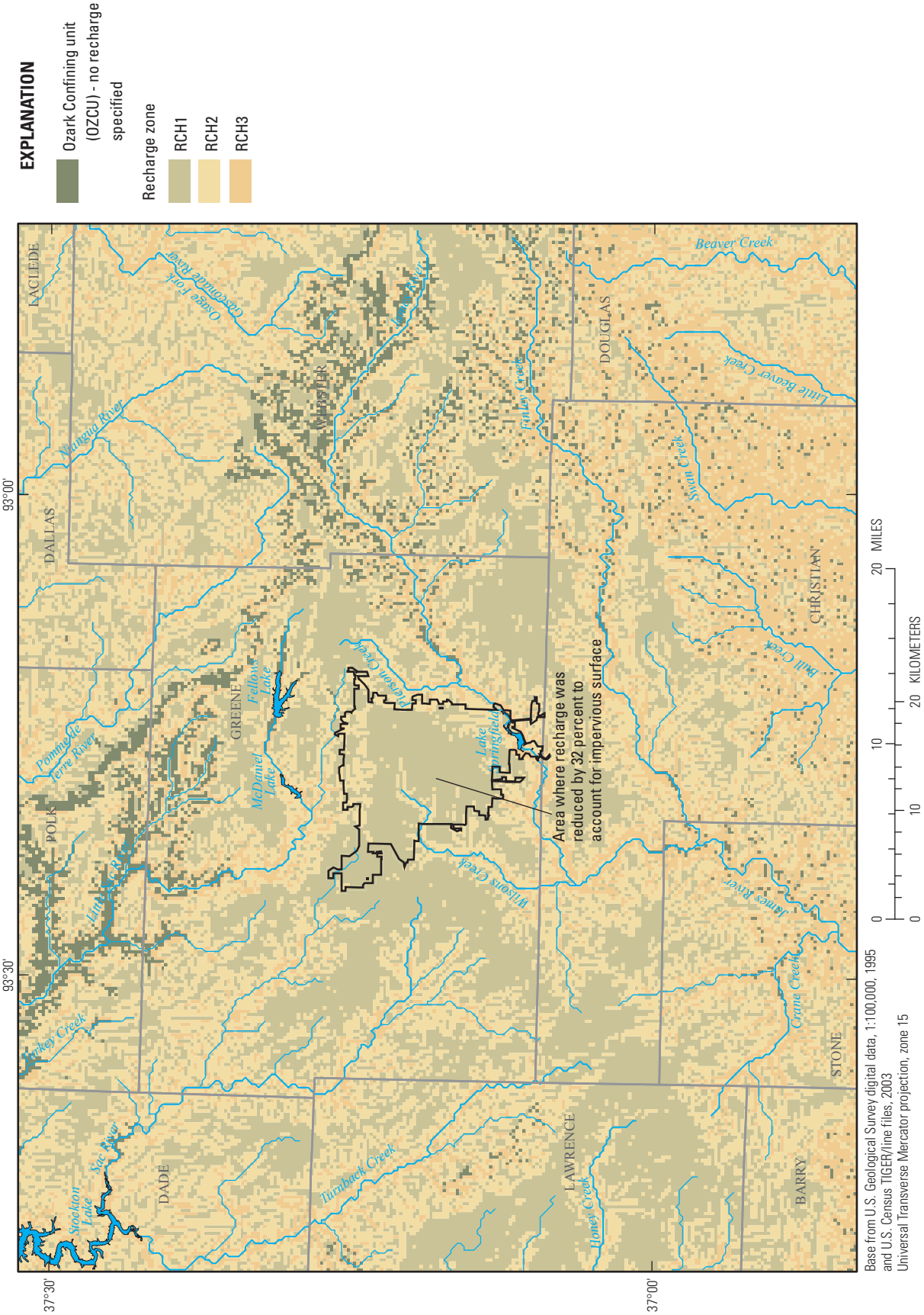


Figure 19. Areally distributed recharge zones.

Table 4. Areally distributed recharge zones and values.

[ft/d, feet per day; in/yr, inches per year; OZCU, Ozark confining unit outcrop area (no recharge specified); —, no data; >, greater than]

Recharge zone (fig. 19)	Land-surface slope (degrees)	Percentage of total precipitation	Recharge to model with mean annual precipitation value of 44.97 inches	
			(in/yr)	(ft/d)
OZCU	—	0.00	0.00	0.00
RCH1	0-1	3.00	1.35	3.08×10^{-4}
RCH2	>1-2	2.70	1.21	2.77×10^{-4}
RCH3	>2	2.10	.944	2.16×10^{-4}
RCH1 (reduced by 32 percent to account for impervious surface in Springfield)	0-1	2.05	.922	2.11×10^{-4}
RCH2 (reduced by 32 percent to account for impervious surface in Springfield)	>1-2	1.85	.830	1.89×10^{-4}
RCH3 (reduced by 32 percent to account for impervious surface in Springfield)	>2	1.44	.645	1.47×10^{-4}

Rivers

Flux to and from river cells is dependent on riverbed conductance and the relative altitudes of head in layer 1 and the river stage. Altitude of the riverbed was obtained from DEM data. Nearly all rivers determined to be perennial in the low resolution (1:100,000 scale) national hydrography dataset (NHD) were included in the model (http://nhd.usgs.gov/index.html) (fig. 21).

Rivers in the area generally flow on gravel, bedrock, or both. Both provide little impediment to flow between the river and the aquifer. As a result, the streambed conductance was calculated based on the vertical hydraulic conductivity of the hydrogeologic unit on which the river was flowing. This value was adjusted during the calibration process by multiplying the streambed conductance by 0.8 for streams flowing on the Springfield Plateau aquifer, by 1.3 for streams flowing on the Ozark aquifer, and by 10,000 for streams flowing on the Ozark confining unit. Streambed conductance ranged from 50 to 9,750 square feet per day (ft^2/d; fig. 22).

To obtain streamflow data for use in calibrating the model, on October 10-12, 2006, a seepage run was performed by the USGS on the James River Basin upstream from the James River at Galena (07052500) streamgage to the headwaters of the river (fig. 23, data on file at USGS, Rolla, Missouri). It was found that James River and Finley Creek generally gain streamflow from the Ozark aquifer and generally lose streamflow to the Springfield Plateau aquifer. In karst areas, the gain in the river flow is often the result of discrete discharge to the river such as spring flow into the bottom of the river. Conversely, in karst areas, flow can be partly or completely lost in a relatively short distance as the river flows on an area of fractured rock or flows into a sinkhole. There may also be interbasin transfer of groundwater through the karst features. Although several flow measurements were made at springs, the 2006 seepage run was too coarse to identify discrete recharge/discharge points in the river.

The model simulates flow to or from rivers as diffuse flow. The karst nature of the area complicates matching the simulated river flows with the observed river flows. Matching the difference in observed flow between two observation points on the river was problematic. To evaluate discharge to rivers in the model, entire basins were chosen rather than a specific reach, which assumes that the karst effects would be reduced somewhat by using larger contributing flow areas. To simplify the karst effects further, it was assumed that the statistical $7Q_2$ values could be used to estimate the base-flow discharge to the rivers.

The $7Q_2$ was computed at gaged sites with, ideally, 10 or more years of continuous discharge record. Fourteen river basins were chosen as control points to evaluate the simulation of the rivers in the model (fig. 21). USGS streamgages exist in 10 of the 14 basins. The gages located on the Sac River (06918440), Little Sac River (06918740), Turnback Creek (06918460), Finley Creek (07052345), and two upstream sites on the James River (07050700 and 07052250) were within the model boundary (fig. 1, and table 6). The gages located on

Table 5. Annual precipitation totals observed and total model recharge specified in the model area, 1907–2008.

[in/yr, inches per year; ft/d, feet per day; —, no data]

Year	Precipitation total (in/yr)	Model recharge (in/yr)	Model recharge (ft/d)	Year	Precipitation total (in/yr)	Model recharge (in/yr)	Model recharge (ft/d)
1907	—	1.136	$2.59x10^{-4}$	1947	39.62	1.001	$2.28x10^{-4}$
1908	—	1.136	$2.59x10^{-4}$	1948	39.45	.996	$2.27x10^{-4}$
1909	—	1.136	$2.59x10^{-4}$	1949	50.32	1.271	$2.90x10^{-4}$
1910	—	1.136	$2.59x10^{-4}$	1950	37.76	.954	$2.18x10^{-4}$
1911	—	1.136	$2.59x10^{-4}$	1951	50.19	1.268	$2.89x10^{-4}$
1912	—	1.136	$2.59x10^{-4}$	1952	29.20	.737	$1.68x10^{-4}$
1913	—	1.136	$2.59x10^{-4}$	1953	25.21	.637	$1.45x10^{-4}$
1914	—	1.136	$2.59x10^{-4}$	1954	37.99	.959	$2.19x10^{-4}$
1915	46.47	1.174	$2.68x10^{-4}$	1955	28.61	.723	$1.65x10^{-4}$
1916	37.80	.955	$2.18x10^{-4}$	1956	28.72	.725	$1.66x10^{-4}$
1917	31.71	.801	$1.83x10^{-4}$	1957	47.90	1.210	$2.76x10^{-4}$
1918	34.62	.874	$2.00x10^{-4}$	1957	50.20	1.268	$2.89x10^{-4}$
1919	38.06	.961	$2.19x10^{-4}$	1958	44.25	1.118	$2.55x10^{-4}$
1920	36.89	.932	$2.13x10^{-4}$	1959	42.99	1.086	$2.48x10^{-4}$
1921	47.21	1.192	$2.72x10^{-4}$	1960	33.09	.836	$1.91x10^{-4}$
1922	36.77	.929	$2.12x10^{-4}$	1961	46.00	1.162	$2.65x10^{-4}$
1923	39.53	.998	$2.28x10^{-4}$	1962	36.85	.931	$2.12x10^{-4}$
1924	45.13	1.140	$2.60x10^{-4}$	1963	27.65	.698	$1.59x10^{-4}$
1925	31.89	.805	$1.84x10^{-4}$	1964	37.90	.957	$2.19x10^{-4}$
1926	40.48	1.022	$2.33x10^{-4}$	1965	44.85	1.133	$2.59x10^{-4}$
1927	62.45	1.577	$3.60x10^{-4}$	1966	36.86	.931	$2.13x10^{-4}$
1928	44.37	1.121	$2.56x10^{-4}$	1967	43.88	1.108	$2.53x10^{-4}$
1929	40.15	1.014	$2.32x10^{-4}$	1968	49.72	1.256	$2.87x10^{-4}$
1930	30.73	.776	$1.77x10^{-4}$	1969	30.19	.762	$1.74x10^{-4}$
1931	38.46	.971	$2.22x10^{-4}$	1970	43.47	1.098	$2.51x10^{-4}$
1932	39.35	.994	$2.27x10^{-4}$	1971	37.53	.948	$2.16x10^{-4}$
1933	43.82	1.107	$2.53x10^{-4}$	1972	39.74	1.004	$2.29x10^{-4}$
1934	36.19	.914	$2.09x10^{-4}$	1973	58.92	1.488	$3.40x10^{-4}$
1935	52.79	1.333	$3.04x10^{-4}$	1974	49.88	1.260	$2.88x10^{-4}$
1936	30.03	.758	$1.73x10^{-4}$	1975	45.12	1.139	$2.60x10^{-4}$
1937	36.16	.913	$2.08x10^{-4}$	1976	32.74	.827	$1.89x10^{-4}$
1938	42.36	1.070	$2.44x10^{-4}$	1977	45.22	1.142	$2.61x10^{-4}$
1939	35.92	.907	$2.07x10^{-4}$	1978	43.48	1.098	$2.51x10^{-4}$
1940	34.22	.864	$1.97x10^{-4}$	1979	46.08	1.164	$2.66x10^{-4}$
1941	48.07	1.214	$2.77x10^{-4}$	1980	27.67	.699	$1.60x10^{-4}$
1942	47.87	1.209	$2.76x10^{-4}$	1981	41.97	1.060	$2.42x10^{-4}$
1943	46.24	1.168	$2.67x10^{-4}$	1982	47.72	1.205	$2.75x10^{-4}$
1944	37.17	.939	$2.14x10^{-4}$	1983	44.13	1.114	$2.54x10^{-4}$
1945	54.40	1.374	$3.14x10^{-4}$	1984	48.53	1.226	$2.80x10^{-4}$
1946	41.51	1.048	$2.39x10^{-4}$	1985	58.99	1.490	$3.40x10^{-4}$

Table 5. Annual precipitation totals observed and total model recharge specified in the model area, 1907–2008.—Continued

[in/yr, inches per year; ft/d, feet per day; —, no data]

Year	Precipitation total (in/yr)	Model recharge (in/yr)	Model recharge (ft/d)
1986	42.19	1.065	2.43×10^{-4}
1987	48.48	1.224	2.80×10^{-4}
1988	44.24	1.117	2.55×10^{-4}
1989	34.07	.860	1.96×10^{-4}
1990	61.29	1.548	3.53×10^{-4}
1991	39.64	1.001	2.29×10^{-4}
1992	48.26	1.219	2.78×10^{-4}
1993	58.05	1.466	3.35×10^{-4}
1994	47.40	1.197	2.73×10^{-4}
1995	42.43	1.072	2.45×10^{-4}
1996	45.96	1.161	2.65×10^{-4}
1997	41.63	1.051	2.40×10^{-4}
1998	48.24	1.218	2.78×10^{-4}
1999	42.87	1.083	2.47×10^{-4}
2000	37.47	.946	2.16×10^{-4}
2001	45.29	1.144	2.61×10^{-4}
2002	37.82	.955	2.18×10^{-4}
2003	42.61	1.076	2.46×10^{-4}
2004	43.23	1.092	2.49×10^{-4}
2005	35.32	.892	2.04×10^{-4}
2006	38.87	.982	2.24×10^{-4}
2007	44.27	1.118	2.55×10^{-4}
2008	60.12	1.518	3.47×10^{-4}
Mean 1971–2000	44.97	1.136	2.59×10^{-4}
Drought (1953)	25.21	.637	1.45×10^{-4}

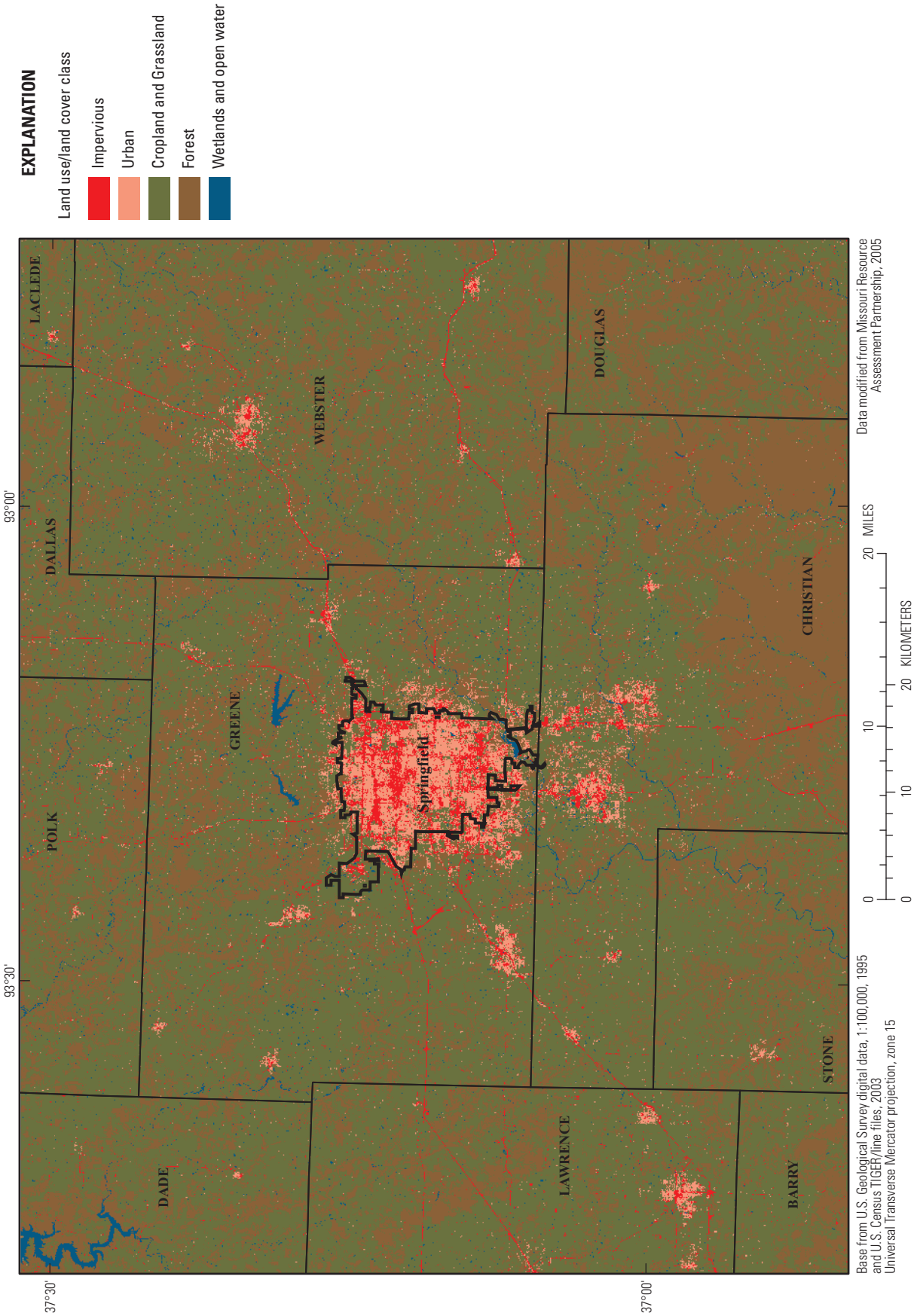


Figure 20. Land use/land cover distribution in the model area.

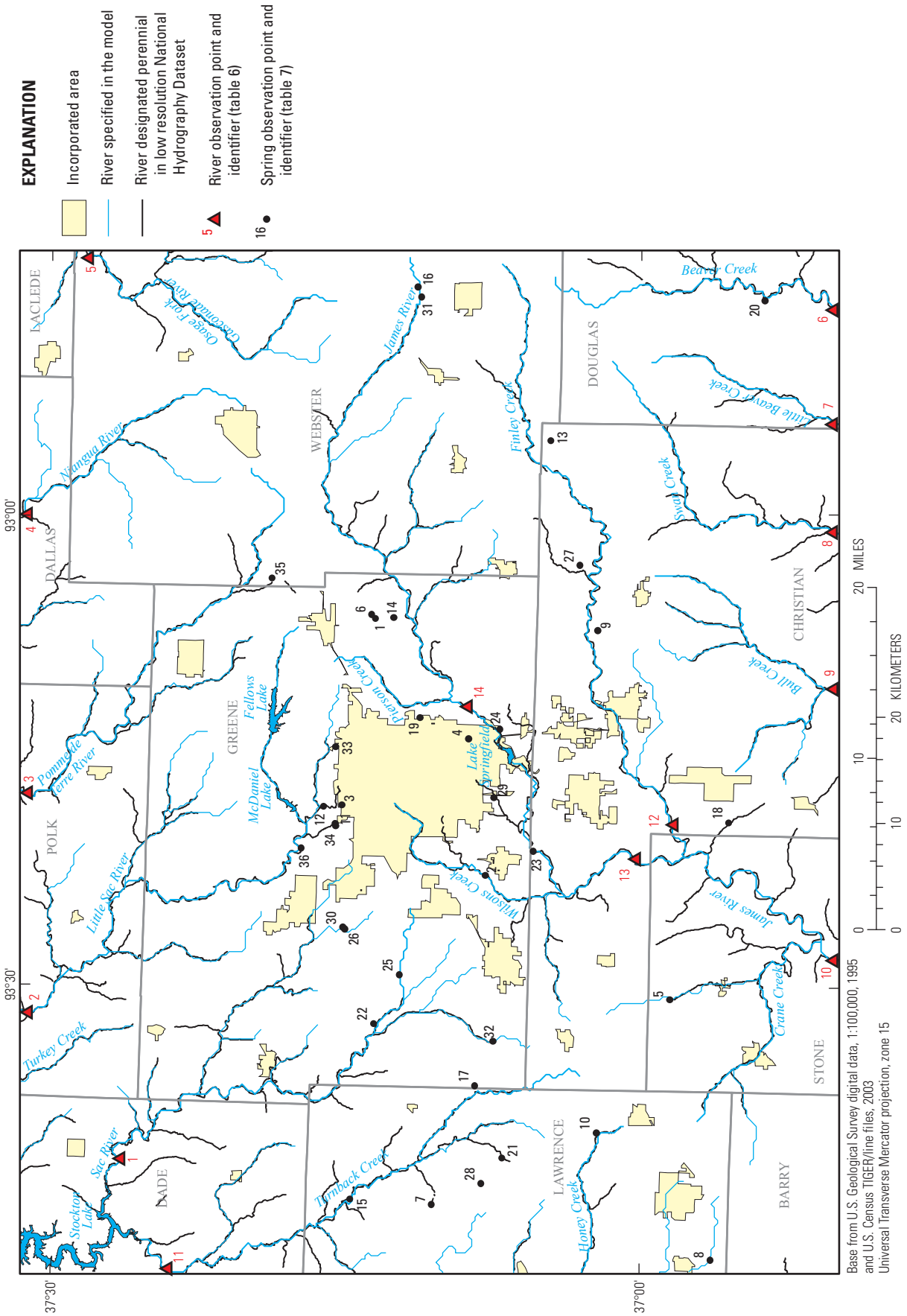


Figure 21. River and spring observation points specified in the model.

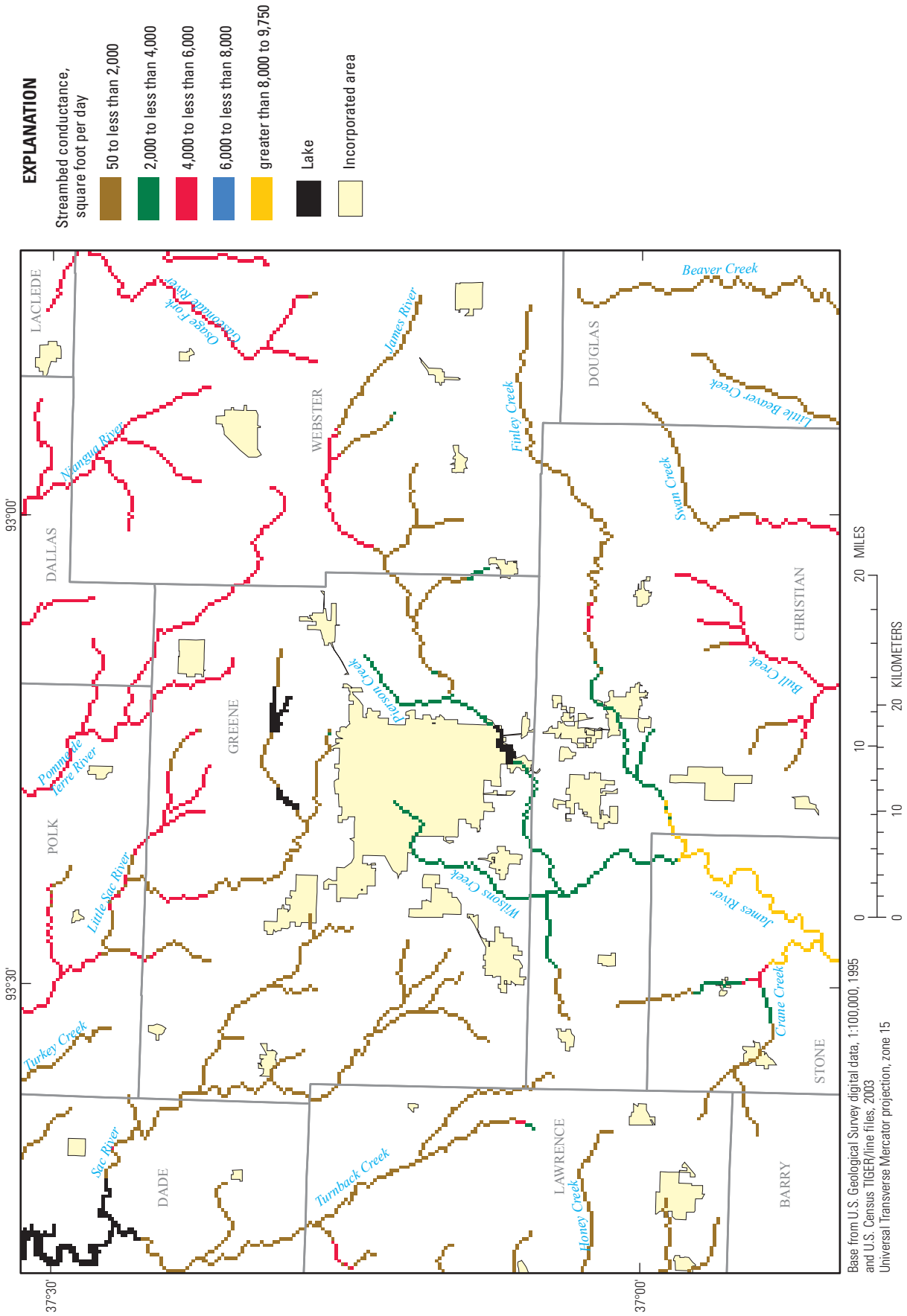


Figure 22. Streambed conductance values for rivers specified in the model and location of lake general-head boundary cells.

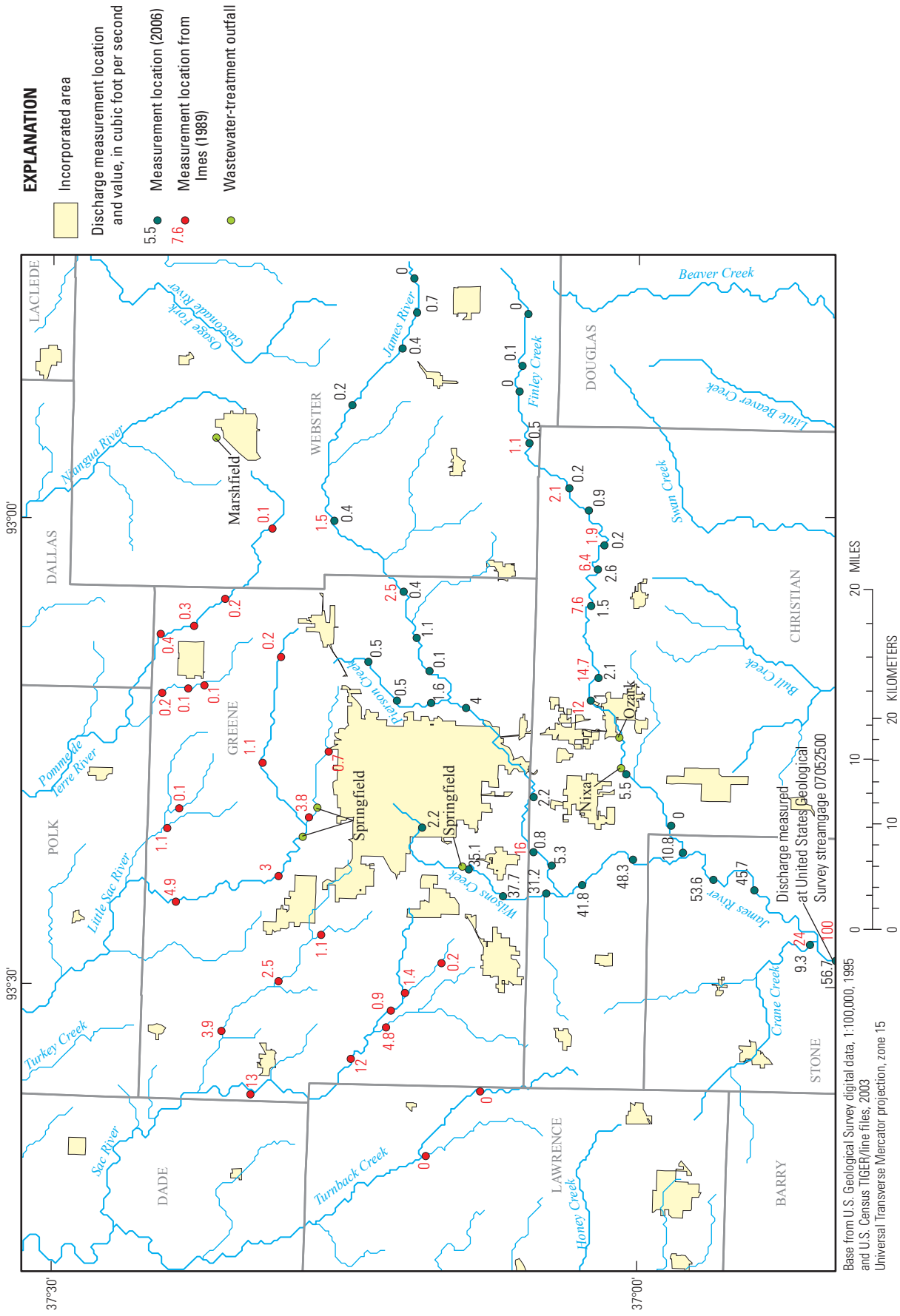


Figure 23. Discharge measurement locations for the seepage run in the James River Basin, 2006, discharge measurement locations from Imes (1989), and locations of selected wastewater-treatment outfalls.

Bull Creek (07053810), Beaver Creek (07054080), Niangua River (06923250), Osage Fork Gasconade River (06927800), Pomme de Terre River (06921070), and the downstream site on the James River (07052500) were outside the model boundary (fig. 1 and table 6). Flow estimates for these gages were adjusted by the proportion of basin area within the model area. Flow estimates for Swan Creek at the model boundary were based on the $7Q_2$ flow at the gage on Bull Creek (07053810) and adjusted to the basin area within the model area. Flow estimates for Little Beaver Creek at the model boundary were based on the $7Q_2$ flow at the gage on Beaver Creek (07054080) adjusted to the basin area within the model area. The $7Q_2$ flow estimates were reduced by the estimated flow of the wastewater outfall in basins that had wastewater outfalls with flows greater than 0.8 cubic feet per second, or 66,000 ft^3/d (cubic feet per day; table 6). Wastewater outfall flow data were obtained from the Missouri Department of Natural Resources (2007).

Springs

Within the model area, 189 springs have been identified by the Missouri Department of Natural Resources (2007; fig. 5). Most of the springs have a relatively small discharge under base-flow conditions and were not simulated in the model. Thirty-six springs were classified by Missouri DNR as having a mean discharge of 1 cubic foot per second (ft^3/s) or greater and were included in the model (fig. 21, table 7). Long-term base-flow data for the springs in the model area are scarce. Base-flow discharge estimates and spring orifice elevation were obtained or inferred from data available in Missouri Department of Natural Resources (2007), Vineyard and Feder, (1982), and Bullard and others (2001).

Groundwater discharge to springs was simulated using the DRN package in MODFLOW (Harbaugh, 2005). Groundwater is discharged from the model at a spring if the potentiometric head in the aquifer is greater than the spring orifice elevation and is discharged at a rate controlled by the drain conductance value. Springs in the area generally discharge directly from fissures in bedrock or through gravel in the spring orifice. This material provides little impediment to flow from the aquifer. The drain conductance value was specified at 10,000 ft^2/d.

General-Head Boundaries

Groundwater flow laterally through the model boundaries, vertically through the bottom of the Ozark aquifer, and into and out of lakes was simulated using general-head boundaries in the model. For general-head boundaries, the direction of flow through the boundary is dependent on the difference between the potentiometric head in the aquifer and the specified reference head, and the flux is regulated by the conductance value. General-head boundaries were not varied with time in this model because temporal fluctuation in these boundaries was unknown.

Lateral Flow at the Model Boundary

A general-head boundary was specified in all three model layers around the entire model perimeter to allow flow laterally into and out of the model. Specified reference head values were derived from measured and inferred water levels (Richards and Mugel, 2008; U.S. Geological Survey, 2007; Gillip and others, 2008, data on file at USGS, Rolla, Missouri). The specified conductance value for each cell along the boundary is a function of the surface area of the cell face in the direction of flow, the horizontal hydraulic conductivity in the cell, and the distance between the cell and the reference-head location. Conductance values ranged from 11.5 to 530.6 ft^2/d in layer 1, from 4.56 to 105.0 ft^2/d in layer 2, and from 59.9 to 1,288 ft^2/d in layer 3.

Vertical Flow Through the Bottom of the Ozark Aquifer

Although the flux of water through the bottom of the Ozark aquifer was anticipated to be relatively small, the direction and magnitude of flow could change as a result of additional pumping stress in the future. A general-head boundary was specified in layer 3 of the model to simulate flow through the bottom of the Ozark aquifer. Reference head values in the St. Francois aquifer were specified as a constant value of 600 ft. Because there are no wells using the St. Francois aquifer in the model area, water levels in a monitoring well in the northern part of Oregon County, Missouri (fig. 1) were investigated (data on file at USGS, Rolla, Missouri). Although this well is located approximately 100 miles east of Springfield, it is open to the St. Francois aquifer and is in a similar structural position relative to the center of the Ozark Dome as the study area. The water-level altitude tended to fluctuate around 600 ft because of recharge to the aquifer. It is assumed that the head in the St. Francois aquifer in the model area is similar to the water levels in the monitoring well, so 600 ft was chosen as an estimated value. The specified conductance value for each cell along the boundary is a function of the surface area of the cell face in the direction of flow, the vertical hydraulic conductivity of the St. Francois confining unit, and the thickness of the St. Francois confining unit. The St. Francois confining unit was estimated to be 250 ft thick in the model area (Imes, 1989), and the vertical hydraulic conductivity was divided into two zones with values of 8.75×10^{-6} and 5.00×10^{-5} ft/d. These values of vertical hydraulic conductivity compare favorably with the values of Imes and Emmett (1994) of about 8.6×10^{-4} ft/d and Imes (1989) of about 3.8×10^{-6} ft/d (table 2). The calculated conductance values for this model in the two zones were 0.035 and 0.200 ft^2/d (fig. 24).

