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Groundwater Resources Program

Hydrogeology and Hydrologic Conditions of the Ozark Plateaus Aquifer System

Scientific Investigations Report 2016–5137

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

Cover: Blue Spring is the seventh largest spring in the Ozarks and has a discharge of approximately 90 million gallons per day. The spring was first named by Native Americans as the Spring of Summer Sky and is characterized by the brilliant turquoise blue of the discharge pool which is more than 300 feet in depth. Blue Spring is 16 miles east of Eminence, Missouri, and drains into the Current River.

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Director

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
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)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
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)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as °C = (°F – 32) / 1.8.

Datum

Vertical coordinate information is referenced to North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Abbreviations

EPA	U.S. Environmental Protection Agency
MVT	Mississippi Valley type
NWIS	National Water Information System
ONSR	Ozark National Scenic Riverways
RASA	Regional Aquifer-System Analysis
SWB	soil water balance
TDS	total dissolved solids
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

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Abstract

The hydrogeology and hydrologic characteristics of the Ozark Plateaus aquifer system were characterized as part of ongoing U.S. Geological Survey efforts to assess groundwater availability across the Nation. The need for such a study in the Ozark Plateaus physiographic province (Ozark Plateaus) is highlighted by increasing demand on groundwater resources by the 5.3 million people of the Ozark Plateaus, water-level declines in some areas, and potential impacts of climate change on groundwater availability. The subject study integrates knowledge gained through local investigation within a regional perspective to develop a regional conceptual model of groundwater flow in the Ozark Plateaus aquifer system (Ozark system), a key phase of groundwater availability assessment. The Ozark system extends across much of southern Missouri and northwestern and north-central Arkansas and smaller areas of southeastern Kansas and northeastern Oklahoma. The region is one of the major karst landscapes in the United States, and karst aquifers are predominant in the Ozark system. Groundwater flow is ultimately controlled by aquifer and confining unit lithologies and stratigraphic relations, geologic structure, karst development, and the character of surficial lithologies and regolith mantle. The regolith mantle is a defining element of Ozark Plateaus karst, affecting recharge, karst development, and vulnerability to surface-derived contaminants. Karst development is more advanced—as evidenced by larger springs, hydraulic characteristics, and higher well yields—in the Salem Plateau and in the northern part of the Springfield Plateau (generally north of the Arkansas-Missouri border) as compared with the southern part of the Springfield Plateau in Arkansas, largely due to thinner, less extensive regolith and purer carbonate lithology.

Precipitation is the ultimate source of all water to the Ozark system, and the hydrologic budget for the Ozark system includes inputs from recharge, losing-stream sections, and groundwater inflows and losses of water to gaining-stream sections, groundwater withdrawals, and surface-water and groundwater outflows to neighboring systems. Groundwater recharge, estimated by a soil-water-balance model, represents about 24 percent, or 11 inches, of 43.9 inches annual precipitation. Recharge is spatially variable, being greater in the northern Springfield Plateau and Salem Plateau than in the southern Springfield Plateau (generally south of the Arkansas border) because of differences in regolith mantle extent and thickness and carbonate lithology and hydraulic properties. Increased precipitation and decreased agricultural land use during the period 1951 through 2011 increased recharge by approximately 5 percent. Although all Ozark streams have losing, neutral, and gaining sections, they are dominantly gaining and are a net sink for groundwater with nearly 90 percent of groundwater recharge returned to springs and streams. Groundwater pumping is a small but important loss of water in the Ozark system hydrologic budget; water-level declines and local cones of depression have been observed around pumping centers and strong concerns exist over potential effects on stream and spring flow.

Data indicate that societal needs for freshwater resources in the Ozark Plateaus will continue to increase and will do so in the context of changing climate and hydrology. Groundwater will continue to be an important part of supporting these societal needs and also local ecosystems. The unique character and hydrogeologic variability across the Ozark system will control how the system responds to future stress. Groundwater of the Ozark system in the northern study area is more dynamic, has greater storage and larger flux, and has greater potential for further development than in the part of the study area south of the Arkansas-Missouri border. Further south in Arkansas, a line exists, roughly defined as 5 miles south of the Springfield Plateau-Boston Mountains boundary, beyond which further extensive municipal or commercial development appears unlikely under current economic and resource-need conditions. A small part of the Ozark system groundwater budget is currently drafted for use, leaving an apparently large component available for further development and use—particularly in the northern Springfield Plateau and Salem Plateau; however, the effects of increased pumping on groundwater's role in maintaining ecosystems and ecosystem services are not quantitatively well understood, and the close relation between groundwater and surface water highlights the importance of further quantitative assessment.

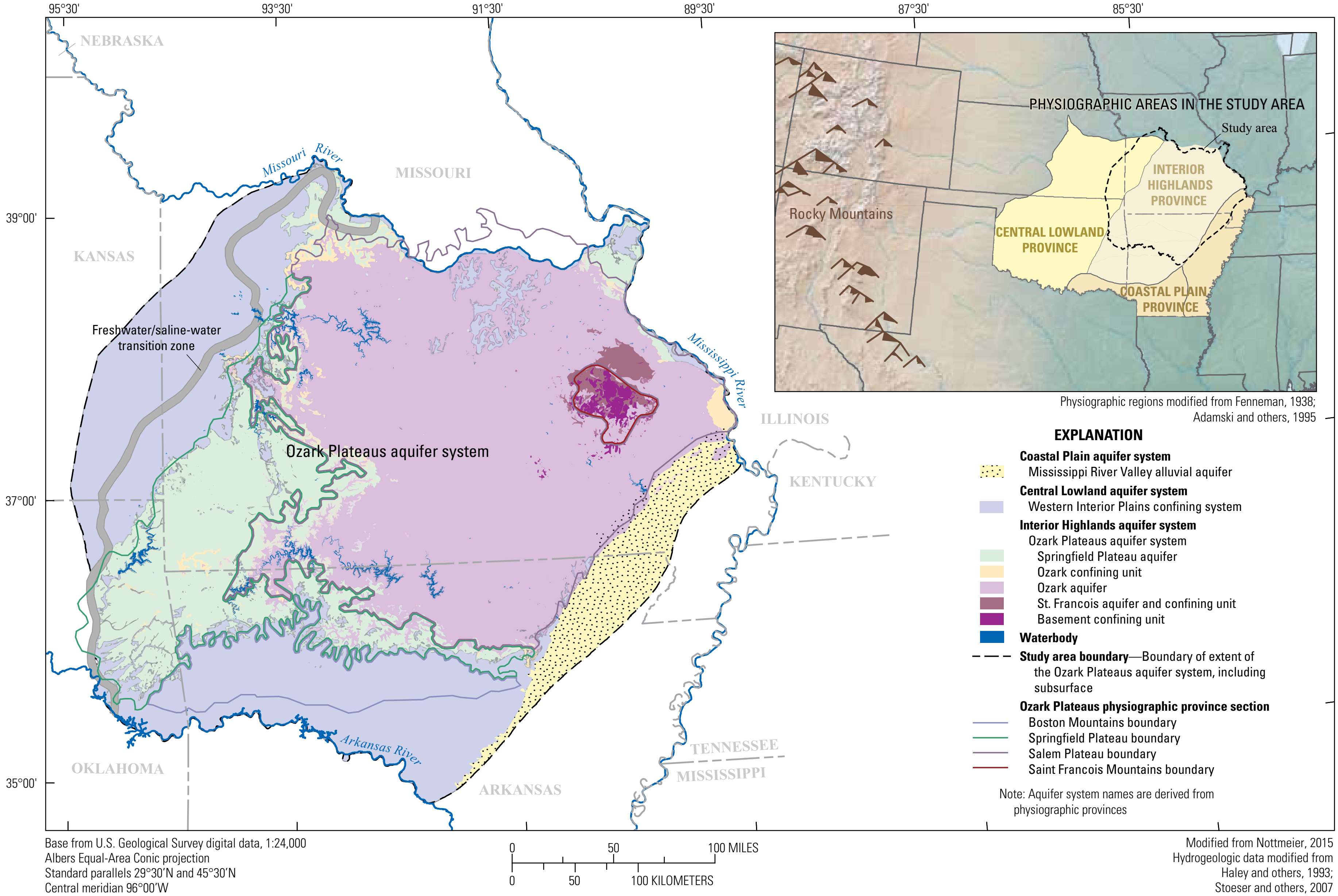
Introduction

The U.S. Geological Survey (USGS) routinely conducts regional-scale studies of major groundwater systems throughout the United States as part of its mission to characterize and assess the quantity and quality of the Nation's water resource (Jorgensen and others, 1996; Dennehy and others, 2016). These regional groundwater assessments commonly comprise multiple objectives, including documenting the effects of human activities on groundwater availability, describing aquifer-system properties, compiling and analyzing geologic, hydrologic, hydraulic, and water-use data, and producing conceptual and numerical models of groundwater flow (Dennehy and others, 2015). In 2014, the USGS began a regional groundwater-availability study of the Ozark Plateaus aquifer system (hereinafter referred to as the "Ozark system"), which covers an area extending across much of southern Missouri and northwestern and north-central Arkansas and smaller areas of southeastern Kansas and northeastern Oklahoma (fig. 1).

The Ozark system generally coincides with the geographic extent of the Ozark Plateaus physiographic province (hereinafter referred to as the "Ozark Plateaus," fig. 1) (Fenneman, 1938). Groundwater is an important resource for the more than 5.3 million people living in the Ozark Plateaus (Minnesota Population Center, 2011), and is important in supporting and maintaining interconnected surface-water resources and key ecosystems (Imes and Emmett, 1994; DuCharme and Miller, 1996; Kresse and others, 2014). The importance of groundwater, coupled with increasing demand on groundwater resources (Czarnecki and others, 2009), declining water levels and development of cones of depression near groundwater pumping centers (Imes and Emmett, 1994), and future projected changes in the hydrologic cycle related to climate change (Karl and others, 2009; Cisneros and others, 2014) highlight the need for an updated assessment of groundwater availability in the Ozark system.

Studies conducted since the USGS Regional Aquifer-System Analysis (RASA) in the 1980s (Imes and Emmett, 1994) have led to considerable, but generally localized refinements of the hydrogeologic framework, groundwater flow, and hydrologic budgets within the Ozark system (fig. 2) (Reed and Czarnecki, 2006; Czarnecki and others, 2009; Richards, 2010). This study combines knowledge gained through studies conducted at multiple geographic scales to build a regional conceptual model of groundwater flow in the Ozark system. Site-specific studies are valuable, and especially critical in karst systems, but the regional-scale analysis of the Ozark system is necessary to provide a quantitative assessment of freshwater resources in the system as a whole.

This report incorporates available data, results of numerous studies, and new interpretive results into a coherent conceptual model. Data and an improved understanding of the system are drawn from USGS and non-USGS sources including graduate academic theses, journals, and caver studies, as well as new data collected and analyzed for the Ozark system study described in this report. This updated synthesis includes (1) a refined description of regional hydrogeologic units, (2) compilation and analysis of recent (through 2010) water-use data for the Ozark system, and (3) an updated hydrologic budget for conditions for the period 2005–14. Additionally, the conceptual model of groundwater flow in the Ozark system is placed into the context of climate change because, ultimately, a changing climate has great effect on the hydrologic cycle. Better characterization and quantification of the hydrologic budget for the Ozark system allows water-resource managers to more effectively adapt to possible climate-change scenarios. A hydrogeologic framework and thicknesses report (Westerman and others, 2016), regional potentiometric surface map (Nottmeier, 2015), digitized surface-water/groundwater interaction seepage-run dataset (Knierim and others, 2015), and 110-year record of modeled site-specific groundwater withdrawals (Knierim and others, 2016) are complementary products that have provided new information enhancing conceptual model development for this report, and are part of the larger Ozark Plateaus Groundwater Availability Study for which a regional groundwater-flow model will be the ultimate product (U.S. Geological Survey, 2015a). The products of this broad effort improve our understanding of groundwater availability in the central United States.



Base from U.S. Geological Survey digital data, 1:24,000
Albers Equal-Area Conic projection
Standard parallels 29°30′N and 45°30′N
Central meridian 96°00′W
North American Datum of 1983

Modified from Nottmeier, 2015
Hydrogeologic data modified from
Haley and others, 1993;
Stoeser and others, 2007

Figure 1. Location and extent of hydrogeologic units in the Ozark Plateaus aquifer system in relation to the Ozark Plateaus Physiographic Province.

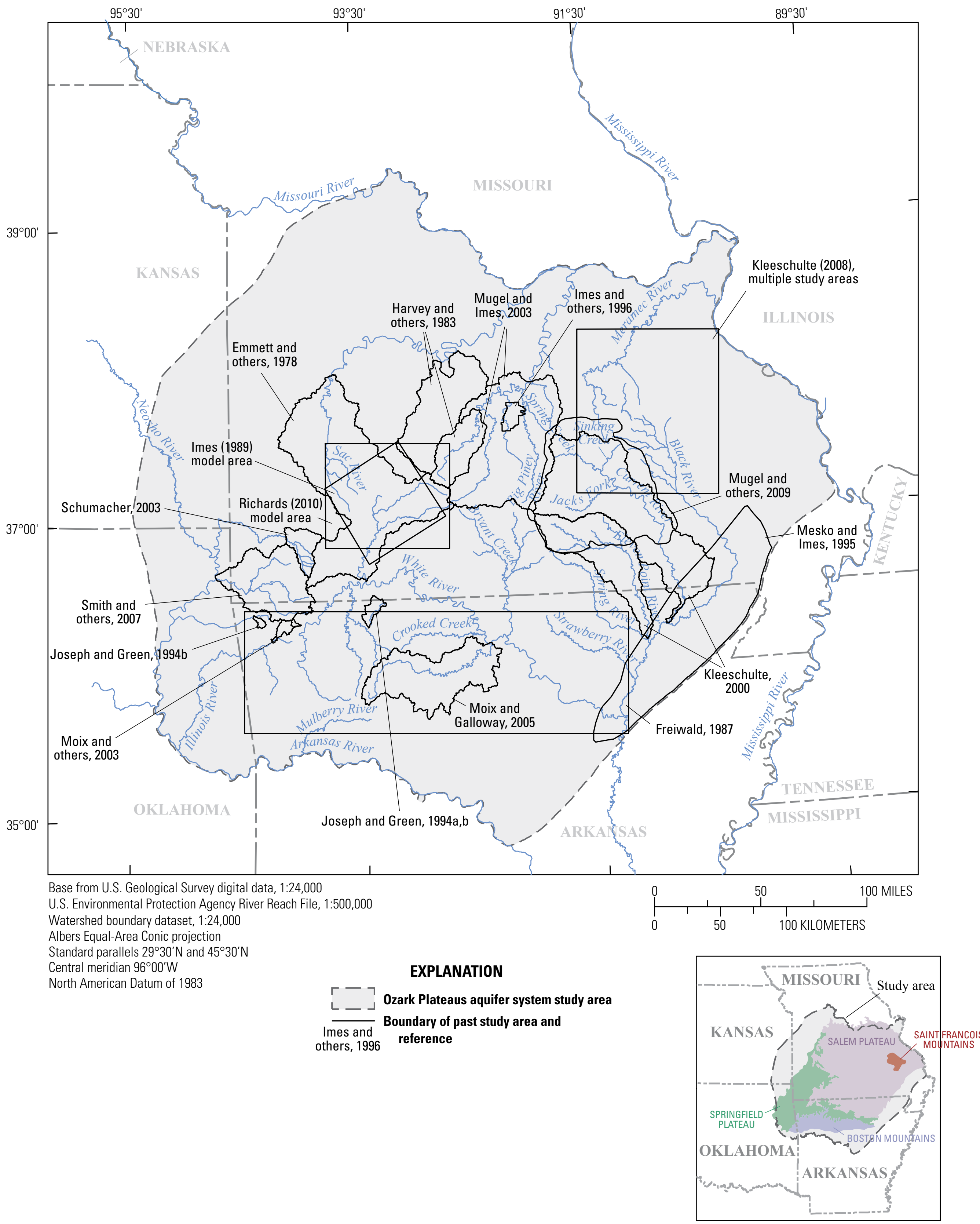
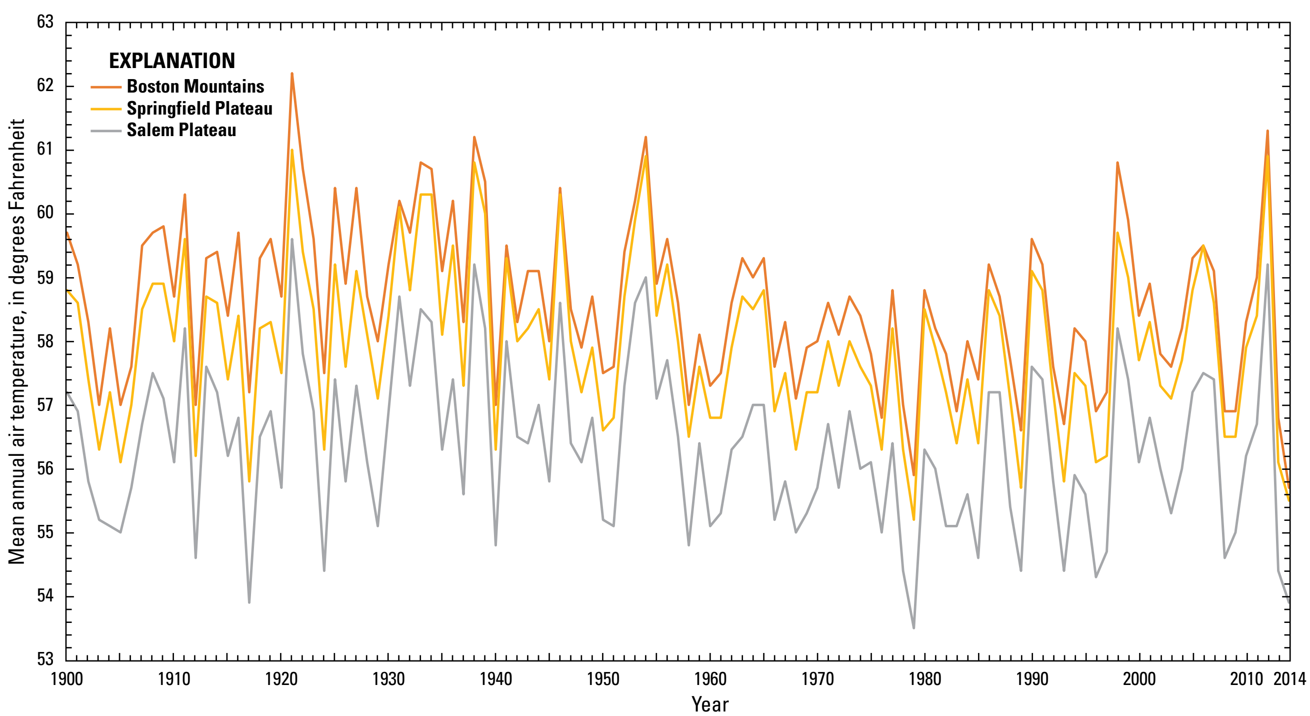


Figure 2. Location and extent of selected past study-area boundaries, including seepage-run studies and groundwater models completed in the Ozark Plateaus aquifer system.

Description of the Study Area

The study area for the Ozark system groundwater availability study includes approximately 69,000 square miles (mi^2) and is bounded by the Missouri River to the north, the Mississippi River to the east, the Mississippi Alluvial Plain to the southeast, the Arkansas River to the south, and the broad regional topographic low extending from northeastern Oklahoma to the Missouri River to the west (fig. 1). The Ozark system predominantly contains freshwater across its extent and is almost entirely surrounded by neighboring saline groundwater-flow systems (Jorgensen and others, 1988). The seven regional hydrogeologic units defined in the study area primarily comprise thick sequences of carbonate rocks with interbedded clastic units. From oldest to youngest, these units are (1) Basement confining unit, (2) St. Francois aquifer, (3) St. Francois confining unit, (4) Ozark aquifer, (5) Ozark confining unit, (6) Springfield Plateau aquifer, and (7) Western Interior Plains confining system (Imes and Emmett, 1994; Jorgensen and others, 1996) (fig. 1). The units between the Basement confining unit and the Western Interior Plains confining system constitute the Ozark system. The outcrop areas of these units correspond with physiographic sections of the Ozark Plateaus: Boston Mountains, Springfield Plateau, Salem Plateau, and St. Francois Mountains (Fenneman, 1938; Imes and Emmett, 1994) (fig. 1). The three plateaus of the Ozark Plateaus dip gently away from the Ozark dome in southeastern Missouri (Adamski and others, 1995; Kresse and others, 2014). The Ozark system is an important aquifer in the Salem and Springfield Plateaus but is marginally productive in the St. Francois and Boston Mountains (MacDonald and others, 1977; Imes and Emmet, 1994). Carbonate units of the Ozark Plateaus have undergone extensive faulting, fracturing, and dissolution, resulting in the region being one of the major karst landscapes in the United States and karst units being the most important aquifers in the Ozarks (Weary and Doctor, 2014).

The Ozark system is located in a temperate climate zone; historical climate data, including annual means for temperature and annual totals for precipitation from 1900 through 2014, (PRISM Climate Group, 2015), were summarized to aid aquifer recharge estimation. Mean annual air temperature for the Ozark system ranged from 54.4 to 60.4 degrees Fahrenheit (°F) from 1900 to 2014 (fig. 3 and table 1); the Boston Mountains had the greatest mean annual air temperature at 58.6 °F, and the Salem Plateau had the lowest at 56.3 °F (fig. 4). Mean annual precipitation for the Ozark system for years 1900 to 2014 ranged from 27.9 to 63.1 inches (in.); the Boston Mountains had the greatest mean annual precipitation at 49.5 in., and the Salem Plateau physiographic section had the lowest at 43.2 in (table 1). Precipitation varied considerably between wet and dry years,



Data from PRISM Climate Group, 2015

Figure 3. Mean annual air temperature for the physiographic sections of the Ozark Plateaus physiographic province (that is, the Boston Mountains, Salem Plateau, and Springfield Plateau) through time.

Table 1. Summary of temperature and precipitation data from 1900 to 2014 using annual and monthly data for the Ozark Plateaus aquifer system study area and sections within the Ozark Plateaus physiographic province (that is, the Boston Mountains, Salem Plateau, and Springfield Plateau).

[Annual means for temperature and annual totals for precipitation included the years from 1900 through 2014; seasonal data were based on monthly means for temperature and monthly totals for precipitation from 1900 through 2014. Fall season represents October, November, and December; winter season represents January, February, and March; spring season represents April, May, and June; summer season represents July, August, and September]

Annual and seasonal data for summarized areas	Temperature (degrees Fahrenheit)				Precipitation (inches)			
	Mean	Median	Minimum	Maximum	Mean	Median	Minimum	Maximum
Ozark Plateaus aquifer system								
Annual	57.2	58.6	54.4	60.4	43.9	42.9	27.9	63.1
Fall	47.8	47.8	42.3	54.5	9.8	11.6	2.9	19.8
Winter	39.7	39.9	30.4	46.7	8.9	8.9	3.4	15.9
Spring	65.8	65.9	61.0	68.9	14.0	13.9	6.4	26.0
Summer	75.6	75.5	71.1	81.7	11.2	11.2	5.1	20.0
Boston Mountains physiographic section								
Annual	58.6	56.3	55.7	62.2	49.5	47.8	28.1	74.0
Fall	49.7	49.7	44.5	55.8	11.8	11.6	2.6	27.1
Winter	42.3	42.6	33.5	49.2	11.2	10.7	3.7	23.2
Spring	66.4	66.4	62.0	70.0	15.3	15.0	4.8	31.1
Summer	76.0	76.0	71.3	82.0	11.4	11.2	5.5	19.9
Salem Plateau physiographic section								
Annual	56.3	56.3	53.5	59.6	43.2	42.5	25.5	63.0
Fall	46.9	46.9	41.3	53.8	9.7	9.3	2.7	19.1
Winter	38.6	38.8	29.4	45.9	8.9	8.7	3.4	17.2
Spring	65.1	65.2	60.2	68.2	13.5	13.3	5.9	26.0
Summer	74.7	74.7	70.4	80.8	11.1	10.8	3.9	21.8
Springfield Plateau physiographic section								
Annual	58.0	58.0	55.2	61.0	44.0	43.0	24.9	65.0
Fall	48.8	48.8	43.3	55.3	9.6	9.0	2.4	19.9
Winter	40.8	41.1	31.3	47.6	8.3	8.2	2.7	17.6
Spring	66.1	66.1	61.5	69.3	14.6	14.6	6.7	28.1
Summer	76.0	76.0	71.1	82.8	11.4	11.5	5.6	20.7

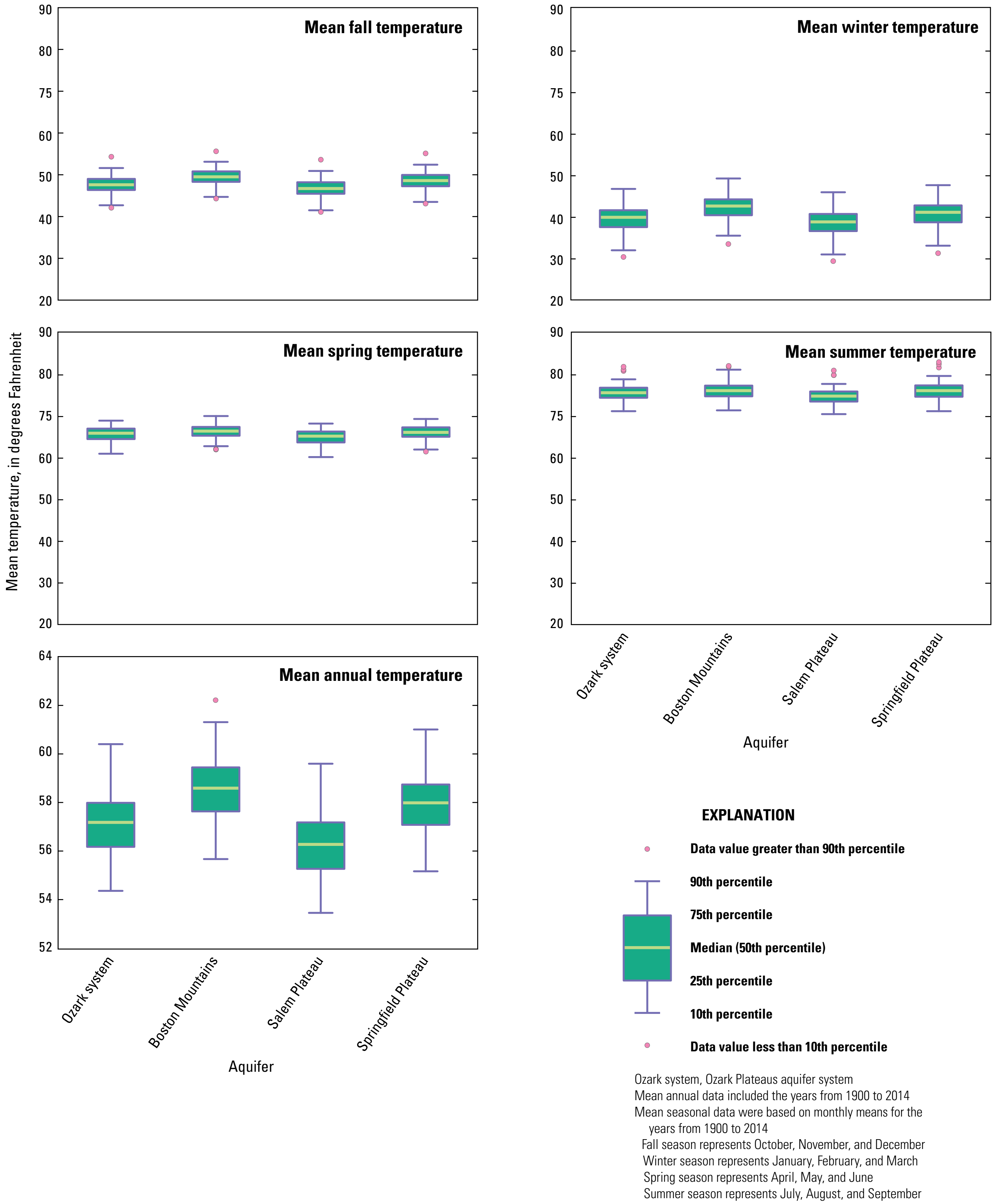


Figure 4. Annual and seasonal mean temperatures for the Ozark Plateaus aquifer system and sections within the Ozark Plateaus physiographic province (that is, the Boston Mountains, Salem Plateau, and Springfield Plateau).

departing from the 43.9-in. mean annual precipitation for the Ozark system by as much as 19.2 in. (figs. 5 and 6). Large swings in annual precipitation can affect recharge to the Ozark system and surface-water availability, resulting in changes in groundwater levels and sudden changes in water-use demands on groundwater and surface-water resources.

