

Prepared in cooperation with the Kansas Water Office

# Quality Characteristics of Ground Water in the Ozark Aquifer of Northwestern Arkansas, Southeastern Kansas, Southwestern Missouri, and Northeastern Oklahoma, 2006–07



Scientific Investigations Report 2009–5093

**Cover photograph.** Geophysical logging of well near Pittsburg, Kansas, August 2007 (Photograph taken by L.M. Pope, USGS).

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By L. M. Pope, H.E. Mehl, and R.L. Coiner

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

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## Conversion Factors, Abbreviations, and Datum

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
inch (in.)	25,400	micrometer (mm)
Volume		
acre-foot (acre-ft)	1,230	cubic meter (m <sup>3</sup> )
Flow rate		
cubic foot per second (ft <sup>3</sup> /s)	0.02832	cubic meter per second (m <sup>3</sup> /s)
million gallons per day (Mgal/d)	0.0438	cubic meter per second (m <sup>3</sup> /s)
gallon per minute (gal/min)	6.31 x 10 <sup>-5</sup>	cubic meter per second (m <sup>3</sup> /s)
Mass		
gram (g)	0.03527	milligrams per day (g/d)
Chemical Constituents		
microgram per liter (µg/L)	1.0	part per billion (ppb)
milligram per liter (mg/L)	1.0	part per million (ppm)
picocuries per liter (pCi/L)	3.7854	picocuries per liter (pCi/L)
microsiemens per inch at 25 degrees Celsius (µS/cm)	2.54	microsiemens per centimeter at 25 degrees Celsius (µS/cm)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$^{\circ}\text{C}=(^{\circ}\text{F}-32)/1.8.$$

Vertical coordinate information is referenced to the “North American Vertical Datum of 1929 (NAVD 29).”

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.

## Acronymns and Other Abbreviations Used in This Report

‰	per thousand parts (permil)
AL	Action Level (U.S. Environmental Protection Agency)
API	American Petroleum Institute
bls	below land surface
BP	before present
<sup>14</sup> C	carbon-14
CaCO <sub>3</sub>	calcium carbonate
CDT	Canon Diablo Triolite
CO <sub>3</sub> <sup>2-</sup>	carbonate
DIC	dissolved inorganic carbon
DOC	dissolved organic carbon
E	estimated
Eh	redox potential
GMWL	Global Meteoric Water Line
<sup>3</sup> H	hydrogen-3
HAL	health advisory level (U.S. Environmental Protection Agency)
HCO <sub>3</sub>	bicarbonate
ICPMS	inductively coupled mass spectrometry
LR	lateral resistivity
M	presence verified but not quantified
MCL	Maximum Contaminant Level (U.S. Environmental Protection Agency)
MCLG	Maximum Contaminant Level Goal (U.S. Environmental Protection Agency)
MRL	method reporting limit
N/A	not applicable
NAD 83	North American Datum of 1983
NAVD 88	North American Vertical Datum of 1988
NAWQA	National Water-Quality Assessment (U.S. Geological Survey)
NTU	nephelometric turbidity unit
NWQL	National Water Quality Laboratory (U.S. Geological Survey)
O	oxygen
ORP	oxidation-reduction potential
pmC	percentage of modern carbon
PVC	polyvinyl chloride
RPD	relative percentage difference
S	sulfur
SDWR Agency)	Secondary Drinking-Water Regulation (U.S. Environmental Protection Agency)
SHE	relative to standard hydrogen electrode
Sr	strontium
<sup>86</sup> Sr/ <sup>88</sup> Sr	ratio of strontium-86 to strontium-88 (isotopes)
USEPA	U.S. Environmental Protection Agency)
USGS	U.S. Geological Survey
VPDB	Vienna Pee Dee Belemite
VSMOW	Vienna Standard Mean Ocean Water



# Quality Characteristics of Ground Water in the Ozark Aquifer of Northwestern Arkansas, Southeastern Kansas, Southwestern Missouri, and Northeastern Oklahoma, 2006–07

By L. M. Pope, H.E. Mehl, and R.L. Coiner

## Abstract

Because of water quantity and quality concerns within the Ozark aquifer, the State of Kansas in 2004 issued a moratorium on most new appropriations from the aquifer until results were made available from a cooperative study between the U.S. Geological Survey and the Kansas Water Office. The purposes of the study were to develop a regional ground-water flow model and a water-quality assessment of the Ozark aquifer in northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma (study area). In 2006 and 2007, water-quality samples were collected from 40 water-supply wells completed in the Ozark aquifer and spatially distributed throughout the study area. Samples were analyzed for physical properties, dissolved solids and major ions, nutrients, trace elements, and selected isotopes. This report presents the results of the water-quality assessment part of the cooperative study.

Water-quality characteristics were evaluated relative to U.S. Environmental Protection Agency drinking-water standards. Secondary Drinking-Water Regulations were exceeded for dissolved solids (11 wells), sulfate and chloride (2 wells each), fluoride (3 wells), iron (4 wells), and manganese (2 wells). Maximum Contaminant Levels were exceeded for turbidity (3 wells) and fluoride (1 well). The Maximum Contaminant Level Goal for lead (0 milligrams per liter) was exceeded in water from 12 wells.

Analyses of isotopes in water from wells along two 60-mile long ground-water flow paths indicated that water in the Ozark aquifer was at least 60 years old but the upper age limit is uncertain. The source of recharge water for the wells along the flow paths appeared to be of meteoric origin because of isotopic similarity to the established Global Meteoric Water Line and a global precipitation relation. Additionally, analysis of hydrogen-3 ( $^3\text{H}$ ) and carbon-14 ( $^{14}\text{C}$ ) indicated that there was possible leakage of younger ground water into the lower part of the Ozark aquifer. This may be caused by cracks or fissures in the confining unit that separates the upper and lower

parts of the aquifer, poorly constructed or abandoned wells, or historic mining activities.

Analyses of major ions in water from wells along the flow paths indicated a transition from freshwater in the east to saline water in the west. Generally, ground water along flow paths evolved from a calcium magnesium bicarbonate type to a sodium calcium bicarbonate or a sodium calcium chloride bicarbonate type as water moved from recharge areas in Missouri into Kansas. Much of this evolution occurred within the last 20 to 25 miles of the flow paths along a water-quality transition zone near the Kansas-Missouri State line and west. The water quality of the Kansas part of the Ozark aquifer is degraded compared to the Missouri part.

Geophysical and well-bore flow information and depth-dependent water-quality samples were collected from a large-capacity (1,900–2,300 gallons per minute) municipal-supply well to evaluate vertical ground-water flow accretion and variability in water-quality characteristics at different levels. Although the 1,050-foot deep supply well had 500 feet of borehole open to the Ozark aquifer, 77 percent of ground-water flow entering the borehole came from two 20-foot thick rock layers above the 1,000-foot level. For the most part, water-quality characteristics changed little from the deepest sample to the well-head sample, and upwelling of saline water from deeper geologic formations below the well was not evident. However, more saline water may be present below the bottom of the well.

## Introduction

The Ozark aquifer is part of the Ozark Plateaus aquifer system that occurs in parts of Arkansas, Kansas, Missouri, and Oklahoma (fig. 1). The Ozark aquifer is a source of freshwater for municipal, domestic, industrial, and irrigation uses, and as such, an interstate concern exists for the long-term sustainability of the resource and protection of the aquifer from water-quality degradation. Since pumping from the aquifer began in the 1880s, substantial ground-water-level declines have been

noted in some areas. Stramel (1957) identified a static water-level decline of more than 100 ft between 1882 and 1954 in the Pittsburg, Kansas area, and Reed and others (1955) documented a water-level decline of more than 400 ft near Miami, Oklahoma, from 1900 to 1950.

Water quality in supply wells completed in the Ozark aquifer potentially could be degraded with increased water demand from a growing population. Increases in pumping rates at major population centers near the Kansas-Missouri State line or in northeastern Oklahoma may further lower water levels in the Ozark aquifer such that, locally, the natural east-to-west flow gradient (Imes and Emmett, 1994) decreases and saline water from the western part of the aquifer (Macfarlane and Hathaway, 1987) migrates to the east. Recently, cones of depressed ground-water levels were identified around major pumping centers (Gillip and others, 2008). Additionally, upwelling of saline water from lower geologic strata may be possible especially at the pumping centers. Lower water levels in the Ozark aquifer may increase the hydraulic gradient between the overlying aquifer system (Springfield Plateau aquifer) and the Ozark aquifer (fig. 1). This increased gradient may draw highly mineralized or contaminated water in the Springfield Plateau aquifer through areas where the intervening confining unit is more permeable or through older or abandoned wells or mining-related exploratory drill holes that are open to both the Springfield Plateau and Ozark aquifers. Commercial lead-and-zinc mining in the Mississippian-age rock formations of the Springfield Plateau aquifer occurred from about 1870 to 1970 in the area of southeastern Kansas, southwestern Missouri, and northeastern Oklahoma known as the Tri-State Mining District (Gibson, 1972). The legacy of this long mining history includes trace element (cadmium, lead, and zinc) contamination of large areas of the Springfield Plateau aquifer (Barks, 1977; Playton and others, 1980; Spruill, 1987) and surface-water sources (Bailey, 1911; Pope, 2005; Juracek, 2006; Angelo and others, 2007).

Because of water quantity and quality concerns within the Ozark aquifer, the State of Kansas in 2004 issued a moratorium on new appropriations from the Ozark aquifer in Kansas with the exclusion of domestic supplies, requests for less than 5 acre-ft of water per year, and temporary and term permits (Kansas Administrative Regulation 5–3–29). This moratorium is to remain in force until a regional ground-water flow model of the Ozark aquifer in parts of northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma (hereinafter referred to as the study area; fig. 1) is developed to simulate the effects of existing and proposed municipal and industrial ground-water withdrawal rates on ground-water levels. This model will extend sufficiently to include the major pumping centers in Joplin, Missouri, Pittsburg, Kansas, and Miami, Oklahoma. The model will be useful in determining recharge areas of selected wells and well fields and will help water managers better understand how surface contamination can potentially affect water quality in supply wells.

In 2005, the U.S. Geological Survey (USGS) entered into a cooperative agreement with the Kansas Water Office to develop a regional ground-water flow model of the study area to include the Ozark and Springfield Plateau aquifers, to construct potentiometric-surface maps of both aquifers, and to conduct an assessment of current water-quality conditions within the Ozark aquifer. The ground-water flow model will be developed using the USGS MODFLOW-2000 (Hill and others, 2000) ground-water flow simulator. During the spring of 2006, ground-water levels were measured at 285 wells in the Ozark and Springfield Plateau aquifers throughout the study area. Results of these measurements were used to construct the potentiometric surface maps that are presented in Gillip and others (2008). Information generated by the combined ground-water flow model development and water-quality assessment will provide water managers the ability to better assess the availability of ground water in their area, to better determine the effects of pumping on ground-water levels, and to better assess the potential for possible future contamination of wells.