Table 6. Estimated 7-day annual low-flow discharge values for the 2-year recurrence interval at selected sites.

[mi², square miles; ft³/s, cubic feet per second; ft³/d, cubic foot per day; $7Q_2$, 7-day annual low-flow discharge for the 2-year recurrence interval; —, no data]

Identifier (fig. 21)	Area of basin contained in study area (mi²)	Basin area at observation point (mi²)	Station number of streamgage used to estimate $7Q_2$ (fig. 1)	River name of streamgage used to estimate $7Q_2$	$7Q_2$ at streamgage (ft³/s)	Streamgage drainage area (mi²)	Observed discharge, corrected for basin area within model area (ft³/s)	Observed discharge of outfalls in basin (ft³/s)	Observed discharge outfall corrected (ft³/s)	Observed discharge outfall corrected (ft³/d) A	Simulated discharge (ft³/d) B	Relative percent difference (100|A-B|/((A+B)/2))	Percent error (100((A-B/A))
1	259	259	06918440	Sac River	17.0	257	17.1	1.20	15.9	1,370,824	1,525,195	11	-11
2	237	237	06918740	Little Sac River	8.10	237	8.10	5.42	2.68	231,552	1,333,779	141	-476
3	176	176	06921070	Pomme de Terre River	6.80	276	5.43	—	5.43	469,169	1,104,528	81	-135
4	137	142	06923250	Niangua River	20.0[1]	377	11.8	1.08	10.7	927,070	674,453	32	27
5	111	157	06927800	Osage Fork Gasconade River	24.0	404	10.6	—	10.6	913,228	637,684	36	30
6	87	163	07054080	Beaver Creek	18.9	298	7.45	—	7.45	643,489	531,189	19	17
7	55	55	07054080	Beaver Creek	6.08	298	2.61	—	2.61	225,228	278,572	21	-24
8	107	107	07053810	Bull Creek	3.30	191	2.47	—	2.47	213,738	541,964	87	-154
9	99	99	07053810	Bull Creek	3.30	191	2.38	—	2.38	205,297	217,236	6	-6
10	965	973	07052500	James River	111	987	109	49	60.7	5,243,055	3,126,645	51	40
11	181	251	06918460	Turnback Creek	25.0	251	18.0	—	18.0	1,555,899	1,184,626	27	24
12	249	261	07052345	Finley Creek	13.0[1]	261	12.4	1.85	10.6	911,520[2]	830,368[2]	9	9
13	462	462	07052250	James River	58.0	462	58.0	47	11.3	973,728[2]	1,159,377[2]	17	-19
14	246	246	07050700	James River	8.90	246	8.90	—	8.90	768,960[2]	646,363[2]	17	16
Totals										11,998,548	11,155,870	7	7

[1]Denotes $7Q_2$ based on 4 years of record

[2]Not included in total because these totals are included in the 07052500 gage

Table 7. Base-flow discharge estimates of selected springs.

[ft, foot; ft^3/s, cubic foot per second; ft^3/d, cubic foot per day; SPA, Springfield Plateau aquifer; OZA, Ozark aquifer; —, no data]

Identifier (fig. 21)	Name	Hydrogeologic unit[1]	Spring altitude[1] (ft)	Observed discharge (ft^3/s)	Observed discharge (ft^3/d) A	Simulated discharge (ft^3/d) B	Relative percent difference (100|A-B|/((A+B)/2))	Percent error (100((A-B/A))
1	Broad Creek Spring	SPA	1,310	18.70	1,615,680	4,380	199	100
2	Rader Spring	SPA	1,115	10.50	907,200	117,203	154	87
3	Dickerson Park Spring	SPA	1,170	14.30	1,235,520	34,723	189	97
4	Sequiota Spring	SPA	1,200	.93	80,179	10,823	152	87
5	Brown Spring (2)	—	1,140	5.12	442,368	20,352	182	95
6	Cavin Cave Spring	SPA	1,340	8.03	693,792	3,325	198	100
7	Cove Spring	—	1,150	3.20	276,480	0	200	100
8	Spring River Spring #1	—	1,290	2.80	241,920	9,356	185	96
9	Unnamed Spring	—	1,180	5.00	432,000	0	200	100
10	Polk Spring	—	1,280	1.87	161,568	9,836	177	94
11	Ritter Spring (East)	SPA	1,125	3.44	297,216	13,329	183	96
12	Fulbright Spring	SPA	1,120	3.35	289,440	10,485	186	96
13	Todd Spring	—	1,350	3.14	271,296	1,944	197	99
14	Treasure Spring	OZA	1,240	3.06	264,384	0	200	100
15	Lumlee Spring	—	904	1.63	140,832	71,508	65	49
16	Mountaindale Spring	—	1,473	.82	70,848	10,968	146	85
17	Hart (J.) Spring	SPA	1,130	1.94	167,616	13,694	170	92
18	Montague	—	1,120	2.71	234,144	0	200	100
19	Jones Spring	SPA	1,208	1.20	103,680	11,686	159	89
20	Jackson Mill Spring	—	1,000	2.24	193,536	10,382	180	95
21	Chesapeake Spring	—	1,060	.28	24,192	68,751	96	-184
22	Chiles Spring	SPA	1,055	2.23	192,499	10,760	179	94
23	Blue Spring	—	1,076	1.57	135,648	28,044	131	79
24	Winoka Spring	SPA	1,116	.23	19,872	49,374	85	-148
25	Hayes Spring	SPA	1,110	1.52	131,328	14,313	161	89
26	Clear Creek Spring	SPA	1,155	1.84	159,391	19,872	156	88
27	Otto Lasley Spring	—	1,260	1.80	155,520	1,923	195	99
28	Sthrom Spring	—	1,200	.03	2,592	0	200	100
29	Ward Spring	SPA	1,175	1.02	88,128	11,778	153	87

Identifier (fig. 21)	Name	Hydrogeologic unit[1]	Spring altitude[1] (ft)	Observed discharge (ft^3/s)	Observed discharge (ft^3/d) A	Simulated discharge (ft^3/d) B	Relative percent difference (100|A-B|/((A+B)/2))	Percent error (100((A-B/A))
30	Clear Creek Park Spring	SPA	1,160	1.53	132,192	16,636	155	87
31	Rumfelt Spring	—	1,500	1.67	144,288	7,425	180	95
32	Trogden Spring	SPA	1,175	1.32	114,048	16,242	150	86
33	Valley Water Mill Spring	—	1,210	1.34	115,776	16,337	151	86
34	Ritter Spring (West)	SPA	1,125	.56	48,384	16,402	99	66
35	Campbell Spring	—	1,250	1.29	111,456	0	200	100
36	Williams Spring	SPA	1,041	1.13	97,632	35,124	94	64
	Total			113.34	9,792,645	666,976	174	93

[1] Data from Missouri Department of Natural Resources, 2007

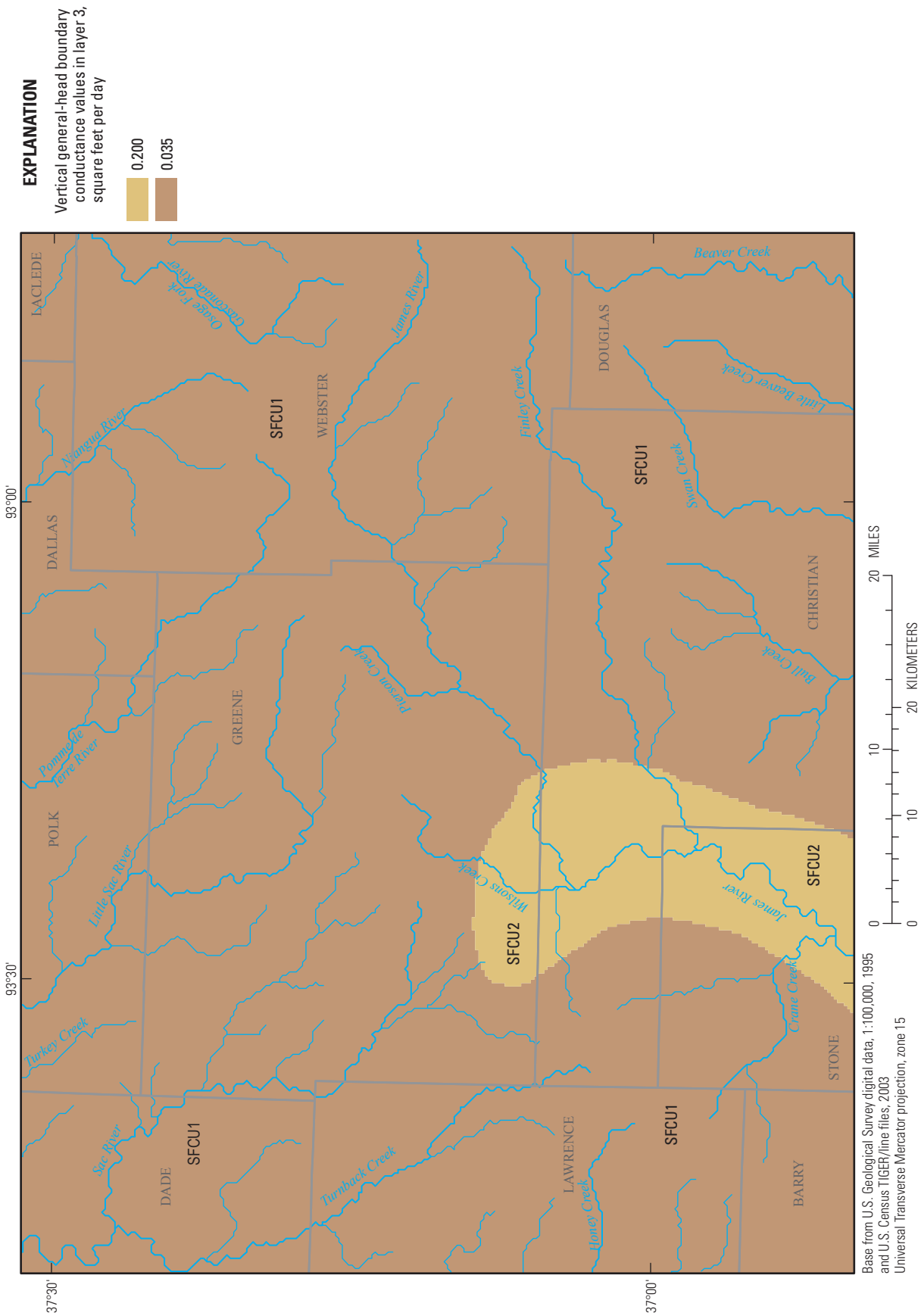


Figure 24. Vertical general-head boundary conductance values for model layer 3 simulating flow through the bottom of the Ozark aquifer.

Lakes

Four lakes were included in the model. McDaniel Lake and Fellows Lake are impoundments on the Little Sac River north of Springfield, Lake Springfield is on the James River south of Springfield, and Stockton Lake is on the Sac River in the northwestern corner of the model area (fig. 1; table 8).

Flow into and out of the lakes included in the model were simulated with a general-head boundary specified in layer 1 in lake cells (fig. 22). Groundwater is discharged from the model to the lake if the potentiometric head in the aquifer is greater than the reference head in the lake (lake-surface altitude). Groundwater is recharged to the model from the lake if the potentiometric head in the aquifer is less than the reference head in the lake (lake-surface altitude). The rate of flow into or out of the boundary is controlled by the conductance value. The lakebed conductance value was specified at 100 ft^2/d for all lakes. The lake-surface altitude was not varied throughout the simulation.

Groundwater Use

All major groundwater users, defined by the Missouri DNR as users that are capable of producing 13,369 cubic feet [100,000 gallons] or more per day, utilize the Ozark aquifer in the model area. Groundwater-use estimates from the Ozark aquifer were compiled for 285 wells within the model area from Missouri DNR census of Missouri public-supply reports (Missouri Department of Natural Resources, 1962–2006), Missouri DNR public water-supply database (data on file at Missouri Department of Natural Resources, Rolla, Missouri), data on file at USGS, Rolla, Missouri, Missouri DNR major water-users database (data on file at Missouri Department of Natural Resources, Rolla, Missouri), and data directly reported by water-supply managers (fig. 25). Data were available from multiple sources for the same time period for many wells, and often the sources would not agree. All data were aggregated for each well to include only the most reliable data to provide the most complete groundwater-use record possible. Prior to 1962, little groundwater-use data was available for wells in the model area. Groundwater-use in a well prior to 1962 was estimated based on the earliest reported value and was computed by reducing this value by 3 percent per year until the year the well became operational. Rural groundwater use in the model area from the Ozark aquifer was estimated using 4,574 domestic Ozark aquifer wells found in the Missouri DNR certified well database (Missouri Department of Natural Resources, 2007; fig. 25). This database contains all certified wells drilled in Missouri after 1986. These wells were included in the model to provide a way of estimating the effect of domestic groundwater use on the Ozark aquifer. However, because it does not include wells drilled prior to 1986, total distributed domestic use was underestimated. Domestic use was not included in the pumpage used in the model prior to 1987.

Groundwater use is listed by stress period for the Ozark aquifer in table 9 and increases from 529 ft^3/d in 1907 to 1,093,268 ft^3/d in 1962 to 2,693,423 ft^3/d in 1987 to 4,330,177 ft^3/d in 2006. Groundwater users (rural domestic use wells omitted) and their pumpage rates in 2006 are shown in figure 26. Groundwater use in 2006 from the 4,574 rural domestic wells in the Ozark aquifer was estimated at 53.5 ft^3/d (400 gallons per day [gal/d]) per well for a total rural use of 245,833 ft^3/d (1,838,000 gal/d). Rural domestic use represents 5.7 percent of the total 4,330,177 ft^3/d (32,389,721 gal/d) groundwater use for 2006. Total rural domestic use in the 4,574 wells was estimated at 123,519 ft^3/d (923,986 gal/d) in 1987. The 1987 estimated value of rural

Table 8. Lakes specified in layer 1 of the model.

[mi^2, square miles; ft, foot; NGVD, National Geodetic Vertical Datum]

Name	Year constructed[1]	Area contained in model (mi^2)	River impounded	Lake-surface altitude[2] (ft above NGVD 1929)	Water use
McDaniel Lake	1929	0.65	Little Sac River	1,123	drinking water
Fellows Lake	1955	1.43	Little Sac River	1,261	drinking water
Lake Springfield	1956	1.04	James River	1,142	cooling water
Stockton Lake	1969	6.28	Sac River	867	drinking water

[1] Missouri Department of Natural Resources, 2008

[2] Data from: U.S. Geological Survey 1:24,000 scale topographic maps

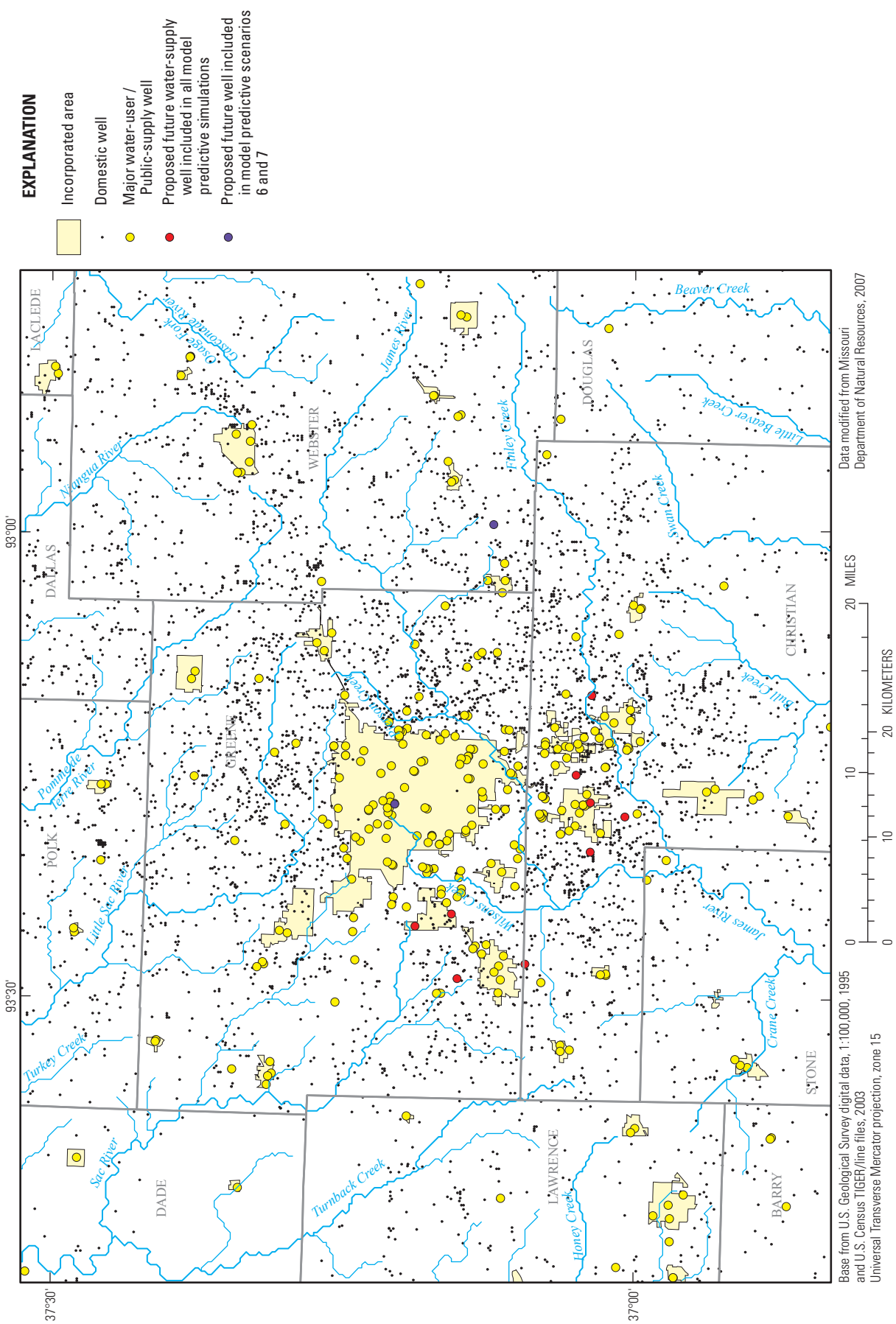


Figure 25. Pumping wells specified in the model area.

domestic use represents 4.6 percent of the total groundwater use of 2,693,423 ft^3/d (20,148,203 gal/d) in 1987 (table 9). To simulate rural growth during the period from 1987 to 2006 the water use was increased linearly from the 1987 value to the 2006 value.

Groundwater use from the Springfield Plateau aquifer was not included in the model. The productivity of the Springfield Plateau aquifer is only sufficient for domestic wells. The spatial distribution and number of wells completed in the Springfield Plateau aquifer is unknown in the model area. In addition, wells drilled prior to 1987 that are open to the Springfield Plateau aquifer often are also open to the Ozark aquifer. After 1987, wells completed in the general model area were required to be cased through the Ozark confining unit (Jim Vandike, Missouri Department of Natural Resources, oral commun., 2007).

Model Calibration

The groundwater model was calibrated by adjusting model parameters to make simulated head and discharge results match water-level altitude observations and groundwater flow to rivers and springs within an acceptable level of accuracy (Konikow, 1978). Parameters adjusted during the calibration process include horizontal and vertical hydraulic conductivity, specific storage, specific yield, riverbed conductance, lakebed conductance, spring conductance, and recharge rates. After each change in these parameters, the simulation was run and simulated head was compared to observed groundwater levels. Layers were divided into zones to allow hydraulic properties to vary spatially. When groups of simulated values were too large or too small relative to the observed values, a zone would be created encompassing those groups of observed values based on geologic criteria or professional judgment. Because changes to the hydraulic properties of a zone have the largest effect on simulated values closest to the zone, adjustment of hydraulic properties of the zone would allow for better agreement between the simulated and observed values in the zone.

Hydraulic Property Estimation

The hydraulic properties in this model were initially estimated based on the properties of rocks with similar hydraulic characteristics, previously published model values, measured values, and values calculated from other hydrologic data (table 2). Hydraulic properties used in calibration include the horizontal and vertical hydraulic conductivity, specific storage, and specific yield (table 10). Hydraulic property zones were created within the model, and values within the zones were adjusted to minimize the difference between simulated and observed values.

Horizontal Hydraulic Conductivity

Hydraulic conductivity is a property that describes the ease with which groundwater can move through the aquifer material (Freeze and Cherry, 1979). Measured horizontal hydraulic conductivity data are scarce in the model area. Vandike and Sherman (1994) calculated a mean horizontal hydraulic conductivity of 2.11 ft/d for the Ozark aquifer from an aquifer test conducted in Greene County. Transmissivity, which was converted to horizontal hydraulic conductivity by dividing by aquifer thickness, can be estimated from specific-capacity well test data using the techniques of Thomasson and others (1960) and Todd (1959). To estimate transmissivity using specific capacity data it was assumed that the aquifer was confined and isotropic, that Darcy's law for flow was applicable, that permeable zones were uniformly distributed vertically through the aquifer, and that the well was 100 percent efficient and fully penetrated the aquifer. Most of the wells in the model area that have specific capacity data do not fully penetrate the aquifer so a correction described in Todd (1959) was applied.

Estimates of Ozark aquifer transmissivity were computed from specific-capacity data for 70 wells in the model area. Hydraulic conductivity ranged from 0.20 to 8.73 ft/d, and was computed by dividing the transmissivity by the aquifer thickness (fig. 27; table 11). Horizontal hydraulic conductivity for the Springfield Plateau aquifer and the Ozark confining unit were estimated from published typical ranges for similar

Table 9. Stress period length, pumping rates, and number of water-level observations used in the model.

[variable, pumping rate varies according to the future scenario tested; ft³/d, cubic foot per day; ft³/s, cubic foot per second; USGS, U. S. Geological Survey; DNR, Missouri Department of Natural Resources; layer 1, Springfield Plateau aquifer and shallow Ozark aquifer observations; layer 3, deep Ozark aquifer observations]

Stress period	Year	Length of stress period (days)	Groundwater-pumping rate		Number of water-level altitude observations				
					USGS[1]		DNR[2]		
			(ft³/d)	(ft³/s)	Layer 1	Layer 3	Layer 1	Layer 3	Total
1		Steady State	0	0.00	42	6	0	34	82
2	1907	365	529	.01	0	0	0	0	0
3	1908	366	545	.01	0	0	0	0	0
4	1909	365	562	.01	0	0	0	0	0
5	1910	365	579	.01	0	0	0	0	0
6	1911	365	2,967	.03	0	0	0	0	0
7	1912	366	3,057	.04	0	0	0	0	0
8	1913	365	3,150	.04	0	0	0	0	0
9	1914	365	3,246	.04	0	0	0	0	0
10	1915	365	9,443	.1	0	0	0	0	0
11	1916	366	9,730	.1	0	0	0	0	0
12	1917	365	10,026	.1	0	0	0	0	0
13	1918	365	10,332	.1	0	0	0	0	0
14	1919	365	10,646	.1	0	0	0	0	0
15	1920	366	10,971	.1	0	0	0	0	0
16	1921	365	11,305	.1	0	0	0	0	0
17	1922	365	11,649	.1	0	0	0	0	0
18	1923	365	12,004	.1	0	0	0	0	0
19	1924	366	12,369	.1	0	0	0	0	0
20	1925	365	14,107	.2	0	0	0	0	0
21	1926	365	16,058	.2	0	0	0	0	0
22	1927	365	19,922	.2	0	0	0	0	0
23	1928	366	20,528	.2	0	0	0	0	0
24	1929	365	21,153	.2	0	0	0	0	0
25	1930	365	35,022	.4	0	0	0	0	0
26	1931	365	36,028	.4	0	0	0	0	0
27	1932	366	38,743	.4	0	0	0	0	0
28	1933	365	39,862	.5	0	0	0	0	0
29	1934	365	41,015	.5	0	0	0	0	0

Stress period	Year	Length of stress period (days)	Groundwater-pumping rate (ft³/d)	Groundwater-pumping rate (ft³/s)	Number of water-level altitude observations: USGS[1] Layer 1	USGS[1] Layer 3	DNR[2] Layer 1	DNR[2] Layer 3	Total
30	1935	365	42,204	.5	0	0	0	0	0
31	1936	366	43,428	.5	0	0	0	0	0
32	1937	365	48,255	.6	0	0	0	0	0
33	1938	365	52,763	.6	0	0	0	0	0
34	1939	365	54,309	.6	0	0	0	0	0
35	1940	366	55,902	.6	0	0	0	0	0
36	1941	365	98,519	1.1	0	0	0	0	0
37	1942	365	109,870	1.3	0	0	0	0	0
38	1943	365	113,156	1.3	0	0	0	0	0
39	1944	366	116,541	1.3	0	0	0	0	0
40	1945	365	120,029	1.4	0	0	0	0	0
41	1946	365	124,508	1.4	0	0	0	0	0
42	1947	365	135,617	1.6	0	0	0	0	0
43	1948	366	141,494	1.6	0	0	0	0	0
44	1949	365	148,223	1.7	0	0	0	0	0
45	1950	365	167,162	1.9	0	0	0	0	0
46	1951	365	187,116	2.2	0	0	0	0	0
47	1952	366	206,598	2.4	0	0	0	0	0
48	1953	365	237,859	2.8	0	0	0	0	0
49	1954	365	376,952	4.4	0	0	0	0	0
50	1955	365	363,322	4.2	0	0	0	0	0
51	1956	366	380,455	4.4	0	0	0	0	0
52	1957	365	394,114	4.6	0	0	0	0	0
53	1958	365	544,878	6.3	0	0	0	0	0
54	1959	365	583,448	6.8	0	0	0	0	0
55	1960	366	600,257	6.9	0	0	0	0	0
56	1961	365	1,076,156	12.5	0	0	0	0	0
57	1962	365	1,093,268	12.7	0	0	0	0	0
58	1963	365	1,191,196	13.8	0	0	0	0	0
59	1964	366	1,234,046	14.3	0	0	0	0	0
60	1965	365	1,203,546	13.9	0	0	0	0	0
61	1966	365	1,270,353	14.7	0	0	0	0	0

Table 9. Stress period length, pumping rates, and number of water-level observations used in the model.—Continued

[variable, pumping rate varies according to the future scenario tested; ft³/d, cubic foot per day; ft³/s, cubic foot per second; USGS, U. S. Geological Survey; DNR, Missouri Department of Natural Resources; layer 1, Springfield Plateau aquifer and shallow Ozark aquifer observations; layer 3, deep Ozark aquifer observations]

Stress period	Year	Length of stress period (days)	Groundwater-pumping rate		Number of water-level altitude observations				
					USGS[1]		DNR[2]		
			(ft³/d)	(ft³/s)	Layer 1	Layer 3	Layer 1	Layer 3	Total
62	1967	365	1,256,259	14.5	0	0	0	0	0
63	1968	366	1,383,728	16.0	0	0	0	0	0
64	1969	365	1,433,336	16.6	0	0	0	0	0
65	1970	365	1,527,494	17.7	0	0	0	0	0
66	1971	365	1,625,549	18.8	0	0	0	0	0
67	1972	366	1,797,899	20.8	0	0	0	0	0
68	1973	365	1,840,615	21.3	0	0	0	0	0
69	1974	365	2,021,967	23.4	0	0	0	0	0
70	1975	365	1,883,362	21.8	0	0	0	0	0
71	1976	366	2,329,281	27.0	0	0	0	0	0
72	1977	365	1,969,073	22.8	0	0	0	0	0
73	1978	365	2,022,072	23.4	0	0	0	0	0
74	1979	365	2,340,508	27.1	0	0	0	0	0
75	1980	366	2,720,889	31.5	0	0	0	0	0
76	1981	365	2,314,257	26.8	0	0	0	0	0
77	1982	365	2,308,995	26.7	0	0	0	0	0
78	1983	365	2,330,251	27.0	0	0	0	0	0
79	1984	366	2,233,418	25.8	0	0	0	0	0
80	1985	365	2,114,842	24.5	0	0	0	0	0
81	1986	365	2,125,795	24.6	0	0	0	0	0
82	1987	365	2,693,423	31.2	9	48	1	10	68
83	1988	366	2,897,164	33.5	0	0	2	55	57
84	1989	365	2,941,884	34.0	81	2	3	61	147
85	1990	365	3,230,375	37.4	11	1	1	57	70
86	1991	365	3,296,308	38.2	16	0	14	55	85
87	1992	366	3,178,253	36.8	21	2	20	86	129
88	1993	365	2,692,654	31.2	13	24	5	70	112
89	1994	365	2,942,806	34.1	0	1	47	66	114
90	1995	365	3,050,711	35.3	1	2	27	68	98
91	1996	366	3,539,861	41.0	9	35	23	43	110

Stress period	Year	Length of stress period (days)	Groundwater-pumping rate (ft^3/d)	Groundwater-pumping rate (ft^3/s)	Number of water-level altitude observations: USGS[1] Layer 1	USGS[1] Layer 3	DNR[2] Layer 1	DNR[2] Layer 3	Total
92	1997	365	3,351,881	38.8	1	1	27	41	70
93	1998	365	3,681,955	42.6	15	8	16	55	94
94	1999	365	3,751,821	43.4	0	1	39	63	103
95	2000	366	3,968,491	45.9	1	2	35	73	111
96	2001	365	3,716,189	43.0	1	2	41	63	107
97	2002	365	3,866,498	44.8	0	19	48	62	129
98	2003	365	3,966,025	45.9	0	10	51	52	113
99	2004	366	3,906,372	45.2	0	7	62	46	115
100	2005	365	4,176,776	48.3	0	16	35	46	97
101	2006	365	4,330,177	50.1	15	132	0	0	147
102-125	2007-2030	365 (366 leap years)	variable	variable	0	0	0	0	0

[1] Data from USGS national water information system database (U.S. Geological Survey, 2007)

[2] Data from Missouri Department of Natural Resources, 2007

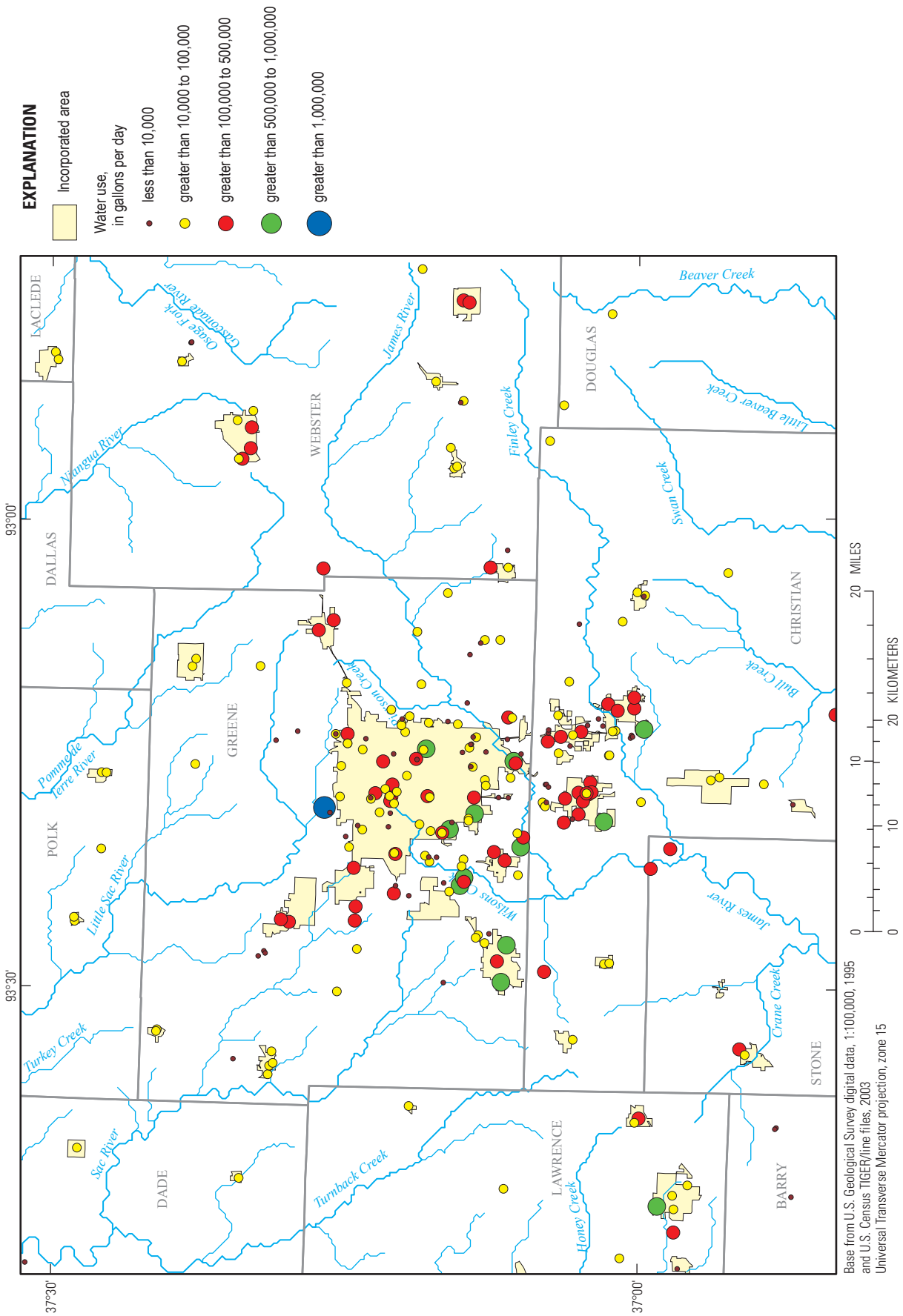


Figure 26. Groundwater use from wells in the Ozark aquifer in 2006 (domestic-supply wells omitted for clarity).

rocks (Freeze and Cherry, 1979) and previously published model values. These horizontal hydraulic conductivity estimates were used as initial values and were zoned and adjusted manually during the calibration process to minimize the difference between simulated and observed values (figs. 28, 29, and 30). Specific-capacity data, aquifer-test data, and other geologic evidence indicate that areas of markedly differing horizontal hydraulic conductivity exists throughout the Ozark aquifer. It is speculated that these differences are a result of karst features such as solution-enlarged fractures or solution-enlarged bedding planes (Jim Vandike, Missouri Department of Natural Resources, oral commun., 2010) in the Ozark aquifer. Small zones were initially placed around some wells in layer 3 of the model where specific capacity data indicated large changes in hydraulic conductivity might exist. However, they were subsequently removed because their presence had little effect on the simulated head distribution in the model and the location, extent, and orientation of those zones was uncertain. Final horizontal hydraulic conductivity values used in this model can be found in table 10.