Land use across the Ozark system is primarily a mosaic of forest and agriculture (especially hay and pastures), with local urban development (fig. 7), which has been the general pattern of land use since development (Jacobson and Primm, 1997). Western expansion of European settlement began as early as the 1700s but generally increased in the late 1800s during the timber-boom period, which included extensive logging across the Ozark Plateaus (Jacobson and Primm, 1997). As of 2011, primary land cover and land use across the Ozark system was forest (approximately 48 percent) and agriculture (approximately 40 percent), and approximately 6 percent was developed (table 2). Groundwater use generally reflects the pattern of land use (figs. 7 and 8), with higher groundwater-withdrawal rates in counties with higher urban development and associated higher public supply, industrial, and commercial water uses and agricultural areas and correspondingly lower groundwater withdrawal rates in counties with forests and dominantly domestic groundwater use. Groundwater-withdrawal rates shown in figure 8 do not include counties along the eastern border of the Ozark system, which withdraw large volumes of water predominantly from shallow alluvial aquifers of the Coastal Plain aquifer system (Schrader, 2008).

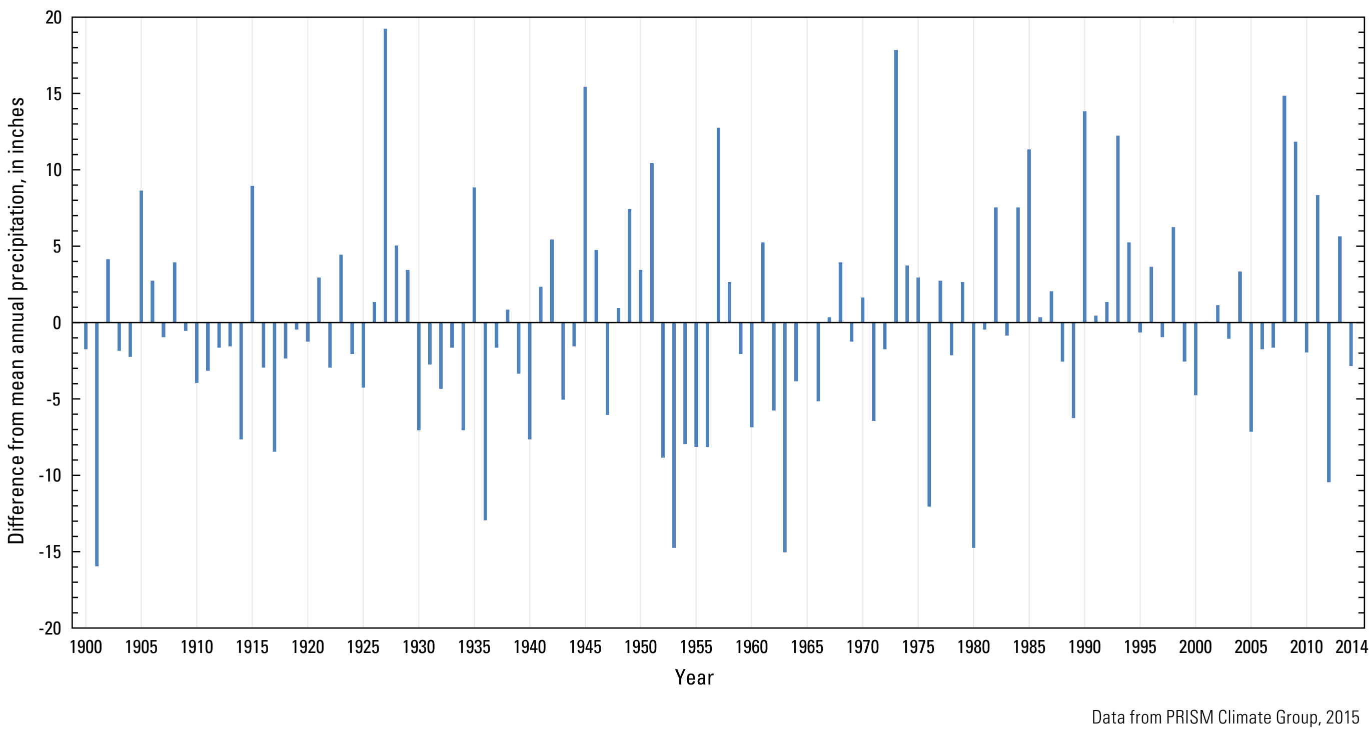


Figure 5. Departure from mean annual precipitation for the Ozark Plateaus aquifer system through time.

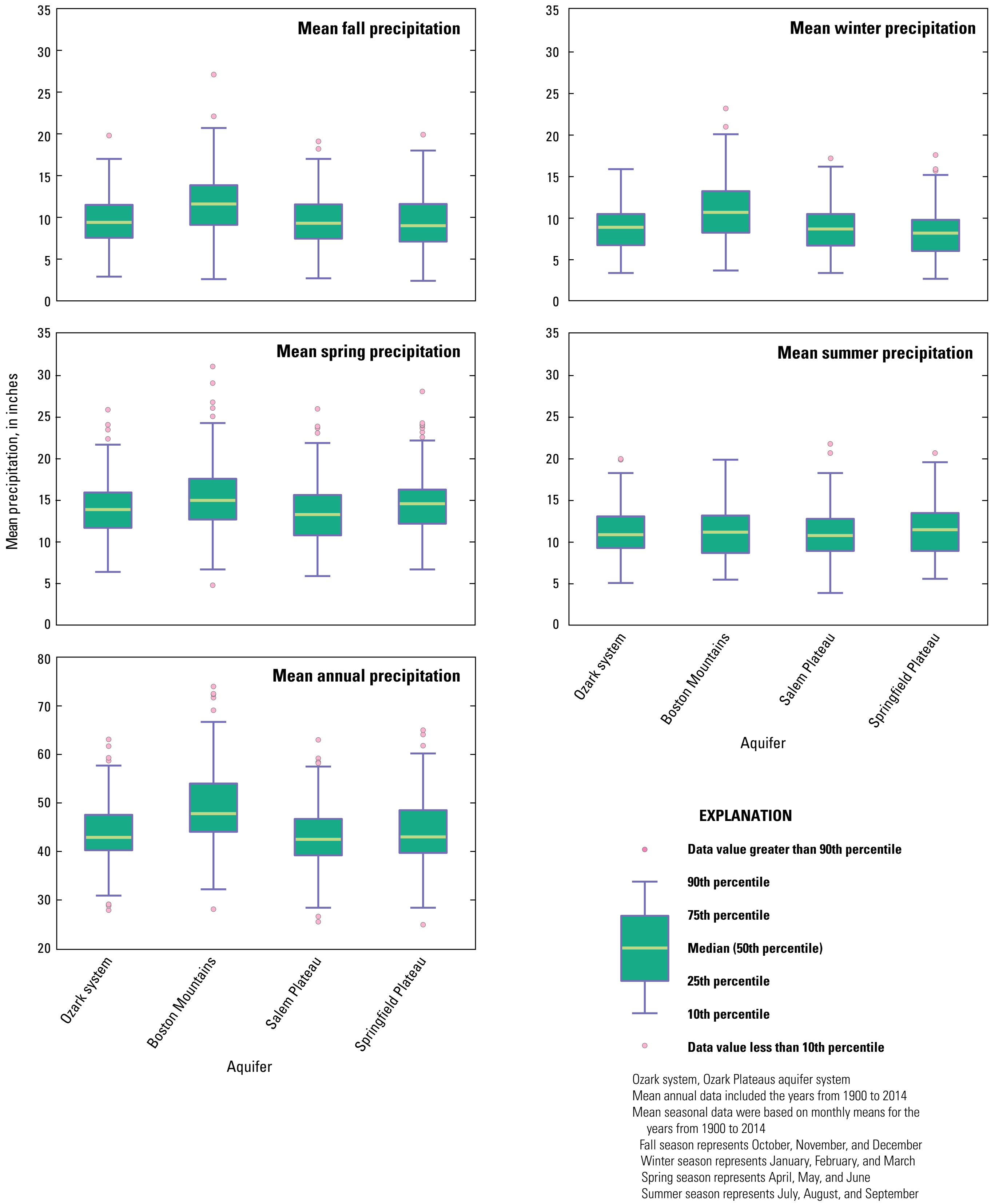


Figure 6. Annual and seasonal mean precipitation for the Ozark Plateaus aquifer system and sections within the Ozark Plateaus physiographic province (that is, the Boston Mountains, Salem Plateau, and Springfield Plateau).

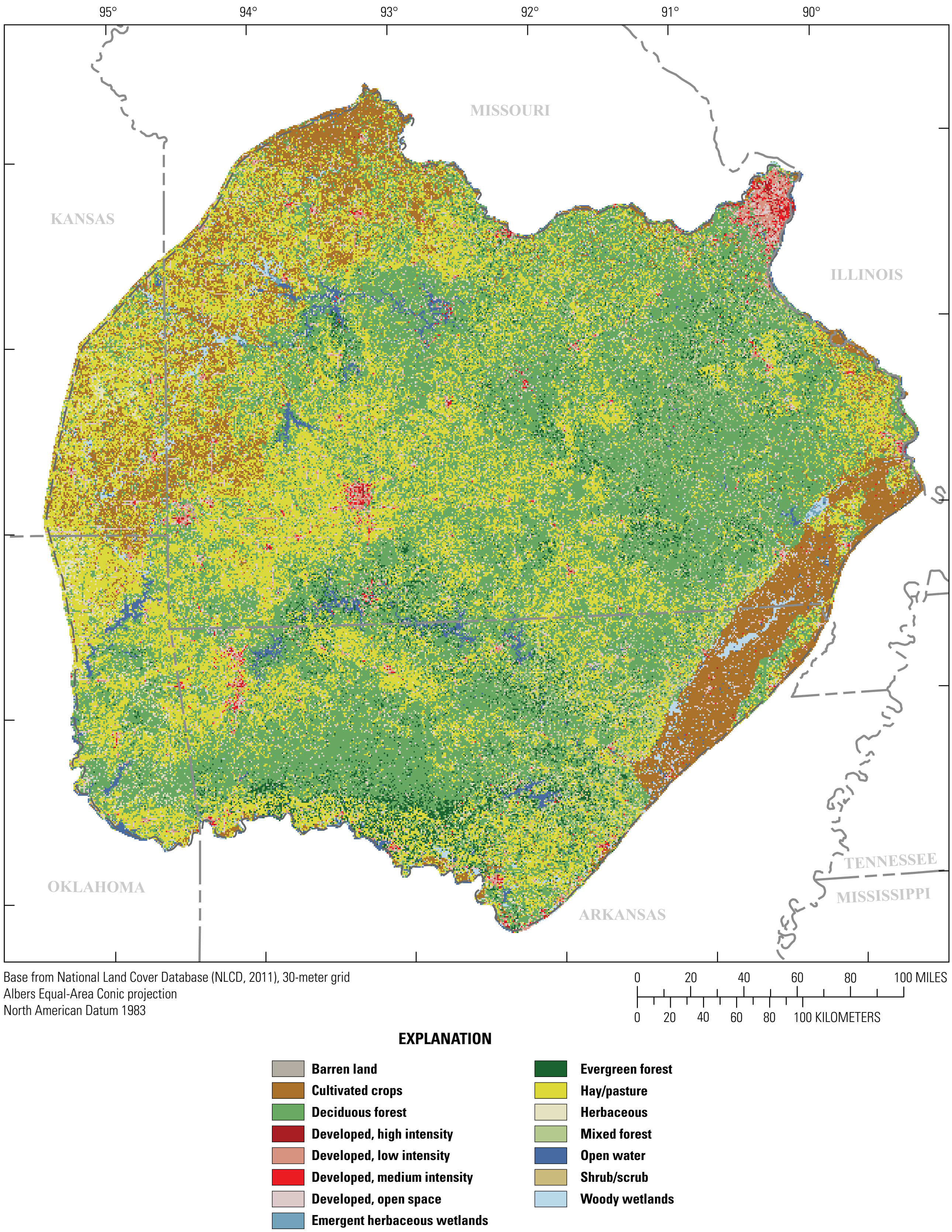


Figure 7. Land use and land cover for the Ozark Plateaus aquifer system.

Table 2. Summary of land use and land cover in the Ozark Plateaus aquifer system.

Land area (percent)	Land-cover category	Land area (percent)	Land-cover category, summary
1.7	Open water	1.7	Open water
4.3	Developed, open space		
1.5	Developed, low intensity		
0.5	Developed, medium intensity		
0.2	Developed, high intensity	6.5	Developed
0.2	Barren land	0.2	Barren land
41.7	Deciduous forest		
3.3	Evergreen forest		
2.6	Mixed forest	47.6	Forest
0.5	Shrub/scrub		
2.2	Herbaceous		
1.5	Woody wetlands		
0.1	Emergent herbaceous wetlands	4.3	Shrubs/ wetlands
29.5	Hay/pasture		
10.3	Cultivated crops	39.8	Agriculture

Hydrogeologic Framework

The hydrogeologic framework of an aquifer system establishes the driving force and boundaries constraining groundwater flow for any given region. The interplay of varying lithologic, stratigraphic, structural, topographic, flow-path, and hydraulic conditions controls the storage, movement, chemistry, and exchange of groundwater between the subsurface and surface environments. Minor differences in the hydrogeologic framework of an aquifer system can cause groundwater characteristics to vary greatly from place to place. This variation is particularly true for a complex karst region, such as the Ozark system, where groundwater storage, flow rates, and chemistry can vary by orders of magnitude across short distances, even across the interface from a flow conduit into rock matrix (Kresic, 2007).

Seven hydrogeologic units are recognized for this study: (1) Basement confining unit, (2) St. Francois aquifer, (3) St. Francois confining unit, (4) Ozark aquifer, (5) Ozark confining unit, (6) Springfield Plateau aquifer, and (7) Western Interior Plains confining system (fig. 1). For the productive hydrogeologic units, the Cambrian St. Francois aquifer is generally an unconfined aquifer in the outcrop areas in the St. Francois Mountains and a confined aquifer where overlain by the St. Francois confining unit. The Ozark aquifer is generally unconfined where upper Cambrian through Devonian rocks are exposed on the Salem Plateau, including some remaining erosional outliers of younger rocks that once covered the plateau, and confined where overlain by the Ozark confining unit; however, the lower units of the Ozark aquifer, particularly the Potosi Dolomite, which is the predominant, high-yielding unit of the Ozark aquifer in southern Missouri (Fuller and others, 1967), are broadly confined by less permeable intervals of the overlying middle Ozark interval. The Springfield Plateau aquifer is generally unconfined in areas where Mississippian rocks are exposed on the Springfield Plateau and confined where overlain by the Western Interior Plains confining system; however, in outcrop zones, extensive chert layers provide partial confinement in many areas (Stanton, 1993). The Boston Mountains constitute a part of the Western Interior Plains confining system, which wraps around the southern and western extents of the Ozark system and includes outcrops of Mississippian to Pennsylvanian rocks (fig. 1). Although part of the Western Interior Plains confining system, the Boston Mountains provide a minor local source of groundwater supply (Kresse and others, 2014)

Extensive karstification of carbonate rocks in the Ozark system has caused aquifer anisotropy and heterogeneity (Kresse and others, 2014). Karst aquifers are typified by varying degrees of porosity and permeability, sometimes described in terms of two or three end-member conceptual models (Ford and Williams, 2007). In a bimodal conceptual model, primary matrix porosity and small-aperture fracture porosity—which are sometimes separated in trimodal conceptual models—give low porosity values for individual small-scale samples but are pervasive through the aquifer matrix and constitute a large proportion of total porosity. Secondary (or tertiary) fracture and dissolution-enhanced porosity are high within focused areas but are a smaller proportion of total porosity. The control of these porosity types on permeability leads to two end-member flow types—diffuse flow (Alley and others, 2002; Ghasemizadeh and others, 2012), in which slower time-averaged flow through diffuse flow paths allows for sustained groundwater input to streams and springs and focused flow, which provides extremely rapid response and transit times during precipitation events. The Ozark system is susceptible to surface-derived contamination because focused flow paths—including karst features such as sinkholes, losing-stream segments, and dissolution-enlarged fractures—rapidly transmit surface water to groundwater aquifers (Adamski and others, 1997; Peterson and others, 2000; Knierim, Hays, and Bowman, 2015). Groundwater flow is ultimately controlled by lithologies exposed at the surface that receive recharge, stratigraphic relations among hydrogeologic units, geologic structure, and modification of carbonate bedrock during distinct periods of karstification over time (Kresse and others, 2014).

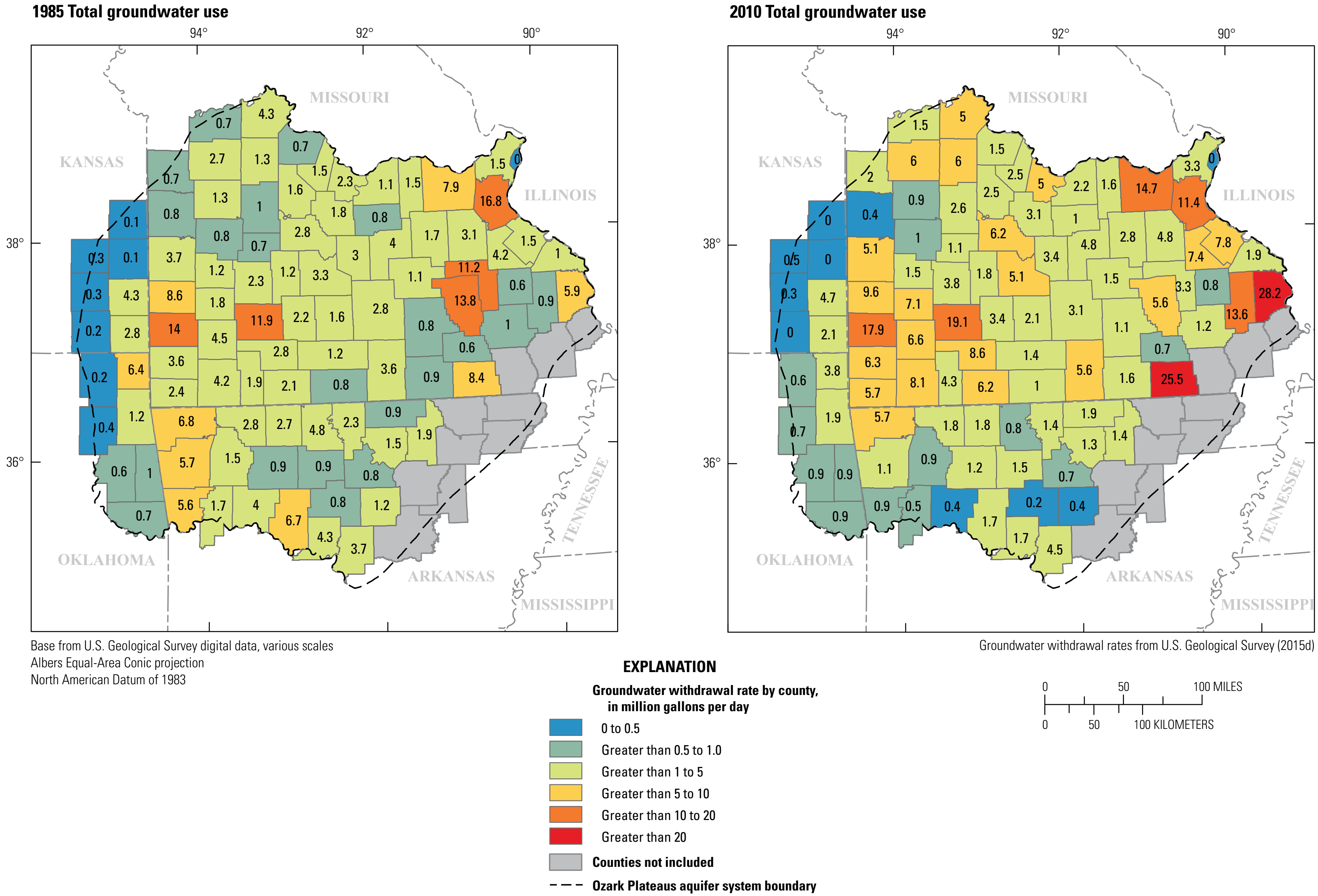


Figure 8. Groundwater use for counties in the Ozark Plateaus aquifer system in 1985 and 2010.

Regionally, groundwater flow in the Ozark system is generally outward from a topographic high—which is oriented along an axis from the St. Francois Mountains in southeastern Missouri to the tristate region of southwestern Missouri, southeastern Kansas, and northeastern Oklahoma (fig. 1)—to discharge areas in the Missouri, Arkansas, and Mississippi River Basins (Adamski and others, 1995; Hays, 1999; Nottmeier, 2015). Hence, surface water and groundwater generally flow outward from the Ozark dome, and the Ozark system receives inflow from surface water and groundwater only along the northwestern margin where the Western Interior Plains confining system borders the Ozark system (see the “Lateral Inflow” section). Locally, groundwater flow is generally from local topographic highs towards stream valleys, with surface streams serving as groundwater hydrologic boundaries; however, because of the karst hydrogeology of the Ozark system, surface-water basins and groundwater recharge areas do not always coincide (Brahana, 1997). The abundant occurrence of groundwater transfer across surface-water drainage-basin divides has been observed in dye-tracing studies and drainage-area-discharge relations (Sullavan, 1974; Vineyard and Feder, 1982; Brahana and Davis, 1998; Mott and others, 2000; Owen and Pavlowsky, 2011). Consideration of interbasin movement of water is an important point for protection and management of groundwater because contributing zones are not apparent at the surface, and contaminants can be introduced into groundwater from unexpected locations.

The Ozark system includes a thick sequence of predominantly carbonate rocks upon which a well-developed karst terrain has formed and, coupled with the humid, temperate climate of the region, results in direct interaction between surface water and groundwater. For example, one of the largest concentrations of springs in the United States is found in the Ozark Plateaus, with springs that yield from less than a gallon to millions of gallons of water per day (Imes and Emmett, 1994; Criss and Osburn, 2009), and the Ozarks are replete with perennial streams where base-flow discharge is maintained by groundwater (termed “gaining streams”). Conversely, many surface-stream reaches also lose considerable amounts of water to the subsurface (termed “losing streams”). Delineating a precise boundary between groundwater and surface water is difficult and ill-advised from the standpoint of effective management and protection of the region’s water resources (Owen and Pavlowsky, 2011). Springs are important discharge points for the Ozark system and tend to occur at contacts of units with varying permeability and near faults or monoclines or in structural lows (Mott and others, 2000). The largest discharge springs and greatest number of springs in the Ozark Plateaus emerge from the Ordovician and Cambrian formations of the Salem Plateau (Vineyard and Feder, 1982). Thousands of springs also emerge from the Mississippian limestones of the Springfield Plateau, but these springs tend to have less discharge than springs in the Salem Plateau (Harvey, 1980). The interaction of groundwater and surface water in the Ozark Plateaus is an intrinsic characteristic of the hydrogeologic framework of the Ozark system because of the karstification of carbonate rocks.

Previous Investigations

The USGS RASA series began in 1978 to appraise groundwater systems in the United States, which included an analysis of regional aquifers in the central Midwest and a summary of groundwater hydrogeology in the Ozark system (Jorgensen and others, 1996). A more detailed analysis of the Ozark system was conducted by Imes and Emmett (1994) and included summaries of major hydrogeologic units, groundwater flow, chemical composition of groundwater, and groundwater use and availability. Additionally, a groundwater model was developed over a 120,000-mi^2 study area to estimate the hydrologic budget and transmissive properties of the Ozark system (Imes and Emmett, 1994). From the model simulation, inflow to the Ozark system was estimated to be approximately 7,000 cubic feet per second (ft^3/s) and was approximately balanced by outflow to streams and springs within the study area (4,000 ft^3/s) and outflow to model-boundary streams (3,000 ft^3/s), with relatively small rates of groundwater withdrawal (Imes and Emmett, 1994).

Regional-scale groundwater models in parts of the Ozark system have been completed by Imes (1989), Christenson and others (1990), Imes (1991), Wittman and others (2003), Reed and Czarnecki (2006), Czarnecki and others (2009), and Richards (2010). The regional-scale models incorporate quantitative projections of future groundwater-withdrawal rates to assess changes in groundwater-flow direction or availability. For example, Imes (1989) found that groundwater withdrawals have changed the potentiometric surface of the Ozark aquifer, which altered the hydrologic budget near the Springfield, Mo., area. In another example, Czarnecki and others (2009) found that groundwater pumping in the Missouri-Kansas-Oklahoma border region caused substantial reduction of groundwater in storage. Richards (2010) presented a groundwater model of the Ozark system in the area of Greene County, Mo.—which has experienced substantially increasing demands on water resources—and used the model to assess sustainability of groundwater resources under various water-use scenarios. Mesko and Imes (1995) compared groundwater flow between two regional groundwater models—the Ozark system model (Imes and Emmett, 1994) and the Mississippi embayment aquifer system model (Brahana and Mesko, 1988; Mesko and Imes, 1995)—at the fall line of the Ozark escarpment (fig. 1). Many of the aforementioned groundwater models used quantitative estimates of recharge originally made by Dugan and Peckenpaugh (1985) who, applying a soil-water-balance approach, used soil hydrologic properties, vegetation types, monthly precipitation, and computed monthly potential evapotranspiration to calculate recharge for the Ozark system.

Regional assessments of hydrogeology, groundwater flow, and groundwater levels in the Ozark system are included in Fuller and others (1967), MacDonald and others (1977), Harvey (1980), Macfarlane and Hathaway (1987), Vandike (1992), Imes and others (1996), Mugel and Imes (2003), and Macfarlane and others (2005). Fuller and others (1967) collected and synthesized data on groundwater provinces, aquifers, water availability, yields, quality, well and spring information, and water use for the Missouri Ozarks. MacDonald and others (1977) provided a thorough summary of the hydrogeology of Ordovician units—including the Roubidoux and Gasconade Formations—in northern Arkansas and Missouri. Harvey (1980) discussed the relation between karst features, recharge to aquifers, groundwater flow, and discharge to springs and surface streams in the Cambrian and Ordovician units of the Springfield and Salem Plateaus. Macfarlane and Hathaway (1987) and Macfarlane and others (2005) discussed groundwater flow and water-level declines in units of the Ozark system, focusing on the Missouri-Kansas-Oklahoma border region. Vandike (1992) described groundwater withdrawals and water-level declines near Rolla, Mo., and concluded that water-level declines would continue into the future. Imes and others (1996) and Mugel and Imes (2003) described the hydrogeologic framework and water use near Fort Leonard Wood Military Reservation in central Missouri.

Conceptual models of the karst hydrogeology of the Ozark system are presented in Adamski and others (1995), Brahana (1997), Orndorff and others (2001), Orndorff and others (2006), Criss and Osburn (2009), Taylor and others (2009), and Kresse and others (2014). Adamski and others (1995) summarized the physical setting of the Ozark Plateaus, such as climate, physiography, hydrogeology, soils, and land use. Brahana (1997) provided a framework for estimating spring recharge-area boundaries by using spring base-flow discharge and localized assessments of karst features. Orndorff and others (2001, 2006) investigated how sandstone units control the development of karst conduits in underlying dolostone; sandstone was found to act as a local confining unit so that increased hydraulic pressure and mixing of groundwater with different geochemistry increased rates of dissolution in dolostone. Criss and Osburn (2009) and Taylor and others (2009) discussed karst features, with a particular focus on caves in the Ozark Plateaus of Missouri and Arkansas, respectively. Kresse and others (2014) thoroughly summarized the hydrogeology, groundwater geochemistry, and groundwater quality of the Springfield Plateau aquifer and the Ozark aquifer in Arkansas.