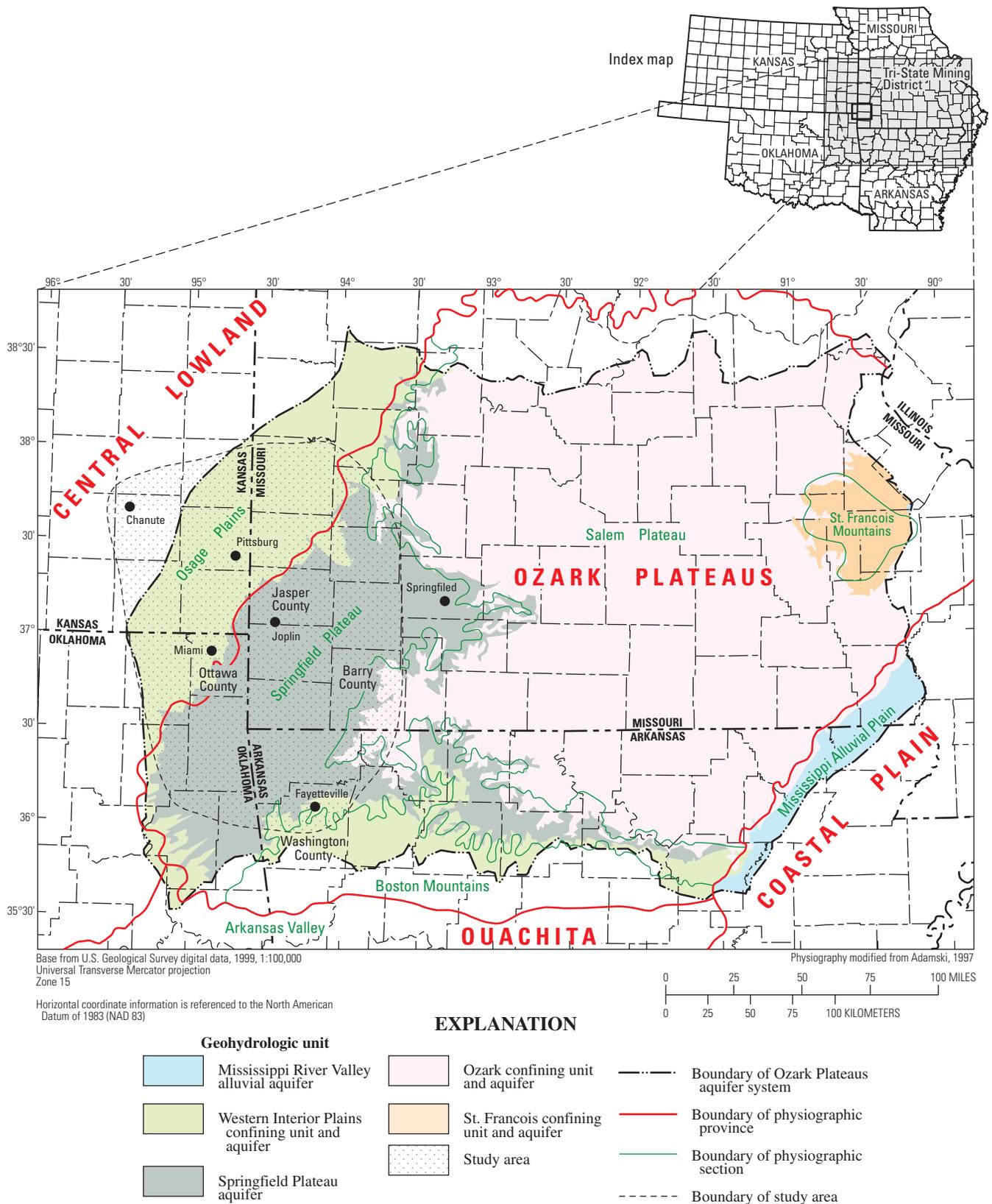
## **Purpose and Scope**

The purpose of this report is to provide an assessment of quality characteristics of water in the Ozark aquifer in northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma. This assessment contains the results of chemical analyses of water from 40 spatially distributed water-supply wells completed in the Ozark aquifer. These results are used to identify spatial variability in aquifer water quality throughout the study area and water quality evolution along two selected ground-water flow paths. Vertical variability in water quality in the Ozark aquifer also is assessed on the basis of a series of samples collected in the vertical profile of a municipal-supply well under pumping conditions.

The scope of this report is limited to an assessment of selected major ions, nutrients, trace elements, and selected isotopes in ground water from wells in the Ozark aquifer in the study area. Many of these water-quality constituents are regulated in drinking-water supplies by the U.S. Environmental Protection Agency (USEPA). The constituents are discussed relative to USEPA drinking-water standards as a frame of reference and to other natural geohydrologic factors that may affect variability in constituent concentrations.

## **Previous Investigations**

Previous investigations in the Ozark Plateaus aquifer system and surrounding areas have produced many publications describing various aspects of all or part of the aquifer system. Stratigraphic succession of the area, including the aquifer system, has been presented by Koenig (1961) and Zeller (1968), and more locally or regionally specific geologic aspects were discussed by Snider (1915), Keroher and Kirby (1948), McCracken (1964, 1967, 1971), Bretz (1965), Denison (1981),



**Figure 1.** Location of Ozark Plateaus aquifer system, surficial extent of geohydrologic units, physiographic areas, and water-quality study area of the Ozark aquifer in parts of Arkansas, Kansas, Missouri, and Oklahoma.

and Thompson (1991). The geohydrology of the area was discussed by Abernathy (1941), Stramel (1957), Emmett and others (1979), Macfarlane and others (1981), and Kleeschulte and others (1985). Ground-water-quality characteristics have been investigated for at least the past 60 years as typified in publications by Williams (1948), Feder and others (1969), Barks (1978), Feder (1979), Macfarlane and others (1981), Christenson and others (1990), and Imes and Davis (1991). Because of the occurrence of the historic Tri-State Mining District within the Ozark Plateaus aquifer system (specifically the Springfield Plateau aquifer, fig. 1), ground-water-quality effects of this past mining activity have been investigated by Barks (1977), Parkhurst (1987), and Spruill (1987), to name a few. More specific, however, to water-quality characteristics in the Ozark aquifer and more directly relevant to the investigation described in this report are the investigations conducted by Darr (1978), Macfarlane and Hathaway (1987), Jorgensen (1989), Imes and Emmett (1994), Adamski and others (1995), Jorgensen and others (1996), and Gillip and others (2008).

Darr (1978) conducted the first detailed investigation into the hydrogeochemistry of the Ozark Plateaus aquifer system. His work led to better understanding of rock-water interactions, the effect of biota on production of hydrogen sulfide, and the hydrogeochemical evolution of ground water. Macfarlane and Hathaway (1987) described the hydrogeology and chemical quality of ground water in Cambrian and Ordovician strata of the lower Paleozoic aquifers in the Tri-State area of southeastern Kansas, southwestern Missouri, and northeastern Oklahoma. Ground water was available throughout these layers in varying amounts depending on lithologies and secondary permeability. Movement of ground water in the aquifers was affected locally by pumping centers, which have produced large cones of depression in several areas. Ground-water quality reflected a transition from fresh-to-saline conditions starting at about the Kansas-Missouri State line. The freshwater part of the aquifer in Missouri generally was a calcium bicarbonate type transitioning to a sodium chloride type in the saline part in Kansas. Concentrations of dissolved solids and chloride were found to increase in a generally westerly direction.

Jorgensen (1989) presented a detailed description of the paleohydrology of the central United States that emphasized the geology of ground water and how the properties of aquifers can be evaluated or estimated from paleohydrologic analysis and concluded that diagenesis resulting from past conditions generally has determined the hydraulic characteristics of present-day aquifers. Also presented was a detailed examination of the geologic processes affecting the central United States from the Precambrian through present day. The area was alternately submerged and exposed by marine transgressions and regressions that deposited sand, calcareous mud, or clay sediment, depending on the time period, that were subsequently lithified over time into distinct layers of sandstone, limestone, and shale that compose the modern-day aquifers and confining units.

Imes and Emmett (1994) discussed the geohydrology of the Ozark Plateaus aquifer system in parts of Kansas, Missouri, and Oklahoma, identified seven geohydrologic units composing the aquifer system, and presented details on the permeability, rock composition, thickness, water levels, and well yields of each unit. Maps presented depicted the areal extent, thickness, and upper surface of each aquifer or geohydrologic unit and the predevelopment potentiometric surface of the aquifers. Maps also showed water type and concentrations of dissolved solids, sulfate, and chloride in ground water from each aquifer on the basis of available chemical analyses. Dissolved-solids concentrations in the aquifers ranged from about 200 mg/L (milligrams per liter) where the aquifers crop out to more than 2,000 mg/L near the western boundary of the aquifers. The authors used a three-dimensional finite-difference model to simulate regional ground-water flow in the Ozark Plateaus aquifer system under predevelopment conditions and concluded that, because the present-day (1994) pumping rates were small compared to the large rates of recharge, the regional predevelopment ground-water budget was probably similar to the present-day budget. Although there was no apparent regional lowering of water levels in the aquifer system, decreased hydraulic heads existed around major pumping centers in Pittsburg, Kansas, Springfield, Missouri, and Miami, Oklahoma.

Adamski and others (1995) described the environmental and hydrologic setting of the Ozark Plateaus study unit of the USGS National Water-Quality Assessment Program (NAWQA) and how related geologic and land-use characteristics may affect water quality. The authors reviewed rock composition, permeability, and well yield of each geohydrologic unit and noted that karst features such as springs, sinkholes, and caves are common in the study unit. Population in the study unit increased 28 percent between 1970 and 1990, to about 2.3 million people (Adamski and others, 1995). Land use was predominantly pasture and cropland in the northwest, and forest and pasture in the southeast, with poultry farms commonly found in the southwestern part of the study unit (Adamski and others, 1995). Lead-zinc mining was common in the past. Total water use for the area during the NAWQA study averaged 1,053 Mgal/d, with ground water accounting for about 58 percent and surface water providing 42 percent. Ground water was described as mostly a calcium or calcium magnesium bicarbonate type with some local wells in confined parts of the aquifers yielding water of calcium sulfate or sodium chloride composition. Dissolved-solids concentrations in ground water ranged from 200 to 300 mg/L but were as much as 10,000 mg/L in the deeper aquifers along the western boundary. The geochemical processes of mineral dissolution, ion exchange, and oxidation-reduction reactions were the dominant natural factors that affected water quality on a regional scale.