Vertical Hydraulic Conductivity

The ability of a hydrogeologic unit to conduct groundwater flow horizontally can differ considerably from its ability to conduct flow vertically. Horizontal flow is likely to be the predominant component of flow in the hydrogeologic units in the model area (Czarnecki and others, 2009). In the model, the ratio of vertical to horizontal hydraulic conductivity is used to account for vertical anisotropy. No measurements of vertical anisotropy for any of the hydrogeologic units have been made in the model area. Initial estimates of the vertical to horizontal hydraulic conductivity ratio were obtained from Czarnecki and others (2009), and these estimates ranged from 1:1 to 1:50 for the hydrogeologic units that were nearest to this model area. Final vertical hydraulic conductivity values after adjustment through model calibration are presented in table 10.

Table 10. Hydraulic property values specified in the calibrated model.

[ft/d, feet per day; 1/ft, per foot]

Zone name	Hydraulic conductivity Horizontal (ft/d)	Hydraulic conductivity Vertical (ft/d)	Specific storage (1/ft)	Specific yield (dimensionless)	Figure number
Springfield Plateau aquifer					
SPA1	2.50	0.050	1.00×10^{-5}	0.003	28
SPA2	2.20	.073	1.00×10^{-5}	.003	28
SPA3	5.00	.167	1.00×10^{-5}	.003	28
Ozark confining unit					
OZCU1	1.00×10^{-6}	2.00×10^{-7}	5.00×10^{-6}	.100	29
OZCU2	2.80×10^{-5}	5.60×10^{-6}	5.00×10^{-6}	.100	29
OZCU3	7.50×10^{-5}	1.50×10^{-5}	5.00×10^{-6}	.100	29
Ozark aquifer					
OZA1	1.30	.130	1.00×10^{-6}	.003	30
OZA2	.35	.070	5.00×10^{-4}	.003	30
OZA3	.35	.035	5.00×10^{-6}	.003	30
OZA4	1.50	.150	1.00×10^{-4}	.003	30
OZA5	.25	.050	5.00×10^{-5}	.003	30
OZA6	.30	.030	1.00×10^{-7}	.003	30
OZA7	.80	.080	1.00×10^{-8}	.003	30
OZA8	3.00	.300	1.00×10^{-5}	.003	30

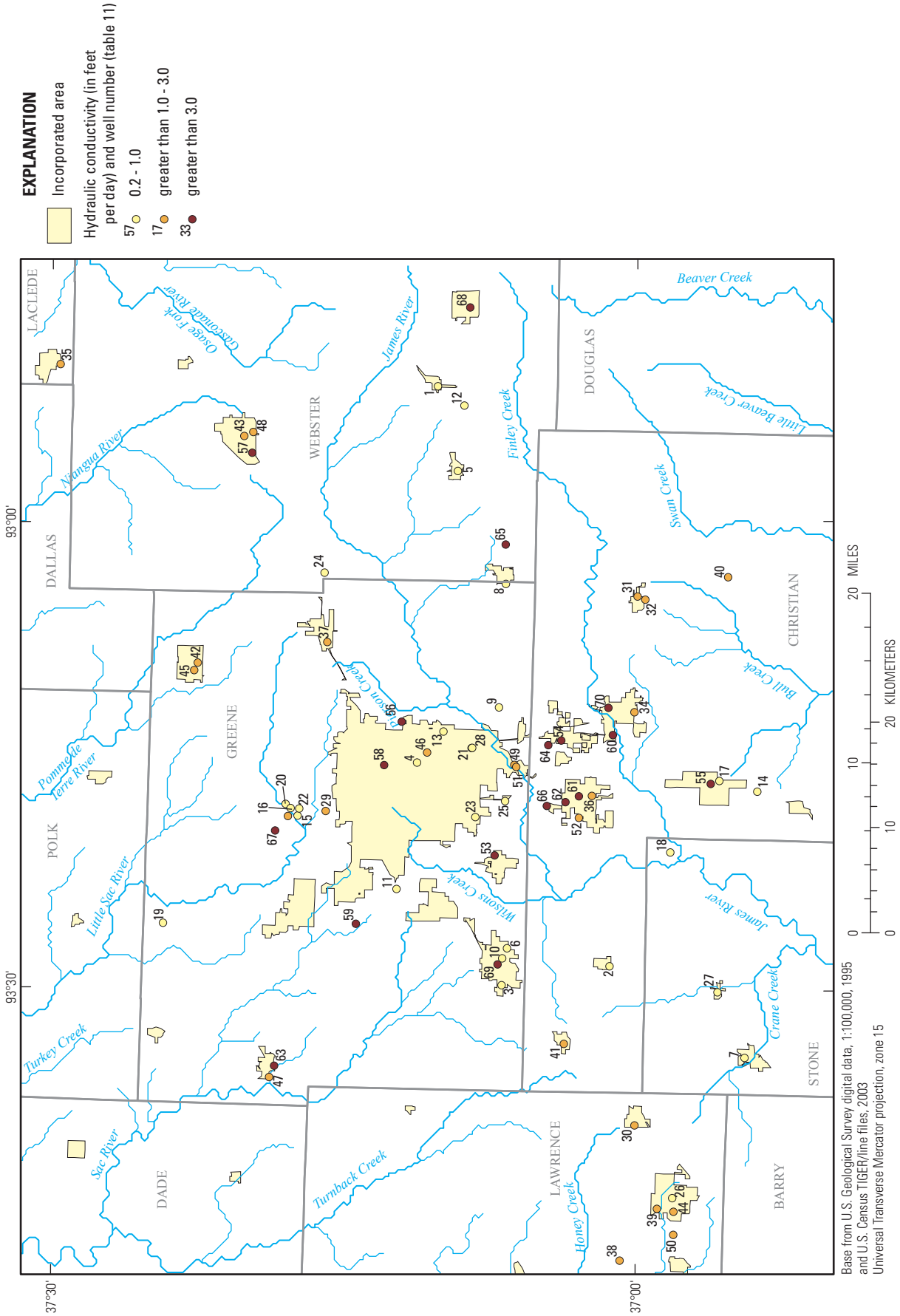


Figure 27. Horizontal hydraulic conductivity in the Ozark aquifer estimated from specific-capacity data of wells.

Table 11. Hydraulic conductivity estimated from specific-capacity data for selected wells in the model area.

[Q_p is the discharge of the well that partially penetrates the aquifer; s_w is drawdown in the pumping well; b_p is the depth of well penetration into the aquifer; b is the aquifer thickness; R_w is the radius of the well; R is the radius of influence of the pumping well; Q_c is the discharge of the well if the well had completely penetrated the aquifer; T is transmissivity; K is hydraulic conductivity; ft^3/d, cubic foot per day; ft, foot; ft^2/d, square foot per day; ft/d, foot per day]

Well number from figure 27	Q_p (ft^3/d)	s_w (ft)	b_p (ft)	b (ft)	R_w (ft)	R (ft)	Q_p/s_w (ft^2/d)	Q_p/Q_c (dimension-less)	Q_c/s_w (ft^2/d)	T (ft^2/d)	K (ft/d)
1	17,326	110	896	1,619	0.25	250	158	0.53	300	330	0.20
2	69,305	470	815	1,299	.42	417	147	.62	236	260	.20
3	105,882	550	1,035	1,243	.42	417	193	.84	230	253	.20
4	105,882	460	1,215	1,326	.50	500	230	.93	248	272	.21
5	28,877	157	935	1,643	.33	333	184	.55	334	368	.22
6	192,513	1,200	750	1,237	.50	500	160	.61	263	289	.23
7	48,128	169	1,287	1,345	.33	333	285	.97	293	323	.24
8	48,128	145	1,310	1,549	.33	333	332	.84	394	433	.28
9	4,813	50	360	1,350	.25	250	96	.26	372	409	.30
10	65,455	242	839	1,238	.33	333	270	.67	404	444	.36
11	7,701	75	290	1,220	.25	250	103	.23	437	481	.39
12	72,193	120	1,600	1,696	.25	250	602	.95	632	696	.41
13	202,139	462	1,108	1,339	.58	583	438	.84	522	575	.43
14	30,802	143	519	1,500	.25	250	215	.33	655	720	.48
15	84,128	170	1,088	1,195	.67	667	495	.93	533	587	.49
16	121,091	240	1,061	1,198	.67	667	505	.90	559	615	.51
17	32,727	100	695	1,501	.25	250	327	.44	745	819	.55
18	13,476	55	463	1,294	.42	417	245	.36	679	747	.58
19	11,551	70	300	1,061	.25	250	165	.28	588	647	.61
20	130,139	230	1,023	1,197	.67	667	566	.87	650	715	.60
21	71,230	167	765	1,328	.33	333	427	.56	756	831	.63
22	145,733	205	1,099	1,197	.67	667	711	.94	760	836	.70
23	244,492	320	1,178	1,264	.50	500	764	.95	807	887	.70
24	192,513	260	1,074	1,390	.50	500	740	.78	954	1,049	.75
25	1,925	10	271	1,266	.25	250	193	.21	907	998	.79
26	77,005	110	899	1,299	.33	333	700	.68	1,025	1,127	.87
27	17,326	55	388	1,376	.25	250	315	.27	1,157	1,272	.92
28	115,508	180	760	1,328	.42	417	642	.57	1,129	1,242	.94
29	404,278	333	1,256	1,256	.75	750	1,214	1.00	1,214	1,335	1.06

Table 11. Hydraulic conductivity estimated from specific capacity data for selected wells in the model area.—Continued

[Q_p is the discharge of the well that partially penetrates the aquifer; s_w is drawdown in the pumping well; b_p is the depth of well penetration into the aquifer; b is the aquifer thickness; R_w is the radius of the well; R is the radius of influence of the pumping well; Q_c is the discharge of the well if the well had completely penetrated the aquifer; T is transmissivity; K is hydraulic conductivity; ft^3/d, cubic foot per day; ft, foot; ft^2/d, square foot per day; ft/d, foot per day]

Well number from figure 27	Q_p (ft^3/d)	s_w (ft)	b_p (ft)	b (ft)	R_w (ft)	R (ft)	Q_p/s_w (ft^2/d)	Q_p/Q_c (dimension-less)	Q_c/s_w (ft^2/d)	T (ft^2/d)	K (ft/d)
30	38,503	48	776	1,285	0.42	417	802	0.60	1,335	1,468	1.14
31	67,380	60	1,043	1,553	.33	333	1,123	.66	1,711	1,883	1.21
32	38,503	40	821	1,549	.33	333	963	.51	1,875	2,063	1.33
33	218,888	160	1,113	1,197	.67	667	1,368	.95	1,443	1,588	1.33
34	103,957	85	925	1,342	.42	417	1,223	.69	1,783	1,961	1.46
35	53,904	50	798	1,206	.33	333	1,078	.65	1,649	1,813	1.50
36	48,128	40	879	1,327	.33	333	1,203	.65	1,847	2,031	1.53
37	231,016	180	891	1,399	.33	333	1,283	.62	2,057	2,263	1.62
38	44,663	74	364	1,244	.33	333	604	.29	2,057	2,263	1.82
39	105,882	76	800	1,232	.50	500	1,393	.65	2,129	2,342	1.90
40	32,920	21	887	1,600	.33	333	1,568	.54	2,923	3,215	2.01
41	80,856	55	815	1,300	.42	417	1,470	.62	2,358	2,594	1.99
42	28,877	23	675	1,242	.33	333	1,256	.53	2,350	2,585	2.08
43	113,583	59	976	1,303	.50	500	1,925	.75	2,554	2,809	2.16
44	76,043	37	913	1,306	.33	333	2,055	.69	2,978	3,276	2.51
45	61,604	33	790	1,237	.33	333	1,867	.63	2,966	3,262	2.64
46	205,219	71	1,217	1,347	.50	500	2,890	.92	3,156	3,472	2.58
47	192,513	84	950	1,091	.42	417	2,292	.88	2,603	2,863	2.62
48	225,241	127	740	1,328	.50	500	1,774	.56	3,168	3,485	2.62
49	154,011	50	1,236	1,319	.67	667	3,080	.95	3,228	3,551	2.69
50	100,107	50	775	1,362	.42	417	2,002	.56	3,549	3,904	2.87
51	178,075	55	1,233	1,301	.67	667	3,238	.97	3,352	3,687	2.83
52	102,032	35	1,072	1,283	.42	417	2,915	.84	3,470	3,818	2.97
53	57,754	25	765	1,249	.33	333	2,310	.60	3,833	4,217	3.37
54	80,856	28	915	1,301	.42	417	2,888	.70	4,118	4,530	3.48
55	50,053	20	787	1,495	.33	333	2,503	.51	4,898	5,388	3.60
56	29,840	10	873	1,334	.25	250	2,984	.63	4,705	5,175	3.88
57	115,508	30	995	1,306	.42	417	3,850	.76	5,053	5,559	4.26
58	86,631	26	855	1,319	.83	833	3,332	.67	4,987	5,486	4.16
59	173,262	37	1,069	1,214	.50	500	4,683	.89	5,247	5,772	4.75

Well number from figure 27	Q_p (ft^3/d)	s_w (ft)	b_p (ft)	b (ft)	R_w (ft)	R (ft)	Q_p/s_w (ft^2/d)	Q_p/Q_c (dimension-less)	Q_c/s_w (ft^2/d)	T (ft^2/d)	K (ft/d)
60	103,957	25	876	1,327	.42	417	4,158	.66	6,333	6,966	5.25
61	57,754	9	1,220	1,298	.33	333	6,417	.95	6,743	7,417	5.71
62	115,508	24	850	1,283	.42	417	4,813	.66	7,292	8,021	6.25
63	28,877	10	470	1,116	.33	333	2,888	.42	6,892	7,581	6.79
64	117,433	21	920	1,298	.42	417	5,592	.71	7,913	8,704	6.70
65	4,813	2	400	1,620	.25	250	2,406	.24	10,187	11,205	6.92
66	52,941	10	815	1,252	.33	333	5,294	.64	8,246	9,070	7.25
67	11,551	20	85	1,183	.25	250	578	.08	7,126	7,838	6.63
68	63,529	10	935	1,571	.33	333	6,353	.58	10,994	12,094	7.70
69	154,011	25	779	1,233	.42	417	6,160	.63	9,777	10,755	8.72
70	231,016	35	830	1,359	.50	500	6,600	.61	10,781	11,859	8.73

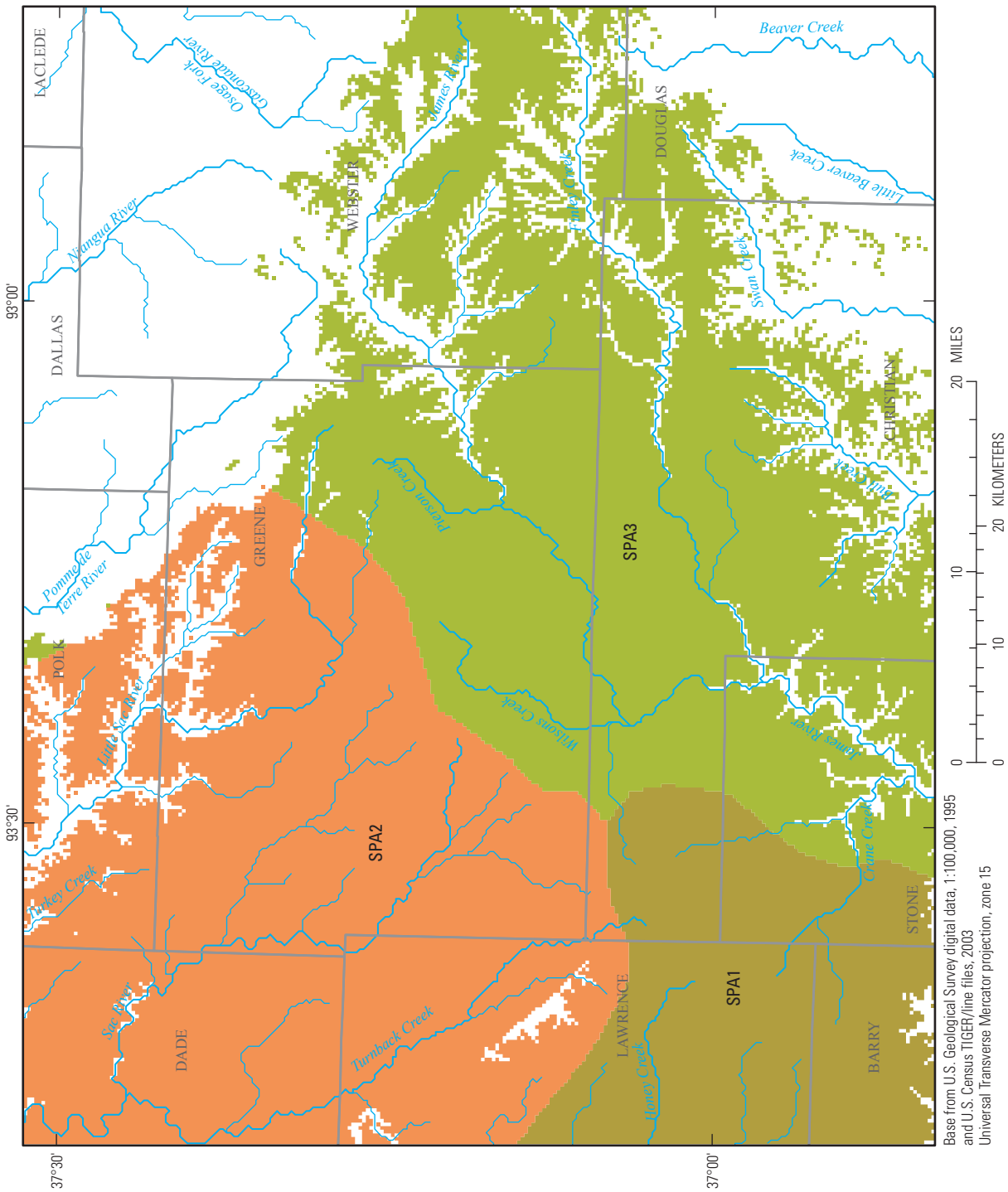
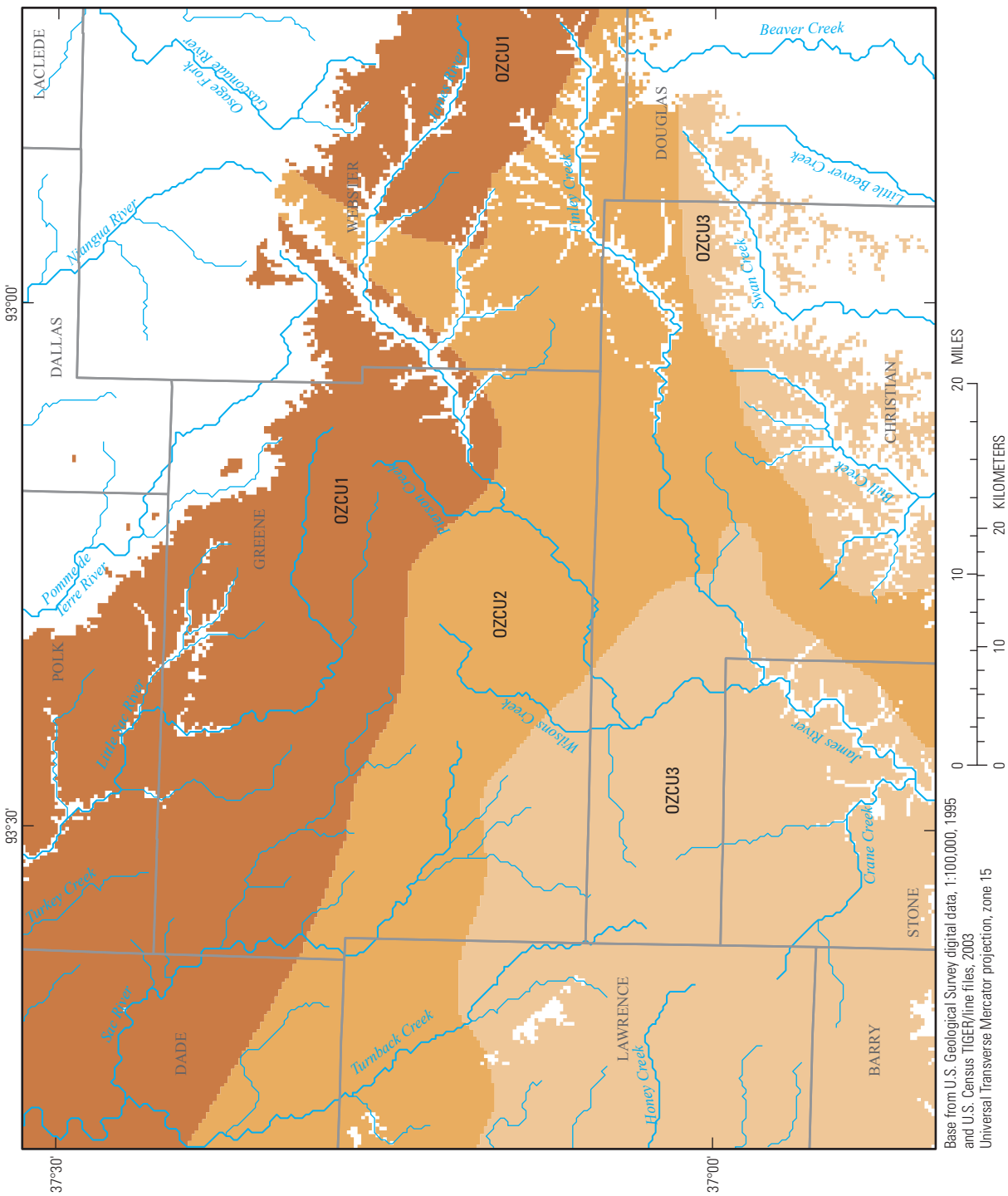


Figure 28. Horizontal and vertical hydraulic conductivity, specific storage, and specific yield zones for the Springfield Plateau aquifer used in the model to calculate composite hydraulic properties.



Base from U.S. Geological Survey digital data, 1:100,000, 1995 and U.S. Census TIGER/line files, 2003
Universal Transverse Mercator projection, zone 15

Figure 29. Horizontal and vertical hydraulic conductivity, specific storage, and specific yield zones for the Ozark confining unit used in the model to calculate composite hydraulic properties.

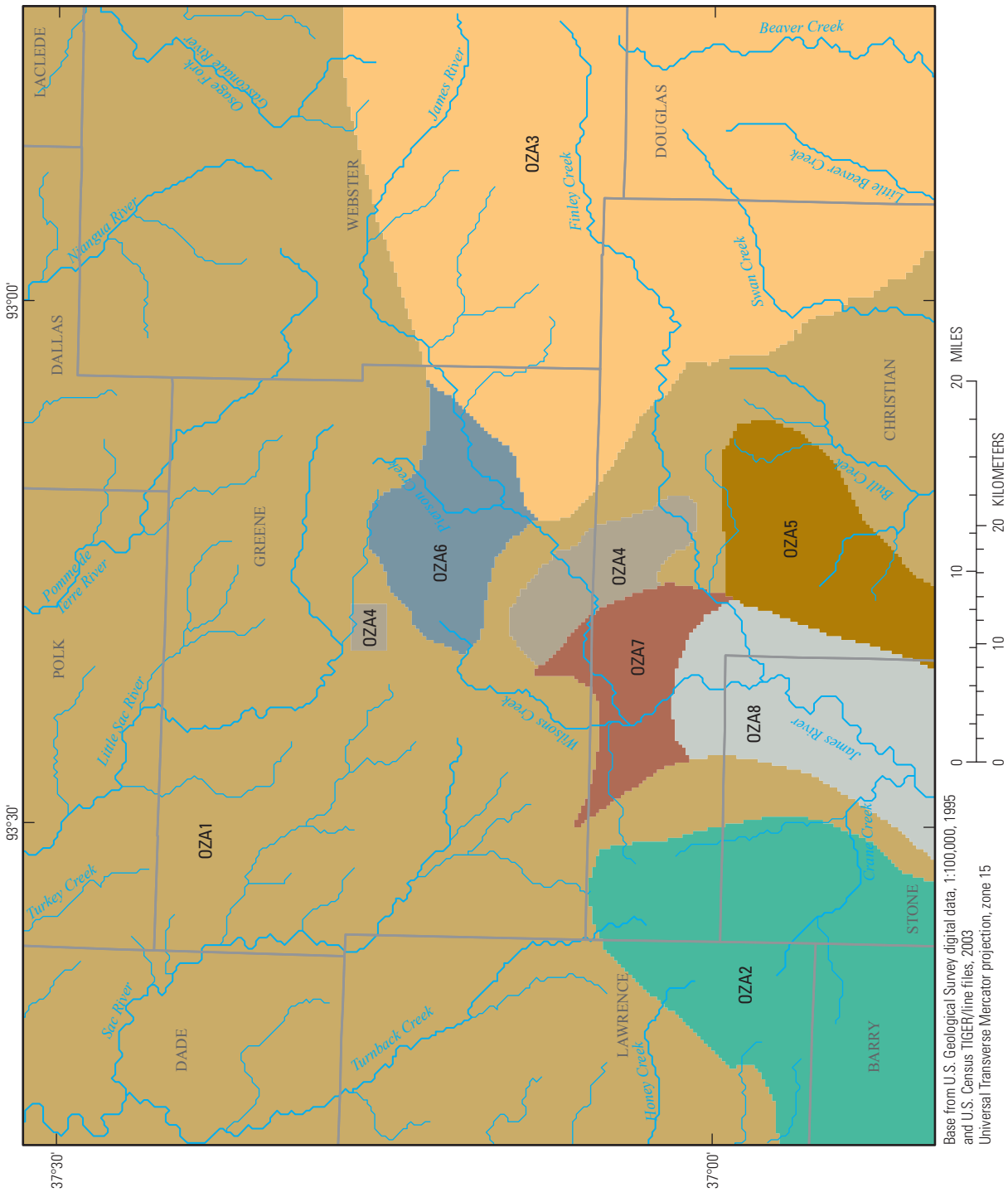


Figure 30. Horizontal and vertical hydraulic conductivity, specific storage, and specific yield zones for the Ozark aquifer used in the model to calculate composite hydraulic properties.

Specific Storage

Specific storage for a saturated confined aquifer is the volume of water released from storage per unit decline in head (Freeze and Cherry, 1979). It describes the water released from storage because of expansion of the water or compaction of the aquifer material and not actual drainage of the aquifer. Vandike and Sherman (1994) computed a storage coefficient in the Ozark aquifer of $1.6x10^{-4}$ from an aquifer test in the Fulbright Spring area of Greene County (fig. 2). This storage coefficient is equivalent to a specific storage of $1.33x10^{-7}$ per ft for an average aquifer thickness of 1,200 ft. This value for the Ozark aquifer and values from Imes (1989) and Czarnecki and others (2009) were used as initial estimates in this model. Final values of specific storage obtained after adjustment during the calibration process are presented in table 10.

Specific Yield

Specific yield is the measure of the volume fraction of the aquifer of water that will drain by gravity from an unconfined aquifer (Freeze and Cherry, 1979). Values of specific yield in this model were estimated based on values used in Imes (1989) and Czarnecki and others (2009) and adjusted during the calibration process. Final specific yield values used in this model are presented in table 10.

Calibrated Hydraulic Properties Compared To Previously Published Values

Hydraulic properties specified for the hydrogeologic units in the calibrated model (table 10) are compared to previously published estimates (table 2) in the following sections. In general, most of the hydraulic properties specified in the calibrated model fit into the range of previously published values for the hydrogeologic units in the model area.

Springfield Plateau Aquifer Calibrated Hydraulic Properties

In this model, the horizontal hydraulic conductivity of the Springfield Plateau aquifer ranged between 2.20 and 5.00 ft/d (table 10), and fit within the range of values used in other groundwater models in the region (table 2). Freeze and Cherry (1979) provide estimates of horizontal hydraulic conductivity for limestone and dolomite that range from about 0.0005 to 0.60 ft/d, and for karst limestone that range from about 0.1 to 2,000 ft/d. For the Springfield Plateau aquifer, Imes (1989) used values of horizontal hydraulic conductivity of 4.3 to 43 ft/d in the Springfield, Missouri area, and Imes and Emmett (1994) specified 21.6 ft/d for the part of their model that overlaps this model area. Reed and Czarnecki (2006) used values of horizontal hydraulic conductivity ranging between 1.3 to 35 ft/d in northeastern Oklahoma, and Czarnecki and others (2009) used 0.89 to 35 ft/d in their model. In this model, the ratio of the vertical to horizontal hydraulic conductivity of the Springfield Plateau aquifer ranged from 1:30 to 1:50 and the vertical hydraulic conductivity ranged from 0.050 to 0.167 ft/d. Reed and Czarnecki (2006) used values of vertical hydraulic conductivity between $2.6x10^{-2}$ and $7.0x10^{-1}$ ft/d, and Czarnecki and others (2009) specified vertical hydraulic conductivity to be between $2.97x10^{-4}$ and 1.00 ft/d in their groundwater model (table 2).

Specific yield was specified as 0.003 for the Springfield Plateau aquifer in this model (table 10). The usual range of specific yield for unconfined aquifers is from 0.01 to 0.30 (Freeze and Cherry, 1979). Imes (1989) specified a specific yield value of $2.00x10^{-2}$ in the Springfield Plateau aquifer. Czarnecki and others (2009) report mean values of specific yield from hydraulic tests in carbonate aquifers in Poland and Spain that range between $6.00x10^{-5}$ and $5.79x10^{-3}$. Specific yield in Czarnecki and others (2009) ranged from $1.00x10^{-2}$ to $1.00x10^{-1}$. Specific yield was specified as $2.00x10^{-1}$ in Reed and Czarnecki (2006) (table 2).

Ozark Confining Unit Calibrated Hydraulic Properties

The horizontal hydraulic conductivity of the Ozark confining unit in this model ranged between $1.00x10^{-6}$ to $7.50x10^{-5}$ ft/d (table 10). Horizontal hydraulic conductivity ranged between $1.0x10^{-5}$ to $4.0x10^{-5}$ in Czarnecki and others (2009). In this model, the vertical to horizontal hydraulic conductivity ratio was 1:5 in the Ozark confining unit, and the vertical hydraulic conductivity ranged between $2.00x10^{-7}$ to $1.50x10^{-5}$ ft/d (table 10). Emmett and others (1978) estimated the vertical hydraulic conductivity for the Ozark confining unit to be about $8.6x10^{-5}$ ft/d. Imes (1989) specified values of vertical hydraulic conductivity of $7.8x10^{-6}$ and $9.5x10^{-6}$ ft/d for the Ozark confining unit near Springfield, Missouri. Christenson and others (1994) used a leakance value between $4.3x10^{-8}$ and $7.7x10^{-8}$ per day (d^{-1}) for the Ozark confining unit in Ottawa County, Oklahoma. Imes and Emmett (1994) used vertical hydraulic conductivity values between $1.7x10^{-3}$ and $4.3x10^{-3}$ ft/d and a leakance value between $5.2x10^{-5}$ and $1.7x10^{-4}$ d^{-1} to simulate flow through the Ozark confining unit. Czarnecki and others (2009) used values of vertical hydraulic conductivity between $2.0x10^{-7}$ and $2.45x10^{-5}$ ft/d for the Ozark confining unit in their groundwater model (table 2).

Specific storage was specified as $5.00x10^{-6}$ per foot and specific yield was specified as 0.100 in this model for the Ozark confining unit (table 10). Specific storage in Czarnecki and others (2009) was specified as $5.0x10^{-6}$ per foot and specific yield was specified as $1.00x10^{-1}$ in their model (table 2).

Ozark Aquifer Calibrated Hydraulic Properties

The horizontal hydraulic conductivity of the Ozark aquifer in this model ranged from 0.25 to 3.00 ft/d (table 10), and was within the range of values specified in other area groundwater flow models and aquifer test results in the region (table 2). Emmett and others (1978) estimated a transmissivity value of 3,974 square feet per day (ft^2/d) from two short-term

pump tests, which the authors state was an anomalously large local value. However, the authors subsequently used a flow-net analysis of Lohman (1972) and determined a value of 670 ft^2/d. Vandike and Sherman (1994) performed a 64-day aquifer test in the Fulbright Spring area (fig. 2) of Greene County using a fully penetrating Ozark aquifer well pumping at a mean rate of 2,382 gal/min and calculated a mean horizontal hydraulic conductivity of 2.11 ft/d for the Ozark aquifer in that area. Imes (1989) specified the horizontal hydraulic conductivity of the Ozark aquifer to be between about 0.7 and 2.6 ft/d in the Springfield, Missouri area. Imes and Emmett (1994) estimated the horizontal hydraulic conductivity in their model to be between about 6.91 ft/d and 11.23 ft/d for the area of the model covered by this report. Czarnecki and others (2009) used horizontal hydraulic conductivity values between about 0.10 and 5.00 ft/d for their groundwater model (table 2). The vertical to horizontal hydraulic conductivity ratio for the Ozark aquifer in this model ranged from 1:5 to 1:10, and the vertical hydraulic conductivity ranged from 0.030 and 0.300 ft/d (table 10). Czarnecki and others (2009) used vertical hydraulic conductivity values between about 5.00×10^{-3} and 1.81 ft/d for their groundwater model (table 2).