Many studies have investigated the interaction of surface water and groundwater in the karst terrain of the Ozark system, providing quantitative estimates of water flux between the surface-water and groundwater systems (see “Stream Leakage” and “Groundwater Discharge to Streams” sections). The magnitude of groundwater/surface-water exchange on various stream reaches in the Ozarks ranges from values below measurable levels to hundreds of cubic feet per second. Examples of surface-water/groundwater interaction studies include Bolon (1953), Emmett and others (1978), Harvey (1980), Harvey and others (1983), Freiwald (1987), Imes (1989), Joseph and Green (1994a, 1994b), Imes and others (1996), Kleeschulte (2000, 2008), Moix and others (2003), Mugel and Imes (2003), Moix and Galloway (2005), Smith and others (2007), Mugel and others (2009), and Richards (2010). Streams in the Ozark Plateaus were found to predominantly comprise gaining sections, with local losing sections, thus highlighting the interaction of surface water and groundwater.

The Ozark Plateaus are one of the major mining districts in the United States, and of particular importance to groundwater levels in the Ozark system, mines in central Missouri and the Missouri-Kansas-Oklahoma border region require dewatering. The histories of lead, zinc, iron ore, and barite mining, along with relevant hydrogeologic data, were presented in Buckley (1908), Abernathy (1941), Reed and others (1955), McKnight and Fischer (1970), Warner and others (1974), Jorgensen and others (1996), Rafferty (2001), and Missouri Department of Natural Resources (2015). Pumping to lower groundwater levels below active mining levels ranged from 0.2 to 7.7 million gallons per day (Mgal/d) at individual mines (Buckley, 1908; Abernathy, 1941; Reed and others, 1955; Warner and others, 1974). Stoffell and others (2008) provided analysis of fluid inclusions in quartz and sphalerite to determine an evaporative seawater origin for the brines that contributed to the Mississippi Valley-type (MVT) mineralization found in the mining districts of the Ozark Plateaus. Different episodes of metal-rich and metal-poor brine migration followed the same paths of higher permeability during basin evolution, helping to explain the spatial heterogeneity of MVT deposits (Stoffell and others, 2008).

Numerous works on groundwater hydrology and geochemistry have been completed at the basin scale or spring recharge-area scale and contribute to a better understanding of shallow groundwater flow in the Ozark system and geologic control on karst features. Examples of such work include, but are not limited to, Vandike (1994), Davis and others (2000), Peterson and others (2000), Peterson and others (2002), Sauer and others (2002), Imes and others (2007), Owen and Pavlowsky (2011), Knierim and others (2013), and Knierim and others (2015). Although regional models show overall topographic control over shallow groundwater flow on a large scale (Imes and Emmett, 1994), groundwater flow on smaller scales follows unpredictable focused flow paths that are controlled less by topography and more by stratigraphy and structure (Brahana, 2011). Groundwater flow paths commonly cross surface topographic divides and are dynamic, frequently changing dominant conduits or direction, as well as changing recharge-area boundaries and size as hydrologic conditions change (Ford and Williams, 2007; Brahana, 2011). Many of the smaller-scale studies include a water-quality component because of the need to characterize groundwater flow paths in vulnerable karst terrain to mitigate contamination of groundwater resources. These less-than-regional, smaller-scale studies provide thorough assessments of processes—biological, chemical, or physical—that control contaminant transport and attenuation and, in combination with the local- and regional-scale studies, can elucidate the mechanisms that control groundwater flow in the highly heterogeneous karst aquifers of the Ozarks.

Geologic Structure

The dominant structural feature defining the Ozark Plateaus is a broad, elliptical dome that has been uplifted during several periods since the Precambrian to bring the Ozark Plateaus to their current altitude (Fenneman, 1938; Nunn and Lin, 2002; Tennyson and others, 2008; Cox, 2009). The core of the dome is in east-central Missouri where units of the St. Francois aquifer crop out (fig. 1); sedimentary units in southern Missouri and Arkansas drape off the margins of the dome, with gentle regional dips generally ranging from 10 to 100 feet per mile (ft/mi) and steeper dips commonly proximal to faults (Frezon and Glick, 1959; Hudson, 2000). Extensive extensional fracturing, jointing, and faulting of Ozark system rocks occurred with uplift (Hudson, 2000), creating secondary porosity that has provided key nucleation points for initiation of dissolution of the carbonate rocks and karst development. Topographic relief in the Ozark Plateaus results from erosional dissection of the plateaus rather than from intense folding and faulting, and erosion has been controlled to a degree by structural features, as well as lithology (Adamski and others, 1995).

During the Appalachian-Ouachita orogeny of the middle Mississippian to Permian Periods, rocks of the Ozark Plateaus were generally subjected to south-to-north verging compression associated with convergence and collision of the North American, European, South American, and African tectonic plates (Thomas, 1989; Viele and Thomas, 1989; Bradley and Kidd, 1991; Hudson, 2000). Hudson (2000) also inferred east-west shortening related to the oblique diachronous closure of the Ouachita orogenic belt along the southern margin of the craton, with collision of the plates beginning in the area of Alabama and progressing obliquely to the Marathon Mountains region of western Texas. The sequence of rocks responded in a predominantly brittle-strain manner; stress fields resulted in joint, fracture, and fault development strongly oriented on east-west, southwest-northeast, southeast-northwest, and north-south trends (fig. 9) related to accommodation of triaxial strain through a combination of normal, strike-slip, and (or) reverse faults and folds with differing strikes (Hudson, 2000). Hudson and others (2011) and Hudson and Murray (2003) presented strain rosettes for data in the Buffalo River at the Salem Plateau-Springfield Plateau boundary area documenting joint, fracture, and fault orientations and related these to the sequential phases of the Ouachita orogeny. Orndorff and others (2001), Weems (2002), and Weary and Schindler (2004) presented joint-orientation data for south-central Missouri that mirrored orientations described by Hudson and others (2011) (fig. 9).

Plastic deformation, or folding, occurs but is less important as a volume-accommodation response near faults across the Salem and Springfield Plateaus; folds and the presence of dips of 10 degrees (°) or more generally indicates proximity of a fault. Gentle east-west trending folds are common in the Boston Mountains near the Arkansas River Valley and Ouachita Mountains south of the Ozarks. These folds also formed in response to the same south-to-north verging compression of the Appalachian-Ouachita orogeny (Hudson and others, 2011). The network of joints, fractures, and faults was critically important in providing the earliest higher permeability groundwater flow paths in this thick sequence of rocks with generally very low primary porosity and permeability, thus providing the nuclei for incipient development of dissolutive porosity in carbonate intervals, leading the way for further extensive dissolution and karst development (Tennyson and others, 2008; Brahana and others, 2009).

Karst Development

Karst development processes and history are important aspects of the geology controlling groundwater hydrology in the Ozark system (Miller and Vandike, 1997). Carbonate bedrock in the Ozark system shows evidence of multiple episodes of karst dissolution events through geologic time (Stoffell and others, 2008), such as paleokarst development during exposure of Ordovician units associated with the Ordovician-Mississippian unconformity and later exposure of Mississippian units associated with the Mississippian-Pennsylvanian unconformity (Webb, 1994; Kresse and others, 2014). Additionally, widespread dissolution features are associated with the lead and zinc ore-bearing fluids that are thought to have moved from the Arkoma Basin and deposited the MVT ores throughout northern Arkansas and southern and central Missouri (Leach and Rowan, 1986). Multiple lines of evidence for hypogene karst development, such as calcite isotopic compositions (Brahana and others, 2009), collapse breccias (McKnight, 1935), and isotopic dating (Brannon and others, 1996; Tennyson and others, 2016), illustrate how this episode of fluid movement and dissolution was a separate occurrence predating recent surface-karst development (Kresse and others, 2014).

The most recent period of epigenetic dissolution and karst development exerts important controls over patterns of groundwater and ultimately surface-water flow, such that the hydrogeology of the region is typified by focused flow paths, aquifer anisotropy, and close connection between surface water and groundwater. Abundant karst features are apparent throughout the Ozark Plateaus, such as ponors, losing and gaining stream reaches, springs, caves, and sinkholes, and typical of karst aquifers, focused flow paths can deliver water from input to discharge points at streams and springs at velocities of tens to thousands of feet per day (Funkhouser and others, 1999; Mott and others, 2000; Hudson and others, 2011). Recent karst development has commonly reactivated,

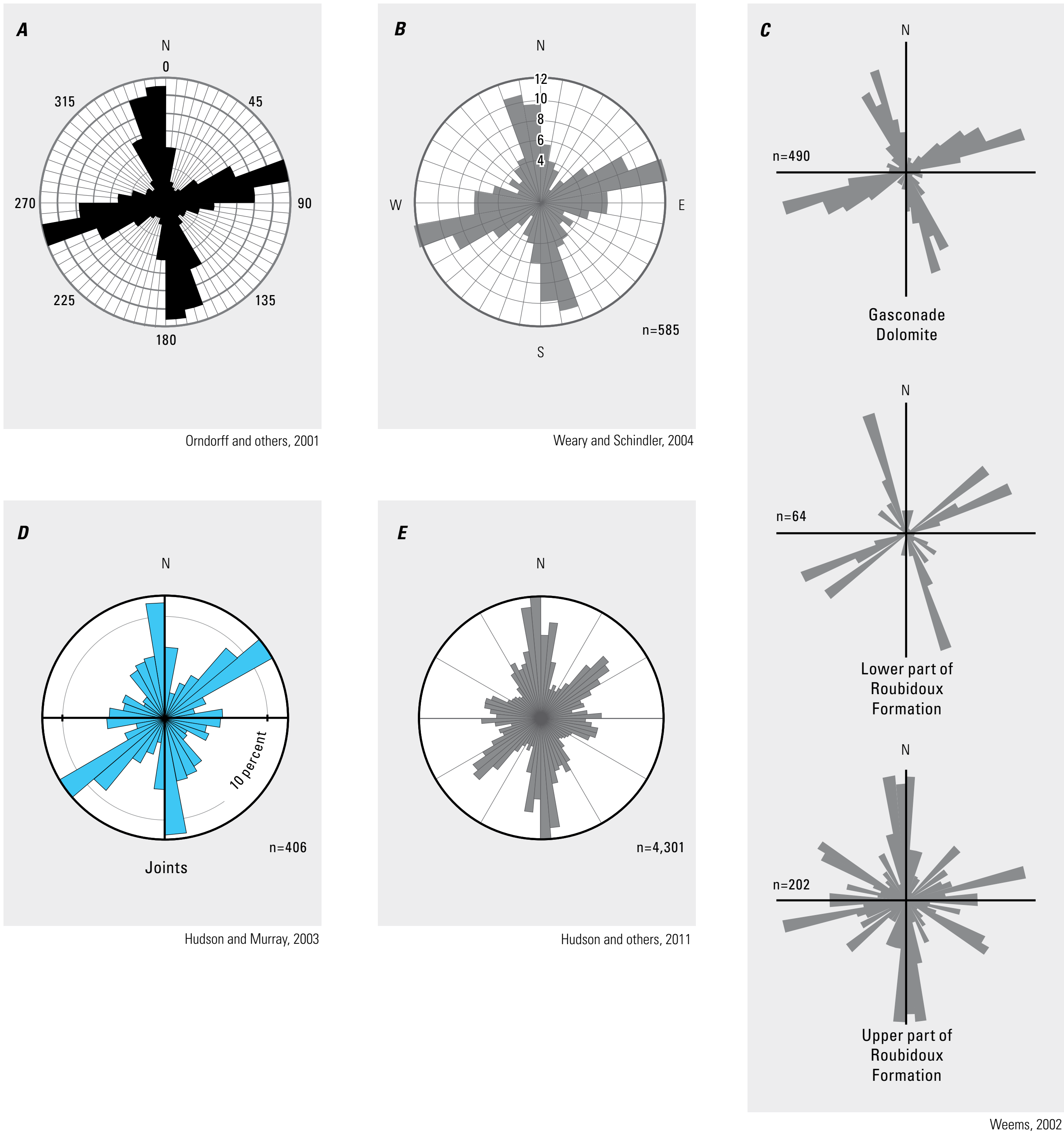


Figure 9. Fracture orientations for central and southern Missouri from *A*, Orndorff and others, 2001; *B*, Weary and Schindler, 2004; and *C*, Weems, 2002; and for northern Arkansas from *D*, Hudson and Murray, 2003; and *E*, Hudson and others, 2011.

following previous dissolution-enhanced flow paths that originally developed during ancient exposure periods, such as those that occurred with the Ordovician-Mississippian and the Mississippian-Pennsylvanian unconformities (Webb, 1994), or hypogene episodes, such as MVT ore emplacement (Leach and Rowan, 1986; Brannon and others, 1996; Tennyson and others, 2008; Brahana and others, 2009). Additionally, epigenetic dissolution and pedogenesis—especially on Mississippian limestones—have resulted in a cherty regolith mantle that varies in thickness throughout the Ozark Plateaus and can cause variable flow rates through the unsaturated zone (Al-Qinna and others, 2014). The regolith mantle is a key characteristic of the karst terrane in the Springfield Plateau. The variable thickness and variable hydraulic properties exert strong control over karst development, recharge, and vulnerability to surface-derived contaminants in the Springfield Plateau aquifer.

Karst development is more advanced—more ubiquitous, uniform, and homogeneous—as evidenced by larger conduits, greater porosity, larger springs, hydraulic characteristics, and greater presence of karst features in the Salem Plateau and in the northern part of the Springfield Plateau (generally north of the Arkansas-Missouri border) as compared with the southern part of the Springfield Plateau in Arkansas (Harvey, 1980; Vineyard and Feder, 1982). This more advanced development is caused by lower contents of chert and other insoluble minerals and lack of extensive regolith mantling in the northern areas of the Ozark system. The degree of karst development across the Ozark system is perhaps best demonstrated by the abundant occurrence of springs and sinkholes and in the importance of groundwater contribution to streamflow. Units in the lower part of the Ozark aquifer host some of the largest springs in the United States; 10 springs are categorized as first-order magnitude springs, with average flow exceeding 100 ft^3/s (Criss and Osburn, 2009). An abundance of springs also discharge from the Springfield Plateau aquifer but tend to be of lower order magnitude (Harvey, 1980). In south-central Missouri, streams may lose flow in areas of exposure of the Springfield Plateau aquifer compared with outcrop areas of the Salem Plateau (Skelton, 1970; Imes, 1989; Richards, 2010). These differences in attributes of the two plateaus provide qualitative evidence of the variable karst development and hydrogeology between the Springfield and Salem Plateaus, but important quantitative questions remain about how this variability may result in different groundwater flow paths and rates and susceptibility to surface-derived contamination in the Springfield Plateau aquifer versus the Ozark aquifer.

Hydrostratigraphy and Lithology

The Ozark system comprises a sequence of Paleozoic clastic and carbonate rocks deposited over the Ozark dome. Uplift and erosion have resulted in older rocks of Cambrian to Devonian age being exposed in the central higher uplift area of the dome; these Cambrian to Devonian rocks constitute the St. Francois and Ozark aquifers and outcrop in the St. Francois Mountains and Salem Plateau. Younger rocks of Mississippian to Pennsylvanian age are exposed on the flanks of the uplift; these Mississippian to Pennsylvanian rocks constitute the Springfield Plateau aquifer and Western Interior Plains confining system and crop out in the Springfield Plateau and Boston Mountains (fig. 1). The Ozark system has been previously divided into five primary hydrogeologic units—(1) Springfield Plateau aquifer, (2) Ozark confining unit, (3) Ozark aquifer, (4) St. Francois confining unit, and (5) St. Francois aquifer—and the Ozark aquifer has been further divided into upper, middle, and lower sections for the updated hydrogeologic framework (Westerman and others, 2016) to better represent the hydraulic properties of the aquifer (fig. 10). The Ozark system has been regionalized in this fashion to support characterization of the aquifer and development of groundwater flow, as well as potential mass-transport and linked watershed models, to aid in better understanding and managing of the water resource represented by the system. Although data available for a limited number of locations or zones within the Ozark Plateaus might enable more detail and complex delineation of aquifers vertically and areally, current (2016) data are insufficient to effectively further delineate the aquifers in a vertical or areal fashion across the extents of the Ozark Plateaus. The Ozark system has been delineated at a regional scale as presented herein to address regional aquifer and groundwater-flow assessment needs and to provide a starting point for more detailed local-scale studies. As a caveat, regional-scale delineations have been demonstrated to provide inaccurate results where site-specific data are needed; hence, scientists and water managers are advised to fully assess specific study and management scale and goals when using regional datasets. Further details regarding methods to update the hydrogeologic framework and results for hydrogeologic-unit thickness and altitude can be found in Westerman and others (2016).

[Blue lines mark boundaries between hydrogeologic units. Shading represents divisions between the upper (green), middle (red), and lower (blue), Ozark aquifer. Modified from Imes and Emmett, 1994 (table 1)]

Era	System	Southeastern Missouri	Southwestern Missouri	Southeastern Kansas	Northeastern Oklahoma	Northern Arkansas	Aquifers and confining units described in the report: Hydrogeologic unit	Aquifers and confining units described in the report: Hydrogeologic system	Physiographic areas[7] described in the report: Section	Physiographic areas[7] described in the report: Province
PALEOZOIC	PENNSYLVANIAN	Pleasanton Formation[1] Marmaton Group[1] Cherokee Shale[1]	Kansas City Group Pleasanton Formation Marmaton Group Cherokee Shale	Kansas City Group Pleasanton Group Marmaton Group Cherokee Group	Marmaton Group Cabaniss Group Krebs Group Atoka Formation Bloyd Shale Hale Formation	McAlester Formation Hartshorne Sandstone Atoka Formation Bloyd Shale Hale Formation		WESTERN INTERIOR PLAINS CONFINING SYSTEM[2]	OSAGE PLAINS	CENTRAL LOWLAND
	MISSISSIPPIAN	Vienna Limestone[1,4] Tar Springs Sandstone[1,4] Glen Dean Limestone[1,4] Hardinsburg Sandstone[1,4] Golconda Formation[1,4] Cypress Formation[1,4] Paint Creek Formation[1,4] Yankeetown Sandstone[1,4] Renault Formation[1,4] Aux Vases Sandstone[1]	Fayetteville Shale Batesville Sandstone Hindsville Limestone Carterville Formation		Pitkin Limestone Fayetteville Shale Batesville Sandstone Hindsville Limestone	Pitkin Limestone Fayetteville Shale Batesville Sandstone			BOSTON MOUNTAINS[8]	OZARK PLATEAUS
		Ste. Genevieve Limestone[3] St. Louis Limestone[3]	St. Louis Limestone	St. Louis Limestone	Moorefield Formation	Moorefield Formation				
		Salem Limestone[3] Warsaw Limestone[3] Keokuk Limestone[3] Burlington Limestone[3] Fern Glen Limestone[3]	Salem Limestone Warsaw Limestone Keokuk Limestone Burlington Limestone Elsey Formation Reeds Spring Formation Pierson Formation[4]	Salem Limestone Warsaw Limestone Keokuk Limestone Burlington Limestone Fern Glen Limestone	Keokuk Limestone[4] Boone Formation Reeds Spring member St. Joe Limestone member	Boone Formation Reeds Spring member St. Joe Limestone member	SPRINGFIELD PLATEAU AQUIFER	OZARK PLATEAUS AQUIFER SYSTEM[5]	SPRINGFIELD PLATEAU[9]	
		Chouteau Limestone Hannibal Shale Bachelor Formation[4]	Northview Shale Sedalia Limestone Compton Limestone	Chouteau Limestone	Northview Shale[6] Compton Limestone[6]		OZARK CONFINING UNIT			
	DEVONIAN	Bushberg Sandstone Glen Park Limestone Chattanooga Shale	Chattanooga Shale	Chattanooga Shale	Woodford Chert Chattanooga Shale	Chattanooga Shale				
		St. Laurent Limestone Grand Tower Limestone Clear Creek Chert[4] Little Saline Limestone Bailey Limestone	Sallisaw Formation[4] Fortune Formation[4]		Sallisaw Formation Frisco Limestone	Clifty Limestone Penters Chert	UPPER OZARK AQUIFER		SALEM PLATEAU[10]	

Figure 10. Generalized correlation of Paleozoic stratigraphic units, regional hydrogeologic units, and physiographic areas in the study area.

PALEOZOIC	SILURIAN	Bainbridge Limestone Sexton Creek Limestone[4]			St. Clair Limestone	Lafferty Limestone St. Clair Limestone Brassfield Limestone	UPPER	OZARK AQUIFER	OZARK PLATEAUS AQUIFER SYSTEM[5]	SALEM PLATEAU[10]	OZARK PLATEAUS
	ORDOVICIAN	Girardeau Limestone Orchard Creek Shale Thebes Sandstone Maquoketa Shale									
		Cape Limestone[4] Kimmswick Limestone Decorah Formation Plattin Limestone Rock Levee Formation[4] Joachim Dolomite Dutchtown Formation[4] St. Peter Sandstone Everton Formation Smithville Formation Powell Dolomite	Kimmswick Limestone Plattin Limestone Joachim Dolomite St. Peter Sandstone Everton Formation Smithville Formation Powell Dolomite	Powell Dolomite	Sylvan Shale Fernvale Limestone Viola Limestone Fite Limestone Tyner Formation Burgen Sandstone undefined units equivalent to Smithville Formation Powell Dolomite	Cason Shale Fernvale Limestone Kimmswick Limestone Plattin Limestone Joachim Dolomite St. Peter Sandstone Everton Formation Smithville Formation Powell Dolomite					
		Cotter Dolomite Jefferson City Dolomite	Cotter Dolomite Jefferson City Dolomite	Cotter Dolomite Jefferson City Dolomite	Cotter Dolomite Jefferson City Dolomite	Cotter Dolomite Jefferson City Dolomite	MIDDLE				
		Roubidoux Formation Gasconade Dolomite Van Buren Formation[4] Gunter Sandstone member[4]	Roubidoux Formation Gasconade Dolomite Gunter Sandstone member[4]	Roubidoux Formation Gasconade Dolomite Van Buren Formation[4] Gunter Sandstone member	Roubidoux Formation Gasconade Dolomite Van Buren Formation[4] Gunter Sandstone member[4]	Roubidoux Formation Gasconade Dolomite Van Buren Formation[4] Gunter Sandstone member[4]	LOWER				
	CAMBRIAN	Eminence Dolomite Potosi Dolomite	Eminence Dolomite Potosi Dolomite	Eminence Dolomite Potosi Dolomite[6]	Eminence Dolomite Potosi Dolomite[6]	Eminence Dolomite Potosi Dolomite					
		Doe Run Formation Derby Formation Davis Formation	Doe Run Formation Derby Formation Davis Formation	undefined units equivalent to Doe Run Formation Derby Formation Davis Formation	undefined units equivalent to Doe Run Formation Derby Formation Davis Formation[6]	undefined units equivalent to Doe Run Formation Derby Formation Davis Formation	ST. FRANCOIS CONFINING UNIT				
		Bonneterre Formation[6] Reagan Sandstone[4] Lamotte Sandstone	Bonneterre Dolomite Reagan Sandstone[4] Lamotte Sandstone	Bonneterre Dolomite[6] Reagan Sandstone Lamotte Sandstone	undefined units equivalent to Bonneterre Dolomite Reagan Sandstone Lamotte Sandstone	Bonneterre Dolomite undefined units equivalent to Reagan Sandstone Lamotte Sandstone	ST. FRANCOIS AQUIFER				
	PRECAMBRIAN IGNEOUS AND METAMORPHIC ROCKS						BASEMENT CONFINING UNIT				

[1]Geologic unit in southeastern Missouri that is stratigraphically equivalent to geologic units in the Western Interior Plains confining system but not part of the confining system.

[2]The Western Interior Plains confining system also includes younger sediments west of the study area.

[3]Geologic unit in southeastern Missouri that is stratigraphically equivalent to geologic units in the Springfield Plateau aquifer but not part of the aquifer.

[4]Unit follows usage of the Missouri Division of Geology and Land Survey.

[5]The Western Interior Plains aquifer system deeply buried in the western part of the study area included, where permeable carbonate rocks in the subsurface are equivalents of the aquifers of the Ozark Plateaus aquifer system (Miller and Appel, 1997).

[6]Unit follows usage of the National Geologic Map Database.

[7]Physiographic areas modified from Fenneman (1938).

[8]The Boston Mountains only include a portion of the Western Interior Plains confining system.

[9]The Springfield Plateau and Salem Plateau are grouped together in Fenneman (1938) but can be separated on the basis of distinct geologic and hydrogeologic characteristics, as noted by the U.S. Geological Survey figure in Fenneman (1938) and Adamski and others (1995). The Ozark confining unit is not explicitly defined as part of the Springfield Plateau, but is grouped with the Springfield Plateau in this report because of similar geologic character.

[10]The metamorphic and igneous portion of the Salem Plateau is also referred to as the "Saint Francois Mountains" but is not a separate physiographic section from Fenneman (1938).

Figure 10. Generalized correlation of Paleozoic stratigraphic units, regional hydrogeologic units, and physiographic areas in the study area.—Continued

Western Interior Plains Confining System

The Western Interior Plains confining system is a regionally important system that extends from the Rocky Mountains east to the Ozark system study area (fig. 1). The confining system overlies the Springfield Plateau aquifer (fig. 10) and restricts vertical exchange of water with the Ozark system at the western margins of the Springfield Plateau and south in the Boston Mountains (fig. 1). In the study area, the Western Interior Plains confining system is represented by Upper Mississippian and Pennsylvanian rocks, primarily shale with minor limestone and sandstone (Jorgensen and others, 1993). Facies and lithologic differences, as well as differing mapping histories, have resulted in different stratigraphic assignments in the four States of the Ozark system (fig. 10); for example, in Arkansas the confining system includes the Mississippian Moorefield Formation because of the formation's greater shale content, whereas in Oklahoma the Springfield Plateau aquifer includes the Moorefield Formation because of a lesser shale content (fig. 10). Fracturing and weathering of near-surface rocks in the Western Interior Plains confining system have enhanced porosity and permeability—generally at depths less than 300 feet (ft)—which also decreases confining-unit effectiveness (Imes and Emmett, 1994). Additionally, relatively permeable intervals of sandstone, limestone, and coal are present in the system, which makes some zones of the Western Interior Plains confining system a viable local target for low-yield wells (Kresse and others, 2014). Generally and more regionally, the less permeable units dominate the hydraulic characteristics of the system and collectively impede flow to and from the underlying Ozark system. The Western Interior Plains confining system has a mean thickness of 1,420 ft and a median thickness of 542 ft in the study area (Westerman and others, 2016).

Springfield Plateau Aquifer

The Springfield Plateau aquifer is the uppermost hydrogeologic unit in the Ozark system and consists of Mississippian limestones (fig. 10) with varying abundances of chert, as well as minor amounts of shale and siltstone. The aquifer overlies the Ozark confining unit except in small areas where the Ozark confining unit is absent, and the Springfield Plateau aquifer directly overlies the Ozark aquifer. The distribution of carbonate facies and lithologies in the lower Mississippian section constituting the Springfield Plateau aquifer is complex; these varying facies and lithologic, combined with long and varied mapping histories, have resulted in differences in the stratigraphic nomenclature applied from one State to another (fig. 10).