Jorgensen and others (1996) provided a summary of the geochemistry of regional aquifers in the study area. Ground water in the Ozark Plateaus generally flows westward toward a broad physiographic low roughly paralleling the Central

Lowland Province (fig. 1). The Western Interior Plains aquifer system (fig. 1) extends westward into Kansas and Oklahoma and ground-water flow is generally toward the east. The authors reviewed the hydrogeologic features of the Ozark Plateaus aquifer system units in detail, and referred to Imes and Emmet's (1994) simulation of ground-water flow. The study by Jorgensen and others (1996) was mainly a review and summary of the large quantities of hydrologic, geologic, and water-quality data pertaining to this area that have been collected over many years. The authors reviewed the data for accuracy and generated various computer models of aquifer properties and hydrologic information. Of particular interest for the study described in this report is their finding that the Ozark aquifer and St. Francois aquifer are similar in hydro-chemistry due to the relatively large permeability of the St. Francois confining unit. Water in these aquifers generally contained less than 500 mg/L dissolved solids and was a calcium magnesium bicarbonate type. Jorgensen and others (1996) also noted that ground water in the Springfield Plateau aquifer contained dissolved-solids concentrations generally less than 300 mg/L and was a calcium bicarbonate type.

Gillip and others (2008) used ground-water levels from 285 wells measured during the spring of 2006 to develop potentiometric-surface maps for the Springfield Plateau and Ozark aquifers to address the effects of changing water use over time. The potentiometric-surface map of the Springfield Plateau aquifer showed a maximum measured water-level altitude of about 1,450 ft in Barry County, Missouri, and a minimum altitude of 579 ft in Ottawa County, Oklahoma. Ground water in this aquifer generally flows to the west, and discharges to regional lakes, rivers, and springs. The potentiometric-surface map of the Ozark aquifer showed a maximum water-level altitude of 1,303 ft in Washington County, Arkansas, and a minimum water-level altitude of 390 ft in Ottawa County, Oklahoma. The ground-water flow in the Ozark aquifer was generally to the west or northwest. Cones of depression around public water-supply wells were present in several counties of Kansas, Missouri, and Oklahoma. The potentiometric-surface map showed the largest cones of depression in Ottawa County, Oklahoma (from about 700 to 390 ft), Jasper County, Missouri (from about 800 to 577 ft), and Barry County, Missouri (from about 1,100 to 800 ft).

## Description of Study Area

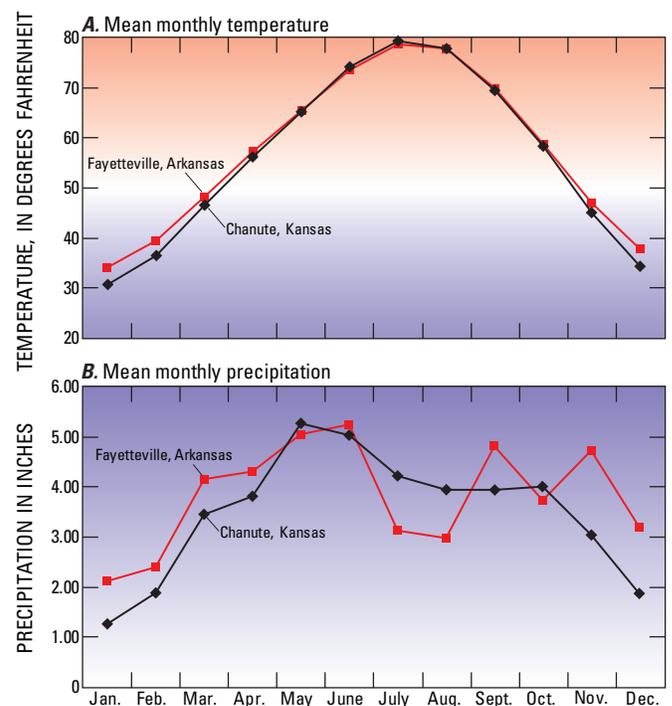
### Climate

The study area (fig. 1) has a continental climate marked by strong seasonality. Temperature and precipitation are affected by strong dry-cold air masses from the Northern Plains in the winter and by moist warm-air masses from the Gulf of Mexico during the summer months. These air masses travel relatively unimpeded by topographic features and may bring abundant amounts of precipitation particularly during

the spring and summer months (National Climatic Data Center, 2008).

Mean air temperature for 1971–2000 varied seasonally, with the lowest mean monthly temperatures occurring in January and the highest in July. Mean monthly temperatures were lower in the northwestern part of the study area than in the southeastern part during the winter and spring months (November to April). For example, January mean temperatures ranged from 30.8°F in Chanute, Kansas, to 34.3°F in Fayetteville, Arkansas (fig. 2A). During the warmer months (May through October), there was less variation in mean monthly temperatures across the study area (generally 2°F or less), with warmer temperatures occurring toward the northwestern part of the study area. July temperatures ranged from 79.5°F in Chanute, Kansas, to 78.9°F in Fayetteville, Arkansas (National Climatic Data Center, 2008).

Mean monthly precipitation followed a seasonal pattern across the study area and was largest during the spring months (April to June) and smallest during the winter months (December to February). Generally, mean annual precipitation increased from northwest to southeast across the study area. For instance, mean annual precipitation for 1971–2000 ranged from 41.95 in. at Chanute, Kansas, to 46.02 in. at Fayetteville, Arkansas (fig. 2B). On a seasonal basis, Fayetteville tends to be wetter than Chanute, with the exception of the mid-summer months (July and August), during which Chanute received about 1 in. more rain on average than Fayetteville.



**Figure 2.** Mean monthly temperature and precipitation at Chanute, Kansas, and Fayetteville, Arkansas, for 1971–2000 (data from National Climatic Data Center, 2008).

## Physiography

Most of the study area is contained within the Osage Plains physiographic section of the Central Lowland Province, and the Springfield Plateau physiographic section of the Ozark Plateaus Province (fig. 1) (Fenneman, 1938). Small parts of the Salem Plateau and Boston Mountains also are included in the study area. The Boston Mountains, Salem Plateau, Springfield Plateau, and St. Francois Mountains compose the four physiographic sections of the Ozark Plateaus Province. The province is underlain by a structural dome of igneous rock that forms the St. Francois Mountains and Paleozoic sedimentary rocks that underlie the other physiographic sections (fig. 3). The topography of these physiographic sections affects the hydrology of the study area.

The northwest segment of the study area falls within the Osage Plains physiographic section of the Central Lowland Province (fig. 1). The Central Lowland Province extends across most of the central United States, from North Dakota to Texas and from Missouri to Colorado. The Osage Plains covers the southeastern one-third of Kansas, west-central Missouri, most of central Oklahoma, and extends into north-central Texas. The region is characterized by soft shale with interbedded sandstone and limestone of Late Mississippian to Pennsylvanian age. Topography in the Osage Plains is gently rolling, with some rare, east-facing escarpments. Land-surface altitudes range from 800 to 1,000 ft (Fenneman, 1938).

The southeast segment of the study area encompasses a large part of the Springfield Plateau physiographic section of the Ozark Plateaus Province (fig. 1). The Springfield Plateau extends from northeast to southwest across southwestern Missouri, southeastern Kansas, northwestern Arkansas, and northeastern Oklahoma. This section is underlain by limestone and cherty limestone of Mississippian age. Topography in this part of the study area is gently rolling hills, with some sinkholes and springs. Land-surface altitudes range from 1,000 to 1,700 ft; however, local topographic relief seldom exceeds 200 to 300 ft and decreases from east to west (Fenneman, 1938).

The southern edge of the study area in Arkansas borders the Boston Mountains. Land-surface altitudes range from 1,200 to more than 2,300 ft. Topography in the Boston Mountains is rugged, with local topographic relief exceeding several hundred feet in some places (Fenneman, 1938).

## Geology

The geologic characteristics of the Ozark aquifer study area have been described in detail in several previous investigations (Macfarlane and Hathaway, 1987; Jorgensen, 1989; Imes and Emmett, 1994; Adamski and others, 1995; Jorgensen and others, 1996). A summary of these characteristics is presented in this report.

The Ozark Plateaus aquifer system consists of six subdivisions. These units, from oldest to youngest, are the basement

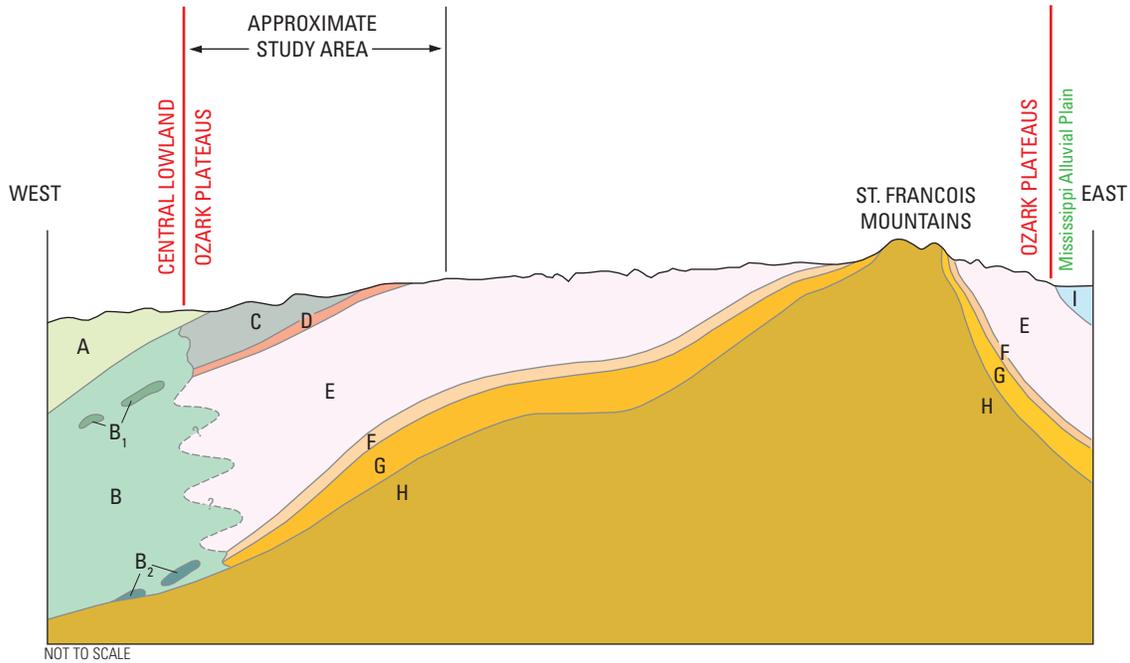
confining unit, St. Francois aquifer, St. Francois confining unit, Ozark aquifer, Ozark confining unit, and Springfield Plateau aquifer (fig. 3). These subdivisions are based on relative rock permeabilities and well yields, and coincide with the physiographic sections of the study area (fig. 1; Imes and Emmett, 1994). The Western Interior Plains aquifer system is adjacent to and west of the Ozark Plateaus aquifer system. The Western Interior Plains confining system overlies the Western Interior Plains aquifer system and the extreme western part of the Ozark Plateaus aquifer system.