The specific storage values of the Ozark aquifer in this model ranged from 1.00×10^{-8} to 5.00×10^{-4} per ft (table 10), and was similar to values specified in previous groundwater-flow models and aquifer test results in the region (table 2). Imes (1989) specified the storage coefficient in the Ozark aquifer to be 1.0×10^{-4}, which is equivalent to a specific storage value of 8.3×10^{-8} per ft for a mean aquifer thickness of 1,200 ft. Specific storage of 1.33×10^{-7} per ft, using an aquifer thickness of 1,200 ft, was computed from data collected by Vandike and Sherman (1994). Czarnecki and others (2009) specified specific storage ranging from 1.00×10^{-7} to 3.97×10^{-5} per ft in the Ozark aquifer (table 2). Specific yield in this model was specified as 0.003 for the Ozark aquifer (table 10). This value is similar to values specified in other groundwater-flow models in the region (table 2). Imes (1989) specified a range of specific yield values from 1.00×10^{-3} to 2.00×10^{-2} in the Ozark aquifer. Czarnecki and others (2009) specified specific yield values ranging from about 3.56×10^{-4} to 7.50×10^{-2} for the Ozark aquifer.

Water-Level Observations

Water-level data from wells were collected during 2006–07 to provide a groundwater model calibration data set. These data were collected from field measurements by USGS personnel, from the Missouri DNR groundwater-monitoring network, and from reported values from water-supply managers. A potentiometric-surface map of the Springfield Plateau aquifer (fig. 31) was constructed using 15 water-level observations collected in 2006 as well as several spring orifice altitudes and streambed elevation values. A potentiometric-surface map of the Ozark aquifer (fig. 3) was constructed by Richards and Mugel (2008) from 119 water-level measurements collected from 115 wells.

The model was calibrated to water-level observations compiled from multiple sources with differing levels of data quality (fig. 8). The steady-state stress period of the model was calibrated to 48 interpolated points from maps of the predevelopment surface of the Springfield Plateau and Ozark aquifers (Imes, 1990a and 1990b) and 34 measured values in the Ozark aquifer obtained from the Missouri Department of Natural Resources (2007) database of geologically logged wells. For the transient stress periods, the data came from measured water levels collected by the USGS during 2006–07 and previously measured data contained in the USGS National Water Information System (http://water.data.usgs.gov/nwis) database. Well construction data for these wells were evaluated, and 507 wells were selected for use as observation points in the model calibration. A second source of data was from the Missouri Department of Natural Resources (2007) database of geologically logged wells. Nine wells were found to be suitable for use as observation points in the model calibration based on construction data. The last source was from the Missouri Department of Natural Resources (2007) database of certified wells that were drilled in Missouri after 1987. These data are less reliable because the location information, date, construction information, and water level, were often not sufficiently documented. However, the value of having a large number of data points outweighed the suspected quality issues. To minimize the error associated with incorrectly located wells from the certified well database or well log database, wells with differences greater than 30 ft between the well land-surface altitude stated in the database and the altitude of the land surface at that point obtained from the USGS DEM were not included as observation points. Evaluation of construction data for these wells led to the selection of 1,569 wells suitable for use as an observation point in the model calibration. A total of 2,076 water-level measurements were used as observation points for the transient model calibration (fig. 8).

Although the difference between simulated head and observed water levels was tested at all of the 2,076 observation points, the primary focus of the transient calibration were water-level measurements completed within the model area during 1987, 1993, 1996, and 2006 in the Ozark aquifer and in 1989 and 2006 in the Springfield Plateau aquifer (table 9). The 2006 data set collected in the Ozark aquifer was the most geographically widespread and was considered the most important of the mass water-level measurement events. The primary focus of calibration was to match the simulated

head with the observed water levels in the Ozark aquifer through time; matching simulated head in the Springfield Plateau aquifer, streamflow and spring flow were secondary. Because of this, the relatively few (15) 2006 data points in the Springfield Plateau aquifer (most of layer 1), and the fact that the streamflow and spring flow values were estimated, made these observations less important during model calibration. Most adjustments to the model variables were made to improve the fit between the simulated head and observed 2006 water levels in the Ozark aquifer (layer 3).

Model fit was evaluated by computing the root mean square error (RMSE), which is a measure of the variation between the simulated and observed values. Model fit is improved by minimizing the RMSE. The equation to calculate the RMSE is:

$$RMSE = \sqrt{\frac{\sum (O - S)^2}{n}} \tag{1}$$

where,

O is the observed water-level altitude in feet,
S is the simulated head in feet, and
n is the number of observations tested.

The accuracy of water-level measurements was the basis for choosing the RMSE used to determine if the model simulation was acceptable. Most water levels collected by USGS were measured with an electric tape, sonic meter, air line reading, or transducer. Practical experience indicates that air line readings are the least accurate and can typically be in error plus or minus (+/-) 20 to 25 ft of the true water-level altitude. Techniques used to measure or estimate historical water levels in wells, water levels collected from the certified well database, and water levels collected from the well log database were not documented.

A second component of accuracy of the water-level measurements is the measuring-point altitude. For the 2006 data, most of the measuring points were located with hand-held global positioning system (GPS) devices; however, most of the measuring-point altitudes were interpolated from USGS 1:24,000 scale topographic maps. Vertical accuracy of altitude data obtained from topographic maps is one-half of the contour interval on the map. Topographic maps of the model area have a contour interval of 10 or 20 ft, so the accuracy of the measuring point altitudes for these wells is +/- 5 or 10 ft.

Water levels naturally fluctuate throughout the year in response to pumping stresses, flux to springs and rivers, and recharge from precipitation. Neither precipitation nor pumping is evenly distributed throughout the year, however, in the model, annual recharge and annual pumpage are applied uniformly throughout the year. The natural fluctuation in the monitoring well at Marshfield (fig. 2) completed in the Ozark aquifer for the period January 1, 2006, to December 31, 2009 is shown in figure 32 (http://waterdata.usgs.gov/mo/nwis/uv/?site_no=372022092542201&PARAmeter_cd=72019).

Water-level measurements are an instantaneous measure of a dynamic system. Because of the way stresses are applied in the groundwater model, the natural fluctuation observed in the groundwater system was converted into a mean annual fluctuation. Precisely matching instantaneous water-level measurements with these mean simulated values is unlikely. The accuracy of the model fit thus depends on the timing of the water-level measurements and the relation of that timing to the groundwater natural fluctuation cycle. This is complicated by the fact that the magnitude of groundwater fluctuation is not uniform spatially in the aquifer, which in turn is related to the stresses and the hydraulic properties of the aquifer. A third component of accuracy of the water-level measurement relative to the model simulated head is the annual fluctuation of the potentiometric surface in the aquifer. For the Ozark aquifer at the Marshfield monitoring well (fig. 2), the mean daily water-level altitude for the period of record from January 1, 2006 to December 31, 2009 was 1,233 ft and the standard deviation was 12.6 ft (fig. 32). Ninety-five percent of the water levels measured in that well would be within +/- 24.7 ft of the mean. If it is assumed that this variability applies to all measurements in the Ozark aquifer, then for any given water-level measurement, there is a 95-percent confidence that the measurement is within +/- 24.7 ft of the mean value.

The maximum assumed error for water-level measurements (+/- 35 ft) is the sum of the maximum errors caused by the water-level measurement errors and measuring-point altitude errors. When combining this error with the assumed water-level fluctuation error (+/- 24.7 ft), the largest possible error in water-level altitude becomes approximately +/- 60 ft. The chance that the maximum error would occur is small; however, knowledge of the maximum error is necessary to assess the RMSE model fit to observed data.

Mean error is a measure of systematic error. It approaches zero when the sum of the measured differences between simulated head and observed water-level altitudes that are greater than zero equals the sum of the differences that are less than zero. A negative mean error indicates that the simulated head is on average greater than the observed water-level altitudes.

In both layers 1 and 3, fit between the simulated head and observed water-level altitudes was good in the steady-state and transient parts of the calibrated model. For the steady-state stress period that simulated the predevelopment conditions, the RMSE was 37.8 ft for layer 1 and 44.5 ft

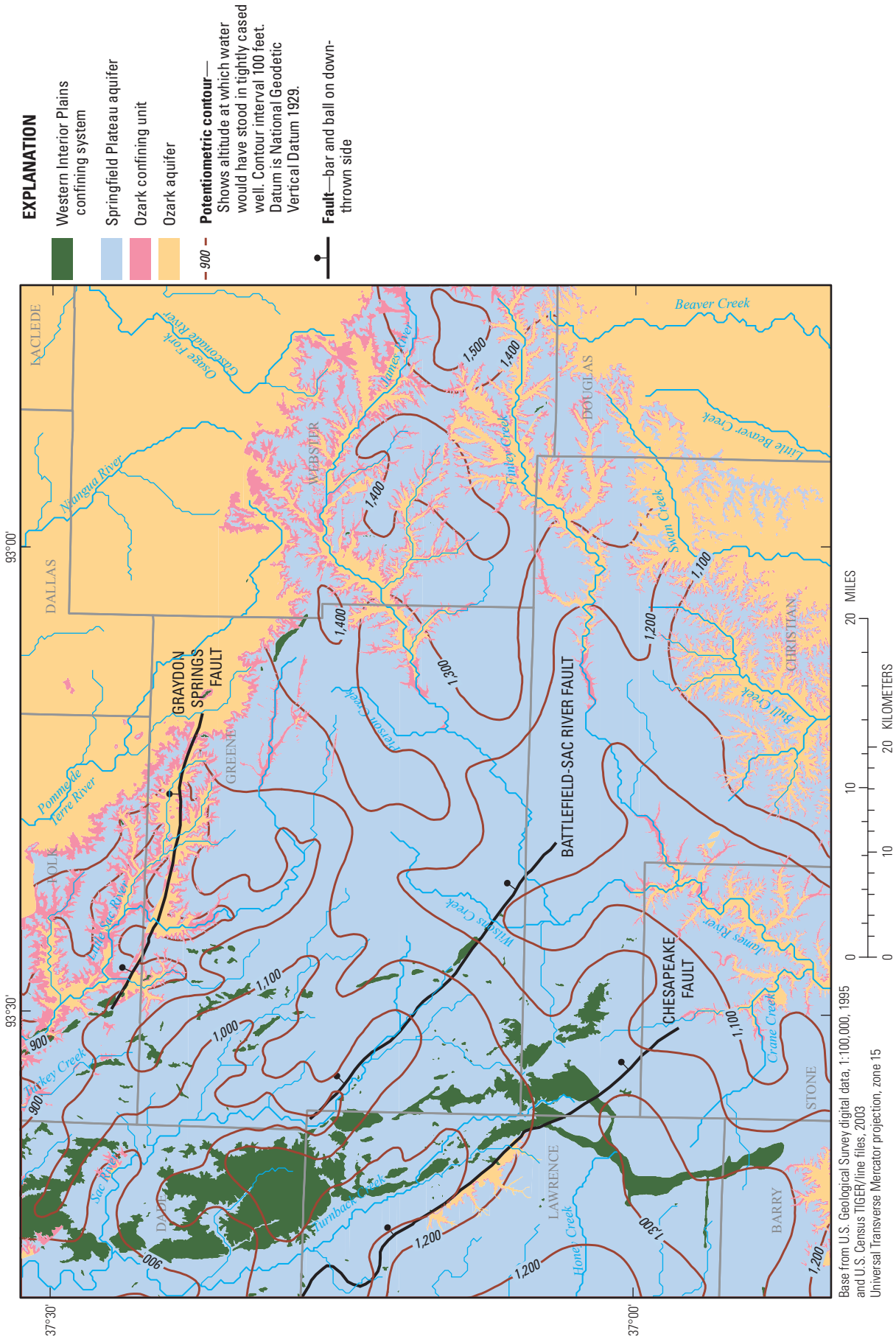


Figure 31. Potentiometric surface of the Springfield Plateau aquifer, 2006.

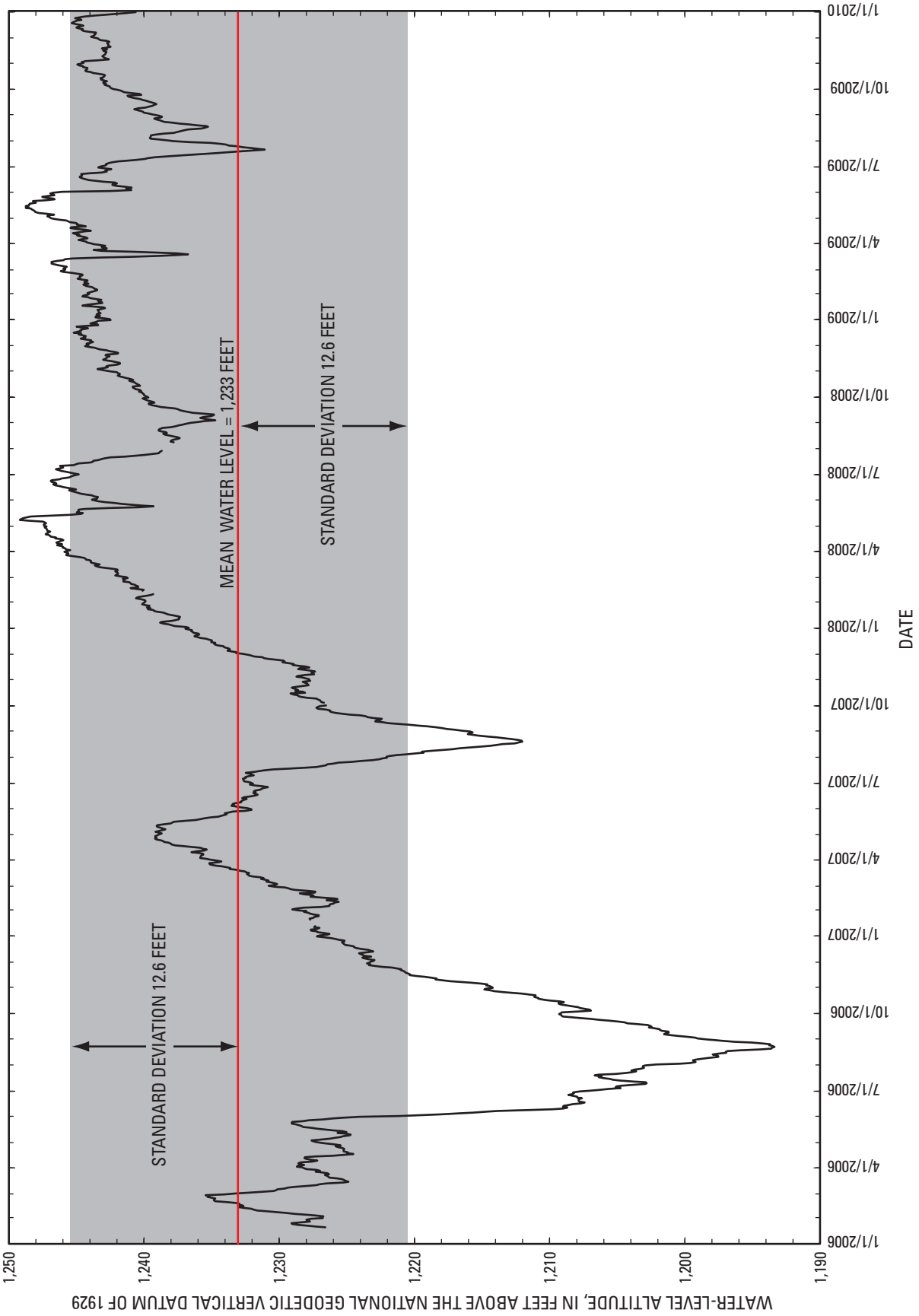


Figure 32. Daily water-level altitude of the Ozark aquifer at the Marshfield monitoring well from January 1, 2006, to December 31, 2009.

for layer 3 and the mean error was -0.93 ft for layer 1 and -0.63 ft for layer 3. The errors between the simulated head and observed water-level altitudes in layer 1 and layer 3 were evenly distributed with the majority of the difference values concentrated around zero. The calibration for the transient part of the simulation was focused on the period from 1987 to 2006. Water-level measurements made by the USGS in 1987, 1993, 1996, and 2006 in the Ozark aquifer and in 1989 and 2006 in the Springfield Plateau aquifer are more numerous and are more reliable than other time periods (table 9). These data were useful for evaluating the model fit, and the following discussion is restricted to those time periods. Maps showing the difference between simulated head and observed water-level altitudes in layer 3 of the model for 1987, 1993, 1996, and 2006 time periods are shown in fig. 33, 34, 35, and 36. Blue symbol colors represent areas where the simulated surface is higher in altitude than the observed water levels, whereas the red symbol colors represent areas where the simulated surface is lower in altitude than the observed water levels. Simulated values within 25 ft of the observation value are shown by a triangle, between 25 ft and 50 ft are shown by a circle, and greater than 50 ft are shown by a square. Simulated values with differences greater than 50 ft from the observed values were labeled with the difference on the figures. The magnitude of the difference between the simulated head and observed water levels for the 2006 data generally was small (< 25 ft) and most of the differences near the largest pumping centers in Nixa, Ozark, and Republic were less than 50 ft (fig. 36). Only two wells east of Springfield had differences greater than 100 ft.

Model fit can also be examined graphically by plotting the simulated head with the observed water-level altitudes and determining the correlation coefficient (R^2) of the linear regression line (Helsel and Hirsch, 1992). The correlation coefficient measures the fit between simulated and observed values; an $R^2 = 1$ indicates a perfect fit. Plots of the relation between the simulated head and observed water-level altitudes in layer 3 for the 1987, 1993, 1996, and 2006 time periods are shown in figure 37. The correlation coefficient ranged from approximately 0.84 in 1996 to 0.94 in 2006 indicating a good correlation between the simulated head and observed water-level altitudes in layer 3. In layer 3, the RMSE was greatest for the 1996 data (65.7 ft), and smallest for the 2006 data (34.9 ft). In layer 3, the mean error for the 2006 data was -8.40 ft.

Histograms of the difference between the simulated head and observed water-level altitudes (observed minus simulated) can be used to graphically evaluate the distribution of the errors. Ideally, the histogram would be symmetric about the mean of the data with the largest number of errors near the mean value, and it would have a relatively narrow range with few extremely large or small values. Histogram plots of the difference between simulated head and observed water-level altitudes in layer 3 for the 1987, 1993, 1996, and 2006 time periods are shown in figure 38. The 1987, 1996, and 2006 data sets in layer 3 were evenly distributed with the majority of the difference values concentrated around zero. The 1993 data set in layer 3 had a good distribution but had a positive skew, indicating that the simulated head was lower than the observed water-level altitudes for many of the observations for that year.

Maps showing the difference between simulated head and observed water-level altitudes in model layer 1 for the 1989 and 2006 time periods are shown in figure 39 and 40. Plots of the relation between the simulated head and observed water-level altitudes in layer 1 for the 1989 and 2006 time periods are shown in figure 41. Histogram plots of the difference between simulated head and observed water-level altitudes in layer 1 for the 1989 and 2006 time periods are shown in figure 42. The majority of the water-level observations were in the northwestern quarter of the model area for the layer 1 data sets in 1989 and 2006. The majority of the difference values were within +/- 50 ft from the observed water-level altitudes for both data sets in layer 1. The RMSE in layer 1 was 47.4 ft with a mean error of 0.15 ft for the 1989 data, and the RMSE was 32.4 ft with a mean error of 7.60 ft for the 2006 data. Correlation of the simulated head and observed water levels in layer 1 was better in 2006 than in 1989. The center of the error distribution for both the 1989 and 2006 data in layer 1 was near zero with the majority of values concentrated near the center.

All of the water-level observation data from 1987 to 2006 (fig. 8) also can be used to evaluate model fit as shown in figure 43. These data are more extensive than the previously discussed observation data sets, which allows for an evaluation of the model fit over more of the model temporal and spatial domain. The following discussion is based on all of the observation data from 1987 to 2006. It should be noted that including water-level data from the Missouri DNR certified well database and the well log database, in addition to combining all years together, will cause the error to increase, primarily because of the inherent accuracy of the water-level measurements and well locations. However, the RMSE of the data by model layer is very close to the previously computed maximum data error of approximately 60 ft. It should also be noted that layer 1 observation data includes water levels measured in the Springfield Plateau aquifer and the Ozark aquifer. Layer 1 Ozark aquifer wells generally were shallow wells measured where the Ozark aquifer crops out. Plots of the relation between the simulated head and observed water-level altitudes in layer 1 and layer 3 are shown in figure 43. Histogram plots of the difference between simulated head and observed water-level altitudes (observed minus simulated) in layer 1 and layer 3 are shown in figure 44. Using all of the data in layer 1 from 1987 to 2006, the RMSE was 47.4 ft and the mean error was 7.12 ft. The simulated head compared to observed water-level altitudes for layer 1 had a correlation coefficient of approximately 0.81. The histogram plot of the error data for layer 1 was evenly distributed and had the majority of the errors near the center of the distribution. Using all of the data in layer 3 from 1987 to 2006, the RMSE was 65.9 ft and the mean error was 26.0 ft. The simulated head compared to observed water-level altitudes for layer 3 had a correlation coefficient of approximately 0.81. The histogram

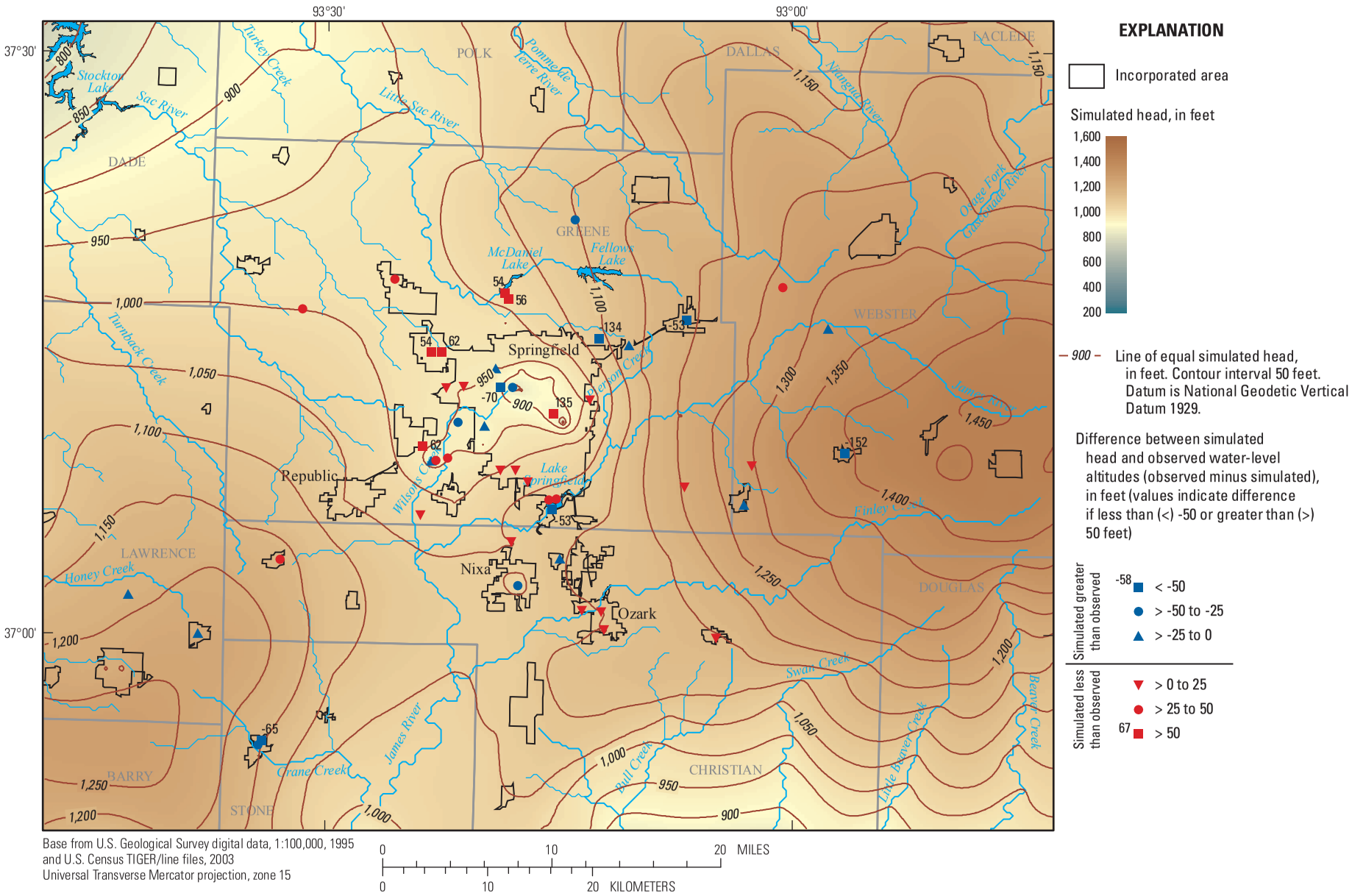


Figure 33. Simulated head in layer 3 and the difference between simulated head and observed water-level altitudes at observation points, 1987.

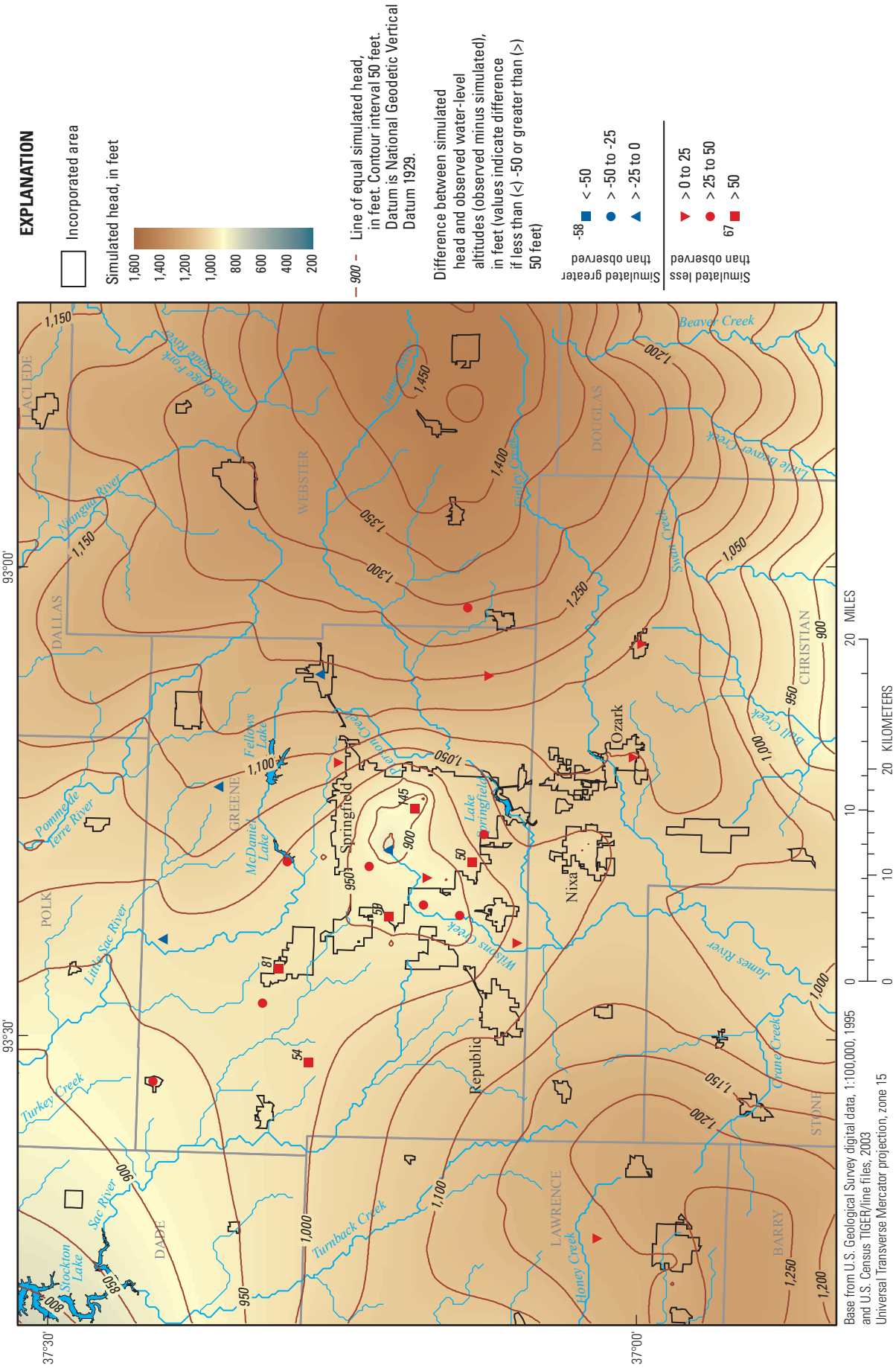
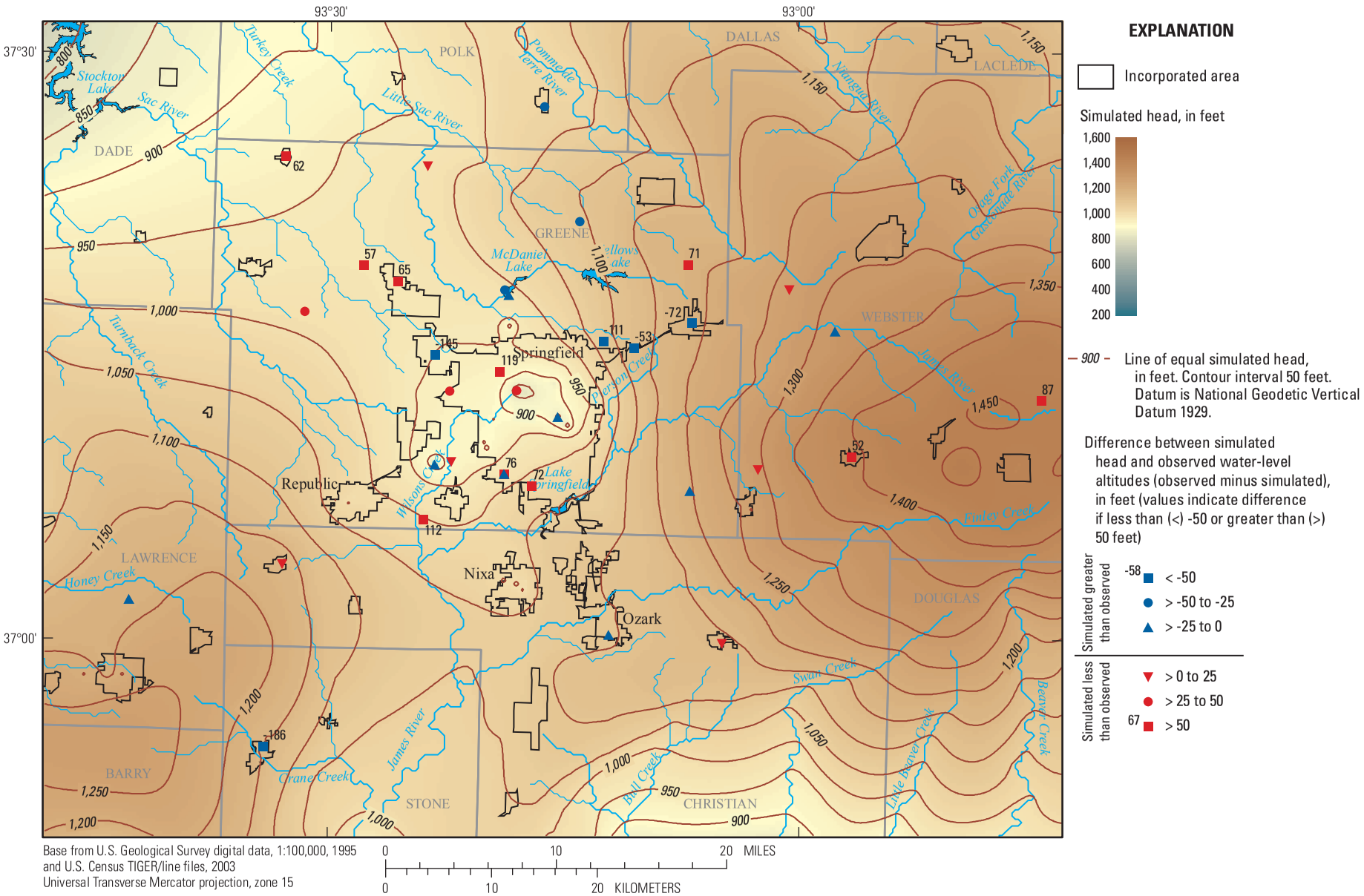


Figure 34. Simulated head in layer 3 and the difference between simulated head and observed water-level altitudes at observation points, 1993.



Base from U.S. Geological Survey digital data, 1:100,000, 1995 and U.S. Census TIGER/line files, 2003
Universal Transverse Mercator projection, zone 15

0 10 20 MILES

0 10 20 KILOMETERS

Figure 35. Simulated head in layer 3 and the difference between simulated head and observed water-level altitudes at observation points, 1996.