In southeastern Kansas and southwestern Missouri, the Keokuk and Burlington Limestones—medium to coarsely crystalline bedded limestone with variable but commonly abundant nodular gray chert (Frick, 1980)—constitute the thickest, most permeable, and most important formations of the Springfield Plateau aquifer (fig. 10). Karst development is typically advanced in the more northerly outcrop areas with development of a mature karst terrane at the surface. In Arkansas, the Boone Formation exclusively represents the Springfield Plateau aquifer (fig. 10); locally in Arkansas the St. Joe Limestone Member has been mapped as a separate formation within the aquifer (Shelby, 1986) but is formally categorized as a member of the Boone Formation by the USGS. The Boone Formation is a gray fine- to coarse-grained, fossiliferous limestone with interbedded chert layers, and chert layers can exceed 70 percent of the interval (Brahana and others, 2009); these chert layers can extend continuously across variable areal scales of tens of feet to miles. The St. Joe Limestone is a dense, fine-grained relatively pure carbonate crinoid limestone and contains very little chert, generally less than 5 percent, as compared with upper sections of the Boone Formation. Karst development is greater, and the occurrence of karst features (for example, caves and springs) is more pronounced in the St. Joe Limestone than in the upper interval of the Boone Limestone. Matrix porosity and permeability of the Boone Formation is very low (Stanton, 1993), but fracturing is common, and dissolution along fractures has greatly enhanced porosity and permeability in the carbonate intervals, ultimately creating the karst terrain that typifies the area (Nunn and Lin, 2002; Brahana and others, 2009). In northeastern Oklahoma, the Springfield Plateau aquifer is composed of the Moorefield Formation, the Keokuk Limestone, and the Boone Formation (fig. 10). The Moorefield Formation varies in lithology from limestone to siltstone and shale. The Boone Formation in Arkansas and Oklahoma and the Keokuk Limestone in Oklahoma are lithologically and hydrogeologically similar to the Burlington and Keokuk Limestones of southwestern Missouri; however, these units in the more southerly parts of the Springfield Plateau aquifer are less permeable because the higher chert and clay contents are less favorable for karst development (Stanton, 1993). The Springfield Plateau aquifer has a mean thickness of 227 ft and a median thickness of 237 ft (Westerman and others, 2016). Although aggregated into a single hydrogeologic unit for the purposes of this study, workers studying the hydrogeology of the region often divide the Springfield Plateau aquifer into three units for effective analysis of more local-scale problems (Stanton, 1993; Tennyson and others, 2016): (1) a relatively high-permeability lower unit (corresponding to the relatively pure limestone of the St. Joe Limestone Member in Arkansas and the Pierson Formation and Reeds Spring Limestone in Missouri), (2) a lower permeability middle unit (corresponding to the dark cherty interval of the lower Boone Formation in Arkansas and the Elsey Formation in Missouri), and (3) a relatively high-permeability upper unit (corresponding to light-gray less cherty purer limestone of the upper part of the Boone Formation in Arkansas and the Burlington and Keokuk Limestones in Missouri).

Ozark Confining Unit

The Ozark confining unit limits movement of groundwater between the underlying Ozark aquifer and the overlying Springfield Plateau aquifer across the Springfield Plateau and south into the Boston Mountains and confines flow in the underlying Ozark aquifer in a small area on the northeastern margin of the Ozark system (fig. 1). The confining unit comprises Mississippian-, Devonian-, Silurian-, and Upper Ordovician-age cherts, limestones, sandstones, and shales (fig. 10). The important geologic formations that constitute the confining unit vary somewhat across the study area. In southeastern Kansas, northeastern Oklahoma, and northern Arkansas, the confining unit is represented by Upper Devonian shales and Lower Mississippian shales and limestones (fig. 10). In the small area on the northeastern margin of the Ozarks in southeastern Missouri (fig. 1), the confining unit comprises 17 formations in the interval between the base of the Upper Ordovician Maquoketa Shale to the top of the Lower Mississippian Chouteau Limestone (fig. 10). Imes and Emmet (1994) recognized that some of these formations are locally important, albeit low-yielding, water-bearing units. To date (2016), these units have not been assigned to specific regional aquifers because of their limited distribution and importance. Considerable variation in shale content throughout the confining unit has been related to effectiveness in impeding vertical flow across the unit (Imes and Emmett, 1994). The Ozark confining unit has a mean thickness of 59 ft and a median thickness of 42 ft (Westerman and others, 2016).

Ozark Aquifer

The Ozark aquifer is the primary groundwater source used in the study area (Imes and Emmett, 1994; Miller and Vandike, 1997). The aquifer is overlain by the Ozark confining unit except where the Ozark aquifer is exposed or where the Ozark confining unit is missing. The aquifer is underlain by the St. Francois confining unit. The Ozark aquifer is in direct hydraulic connection with the Springfield Plateau aquifer in some isolated areas where the Ozark confining unit is missing. The Ozark aquifer is divided into the upper, middle, and lower Ozark aquifers on the basis of water-level, water-quality, and lithologic data to better capture the spatial variation in the hydrologic property differences of the various rock formations that make up these hydrogeologic units (Westerman and others, 2016).

The upper Ozark aquifer comprises an Upper Ordovician through Devonian sequence of rocks (Imes and Emmett, 1994); the important water-bearing formations that are more widely distributed and recognizable are, in ascending order, Everton Formation, St. Peter Sandstone, Joachim Dolomite, Plattin Limestone, Kimmswick Limestone, and Fernvale Limestone (fig. 10). The upper Ozark aquifer is absent across much of the Salem Plateau but is exposed along some boundary areas to the east, north, and south and in some deeply eroded areas within the Springfield Plateau along deeply incised streams and on uplifted fault blocks. The upper Ozark aquifer is generally unconfined where present in outcrop across the Salem Plateau and is confined in the Springfield Plateau and Boston Mountains. The upper Ozark aquifer differs from the lower Ozark aquifer in predominant lithologies, groundwater levels, areas of exposure and confinement, yields, and geochemistry (Imes and Emmett, 1994; Kresse and others, 2014). Limestone-dominated, dolostone, and shale intervals are common; sandstone units are present but less common. As is the case for the lower Ozark aquifer, primary porosity and permeability values for the upper Ozark aquifer are relatively small for much of the section (Imes and Emmett, 1994). Unlike the lower Ozark aquifer, karst development and secondary porosity development are less progressed in the upper Ozark aquifer; hence, gross porosity and permeability and water yields in the upper Ozark aquifer tend to be less. The upper Ozark aquifer has a mean thickness of 649 ft and a median thickness of 590 ft (Westerman and others, 2016).

The middle Ozark aquifer comprises the Ordovician Jefferson City Dolomite and Cotter Dolomite (fig. 10). This sequence is composed predominantly of dense, low-porosity, low-permeability dolostones that exhibit a narrow range of reported hydrogeologic properties (Winslow, 1894; Purdue and Miser, 1916; Howe and Koenig, 1961; Miller and Vandike, 1997; McFarland, 2004). This interval of low-permeability rocks provides for minor domestic water supply but does not serve as a regionally important aquifer. The hydraulic characteristics (low permeability, low storage) contrast markedly with bounding units, and as a result, the middle Ozark aquifer acts to restrict flow to a degree between the better quality lower and upper Ozark aquifers; hence, the middle Ozark aquifer serves as a confining unit hydrologically. The middle Ozark aquifer has a mean thickness of 504 ft and a median thickness of 416 ft (Westerman and others, 2016).

The lower Ozark aquifer includes, in ascending order, the Cambrian Potosi Dolomite and Eminence Dolomite and the Ordovician Van Buren Formation, Gasconade Dolomite, and Roubidoux Formation (fig. 10). Because of the distribution, accessibility, thickness, and hydrologic properties of the lower Ozark aquifer, it is the most important and productive part of the Ozark aquifer within the Ozark system (Westerman and others, 2016). The lower Ozark aquifer is exposed and variably unconfined and confined within central and eastern areas of the Salem Plateau and is confined where the middle Ozark aquifer is present; confinement of the lower Ozark aquifer is dependent upon the presence and competence (fracturing, weathering, and dissolution) of overlying lower permeability formations. The formations constituting the lower Ozark aquifer are predominantly dolostones, with sandstone and shale intervals being less abundant (Miller and Vandike, 1997). Original matrix porosity and permeability of these formations are very low, but fracturing and dissolution have greatly enhanced porosity and permeability across much of the central Ozark Plateaus (Miller and Vandike, 1997;

Orndorff and others, 2001); as a result, these rocks host some of the largest karst springs and represent some of the most productive karst aquifer rocks in the United States (Orndorff and others, 2006; Brahana, 2011; Kresse and others, 2014). Porosity is less enhanced in areas of confinement. The lower Ozark aquifer has a mean thickness of about 1,006 ft and a median thickness of 885 ft (Westerman and others, 2016).

St. Francois Confining Unit

The St. Francois confining unit hydraulically isolates the overlying Ozark aquifer from the underlying St. Francois aquifer. The confining unit comprises intervals of relatively low-permeability shale, siltstone, dolostone, and limestone of Upper Cambrian age (fig. 10). The unit is divided stratigraphically into the Davis Formation—a clastic-dominated unit containing abundant shale—and the Derby Dolomite and Doe Run Dolomite. The latter two units, as the names imply, are predominantly dense, generally low-permeability dolostone (Miller and Vandike, 1997). The St. Francois confining unit has a mean thickness of about 235 ft and a median thickness of about 228 ft (Westerman and others, 2016).

St. Francois Aquifer

The basal hydrogeologic unit of the Ozark system is the Cambrian St. Francois aquifer, which comprises permeable sandstones and dolostones of the Lamotte Sandstone, Reagan Sandstone, and Bonneterre Dolomite (fig. 10). These formations overlie the igneous and metamorphic Basement confining unit. Wells completed in the St. Francois aquifer generally yield 100 to 500 gallons per minute (gal/min); however, this aquifer is rarely used beyond its limited outcrop area because overlying aquifers offer shallower sources of water (Imes and Emmett, 1994). The St. Francois aquifer has a mean thickness of about 316 ft and a median thickness of about 291 ft (Westerman and others, 2016).

Basement Confining Unit

The Basement confining unit for the Ozark system primarily comprises Precambrian igneous rocks that constitute an extensive granitic complex that extends across much of the midcontinent (Kisvarsanyi, 1981; Lillie and others, 1983) and serves as the base confining unit across this region (Jorgensen and others, 1996; Miller and Vandike, 1997). The Basement confining unit is exposed across a large area at the core of the Ozark uplift in and southwest of the St. Francois Mountains (fig. 1). These igneous and metamorphic rocks exhibit very low permeability and serve as an effective confining unit (Imes and Emmett, 1994).

Aquifer Tests and Hydraulic Properties

Hydraulic properties of groundwater aquifers describe how groundwater is stored and how it flows through aquifers and will vary depending on aquifer material, porosity, permeability, aquifer thickness, and saturation state. A variety of aquifer tests—typically completed by pumping groundwater wells and observing water-level drawdown and recovery at one or more wells—have been completed throughout the Ozark system to calculate specific capacity, transmissivity, hydraulic conductivity (generally horizontal for aquifers and vertical for confining units), and storage coefficient (or storativity) (Vandike, 1992; Miller and Vandike, 1997; Macfarlane, 2007; Pugh, 2008). Groundwater models require hydraulic properties data, the sources of which are field aquifer tests. These usually sparse point data are input and extrapolated across broad areas during model calibration. Many wells in the Ozarks are open-hole completions (cased only to some depth below the surface) and produce water from multiple formations and often multiple aquifers (as delineated for this study); therefore, data obtained by aquifer tests are often not directly representative of properties of individual aquifers. This disparity highlights the importance of adjustment of hydraulic-property distributions during model calibration and parameter estimation. Parameter estimation is applied to determine hydraulic-property distributions that minimize differences between observed and calculated hydraulic heads, and these model-generated hydraulic-property distributions are ultimately used for running model scenarios (Reed and Czarnecki, 2006; Czarnecki and others, 2009; Richards, 2010). More hydraulic-property data are available for the Ozark aquifer than for the Springfield Plateau or St. Francois aquifers (fig. 11 and tables 3 and 4) because of the greater reliance on the Ozark aquifer for groundwater supply. Additionally, typical of many groundwater systems, substantially more hydraulic-property data are available for aquifers than for associated confining units. Data on specific capacity—the amount of water-level drawdown per unit well yield—from groundwater wells in Missouri (n = 844) (Missouri Department of Natural Resources, 2007) and Kansas (n = 11) (Kansas Geological Survey, 2014) provided additional data for estimation of hydraulic conductivity of Ozark system hydrogeologic units (Richards, 2010), but because of the widespread use of open-hole completion across the Ozarks, these data integrate the properties across the length of open-hole completion and provide a generalized or averaged assessment of hydraulic properties.

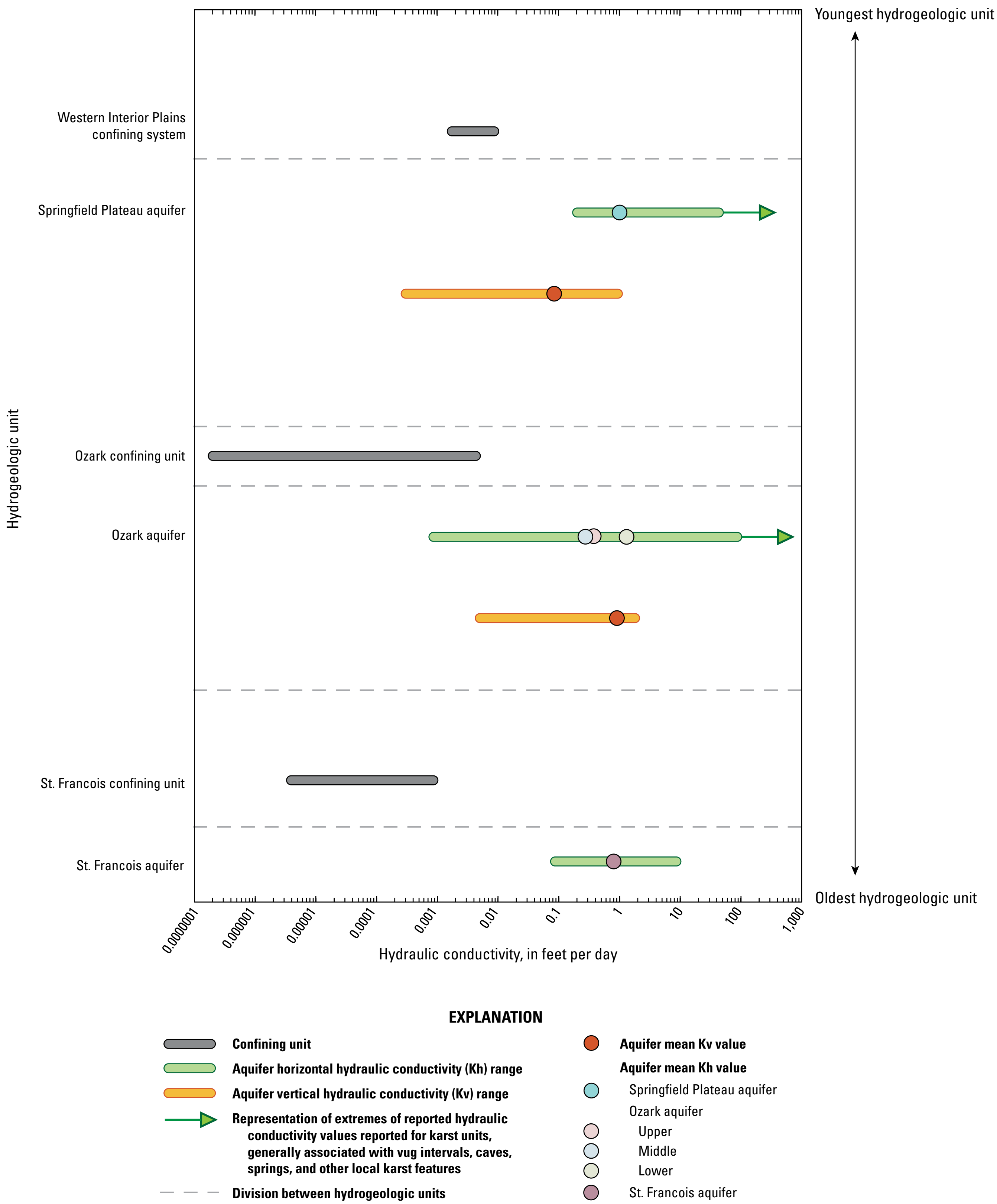


Figure 11. Reported select hydraulic-conductivity information for Ozark Plateaus aquifer system hydrogeologic units.

Table 3. Summary of hydraulic properties for the Ozark Plateaus aquifer system.

[--, no data; OK, Oklahoma; MO, Missouri; AR, Arkansas; KS, Kansas]

Well yield (gallons per minute)	Hydraulic conductivity		Storage coefficient	Method	Hydrogeologic unit	Location	Reference
	Horizontal (feet per day)	Vertical (feet per day)					
--	--	0.001728–0.00864	--	Modeling	Western Interior Plains confining system	Interior Plains	Imes and Emmett, 1994
--	25,000	10,000	--	Modeling	Mines, Springfield Plateau aquifer	Missouri-Kansas-Oklahoma border area	Czarnecki and others, 2009
--	50,000	--	--	Modeling	Mines, Springfield Plateau aquifer	Missouri-Kansas-Oklahoma border area	Reed and Czarnecki, 2006
--	21.6	--	--	Modeling	Springfield Plateau aquifer	Ozarks	Imes and Emmett, 1994
1–750	--	--	--	Well data	Springfield Plateau aquifer	Northeastern OK	Christenson and others, 1994
--	4.3–43	--	--	Modeling	Springfield Plateau aquifer	Southern MO	Imes, 1989
--	0.89–35	0.0003–1	--	Modeling	Springfield Plateau aquifer	Missouri-Kansas-Oklahoma border area	Czarnecki and others, 2009
--	1.3–35	0.026–0.7	--	Modeling	Springfield Plateau aquifer	Missouri-Kansas-Oklahoma border area	Reed and Czarnecki, 2006
--	0.2–8.73	--	--	Aquifer tests	Springfield Plateau aquifer	Southern MO	Richards, 2010
--	2.2–5.0	0.05–0.167	--	Modeling	Springfield Plateau aquifer	Southern MO	Richards, 2010
--	--	0.0043–0.000864	--	Modeling	Ozark confining unit	Ozarks	Imes and Emmett, 1994
--	--	0.0000078–0.0000095	--	Modeling	Ozark confining unit	Southern MO	Imes, 1989
--	0.0000864	--	--	Modeling	Ozark confining unit	Southern MO	Imes, 1991
--	0.00001–0.00004	0.0000002–0.0000245	--	Modeling	Ozark confining unit	Missouri-Kansas-Oklahoma border area	Czarnecki and others, 2009
--	0.000001–0.000075	0.0000002–0.000015	--	Modeling	Ozark confining unit	Southern MO	Richards, 2010
--	--	0.000086	--	Modeling	Ozark confining unit	Southern MO	Emmett and others, 1978
10–950	--	--	0.000000009–0.0066	Aquifer tests	Ozark aquifer	Ozarks in MO	Miller and Vandike, 1997
--	0.864–69.1	--	--	Modeling	Ozark aquifer	Ozarks	Imes and Emmett, 1994
--	0.000864–86.4	--	--	Aquifer tests	Ozark aquifer	Ozarks	Imes and Emmett, 1994
10–1,000	--	--	0.000001	Aquifer tests	Ozark aquifer	Northeastern OK	Christenson and others, 1994
--	0.7–2.6	--	0.0001	Modeling	Ozark aquifer	Southern MO	Imes, 1989
--	0.17–0.26	--	--	Modeling	Ozark aquifer	Southern MO	Imes, 1991
40–600	0.28–9.81	--	--	Aquifer tests	Ozark aquifer	Northern AR	Pugh, 2008
--	0.10145–5	0.005–1.8083	--	Modeling	Ozark aquifer	Missouri-Kansas-Oklahoma border area	Czarnecki and others, 2009
--	0.25–3.0	0.03–0.15	--	Modeling	Ozark aquifer	Southern MO	Richards, 2010
150–990	--	--	--	Aquifer tests	Ozark aquifer	Southern MO	Vandike, 1992
--	--	--	0.0002	Aquifer tests	Ozark aquifer	Southern MO	Feder and others, 1969
--	11.3	--	0.000113–0.000132	Aquifer tests	Ozark aquifer	Southeastern KS	Macfarlane, 2007
--	--	--	0.00078	Aquifer tests	Ozark aquifer	Southeastern KS	Stramel, 1957
--	--	0.000864	--	Modeling	St. Francois confining unit	Ozarks	Imes and Emmett, 1994
--	--	0.0000039	--	Modeling	St. Francois confining unit	Southern MO	Imes, 1989
100–500	0.0864–8.64	--	--	Aquifer tests	St. Francois aquifer	Ozarks	Imes and Emmett, 1994
--	0.17–[1]8.641	--	0.0026–0.0085	Aquifer tests	St. Francois aquifer	Southeastern MO	Warner and others, 1974

[1]Hydraulic conductivity estimated in Imes and Emmett (1994) by using data from Warner and others (1974).

Table 4. Summary of median hydraulic property values for the Ozark Plateaus aquifer system estimated from specific capacity of wells in Missouri (well data from Missouri Department of Natural Resources, 2007) and Kansas (well data from Kansas Geological Survey, 2014).

Saturated thickness (feet)	Specific capacity (gallons per minute per foot)	Transmissivity (square feet per day)	Hydraulic conductivity (feet per day)	Hydrogeologic unit	Number of wells
1,524	443	1,013	0.71	Ozark aquifer (entire)	68
665	87	366	0.37	Upper Ozark aquifer	11
884	444	984	1.07	Lower Ozark aquifer	421
638	291	524	0.80	St. Francois aquifer	30

In a trimodal conceptual model of porosity, karsted carbonate rocks include three end members of porosity: (1) primary from the bulk-rock characteristics of the matrix, (2) secondary from later stages of fracturing, and (3) tertiary from dissolution via groundwater that increases the aperture of fractures, forming conduits (Ford and Williams, 2007; Kresic, 2007). Note that most authors generally refer to dissolution as a type of secondary porosity (Hays and others, 1996). Primary porosity is important for providing storage capacity, but tertiary porosity creates highly connected and conductive groundwater flow paths through the aquifer (Kresic, 2007); these end members result in aquifer-permeability measurements that will vary depending on the scale of measurement (Halihan and others, 1999). Fracture and bedding-plane apertures and abundance of dissolution features typically decrease with depth as surface-flow-driven karst development decreases and lithostatic pressure increases (Drogue, 1980). Correspondingly, groundwater storage, hydraulic conductivity, and well yields decrease with depth in carbonate units of the Ozark system (Lamonds, 1972); therefore, heterogeneity in aquifer properties—both horizontal and vertical—are observable throughout the Ozark system depending on the aquifer type, degree of karstification, and scale of observation.

Western Interior Plains Confining System

The Western Interior Plains confining system confines part of the Springfield Plateau aquifer on the southern and western margins of the Ozark system (fig. 1). The confining system is composed dominantly of shale, with lesser amounts of limestone and sandstone (Jorgensen and others, 1996; Westerman and others, 2016). Hydraulic-property data within the Western Interior Plains confining system are limited because regionally the units act as a confining system, although shallow zones of fractured and weathered rock or localized zones of higher permeability can provide an important local water supply (Kresse and others, 2014). Wells are generally low yielding, rarely exceeding 1–5 gal/min, with a maximum discharge of approximately 60 gal/min (Cordova, 1964). Imes and Emmett (1994) estimated from groundwater modeling that vertical conductivity throughout the Western Interior Plains confining system ranged from 1.7×10^{-3} to 8.6×10^{-3} foot per day (ft/d) (fig. 11, table 3).

Springfield Plateau Aquifer

The Springfield Plateau aquifer is exposed and variably confined by chert layers of limited areal extent across most of the Springfield Plateau and more effectively confined where the Western Interior Plains confining system is present in the southern and western parts of the study area (fig. 1). The chert layers are dense and relatively impermeable and often provide local confinement at areal scales up to miles in extent. Seasonal variability in confinement is observed when changes in recharge result in large water-level fluctuations, with water levels rising above or dropping below chert layers to change confinement status. The karsted carbonate lithologies of the Springfield Plateau aquifer have highly variable aquifer characteristics; the heterogeneity is difficult to characterize because of the paucity of hydraulic-property data for the Springfield Plateau aquifer. Horizontal hydraulic conductivity generally ranges from 0.2 to 43 ft/d (table 3), with maximum reported values greater than 1,000 ft/d observed locally (Stanton, 1993) as a result of development of secondary and tertiary porosity through tectonic and diagenetic processes, particularly dissolution of bedrock along joints, fractures, and bedding planes. Hydraulic conductivity values of matrix-type porosity blocks are much lower, on the order of 10^{-7} ft/d or even less (Van den Heuvel, 1979). Estimates of vertical hydraulic conductivity through the Springfield Plateau aquifer are typically an order of magnitude lower than horizontal hydraulic conductivity (Adamski and others, 1995); values range from 3×10^{-4} to 1 ft/d (fig. 11, table 3).

Well yields in the aquifer reflect porosity type, such that where wells intersect highly porous and permeable zones, yields of 10–100 gal/min or more are observed (table 3) (Imes and Emmett, 1994; Kresse and others, 2014). In contrast, where wells are completed in zones with little secondary or tertiary development of porosity and permeability, well yields are typically less than 2 gal/min (Kresse and others, 2014). Most well yields from the Springfield Plateau aquifer are on the lower end of the range, yielding less than 20 gal/min (Macfarlane and Hathaway, 1987; Adamski and others, 1995; Miller and Appel, 1997). Because well yields generally decrease with depth in karsted carbonate aquifers, well depths rarely exceed 300 ft in the Springfield Plateau aquifer (Lamonds, 1972; Imes and Emmett, 1994).

Higher well yields have been observed in mining areas, especially the Missouri-Kansas-Oklahoma border region mining district, where approximately 2.9–7.7 Mgal/d of groundwater have been withdrawn to lower the water table below the level of the active mines (Reed and others, 1955). These high yields are the result of greater natural permeability in mineralized zones and enhanced permeability in engineered mine shafts and adits, increasing groundwater flow (Reed and others, 1955), although the zones of high hydraulic conductivity are restricted to areas within the immediate vicinity of the mines. To simulate these zones in groundwater models, very high horizontal hydraulic conductivities were used to represent the open mine shafts and subsequent conduit flow (fig. 11, table 3), ranging from 25,000 (Czarnecki and others, 2009) to 50,000 ft/d, though such values are not representative of the natural groundwater-flow system (Reed and Czarnecki, 2006).

Ozark Confining Unit

The Ozark confining unit, where present, separates and restricts groundwater flow between the overlying Springfield Plateau aquifer and the underlying Ozark aquifer. The hydraulic connection between the Ozark and Springfield Plateau aquifers varies across the Ozark system because the Ozark confining unit is missing in some areas and local variations in lithology and structure control leakance through the confining unit (Imes and Emmett, 1994; Miller and Appel, 1997). Vertical hydraulic conductivity has been estimated by groundwater modeling to range from 2×10^{-7} to 4×10^{-3} ft/d (fig. 11, table 3).

Ozark Aquifer

The Ozark aquifer is the primary groundwater source for water supply in the Ozark system and includes a thick sequence of interbedded carbonate and clastic units, dominated by dolostone and limestone (Miller and Appel, 1997; Czarnecki and others, 2009). Varying lithologies—such as sandstone compared to limestone or dolostone—and karstification of carbonate units have led to varying degrees of porosity and permeability, such that horizontal hydraulic conductivity of the Ozark aquifer ranges from 9×10^{-4} to 90 ft/d (fig. 11, table 3) and varies depending on the formation and hydrogeologic unit (that is, upper, middle, or lower); however, most groundwater wells are open to several zones within the aquifer, and therefore hydraulic-conductivity estimates do not always reflect discrete formations or hydrogeologic units within the aquifer (Imes and Emmett, 1994). Median hydraulic conductivity was estimated to be 0.7 ft/d for 68 wells that penetrate variable depths within the Ozark aquifer (table 4; Missouri Department of Natural Resources, 2007; Kansas Geological Survey, 2014).

Well yields and depths within the upper Ozark aquifer are comparable to those of the exposed Springfield Plateau aquifer, with relatively low yields that are reflective of generally low permeability (Fuller and others, 1967; Miller and Vandike, 1997; Kresse and others, 2014). Median hydraulic-conductivity data are scarce, but horizontal hydraulic conductivity was estimated to be 0.4 ft/d for 11 wells sourced from the upper Ozark aquifer (table 4; Missouri Department of Natural Resources, 2007; Kansas Geological Survey, 2014) and located in the northeastern part of the Ozark Plateaus (fig. 1). Units capable of producing groundwater in northern Arkansas include the St. Peter Sandstone, Joachim Dolomite, and Plattin Limestone, with yields generally between 10 and 50 gal/min (Miller and Vandike, 1997).