The Ozark Plateaus aquifer system formed largely as a result of processes that favored marine carbonate sediment deposition modified by karstification during periods of sub-aerial exposure. It consists mainly of a Paleozoic sequence of sedimentary rocks of Cambrian to Mississippian age (table 1). The system is confined below by a basement confining unit of Precambrian age and above by the Western Interior Plains confining system of Pennsylvanian age (Macfarlane and Hathaway, 1987).

A basement complex of igneous and metamorphic rocks dating to Precambrian time underlies much of the central United States, including the study area. During the Precambrian, uplift diagenesis, referred to in the study area as the Ozark Uplift, formed a large land mass nearly 2,000 ft thick that became deeply eroded and faulted by Cambrian time (Jorgensen, 1989). Faulting and fracturing of the layer has resulted in anisotropic permeability that can facilitate ground-water flow (Jorgensen and others, 1996).

During Early and Middle Cambrian time, the study area was above sea level. The climate was most likely warm and wet, with geological processes eroding and faulting the exposed Precambrian rock layer. Much of this area was engulfed by a marine sea during the Late Cambrian, which deposited permeable nearshore sand along with calcareous mud in some areas (Jorgensen and others, 1996). During this time, uplift diagenesis occurred during periods of marine recession that resulted in lithification of the sand and mud layers. These layers formed the sandstone and dolomite that are characteristic of the St. Francois aquifer and St. Francois confining unit (table 1). Connate marine water most likely was purged from the sediment during periods of recession. Secondary permeability resulted from erosion, which removed overburden load and caused extensional fracturing. This created paths along which dissolution occurred, especially that of calcareous material (Jorgensen, 1989).

Since Cambrian time, the central United States has undergone relatively gentle deformation, resulting in upwarp and downwarp of the Earth's crust over large areas. Ordovician time was likely warm and humid, and calcareous mud was the predominant sediment in shallow seas. Calcareous mud was lithified to limestone, especially during periods of recession. The limestone was dolomitized near coastlines, and erosion continued to cause extensional fracturing. Processes during this time tended to increase porosity and permeability (Jorgensen, 1989).



**EXPLANATION**

Hydrogeologic unit

**WESTERN INTERIOR PLAINS CONFINING AND AQUIFER SYSTEM**

- A Western Interior Plains confining system
- B Western Interior Plains aquifer system
- B<sub>1</sub> Stratigraphically equivalent to Ozark confining unit
- B<sub>2</sub> Stratigraphically equivalent to St. Francois confining unit

**OZARK PLATEAUS AQUIFER SYSTEM**

- C Springfield Plateau aquifer

**Ozark Plateaus confining unit and aquifer**

- D Ozark confining unit
- E Ozark aquifer

**St. Francois confining unit and aquifer**

- F St. Francois confining unit
- G St. Francois aquifer
- H Basement confining unit

**MISSISSIPPI RIVER VALLEY ALLUVIAL AQUIFER**

- I Post-paleozoic sediment

-----?----- **Indefinite boundary of transition zone between fresh and saline ground water**

**Figure 3.** Generalized geohydrologic section showing Ozark Plateaus aquifer system and adjacent hydrologic units (from Imes and Emmett, 1994).

During the Silurian and Devonian periods, the sea again receded and almost the entire study area underwent uplift diagenesis, resulting in extensional fracturing and the development of regional-flow systems of ground water (Adamski and others, 1995). These flow systems flushed out much of the existing formational water from previous layers, and the permeability of the exposed rocks was increased by erosional processes (Jorgensen, 1989). The result of these processes was the Ozark aquifer geohydrologic unit (table 1).

Toward the end of the Devonian and the beginning of Mississippian time, the area was again inundated by a warm sea. Layers of sand were deposited near the shoreline, whereas clay was predominantly deposited offshore (Jorgensen and others, 1996). These extensive deposits of clay were characterized by very slight permeability that restricted the flow of water from the underlying carbonate rock layers to overlying sediment.

The clay layers were covered by calcareous sediment by the cyclic, recessive sea of the Late Mississippian. Burial diagenesis further decreased porosity of the clay layer, ultimately creating the characteristic shale of the Ozark confining unit (table 1). The overlying calcareous sediment became lithified to the limestone of the Springfield Plateau aquifer as the Late Mississippian sea receded (table 1).

The transgressions and regressions of the inland sea continued to advance and recede throughout the Pennsylvanian and Permian Periods and the Mesozoic and Cenozoic Eras. The study area continued to experience diagenetic processes that further formed the aquifer system and overlying topography. Gradual uplift continued to increase the altitude of the study area above sea level, and by the Mesozoic Era it was no longer being inundated. No significant deposition occurred in the Ozark Plateaus after the Pennsylvanian Period. By the end of the Permian, Pennsylvanian rocks that had been deposited around the St. Francois Mountains were being eroded, further developing and extending the regional ground-water flow system in the underlying permeable Cambrian and Ordovician rocks (Jorgensen, 1989; Adamski and others, 1995; Jorgensen and others, 1996).

## Geohydrology

Ground water in the Ozark Plateaus aquifer system flows from the Ozark Plateaus in the east towards the Western Interior Plains aquifer system in the west (fig. 3). The Ozark Plateaus aquifer system and the Western Interior Plains aquifer system are similar in that they both consist of dolostone, limestone, and sandstone. However, the water present in the Western Interior Plains aquifer system is briny, whereas the Ozark Plateaus aquifer system consists of fresh, nonsaline water. The freshwater mixes with the nearly stagnant saline water at a transition zone along the western edge of the Ozark Plateaus aquifer system (Macfarlane and Hathaway, 1987).

Because soil and subsoil in the Ozark region is relatively thin and near-surface faults and fracture systems are common,

precipitation may quickly infiltrate into the aquifer system. Rapid infiltration may allow surface contaminants to enter the ground-water system. Ground-water levels rise quickly after rainfall. This rapid infiltration causes widespread dissolution of the overlying carbonate rocks and helps flush out saline connate water to create a more freshwater system. Ground-water flow is almost entirely topographically controlled (Jorgensen, 1989). Ground water moving through the shallow part of the aquifer system follows short (usually less than 10 mi) local flow paths that terminate at nearby streams (Imes and Emmett, 1994).

Igneous and metamorphic rocks of the basement confining unit underlie the study unit. The Precambrian batholith is exposed at the St. Francois Mountains (fig. 3). This highest point of the batholith remained exposed during some periods of deposition by advancing seas. Erosion has left the Precambrian rocks exposed. Precambrian rocks have some secondary permeability that is generated from fractures in the rocks (Jorgensen, 1989). They are used locally as a ground-water source where they crop out, although well yields are usually less than 10 gal/min (Imes and Emmett, 1994).

The St. Francois aquifer lies beneath the Salem Plateau and St. Francois Mountains, and is separated from the Ozark aquifer by the St. Francois confining unit (figs. 1 and 3). The St. Francois aquifer is as much as 900 ft thick in Missouri and as much as 500 ft thick in northern Arkansas (Adamski and others, 1995). The St. Francois aquifer is rarely used as a drinking-water supply where overlain by the thicker Ozark aquifer. Because of this, its present-day potentiometric surface probably varies little from the predevelopment potentiometric surface. Wells penetrating this aquifer rarely yield more than 50 gal/min, except those penetrating a significant thickness of the Lamotte Sandstone which may yield 100 to 500 gal/min (table 1, Imes and Emmett, 1994). The St. Francois confining unit hydraulically separates the Ozark aquifer from the underlying St. Francois aquifer and crops out around the St. Francois Mountains (fig. 3; Macfarlane and Hathaway, 1987). The thickness of the slightly permeable rocks of the confining unit averages between 200 and 400 ft (Imes and Emmett, 1994).

The unconfined part of the Ozark aquifer extent coincides with the Salem Plateau physiographic section (fig. 1) and consists of a thick sequence of dolomite, sandstone, limestone, and shale (table 1). The Ordovician rocks range in thickness from about 300 ft in northeastern Oklahoma to nearly 4,000 ft in northern Arkansas, and the aquifer averages between 1,500 and 2,000 ft thick throughout much of the study area (Imes, 1990). The aquifer is confined in the west by the Ozark confining unit but unconfined beneath much of the Salem Plateau (fig. 3; Imes and Emmett, 1994).

The potentiometric surface of the unconfined Ozark aquifer generally mimics the overlying topography. Exceptions to this are known to occur in karst areas where ground water can move through conduit flow systems across surface-water divides separating adjacent river basins. Ground-water levels in wells completed in this aquifer average from 700 to 1,000 ft above NAVD 88 over much of the Salem Plateau. Within the

**Table 1.** Geologic and geohydrologic units in Ozark Plateaus aquifer system and adjacent areas, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma (modified from Imes and Emmett, 1994).