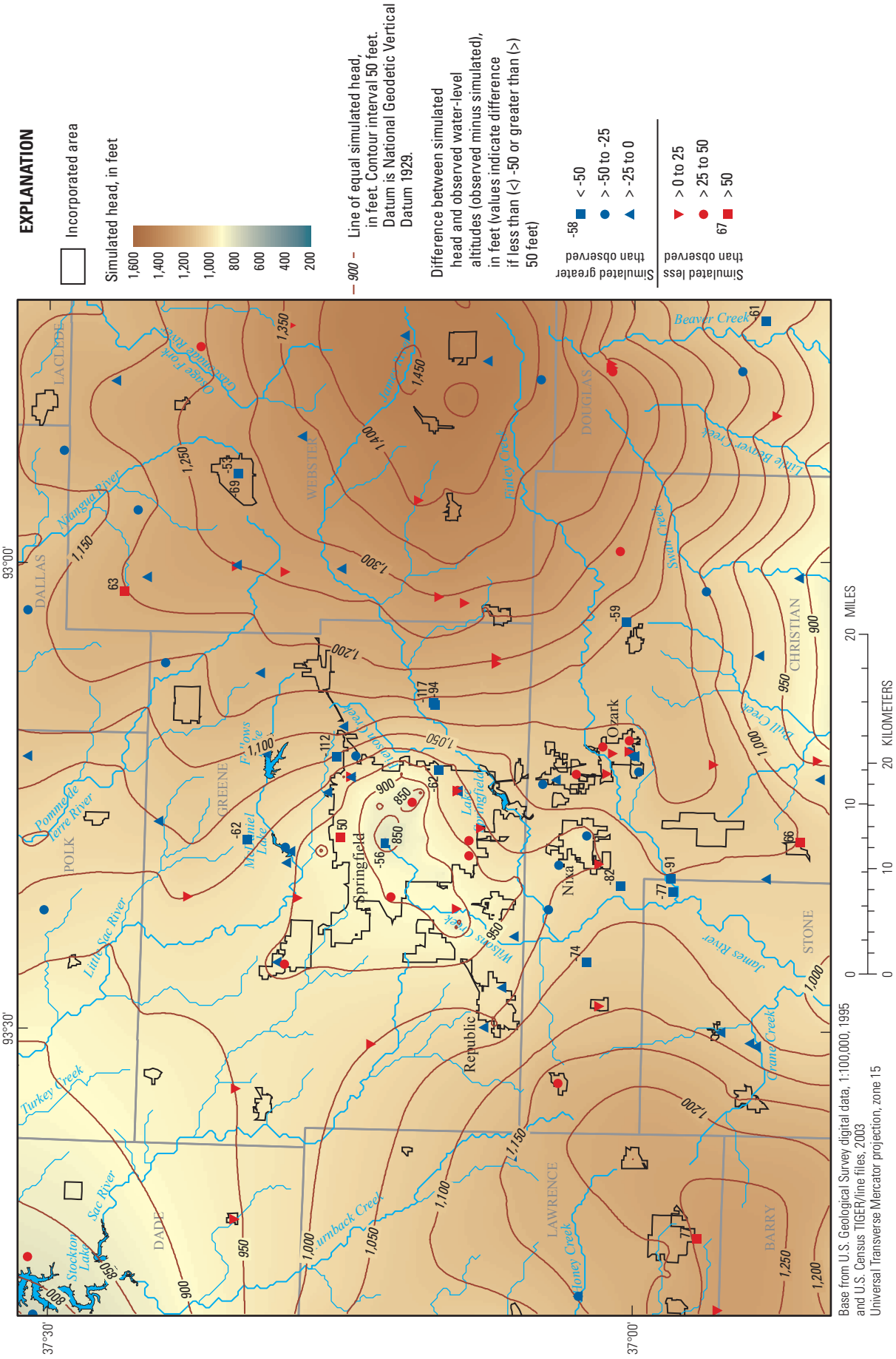


Figure 36. Simulated head in layer 3 and the difference between simulated head and observed water-level altitudes at observation points, 2006.

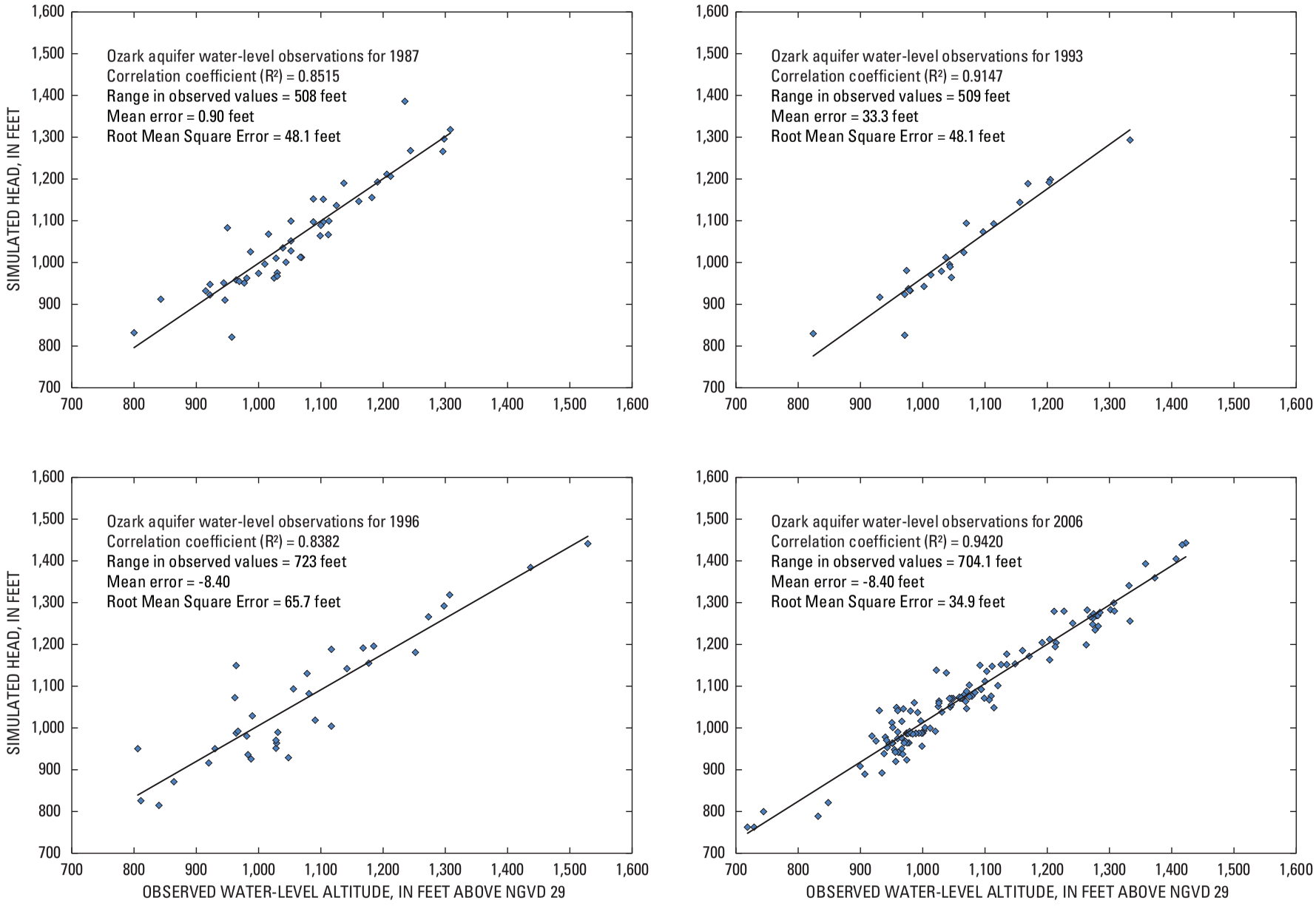


Figure 37. Relation between simulated head and observed water-level altitudes for selected measurements for layer 3 in the model.

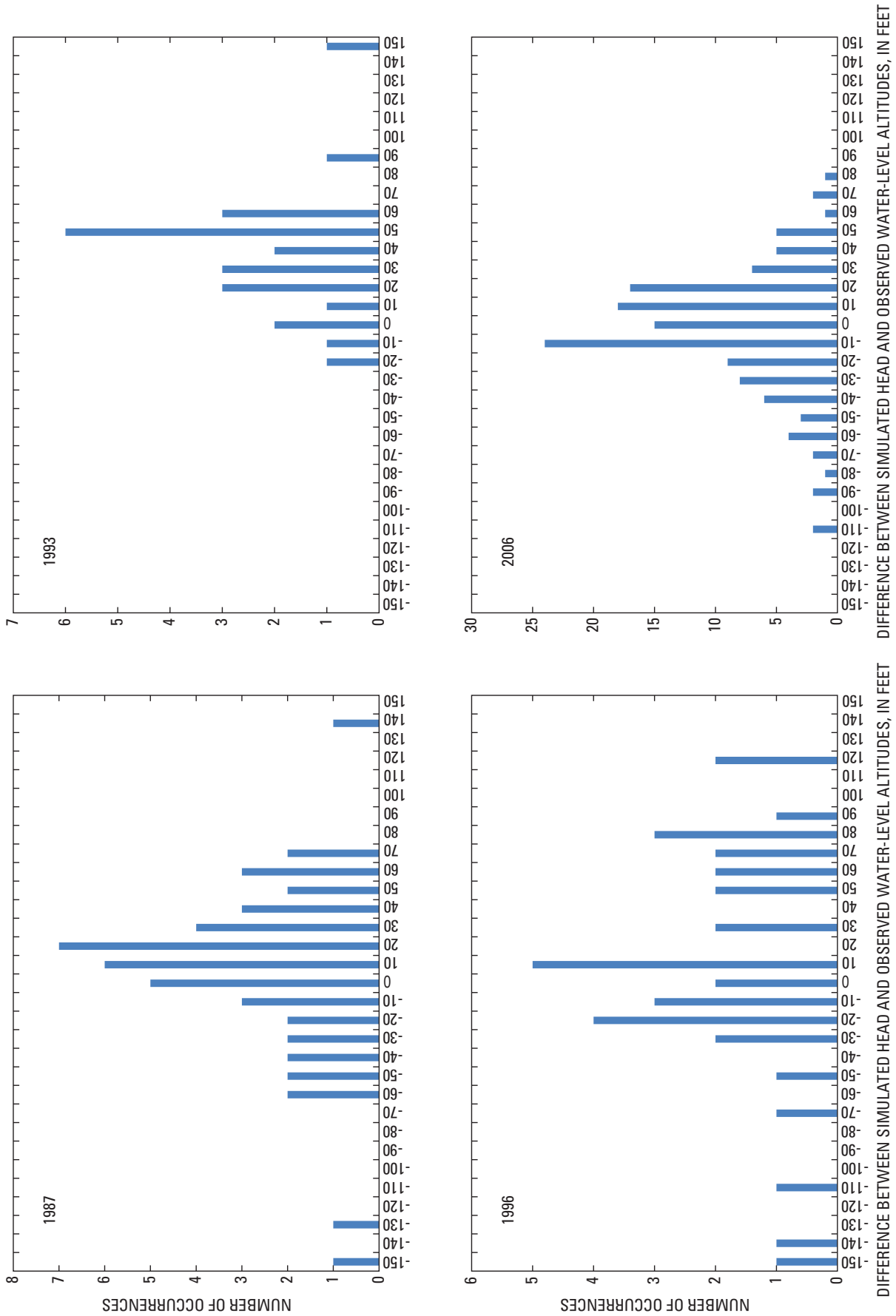


Figure 38. Difference between simulated head and observed water-level altitudes (observed minus simulated) for selected measurements for layer 3 in the model.

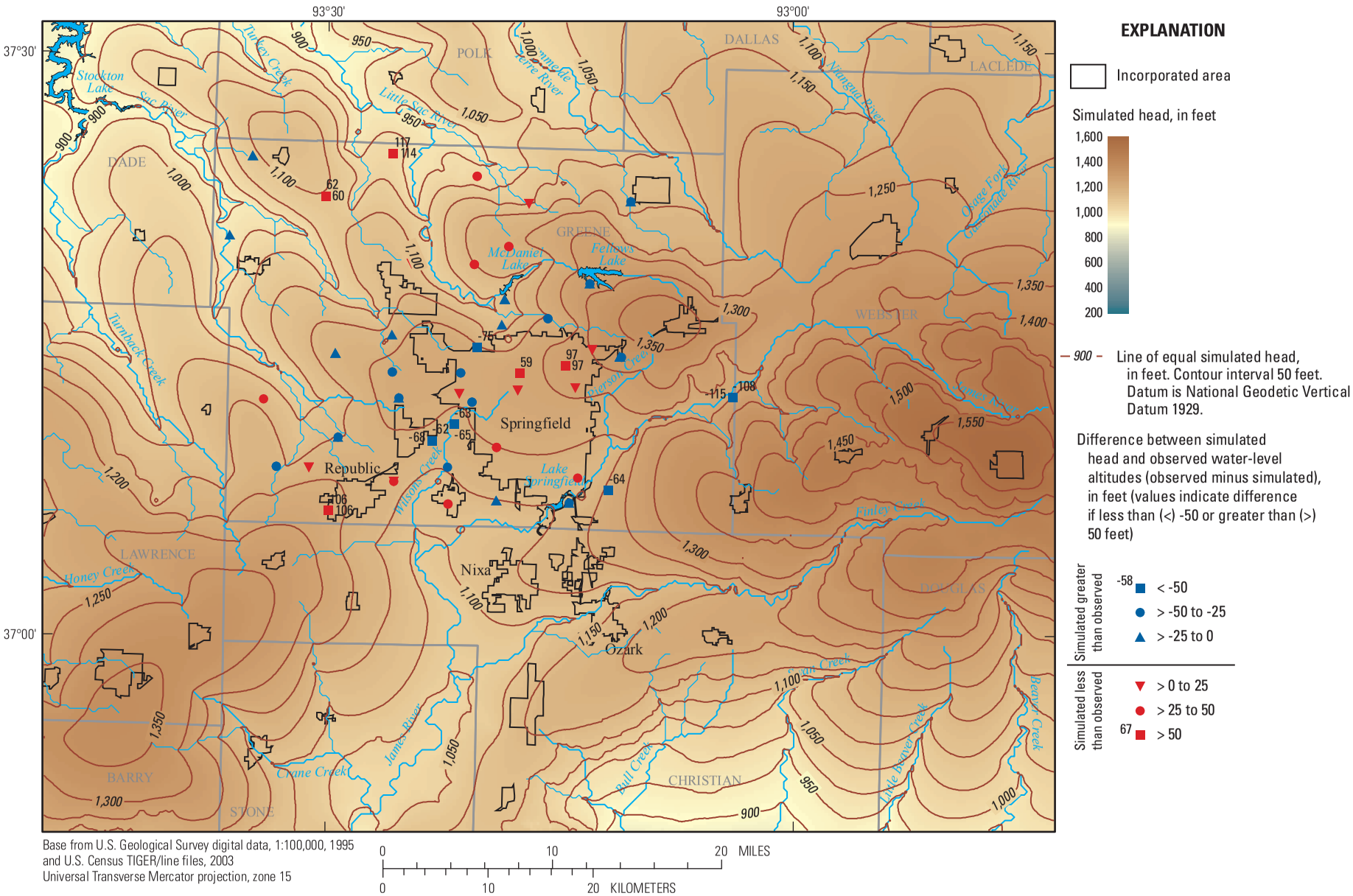


Figure 39. Simulated head in layer 1 and the difference between simulated head and observed water-level altitudes at observation points, 1989.

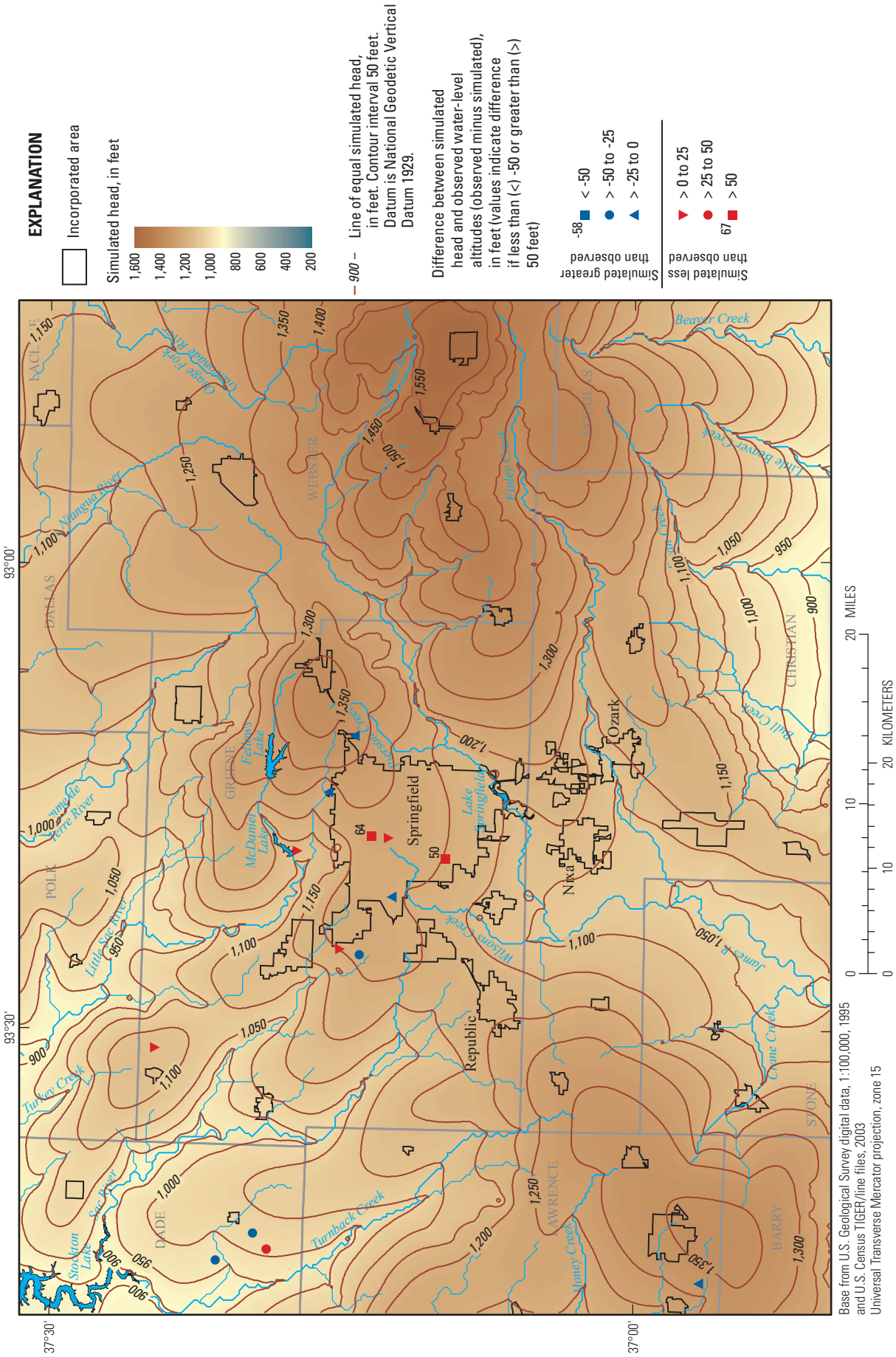


Figure 40. Simulated head in layer 1 and the difference between simulated head and observed water-level altitudes at observation points, 2006.

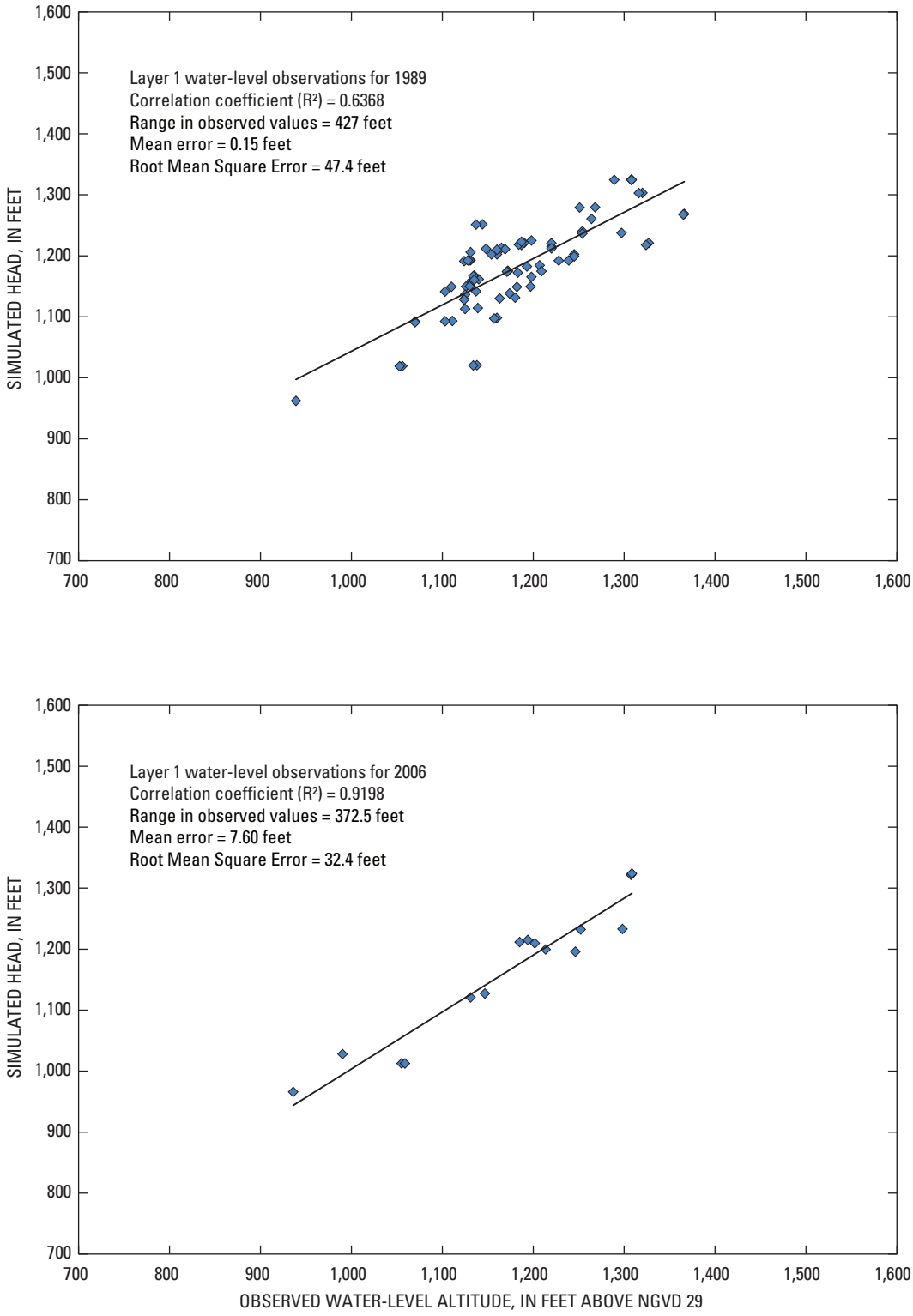


Figure 41. Relation between simulated head and observed water-level altitudes for selected measurements for layer 1 in the model.

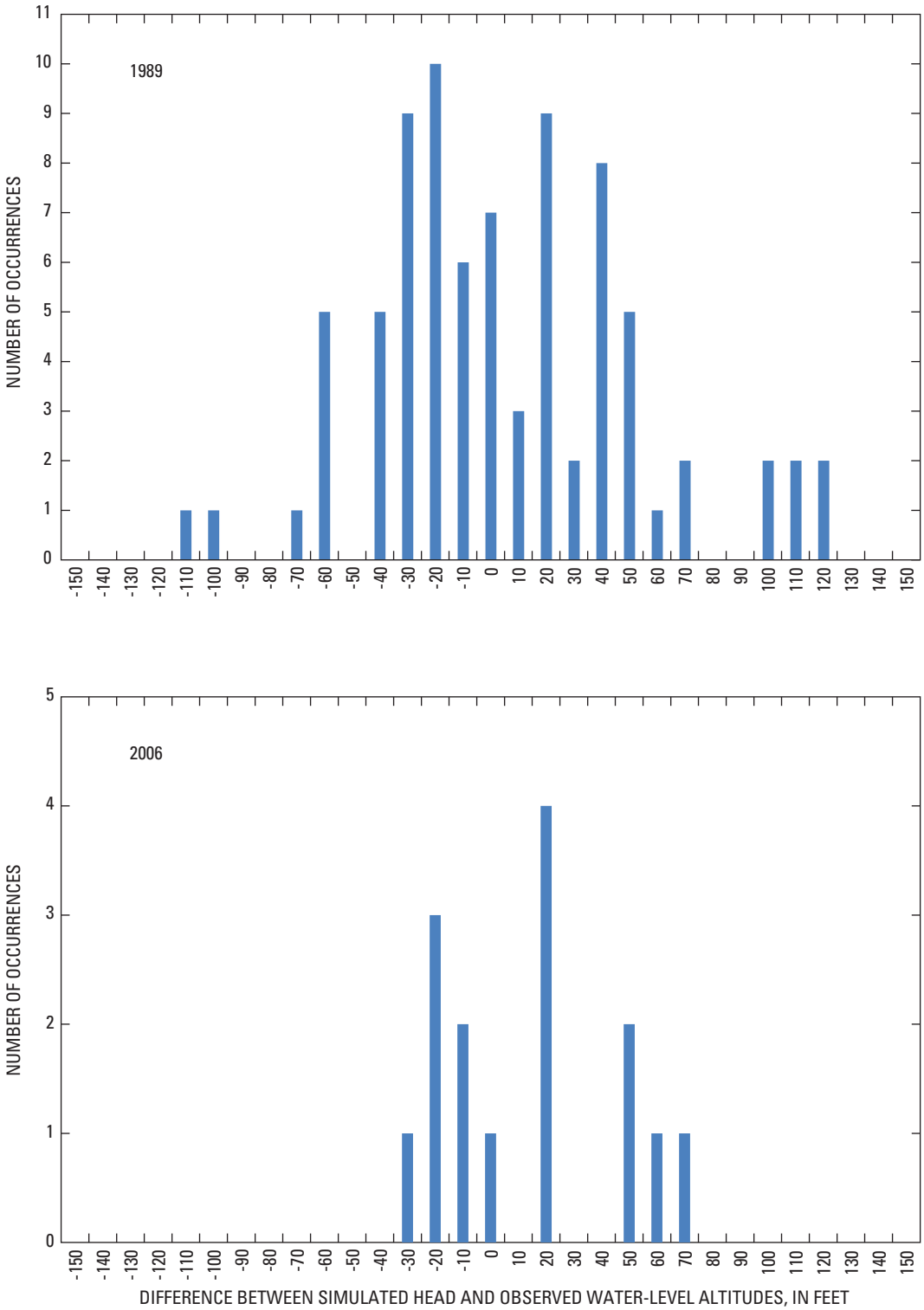


Figure 42. Difference between simulated head and observed water-level altitudes (observed minus simulated) for selected measurements for layer 1 in the model.

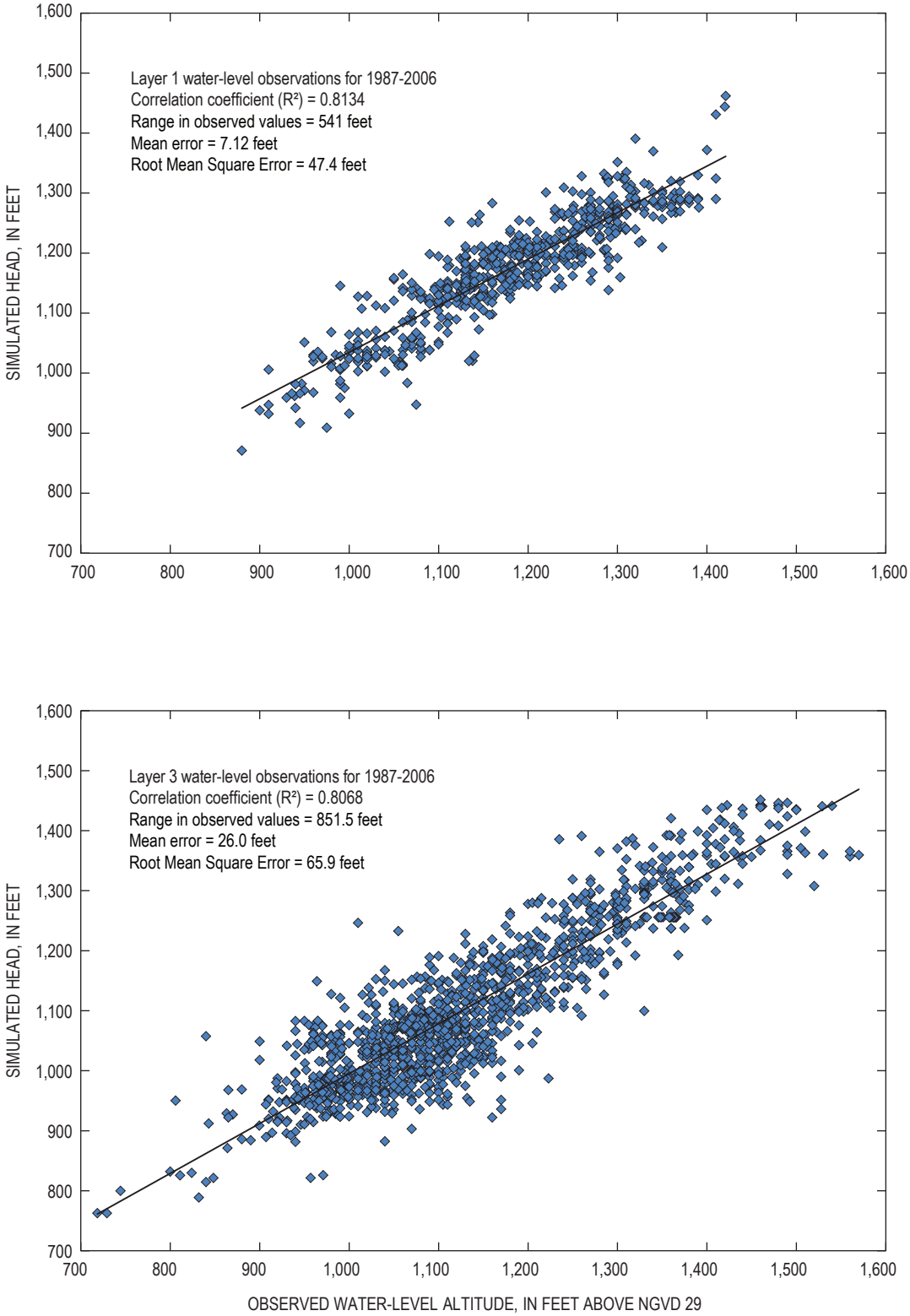


Figure 43. Relation between simulated head and observed water-level altitudes for all measurements made from 1987 to 2006 for layer 1 and layer 3 in the model.

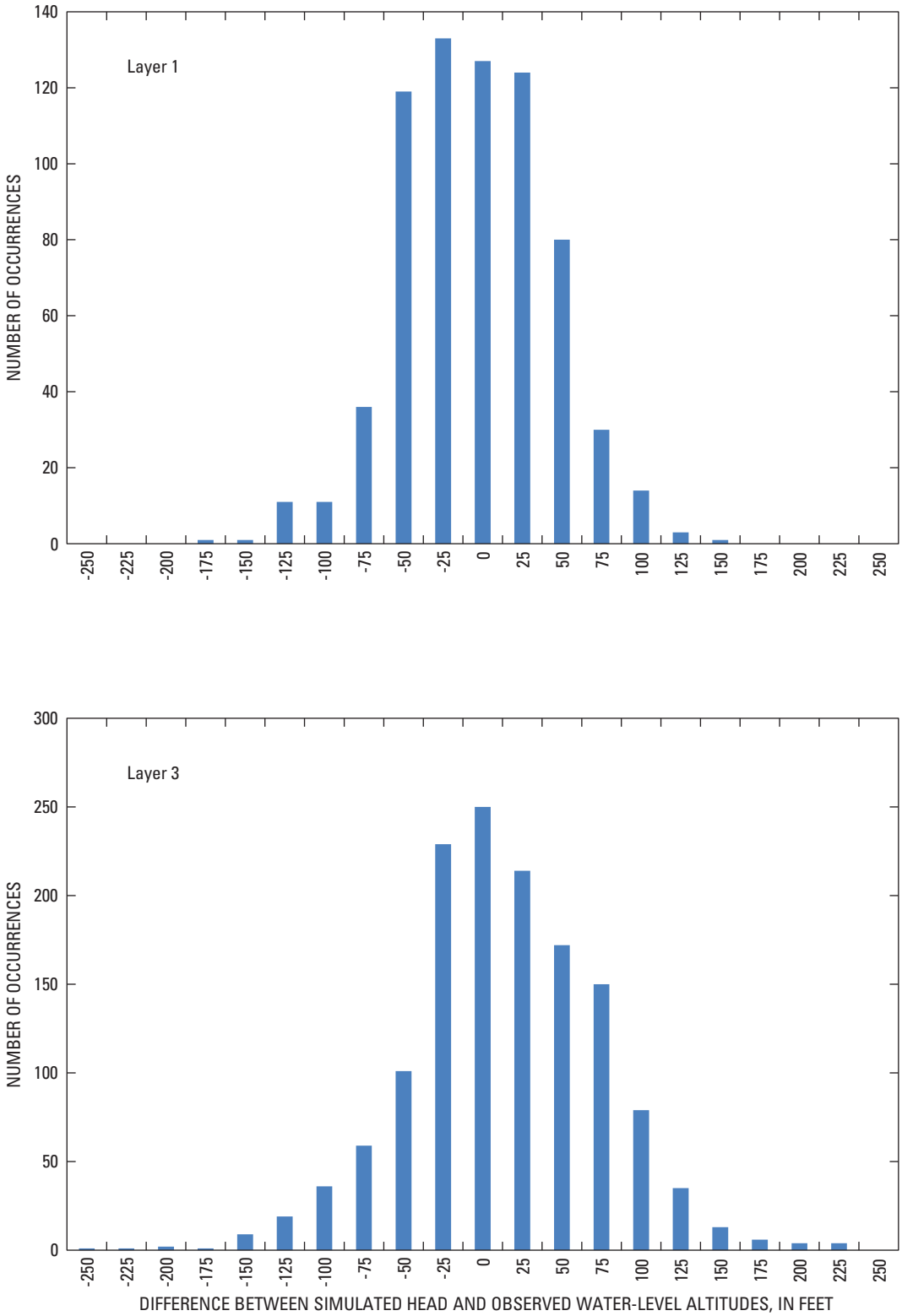


Figure 44. Difference between simulated head and observed water-level altitudes (observed minus simulated) for all measurements made from 1987 to 2006 for layer 1 and layer 3 in the model.

plot of the error data for layer 3 was evenly distributed and had the largest concentration of errors near the center of the distribution.