The middle Ozark aquifer includes a relatively thick sequence of dolostones and is less permeable than units in the lower Ozark aquifer (Imes, 1991; Miller and Vandike, 1997). Horizontal hydraulic conductivity was estimated to be approximately 0.3 ft/d on the basis of groundwater modeling (Imes, 1991) and aquifer tests (Pugh, 2008). Vertical hydraulic conductivity through the middle Ozark aquifer is also relatively low, such that the unit can function as a leaky confining unit (Miller and Vandike, 1997). The middle Ozark aquifer is generally not considered an important groundwater resource throughout the Salem Plateau (Miller and Vandike, 1997); groundwater wells typically yield less than 25 gal/min (Imes and Emmett, 1994; Miller and Vandike, 1997), with 40 gal/min observed locally (Pugh, 2008). The aquifer can be important locally, however, because well yields are sufficient to meet domestic needs.

Generally, units of the lower Ozark aquifer are much more productive than the overlying middle and upper Ozark intervals because of greater permeability and porosity (Imes and Emmett, 1994; Miller and Vandike, 1997). These rocks host some of the largest karst springs and represent some of the most productive karst aquifer rocks in the United States. Imes and Emmet (1994) noted the Potosi Dolomite as likely the most permeable geologic unit within the Ozark aquifer and the most productive target for groundwater in the Ozarks; most of the public-supply wells in southern Missouri are completed in the Potosi Dolomite. Although many of the largest, first-magnitude springs in the Ozarks emerge from relatively low-permeability formations, all of these springs are actually predominantly sourced by water upwelling from the underlying Potosi Dolomite (Vineyard and Feder, 1982); locally, in zones of well-developed vugs and dissolution channels, hydraulic conductivities in the lower Ozark aquifer can exceed 1,000 ft/d, evidenced by the abundant first-order springs sourced by the aquifer (Feder and others, 1969; Feder, 1979; Vineyard and Feder, 1982). Vertical hydraulic conductivities in the lower Ozark aquifer also must attain locally high values as evidenced by the numerous springs that emerge from overlying units that are sourced by the lower Ozark aquifer (Feder and others, 1969; Vineyard and Feder, 1982). The overlying Eminence Dolomite exhibits lower porosity and permeability but still yields abundant water. In the southern parts of the study area in Arkansas and Oklahoma, the Potosi and Eminence Dolomites are generally undifferentiated (Caplan, 1960; McCracken, 1964), and porosity and permeability are much lower, making these units of secondary importance for water supply in Arkansas and Oklahoma. Sandstone intervals of the Roubidoux Formation and Gunter Sandstone Member of the Gasconade Dolomite are important water-production targets where they are relatively thick, generally 10 ft or more, and porous.

Pugh (2008) summarized aquifer-test data for the Ozark system in northern Arkansas and found that major water-bearing formations had mean hydraulic conductivities of 0.9 ft/d (Potosi Dolomite), 0.5 ft/d (Gunter Sandstone Member), and 1.5 ft/d (Roubidoux Formation). Median hydraulic conductivity was estimated to be 1.1 ft/d for 421 wells that penetrate units within the lower Ozark aquifer (table 4; Missouri Department of Natural Resources, 2007; Kansas Geological Survey, 2014). Groundwater wells penetrating the full thickness of the Ozark aquifer generally yield between 50 and 100 gal/min but can yield more than 1,000 gal/min where wells penetrate the lower Ozark aquifer (Adamski and others, 1995). For example, reported yields from the Roubidoux Formation and the Gunter Sandstone Member vary widely, with yields for the Roubidoux Formation ranging from less than 10 gal/min to approximately 600 gal/min (Melton, 1976; MacDonald and others, 1977; Kilpatrick and Ludwig, 1990; Miller and Vandike, 1997; Renken, 1998; Prior and others, 1999) and yields for the Gunter Sandstone Member ranging from less than 100 gal/min to approximately 600 gal/min (Melton, 1976; MacDonald and others, 1977; Kilpatrick and Ludwig, 1990; Imes and Emmett, 1994; Adamski and others, 1995; Renken, 1998; Prior and others, 1999; Czarnecki and others, 2014).

St. Francois Confining Unit

The St. Francois confining unit separates and restricts groundwater flow between the overlying Ozark aquifer and the underlying St. Francois aquifer (Imes and Emmett, 1994; Miller and Appel, 1997). The confining unit is generally present throughout the subsurface in the Ozark system but is missing in areas near the St. Francois Mountains (Imes and Emmett, 1994). In these areas, the St. Francois aquifer is also absent, presumably because deposition of St. Francois aquifer sediments did not occur because of structural highs in the underlying Basement confining unit (Czarnecki and others, 2009). Vertical hydraulic conductivity ranges from 4×10^{-6} to 9×10^{-4} ft/d (fig. 11, table 3), and leakance through the confining unit is controlled by the amount of shale present in the unit (Imes and Emmett, 1994).

St. Francois Aquifer

The St. Francois aquifer is the lowermost aquifer in the Ozark system and is generally used only locally where the aquifer formations crop out (Miller and Appel, 1997). Because of the limited use of the St. Francois aquifer, limited hydraulic-property data are available (fig. 11, tables 3 and 4). Imes and Emmett (1994) estimated horizontal hydraulic conductivity of the aquifer near the St. Francois Mountains to be from 0.09 to 9 ft/d, but data outside of the outcrop area are limited because deep wells that penetrate the St. Francois aquifer are typically also open to shallower overlying aquifers. Median horizontal hydraulic conductivity was estimated to be 0.80 ft/d for 30 wells located near the St. Francois Mountains that likely were completed in the St. Francois (table 4; Missouri Department of Natural Resources, 2007). Imes and Emmett (1994) also estimated the hydraulic conductivity of the St. Francois aquifer in the New Lead Belt district of southeastern Missouri to range from 0.17 to 8.6 ft/d by using aquifer-test data from Warner and others (1974). Well yields from the St. Francois aquifer typically range from 100 to 500 gal/min (Imes and Emmett, 1994; Miller and Appel, 1997), and some wells open to the overlying Ozark aquifer can increase yields by 100–200 gal/min by penetrating the St. Francois aquifer (Miller and Vandike, 1997). Large groundwater-withdrawal rates are achieved in mining areas where the St. Francois aquifer is pumped to lower groundwater heads below the level of the mines; total withdrawal rates from 16 to 26 Mgal/d have been reported in the Old and New Lead Belt districts (Buckley, 1908; Warner and others, 1974); however, high withdrawal rates are generally restricted to wells near mines that intersect zones of high hydraulic conductivity, resulting in well yields from 450 to 4,900 gal/min from the St. Francois aquifer (Warner and others, 1974).

Basement Confining Unit

The Basement confining unit forms the lowermost base of the larger Central Midwest Regional aquifer system—which includes the Ozark system (Imes and Emmett, 1994; Jorgensen and others, 1996). Because of the crystalline texture of the rocks, the Basement confining unit is nearly impermeable and does not yield substantial amounts of water in the Ozark system (Imes and Emmett, 1994; Miller and Vandike, 1997). In eastern Missouri where the Basement confining unit crops out in the St. Francois Mountains (fig. 1), fractures and faults—from unloading of sediment and rocks and subsequent pressure decreases over geologic time—provide some storage capacity and permeability; however, well yields rarely exceed 10 gal/min (Imes and Emmett, 1994).

Hydrologic Conditions

The hydrologic status of the aquifer system is defined by fluxes and quality of water moving into the aquifer system from water sources, along flow paths within the framework of the aquifer system, to discharge out of the aquifer. Hydrologic conditions are subject to change through time; change can be imposed by human activities, such as water abstraction or land-use change, or by natural phenomena, such as climate change. Understanding the current qualitative and quantitative status of an aquifer—including aquifer-budget terms such as recharge, discharge, and storage—and future changes in the aquifer are critical to aquifer management and protection.

Sources of Water to the Ozark Plateaus Aquifer System

The ultimate source of all water to the Ozark system is precipitation, the preponderance of which falls over the Ozark Plateaus. Sources of water to the Ozark system include recharge from precipitation, stream leakage from losing-stream sections, and lateral inflow (fig. 12). The quantitative relations among precipitation timing, intensity, and duration, evapotranspiration, surface runoff, and infiltration—especially in karst geology—are important for controlling the amount of water recharging groundwater aquifers of the Ozark system. Recharge may move diffusely through soil and bedrock-matrix porosity or may be focused through karst features such as sinkholes, exposed fractures and conduits, and losing streams (Harvey, 1980). Streams in the Ozark Plateaus typically include both gaining and losing sections, and any stream leakage from losing sections provides a source of recharge to groundwater aquifers. Because the topography of the Ozark Plateaus is controlled by the Ozark dome, most surface streams flow away from the dome and outward towards the edges of the Ozark system. A relatively small amount of lateral groundwater inflow occurs along the western margin of the Ozark Plateaus where groundwater from the Western Interior Plains aquifer system (hereinafter referred to as the "Plains system") mixes with Ozark system groundwater (Jorgensen and others, 1996).

Aquifer Recharge

Recharge to aquifers in the Ozark system is dominated by meteoric water infiltrating through soil and regolith into bedrock aquifers. Recharge is generally the amount of precipitation not lost to evapotranspiration or runoff in surface streams that is able to infiltrate into the subsurface (Fetter, 2001; Sauer and others, 2002). Shallow and unconfined parts of aquifers receive this recharge directly from infiltration of precipitation or surface runoff. Deeper aquifer zones, where the aquifer is confined by overlying confining units, receive recharge via vertical leakage through fractures and faults (Imes and Emmett, 1994; Schrader, 2005; Czarnecki and others, 2009). The shallow groundwater system is closely connected to surface water in the Ozark Plateaus. Losing sections of streams are common and contribute to groundwater recharge, and groundwater can reemerge and discharge to springs and gaining sections of streams. Recharge to the deeper confined groundwater-flow system depends on the geographic extent of where the aquifer formations crop out at the surface (Schrader, 2005) and the permeability of overlying confining units (MacDonald and others, 1977); therefore, the rate of recharge to the Ozark system is generally greater where the aquifer is shallow and unconfined and less for the deeper confined aquifer areas (Imes and Emmett, 1994). Recharge rates for the Ozark system range from 0.04 to 15 inches per year (in/yr)—which constitutes zero to 30 percent of annual precipitation—generally across outcrop areas of the Springfield Plateau aquifer and Ozark aquifer (table 5). Recharge moving vertically from the Springfield aquifer to the Ozark aquifer is greater in areas where the Ozark confining layer is thin or absent or faulted and fractured.

The rate of recharge to the Ozark system varies spatially and temporally (Dugan and Peckenpaugh, 1985; Imes and Emmett, 1994) because of differences in precipitation (figs. 5 and 6), temperature (figs. 3 and 4, table 1), topography, surficial geology, vegetation, and soil type across the study area (MacDonald and others, 1977). Strong control on recharge is exerted by variability in regolith mantle thickness and relative purity of carbonate facies. The lesser thickness and extent of the regolith mantle in the northern Springfield Plateau and Salem Plateau in Missouri as compared with the southern Springfield Plateau in Arkansas result in a considerable difference in recharge across the plateaus.

Temperature and precipitation varied seasonally for the Ozark system as shown by seasonal data based on monthly temperature and precipitation means from 1900 to 2014 (PRISM Climate Group, 2015). The greatest precipitation occurred during the spring season and the lowest during the winter season (fig. 6 and table 1); distribution of precipitation was bimodal, with secondary precipitation peaks occurring in the fall and secondary lows occurring in the summer. Fall season represents October, November, and December; winter season represents January, February, and March; spring season represents April, May, and June; and summer season represents July, August, and September. The greatest mean seasonal precipitation observed for the Ozark system, 14.0 in., occurred during the spring. By comparing the individual physiographic sections, the Boston Mountains had the highest mean seasonal precipitation at 15.3 in. (spring), and the Springfield Plateau had the lowest mean seasonal precipitation at 8.3 in. (winter). In the southern part of the Ozark system study area, the greatest precipitation occurred during the months of March through May and November and December (Pugh and Westerman, 2014). Seasonal precipitation for the Ozark system varied around the mean by approximately 170–208 percent.

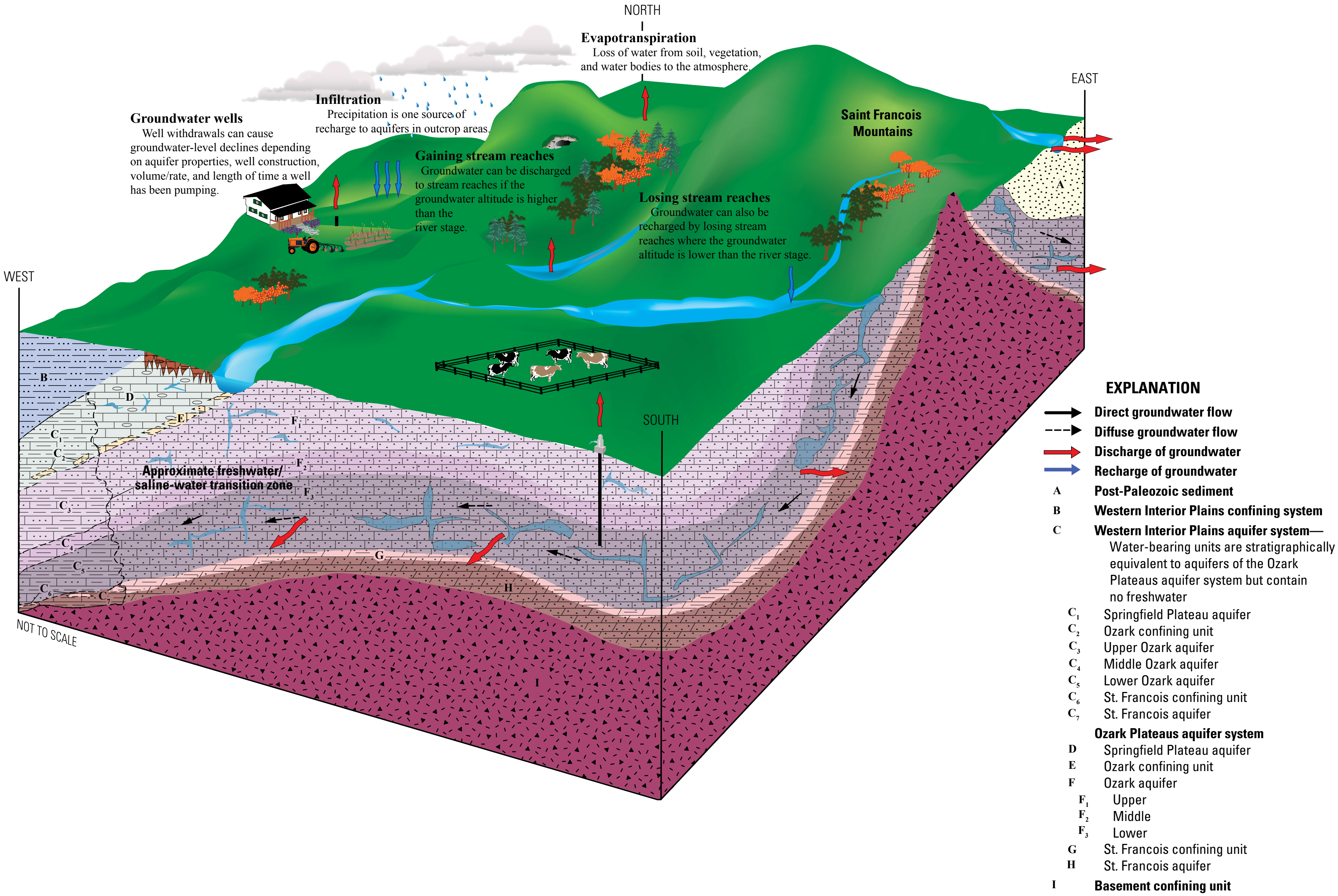


Figure 12. Conceptual hydrologic budget for the Ozark Plateaus aquifer system.

Table 5. Summary of recharge estimates from the literature for the Ozark Plateaus aquifer system.

[AR, Arkansas; OK, Oklahoma; NA, not available; MO, Missouri]

Recharge (inches per year)	Percent of precipitation[1]	Method	Aquifer	Location	Reference
5.7	10	Spring recharge area	Springfield Plateau	Northern AR	Pennington, 2010
5.3	13	Groundwater model	Springfield Plateau	Northeastern OK	Reed and Czarnecki, 2006
5.0–15.0	12–30	Hydrologic budget	Springfield Plateau	Ozarks	Dugan and Peckenpaugh, 1985
0.09	NA	Groundwater model	Springfield Plateau	Southern MO	Imes, 1989
1.6	4	Groundwater model	Springfield Plateau	Ozarks	Imes and Emmett, 1994
9.0–14.0	NA	Spring recharge area	Springfield Plateau	Southern MO	Imes and others, 2007
1.7–3.6	4–9	Spring recharge area	Springfield Plateau	Northern AR	Knierim and others, 2013
0.8	NA	Spring recharge area	Springfield Plateau	Southern MO	Neill and others, 2004
4	10	Hydrologic budget	Springfield Plateau	Northern AR	Sauer and others, 2002
0.8–0.9	NA	Water-table fluctuations	Springfield Plateau	Southern MO	Richards, 2010
0.6–1.4	1–3	Groundwater model	Springfield Plateau	Southern MO	Richards, 2010
0.9	2	Groundwater model	Ozark	Ozarks	Imes and Emmett, 1994
0.04	NA	Groundwater model	Ozark	Southern MO	Imes, 1989
0.1–3.5	0–8	Groundwater model	Ozark	Southwestern Ozarks	Czarnecki and others, 2009

[1]Percent of precipitation calculated when precipitation values were provided in the referenced report.

The Springfield Plateau in the summer had the highest air temperature at 82.8 °F, and the Salem Plateau during the winter had the lowest at 29.4 °F (fig. 4 and table 1). Interseason temperature variability was greatest during the winter season across the Ozark system, with temperatures varying up to 40 percent.

Because of seasonal variability of precipitation and temperature, rates of evapotranspiration, which range from 30 to 35 in/yr, also change throughout the year (Adamski and others, 1995). Evapotranspiration is generally greatest during the summer and lowest during the winter, following the pattern of solar radiation (Brye and others, 2004); therefore, any potential recharge from precipitation during the summer is greatly reduced by evapotranspiration; water levels in shallow wells across the Ozark Plateaus generally increase during the winter to early spring wet season, but cease any increase or decline as the growing season begins. Surface topography also controls recharge because the position of the water table tends to reflect topography (Imes and Emmett, 1994; Schrader, 2005), and surface runoff is generally greater (that is, recharge is less) where slopes are steeper (Dugan and Peckenpaugh, 1985; Stieglitz and others, 1997). Recharge rate is dependent on surficial geology and soil type: permeable soils and fractured and karsted carbonate units exposed at the surface enhance recharge, whereas low-permeability soils, thick, clayey regolith, and low-permeability bedrock exposures impede recharge. The Ozark Plateaus are mantled by a cherty regolith, which ranges in thickness from zero to more than 100 ft, and can have variable hydraulic conductivities depending on the soil texture (Dugan and Peckenpaugh, 1985) and the presence of macropores (Leh and others, 2008), exerting a strong control over runoff and infiltration. Generally, recharge increases with higher soil hydraulic conductivity, which is greatest where soil texture is coarse or includes macropores (Dugan and Peckenpaugh, 1985; Leh and others, 2008).

Recharge values from groundwater-flow models are often initially input as estimates from aquifer tests and other data and adjusted during subsequent model-calibration simulations (Czarnecki and others, 2009). Recharge may be equally distributed across the model study area (Reed and Czarnecki, 2006) or vary spatially depending on model calibration (Imes and Emmett, 1994; Czarnecki and others, 2009). For example, Czarnecki and others (2009) found that recharge values needed to be substantially lower than the model inputs taken from Dugan and Peckenpaugh (1985) to accurately represent observed water levels in the study area of the Ozark system, similar to model results from Imes (1989) and Imes and Emmett (1994). Recharge calculated from groundwater-flow models of the Ozark system range from 0.04 to 5.3 in/yr (table 5).

Recharge rates for the Ozark system have also been estimated by using water-table fluctuation methods (Risser and others, 2005; Richards, 2010), hydrologic budgets (Dugan and Peckenpaugh, 1985; Sauer and others, 2002), and spring recharge-area calculations. The results from these methods have indicated highly variable recharge for the Ozark system, ranging between 0.8 and 15 in/yr (table 5) and illustrate the importance of rainfall, temperature, soil properties, and land use in controlling recharge rates.

Soil-water-balance (SWB) models are a means of calculating shallow groundwater recharge by using meteorological, soils, topographic, and land-use and land-cover data (Westenbroek and others, 2010). SWB models simulate the physical process of water movement through soil, taking into account soil properties such as transmissivity and maximum soil-moisture holding capacity. Additionally, SWB models account for loss of water through evapotranspiration by using a modified Thornthwaite-Mather approach that incorporates minimum and maximum daily air temperature (Thornthwaite, 1948; Thornthwaite and Mather, 1957). Ultimately, SWB models enable better understanding of the flux and storage of water and output a detailed recharge distribution across a study area (Westenbroek and others, 2010). An updated estimate of recharge for the Ozark system was completed for this study by using an SWB model (for the period 2005–14) and was critical for the development of the hydrologic-budget analysis. Further use and expansion of the SWB model is expected in support of an Ozark system groundwater-flow model (U.S. Geological Survey, 2015a) as SWB models provide spatially distributed recharge estimates at various time scales.

The model structure for the SWB consists of tabular and gridded datasets containing precipitation and temperature data, hydrologic soils group, available soil-water capacity, and land-use and land-cover data. The SWB model grid was extended to an area larger than the Ozark system boundary to minimize potential boundary-effect model error. The SWB model grid was set at a uniform 1-square-kilometer grid spacing of 524 rows and 543 columns, totaling 284,532 cells; however, the final analysis included data from the 178,584 cells contained within the Ozark system study area boundary.

Daily maximum temperature, minimum temperature, and total precipitation grids were constructed for the period 2005–14. These weather data were obtained from National Oceanic and Atmospheric Administration (NOAA) daily surface observations (National Oceanic and Atmospheric Administration, 2011) recorded at 28 NOAA-operated meteorological stations (table 6) and interpolated into a surface by using the thin plate spline function within the fields package (Nychka and others, 2015) for R (R Core Team, 2015). The daily climate grids were transcribed to American Standard Code for Information Interchange data grids by using R for processing in the SWB model.

The SWB model incorporates land-use and land-cover data in calculation of net recharge. Land-use classification grids were constructed from the Multi-Resolution Land Characteristics Consortium 2011 National Land Cover Database (NLCD) (Homer and others, 2015). The NLCD dataset includes 15 different land-cover classifications for the Ozark system for 2011 (table 2). Land use and land cover across the Ozark system are primarily a mosaic of forest and agriculture, with local urban development (fig. 7). Nearly half of the study area is forested (48 percent), approximately 40 percent is used for agriculture (with agricultural land use dominated by hay production and pastures), and approximately 7 percent is developed (table 2).

Table 6. Precipitation stations used in the soil-water-balance model and shown on figure 13.

[KS, Kansas; US, United States; MO, Missouri; OK, Oklahoma; AR, Arkansas; IL, Illinois; NW, northwest]

Map identification number	Station name	Latitude (decimal degrees)	Longitude (decimal degrees)
1	Chanute Martin Johnson Airport KS US	37.670	-95.484
2	Coffeyville Municipal Airport KS US	37.091	-95.566
3	Joplin Regional Airport MO US	37.147	-94.502
4	Muskogee Davis Field OK US	35.657	-95.361
5	Poplar Bluff Municipal Airport MO US	36.773	-90.325
6	Springfield Regional Airport MO US	37.240	-93.390
7	St. Louis Lambert International Airport MO US	38.753	-90.374
8	Vichy Rolla National Airport MO US	38.131	-91.768
9	West Plains Municipal Airport MO US	36.878	-91.903
10	Little Rock Adams Field AR	34.727	-92.238
11	Ozark Regional Airport Mountain Home AR	36.368	-92.470
12	Cape Girardeau Regional Airport MO	37.225	-89.570
13	Fort Smith Regional Airport AR	35.333	-94.362
14	Jefferson City Memorial Airport MO	38.591	-92.155
15	Jonesboro Municipal Airport AR	35.831	-90.646
16	Carbondale Southern Illinois Airport IL	37.779	-89.249
17	Harrison Boone County Airport AR	36.266	-93.156
18	Fayetteville Drake Field Airport AR	36.009	-94.169
19	Fayetteville/Springdale NW AR Regional	36.283	-94.300
20	Russellville Municipal Airport	35.257	-93.094
21	Sedalia Memorial Airport	38.704	-93.183
22	Olathe New Century Aircenter	38.831	-94.889
23	Kansas City International Airport	39.297	-94.730
24	Tulsa International Airport	36.199	-95.887
25	Lee's Summit Municipal Airport	38.959	-94.371
26	Columbia Regional Airport	38.816	-92.218
27	Spirit of St. Louis Airport	38.657	-90.655
28	Chillicothe Agricultural Science Center	39.823	-93.579

Hydrologic soils group and available soil-water capacity values were assigned for each SWB model grid cell on the basis of U.S. Department of Agriculture Natural Resources Conservation Service (NRCS) soil classifications (Natural Resources Conservation Service, 2015). The NRCS data identify four major hydrologic soils groups based on water-transmissivity characteristics, with letter designations (A through D) grouping soils with similar physical and runoff characteristics. Data for hydrologic soil groups provided in the NRCS Soil Survey Geographic Database (SSURGO) dataset (Soil Survey Staff, 2013) were used to construct gridded hydrologic soils datasets and associated lookup tables used as input for hydrologic capacity in the SWB model.

Combined land-use and land-cover data, soil-water-capacity data, and plant water-interception coefficient data were used in the model to determine maximum soil-moisture holding capacity for each grid cell. Available soil-water capacity is the water held in soil between soil-field capacity and the permanent wilting point (U.S. Department of Agriculture, 1998). Available soil-water capacity is primarily controlled by soil texture; coarse soils have a lower capacity to store water because of the larger pore space between grains and associated capillary effects (U.S. Department of Agriculture, 1998). Available soil-water-capacity data from the SSURGO dataset (Soil Survey Staff, 2013) were used to define gridded datasets for the SWB model. All soils data used for this model were retrieved by using the soilDB package (Beaudette and Skovlin, 2015) for R (R Core Team, 2015).

The SWB model used in this analysis calculates recharge (R) as follows:

$$R = P - I - O - ET, \quad (1)$$

where gross precipitation (P) is an input to the model from NOAA climate data (National Oceanic and Atmospheric Administration, 2011), and interception (I), outside runoff (O), and actual evapotranspiration (ET) are calculated by using meteorological, soils, land-use, land-cover, and topographic data. Note that the SWB model is not meant to model surface-water and groundwater interaction and so the variable O represents surface flow that flows out of the model domain or has reached a model cell of open water (Westenbroek and others, 2010).

The SWB model run for the period 2005–14 indicated that the mean recharge rate for the Ozark system was approximately 13.4 in/yr and recharge accounted for approximately 24 percent of gross precipitation. Model results ranged from zero (areas of open water) to 32 in/yr and were spatially variable throughout the Ozark system (fig. 13; see appendix 1). Approximately 58 percent of precipitation was lost to actual evapotranspiration, 10 percent to interception as water was captured and held by vegetation (considered separately from evapotranspiration), and 4 percent to runoff outside of the model boundary. The range of recharge rates produced by the SWB model most closely correspond to recharge estimates from Dugan and Peckenpaugh (1985) (table 5), which similarly used climate, vegetation, and soils data to estimate recharge across the Ozark system.

Stream Leakage

Streams in the Ozark Plateaus include gaining, neutral, and losing sections (fig. 14; Knierim, Wagner, and others, 2015), and any stream leakage from losing sections provides a source of recharge to groundwater aquifers (see https://www.youtube.com/watch?v=CTw4cfZyTMw&list=FL6WRsm6BFPA-IuAlLsaNgKA for more information of groundwater and surface-water interaction). Surface-water contribution to aquifers can be substantial and, depending on flow conditions, can occur rapidly over short distances in the stream channel. For example, Harvey (1980) studied the Ordovician and Cambrian rocks of the Springfield and Salem Plateaus of southern Missouri and northern Arkansas and found that, depending on antecedent conditions, streams in the Ozark Plateaus can lose 50–90 percent of flow during storm events with 2–6 in. of rain (Harvey, 1980). In another example, the Gasconade River in south-central Missouri lost 24.6 ft^3/s, or 86 percent of flow, along a studied reach during an extreme drought as streamflow entered a sinkhole (Bolon, 1953). In addition to sinkholes, losing sections of streams, ponors, swallets, and estavelles tend to be associated with structural faults (Aley, 1978; Freiwald, 1987; Imes and others, 1996), which provide flow paths for surface water to rapidly enter the subsurface. Local geology also controls the dominance of losing-stream sections. For example, in south-central Missouri, streams generally lose flow in areas where the Springfield Plateau aquifer is exposed (Skelton, 1970; Imes, 1989; Richards, 2010).