Erath- em	System	Southwestern Missouri	Southeastern Kansas	Northeastern Oklahoma	Northwestern Arkansas	Geohydrologic unit	
PALEOZOIC	MISSISSIPPIAN	St. Louis Limestone Salem Limestone Warsaw Limestone Keokuk Limestone Burlington Limestone Elsey Formation Reeds Spring Limestone Pierson Limestone	St. Louis Limestone Salem Limestone Warsaw Limestone Keokuk Limestone Burlington Limestone  Fern Glen Limestone	Moorefield Formation  Keokuk Limestone  Boone Formation Reeds Spring Member St. Joe Limestone Member	    Boone Formation Reeds Spring Member St. Joe Limestone Member	SPRINGFIELD PLATEAU AQUIFER	
		Northview Shale Sedalia Limestone Compton Limestone	Chouteau Limestone	Northview equivalent  Compton equivalent		OZARK CONFINING UNIT	
	DEVONIAN	Chattanooga Shale	Chattanooga Shale	Woodford Chert Chattanooga Shale	Chattanooga Shale	OZARK AQUIFER	
		Callaway Limestone Fortune Formation	Absent	Sallisaw Formation Frisco Limestone	Clifty Limestone Penters Chert		
	SILU- RIAN	Absent	Absent	St. Clair Limestone	Lafferty Limestone St. Clair Limestone Brassfield Limestone	OZARK AQUIFER	
	ORDOVICIAN	Kimmswick Limestone Plattin Limestone Joachim Dolomite St. Peter Sandstone Everton Formation Smithville Formation Powell Dolomite Cotter Dolomite Jefferson City Dolomite Roubidoux Formation Gasconade Dolomite Van Buren Formation Gunter Sandstone Member	Cotter Dolomite Jefferson City Dolomite Roubidoux Formation Gasconade Dolomite Van Buren Formation Gunter Sandstone Member	Sylvan Shale Fernvale Limestone Viola Limestone Fite Limestone Tyner Formation Burgen Sandstone  Smithville Formation Powell Dolomite Cotter Dolomite Jefferson City Dolomite Roubidoux Formation Gasconade Dolomite Van Buren Formation Gunter Sandstone Member	Cason Shale Fernvale Limestone Kimmswick Limestone Plattin Limestone Joachim Dolomite St. Peter Sandstone Everton Formation Smithville Formation Powell Dolomite Cotter Dolomite Jefferson City Dolomite Roubidoux Formation Gasconade Dolomite Van Buren Formation Gunter Sandstone Member		
		CAMBRIAN	Eminence Dolomite Potosi Dolomite	Eminence Dolomite Potosi Dolomite	Eminence Dolomite Potosi Dolomite		Eminence Dolomite Potosi Dolomite
	Doe Run Dolomite Derby Dolomite Davis Formation		Doe Run Dolomite Derby Dolomite Davis Formation	Doe Run Dolomite Derby Dolomite Davis Formation	Doe Run Dolomite Derby Dolomite Davis Formation		
	Bonneterre Dolomite Reagan Sandstone Lamotte Sandstone		Bonneterre equivalent Reagan Sandstone Lamotte Sandstone	Bonneterre equivalent Reagan Sandstone Lamotte Sandstone	Bonneterre Dolomite Reagan Sandstone Lamotte Sandstone		
		PRECAMBRIAN IGNEOUS AND METAMORPHIC ROCKS					BASEMENT CONFINING UNIT

study area, the potentiometric surface generally increases from 600 to 700 ft in the northwest to 1,200–1,300 ft in the southeast. Major pumping centers are marked by sharp decreases in ground-water levels, particularly in northeastern Oklahoma and southwestern Missouri (Gillip and others, 2008). Precipitation recharges the Ozark aquifer where it is unconfined. Ground water flows mostly laterally from the higher altitudes to points of discharge in springs and seeps along streams and downgradient to Kansas and Oklahoma. The confined part of the Ozark aquifer is recharged by lateral ground-water flow from the unconfined area and, in places, by leakage through the overlying confining unit. Deep wells in the Salem Plateau may yield more than 1,000 gal/min. Shallow domestic wells typically yield only 25 gal/min or less (Imes and Emmett, 1994).

The Ozark confining unit overlies the Ozark aquifer, averages about 60 to 80 ft in thickness, but can reach a thickness of 120 ft in southeastern Kansas (Adamski and others, 1995). The shale and dense limestone in the Ozark confining unit hydraulically separate the overlying Springfield Plateau aquifer from the underlying Ozark aquifer. The confining unit is not present in the Salem Plateau where the Ozark aquifer is unconfined (fig. 3; Imes and Emmett, 1994).

The Springfield Plateau aquifer coincides with the Springfield Plateau (fig. 1) and consists of limestone and cherty limestone of Mississippian age. The aquifer is confined by the Western Interior Plains confining system where it underlies the Boston Mountains and Osage Plains and unconfined where it underlies the Springfield Plateau (fig. 3; Imes and Emmett, 1994). The thickness of the aquifer ranges from about 100 ft in south-central Missouri to about 400 ft in southeastern Kansas (Adamski and others, 1995). The potentiometric surface of the unconfined Springfield Plateau aquifer generally reflects the overlying topography. Ground-water levels range from 700 ft above NAVD 88 in west-central Missouri, eastern Kansas, and northeastern Oklahoma, to more than 1,400 ft above NAVD 88 in southwestern Missouri and northwestern Arkansas (Gillip and others, 2008). The unconfined part of the Springfield Plateau aquifer is recharged nearly everywhere by precipitation. Wells penetrating this aquifer commonly yield less than 20 gal/min. Because of this, the aquifer is rarely used for public supply. However, springs from the aquifer have been used as a water source for towns in Arkansas, Missouri, and Oklahoma, (Imes and Emmett, 1994).

The Western Interior Plains confining system coincides with the Boston Mountains physiographic section in the south and the Osage Plains physiographic section in the west (fig. 1). Rocks of Late Mississippian to Pennsylvanian age form the near-surface confining system (table 1). Lithologies include relatively permeable sandstone and limestone beds separated by thick layers of impermeable shale that result in an overall small permeability. The system is from 40 to 800 ft thick in the Osage Plains but averages between 1,500 and 2,000 ft in thickness in the Boston Mountains (Adamski and others, 1995). Regionally, the unit impedes the vertical and lateral flow of water. Wells in the area typically have small yields

and are used only for domestic and stock supplies (Imes and Emmett, 1994).

## Methods of Investigation

Methods for the water-quality investigation of the Ozark aquifer described in this report included components of well selection, sample collection, sample analyses, and quality-assurance procedures for verification of analytical results. Additional procedures were conducted at a large-capacity municipal-supply well to determine aquifer geophysical characteristics and well-bore flow quantity and quality characteristics. Equipment used for onsite measurements of physical properties of ground water and borehole geophysics are listed in table 2.

## Well Selection and Sample Collection

Within the study area, 40 water-supply wells were selected for collection of water-quality samples (table 3; fig. 4). Most of the wells (35) were water-supply wells, but three were for domestic use and two were for industrial use (table 3). The wells were selected on the basis of completion in and isolation of the Ozark aquifer. The wells were distributed spatially to provide as broad an assessment as possible of water-quality characteristics within the study area. Additional selection criteria included wells that were frequently pumped, accessible, and provided access to water at the wellhead prior to treatment practices such as chlorination or filtration.

The 40 wells were sampled once between September 19, 2006 and June 1, 2007, for this reconnaissance assessment of the Ozark aquifer. Samples were collected and processed in a mobile water-quality laboratory. Teflon-lined polyethylene tubing was used to connect the well to the mobile laboratory. Generally, the tubing was connected to a sillcock or petcock valve or some other access point on the wellhead, and water was routed to the laboratory vehicle as the well was pumped. Because the sampled wells provide public or domestic water supplies, most, if not all, are pumped one to several times daily during periods of high demand.

Sampling and preservation protocols followed during this investigation are described in detail in Wilde and others (1999). To minimize the risk of sample contamination, all sample collection and preservation took place in dedicated environmental chambers consisting of clear polyethylene bags supported by tubular polyvinyl chloride (PVC) frames. Sampling equipment that extended from the sampling point near the wellhead to the sampling chamber inside the mobile laboratory was decontaminated thoroughly between each sample collection using a sequence of nonphosphate detergent wash and deionized water rinse.

If sampled wells were not pumping upon arrival, the operator/owner was asked to turn on the well pump. During the initial pumping period, measurements of specific

**Table 2.** Equipment used for onsite measurements of physical properties of ground water and borehole geophysics.

[ $\mu\text{S}/\text{cm}$ , microsiemens per centimeter at 25 degrees Celsius;  $^{\circ}\text{C}$ , degrees Celsius;  $\text{mg}/\text{L}$ , milligrams per liter;  $\text{mV}$ , millivolts; NTU, nephelometric turbidity units; ohm/meters, ohms per meter;  $\text{mmho}/\text{m}$ , microohms per meter; in., inch; cm, centimeter; cps, counts per second]

Physical property	Instrument <sup>1</sup>	Range of possible measurement	Resolution	Accuracy
Specific conductance	YSI 600XL multiparameter water-quality monitor, 6560 Sensor	0 to 100 $\mu\text{S}/\text{cm}$	0.001 to 0.1 $\mu\text{S}/\text{cm}$ (range dependent)	$\pm 0.5$ percent of reading + 0.001 $\mu\text{S}/\text{cm}$
pH	YSI 600XL multiparameter water-quality monitor, 6561 Sensor	0 to 14 standard units	0.01 standard unit	$\pm 0.2$ standard unit
Temperature	YSI 600XL multiparameter water-quality monitor, 6560 Sensor	-5 to +50 $^{\circ}\text{C}$	0.01 $^{\circ}\text{C}$	$\pm 0.15^{\circ}\text{C}$
Dissolved oxygen	YSI 600XL multiparameter water-quality monitor, 6562 Rapid Pulse™ Sensor	0 to 50 $\text{mg}/\text{L}$	0.01 $\text{mg}/\text{L}$	0 to 20 $\text{mg}/\text{L}$ ; $\pm 0.2$ $\text{mg}/\text{L}$ or 2 percent of reading, whichever is greater; 20 to 50 $\text{mg}/\text{L}$ ; $\pm 6$ percent of reading
Oxidation-reduction potential	YSI 600XL multiparameter water-quality monitor	-999 to +999 mV	0.1 mV	$\pm 20$ mV
Physical property	Instrument <sup>1</sup>	Range of possible measurement	Estimated detection limit	
Turbidity	Hach 2100P Turbidimeter	0 to 1,000 NTU	0.01 NTU on lowest range	
Borehole geophysics	Instrument <sup>1</sup>	Range of possible measurement	Accuracy	
Natural gamma	Century Geophysical 9144 Series E-Logging Tool	0-400,000 cps	$\pm 5$ percent	
Natural gamma	Century Geophysical 9512 Logging Tool	0 to 10,000 cps	$\pm 5$ percent	
16-in. (16N) & 64-in. Normal (64N) & lateral resistivity (LR)	Century Geophysical 9144 Series E-Logging Tool	0-2,000 ohm/meters	$\pm 5$ percent	
Fluid resistivity	Century Geophysical 9144 Series E-Logging Tool	0-100 ohm meters	$\pm 5$ percent	
Specific conductance	Century Geophysical 9512 Logging Tool	5 to 3,000 $\text{mmho}/\text{m}$	$\pm 5$ percent @ 30 $\text{mmho}/\text{m}$	
Borehole caliper	Century Geophysical 9074 Series Three Arm Caliper, model 7074 short-arm caliper	5.1 to 76.2 cm (2 to 30 in.)	+/-0.38 cm (0.15 in.)	

<sup>1</sup>YSI (YSI Incorporated, Yellow Springs, Maryland).

Hach (Hach Company, Loveland, Colorado).