Streamflow Observations

Low-flow seepage-run data collected by Emmett and others (1978) and USGS in 2006 (fig. 23) were used to help estimate base-flow rates for selected sites. Base-flow rates for selected sites were also estimated from computed USGS $7Q_2$ low-flow frequency data at gaged sites and estimated at ungaged sites (table 6). Streamflow in the area is largely influenced by the karst groundwater system with discrete discharge in the river channel and long losing stream reaches. The model simulates diffuse discharge to, or recharge from the groundwater to the streams. Matching flows to streams and springs in this hydrogeologic setting with a groundwater model is challenging. In addition to the karst system, several lakes that provide drinking water or cooling water are located on the rivers. The process of removing drinking water from a lake in one basin (McDaniel Lake and Fellows Lake in the Little Sac River Basin) and discharging the water as wastewater effluent into another basin (Wilsons Creek in the James River Basin) complicates the base-flow estimates to the rivers. Base-flow estimates had to be corrected using discharge estimates from the wastewater-treatment facilities in the basin. To help reduce the effects of karst flow and other complicating factors at individual stream reaches, river basins at selected gaged sites and some ungaged sites were used to evaluate the groundwater flow to the rivers in the model (table 6).

Because the mean rainfall for the period 1987 to 2006 was 44.16 inches and was close to the 44.97 in/yr mean annual rainfall for the period 1971–2000 (National Climatic Data Center, 2008), the $7Q_2$ values were compared to the simulated discharge at the observation points near the end of the simulation in 2006. The relative percent difference between simulated and observed streamflow ranged from 6 to 141 percent (table 6) with a median relative percent difference of 40 percent. Taken as a whole, total observed $7Q_2$ discharge in rivers was 11,998,548 ft^3/d, compared to total simulated discharge from the model to rivers of 11,155,870 ft^3/d, or a relative percent difference of 7 percent.

Spring-Flow Observations

Spring-flow observation data were obtained or inferred from data available in Missouri Department of Natural Resources (2007), Vineyard and Feder, (1982), and Bullard and others (2001) for springs with a mean discharge of 86,400 ft^3/d (1 ft^3/s) or greater. Not all springs occurring in the model area were included in the model. The difference between simulated and observed spring discharge is listed in table 7. The relative percent error between simulated and observed spring discharge ranged from 65 to 200 percent. Taken as a whole, total observed discharge from springs in the model was 9,792,645 ft^3/d, compared to the total simulated discharge of 666,976 ft^3/d, or a relative percent difference of 174 percent (table 7). Error between simulated and observed spring discharge may be caused by uncertainty in the observed spring discharge and uncertainty in the simulated spring discharge related to the model grid spacing, horizontal and vertical hydraulic conductivity errors, proximity to other boundary conditions, and karst conduit flow. The grid spacing might affect the simulated discharge because the land-surface altitude of the cells was averaged over a 1,000-ft by 1,000-ft area. This has the effect of lowering the overall land-surface altitude in steep terrain where many springs discharge from hillsides adjacent to rivers. As a result, the spring altitude may be too high relative to the land-surface altitude. Hydraulic conductivity errors can cause flow to be restricted at the spring. Springs in close proximity to another model boundary, such as a river cell, may receive less flow when water that would have discharged to the spring is redirected toward the river. Because the model is simulating groundwater flow as porous-media flow, the karst flow to springs by conduit flow is not adequately represented.

The majority of spring flow in the model area ultimately flows to a river by overland flow and is removed from the model area as streamflow. Even though spring flow is under simulated in the model, the total volume of water leaving the model area, estimated by $7Q_2$ low-flow discharge, includes spring flow. When water discharges to a spring, the groundwater model removes that discharge and it cannot reenter the system. If the simulated stream discharge matched the estimated stream discharge and the simulated spring discharge matched the estimated spring discharge, then, in effect, spring flow would be counted twice. The springs in the model represent maximum water-level altitudes in those cells and help locally constrain the head distribution in layer 1 of the model.

Water Budget

The water budget was computed using ZONEBUDGET (Harbaugh, 1990) to determine the volumetric flow rate of water through the model. The flow budget is identical from stress period 1 (initial steady-state stress period) through stress period 101 (year 2006) and is similar for stress periods 102 (year 2007) through 125 (year 2030) in all model scenarios. The computed flow budget for the three layers in the model at the end of the initial steady-state stress period, the 101st stress period (year 2006), and the 125th stress period (year 2030) for hypothetical scenario 7 is shown in table 12. Total input into the model for hypothetical scenario 7 computed as the sum of the storage, rivers, general heads, and recharge inputs for the three layers of the model (table 12) was 23,660,140 ft^3/d for the initial steady-state stress period, 24,354,810 ft^3/d for 2006,

Table 12. Flow budget for the three layers of the model at the end of the initial steady-state stress period, the 101st stress period (2006), and the 125th stress period (2030) for hypothetical scenario 7.

[ft³/d, cubic foot per day; LAYER 1, model layer 1; LAYER 2, model layer 2; LAYER 3, model layer 3; —, no data; <, less than; zero flow-budget terms not included in table; values have been rounded]

Flow component	Initial steady-state stress period						2006						2030 scenario 7					
	LAYER 1		LAYER 2		LAYER 3		LAYER 1		LAYER 2		LAYER 3		LAYER 1		LAYER 2		LAYER 3	
	ft³/d	percent	ft³/d	percent	ft³/d	percent	ft³/d	percent	ft³/d	percent	ft³/d	percent	ft³/d	percent	ft³/d	percent	ft³/d	percent
In																		
Storage	—	—	—	—	—	—	941,920	4	150,150	1	1,987,300	16	314,860	1	176,470	1	2,806,300	18
Rivers	1,173,100	4	0	0	0	0	1,496,100	6	0	0	0	0	1,672,200	6	0	0	0	0
General Heads	775,990	3	868,550	6	112,500	1	813,170	3	887,640	6	160,530	1	783,450	3	890,250	5	175,380	1
Recharge	20,730,000	74	0	0	0	0	17,918,000	70	0	0	0	0	20,713,000	75	17,088	< 1	0	0
From Layer 1	—	—	9,699,600	65	—	—	—	—	10,492,000	70	—	—	—	—	12,643,000	74	—	—
From Layer 2	5,226,200	19	—	—	9,513,300	99	4,260,300	17	—	—	10,632,000	83	4,121,300	15	—	—	12,828,000	81
From Layer 3	—	—	4,304,000	29	—	—	—	—	3,483,500	23	—	—	—	—	3,350,700	20	—	—
Total In	27,905,000		14,872,000		9,625,800		25,429,000		15,013,000		12,780,000		27,605,000		17,078,000		15,810,000	
Out																		
Storage	—	—	—	—	—	—	6,175	< 1	320	< 1	19,586	< 1	5,762	< 1	436	< 1	2,702	< 1
Wells	0	0	0	0	0	0	0	0	0	0	4,330,200	34	0	0	0	0	7,582,600	48
Springs	785,240	3	0	0	0	0	666,260	3	0	0	0	0	663,360	2	0	0	0	0
Rivers	16,260,000	58	0	0	0	0	13,217,000	52	0	0	0	0	13,167,000	48	0	0	0	0
General Heads	1,160,700	4	132,330	1	5,319,000	55	1,047,300	4	121,070	1	4,944,800	39	1,124,900	4	127,760	1	4,872,700	31
To Layer 1	—	—	5,226,200	35	—	—	—	—	4,260,300	28	—	—	—	—	4,121,300	24	—	—
To Layer 2	9,699,600	35	—	—	4,304,000	45	10,492,000	41	—	—	3,483,500	27	12,643,000	46	—	—	3,350,700	21
To Layer 3	—	—	9,513,300	64	—	—	—	—	10,632,000	71	—	—	—	—	12,828,000	75	—	—
Total Out	27,905,000		14,872,000		9,623,000		25,429,000		15,013,000		12,778,000		27,605,000		17,078,000		15,809,000	

and 27,548,998 ft^3/d for 2030. Additional ZONEBUDGET analyses were performed to determine only the flow component through the lateral model boundary from each model layer and flow through the bottom of layer 3 in the model, which are included in general heads in table 12. Flow through general-head boundaries representing lakes in layer 1 are not included in the ZONEBUDGET following analysis. At the end of the initial steady-state stress period in scenario 7, there was a net flow of 2,240 ft^3/d into layer 1, a net flow of 736,220 ft^3/d into layer 2, and a net flow of 3,305,900 ft^3/d out of layer 3 through the lateral model boundary. Net flow through the bottom of layer 3 was 1,900,700 ft^3/d out of the model, which represents about 8.0 percent of the total input to the model in the initial steady-state stress period. At the end of stress period 101 (year 2006) in scenario 7, there was a net flow of 114,010 ft^3/d into layer 1, a net flow of 766,570 ft^3/d into layer 2, and a net flow of 3,001,670 ft^3/d out of layer 3 through the lateral model boundary. Net flow through the bottom of layer 3 was 1,782,500 ft^3/d out of the model, which represents about 7.3 percent of the total input to the model in 2006. At the end of stress period 125 (year 2030) in scenario 7, there was a net flow of 28,570 ft^3/d into layer 1, a net flow of 762,490 ft^3/d into layer 2, and a net flow of 3,004,850 ft^3/d out of layer 3 through the lateral model boundary. Net flow through the bottom of layer 3 was 1,692,800 ft^3/d out of the model, which represents about 6.1 percent of the total input to the model in 2030 for hypothetical scenario 7.

Sensitivity Analysis

Sensitivity analysis of the model was performed to assess the response of the model to changes in the various input parameters used in the model. Every change to a model parameter in this model will cause changes to the distribution of head in the aquifers and subsequently, discharge to rivers and springs. The model is considered sensitive to the parameter when a small change in the parameter causes a large change in the distribution of simulated head. When the model is sensitive to a parameter, the parameter is more accurately determined during model calibration. When a model is insensitive to a parameter, the parameter is less accurately determined during model calibration.

Horizontal hydraulic conductivity, vertical hydraulic conductivity, specific storage, and specific yield were tested for all zones in the Springfield Plateau aquifer, the Ozark confining unit, and the Ozark aquifer. In addition, spring drain conductance, lake general-head boundary conductance, river conductance, perimeter general-head boundary conductance in all layers, and recharge zone boundary conditions were tested.

The calibration-period sensitivity test consisted of increasing each model parameter by 10 percent while holding the other parameters constant and running the model. Simulated head was compared between the calibrated model and the model results with the 10-percent parameter adjustments. The differences were computed by subtracting the head of the adjusted parameter model results from the head of the calibrated model at the 2,076 water-level observation points. The RMSE of these differences was computed and tabled by rank (table 13). The 10 most sensitive model parameters included the horizontal hydraulic conductivity in the Ozark aquifer in zones 1, 3, and 6 (fig. 30); recharge in zones 1 and 2 (fig. 19); the specific storage of the Ozark aquifer in zone 4 (fig. 30); and the vertical and horizontal hydraulic conductivity of the Ozark confining unit in zones 2 and 3 (fig. 29). The 10 least sensitive parameters were the specific yield in the Ozark aquifer in zones 8, 5, 6, 7, 2, and 4 (fig. 30); the specific storage in the Ozark aquifer in zone 7 (fig. 30); and the specific storage in the Springfield Plateau aquifer in zones 1, 2, and 3 (fig. 28). Sensitivity analysis was not performed on values of groundwater use because it was assumed that these values were better known than the parameters specified in the sensitivity analysis.

Maps of the simulated head change between the calibrated model and the model with an adjusted hydraulic parameter can be examined to help understand how changes in hydraulic properties affect the simulated head distribution. Of the top five most sensitive parameters in the model, two were for horizontal hydraulic conductivity in the Ozark aquifer and two were for recharge. Maps of the simulated head change in layer 1 and layer 3 for the sensitivity parameters horizontal hydraulic conductivity in zone 1 of the Ozark aquifer (OZHK1, table 13; OZA1, fig. 30) and the recharge in zone 1 (RCHZ1, table 13; RCH1, fig. 19) are shown in figure 45 and 46. When the horizontal hydraulic conductivity of a particular zone is increased, the head gradient will decrease and the potentiometric surface will become flatter. The greatest changes will occur in the zone where the parameter was adjusted, however, some change will occur outside the zone. After the adjustment of the horizontal hydraulic conductivity in the Ozark aquifer zone 1, the simulated head in layer 3 (fig. 45; LAYER 3) increased in the vicinity of pumping wells in zone 1 of the Ozark aquifer in central Greene County and decreased in the northeastern, southwestern, and south-central part of the model area. Simulated head in layer 1 also decreased in approximately the same area as in layer 3 because the lower potentiometric surface in layer 3 allowed more water to pass through layer 2, which resulted in lower head in layer 1 (fig. 45; LAYER 1). When recharge is increased in a particular zone, the head tends to increase in all layers throughout the model. The magnitude of the simulated head increase in layer 1, the layer where recharge is applied, is greater than the magnitude in layer 3 (fig. 46).

Table 13. Sensitivity of model to changes in parameter values.

[SPA, Springfield Plateau aquifer; OZCU, Ozark confining unit; OZA, Ozark aquifer; SFCU1, general-head boundary conductance simulating flow through the bottom of the Ozark aquifer in zone 1; SFCU2, general-head boundary conductance simulating flow through the bottom of the Ozark aquifer in zone 2; HK, horizontal hydraulic conductivity; KZ, vertical hydraulic conductivity; SS, specific storage; SY, specific yield; RCH, recharge; RIV, river conductance; SPRG, drain conductance; GHB, general-head boundary conductance; RBSP, river conductance for rivers flowing on the Springfield Plateau aquifer; RBCU, river conductance for rivers flowing on the Ozark confining unit; RBOZ, river conductance for rivers flowing on the Ozark aquifer; LAKE, general-head boundary conductance simulating lakes; GHB1, general-head boundary conductance simulating flow through model boundary in layer 1; GHB2, general-head boundary conductance simulating flow through model boundary in layer 2; GHB3, general-head boundary conductance simulating flow through model boundary in layer 3; RMSE, root mean square error; —, no data]

Parameter name	Calibration period		Prediction period		Hydrogeologic unit	Parameter type	Zone name	Calibrated parameter value (variable units)
	RMSE	Rank RMSE	RMSE	Rank RMSE				
OZHK1	2.048	1	3.850	1	OZA	HK	OZA1	1.30
RCHZ1	1.684	2	1.781	4	—	RCH	RCH1	Precipitation*3.0 percent
OZSS4	1.425	3	2.983	2	OZA	SS	OZA4	1.00×10^{-4}
OZHK3	1.373	4	1.352	10	OZA	HK	OZA3	.35
RCHZ2	1.354	5	1.410	9	—	RCH	RCH2	Precipitation*2.7 percent
OZHK6	1.222	6	2.449	3	OZA	HK	OZA6	.30
CUKZ3	1.167	7	1.652	5	OZCU	KZ	OZCU3	1.50×10^{-5}
CUHK3	1.157	8	1.616	6	OZCU	HK	OZCU3	7.50×10^{-5}
CUHK2	.995	9	1.535	7	OZCU	HK	OZCU2	2.80×10^{-5}
CUKZ2	.944	10	1.451	8	OZCU	KZ	OZCU2	5.60×10^{-6}
SFCU1	.898	11	.816	13	SFCU	GHB	SFCU1	.035
SPHK2	.882	12	.880	12	SPA	HK	SPA2	2.20
RCHZ3	.707	13	.718	14	—	RCH	RCH3	Precipitation*2.1 percent
SFCU2	.656	14	.579	16	SFCU	GHB	SFCU2	.200
SPHK3	.638	15	.579	15	SPA	HK	SPA3	5.00
OZHK2	.384	16	.409	18	OZA	HK	OZA2	.35
OZHK7	.360	17	.902	11	OZA	HK	OZA7	.80
OZHK4	.352	18	.548	17	OZA	HK	OZA4	1.50
SPHK1	.311	19	.313	23	SPA	HK	SPA1	2.50
OZKZ3	.307	20	.321	22	OZA	KZ	OZA3	.035
OZKZ1	.234	21	.342	20	OZA	KZ	OZA1	.130
OZHK8	.234	22	.257	26	OZA	HK	OZA8	3.00
RBOZ	.230	23	.334	21	OZA	RIV	—	975 to 9,750
OZHK5	.208	24	.301	24	OZA	HK	OZA5	.25
GHB3	.200	25	.200	28	—	GHB	—	59.9 to 1,288
OZSS1	.168	26	.237	27	OZA	SS	OZA1	1.00×10^{-6}

Parameter name	Calibration period		Prediction period		Hydrogeologic unit	Parameter type	Zone name	Calibrated parameter value (variable units)
	RMSE	Rank RMSE	RMSE	Rank RMSE				
OZSS3	.103	27	.352	19	OZA	SS	OZA3	5.00×10^{-6}
OZSS5	.083	28	.261	25	OZA	SS	OZA5	5.00×10^{-5}
RBSP	.075	29	.084	31	SPA	RIV	—	1,000 to 3,333
OZSS2	.073	30	.181	30	OZA	SS	OZA2	5.00×10^{-4}
SPKZ2	.067	31	.066	34	SPA	KZ	SPA2	.073
GHB1	.064	32	.064	35	—	GHB	—	11.5 to 530.6
OZKZ6	.063	33	.182	29	OZA	KZ	OZA6	.030
GHB2	.059	34	.060	38	—	GHB	—	4.56 to 105.0
LAKE	.039	35	.067	33	—	GHB	—	100
SPKZ3	.032	36	.048	44	SPA	KZ	SPA3	.167
OZSY1	.031	37	.046	46	OZA	SY	OZA1	.003
CUHK1	.031	38	.042	47	OZCU	HK	OZCU1	1.00×10^{-6}
CUKZ1	.029	39	.061	36	OZCU	KZ	OZCU1	2.00×10^{-7}
SPSY2	.028	40	.004	62	SPA	SY	SPA2	.003
OZKZ5	.027	41	.056	40	OZA	KZ	OZA5	.050
CUSY1	.027	42	.035	48	OZCU	SY	OZCU1	.100
OZKZ8	.026	43	.075	32	OZA	KZ	OZA8	.300
RBCU	.026	44	.055	41	OZCU	RIV	—	50 to 3,750
SPKZ1	.025	45	.026	50	SPA	KZ	SPA1	.050
SPSY3	.021	46	.008	57	SPA	SY	SPA3	.003
CUSY2	.019	47	.047	45	OZCU	SY	OZCU2	.100
OZSS8	.018	48	.030	49	OZA	SS	OZA8	1.00×10^{-5}
SPRG	.018	49	.055	42	—	SPRG	—	10,000
OZKZ7	.014	50	.058	39	OZA	KZ	OZA7	.080
OZSS6	.012	51	.013	53	OZA	SS	OZA6	1.00×10^{-7}
OZKZ2	.012	52	.012	54	OZA	KZ	OZA2	.070
OZSY3	.012	53	.010	56	OZA	SY	OZA3	.003

Table 13. Sensitivity of model to changes in parameter values.—Continued

[SPA, Springfield Plateau aquifer; OZCU, Ozark confining unit; OZA, Ozark aquifer; SFCU1, general-head boundary conductance simulating flow through the bottom of the Ozark aquifer in zone 1; SFCU2, general-head boundary conductance simulating flow through the bottom of the Ozark aquifer in zone 2; HK, horizontal hydraulic conductivity; KZ, vertical hydraulic conductivity; SS, specific storage; SY, specific yield; RCH, recharge; RIV, river conductance; SPRG, drain conductance; GHB, general-head boundary conductance; RBSP, river conductance for rivers flowing on the Springfield Plateau aquifer; RBCU, river conductance for rivers flowing on the Ozark confining unit; RBOZ, river conductance for rivers flowing on the Ozark aquifer; LAKE, general-head boundary conductance simulating lakes; GHB1, general-head boundary conductance simulating flow through model boundary in layer 1; GHB2, general-head boundary conductance simulating flow through model boundary in layer 2; GHB3, general-head boundary conductance simulating flow through model boundary in layer 3; RMSE, root mean square error; —, no data]

Parameter name	Calibration period		Prediction period		Hydrogeologic unit	Parameter type	Zone name	Calibrated parameter value (variable units)
	RMSE	Rank RMSE	RMSE	Rank RMSE				
CUSY3	.011	54	.060	37	OZCU	SY	OZCU3	.100
CUSS2	.006	55	.019	51	OZCU	SS	OZCU2	5.00×10^{-6}
OZKZ4	.004	56	.006	58	OZA	KZ	OZA4	.150
CUSS1	.004	57	.011	55	OZCU	SS	OZCU1	5.00×10^{-6}
SPSY1	.002	58	.001	66	SPA	SY	SPA1	.003
CUSS3	.002	59	.006	59	OZCU	SS	OZCU3	5.00×10^{-6}
SPSS2	.002	60	.002	63	SPA	SS	SPA2	1.00×10^{-5}
OZSS7	.002	61	.001	67	OZA	SS	OZA7	1.00×10^{-8}
OZSY8	.001	62	.049	43	OZA	SY	OZA8	.003
OZSY5	.001	63	.002	65	OZA	SY	OZA5	.003
SPSS3	.001	64	.005	61	SPA	SS	SPA3	1.00×10^{-5}
OZSY6	.001	65	.000	69	OZA	SY	OZA6	.003
OZSY7	.001	66	.019	52	OZA	SY	OZA7	.003
OZSY2	.001	67	.002	64	OZA	SY	OZA2	.003
SPSS1	.001	68	.000	68	SPA	SS	SPA1	1.00×10^{-5}
OZSY4	.001	69	.005	60	OZA	SY	OZA4	.003

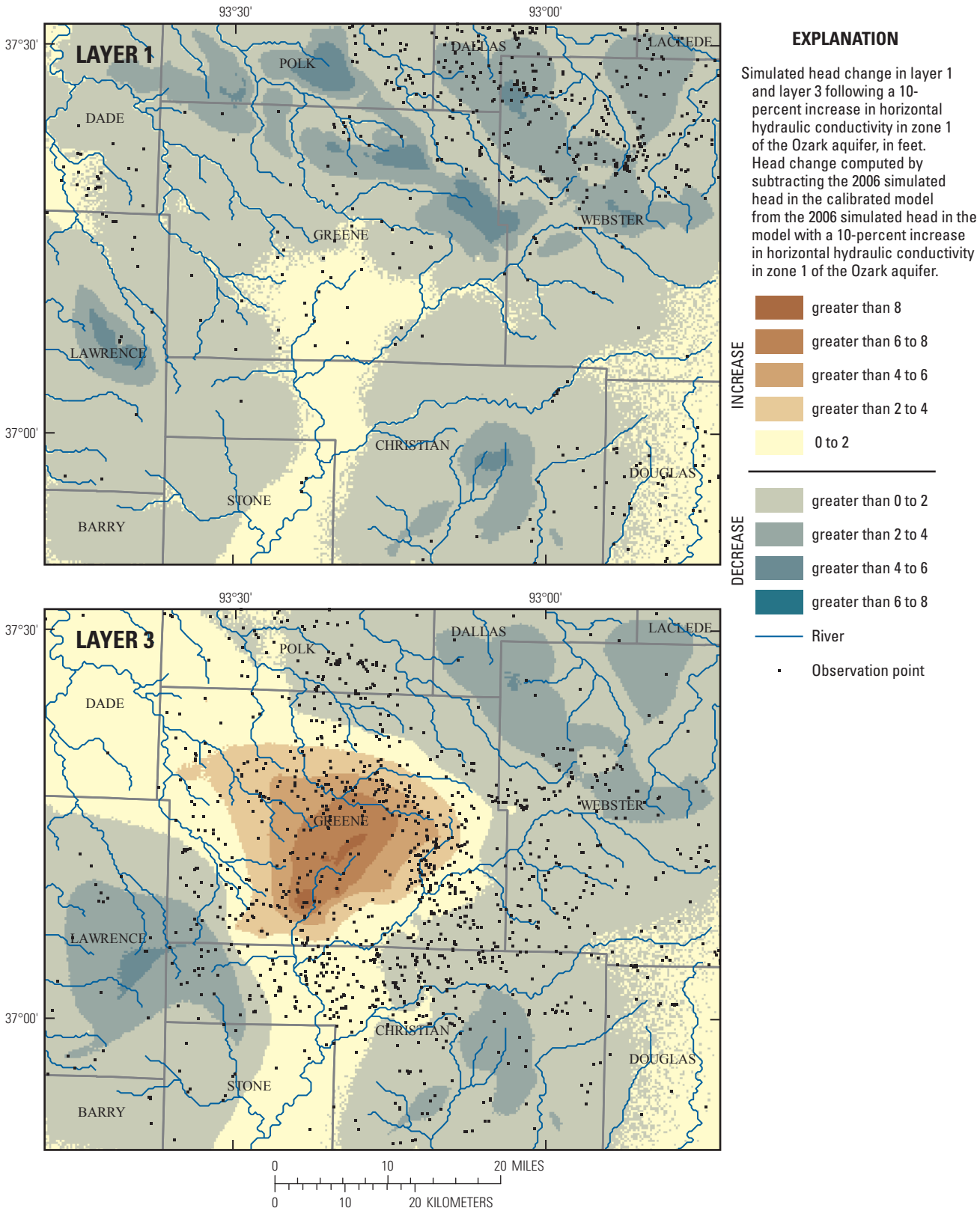


Figure 45. Simulated head change in layer 1 and layer 3 following a 10-percent increase in horizontal hydraulic conductivity in zone 1 of the Ozark aquifer (OZHK1, table 13; OZA1, fig. 30) computed at the end of the calibration period in 2006.

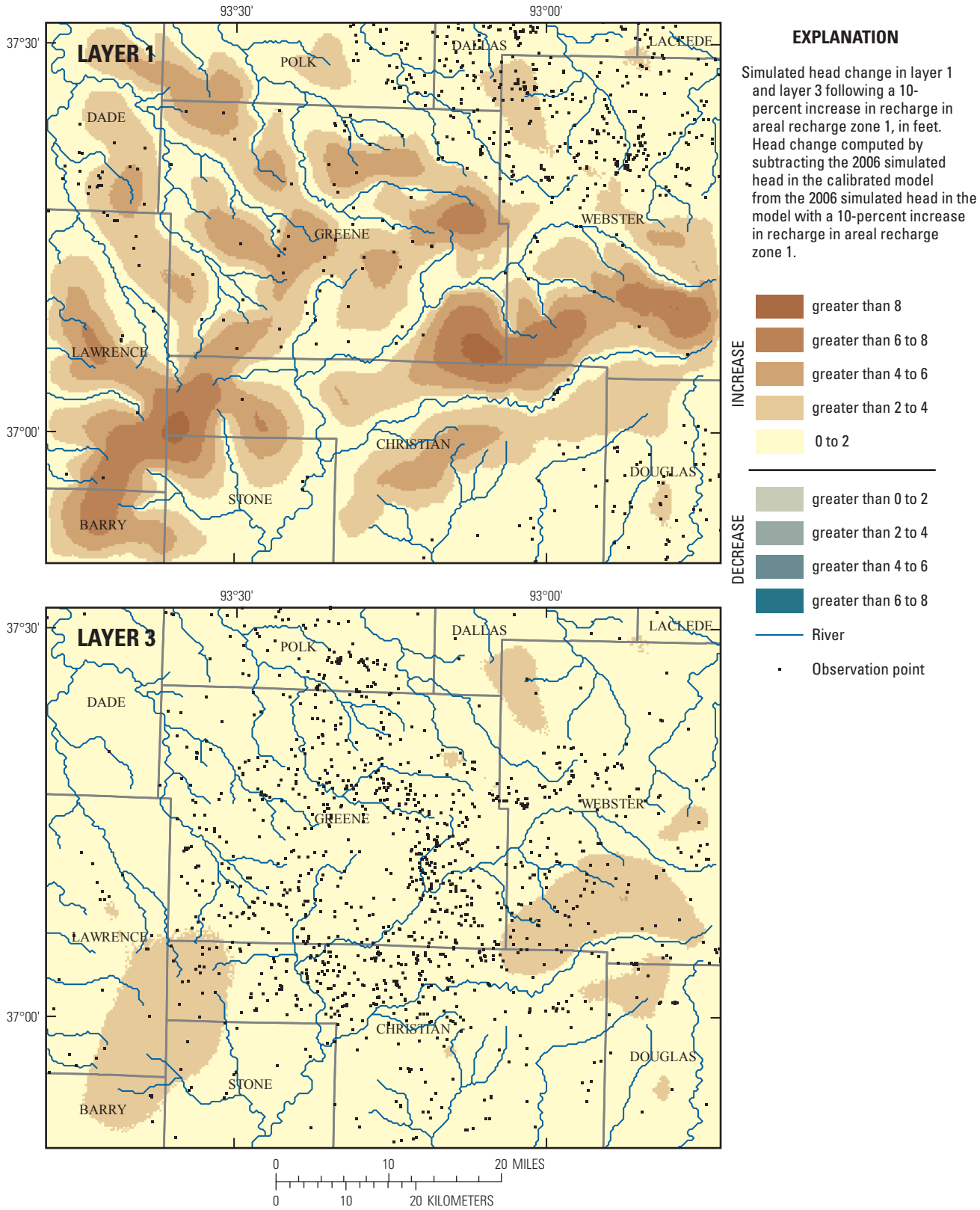


Figure 46. Simulated head change in layer 1 and layer 3 following a 10-percent increase in recharge in areal recharge zone 1 (RCHZ1, table 13; RCH1, fig. 19) computed at the end of the calibration period in 2006.

The prediction-period sensitivity test consisted of increasing each model parameter by 10 percent while holding the other parameters constant and evaluating the simulated head change at the end of the prediction period. Predictive simulation scenario 7, discussed in more detail in the Low and High Population Growth with New Industrial Wells section of the report, was used to evaluate the sensitivity of the hydraulic parameters on the model predicted results. At the end of the simulation period on day 365 in the year 2030, the head distribution was compared between the calibrated model results and the model results with adjusted parameters. The differences were computed at the 2,076 observation points by subtracting the head obtained from the adjusted parameter value model from the head obtained from the calibrated model. The RMSE of these differences was computed and tabled by rank (table 13). Although the ranks of the hydraulic parameters are not identical, the top 10 most sensitive parameters for model calibration are also the top 10 parameters for model prediction. Relative to the predictive simulation results, the model is most sensitive to the horizontal hydraulic conductivity of the Ozark aquifer in zones 1 and 6 (fig. 30), to the specific storage of the Ozark aquifer in zone 4 (fig. 30), to the recharge in zone 1 (fig. 19), and to the vertical hydraulic conductivity of zone 3 in the Ozark confining unit (fig. 29). The horizontal hydraulic conductivity of zone 6 in the Ozark aquifer (fig. 30) substantially moved up in rank relative to the calibration period sensitivity rank. This is an indication that it takes greater simulation time and more stress on the system to reveal the importance of this parameter. A possible implication of this could be that inaccuracy in these parameters could cause larger uncertainty in the simulated head distribution as the length of the predictive simulation is increased. Distribution of the simulated head change after increasing the horizontal hydraulic conductivity in the Ozark aquifer zone 1 (OZHK1, table 13; OZA1, fig. 30) computed at the end of the prediction period in 2030 is presented in figure 47. After the adjustment of the horizontal hydraulic conductivity in the Ozark aquifer zone 1, the head in layer 3 (fig. 47; LAYER 3) increased in the vicinity of pumping wells in zone 1 of the Ozark aquifer in central Greene County and decreased in the northeastern, southwestern, and south-central part of the model area. Distribution of the simulated head change computed at the end of 2030 (fig. 47) is similar to the distribution computed at the end of the calibration period in 2006 (fig. 45), however, the magnitude of the change is larger at the end of 2030.

Effects of Projected Groundwater Use

The increase in groundwater demand from future population growth and the construction and pumping of new high-capacity wells in the model area will increase the stress on the Ozark aquifer. Seven hypothetical scenarios, provided to the USGS by the Greene County Resource Management Department in consultation with area communities, were investigated using the calibrated model to assess changes in the potentiometric surface in the Ozark aquifer because of future stress increases (table 14). Each hypothetical scenario was simulated from the year 2007 to 2030.

Comparison of the low and high population growth rate in scenarios 2 with 4, 3 with 5, and 6 with 7 (table 14) indicates that there is not a large enough difference in the growth rates to cause substantial head change between the two. The largest changes occur to the potentiometric surface when new high capacity wells are added to the model (scenarios 6 and 7). The changes are large at the model cells with the new wells, but diminish relatively quickly as the distance from the well increases. Little change in drawdown was predicted in Nixa, Ozark, and Republic because of the installation of the new industrial wells (relative to scenarios 2 through 5).