Many of the seepage studies in the Ozark Plateaus provide examples where streams alternate between gaining and losing along single reaches (fig. 14) or gain flow from karst springs, which highlights the dynamic nature of surface water and groundwater in karst terrain. For example, Current River and Jacks Fork (fig. 2) were found to gain substantial flow from springs, such that streams were interpreted as predominantly gaining (Mugel and others, 2009). The most important source of recharge for many of the major springs, however, was found to be losing-stream reaches, highlighting the close interaction between surface water and shallow groundwater in the Ozark system. For example, the Big Spring recharge area includes 246 miles of losing-stream reaches that contribute flow to the spring; Big Spring—the largest spring in Missouri with a mean annual discharge of 446 ft^3/s—then discharges into the Current River, contributing approximately 32 percent of the total discharge at that location (Mugel and others, 2009). Groundwater flow sourced from stream seepage is not bound by surface watershed boundaries; Aley (1978) showed that tributaries to the Eleven Point River lost much of their flow to the subsurface, and that flow ultimately resurged at Big Spring on the Current River.

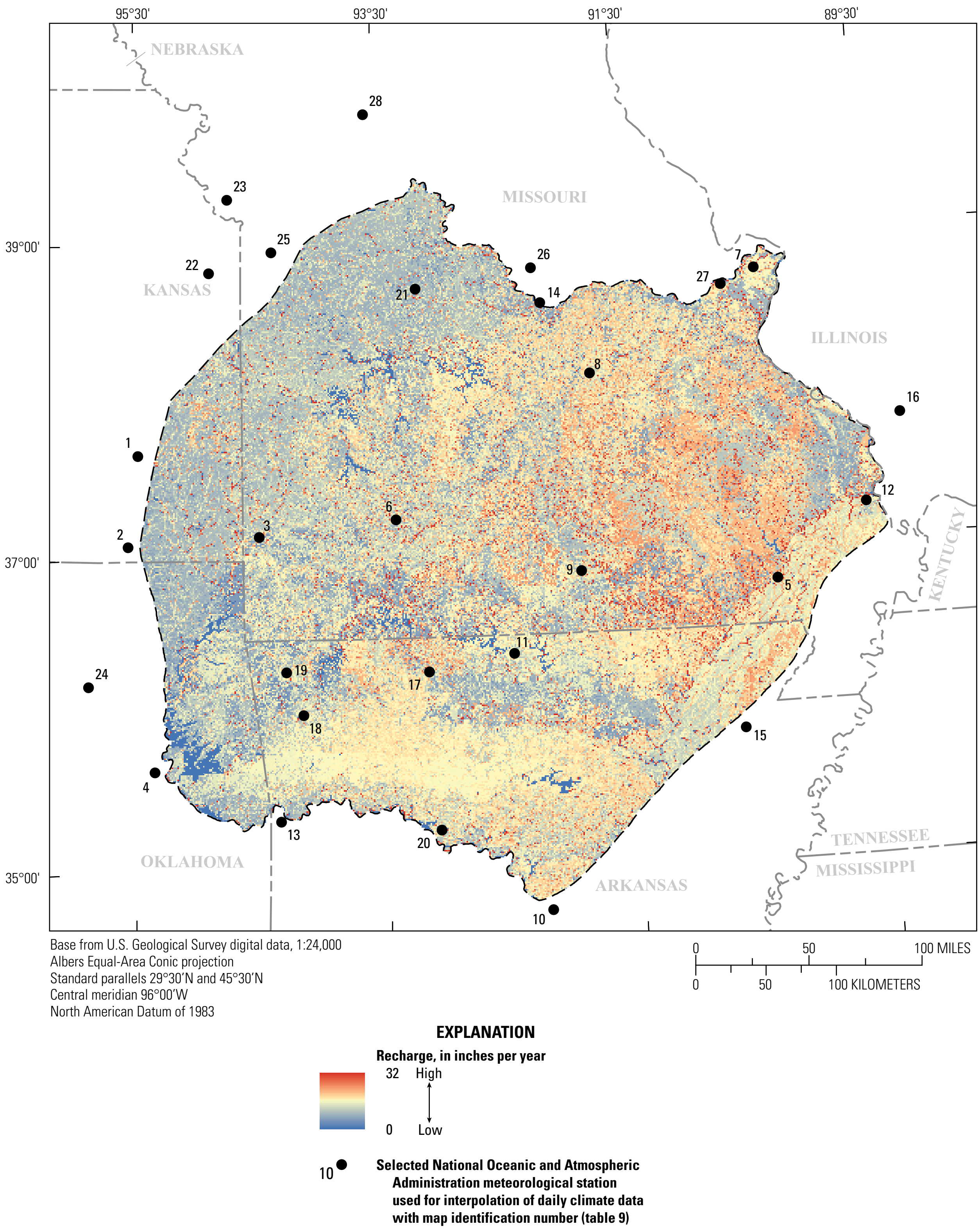


Figure 13. Recharge estimates for the Ozark Plateaus aquifer system from the soil-water-balance model.

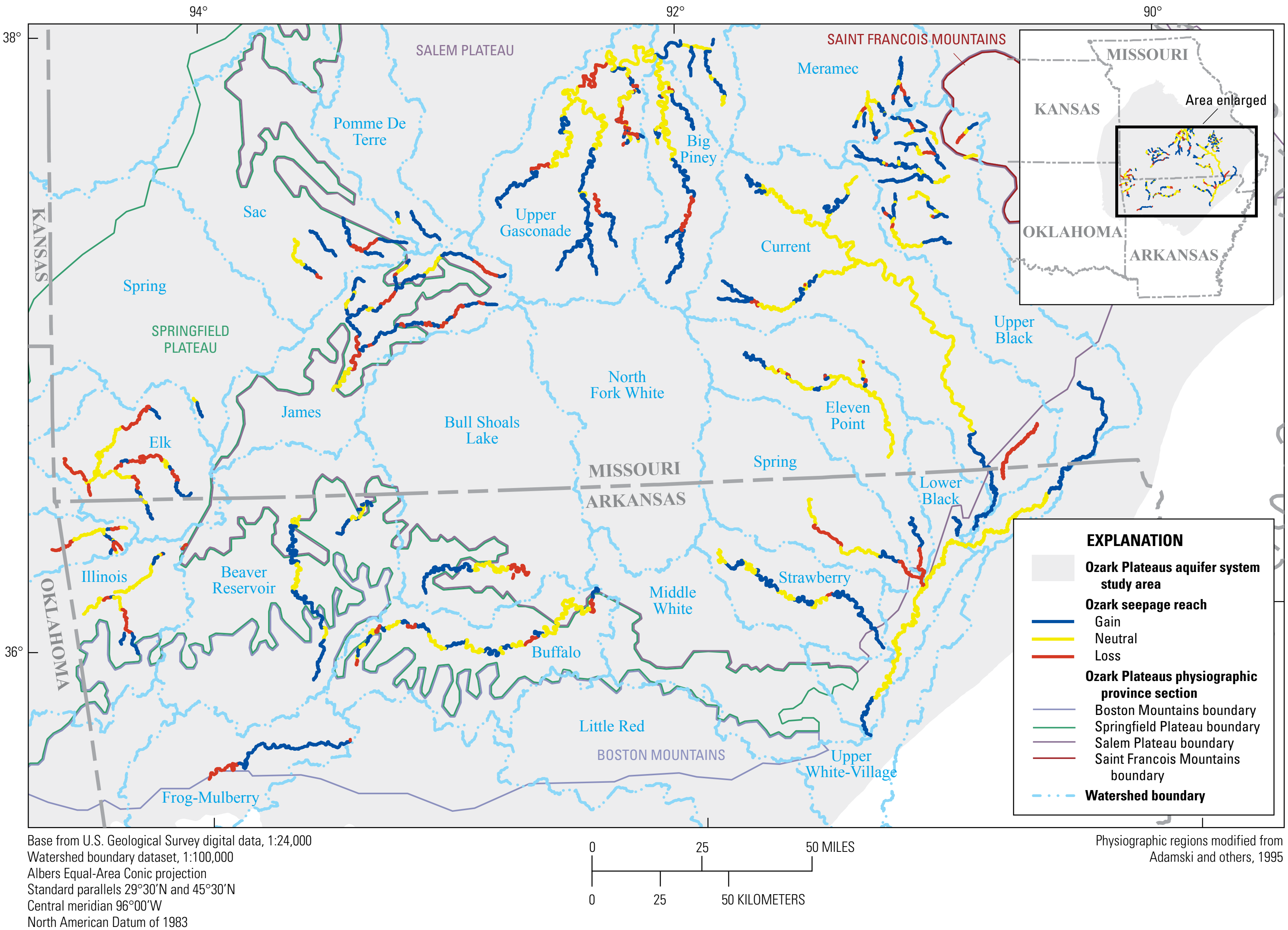


Figure 14. Summary of surface-water/groundwater interaction from digitized seepage-run studies (Knierim and others, 2015).

In gain-loss studies conducted in the southern Ozarks of Arkansas, numerous losing sections of streams were observed. Freiwald (1987) measured eight streams across the southern Ozarks (fig. 2), and although groundwater contributed considerable flow to streams measured in 51 of 61 reaches, losing sections were also identified (fig. 14). Joseph and Green (1994a, b) identified losing reaches, interspersed with gaining reaches, on two streams in northwestern Arkansas.

The proportion of surface water lost to the aquifer can change with flow conditions. Imes and others (1996) conducted a seepage study of two Ozark streams during winter (high base flow) and early fall (low base flow) conditions (fig. 2). Measurements on the larger stream (Big Piney River, with discharge ranging from 300 to 450 ft^3/s at high base flow and 150 to 200 ft^3/s at low base flow) and the smaller stream (Roubidoux Creek, with discharge ranging from zero to 60 ft^3/s at high base flow and zero and 25 ft^3/s at low base flow) showed that the exchange of water between the aquifer and streams was dynamic, alternating between gaining and losing on very short stream reaches and varying considerably with changing hydrologic conditions (fig. 14) (Imes and others, 1996; Mugel and Imes, 2003; Kleeschulte, 2000; Kleeschulte, 2008).

These seepage studies, combined with data compiled for the companion Ozark system study reports by Knierim and others (2015) and Nottmeier (2015), show that losing sections, though generally rarer than gaining sections in terms of number of sections and total stream mileage, are relatively common and are commonly interspersed with gaining sections. Data also show that many Ozark streams are generally losing in the rugged, high-relief headland parts of the watersheds and generally gaining in the lower gradient parts of the watersheds (for example, the Black River). Loss along measured reaches varied greatly, with zero to 100 percent of flow observed moving into the subsurface; median loss for the studies was approximately 30 percent of flow. Data show that shallow-aquifer hydraulic conductivity limits stream loss as the percentage lost during high flow tended to be less than the percentage loss during low flow. In addition, much of the actual flow lost on losing reaches has been shown to be added back in gaining sections and local springs. Ultimately, although considerable volumes of water move into the subsurface in streams, Ozark streams quantitatively gain more water than is lost (Knierim and others, 2015). Notably lacking for Ozark streams is any one study that synoptically quantifies stream gain and loss along an entire stream; this deficiency detracts from the accuracy of water-budget quantitation at the watershed scale.

Lateral Inflow

Lateral inflow is not volumetrically important for surface water or groundwater for the Ozark system because of a radial regional flow pattern that is a predominant feature of the Ozark system hydrology. Surface water and groundwater generally flow outward from the relatively high-elevation Ozark dome towards the margins of the Ozark system (Imes and Emmett, 1994). Although inflow from streams is an important source of recharge to the Ozark system, this inflow is internal to the system. In keeping with topographic control, streams originating within the boundaries of the Ozark Plateaus account for the preponderance of stream-derived inflow. Exceptions occur in the Marais des Cygnes and Osage Rivers systems, where surface water from eastern Kansas flows into the Missouri River, which forms the northern boundary of the Ozark system, and the Neosho River, where surface water from the west flows into the Arkansas River, which forms the southern boundary of the Ozark system (Imes and Emmett, 1994). The volume of water is relatively minor, and no considerable inflow of surface water is contributed by streams to the Ozark system across lateral boundaries. Generally, major streams impinging on the region divert around the uplift and serve as hydrologic boundaries that receive water rather than deliver water to the Ozark system.

Similar to surface-water flow, net movement of groundwater is away from the St. Francois Mountains at the core of the Ozarks and outward from most boundaries 360° around the Ozark Plateaus. The notable exception to this predominantly lateral groundwater outflow is an influx of groundwater across the western margin of the Ozark system from groundwater of the Plains system and potentially from the Anadarko Basin of central Oklahoma (Jorgensen and others, 1986; Banner and others, 1989; Jorgensen and others, 1993; Musgrove and Banner, 1993). West of the Ozark system, groundwater from the Plains system flows west to east along flow paths originating in the front ranges of the eastern Rocky Mountains and becomes increasingly saline because of leakage from overlying evaporite deposits of the Western Interior Plains confining system (Banner and others, 1989; Musgrove and Banner, 1993; Jorgensen and others, 1996). The generally eastward regional flow direction for this more saline groundwater impinges on the groundwater of the Ozark system to create a broad freshwater/saline-water transition zone extending from northeastern Oklahoma to west-central Missouri (fig. 1) (Jorgensen and others, 1986; Jorgensen and others, 1993). Groundwater from the two aquifer systems mixes and discharges upwards through the leaky Western Interior Plains confining system, emerging from springs and gaining-stream reaches of the tributaries and main stems of the Osage River, Neosho River, Blackwater River, and the Missouri River (Jorgensen and others, 1993). Signor and others (1997) estimated velocities on the order of 40 ft per million years for Plains system groundwater. The long flow path and low velocity result in increased residence time, and greater rock/water interaction and leakage of water from overlying Permian evaporite sequences in Plains system groundwater imparts a geochemistry notably different from that of groundwater recharged in the Ozark system.

Groundwater of the Plains system is a sodium-chloride water type with very high levels of total dissolved solids

(TDS); TDS values approaching the mixing zone may exceed 50,000 milligrams per liter (mg/L) (Jorgensen and others, 1986), and chloride values often exceed 5,000 mg/L (Banner and others, 1989; Musgrove and Banner, 1993). The predominant water type for the Ozark system is a calcium-bicarbonate type, with a calcium-magnesium-bicarbonate type common for dolomite-dominated intervals (Adamski and others, 1995). Contribution from Plains system groundwater is evidenced by the relatively high salinity and other geochemical effects of the mixing of the two groundwater types observed throughout wells and springs near the freshwater/saline-water transition zone (Woodward, 1890; Schweitzer, 1892; Shepard, 1907; Carpenter and Miller, 1969; Miller, 1971; Jorgensen and others, 1986). For example, groundwater salinities along the western flank of the Ozark system commonly exceed 20,000 mg/L in both the Springfield Plateau and Ozark aquifers (Jorgensen and others, 1986), whereas salinities of Ozark system groundwater away from the freshwater/saline-water transition zone are typically less than 300 mg/L and dominantly comprise carbonate species (Adamski and others, 1995).

Available base-flow chloride data were compiled for springs (n = 35), wells (n = 21), and sites sampled on seven streams (n = 864) on the western flank of the Ozark system from the USGS National Water Information System (NWIS) Water-Quality Data for the Nation database (U.S. Geological Survey, 2015c); a text file listing sample locations is available in appendix 2. A binary mixing model was applied to provide an estimate of the range of Plains system groundwater contribution compared to Ozark system groundwater contribution across the freshwater/saline-water transition zone. The linear concentration-based mixing-model equation applied was

$$C_{MIX} = fC_{WIP} + (1\text{-}f)C_{OZ}, \qquad (2)$$

where

C_{MIX} is the chloride concentration of the mixed groundwater,

C_{WIP} is the chloride concentration of the Plains system end-member contribution,

C_{OZ} is the chloride concentration of the Ozark system end-member contribution, and

f is the fractional abundance of the Plains system groundwater in the resultant two-member mixture.

Groundwater chloride concentrations across most of the Ozark Plateaus are generally less than 4 mg/L, with the exception of zones proximal to the Western Interior Plains confining system and areas proximal to the freshwater/saline-water transition zone (Jorgensen and others, 1986; Adamski and others, 1995). Groundwater chloride data for the Plains system near the terminus of the west-east flow path indicate a chloride end-member concentration of approximately 16,000 mg/L (Jorgensen and others, 1986; Banner and others, 1989; Musgrove and Banner, 1993). As a quality check, the C_{WIP} end-member value was compared to the 99th-percentile chloride concentration for springs and wells in the freshwater/saline-water transition zone from the NWIS database—15,800 mg/L. Because of the large difference in the end-member concentrations between C_{WIP} and C_{OZ}, calculations of f are relatively insensitive to as much as 20 percent error in the end-member concentration values applied; for example, varying both end-member values by 20 percent varies f by less than 0.5 percent.

The fractional contribution of groundwater from the Plains system to springs, wells, and streams near the freshwater/saline-water transition zone ranged from 0.01 to 1.3 percent (median values) and from 0.1 to 20.6 percent (mean values). For Ozark system springs located near the freshwater/saline-water transition zone with data available in the NWIS database, chloride concentrations ranged from 1.9 to 13,300 mg/L. The estimated percentage contribution of Plains system groundwater to these springs ranged from zero to 83 percent, with a mean of 3.2 percent and a median of 0.01 percent. For Ozark system wells located near the freshwater/saline-water transition zone with data available in the NWIS database, chloride concentrations ranged from 1.4 to 15,800 mg/L. The estimated percentage contribution of Plains system groundwater to these wells ranged from zero to 99 percent, with a mean of 20.6 percent and a median of 1.3 percent. For selected Ozark system stream reaches located near the freshwater/saline-water transition zone with data available in the NWIS database, chloride concentrations ranged from 3 to 565 mg/L. The estimated percentage contribution of Plains system groundwater to these streams ranged from zero to 3.5 percent, with a mean of 0.1 percent and a median of 0.1 percent. Despite contribution of saline groundwater from the Plains system to surface water within the Ozark Plateaus and groundwater at the margins of the Ozark system, the net flux of Plains system groundwater into the Ozark system is considered negligible and typically not included in groundwater models (Imes and Emmett, 1994).

Loss of Water from the Ozark Plateaus Aquifer System

Loss of groundwater from the Ozark system includes evapotranspiration, groundwater flow to gaining stream sections and springs, groundwater withdrawals for various water uses, and lateral groundwater outflow. Streams in the Ozark Plateaus can be classified into neutral-, gaining-, and losing-section categories along measured reaches (fig. 14), but most Ozark streams show an overall net gain in water, which represents a loss of water from Ozark system aquifers. Streams—in combination with geological controls—define Ozark system boundary extents, with a considerable amount of water exiting the Ozark system at these boundaries.

Groundwater Discharge to Streams

The contribution of groundwater to base flow of streams and discharge to wetlands and lakes constitutes an important “use” of groundwater—sometimes referred to as “instream use”—that is easily overlooked. Groundwater maintenance of base flow supports a plethora of processes and provides a time-averaged input of water to surface-water bodies (Fetter, 2001); otherwise, surface water may have a discontinuous or “flashy” source of water because of spatial and temporal variability of precipitation, coupled with rapid downstream flow and high evapotranspiration rates. The potential for decrease of the groundwater contribution to streams and subsequent stream depletion due to increased pumping or decreased recharge as the climate changes is an important issue for the region. Important aquatic species and diverse aquatic ecosystems have evolved to depend on groundwater input to streams, wetlands, and lakes, particularly during the dry season and drought (Missouri Department of Natural Resources, 2003; Moix and Galloway, 2005). Groundwater base-flow input also moderates temperature and affects water quality in streams (Freiwald, 1987). Humans also rely on the continuity of groundwater contribution to stream base flow to maintain typical surface-water uses during the dry season and drought, and development of groundwater resources can result in shifting of a considerable amount of discharge from streams and wetlands to wells (Imes and Emmett, 1994; Barlow and Leake, 2012). The reduction of streamflows, particularly during dry periods, and the desiccation of wetlands have a deleterious impact on many important aquatic species and aquatic ecosystems and on human water uses, including consumptive use for irrigation, industry, and drinking water, as well as recreational uses, such as fishing and boating (Rolls and others, 2012). Minimum streamflows, which are strongly dependent upon groundwater base-flow input, are one of the important criteria that State water regulators and planners consider when conducting resource planning and determining conjunctive use, water allotment, and sustainable yields (Missouri Department of Natural Resources, 2003; Kresse and others, 2014).

Groundwater contribution to streams, wetlands, and lakes and the ecosystems supported by this interchange of water provide considerable human benefit, although this benefit is typically difficult to quantify. Traditionally, the benefits that people receive from the natural processes that occur in healthy aquatic ecosystems—such as clean water for drinking and other uses, decomposition of wastes, and amelioration of contamination—have often been largely overlooked and rarely assessed and quantified in terms of economic benefit (Costanza and others, 1997). Within the last decade, the benefits inherent in the multitude of resources and processes that are supplied by ecosystems have begun to be recognized and assessed in terms of “dollars-and-cents” economic benefit. These benefits have been termed “ecosystem services.” Ecosystem services are now a market-oriented objective recognized by Federal agencies including the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Agriculture (USDA) and were included in the Conservation Title in 2007 and later in the Farm Bill (Johnson, 2009). The USDA has set policy for agriculture and forestry programs to provide environmental offsets and develop economic accounting practices and procedures for quantifying environmental goods and services (U.S. Department of Agriculture, 2006), with the goals of enhancing fish and wildlife habitat, pollutant management, surface-water runoff and floodwater management, water sustainability, and cultural benefits. Groundwater contribution to streams, lakes, and wetlands is a critical component of ecosystem health in many aquatic systems and ultimately to ecosystem services that benefit people and our activities; the advent of practical economic accounting procedures to quantify these groundwater benefits and incorporate this remunerative benefit into resource analysis, planning, and allocation efforts is an important advancement in water-resource management. Groundwater-modeling results could be a key component in understanding and predicting ecosystem services affected by groundwater.

Viewed from headland to lowland areas, seepage data for larger Ozark streams generally show an overall net gain in water, such that groundwater contributes to base flow either as direct seepage into streams or from springs that serve as tributaries to streams. For example, the Eleven Point and Current Rivers in south-central Missouri were studied to determine whether interbasin transfer of water was occurring, and streams were found to be predominantly gaining through the measured reaches during the gain-loss study (Kleeschulte, 2000). Twelve percent of the total 747 ft^3/s flow at the most downstream measurement site was calculated to have accrued from diffuse groundwater inflow through the streambed. Much of the remainder of streamflow was contributed through spring resurgences at the head of spring runs or other tributaries, which appeared to be groundwater derived inasmuch as little to no surface-water runoff was occurring during the low-flow measurement (Kleeschulte, 2000). The Current River gained 430 ft^3/s over the approximately 24 miles of studied reach (Kleeschulte, 2000). The Current River was sampled again in 2006 as part of a hydrologic characterization of the Ozark National Scenic Riverways (ONSR) and was found to predominantly gain flow from springs, either directly from identified springs or from surface-water tributaries where discharge in headwaters likely originated from springs (Mugel and others, 2009). Groundwater contributions to surface streams via conduit flow—or more concentrated groundwater flow paths—can be an important component of base flow in karst settings, and the ONSR provides an example of such an area. For example, 13 of the larger springs in the ONSR accounted for a calculated 82 percent of discharge in the Current River below Big Spring (or 867 ft^3/s of 1,060 ft^3/s total discharge) (Mugel and others, 2009). Spring discharge also represented a calculated 72 percent (114 ft^3/s) of the 159 ft^3/s of discharge derived from the Gasconade River and its smaller tributaries (Mugel and Imes, 2003).

Across the Ozarks, streams have typically been characterized as showing a net gain from groundwater, even though neutral and losing reaches also were identified. Numerous studies that included seepage analyses reflect these findings across the Ozarks, including Kleeschulte (2008), focusing on the Meramec and Black River Basins of the central Ozarks; Skelton (1970, 1976), Emmett and others (1978), Imes (1989), and Richards (2010), all focusing on the James and Sac River Basins of the west-central Ozarks; Joseph and Green (1994a, b), focusing on Yocum and Spavinaw Creeks in the southwestern Ozarks; Schumacher (2003), focusing on Shoal Creek in the west-central Ozarks; Smith and others (2007), focusing on the Upper Elk River Basin in the west-central Ozarks; and Bolon (1953) and Mugel and Imes (2003), both focusing on the Gasconade River Basin in the north-central Ozarks.

The proportion of groundwater gained by streams can change with flow conditions. Imes and others (1996) conducted a seepage study during low and high base-flow conditions and found that streams alternated between gaining and losing on very short reaches. For example, on gaining sections of Roubidoux Creek, the stream gained 31 percent (3 ft^3/s) and 28 percent (19 ft^3/s) of flow during low and high base-flow conditions, respectively. On gaining sections of the Big Piney River, the stream gained 19 percent (44 ft^3/s) and 43 percent (247 ft^3/s) of flow during low and high base-flow conditions, respectively (Imes and others, 1996). Harvey and others (1983) conducted groundwater seepage runs for the Niangua River, Osage Fork, and Grandglaize Creek in south-central Missouri and determined that groundwater contributed 73–96 percent of total base flow for the reaches studied, depending on recent rainfall conditions.

Inspection of seepage measurement data presented in these numerous reports, as well as data compiled for the seepage component of the Knierim and others (2015) Ozark system study and the Nottmeier (2015) potentiometric map, indicates a tendency for Ozark streams to be generally losing in the rugged, high-relief headland parts of watersheds and generally gaining in the medial to lower stream reaches. This observation is consistent with the general observation for the Ozarks that the shallow groundwater table is a subdued reflection of topography; that is, topographic highs in an area are mirrored by water-table highs, and topographic lows correspond with a lower water table. The “subdued” characterization refers to the tendency of water levels to be deeper below ground surface in topographically high areas and shallow in topographically low areas.

The studies discussed in this section highlight the interaction of surface and groundwater in the Ozarks and provide examples where groundwater contributes substantial volumes of flow to surface streams. Gaining streams represent a loss of water from Ozark system aquifers. Harvey (1980) noted that the magnitude of groundwater contribution at the regional scale from the Ozark system to surface streams is highlighted by the 50-percent increase in flow of the Mississippi River near Cape Girardeau, Mo., compared to flows upstream on the Missouri River at Boonville, Mo., and the Mississippi River at Alton, Ill. (for flow at the 7-day minimum expected once every 10 years, or 7-day Q_{10}); therefore, groundwater flow to streams is an important loss of water from the Ozark system over both local and regional scales. The dynamic nature of surface-water/groundwater interaction in karst terrain also means that groundwater may contribute flow to surface streams, which may then sink back into the groundwater aquifer, or vice versa, along individual stream channels.

Groundwater Withdrawals

Groundwater is withdrawn from the Ozark system for multiple uses including public supply, domestic use, industrial purposes, mining, livestock watering, aquaculture, and irrigation of crops. Total groundwater withdrawals in the Ozark system—excluding 10 counties along the eastern border, which likely withdraw water from the shallow alluvial aquifers of the Coastal Plain aquifer system (fig. 8)—were estimated to be approximately 380 Mgal/d in 2010 and have increased over time (U.S. Geological Survey, 2014; U.S. Geological Survey, 2015d) (fig. 15). Groundwater use accounted for approximately 26.2 percent of the 1,400-Mgal/d total consumptive water use (nonconsumptive thermoelectric power-generation water use is 4,200 Mgal/d). The NWIS water-use categories, such as thermoelectric power generation, were consolidated into five water-use divisions to aid in interpretation and analysis of the water-use data; the divisions are (1) public supply, (2) business, (3) agriculture, (4) livestock, and (5) domestic. Table 7 summarizes the five divisions discussed in this report and how the divisions relate to NWIS categories.