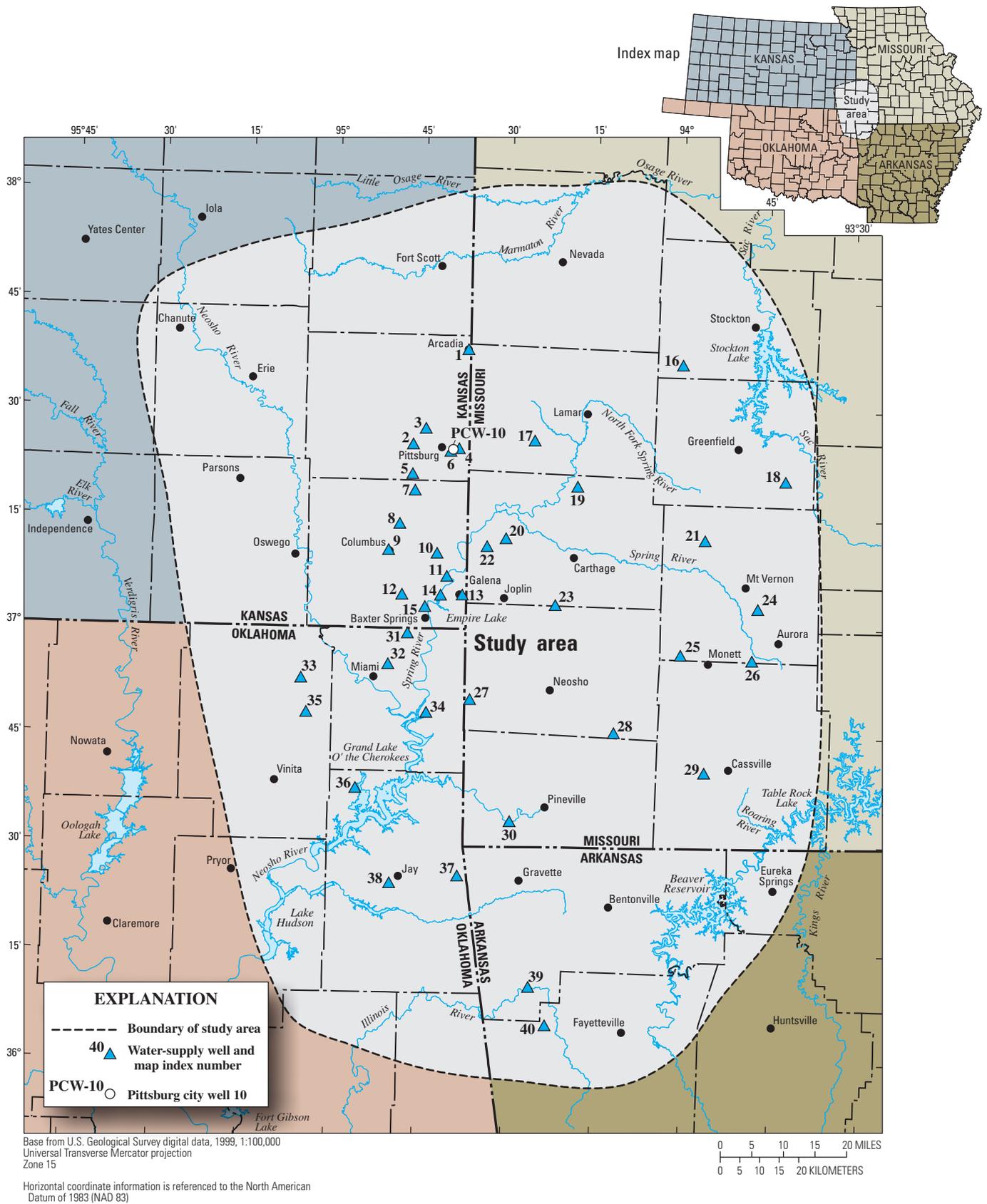
Century Geophysical (Century Geophysical Corporation, Tulsa, Oklahoma).

**12 Quality Characteristics of Ground Water in the Ozark Aquifer of Arkansas, Kansas, Missouri, and Oklahoma, 2006–07**

**Table 3.** Selected well information for sampled water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.

[USGS, U.S. Geological Survey; bls, below land surface; --, not available]

Map index number (fig. 4)	USGS site identification number	Sampling date (month/day/year)	Depth of well, bls (feet)	Water use
Kansas				
1	373821094372401	9/19/2006	--	Water supply
2	372512094464201	9/19/2006	--	Water supply
3	372725094443101	9/19/2006	1,113	Water supply
4	372440094384201	9/20/2006	1,045	Water supply
5	372111094464101	9/19/2006	970	Water supply
6	372418094400801	9/20/2006	1,050	Water supply
7	371847094461601	9/20/2006	--	Water supply
8	371413094484701	10/11/2006	1,100	Water supply
9	371037094503501	9/21/2006	--	Water supply
10	371012094421801	9/29/2006	900	Water supply
11	370701094403001	9/21/2006	--	Water supply
12	370430094481401	9/21/2006	1,050	Water supply
13	370430094375201	9/22/2006	1,177	Water supply
14	370426094413501	9/29/2006	1,204	Water supply
15	370246094441301	9/22/2006	1,175	Water supply
Missouri				
16	373633094000301	5/29/2007	1,215	Water supply
17	372551094254101	12/13/2006	900	Water supply
18	372028093421501	5/29/2007	892	Water supply
19	371937094180801	12/13/2006	1,505	Water supply
20	371219094302401	5/30/2007	1,265	Water supply
21	371251093564101	12/11/2006	1,250	Industrial
22	371116094333901	5/30/2007	920	Water supply
23	370313094214601	12/12/2006	1,518	Industrial
24	370249093470001	12/11/2006	410	Water supply
25	365620094000701	12/12/2006	1,309	Water supply
26	365539093475101	12/12/2006	715	Domestic
27	365006094361601	5/30/2007	1,456	Water supply
28	364541094113101	5/31/2007	950	Water supply
29	364010093555901	5/31/2007	1,002	Water supply
30	363312094291001	5/30/2007	800	Water supply
Oklahoma				
31	365905094470701	5/22/2007	1,110	Water supply
32	365447094502401	5/22/2007	1,108	Water supply
33	365242095051701	5/21/2007	1,200	Water supply
34	364807094434201	5/23/2007	1,150	Water supply
35	364759095041401	5/23/2007	1,418	Water supply
36	363741094553201	5/24/2007	1,500	Water supply
37	362532094375501	5/24/2007	1,160	Domestic
38	362427094493001	5/24/2007	1,442	Water supply
Arkansas				
39	361025094253501	6/1/2007	700	Domestic
40	360509094224101	6/1/2007	1,815	Water supply



**Figure 4.** Map showing location of 40 water-supply wells sampled as part of an assessment of ground-water quality in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.

conductance, pH, water temperature, dissolved oxygen, and oxidation-reduction potential (ORP) were monitored every 5 minutes in a closed-cell, flow-through chamber until stable readings were obtained. Turbidity also was measured every 5 minutes using a portable turbidity meter. Once stable readings of these physical properties were obtained, water flow inside the mobile laboratory was redirected to the clean sampling chamber where sample water was collected for processing and preservation. Constituents analyzed in water samples are listed in table 13 in the “Supplemental Information” section at the back of this report.

Samples analyzed for major ions, nutrients, and trace elements were filtered through a 0.45- $\mu\text{m}$  pore-size disposable-capsule filter and collected in precleaned plastic bottles that were rinsed onsite with filtered ground water. Samples analyzed for concentrations of major cations and trace elements were preserved to a pH of less than 2.0 standard units using ultrapure nitric acid. A filtered, unpreserved sample was collected for major anion analysis. Additionally, an unfiltered sample was collected for onsite titration of carbonate alkalinity (acid neutralizing capacity). Nutrient samples were filtered (0.45- $\mu\text{m}$  pore size) into onsite-rinsed brown plastic bottles and were chilled on ice, with no preservation, and delivered to the analyzing laboratory within 24 hours.

## Sample Analysis

Analysis of all water-quality samples, except the determination of strontium isotope ratio, was performed by the USGS National Water-Quality Laboratory (NWQL) in Lakewood, Colorado, or its contract laboratory according to methods

listed in table 4. Determination of strontium isotope ratio was performed at the University of Colorado, Department of Geological Sciences, Boulder, Colorado. Strontium was separated from the water samples using an ion-specific resin (SrSpec from Eichrom Industries, Lisle, IL) in a Class 100 clean room. Strontium isotope measurements were performed on a Finnigan-MAT 261 thermal ionization mass spectrometer (Finnigan MAT, San Jose, CA). All data were obtained in four-collector static mode and normalized to strontium-86/strontium-88 ( $^{86}\text{Sr}/^{88}\text{Sr}=0.1194$ ). Results of all physical measurements and chemical analyses of water samples from the 40 selected wells are listed in tables 13–16 in the “Supplemental Information” section at the back of this report.

## Geophysical Logging, Well-Bore Flow, and Depth-Dependent Sampling

The combination of borehole geophysical information and well-bore flow and depth-dependent water-quality data can be effective in assessing differences in aquifer properties and water quality with depth (Izbicki and others, 1999). These data may help to identify different water-bearing units with depth, changes in natural ground-water chemistry with depth, and human-related or natural contaminants with depth. The underlying utility of this combined hydrogeologic information is the potential identification of contaminant origin and the flow path through which the contamination may have entered the well. Sources of contamination may be from lateral flow or possibly through vertical migration from deeper or overlying geologic formations. Sampling in a large-capacity well while pumping would maximize the chance of observing the

**Table 4.** Laboratory analysis methods for measured water-quality constituents.

[USGS, U.S. Geological Survey; NWQL, National Water-Quality Laboratory; ICPMS, inductively coupled plasma mass spectrometry; C, Carbon; O, oxygen; S, sulfur; Sr, strontium]

Constituent group	Analysis method	Method reference
Major ions (USGS schedule 2750)	Atomic absorption spectrometry, ICPMS	Fishman (1993)
Trace elements (USGS schedule 2710, laboratory code 2707)	Atomic absorption spectrometry, ICPMS	Faires (1993)
Nutrients (USGS schedule 2752)	Various methods	Fishman (1993); Patton and Kryskalla (2003)
Isotopes		
Deuterium/Protium ratio (USGS laboratory code 1574)	Gaseous hydrogen equilibration	Coplen and others (1991)
Tritium (USGS laboratory code 2770)	Electrolytic enrichment, beta counting	Thatcher and Janzer (1977)
$^{14}\text{C}$ (USGS laboratory code 2010)	Accelerator mass spectrometry	Beukens (1992)
$^{13}\text{C}/^{12}\text{C}$ ratio (USGS 440)	Mass spectrometry	Gleason and others (1969)
$^{18}\text{O}/^{16}\text{O}$ ratio (USGS laboratory code 489)	Mass spectrometry	Epstein and Mayeda (1953)
$^{34}\text{S}/^{32}\text{S}$ ratio (USGS laboratory code 1951)	Isotope ratio mass spectrometry	Révész and Qi (2006)
$^{87}\text{Sr}/^{86}\text{Sr}$ ratio	Mass spectrometry	See description in “Sample Analysis” section of text

migration of contaminants to the well. Knowledge of potential contaminant flow paths may provide ground-water managers with the information needed to implement operational or conservation measures to mitigate contaminant flux, thereby increasing utility and useful life of the resource and reducing potential treatment costs.