Projected Groundwater Use

Projected groundwater use was estimated using a low rate and a high rate of projected population growth (Greene County Resource Management Department, written commun., 2008) for 12 communities, the unincorporated part of Greene County, and the rural domestic users (table 15). The percentages shown in table 15 were applied directly to the 2006 pumpage rates reported for each community or group for the appropriate scenario in table 14. For both low and high growth scenarios, each of the 12 communities and the unincorporated part of Greene County had a different rate of growth. The same rate of growth was used for the unincorporated part of Greene County and the rural domestic users. Future population growth for all communities and the unincorporated part of Greene County, except Battlefield, was based on linear growth rates established between the years 2000 and 2007 (Greene County Resource Management Department, written commun., 2008). Future population growth for the community of Battlefield was based on linear growth rates of population between 1980

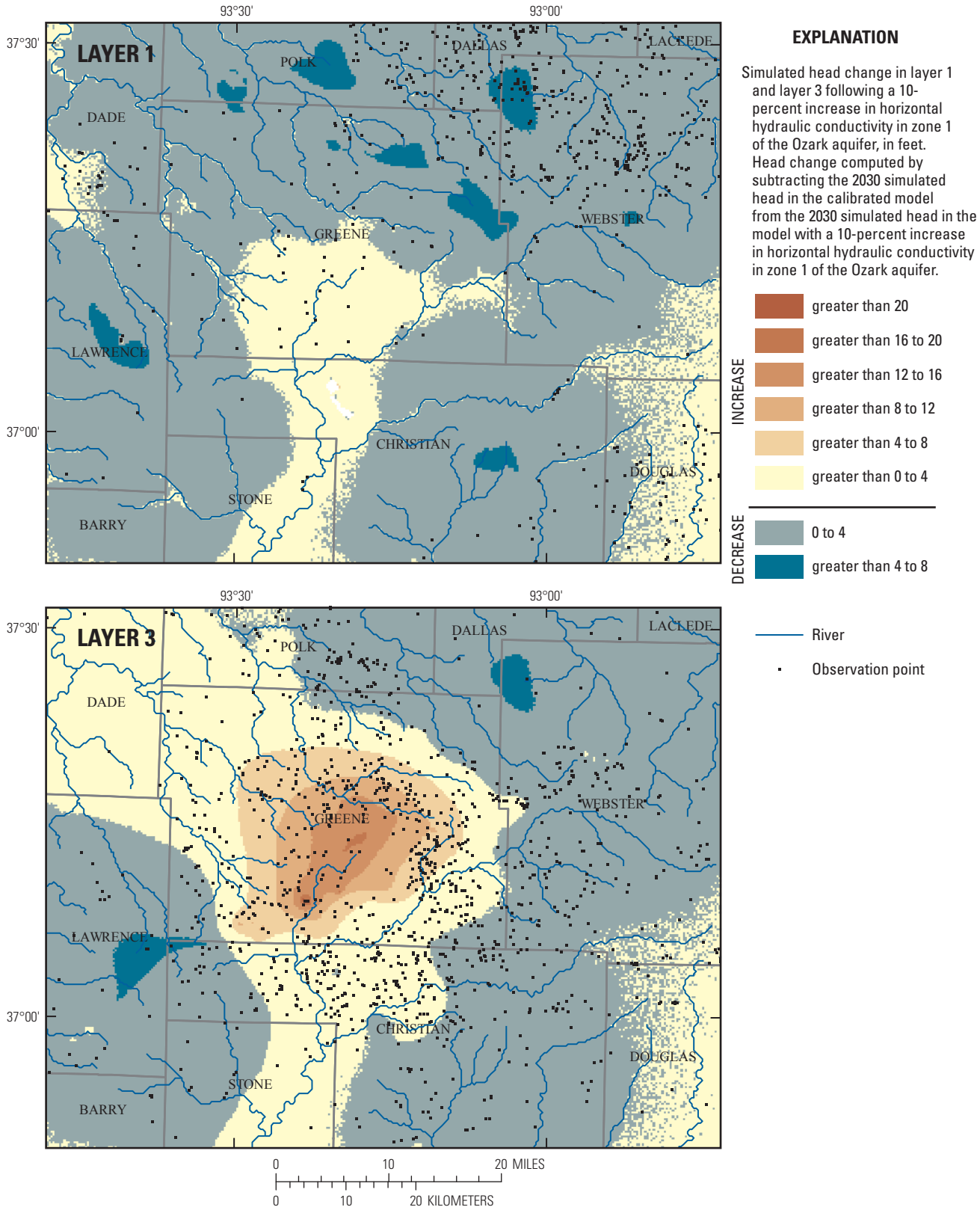


Figure 47. Simulated head change in layer 1 and layer 3 following a 10-percent increase in horizontal hydraulic conductivity in zone 1 of the Ozark aquifer (OZHK1, table 13; OZA1, fig. 30) computed at the end of the prediction period in 2030 for scenario 7.

Table 14. Hypothetical pumping scenarios 2007 to 2030.

[ft/d, foot per day; ft^3/d, cubic foot per day; ft, foot]

Hypothetical scenario number	Predictive simulation period 2007 to 2030: Future scenario conditions	Predictive simulation period 2007 to 2030: Recharge rate (ft/d)	Pumping Rate in 2030 (ft^3/d)	Maximum head decline at Springfield (ft)	Head decline in Nixa, Ozark, and Republic, area (ft)	Summary of results
1	Water use fixed at 2006 rate	2.59×10^{-4}	4,330,177	61.5	15 to 45	Continued decline in the Springfield, Nixa, Ozark, and Republic area
2	Low growth rate; Drought 2010 to 2013	2.59×10^{-4} (1.45×10^{-4} drought conditions)	7,109,711	203.4	greater than 100	Continued decline in the Springfield, Nixa, Ozark, and Republic area
3	Low growth rate; Drought 2027 to 2030	2.59×10^{-4} (1.45×10^{-4} drought conditions)	7,109,711	203.9	greater than 100	Simulated head lower than scenario 2 where Ozark aquifer is exposed; similar to scenario 2 elsewhere
4	High growth rate; Drought 2010 to 2013	2.59×10^{-4} (1.45×10^{-4} drought conditions)	7,220,436	206.9	greater than 100	Simulated head lower than scenario 2 in the vicinity of the cities of Springfield, Nixa, Ozark, and Republic; similar to scenario 2 elsewhere
5	High growth rate; Drought 2027 to 2030	2.59×10^{-4} (1.45×10^{-4} drought conditions)	7,220,436	207.3	greater than 100	Simulated head lower than scenario 4 where Ozark aquifer is exposed; similar to scenario 4 elsewhere
6	Low growth rate; New industrial wells	2.59×10^{-4}	7,500,601	641.0	greater than 100	Simulated head similar to scenarios 2 through 5 in the vicinity of the cities of Republic, Ozark, and Nixa; simulated head lower near the new industrial wells; potentiometric surface 10 to 40 ft lower in Rogersville and Fordland than scenarios 2 through 5; simulated head higher where Ozark aquifer is exposed relative to simulated head in scenario 3 and scenario 5
7	High growth rate; New industrial wells	2.59×10^{-4}	7,582,583	648.2	greater than 100	Similar results to scenario 6, but greater decline at the new industrial wells

Table 15. Projected population growth per year (in percent of 2006 population) and number of wells in 2006 per percentage range of total operating capacity.

[—, no data]

Community or group	Growth rate (in percent of 2006 population)[1]		Total percent growth from 2006 to 2030		Number of wells in 2006 per percentage range of total operating capacity			
	Low	High	Low	High	0-25	25-50	50-75	75-100
Ash Grove	1.089	1.124	26.1	27.0	—	—	—	—
Battlefield	2.300	2.919	55.2	70.1	—	—	—	—
Fair Grove	2.776	2.875	66.6	69.0	—	—	—	—
Greene County (Unincorporated)	2.531	2.578	60.7	61.9	—	—	—	—
Marshfield	2.752	2.782	66.1	66.8	0	3	0	0
Nixa	4.995	5.140	119.9	123.3	7	0	0	0
Ozark	6.251	6.317	150.0	151.6	12	1	0	0
Republic	4.891	5.017	117.4	120.4	1	2	0	1
Rogersville	6.997	7.345	167.9	176.3	—	—	—	—
Springfield	.215	.236	5.2	5.7	2	4	1	0
Strafford	1.823	1.945	43.8	46.7	1	2	0	0
Walnut Grove	.765	.848	18.4	20.4	—	—	—	—
Willard	.804	.862	19.3	20.7	0	0	2	2
Rural domestic use	2.531	2.578	60.7	61.9	—	—	—	—

[1] Source: Greene County Resource Management Department, written commun., 2008

and 2007 (Greene County Resource Management Department, written commun., 2008). A graph showing the population projections using the high population growth rate for 11 communities is shown in figure 48. Population for Springfield and the unincorporated part of Greene County were omitted for clarity from figure 48. The slope of the lines on figure 48 indicates the rate of population growth per year for each community. Future pumpage rates data were computed annually from 2007 to 2030 based on the growth rate and the 2006 reported pumpage rates for each well. Low growth rates ranged from 0.215 percent per year in Springfield to 6.997 percent per year in Rogersville, and total growth from 2006 to 2030 at the low growth rate ranged from 5.2 percent in Springfield to 167.9 percent in Rogersville (table 15). High growth rates ranged from 0.236 percent per year in Springfield to 7.345 percent per year in Rogersville, and total growth from 2006 to 2030 at the high growth rate ranged from 5.7 percent in Springfield to 176.3 percent in Rogersville (table 15).

Because pumpage rates for wells can increase dramatically in future projections, future pumpage rates for wells may exceed the actual capacity of an individual well. This is not a realistic situation because water managers could install new wells or redistribute pumping within their water system. The problem of future pumpage rates exceeding the capacity of the well becomes more likely the further into the future the estimates are made. In an effort to make the pumpage rates more realistic for individual wells and water systems, major groundwater users in the model area were asked to provide an estimate of what percent of the total capacity of each well in their system was being used in 2006. The communities of Marshfield, Nixa, Ozark, Republic, Springfield, Strafford, and Willard, reported this information for the wells in their water systems (table 15). The groundwater use in these communities' 41 wells represents approximately 40 percent of the groundwater use in the model area in 2006. In addition, major groundwater users in the model area were asked to provide information about when existing wells were likely to be removed from service and when and where new wells were planned to be drilled and operated (fig. 25). The communities of Nixa, Ozark, Republic, and Springfield reported plans to decommission old wells, install new wells, or both. When building the future groundwater-use data set, the computed future pumpage rate, for wells that had current (2006) capacity data reported, was compared to the reported capacity. If the computed future pumpage rate exceeded the reported capacity of the well, the excess was redistributed to other wells in the community's system including new wells when they became available.

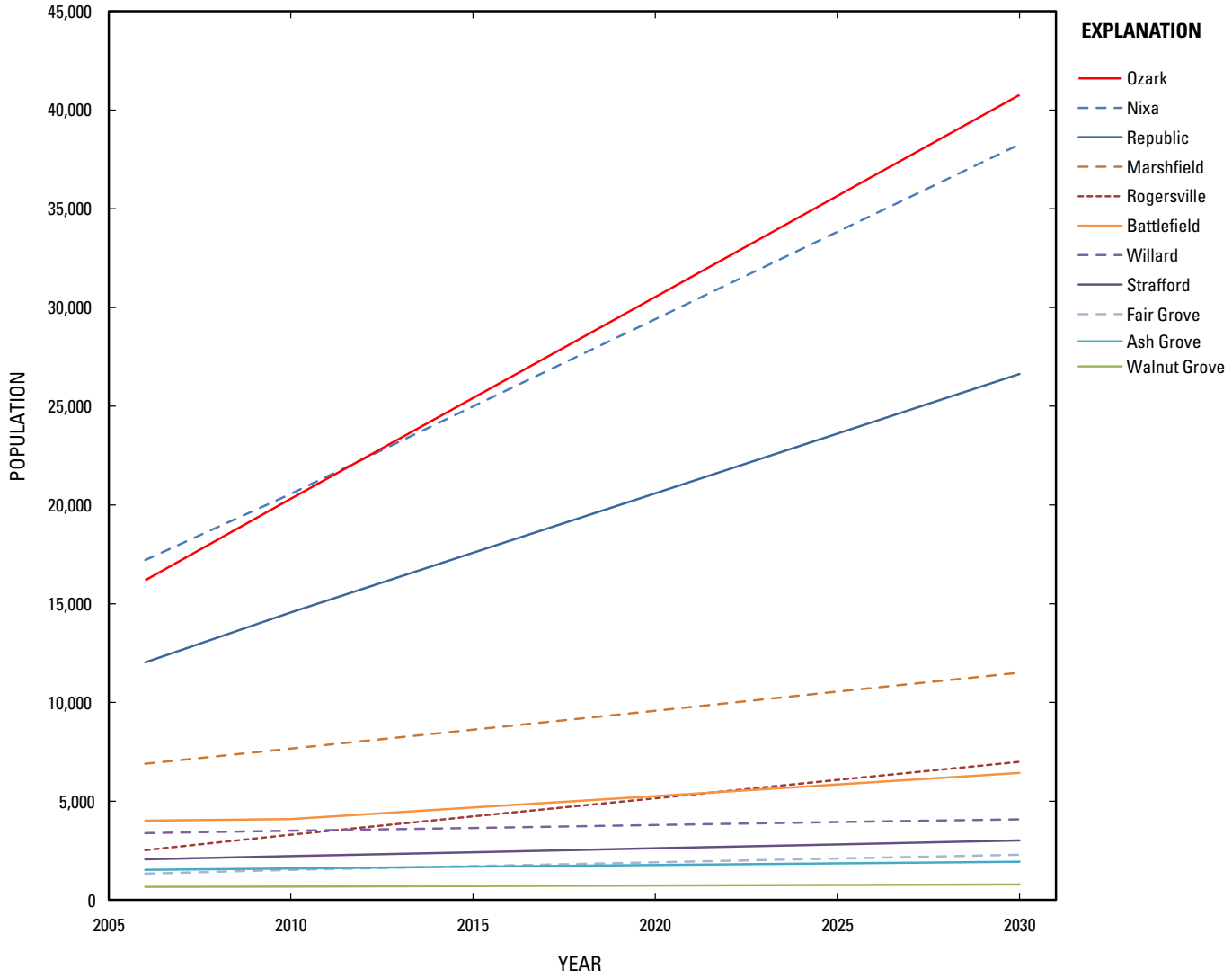


Figure 48. Estimated high growth population change from 2006 to 2030 for selected communities in the model area (Greene County Resource Management Department, written commun., 2008).

For each well in a community's water system, Ozark for example, groundwater use in excess of the reported capacity of an individual well was added to the well in the system with the lowest pumpage rate. The wells in the system were then reevaluated to determine if any wells exceeded the reported capacity, and the process was repeated. If it was determined that all wells in the system were at or exceeded their reported capacity, then no further redistribution was performed and future pumpage rate in the wells was allowed to increase at the specified rate beyond the reported capacity. Future groundwater use in wells that had no reported capacity was allowed to increase at the specified rate. In the future pumpage rate computations, wells that were specified by major groundwater users to be decommissioned were turned off, and those specified to be installed were turned on in the specified year. For the seven communities that reported well capacity information, future groundwater use in 2030 did not exceed the system capacity in any of the communities; however, 10 of the 41 wells belonging to those communities were computed to be at their reported capacity in 2030.

Continued Pumpage at the 2006 Rate

To provide a frame of reference for change because of drought, population growth, and installation of new industrial wells, hypothetical scenario 1 was developed to show the effects of continued pumpage at the 2006 rate. Beginning in 2009, precipitation was assumed to be constant at a rate equal to the 1971–2000 mean of 44.97 in/yr (recharge = 2.59×10^{-4} ft/d), and pumping was

held at a constant equal to the 2006 rate. Figure 49 shows the resulting head distribution at the end of the simulation in 2030 for hypothetical scenario 1. The simulation indicates that the potentiometric surface in the Springfield area continues to decline (fig. 49) with a maximum drawdown obtained from the model of 61.5 ft relative to the 2006 level occurring at major pumping centers. Drawdown in the Nixa, Ozark, and Republic areas could range from 15 to 45 ft if pumping were continued at 2006 rates.

Drought Effects and Low Population Growth

To simulate the effects that low population growth and drought conditions could have on the future head distribution in the Ozark aquifer, hypothetical scenario 2 was developed. The mean value of recharge (table 5; precipitation = 44.97 in/yr; recharge = 2.59×10^{-4} ft/d) was used for 2009. The drought conditions (table 5; precipitation = 25.21 in/yr; recharge = 1.45×10^{-4} ft/d) were simulated at the beginning of the future simulation period for a 4-year period beginning in 2010 and continuing through 2013. Beginning in 2014 and continuing through the end of the simulation, the mean value of recharge was used. Groundwater-use increases during the drought period do not account for extra increases in groundwater use, such as lawn watering, as a result of the drought. Figure 50 shows the resulting head distribution at the end of the simulation in 2030 for hypothetical scenario 2. Population growth increases groundwater demand and causes larger potentiometric-surface declines around the major pumping centers in the model area. Maximum declines continue to be in the Springfield area (203.4 ft obtained from the model); however, maximum groundwater declines in Nixa, Ozark, and Republic, relative to the 2006 levels, are greater than 100 ft (fig. 50).

Hypothetical scenario 3 investigates the effects of a 4-year drought at the end of the simulation in combination with a low population growth rate. The drought conditions (table 5; precipitation = 25.21 in/yr; recharge = 1.45×10^{-4} ft/d) were simulated at the end of the future simulation period for a 4-year period beginning in 2027 and continuing through 2030. Groundwater-use increases during the drought period do not account for extra increases in groundwater use, such as lawn watering, as a result of the drought. Beginning in 2009 and continuing through 2026, the mean value of recharge was used. Figure 51 shows the resulting head distribution at the end of the simulation in 2030 for hypothetical scenario 3. The head distribution in the Ozark aquifer of hypothetical scenario 3 is similar to the head distribution for hypothetical scenario 2 in the vicinity of the cities of Nixa, Ozark, Republic, and Springfield, and the maximum drawdown of 203.9 ft obtained from the model, which occurred in Springfield was nearly identical. Simulated head is higher in the northeastern and southeastern part of the model area in scenario 2 than in scenario 3 where the Ozark aquifer is exposed.

Drought Effects and High Population Growth

Hypothetical scenarios 4 and 5 were developed to examine the effects of high population growth rates combined with drought conditions at the beginning (scenario 4) and end (scenario 5) of the simulation period. Scenario 4 (fig. 52) was similar to scenario 2 with the mean value of recharge (2.59×10^{-4} ft/d) used for 2009, drought conditions (1.45×10^{-4} ft/d) between 2010 and 2013, and mean recharge from 2014 to 2030. Groundwater-use increases during the drought period do not account for extra increases in groundwater use, such as lawn watering, as a result of the drought. Scenario 5 (fig. 53) was similar to scenario 3 with the mean value of recharge used between 2009 and 2026 and drought conditions from 2027 to 2030. Maximum declines obtained from the model in scenario 4 (206.9 ft) and 5 (207.3 ft) occur in the Springfield area; however, maximum groundwater declines in Nixa, Ozark, and Republic, relative to the 2006 levels, are greater than 100 ft (figs. 52 and 53). Similar to scenarios 2 and 3, the drought conditions at the end of the simulation period for scenario 5 caused the potentiometric surface to be lower than the potentiometric surface in scenario 4 where the Ozark aquifer is exposed (figs. 52 and 53).

Simulated head is lower and drawdown areas are expanded somewhat under the high population growth rate scenarios (4 and 5) when compared to the low population growth rate scenarios (2 and 3) under both drought simulation conditions. Both high growth rate scenarios (4 and 5) have lower potentiometric surfaces than either low growth rate scenario (2 and 3) in the vicinity of the cities of Nixa, Ozark, Republic, and Springfield.

Low and High Population Growth with New Industrial Wells

Scenarios 6 and 7 were developed to investigate the effect that proposed new industrial wells could have on the potentiometric surface in the Ozark aquifer. Two industrial wells pumping continuously from 2010 through 2030 were added to the simulation. The pumping rate from the two wells began at approximately 173,262 ft^3/d (approximately 900 gal/min) and was increased at the same rate as the Greene County unincorporated wells for the low and high population growth-rate scenarios. In 2030 the two wells were pumping 252,460 ft^3/d (approximately 1,311 gal/min) under the low growth rate conditions (scenario 6) and 254,820 ft^3/d (approximately 1,324 gal/min) under the high growth rate conditions (scenario 7). The locations of these wells (fig. 25) were provided to the USGS by Greene County Resource Management Department (written commun., 2008). One well was located in the downtown area of Springfield and the second was located approximately 3.5 miles east of

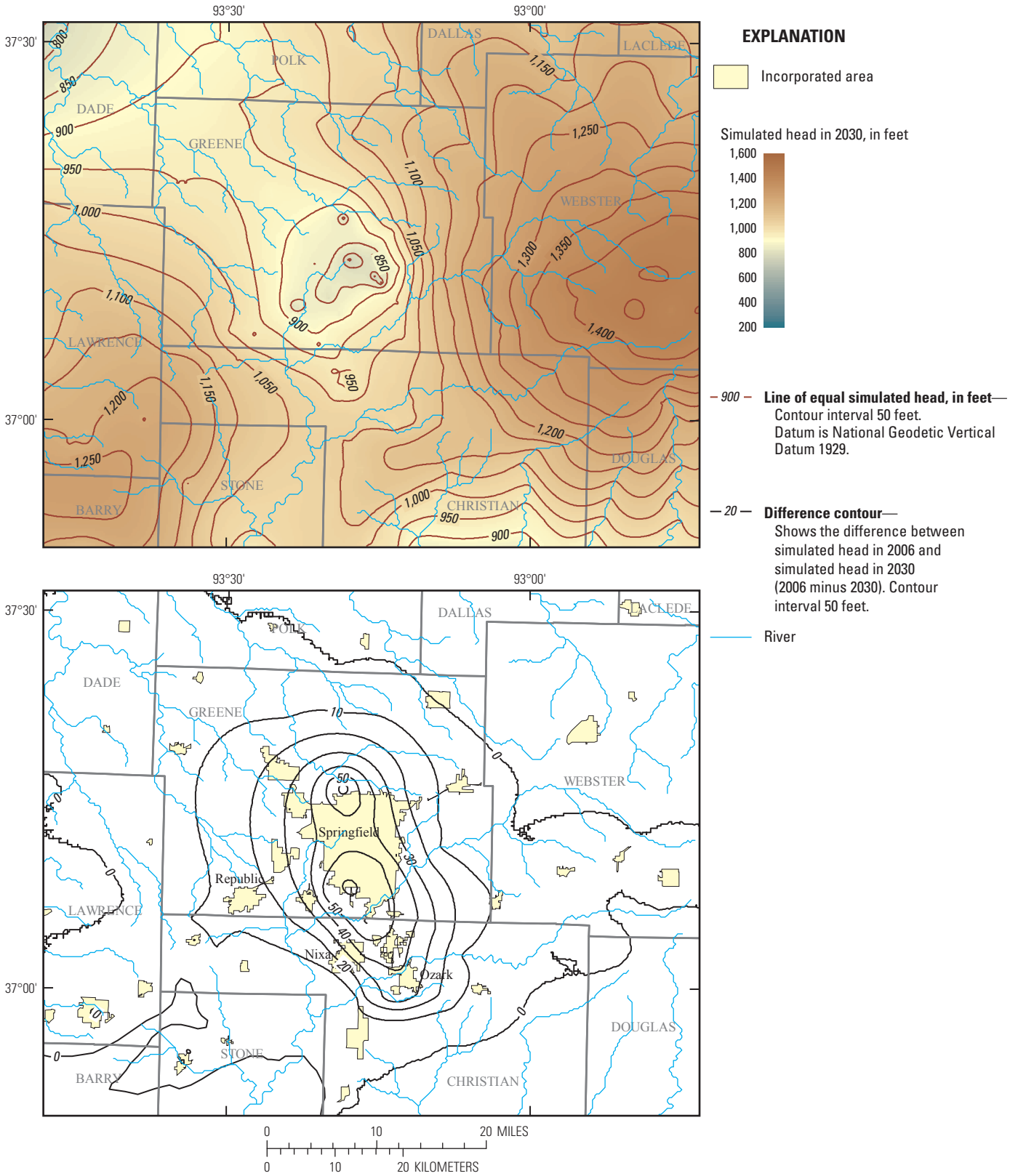


Figure 49. Simulated head at the end of 2030 in layer 3 and difference in simulated head between 2006 and 2030 (2006 minus 2030) for hypothetical scenario 1—groundwater use fixed at 2006 rate.

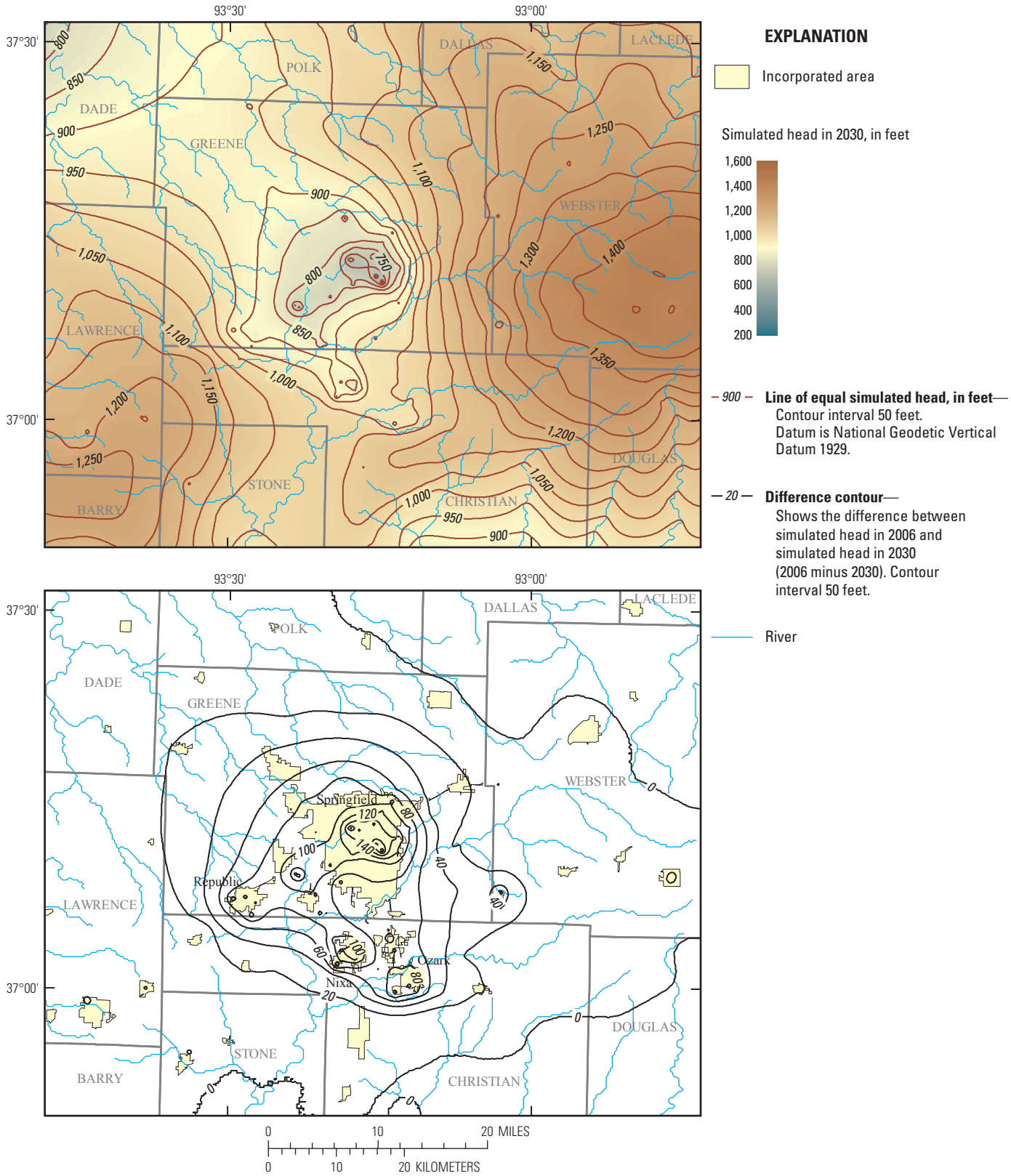


Figure 50. Simulated head at the end of 2030 in layer 3 and difference in simulated head between 2006 and 2030 (2006 minus 2030) for hypothetical scenario 2—low groundwater-use growth rate and 4-year drought from 2010 to 2013.

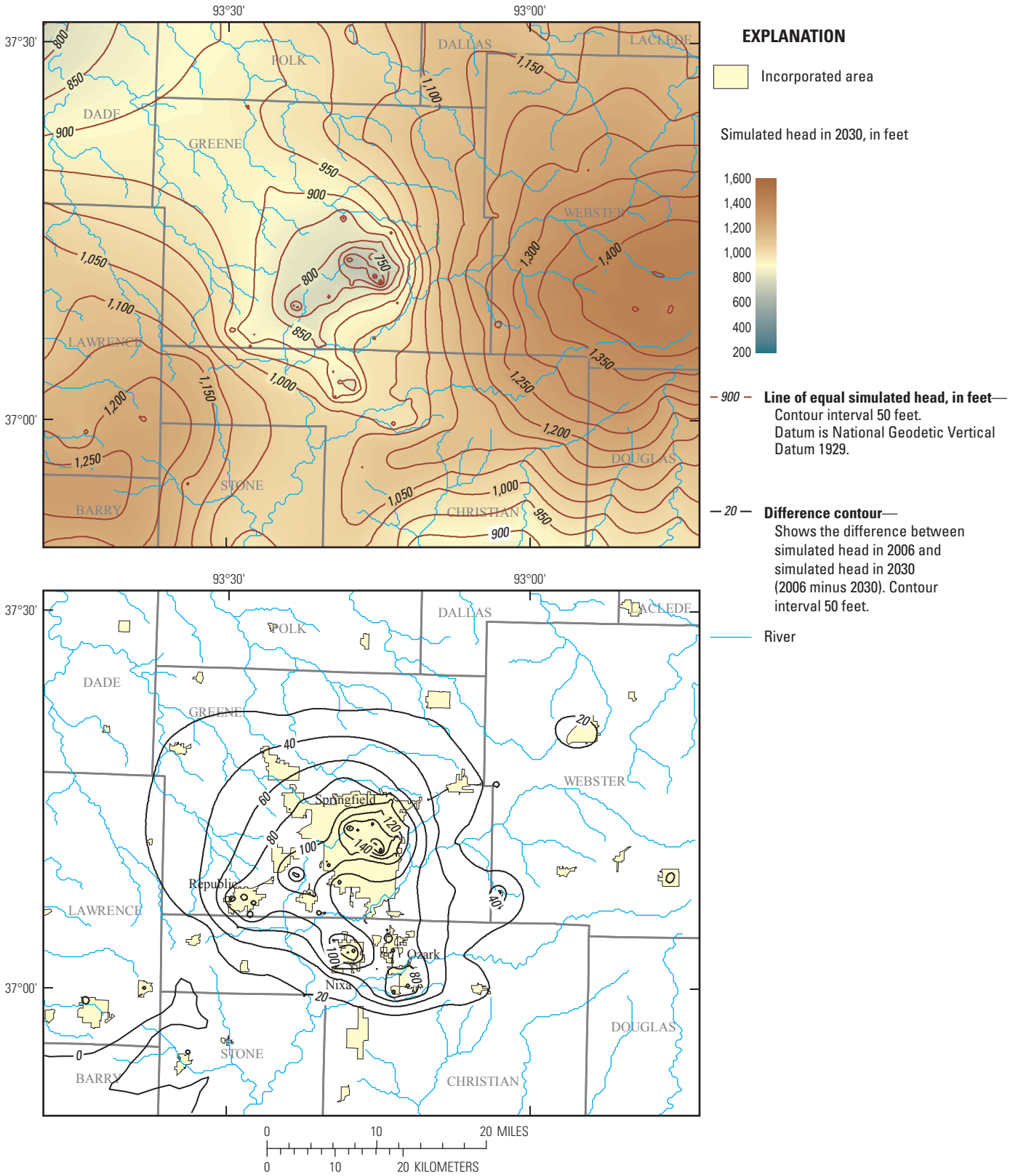


Figure 51. Simulated head at the end of 2030 in layer 3 and difference in simulated head between 2006 and 2030 (2006 minus 2030) for hypothetical scenario 3—low groundwater-use growth rate and 4-year drought from 2027 to 2030.