Although groundwater withdrawals account for less than 10 percent of the total withdrawals from the Ozark system, groundwater provides an important resource for people living in the Ozark Plateaus. The largest division of groundwater use is public supply (including water withdrawn by public and private water suppliers that furnish water to at least 25 people or have a minimum of 15 service connections (Pugh and Holland, 2015), which has accounted for 34 to 44 percent of total groundwater use since 1985. Additionally, an estimated 63 Mgal/d of water was withdrawn for domestic self-supply in 2010, with nearly all withdrawals assumed to be from groundwater (Maupin and others, 2014; Pugh and Holland, 2015). Groundwater used for public supply and domestic self-supply totaled 212 Mgal/d in 2010, or approximately 56 percent of total groundwater use, highlighting the importance of groundwater as a drinking-water source in the Ozark system. Missouri has the largest land-surface area and population within the Ozark system and is also the largest user of groundwater from the Ozark system; in 2010, Missouri withdrew 331.0 Mgal/d (87 percent) of the total groundwater used, of which approximately 124.7 Mgal/d (38 percent)

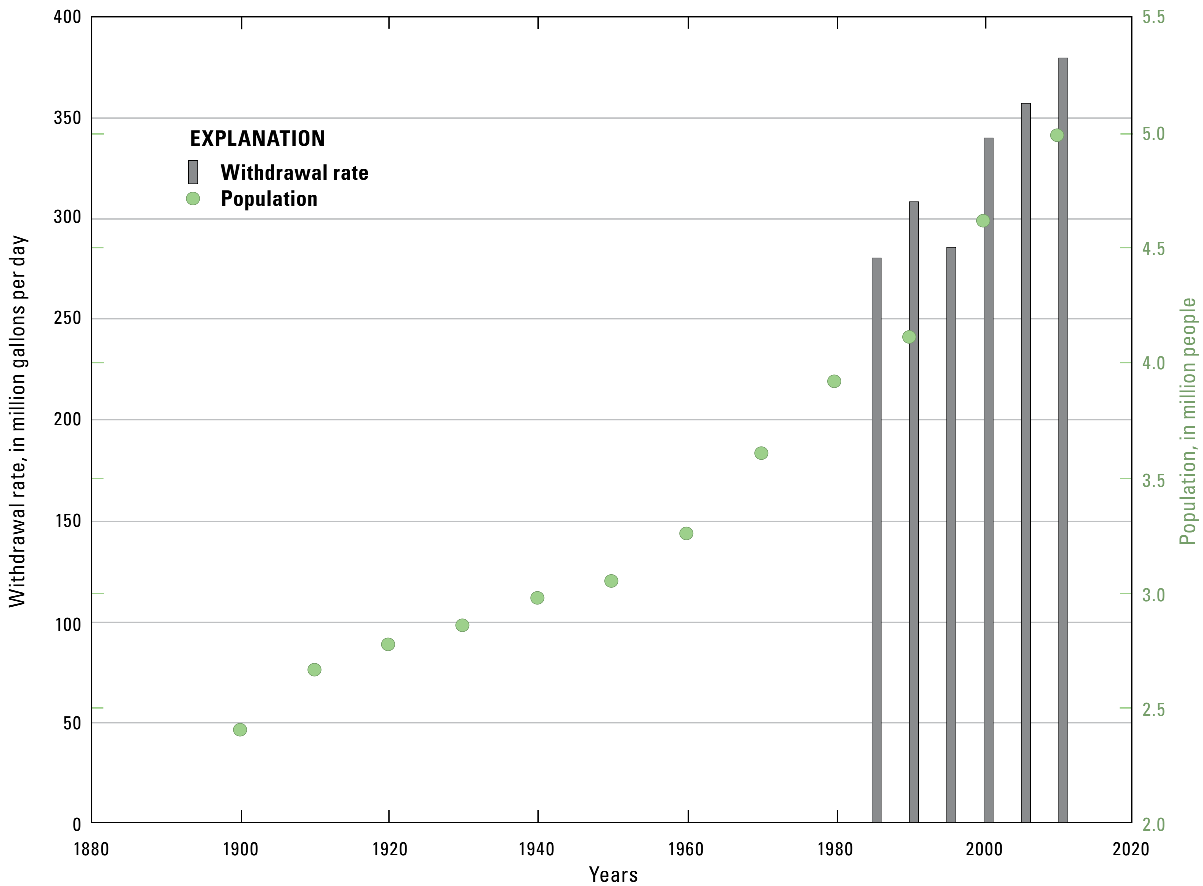


Figure 15. Groundwater-withdrawal rate compared to population through time for counties in the Ozark Plateaus aquifer system (Minnesota Population Center, 2011; U.S. Geological Survey, 2015d).

Table 7. Water-use divisions compared to National Water Information System (NWIS) water-use categories.

Use division	NWIS categories
Livestock	Livestock
Domestic	Domestic (self-supplied)
Agriculture	Irrigation, aquaculture
Public supply	Public supply
Business	Thermoelectric power generation, industrial (self-supplied), mining, commercial (self-supplied)

was for public supply (table 8). Public supply use from groundwater is generally evenly distributed across the Ozark system, with higher withdrawal rates in Missouri as of 2010 (fig. 8). Self-supplied domestic use tends to be concentrated in counties in south-central Missouri and north-central Arkansas, although the spatial distribution has changed between 1985 and 2010.

Agriculture groundwater use (85.4 Mgal/d), including irrigation and aquaculture, falls second after combined public supply and domestic use (table 8). At the eastern border of the Ozark system, agriculture in eastern Arkansas and southeastern Missouri is dominated by row-crop agriculture, including production of cotton, rice, and soybeans (Missouri Department of Natural Resources, 2003; Pugh and Holland, 2015); however, as previously noted, counties at the eastern border of the Ozark system withdraw a majority of the groundwater from shallow alluvial aquifers (Pugh and Holland, 2015) and were therefore excluded from the analysis of water use in the Ozark system (fig. 8). Southwestern Missouri also withdraws groundwater for agriculture, and in 2010 groundwater-withdrawal rates for that area were highest in Barton County (8.01 Mgal/d). Historically, Barton County has been a top county for hay and sorghum production in the State of Missouri (Missouri Department of Natural Resources, 2003).

Business use includes thermoelectric power generation, industrial, mining, and commercial uses of groundwater (table 7). In 2010, business use of groundwater was 60.9 Mgal/d (table 8), with approximately 96 percent of the use in Missouri, especially southeastern and southwestern Missouri. Three counties in Missouri—Cape Girardeau, Jasper, and Greene Counties—accounted for approximately 27.2 Mgal/d, or 45 percent of total business use in 2010 (Minnesota Population Center, 2011). Cape Girardeau County includes dominantly industrial users, Jasper County includes thermoelectric power generators, and Greene County includes a mix of industrial and thermoelectric users.

Although livestock watering is the smallest groundwater-use division in the Ozark system (table 8), poultry, hogs, and cattle are important components of the economy in all four States. Benton, Washington, and Carroll Counties in northwestern Arkansas were the top three counties for agricultural sales of poultry, eggs, and cattle in Arkansas (U.S. Department of Agriculture, 2012). Groundwater use for livestock is typically not reported because small water users—defined as users who are capable of pumping less than 50,000 gallons per day (gal/d) annually—are not required to report water use; therefore, livestock groundwater use is estimated from livestock population multiplied by an animal-specific water requirement, ranging from 0.04 to 30 gal/d per animal (Holland, 2007). Available data show that the highest livestock groundwater use in the Ozark system is in Benton, Washington, and Carroll Counties, which together accounted for approximately 2.80 Mgal/d, or 13 percent, of total livestock water use in 2010.

Although total groundwater use in the Ozark system is relatively small compared to surface-water use, the mostly carbonate units of the Ozark system are the primary source of freshwater for many public water users and nearly all of the self-supplied domestic water users in the Ozark Plateaus (Imes and Emmett, 1994); as a result, the Ozark system is a critically important resource for much of the Ozarks. Water-level declines have been observed around municipal and industrial pumping centers in Miami, Okla.; Pittsburg, Kans.; and Springfield, Mo. (Imes and Emmett, 1994). For example, by the 1970s a cone of depression had formed near Springfield, Mo., which continued to enlarge through the 1980s (Imes, 1989), causing the city of Springfield to supplement the municipal water supply with surface water (Richards, 2010). Cones of depression in the Ozark system—primarily in the Ozark aquifer—tend to be localized with steep hydraulic gradients because of the aquifer properties typical of carbonate units.

The high hydraulic conductivities observed in the Ozark system—as much as 1,000 ft/d (Stanton, 1993)—are zones of high permeability representing karst conduits. Although these flow paths are effective in transmitting groundwater rapidly through the aquifer, the preponderance of groundwater is stored in low-porosity matrix blocks where hydraulic conductivity is low. The volume of low-porosity matrix is much greater than the relative volume of karsted rock with high hydraulic conductivity and high porosity; however, matrix porosity is so low that storage is often low. Wide-ranging storage coefficients of 9×10^{-9} to 7×10^{-3} for the Ozark aquifer reflect these porosity types (table 3).

Table 8. Groundwater use in 2010 by division for portions of the four States in the Ozark Plateaus aquifer system.

[Values are in million gallons per day. Water-use data are from the National Water Information System (U.S. Geological Survey, 2015d)]

State	Public supply	Domestic	Agriculture	Business	Livestock	Total
Arkansas	15.4	4.7	3.7	0.2	7.8	31.7
Kansas	5.2	0.0	0.0	1.2	1.2	7.7
Missouri	124.7	55.3	81.1	58.2	11.8	331.0
Oklahoma	3.4	3.3	0.7	1.3	1.1	9.8
Total	148.7	63.3	85.4	60.9	21.9	380.2

Hydraulic characteristics of carbonate units of the Ozark system cause cones of depression around pumping wells to be small in extent. By way of example, one of the larger cones of depression in the Ozarks is near Springfield, Mo., measured approximately 6 by 8 miles in 2006–7 (Richards and Mugel, 2008), and is therefore not distinctive on regional-scale potentiometric-surface maps (Nottmeier, 2015). Despite the local importance of cones of depression in the Ozark aquifer, the hydraulic properties of the carbonate units limit pumping from the aquifer and limit the cones from expanding. Because of the relatively minor volume of groundwater stored in the carbonate units, declines in aquifer recharge, such as occur during periods of drought, can create substantial decreases in water availability at seasonal time scales.

Lateral Outflow

Streams and geological controls define Ozark system boundary extents. The northern boundary of the Ozark system is defined by the Missouri River Valley, where a major component of Ozark system groundwater discharges (Imes and Emmett, 1994). In similar fashion, the Mississippi River Valley forms the eastern boundary of the Ozark system from its confluence with the Missouri River Valley to the Mississippi Alluvial Plain (fig. 1). To a degree, this designation is somewhat arbitrary because Ordovician and Cambrian hydrogeologic units dip steeply below the river axis and available groundwater data show no indication of upwards discharge from these deeply buried units into the Mississippi River Valley (Imes and Emmett, 1994; Mesko and Imes, 1995); therefore, Ozark system groundwater could conceivably flow eastward beneath the Mississippi River because the Paleozoic hydrogeologic units are known to extend to the east. Imes and Emmett (1994) estimated that approximately 2,000 Mgal/d of groundwater flows laterally from the Ozark system and discharges to streams at the Ozark system boundaries, such as the Mississippi, Missouri, Neosho, and Arkansas Rivers (fig. 1).

To the southeast of the Ozark Plateaus, the Paleozoic hydrogeologic units of the Ozark system extend beneath the Mississippi Alluvial Plain, but the alluvial plain boundary is regarded as the approximate southeastern boundary of the Ozark system. Modeling work of Imes and Emmett (1994) and Mesko and Imes (1995) determined that much of the groundwater moving through the Paleozoic rocks discharges upward into overlying Cretaceous, Tertiary, and Quaternary sediments as the water moves out into the Mississippi Alluvial Plain. Mesko and Imes (1995) conducted regional groundwater-flow simulations linking the Ozark system (Imes and Emmett, 1994) and the Mississippi embayment regional aquifer system (Brahana and Mesko, 1988) groundwater models. Simulation results indicated that the rate of groundwater moving from the Ozark system under the fall line was 650–800 ft^3/s (420–517 Mgal/d) greater than the rate of recharge to the Mississippi embayment in that area. The most likely alternative discharge for this water-budget discrepancy was postulated to be stream discharge; hence, model results indicated that a considerable volume of groundwater might be discharging to Mississippi embayment streams. Seepage measurements were conducted to determine if this additional water-budget component could be discerned in embayment streams; data from the Black and Current Rivers and their major tributaries indicated that groundwater did indeed contribute substantial flow to the streams—an amount in excess of that expected from local recharge in the alluvial aquifer. Total groundwater contribution to the streams was more than 1,500 ft^3/s, and total stream loss was about 500 ft^3/s; therefore, a total gain of approximately 1,000 ft^3/s and an average gain of 2.6 ft^3/s per mile for the streams were observed (Mesko and Imes, 1995). The hydrologic measurement results from Mesko and Imes (1995) were in precise agreement with model results and illustrated the scale and importance of groundwater contribution to streamflow at the Ozark system margins. Recharge distributions examined by Clark and Hart (2009) are consistent with the interpretations of influx of Ozark system water described by Mesko and Imes (1995).

The southern boundary of the Ozark system is set as the Arkansas River, although this is a somewhat arbitrary assignment and probably does not define a firm, technical flow boundary (similar to the Mississippi River eastern boundary and Mississippi embayment southeastern boundary), inasmuch as the Paleozoic aquifer units are known to extend south beyond the Arkansas River, and several thousand feet of Pennsylvanian shale of the Western Interior Plains confining system separates the aquifer system from the river. Discharge upward into the Arkansas River is therefore likely considerably impeded, and Ozark system water may continue some degree of lateral movement. Available stream data for the northern tributaries of the Arkansas River do not indicate any contribution of groundwater from the deeply buried units of the Ozark system (Imes and Emmett, 1994). Imes and Emmett (1994) inferred that Ozark system flow lines curved to the southeast, with groundwater ultimately discharging upward into the younger, more permeable sediments of the Mississippi Alluvial Plain. This interpretation is supported by Mesko and Imes (1995) and also by the occurrence of high TDS in springs that emerge along the Ozark Highlands-Coastal Plain fall line (Kresse and others, 2014). Groundwater-flow rates in the Ozark system from the Springfield Plateau to the south along the steeply plunging strata beneath the Boston Mountains are likely relatively slow and probably reflect decreasing aquifer transmissivity, although aquifer-characteristic data are sparse (Melton, 1976; MacDonald and others, 1977). Wells completed in the Ozark aquifer beneath the Western Interior Plains confining system in the Boston Mountains exhibit typically poor water quality that indicates a long residence time; a high degree of rock/water interaction; minimal flushing by relatively young, fresh recharge; and stagnation of flow. A general trend of decreasing yields and water quality in the Ozark aquifer farther south beneath the Boston Mountains has been observed by Melton

(1976), MacDonald and others (1977), and Prior and others (1999). These water-quality and flow data indicate that the southern boundary approximates a stagnation zone, rather than being a dynamic flow boundary, with the flux of freshwater from the updip sections of the aquifer into and through the downdip area of the Boston Mountains being insufficient to drive out saline formation waters. This characterization of flow highlights the importance of the White River serving as both a local, internal groundwater-flow boundary in the Ozark Plateaus and serving as a regional-scale boundary affecting deeper flow. In the Boston Mountains, particularly where the Ozark system lies beneath thick Mississippian and Pennsylvanian shales, the combination of decreasing water quality, diminishing yields, and greater drilling costs for completing wells (where depths to the aquifer exceed 1,000 ft) limits use and defines a pragmatic boundary beyond which groundwater production from the Ozark aquifer has not proven viable. All municipal wells producing from the Ozark aquifer that are located more than 5 miles south of the Springfield Plateau-Boston Mountains boundary have been abandoned because of a combination of marginal well yields and poor water quality, including wells at South Mountain, Leslie, Nail-Swain (west of Deer, Ar.), Compton, Mockingbird Hill (southwest of Jasper, Ar.), Hasty, and Piercetown. In these wells, concentrations of specific dissolved constituents were consistently reported above relevant EPA-mandated levels, including radium and fluoride.

The Cherokee Lowlands, a broad topographic low that serves as the southwestern boundary of the Ozark Plateaus physiographic province (Fenneman, 1938), was chosen to serve as the approximate western boundary of the Ozark system. The hydrologic boundary is remarkably abrupt in the transition between the nearly stagnant, slowly eastward-flowing saline water of the Plains system and the westward-flowing freshwater of the Ozark system. Within this freshwater/saline-water transition zone, Ozark system groundwater mixes with the saline water and either discharges into shallower aquifers or discharges as base flow into the Osage and Neosho Rivers and their tributaries (Jorgensen and others, 1993; Jorgensen and others, 1996).

Christenson and others (1994) described spatial changes in Ozark aquifer groundwater chemistry and delineated a geochemical transition zone at the western edge of the Springfield Plateau in northeastern Oklahoma. The transition zone is characterized by a change from relatively low dissolved-solids concentrations of generally less than 200 mg/L and chemistry dominated by calcium, magnesium, and bicarbonate ions to high dissolved-solids concentrations of 800 mg/L or greater and chemistry dominated by sodium and chloride ions.

Christenson and others (1994) noted that salinities and large concentrations of radium limited use of the Ozark aquifer in northeastern Oklahoma, constituting a practical boundary for viable water use from the Ozark aquifer similar to that seen in the Boston Mountains in Arkansas. Spiker (1977) noted similar groundwater chemistry and groundwater-use problems in extreme southeastern Kansas, with wells completed in the Ozark aquifer exhibiting elevated radium and dissolved-solids concentrations.

Within the Ozark Plateaus, two east-west trending topographic divides exercise regional control on groundwater and surface-water flow and interaction. A topographic ridge over the high axis of the Springfield Plateau, Salem Plateau, and St. Francois Mountains (fig. 1) extending from the tristate area to the Mississippi River east of the St. Francois Mountains partitions the Ozarks into two groundwater provinces of nearly equal area (Nottmeier, 2015). North of the divide, groundwater moves from the uplands and discharges into the Missouri, Mississippi, Meramec, Osage, and Gasconade Rivers and tributaries. South of the divide, groundwater discharges into the Neosho, Spring, and White Rivers. A second east-west trending divide is defined by the topographic high of the Boston Mountains in northern Arkansas. Groundwater north of the divide flows to the White, Buffalo, and Illinois Rivers. The combination of these divides directs considerable flow to the White River and accentuates the importance of the river as a drain and internal flow boundary in the Ozarks. This importance is highlighted by water-quality and flow information south of the White River in the Boston Mountains, which indicates relatively minor flow in that zone, as previously discussed in the Lateral Outflow section. Groundwater south of the divide formed by the Boston Mountains flows towards the Arkansas River (Seaber and others, 1987). The relatively low permeability of the Western Interior Plains confining system greatly impedes recharge to the underlying Ozark system in the Boston Mountains, and the high TDS values of Ozark system groundwater indicate that flow rates are low and residence time is high, presenting a relatively stagnant, nondynamic, and marginal aquifer in this region of the Ozark system.

Groundwater in Storage

Aquifer storage represents the quantity of water that resides in an aquifer, and the available storage volume may act as a source or sink for groundwater as stresses on an aquifer system change spatially or temporally. Changes in storage may be quantified as the storativity, which is the volume of water released from storage per unit decline in hydraulic head in the aquifer per unit area of the aquifer. Storativity is a dimensionless quantity and ranges between zero and the effective porosity of the aquifer. Water is yielded from storage by different means for the confined versus the unconfined areas of an aquifer. Under confined conditions, water is yielded because of the compressibility of the aquifer rock matrix and, to a much lesser degree, by the expansivity of water. Aquifer compression and water expansion occur as water is removed from a confined aquifer, fluid pressure decreases, and lithostatic (overburden) stress is transferred to the aquifer matrix. A confined aquifer is always fully saturated. In an unconfined aquifer, drainable effective porosity is actually dewatered, and the aquifer becomes unsaturated as water is removed from storage (Fetter, 2001).

Changes in the fluxes of water coming into and out of an aquifer system can cause subsequent changes in groundwater storage. Increased pumping related to population increases, changes in climate affecting precipitation and evapotranspiration, and—on a more local scale—mining dewatering activities and construction of reservoirs have resulted in changing stresses on the Ozark system that have affected groundwater levels and groundwater storage (Warner and others, 1974; Imes, 1989; Richards, 2010). As water is released from storage in areas where the Ozark aquifer is unconfined, changing groundwater gradients enhance the opportunity for recharge from stream or reservoir leakage. Under such conditions, storage alternately serves as a source and a sink as water is removed and then added back through recharge. Conversely, during wet periods (or construction of reservoirs), water levels rise, water in storage increases, and changes in gradient result in streams gaining more flow as storage is filled. Large-scale groundwater pumping can upset such a balance, resulting in depletion of aquifer storage, which in turn decreases water levels and streamflow (Wagner and others, 2014). Decreases in aquifer storage have necessitated decreasing the degree of reliance on groundwater from some aquifers and shifting to surface-water use to meet the growing demand (Richards, 2010). Understanding the timing and magnitude of changes in aquifer storage is critically important in assessing and planning for groundwater availability.

Karst aquifers are characterized by several types of heterogeneously distributed porosity: intergranular rock-matrix pores, rock discontinuities such as fractures and bedding planes, and dissolution voids such as vugs and conduits (Ford and Williams, 2007). This complex porosity varies greatly from matrix-porosity-dominated clastic systems and has strong control on the character of storage, as well as hydraulic conductivity. Total storage within a karst system is distributed, generally unequally, across the porosity types with matrix porosity often constituting a large percentage of storage as compared to fracture or conduit porosity (Kresic, 2007). These porosity types have a strong control on water-level response during pumping of a karst aquifer (Kresic, 2007). For example, Tsoflias and others (2001) showed that fracture porosity rapidly yielded water during pumping, but these fractures were rapidly dewatered when pumping rates exceeded the rate at which matrix porosity yielded water into the fracture and well bore, resulting in a rapid water-level decline during early stages in pumping and a slower decline during later pumping as matrix porosity yielded water to far-reaching fractures (Tsoflias and others, 2001).

Hydrologic Budget for the Ozark Plateaus Aquifer System

Inflows and outflows of water to the Ozark system can be conceptualized as a hydrologic budget to determine the magnitude of water sources and groundwater flow into, through, and out of the system (figs. 12 and 16). As discussed, sources of water to the Ozark system include recharge from precipitation (the amount not lost to evapotranspiration, interception, or runoff), stream leakage from losing-stream sections, and lateral inflow. Loss of water from the Ozark system includes groundwater flow to gaining-stream sections and springs, lateral groundwater outflow, and groundwater withdrawals for various water uses. Estimates of water-volume rates from each of these categories can be calculated using data synthesized for this study to provide an up-to-date hydrologic budget for the Ozark system. The Ozark system is assumed to be at or near hydrologic equilibrium, and so gains and losses of water are balanced.

Precipitation over the 69,000-mi^2 study area ranges from 27.9 to 63.1 in/yr (fig. 6) and averages 43.9 in/yr (PRISM Climate Group, 2015). Precipitation provides an approximate average input of 144,000 Mgal/d to the Ozark system, of which 25,300 Mgal/d (approximately 18 percent) and 69,800 Mgal/d (approximately 48 percent) fall on the Springfield and Salem Plateaus, respectively, based on the surface-area proportions of these plateaus relative to the Ozark system boundaries (table 9). The remaining precipitation falls over the Boston Mountains and does not enter the Ozark system. Based on SWB model results (appendix 1), 58 percent of precipitation is lost to evapotranspiration, 10 percent is captured via interception by vegetation, and 6 percent is estimated to flow out of the model boundary or be available to recharge downslope areas (table 9); therefore, an estimated 24 percent of precipitation contributes to groundwater recharge across the Ozark system, resulting in a net volume of 22,800 Mgal/d of freshwater. The remaining 2 percent of precipitation not accounted for in table 9 includes changes in soil moisture and rejected recharge in the SWB model (Westenbroek and others, 2010). These results are similar to hydrologic-budget estimates made by Imes and Emmett (1994), which ultimately used recharge estimates from models of climate, vegetation, and soil data (Dugan and Peckenpaugh, 1985), similar to inputs for the SWB model.

Recharge estimates using climate, vegetation, and soil data generally reflect shallow groundwater recharge, which represents recharge to the Springfield Plateau aquifer where exposed on the Springfield Plateau and to the Ozark aquifer where exposed on the Salem Plateau; therefore, on the basis of the surface area of the plateaus and results from the SWB model, the Springfield Plateau aquifer is calculated to receive 6,000 Mgal/d of recharge, and the Ozark aquifer is calculated to receive 16,800 Mgal/d of recharge (fig. 16, table 9). Recharge to deeper confined parts of groundwater aquifers by vertical leakage will be substantially less than shallow recharge, with estimates ranging from approximately zero to 8 percent of precipitation (table 9). By using the hydrologic budget from Imes and Emmett (1994), approximately 8 percent (500 Mgal/d) of recharge to the Springfield Plateau aquifer contributes groundwater to the underlying Ozark aquifer (table 9). The 500 Mgal/d of groundwater lost via vertical leakage from the Springfield Plateau aquifer therefore provides a source of recharge to the confined part of the Ozark

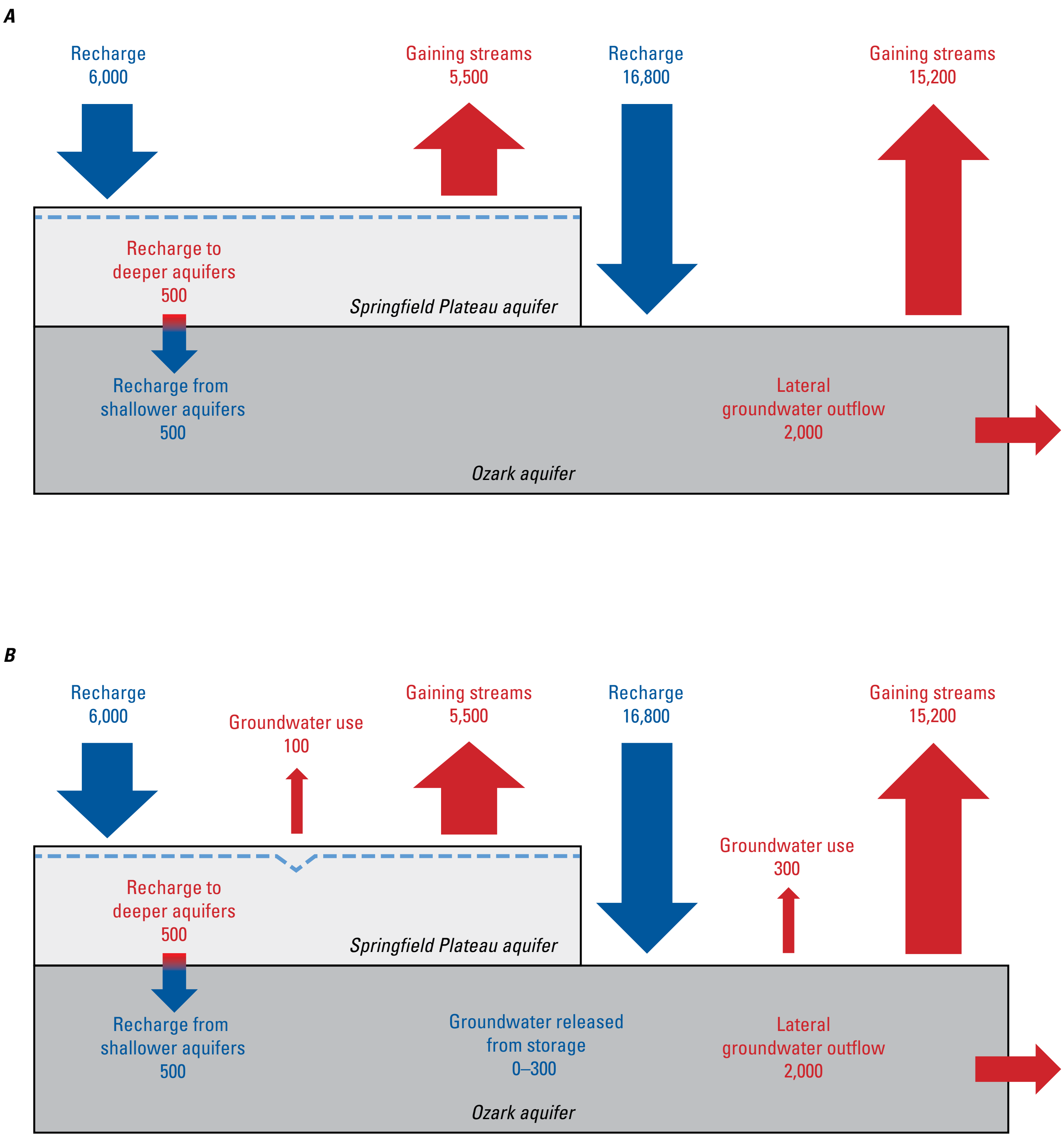


Figure 16. Conceptual hydrologic budget (in million gallons per day) for *A*, pre-development and *B*, post-development conditions in 2014 for the Ozark Plateaus aquifer system.