A water-supply well in the Pittsburg, Kansas, well field was selected as a representative location in a major pumping center from which to evaluate geophysical and well-bore and water-quality (vertical variability) characteristics in the Ozark aquifer. This well (Pittsburg city well 10, PCW-10) is located about 0.25 mi south of Pittsburg city well 8, PCW-8, which is well 6 in figure 4 that was sampled as part of the spatial-distribution, water-quality assessment described in this report. Geophysical logging was conducted in well PCW-10 on June 8, 2007, during a period of well maintenance when the pump was removed. Logging included measurements of borehole caliper, natural gamma, specific conductance, normal and lateral resistivity, fluid resistivity, and water temperature (table 2). These measurements were made using equipment supplied by and personnel from the USGS Texas Water Science Center, Austin, Texas.

Vertical variability in well-bore flow (velocity-log data) and water quality was determined in well PCW-10 using a well-bore flow and depth-dependent water sampler (Izbicki and others, 1999). This device is a high-pressure hose equipped with valves for dye injection and sample collection under pumping conditions. The hose is mounted on a power-driven reel and can be used to collect velocity-log data and, after appropriate cleaning, depth-dependent water-quality samples.

Velocity-log data were collected using a water/Rhodamine dye mixture (tracer) and a “tracer-pulse method” of injecting the dye mixture into the borehole flow. When using this method, the hose is filled with the dye mixture, lowered to a specific depth, and a pulse of the mixture is injected. The travel time of the dye to a fluorimeter at the surface is measured. The process was repeated at about 10-ft intervals from the bottom of the well casing at 550 ft bls (below land surface) to the bottom of the borehole at 1,050 ft bls. The velocity was calculated as the difference in traveltimes between successive intervals. Using diameter of the borehole and interval velocities, flow volume for each interval was calculated along with the volume of water entering each interval from the geologic formations. Velocity-log data were collected from well PCW-10 on August 6–7, 2007, at a pumping rate of 2,300 gal/min using equipment provided by and personnel from the USGS Oklahoma Water Science Center, Oklahoma City, Oklahoma.

Depth-dependent water-quality samples were collected from well PCW-10 on August 13–14, 2007, while the well was pumping at a rate of 1,900 gal/min. The well had been pumping continuously at about this rate since velocity-log data were collected on August 6–7, 2007. The same equipment used by the same personnel that collected the velocity-log data were used to collect water-quality samples after thorough cleaning and decontamination of the collection

hose with a nonphosphate soap and deionized-water rinse to remove residual traces of the dye mixture and other potential contaminants. To collect a water-quality sample at a specific depth, the hose was pressurized with nitrogen gas to greater than the hydrostatic pressure at the specific depth and lowered into the well. At the desired sample depth, the hose was vented at the surface allowing water to enter the hose through a one-way valve. The hose was retrieved, and the collected sample drained from the hose and subsequently processed into subsamples for analyses of selected water-quality constituents. Samples were collected at 487, 687, 787, 877, 937, and 1,030 ft bls and at the well head. The sample at 487 ft bls was collected from between the well casing and the pump discharge pipe. Each sample represents the average cumulative constituent concentration of all the water in the vertical profile below it. Samples were processed and analyzed using the same methods and procedures as previously outlined in previous sections of this report.

## Unstable Isotope Analysis

The radionuclide carbon-14  $^{14}\text{C}$  has been used since the 1950s to age date materials or compounds containing carbon.  $^{14}\text{C}$  is produced continuously in the atmosphere by the reaction of cosmic ray neutrons on  $^{14}\text{C}$  and has a decay half-life of 5,730 years. Concentrations of  $^{14}\text{C}$  usually are reported as activity referenced to an international standard known as “modern carbon” and is defined as 95 percent of the  $^{14}\text{C}$  activity in 1950 according to the National Bureau of Standards oxalic acid standard (Clark and Fritz, 1997). Measured  $^{14}\text{C}$  activity is expressed as a percentage of modern carbon (pmC) (Clark and Fritz, 1997). The radiocarbon age of dissolved inorganic carbon (DIC) in ground water is obtained by measurement of residual radioactivity and compared with the activity in a modern carbon standard. The method is useful for dating carbon-containing material in the range of 1,000 to 40,000 years (Kendall and others, 1995). Carbon-dead water has no  $^{14}\text{C}$  activity. Dilution of younger water with carbon-dead water results in errors.

Tritium is produced naturally in small amounts of cosmic radiation but was distributed in much greater quantities by atmospheric testing of thermonuclear weapons between 1951 and 1980 (Clark and Fritz, 1997). Tritium has a decay half-life of 12.32 years. The occurrence of tritium in ground water, therefore, can be used as an indicator of modern (after 1952) recharge. If the level of tritium in water is less than 2.6 pCi/L, it is considered “dead” water and indicates that the ground water came from water recharged before 1952.

## Quality Assurance

Quality-assurance samples collected included concurrent- replicate environmental samples, source-water blanks, and equipment blanks. Replicate environmental samples were used to assess the combined effects of onsite and laboratory

procedures on measurement variability. Blank samples were used to verify that decontamination procedures were adequate and that onsite and laboratory protocols and sample shipment did not contaminate the samples.

A concurrent-replicate sample for the study described in this report is defined as one where subsamples (individual sample bottles or containers) within a sample set (group of bottles or containers) were filled immediately after the equivalent bottle for the primary environmental sample. For instance, the concurrent-replicate bottle for nutrient analyses was filled immediately after the same bottle for the primary sample, and so forth. This alternating sequence was continued until both the primary and replicate sample sets were collected.

A target goal for variability among analyses of concurrent-replicate samples was a relative percentage difference (RPD) of  $\pm 20$  percent except when constituent concentrations were at or near the method reporting limit (MRL) for that constituent (table 13 in the “Supplemental Information” section at the back of this report). RPD was calculated as the difference in replicate analyses divided by the mean and expressed as a percentage. RPDs between paired constituent concentrations were calculated and summarized (table 5) if a constituent was detected at greater than the MRL, or if it was detected at less than the MRL and reported as an estimated value. An RPD was not calculated for a replicate pair if one or both analyses were reported as less than the MRL. Concurrent-replicate samples consisted of subsamples collected (from same sampling site) during the same sampling procedure. Four pairs of concurrent-replicate ground-water samples were collected during the study described in this report. No RPDs were available for nitrite, phosphorus, aluminum, antimony, beryllium, cadmium, cobalt, silver, thallium. Most RPDs were less than the  $\pm 20$ -percent target except for bromide, total nitrogen, orthophosphate, chromium, mercury, nickel, selenium, uranium, and zinc where replicate values were at or near the MRLs. In addition RPD exceeded the target goal for  $^{14}\text{C}$ , where no MRL is specified, and for copper and tritium where replicate values were not less than the MRL. The maximum RPDs were 24 percent for copper; 29 percent for  $^{14}\text{C}$ ; and an anomalously large 640 percent for tritium. For wells with replicate analyses, analytical results of these paired samples were averaged prior to assessment, presentation, and discussion in this report. Cation/anion balance had to be within 5 percent to be acceptable.

Five blank samples were analyzed for specific conductance and concentrations of major ions, nutrients, and trace elements (table 6). One source-water blank and four equipment blank samples were produced. The source-water blank sample (blank 1) was prepared by collecting deionized water at a USGS office and subjecting it to bottling, preservation, and shipping protocols only. Two constituents were found in blank 1, but in small, estimated concentrations—ammonia (0.01 mg/L) and mercury (0.007  $\mu\text{g/L}$ ), both less than the MRL. Equipment-blank solutions (blank samples 2–5) passed through all sampling equipment and were collected using the same protocols as for environmental samples. Blank samples

2, 4, and 5 were prepared with the equipment used to sample wells in Arkansas, Kansas, and Missouri. Blank samples 2 and 5 were prepared at a USGS office, but blank sample 4 was produced onsite during sample collection. Blank sample 3 was produced at the USGS Oklahoma Water Science Center (Oklahoma City) with the equipment used to sample the Oklahoma water-supply wells.

Several constituents were found in the equipment blank samples, although in relatively small concentrations. Blank sample 2 had a specific conductance of 3.0  $\mu\text{S/cm}$  and contained ammonia (estimated 0.01 mg/L), total nitrogen (0.08 mg/L), barium (1.4  $\mu\text{g/L}$ ), chromium (estimated 0.05  $\mu\text{g/L}$ ), copper (0.6  $\mu\text{g/L}$ ), lead (estimated 0.06  $\mu\text{g/L}$ ), mercury (estimated 0.006  $\mu\text{g/L}$ ), nickel (0.15  $\mu\text{g/L}$ ), and zinc (1.2  $\mu\text{g/L}$ ). Blank sample 3 had a specific conductance of 22  $\mu\text{S/cm}$  and contained calcium (0.05 mg/L), chloride (0.5 mg/L), silica (0.1 mg/L), total nitrogen (estimated 0.04 mg/L), barium (0.3  $\mu\text{g/L}$ ), lead (estimated 0.11  $\mu\text{g/L}$ ), mercury (estimated 0.007  $\mu\text{g/L}$ ), and zinc (0.7  $\mu\text{g/L}$ ). Water from blank sample 4 had a specific conductance of 4  $\mu\text{S/cm}$ , and only one chemical constituent was present in a measurable quantity, total nitrogen, estimated at 0.05 mg/L (less than the MRL of 0.06 mg/L). Blank sample 5 contained dissolved solids (13 mg/L), barium (presence verified but not quantified), copper (0.73  $\mu\text{g/L}$ ), and zinc (1.4  $\mu\text{g/L}$ ).

In general, the results of equipment-blank analyses are comparable with the exception of calcium, chloride, and silica, which were detected only in blank sample 3. Source water may provide trace amounts of contamination in the form of ammonia and mercury. The constituents that were detected in the equipment blanks and not found in the source-water blank were dissolved solids, total nitrogen, barium, chromium, copper, lead, nickel, and zinc. Thus, sampling equipment and protocols may provide trace contamination from these constituents. The most significant contamination came in the form of copper and zinc, which were detected in equipment blanks at concentrations greater than the minimum found in the 40 water-supply wells sampled in the study. Small concentrations (especially near the MRLs) of these constituents in environmental samples may be the result of contamination from equipment. However, because of a 20- to 30-minute purge of sampling equipment with well water prior to sample collection at each site, contamination from cleaning procedures or “carry over” between wells is believed to be insignificant.