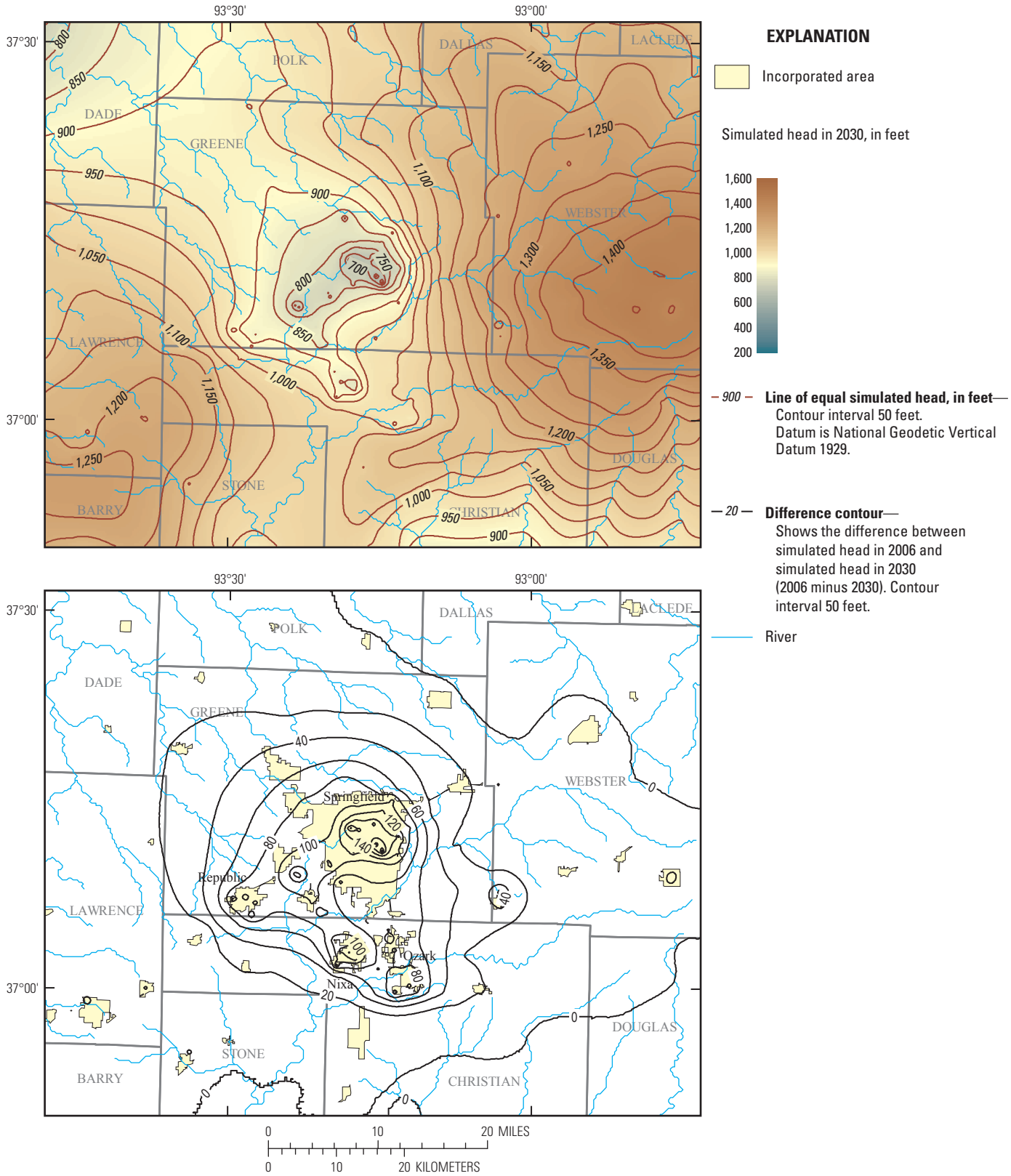


Figure 52. Simulated head at the end of 2030 in layer 3 and difference in simulated head between 2006 and 2030 (2006 minus 2030) for hypothetical scenario 4—high groundwater-use growth rate and 4-year drought from 2010 to 2013.

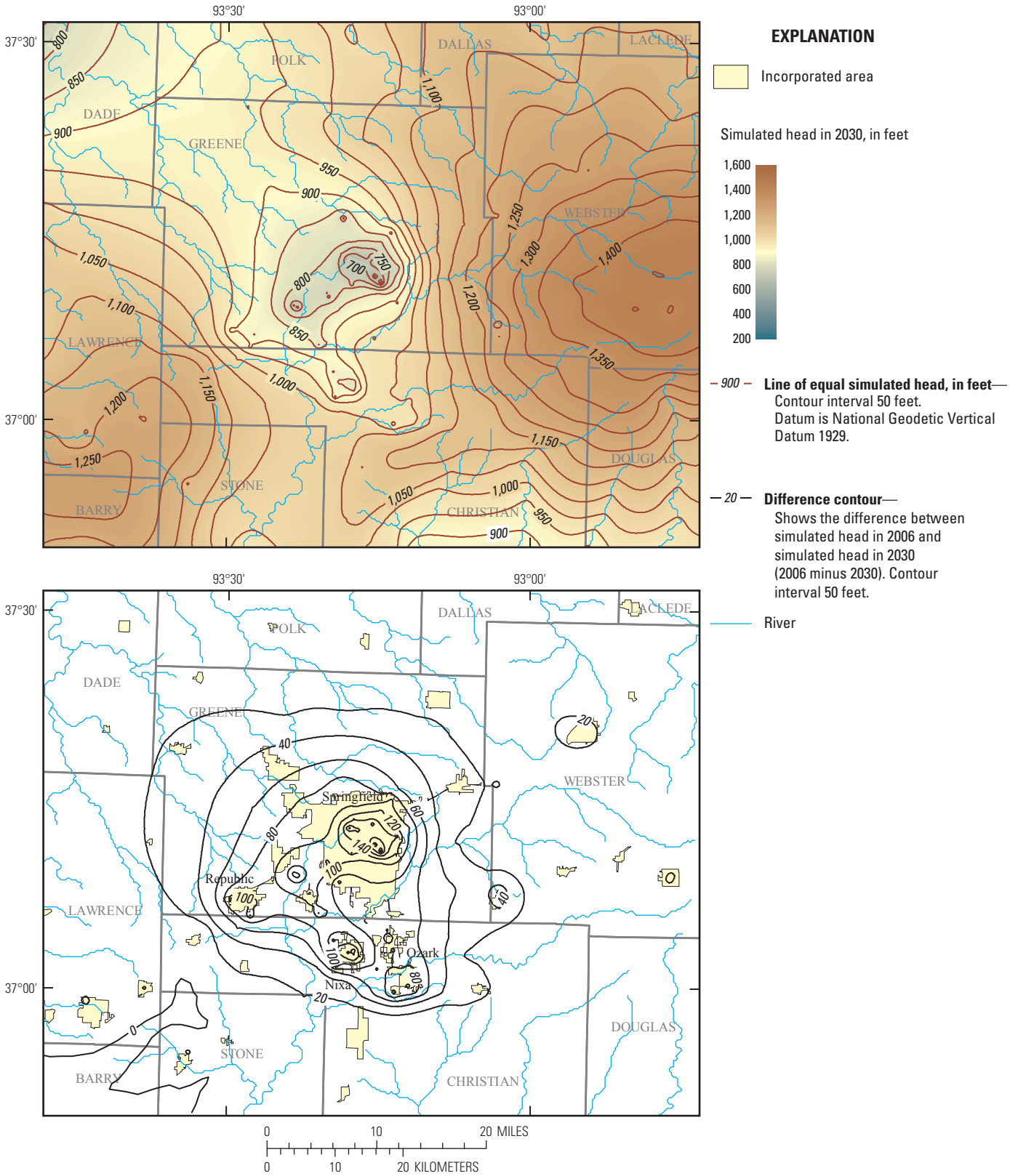


Figure 53. Simulated head at the end of 2030 in layer 3 and difference in simulated head between 2006 and 2030 (2006 minus 2030) for hypothetical scenario 5—high groundwater-use growth rate and 4-year drought from 2027 to 2030.

Rogersville (fig. 2). Mean recharge (2.59×10^{-4} ft/d) was used for scenarios 6 and 7 between 2009 and 2030.

The lowest simulated head in scenario 6 (fig. 54) occurred at the new industrial well located in Springfield and the head was less than 200 ft (examination of the model cell containing the well determined the head to be approximately 189 ft). The approximate altitude of the bottom of the Ozark aquifer at that location is at -280 ft below NGVD 29 and the total thickness of the aquifer is approximately 1,300 ft. There is approximately 469 ft of saturated Ozark aquifer at the location of the new industrial well located in Springfield at the end of 2030. Both new industrial wells produce a relatively steep cone of depression. The maximum drawdown in scenario 6 relative to the 2006 levels also occurred at the new industrial well located in Springfield and was 641.0 ft lower than the 2006 level. There is a small, 5 ft, potentiometric surface increase, relative to 2006 levels in the northeastern and southeastern part of the model area. This is most likely because the aquifer is recovering from the relatively low precipitation that occurred in 2005 and 2006.

Simulated head for scenario 7 (fig. 55) was very similar to scenario 6 with a minimum altitude below 250 ft occurring at the new industrial well located in Springfield. Examination of the model output at the cell containing the well revealed the head to be approximately 182 ft. The maximum drawdown in scenario 7, relative to 2006 levels, also occurred at the new industrial well located in Springfield and was 648.2 ft lower than the 2006 level. The potentiometric surface in scenario 7 increases similarly in both magnitude and location as scenario 6.

Scenarios 6 and 7 with new industrial wells produce a relatively steep cone of depression around the new wells. The difference between scenario 3 and scenario 6 is shown in figure 56. The potentiometric surface is higher in scenario 6 when compared to scenario 3 where the Ozark aquifer is exposed, most likely because of the drought conditions simulated in scenario 3. It is also evident that the majority of the change between the two scenarios occurs at the new industrial wells. Simulated head differences between scenario 3 and scenario 6 that are greater than 50 ft are confined to the areas within approximately 2.5 miles of the new wells. The potentiometric surface is from 10 to 40 ft lower in Rogersville and Fordland in scenario 6 relative to scenario 3 because of drawdown associated with one of the new industrial wells. Under scenario 6 the cities of Nixa, Ozark, and Republic will experience little additional drawdown when compared to scenario 3 drawdown.

Model Limitations

By definition, a model is a simplification of reality, and therefore, a groundwater model approximates actual conditions. The flow system is greatly simplified, and the accuracy of the model results depends on the accuracy and completeness of the input data. The following limitations need to be considered when interpreting the model results presented in this report. The MODFLOW software simulates groundwater flow as porous media flow; however, karst features present in the model area as well as the lithology of the aquifer material indicate flow to be, at least partially, conduit flow along bedding planes, joints, and fractures. Lack of data on base flow to rivers and springs and few hydraulic property tests of the hydrogeologic units in the model area result in poorly constrained values of hydraulic conductivity, specific storage, and specific yield. Well pumping rates used in the model were annual total values and were applied uniformly throughout the stress period (year), however, pumping rates are not uniform and this could add uncertainty to the results. Recharge was applied uniformly throughout a stress period (year) and distributed over the model area based on land slope; however, recharge is not uniform either temporally or spatially. The relation between precipitation and recharge is not likely to be linear as it was assumed in this model. Model cells were 1,000 ft by 1,000 ft so land-surface altitudes and altitudes of rivers had to be averaged over a model cell, which is less exact in areas with larger relief. When water discharges to a spring, the groundwater model removes that discharge and it cannot reenter the system. Position of springs and pumping wells could not be precisely located because of the cell size. Because of the cell size, the model is of limited use for detailed groundwater-flow analysis near a single well. Discretization of the hydrogeologic units in the model combined several units into layers 1 and 2. This caused difficulty interpreting the head in layers 1 and 2, particularly in model cells that combined hydrogeologic units. General-head boundaries, rivers, and drains (springs) require the assumption that the specified head does not vary during the entire simulation, and that the conductance value governing the interaction of the groundwater with the boundary is known. Neither assumption is likely to be true. Little is known about the hydraulic properties of the St. Francois confining unit and the head distribution in the underlying St. Francois aquifer, and as a result, assumptions of these values are likely to be in error.

Many faults are evident at the land surface in the model area and likely continue through the confining unit, but it is unknown whether the faults are flow conduits or barriers. The assumption of homogeneity of hydraulic properties in cells and zones can cause inaccuracies. Pumpage from the Springfield Plateau aquifer (although likely small) was ignored in the model. Drawdown in the Ozark aquifer near Springfield has caused the aquifer to be unconfined in that area. Numerical instability in the model necessitated modeling layer 2 and layer 3 as confined, which could cause future potentiometric-surface predictions to be in error in this area. The potentiometric-surface predictions are likely too high where the Ozark aquifer is unconfined or becomes unconfined as the simulation progresses. Predictive simulations are based on a predefined set of conditions that are merely estimates of what is expected to happen in the future. There is great

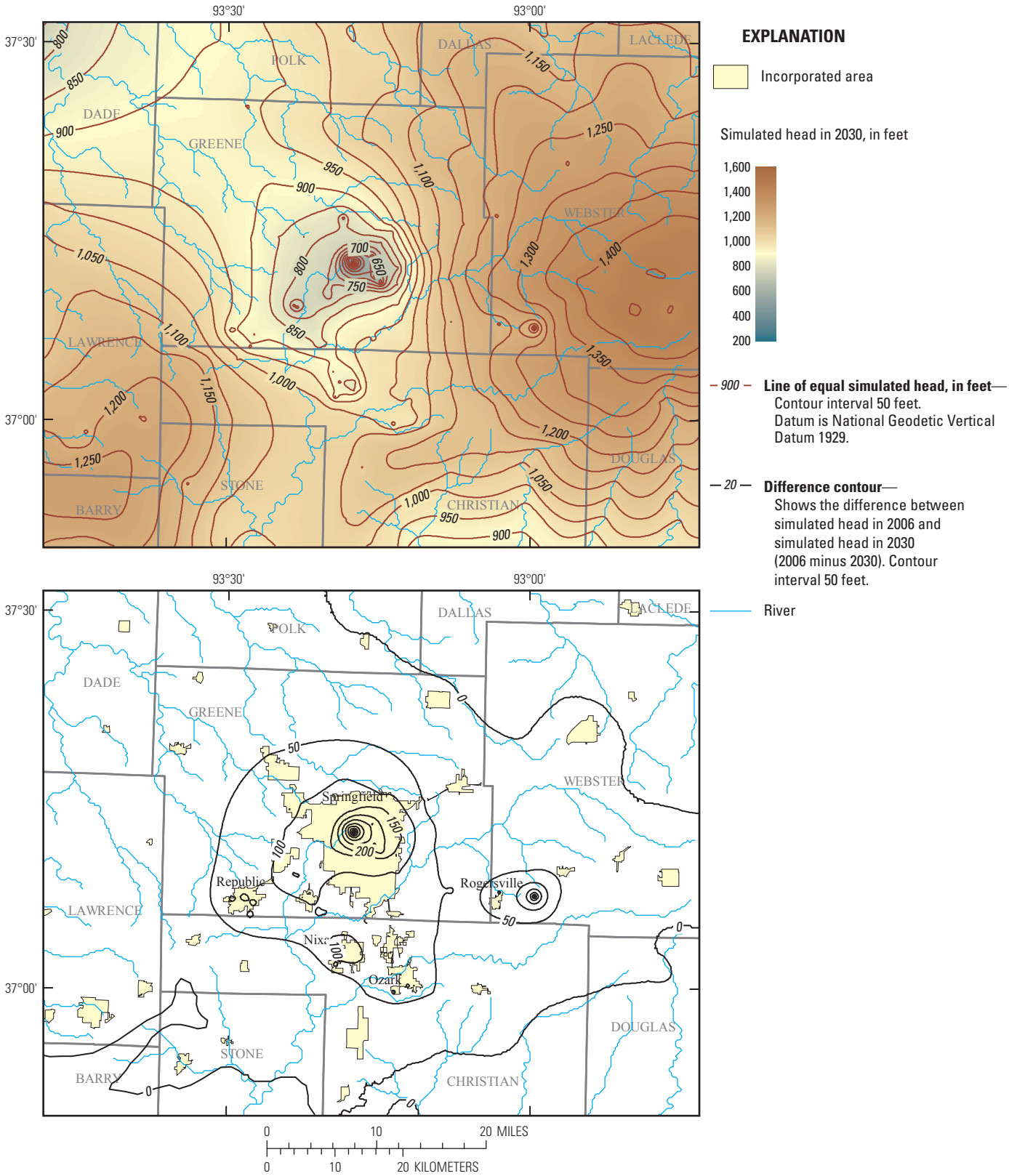


Figure 54. Simulated head at the end of 2030 in layer 3 and difference in simulated head between 2006 and 2030 (2006 minus 2030) for hypothetical scenario 6—low groundwater-use growth rate and two new industrial wells.

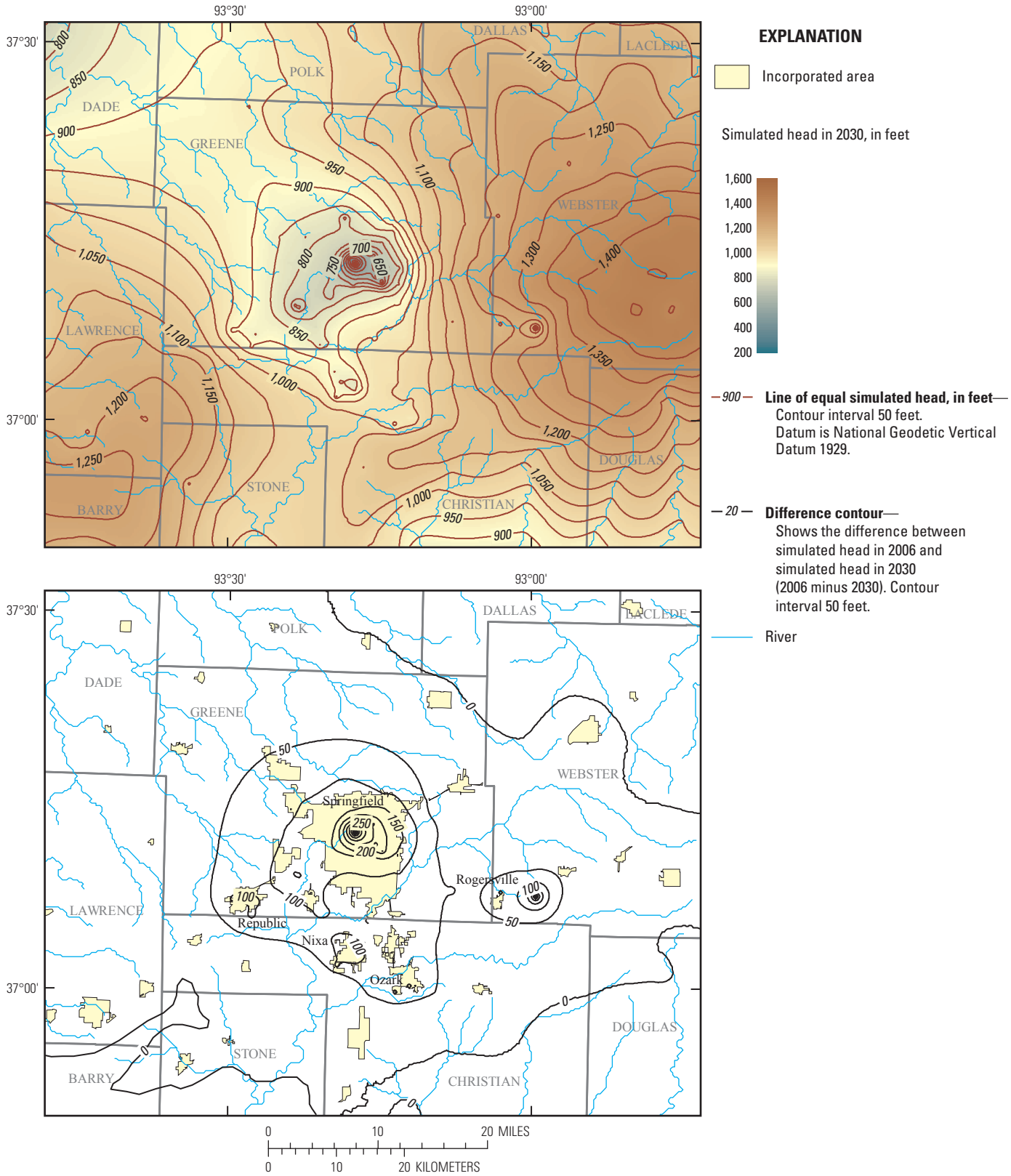
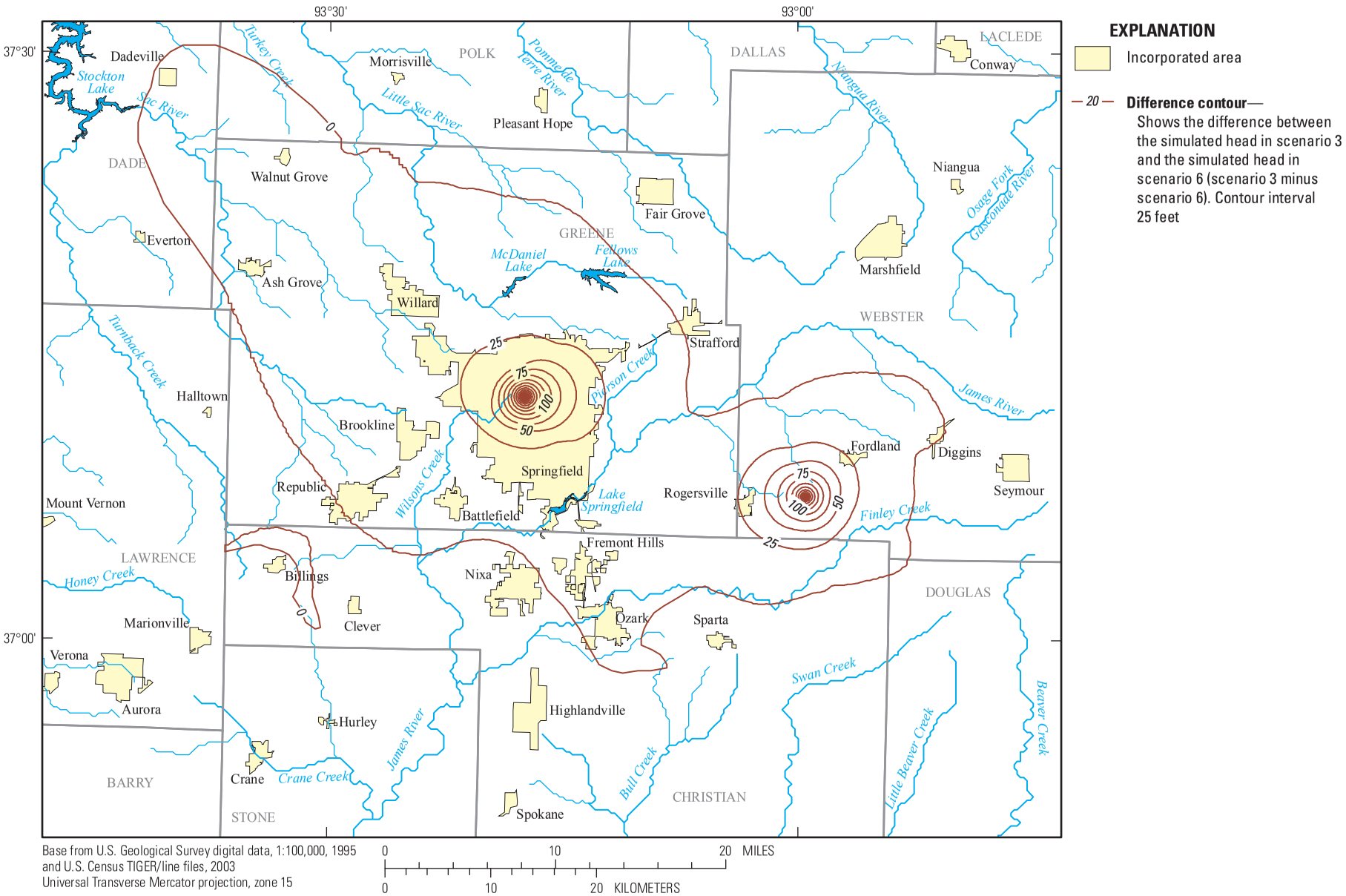


Figure 55. Simulated head at the end of 2030 in layer 3 and difference in simulated head between 2006 and 2030 (2006 minus 2030) for hypothetical scenario 7—high groundwater-use growth rate and two new industrial wells.



Base from U.S. Geological Survey digital data, 1:100,000, 1995 and U.S. Census TIGER/line files, 2003
Universal Transverse Mercator projection, zone 15

0 10 20 MILES

0 10 20 KILOMETERS

Figure 56. Difference in simulated head in 2030 between scenario 3 and scenario 6.

uncertainty in these estimates, and as a result, the predictions from the model also have great uncertainty. The best use of the predictions is for comparison between future conditions.

Summary and Conclusions

Groundwater use from the Ozark aquifer in and around Greene County, Missouri, has increased since it was first used as a drinking-water source as early as 1907. Historical groundwater pumping from the Ozark aquifer caused a cone of depression to form beneath Springfield. Periods of rapid growth in the 1970s and 1980s coupled with a growing cone of depression led water managers in Springfield to seek an alternate source of water to meet their future needs. The demand for groundwater in the area was reduced when Springfield completed a pipeline in 1996 to bring water from Stockton Lake to the city. Even though Springfield reduced its dependence on groundwater, all other residential, commercial, industrial, and municipal users in the region rely exclusively on groundwater to meet their water needs. Groundwater-level measurements made in 2006–07 indicated that the cone of depression beneath Springfield has continued to expand and deepen. A groundwater-flow model was developed by the U.S. Geological survey (USGS) in cooperation with Greene County, Missouri, the U.S. Army Corps of Engineers, and the Missouri Department of Natural Resources to assess the effect that increased groundwater demand is having on the long-term availability of groundwater in Greene County, Missouri, and the surrounding area. The purpose of this report is to document the groundwater-flow model that characterizes groundwater flow within a part of the Ozark Plateaus aquifer system in the vicinity of Greene County, Missouri.

The three hydrogeologic units that were represented in the model were, from top to bottom, the Springfield Plateau aquifer, the Ozark confining unit, and the Ozark aquifer. The Springfield Plateau aquifer is composed of coarse crystalline, cherty limestone, and wells in the aquifer yield only sufficient amounts of water for domestic and stock use. The Ozark confining unit is composed of fine-grained limestone, siltstone, and shale and confines the underlying Ozark aquifer. The Ozark aquifer is composed of dolomite and sandstone, and is the primary aquifer for most of southern Missouri. Wells open to the entire Ozark aquifer typically yield 1,000 gallons per minute, which makes this aquifer suitable for industrial and municipal needs. The Springfield Plateau aquifer is exposed at the surface over much of the model area. The Ozark confining unit is exposed in narrow bands between outcrops of the Springfield Plateau aquifer and the Ozark aquifer. The Ozark aquifer is exposed at the surface in the northeastern and southeastern parts of the model area and along some river valleys. Karst features such as sinkholes, springs, caves, and losing streams are present in both aquifers, but the majority of these features occur in the Springfield Plateau aquifer.

A part of the precipitation that falls on the exposed aquifers in the study area recharges the groundwater by infiltration. Groundwater generally flows from the recharge areas of the aquifers in the uplands where they are exposed to the discharge areas along rivers and springs. Groundwater may be captured along its flow path by pumping wells, and groundwater flow occurs laterally both into and out of the study area. The gradient is generally downward from the Springfield Plateau aquifer through the confining unit and into the Ozark aquifer. Groundwater can flow vertically through the bottom of the Ozark aquifer. Karst flow, particularly in the Springfield Plateau aquifer, can move large quantities of water through the system in a relatively short time. Rivers in the area include gaining and losing reaches.

Tops and bottoms of the hydrogeologic units were mapped and discretized into the model grid. The model was divided into three layers with the layer boundaries crossing hydrogeologic unit boundaries in some areas. The area was divided into a regularly spaced grid of 253 rows and 316 columns with 1,000 feet by 1,000 feet cells. Composite hydraulic properties for the model were computed from the hydraulic properties of the individual hydrogeologic units for each cell containing multiple hydrogeologic units. A groundwater model with annual stress periods was developed using a transient calibration period from 1987 to 2006 and a prediction period from 2007 to 2030.

Recharge in the model was estimated independently using water-level data from a long-term monitoring well using the water-table fluctuations method. Rivers and springs were used as boundary conditions in the model. Rivers acted as both recharge and discharge points for the groundwater, whereas the springs served to locally constrain head in layer 1 of the model. Groundwater flow laterally through the model boundaries, leakage through the bottom of the Ozark aquifer, and flow into and out of lakes was simulated with general-head boundaries in the model.

Annual precipitation data were compiled for the model area for use in estimating the model recharge and ranged from 25.21 inches in 1953 to 62.45 inches in 1927. Areal recharge was calculated as approximately 2.53 percent of the annual precipitation and distributed based on land slope and adjusted in the Springfield area based on impervious surface. The mean annual precipitation for the period 1971–2000 was 44.97 inches in the model area, which calculates to 2.59×10^{-4} feet per day of recharge in the model. Annual pumpage data were estimated prior to 1962 and from 1962 to 2006, were collected from multiple sources including: USGS, Missouri Department of Natural Resources major water user database, Missouri Department of Natural Resources public water-supply database, Greene County, and reported use from groundwater users. Pumpage rates in the model area increased from 1,093,268 cubic feet per day in 1962 to 2,693,423 cubic feet per day in 1987 to 4,330,177 cubic feet per day in 2006.

There were relatively few measured hydraulic property values available in the model area. One aquifer test north of Springfield in the Ozark aquifer calculated the mean horizontal

hydraulic conductivity to be 2.11 feet per day and the storage coefficient to be $1.6x10^{-4}$. Horizontal hydraulic conductivity values at selected wells were computed from specific capacity data and ranged from 0.20 to 8.73 feet per day in the Ozark aquifer. Hydraulic properties were estimated from these data, from values used in other groundwater models, and published values for aquifer materials. Estimated values were adjusted throughout the calibration process to minimize the difference between simulated head and observed water levels. In the calibrated model, horizontal hydraulic conductivity for the Springfield Plateau aquifer ranged from 2.20 to 5.00 feet per day, vertical hydraulic conductivity ranged from 0.050 to 0.167 feet per day, specific storage was $1.00x10^{-5}$ per foot, and specific yield was 0.003. The Ozark confining unit horizontal hydraulic conductivity ranged from $1.00x10^{-6}$ to $7.50x10^{-5}$ feet per day, vertical hydraulic conductivity ranged from $2.00x10^{-7}$ to $1.50x10^{-5}$ feet per day, specific storage was $5.00x10^{-6}$ per foot, specific yield was 0.100. The Ozark aquifer horizontal hydraulic conductivity ranged from 0.25 to 3.00 feet per day, vertical hydraulic conductivity ranged from 0.030 to 0.300 feet per day, specific storage ranged from $1.00x10^{-8}$ to $5.00x10^{-4}$ per foot, and specific yield was 0.003.

Water-level observation data for the Springfield Plateau aquifer and the Ozark aquifer were compiled from multiple sources. The steady-state part of the model was calibrated to water levels obtained from the Missouri Department of Natural Resources well log database supplemented with observation points interpolated from published predevelopment potentiometric surface maps of the Springfield Plateau and Ozark aquifers. The transient part of the model was primarily calibrated to water levels collected in 2006–07 by the USGS. Additional water-level measurements collected by the USGS in 1987, 1989, 1993, and 1996 also were used. Water-level data obtained from the Missouri Department of Natural Resources certified well database and the Missouri Department of Natural Resources well-log database also were used as water-level observations. A total of 2,076 water-level observations were used for calibration of the transient part of the model. Base-flow observations were estimated using the 7-day annual low-flow discharge values for the 2-year recurrence interval computed at USGS gage locations and estimated at ungaged sites. Spring-flow observations were obtained from various sources, including the Missouri Department of Natural Resources database, the USGS database, and published values.

The model was most sensitive to recharge and to horizontal hydraulic conductivity and specific storage in specific zones in the Ozark aquifer. The model was least sensitive to the specific yield in specific zones in the Ozark aquifer and specific storage in specific zones in the Springfield Plateau aquifer. The model was most sensitive to the same 10 model parameters during both the calibration period, 1987 to 2006, and the prediction period, 2007 to 2030, although the order was somewhat different.

Population and the associated groundwater use were estimated for 12 communities and the unincorporated area of Greene County based on past growth. Each was analyzed individually, and a low and high rate of growth, relative to the 2006 population, was computed for each community or group. Low growth rates ranged from 0.215 percent per year in Springfield to 6.997 percent per year in Rogersville. Total growth from 2006 to 2030 at the low growth rate ranged from 5.2 percent in Springfield to 167.9 percent in Rogersville. High growth rates ranged from 0.236 percent per year in Springfield to 7.345 percent per year in Rogersville. Total growth from 2006 to 2030 at the high growth rate ranged from 5.7 percent in Springfield to 176.3 percent in Rogersville.

Seven hypothetical scenarios provided to the USGS by the Greene County Resource Management Department were simulated from 2007 to 2030. The first hypothetical scenario was to run the simulation using the 2006 pumping rates. The potentiometric surface from 2006 to 2030 showed continuous decline in the Springfield area, with a maximum decrease of approximately 62 feet. Decline in the Nixa, Ozark, and Republic area ranged from about 15 to 45 feet. Two population growth rates were used to estimate groundwater demand in the future scenarios. Hypothetical scenarios 2 and 3 examined the effects that the low population growth rate combined with a 4-year drought (precipitation = 25.21 inches per year) either at the beginning or the end of the simulation could have on the head distribution in the Ozark aquifer. For both scenarios, the lowest 2030 simulated head occurred in Springfield and had a maximum change from the 2006 levels of approximately 203 feet. There was little difference in the potentiometric surface relative to the timing of the drought period except for where the Ozark aquifer is exposed. For scenarios 2 and 3, maximum groundwater declines at Nixa, Ozark, and Republic, relative to the 2006 levels, were greater than 100 feet. Hypothetical scenarios 4 and 5 examined the effects that the high population growth rate combined with a 4-year drought at the beginning or the end of the simulation could have on the potentiometric surface in the Ozark aquifer. Results of scenarios 4 and 5 were similar to the scenario 2 and 3 results. The maximum change occurred in the same vicinity and was approximately 207 ft lower than the 2006 levels. Potentiometric-surface declines for the high population growth scenarios 4 and 5 were similar to the low population growth scenarios 2 and 3 in the communities of Nixa, Ozark, and Republic. Hypothetical scenarios 6 and 7 examined the effects of the low and high growth rates in combination with the installation and operation of two new 900 gallon per minute (2010 rate) industrial wells in the model area. Little difference was noted in the potentiometric surface between the low and high growth scenarios 6 and 7. Both had substantial drawdown at the new wells (greater than 640 ft compared to the 2006 levels), but the difference between the two was less than 7 feet. The difference between all the low and high population growth scenarios was small. The drawdown at the new wells diminished relatively quickly with increased distance from the

well. Simulated head in Nixa, Ozark, and Republic was nearly the same for scenarios 2 through 7; the potentiometric surface in 2030 near these towns could decline 100 feet or more from the 2006 levels. Because model layers 2 and 3 were simulated as confined, drawdown in the wells in the area of the Ozark aquifer that is unconfined or becomes unconfined during the simulation period will likely be under predicted.

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