Table 9. Hydrologic-budget values for the Springfield Plateau aquifer and Ozark aquifer.

[The 2 percent of precipitation not accounted for includes changes in soil moisture and rejected recharge in the soil-water-balance model. Mgal/d, million gallons per day; blue shading, gain; red shading, loss; NA, not applicable; neg., negligible volume, gain, or loss]

Budget component	Springfield Plateau aquifer			Ozark aquifer			Source
	Volume (Mgal/d)	Percent of precipitation	Percent of recharge	Volume (Mgal/d)	Percent of precipitation	Percent of recharge	
Precipitation	25,300	100	NA	69,800	100	NA	PRISM Climate Group, 2015
Evapotranspiration	14,700	58	NA	40,500	58	NA	SWB model[1]
Interception	2,500	10	NA	7,000	10	NA	SWB model
Outside surface-water runoff	1,500	6	NA	4,200	6	NA	SWB model
Recharge (direct, via precipitation)	6,000	24	100	16,800	24	97	SWB model
Recharge from shallower aquifers	NA	NA	NA	500	NA	3	Imes and Emmett, 1994
Lateral groundwater inflow	neg.	NA	NA	neg.	NA	NA	Imes and Emmett, 1994
Losing streams	neg.	NA	NA	neg.	NA	NA	Seepage-run dataset[2]
Recharge to deeper aquifers	500	NA	8	neg.	NA	NA	Imes and Emmett, 1994
Lateral groundwater outflow	NA	NA	NA	2,000	NA	12	Imes and Emmett, 1994
Gaining streams and springs	5,500	NA	92	15,200	NA	88	Seepage-run dataset
Groundwater use	100	NA	2	280	NA	2	U.S. Geological Survey, 2015d

[1]Soil-water-balance (SWB) model, see "Aquifer Recharge" section in the text.

[2]Analysis of seepage-run dataset from Knierim and others (2015).

aquifer where the Ozark confining unit is absent or faulted and fractured. A smaller amount of groundwater moves by vertical leakage from the Ozark aquifer to the underlying St. Francois aquifer; 20 Mgal/d (0.1 percent of recharge to the Ozark aquifer) flows from the Ozark aquifer to the deeper St. Francois aquifer, which is generally a negligible amount for the scale of the regional hydrologic budget (table 9; Imes and Emmett, 1994).

Surface-water and lateral groundwater inflows to the Ozark system from outside Ozark system boundaries are generally minimal because of the topographic and geologic geometry of the Ozark Plateaus. Inflow from surface streams originating outside of the Ozark system is minimal because of the topography of the Ozark dome (see "Lateral Inflow" section). Lateral groundwater inflow to the Ozark system occurs primarily in the broad freshwater/saline-water transition zone on the northwestern margins of the system (fig. 1), where saline water from the Plains system mixes with freshwater from the Ozark system, contributing approximately 0.01–1.3 percent of groundwater in springs, wells, and streams near the boundary (see "Lateral Inflow" section). As a result, lateral groundwater inflow from the Western Interior Plains—similar to surface-water inflow—provides a minimal component of the hydrologic budget (table 9).

Groundwater outflow from the Ozark system occurs as lateral outflow to adjacent groundwater and surface-water systems at the Ozark system boundaries, to springs at the land surface, and to contribution of base-flow discharge in streams within the Ozark Plateaus. Lateral groundwater outflow from the Ozark system to the Mississippi embayment regional aquifer system has been estimated at approximately 1,000 ft^3/s, or 650 Mgal/d (Mesko and Imes, 1995). Quantitative measurements are not available at the other boundaries of the Ozark system, although Imes and Emmett (1994) estimated through groundwater modeling approximately 2,000 Mgal/d discharge to streams at all the boundaries of the Ozark system. This flow is assumed to predominantly discharge from the Ozark aquifer, resulting in a loss of approximately 12 percent of the recharge to the Ozark aquifer (table 9). A major loss of groundwater from the Ozark system occurs as groundwater emerges at springs and also contributes to base-flow discharge of streams (see "Groundwater Discharge to Streams" section).

The USGS seepage-run studies were digitized to provide an estimate of surface-water/groundwater interaction throughout the Ozark Plateaus (Knierim and others, 2015), and by using this dataset, an estimate of groundwater loss from the Ozark system was calculated. Based on the seepage run data (Knierim and others 2015), the amount of groundwater discharging to springs or flowing directly into the streambed as diffuse or point discharge ranged from -7.4 ft^3/s per river mile (groundwater recharge) to 16.0 ft^3/s per river mile (groundwater discharge), with a mean of 1.9 ft^3/s

per river mile. As a result, streams in the Ozark Plateaus are predominantly gaining, which represents discharge of groundwater from the Ozark system. By multiplying a mean discharge of 1.9 ft^3/s per river mile by the total length of surface streams in the Ozark Plateaus (not including first- and second-order streams because seepage studies were generally completed on medium-sized streams), the net loss of groundwater from the Ozark system to streams and springs was approximately 25,400 Mgal/d. Within the Ozark Plateaus, seepage-run studies were completed predominantly in the Springfield and Salem Plateaus (fig. 14), with approximately 27 percent of studies completed in the Springfield Plateau and approximately 73 percent completed in the Salem Plateau. By using these same ratios, groundwater discharge to streams and springs was estimated to account for a loss of 6,900 Mgal/d (115 percent of recharge) from the Springfield Plateau aquifer and 18,500 Mgal/d (110 percent of recharge) from the Ozark aquifer.

Estimates of groundwater discharge to springs and streams from the seepage-run dataset likely overestimate rates of groundwater flow because recharge to the Ozark system is less than the calculated outflow component. The mean discharge from groundwater to streams was 1.9 ft^3/s per river mile, but the median was 0.6 ft^3/s per river mile, providing evidence that the seepage-run dataset (Knierim and others, 2015) may be positively skewed and thus overestimates the loss of groundwater. By using the other components of the hydrologic budget, groundwater discharge to springs and streams may account for approximately 92 percent of recharge from the Springfield Plateau aquifer (or 5,500 Mgal/d) and approximately 88 percent of recharge from the Ozark aquifer (or 15,200 Mgal/d) (table 9). A net discharge of 20,700 Mgal/d from the Ozark system to springs and streams results in approximately 1.0 ft^3/s per river mile of water gained by streams in the Ozark Plateaus, either from springs discharging adjacent to the stream or from diffuse and point discharge directly into the streambed. On the basis of the seepage dataset (Knierim and others, 2015), discharge from springs is approximately 1,500 Mgal/d, which is in close approximation of the sum of discharge from the largest springs in Missouri, estimated to be 1,300 Mgal/d (Vineyard and Feder, 1982).

The hydrologic budget representing predevelopment steady-state conditions is approximately balanced where loss of groundwater through discharge to springs and gaining streams, lateral groundwater outflow, and vertical leakage account for the gain in freshwater recharge to the Ozark system (fig. 16). After approximately 1900, groundwater withdrawals from the Ozark system for public and domestic supply, industrial and commercial purposes, mining, livestock, and irrigation increased. In 2010, 380 Mgal/d of groundwater were pumped from the Ozark system (U.S. Geological Survey, 2015d), accounting for approximately 2 percent of recharge (table 9). Although groundwater use is a small component of the hydrologic budget in the Ozark system, water-level declines and local cones of depression have been observed around pumping centers in Miami, Okla.; Pittsburg, Kans.; and Springfield and Joplin, Mo. (Imes, 1989; Imes and Emmett, 1994; Richards, 2010; Nottmeier, 2015). As a result, release of groundwater from storage has occurred in the Ozark system since predevelopment and is probably on the order of zero to 2 percent of recharge, similar in scale to the amount of groundwater removed by pumping.

Changes in Hydrologic Conditions from 1900 to Present

The Ozark system has experienced substantial changes since 1900 because the landscape of the Ozark Plateaus was altered during western expansion of European settlement, and groundwater use increased with the increasing population (Adamski and others, 1995; Clingenpeel, 1999; Hays, 1999). Components of the hydrologic budget for the Ozark system are altered by shifts in inflows and outflows, meaning that changes in precipitation, temperature, land-use patterns, and groundwater withdrawals all affect groundwater availability. Long-term analysis of groundwater levels and climate trends in the Ozark system are scarce, partly because of a paucity of long-term groundwater-level data (Kresse and others, 2014), although groundwater models generally include water-use scenarios for periods of decreased precipitation and drought (Richards, 2010). As a result, understanding historical changes in recharge (inflow), groundwater use (human-induced outflow), and surface-water/groundwater interaction (outflow) can aid modelers in more accurately predicting future water availability.

Aquifer Recharge

Recharge to the Ozark system is a function of climate, topography, soil type, and land use. Changes in these components will ultimately affect net inflow to the Ozark system and the hydrologic budget. Of the factors that control recharge, changes in primarily temperature, precipitation, and land use can be evaluated to qualitatively assess recharge over time. The period 1951–2011 defined a trend of increasing mean annual precipitation of 0.27 percent annually in the southern Ozark Plateaus (in northern Arkansas and southern Missouri) (Wagner and others, 2014), which—holding other components in the hydrologic-budget constant—would increase recharge to the Ozark system. Streamflow at a majority of gage stations in the Springfield and Salem Plateaus also increased significantly between 1951 and 2011 (Wagner and others, 2014), providing evidence that possible increases in potential evapotranspiration due to increasing global temperatures (Intergovernmental Panel on Climate Change, 2014) were not great enough to offset the greater precipitation. Land-use patterns in the Ozark Plateaus have also been modified since 1900, with substantial clearing of forests for pastures and row-crop agriculture during the timber-boom period of the late 1800s, followed by a decrease in the acreage of cultivated and pasture land beginning in approximately

1960 (Jacobson and Primm, 1997). Results from the SWB model for the Ozark Plateaus indicate that mean recharge was higher in forested areas (15.9 in/yr) compared to pastures (11.2 in/yr) or crops (12.0 in/yr). If recharge is correlated to land-use type, then recharge may have also decreased from 1900 to the mid-1900s because of logging and the resulting shift to cleared land, followed by increasing recharge as tree growth ensued and areas were reforested. The combination of significant increases in precipitation since 1951 (Wagner and others, 2014) and decreases in the acreage of pasture and crops (Jacobson and Primm, 1997) may have contributed to increases in net recharge to the Ozark system since the mid-1900s.

Groundwater Withdrawals

Early records of groundwater-withdrawal rates are difficult to acquire, but water-use values were generally available beginning in the mid-1900s. Prior to 1900, groundwater withdrawals from the Ozark system were assumed to effectively be zero and presumably increased with increasing population as the Ozark Plateaus were settled during western expansion (fig. 15). The Missouri Department of Natural Resources began the Census of Missouri Public Water Systems in 1962, which provides the earliest widespread records of water use in the Ozark system. Groundwater-withdrawal rates for major public water suppliers (municipalities and public water-supply districts) were approximately 25 Mgal/d in 1962 (Missouri Division of Health, 1962). In 2010, groundwater-withdrawal rates in Missouri from the public supply water-use division (124.7 Mgal/d) accounted for approximately 33 percent of the total 380.2 Mgal/d of groundwater use in the Ozark system (table 8). Assuming this same ratio, the total groundwater-withdrawal rate in 1962 may have been 76 Mgal/d for the Ozark system. Between 1962 and 2010, groundwater use in the Ozark system increased approximately 400 percent. During approximately the same period, population increased from 3.3 million people in 1960 to 5.0 million people in 2010 (not including population in the eastern counties of the Ozark system that withdraw groundwater primarily from shallow alluvial systems) (Minnesota Population Center, 2011), or an increase of 52 percent. As a result, population and groundwater use have increased in the Ozark system since development (fig. 15), but the relative change has not been equivalent, providing evidence that per capita consumption of groundwater and withdrawal rates for other water-use categories (such as agriculture or business) have also increased.

Although groundwater use in the Ozark system has increased over time, the relative magnitude of increase is not as large in some areas that have experienced a shift to surface-water resources. For example, in northwestern Arkansas, total groundwater use was greater in 1985 than 2010 (fig. 8). The decrease in groundwater use reflects a shift in public water supply to surface water after Beaver Lake Reservoir was impounded in 1963, and a water-delivery infrastructure that grew through 2010 and beyond. In 2010, Benton County withdrew approximately 61 Mgal/d from surface water for public supply (U.S. Geological Survey, 2015c), which would represent a substantial amount of groundwater use if Beaver Lake Reservoir was not available. Notably, because of the connection between surface water and groundwater in the Ozark Plateaus, an important question remains of how much inflow to Beaver Lake Reservoir is supported by groundwater contribution to surface-water inflows to the lake. In another example, the city of Springfield, Mo., similarly reallocated a portion of water use to surface-water resources from Stockton Lake after groundwater pumping resulted in a localized cone of depression by the 1970s (Richards, 2010), although inflows to Stockton Lake and the James River (another surface-water source for Springfield) are partially supported by groundwater.

Stream Interaction

Analysis of historical precipitation and surface-water trends in the Ozark Plateaus can elucidate changes in surface-water/groundwater interaction over time. Significant increases in annual mean daily streamflow, induced by increased annual precipitation, were noted at 11 of 14 gage stations located in the Springfield and Salem Plateaus for the period 1951–2011 (Wagner and others, 2014). On the basis of the hydrologic budget for the Ozark system (fig. 16), much of the contribution to base-flow discharge is from shallow groundwater, meaning that increases in precipitation and recharge to the Ozark system can increase groundwater outflow to streams. Conversely, during periods of drought as precipitation and recharge decrease, streamflow subsequently decreases, partly because of the lowered outflow from groundwater to streams. As an example, mean annual discharge from Big Spring near Van Buren, Mo., ranged from 289 to 648 ft^3/s between 1922 and 2014 (U.S. Geological Survey, 2015b). Years of lower discharge at Big Spring correspond to negative departures from median annual precipitation for the Ozark Plateaus (fig. 5), providing evidence that decreasing precipitation can decrease discharge from karst springs in the Ozark Plateaus, although groundwater does provide a strongly modulated, or time-averaged, contribution to streamflow as compared to surface runoff. If the trend in increasing precipitation for the Springfield and Salem Plateaus continues (Wagner and others, 2014), then greater groundwater contribution to springs and streams may be predicted.

Climate Change and Groundwater Resources

Milly and others (2008, p. 10) state that hydrologic stationarity—the concept that natural hydrologic systems vary within a known and unchanging range—is “dead,” that is to say no longer valid and useable. The effect of this demise on groundwater management and water management in general is profound. Our traditional approach to predicting hydrologic conditions and managing water resources has been based almost completely on stationarity. Hydrologic stationarity has failed as a result of the Earth's changing climate. Precipitation distribution, means, and extremes; evapotranspiration rates; and river discharge characteristics have changed because of climate forcing (Intergovernmental Panel on Climate Change, 2007a; Intergovernmental Panel on Climate Change, 2007b). A warming climate accelerates the hydrologic cycle, increasing atmospheric humidity and water transport; hence, where prevailing atmospheric water-vapor fluxes converge, precipitation increases, but increasing humid-zone to dry-zone gradients and poleward expansion of the subtropical dry zone result in broad areas of greater aridity (Held and Soden, 2006; Lu and others, 2007). Increased extremes of precipitation and surface runoff will increase the importance of groundwater as a moderated water-budget component, yet groundwater will be affected by changing recharge and evapotranspiration as well.

Understanding the inflows and outflows of water to and from the Ozark system (fig. 16) can help water-resource managers more effectively adapt to various climate-change scenarios under conditions of nonstationarity. Climate change is predicted to alter the hydrologic cycle, and for each degree Celsius of temperature increase, approximately 7 percent of the global population will be exposed to decreasing renewable water resources (Cisneros and others, 2014), although changes at the local scale may vary. Increasing temperature affects the hydrologic cycle by altering timing and amounts of precipitation, rates of evapotranspiration, and the amount of water stored in various reservoirs (Gurdak and others, 2009), which ultimately change inflows and outflows to groundwater aquifers. For example, high temperatures increase rates of potential evapotranspiration (Cisneros and others, 2014), leading to decreases in soil moisture, thus decreasing moisture available for groundwater recharge. In a warm climate, precipitation is predicted to increase in intensity, likely increasing surface-water runoff in humid climates because soils become saturated more quickly and increasing the surface-runoff/infiltration ratio (Cisneros and others, 2014), which also ultimately decreases groundwater recharge. The frequency of flooding has also increased in the central United States (Mallakpour and Villarini, 2015), providing another mechanism for decreased groundwater recharge as rainfall occurs during shorter, increasingly intense periods, resulting in more water being shunted to the surface-runoff flow path. Additionally, higher temperatures are likely to increase societal demand for freshwater, and in combination with decreased aquifer recharge, may further stress groundwater resources (Cisneros and others, 2014). The uncertain nature of future human and climate effects and the slow response of groundwater systems to perturbation cause prediction of future changes in groundwater-resource availability to be difficult.

Predictions of climate change in the Ozark Plateaus are hampered by climate models of North America that typically separate Missouri and Arkansas into different regions; for example, modeling Missouri as part of the central United States and midwestern regions, which does not include Arkansas (Karl and others, 2009; Patriocola and Cook, 2013), or modeling the western extent of the Ozark Plateaus (west of the 92° meridian) as part of the Great Plains (Cook and others, 2015). Despite these limitations, regional-scale models provide better assessments of interaction among physical drivers of climate change (for example, cloud cover, soil moisture, and wind direction). General circulation models for the central United States predict decreasing precipitation and increasing temperatures through 2050, including an annual mean temperature increase ranging from 3.0 to 6.0 °F across the Ozark Plateaus and greater mid-South to Midwest (Karl and others, 2009). Some regional-scale climate models that more accurately model cloud cover predict decreased temperatures over the Ozark Plateaus (Liang and others, 2006).

Precipitation patterns—including the timing, intensity, and seasonality of rainfall—are also predicted to change. Seasonal increases in precipitation are projected to occur during the winter months within the next 50 years across the Ozark Plateaus and greater mid-South to Midwest, ranging from 2 to 15 percent (Karl and others, 2009). Extreme precipitation events are also projected to increase, with the frequency of spring-time downpours increasing by approximately 15 percent compared with a 1961–90 baseline (Hayhoe and others, 2009). Summer precipitation is projected to decrease by an average of 1–4 percent, and the average time between rain events is expected to increase (Karl and others, 2009). The midwestern region of the central United States (including Missouri) is predicted to have wetter (precipitation) conditions in April and May and drier conditions in July and August through the year 2050 (Patriocola and Cook, 2013). Additionally, heat waves are predicted to become more frequent and occur over longer durations through the year 2050 (Patriocola and Cook, 2013). The Great Plains (including the western part of the Ozark Plateaus) is predicted to experience a greater risk of decadal or multidecadal drought during the period of 2050–99, compared to historic drought occurrences (Cook and others, 2015). Despite variability in individual models, climate models collectively predict increased periods of water stress—due to some combination of changing seasonal inputs of precipitation and periods of drought—so demands on groundwater resources in the Ozark system are likely to increase in the future.

Summary

The Ozark Plateaus aquifer system underlies parts of the central United States and generally coincides with the geographic extent of the Ozark Plateaus physiographic province. Groundwater is an important resource for the more than 5.3 million people living in the Ozarks and is important in supporting and maintaining interconnected surface-water resources and key aquatic ecosystems. Increasing demand on groundwater resources, water-level declines in some areas, and potential impacts of climate change show a need for updated assessment of groundwater availability in the Ozark system. The subject study combines knowledge gained through local-scale efforts with regional study perspectives to develop a regional conceptual model of groundwater flow in the Ozark system, a key phase of groundwater availability assessment. This synthesis includes (1) a refined description of regional hydrogeologic units, (2) compilation and analysis of recent (through 2010) water-use data for the Ozark system, and (3) an updated hydrologic budget for conditions for the period 2005–14. The study is part of the larger Ozark Plateaus Groundwater Availability Study for which a regional groundwater-flow model will be the ultimate product.

The Ozark system extends across much of southern Missouri and northwestern and north-central Arkansas and smaller areas of southeastern Kansas and northeastern Oklahoma and comprises the Springfield Plateau aquifer, Ozark confining unit, Ozark aquifer, St. Francois confining unit, and St. Francois aquifer. The Ozark aquifer has been divided into upper, middle, and lower sections to better capture the spatial variation in the hydrologic property differences of the various rock formations that make up these hydrogeologic units. The Western Interior Plains confining system confines part of the Springfield Plateau aquifer on the southern and western margins of the Ozark system, and the Basement confining unit is the base confining unit of the Ozark system.

The Ozark Plateaus are one of the major karst landscapes in the United States, and karst aquifers are predominant in the Ozark system. Groundwater flow is ultimately controlled by lithologies of the constituent formations, stratigraphic relations among hydrogeologic units, geologic structure, modification of carbonate bedrock during distinct periods of karstification over time, and the character of exposed lithologies and regolith mantle at the surface that control recharge. Dissolution and pedogenesis—especially pronounced on the Mississippian limestones—have resulted in the cherty regolith mantle. The regolith mantle commonly impedes flow through the unsaturated zone, affecting recharge, karst development, and vulnerability to surface-derived contaminants and is a defining element of Ozark karst. Structural modification and extensive dissolution of carbonate rocks in the Ozark system has caused aquifer anisotropy and heterogeneity. Karst development is more advanced—as evidenced by larger springs, hydraulic characteristics, and higher well yields in the Salem Plateau and in the northern part of the Springfield Plateau (generally north of the Arkansas-Missouri border) as compared with the southern part of the Springfield Plateau in Arkansas, largely due to thinner, less extensive regolith and purer carbonate lithology.

The Springfield Plateau aquifer is composed predominantly of Mississippian limestones and interbedded chert. Well yields range to more than 100 gallons per minute (gal/min) but are typically closer to 10 gal/min. The upper Ozark aquifer comprises primarily upper Ordovician through Devonian dolostone and limestone. Well yields in the upper Ozark aquifer are similar to those of the exposed Springfield Plateau aquifer. The middle Ozark aquifer is composed predominantly of dense, low-porosity, low-permeability dolostone and acts regionally as a confining unit. The lower Ozark aquifer is the most important aquifer in the study area and is primarily composed of highly karsted Cambrian and Ordovician dolostones. Groundwater wells penetrating the lower Ozark aquifer often yield 100 gal/min or more and can yield more than 1,000 gal/min. The St. Francois aquifer comprises permeable Cambrian sandstones and dolostones and can yield 100–500 gal/min in its outcrop area.

The ultimate source of all water to the Ozark system is precipitation. Proximate sources of water to the Ozark system include recharge from precipitation, stream leakage from losing stream sections, and lateral inflow. Over the 69,000-square mile study area, an average precipitation of 43.9 inches per year results in approximately 144,000 million gallons per day (Mgal/d) of freshwater input. Results of a soil-water-balance model indicate that 58 percent of precipitation is lost to evapotranspiration, 10 percent is captured and stored by vegetation, and 6 percent flows out of the model boundary. An estimated 24 percent of precipitation contributes to groundwater recharge across the entire Ozark system, resulting in input of 6,000 Mgal/d to the Springfield Plateau aquifer and 16,800 Mgal/d to the Ozark aquifer. Total recharge and surficial recharge per unit area is greater in the northern Springfield Platea and Salem Plateau than in the southern Springfield Plateau (generally south of the Arkansas border) because of differences in regolith mantle extent and carbonate lithology. At the small watershed to subregional scale, data indicate that many Ozark streams are losing water in the rugged, high-relief headland parts of watersheds and gaining water in the lower gradient parts of the watersheds. Surface-water and lateral groundwater inflow to the Ozark system are generally minimal because of the topographic gradient imposed by uplift of the Ozark dome. The notable exception to this predominantly lateral groundwater outflow is an influx of saline groundwater across the western margin of the Ozark system from groundwater of the Western Interior Plains aquifer system, which is recharged in the front ranges of the eastern Rocky Mountains. Saline groundwater in the Western Interior Plains aquifer system travels to a saline water/freshwater mixing (or transition) zone on the western boundary of the Ozark system. Springs and streams in the transition zone show a measurable contribution of the far-traveled Western Interior Plains aquifer system groundwater; however, this net flux of groundwater into the Ozark system is negligible within the overall Ozark system budget. Available data indicate that recharge into the Ozark system is influenced by annual to decadal variability in climate and by changes in land use and land cover. Significant increases in precipitation from 1951 through 2011 and decreases in the acreage of pasture and crop land beginning around the early 1960s likely resulted in increased net recharge to the Ozark system since the mid-1900s. Projected changes in climate and continued land-use development indicate strong potential for further effects on the hydrologic cycle, recharge, and groundwater availability in the Ozark system.

Loss of water from the Ozark system includes groundwater flow to gaining stream sections and springs, lateral outflow, vertical outflow, and groundwater withdrawals for various water uses. Of the amount of precipitation that recharges the Ozark system, most of the water is returned to springs and gaining stream sections in the Ozark Plateaus. Approximately 5,500 Mgal/d and 15,200 Mgal/d of groundwater are discharged to streams and springs from the Springfield Plateau aquifer and Ozark aquifer, respectively. At the regional scale, analysis of seepage data shows that, on average, streams throughout the Ozark Plateaus are dominantly gaining; hence, streams are not a net source of water to the Ozark system, but are rather a sink. Approximately 2,000 Mgal/d of groundwater is estimated to flow laterally from the Ozark system and discharge to streams and rivers at the Ozark system boundaries, such as the Mississippi, Missouri, and Neosho Rivers. Groundwater is withdrawn from the Ozark system for multiple uses including public supply, domestic use, industrial purposes, mining, livestock watering, aquaculture, and irrigation of crops. Historically, groundwater was the primary source for municipal supply across the Ozark Plateaus; however, limited groundwater yields in some areas, extensive contamination from surface activities, and an expanding surface-water-supply delivery infrastructure have resulted in a decrease in the relative proportion of groundwater used as compared to surface water. Despite this trend in relative use amounts, total groundwater use in the Ozark system has increased from approximately 280 Mgal/d in 1985 to 380 Mgal/d in 2010; groundwater demand is expected to continue increasing in the future. Although groundwater use is a small component of the hydrologic budget in the Ozark system, water-level declines and local cones of depression have been observed around pumping centers in Miami, Oklahoma; Pittsburg, Kansas; and Springfield and Joplin, Missouri; therefore, release of groundwater from storage has occurred in the Ozark system since predevelopment and is estimated to be as much as 380 Mgal/d.

The future will bring changes in climate and hydrology and increasing societal need for water resources in the Ozarks. Groundwater will continue to be an important part of supporting these societal needs and also local ecosystems. Differences in hydrogeology across the Ozarks will impose differences in how the Ozark system responds to future climate change and in the quantity of additional groundwater available for use.

Groundwater of the Ozark system in the northern study area is more dynamic, has greater storage and larger flux, and has greater potential for further development than in the southern part of the study area. A line exists, roughly defined as 5 miles south of the Springfield Plateau-Boston Mountains boundary in Arkansas, beyond which further extensive municipal or commercial development appears unlikely under current economic and resource need conditions. Currently, a small part of the total Ozark system groundwater budget is drafted for use, leaving an apparently large component available for further development and use—particularly in the northern study area (the northern Springfield Plateau and Salem Plateau). The effects, however, of abstracting considerable additional groundwater in maintaining ecosystems and ecosystem services are not quantitatively well understood, and the intimate relation between groundwater and surface water highlights the importance of further quantitative assessment.

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