Qualitative data remark codes may be associated with water-quality data presented in this report (tables 13–18 in the “Supplemental Information” section at the back of this report). For instance, many trace-element concentrations (table 17) were reported as “less than” (<) an analytical method reporting limit. Also, many concentrations that were quantifiable but less than established method reporting limits were reported as estimated (E). All of these data were used in statistical-analysis applications presented in this report. For percentile and median concentration determinations, “less than” qualified data were ranked according to their numeric value before the corresponding nonqualified numeric values (assuming a

**Table 5.** Statistical summary of absolute relative percentage differences (RPDs) between selected water-quality constituents in concurrently collected replicate samples of ground water from water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.

[N, number of replicate pairs; --, not determined; δ, del; C, carbon; H, hydrogen; O, oxygen; S, sulfur; Sr, strontium]

Constituent	Absolute relative percentage difference				
	N	Minimum	Median	Mean	Maximum
Major ions					
Dissolved solids	4	0	1.0	2.0	6.1
Calcium	4	0	.9	1.3	3.3
Magnesium	4	0	0	1.9	7.4
Potassium	4	0	0	.5	1.9
Sodium	4	0	0	.3	1.2
Alkalinity	3	0	0	0	0
Bicarbonate	3	0	0	0	0
Bromide	3	0	3.4	23	67
Chloride	4	0	0	0	0
Fluoride	4	0	2.7	3.4	8.0
Silica	4	0	.5	.5	1.1
Sulfate	4	0	0	.5	2.2
Nutrients					
Nitrogen, ammonia, as nitrogen	3	0	0	1.6	4.7
Nitrogen, nitrite plus nitrate, as nitrogen	1	--	--	--	8.7
Nitrogen, nitrite, as nitrogen	0	--	--	--	--
Total nitrogen	3	0	4.4	18	50
Orthophosphate, as phosphorus	4	0	0	7.1	29
Phosphorus	0	--	--	--	--
Trace elements					
Aluminum	0	--	--	--	--
Antimony	0	--	--	--	--
Arsenic	2	6.1	6.3	6.3	6.5
Barium	4	0	0	0	0
Beryllium	0	--	--	--	--
Boron	4	0	4.9	4.4	7.6
Cadmium	0	--	--	--	--
Chromium	1	--	--	--	140
Cobalt	0	--	--	--	--
Copper	1	--	--	--	24
Iron	3	0	2.6	3.3	7.4
Lead	2	8	12	12	15
Lithium	4	1.1	4.2	4.3	7.6

**Table 5.** Statistical summary of absolute relative percentage differences (RPDs) between selected water-quality constituents in concurrently collected replicate samples of ground water from water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.—Continued[N, number of replicate pairs; --, not determined;  $\delta$ , del; C, carbon; H, hydrogen; O, oxygen; S, sulfur; Sr, strontium]

Constituent	Absolute relative percentage difference				
	N	Minimum	Median	Mean	Maximum
Trace elements					
Manganese	4	0	2.7	2.9	6.2
Mercury	1	--	--	--	25
Molybdenum	3	0	8.0	6.2	11
Nickel	4	0	23	34	91
Selenium	2	40	45	45	50
Silver	0	--	--	--	--
Strontium	4	0	1.2	1.0	1.4
Thallium	0	--	--	--	--
Uranium	4	0	6.9	9.0	22
Vanadium	1	--	--	--	0
Zinc	2	11	61	61	110
Isotopes					
$\delta^{13}\text{C}$	2	1.2	1.8	1.8	2.5
$^{14}\text{C}$	2	22	25	25	29
$\delta^2\text{H}$	2	.2	.4	.4	.5
Tritium	2	42	340	340	640
$\delta^{18}\text{O}$	2	.6	.8	.8	.9
$\delta^{34}\text{S}$	2	.5	.8	.8	1.2
$^{87}\text{Sr}/^{86}\text{Sr}$	2	0	0	0	0

**Table 6.** Results of analyses of source water used to decontaminate sampling equipment between sample collections and equipment-blank samples processed with source water, 2006–07.

[ $\mu\text{S}/\text{cm}$ , microsiemens per centimeter at 25 degrees Celsius; <, less than; N, nitrogen; E, estimated quantity; P, phosphorus; M, presence verified but not quantified]

Blank type, date, physical property, or constituent	Blank sample				
	1	2	3	4	5
Blank type	Source water	Equipment	Equipment	Equipment	Equipment
Date (month/day/year)	9/13/2006	9/13/2006	5/21/2007	6/1/2007	8/7/2007
Physical properties					
Specific conductance ( $\mu\text{S}/\text{cm}$ )	<2.6	3.0	22	4.0	<2.6
Dissolved solids and major ions, in milligrams per liter					
Dissolved solids	<10	<10	<10	<10	13
Calcium	<.02	<.02	.05	<.02	<.02
Magnesium	<.008	<.008	<.014	<.014	<.014
Sodium	<.20	<.20	<.20	<.20	<.20
Potassium	<.16	<.16	<.04	<.04	<.04
Sulfate	<.18	<.18	<.18	<.18	<.18
Chloride	<.20	<.20	.50	<.12	<.12
Fluoride	<.10	<.10	<.10	<.10	<.10
Bromide	<.02	<.02	<.02	<.02	<.02
Silica	<.04	<.04	.10	<.018	<.02
Nutrients, in milligrams per liter					
Ammonia, as N	E.01	E.01	<.010	<.02	<.020
Nitrite plus nitrate, as N	<.060	<.060	<.060	<.060	<.06
Nitrite, as N	<.002	<.002	<.002	<.002	<.002
Total nitrogen, as N	<.06	.08	E.04	E.05	<.06
Orthophosphate, as P	<.006	<.006	<.006	<.006	<.006
Phosphorus	<.004	<.004	<.004	<.006	<.006
Trace elements, in micrograms per liter					
Aluminum	<1.6	<1.6	<1.6	<1.6	<1.6
Antimony	<.20	<.20	<.06	<.06	<.06
Arsenic	<.12	<.12	<.12	<.12	<.12
Barium	<.20	1.4	.30	<.08	M
Beryllium	<.06	<.06	<.06	<.06	<.06
Boron	<8.0	<8.0	<8.0	<8.0	<8.0
Cadmium	<.04	<.04	<.04	<.04	<.04
Chromium	<.04	E.05	<.12	<.12	<.12
Cobalt	<.04	<.04	<.04	<.04	<.04
Copper	<.40	.60	<.40	<.40	.73
Iron	<6.0	<6.0	<6.0	<6.0	<6.0
Lead	<.08	E.06	E.11	<.12	<.12
Lithium	<.60	<.60	<.60	<.60	<.60

**Table 6.** Results of analyses of source water used to decontaminate sampling equipment between sample collections and equipment-blank samples processed with source water, 2006–07.—Continued[ $\mu\text{S}/\text{cm}$ , microsiemens per centimeter at 25 degrees Celsius; <, less than; N, nitrogen; E, estimated quantity; P, phosphorus; M, presence verified but not quantified]

Blank type, date, physical property, or constituent	Blank sample				
	1	2	3	4	5
	Source water	Equipment	Equipment	Equipment	Equipment
Date (month/day/year)	9/13/2006	9/13/2006	5/21/2007	6/1/2007	8/7/2007
Trace elements, in micrograms per liter—Continued					
Manganese	<0.20	<0.20	<0.20	<0.20	<0.20
Mercury	E.007	E.006	E.007	<.010	<.010
Molybdenum	<.40	<.40	<.12	<.12	<.10
Nickel	<.06	.15	<.06	<.06	<.06
Selenium	<.08	<.08	<.08	<.08	<.08
Silver	<.20	<.20	<.10	<.10	<.10
Strontium	<.80	<.80	<.80	<.80	<.80
Thallium	<.04	<.04	<.04	<.04	<.04
Uranium	<.04	<.04	<.04	<.04	<.04
Vanadium	<.10	<.10	<.04	<.04	<.04
Zinc	<.60	1.2	.70	<.60	1.4

ranking order from smallest to largest), and estimated values were ranked as nonqualified values in numerical sequence (for example, E1, <2, 2, E3, <5, 5, 8, 12, and so forth).

## Quality Characteristics of Ground Water

Ground water in the Ozark aquifer is used to a limited extent for domestic supply but is used more extensively for public and industrial supplies and for irrigation. The USEPA has established drinking-water standards for physical properties and chemical constituents that may have adverse effects on human health or that may affect the odor, appearance, or desirability of water (U.S. Environmental Protection Agency, 2006). These water-quality standards include Maximum Contaminant Levels (MCLs), Secondary Drinking-Water Regulations (SDWRs), and Maximum Contaminant Level Goals (MCLGs). An MCL is a regulatory, enforceable maximum-permissible concentration for a contaminant in drinking water that is delivered to any user of a public-water system. MCLs are set at levels to protect human health from all expected deleterious effects. An SDWR is a nonenforceable guideline regarding cosmetic (tooth or skin discoloration) or aesthetic (taste, odor, or color) effects of drinking water. An MCLG is a

nonenforceable health goal that is set at a level with no known adverse human-health effects.

Results of physical measurements and chemical analyses of ground-water samples collected from 40 water-supply wells in the Ozark aquifer study area (fig. 4) are presented in tables 14–17 in the “Supplemental Information” section at the back of this report. These data were assessed or evaluated in the context of spatial distribution and evolution along selected flow paths. Data were also assessed relative to USEPA drinking-water standards and to natural hydrologic factors or human-related activities.

## Spatial Distribution

The spatial distribution of water-quality characteristics throughout the study area was summarized statistically and assessed with the use of analysis of water samples from 40 water-supply wells completed in the Ozark aquifer. Fifteen wells were located in each of Kansas and Missouri, eight in Oklahoma, and two in Arkansas (fig. 4). Well-selection criteria were discussed previously in the “Methods of Investigation” section of this report. Water-quality measurements or constituent groups assessed included physical properties, dissolved solids and major ions, nutrients, and trace elements, and selected isotopes.

## Physical Properties

Physical properties were measured or analyzed in water from each of the 40 water-supply wells (fig. 4) sampled during this study (table 14 at the back of this report). Measurements made at the time of sample collection included specific conductance, pH, water temperature, dissolved oxygen, and turbidity, and oxidation-reduction (redox) potential. A statistical summary and USEPA standards for physical properties in water from the 40 wells sampled during this study are presented in table 7.

Specific conductance describes the ability of water to conduct an electrical current and provides an indication of dissolved ions in solution. Specific conductance generally has a direct relation with major ion concentrations (Hem, 1992). Specific conductance of water from the sampled wells was less than 500  $\mu\text{S}/\text{cm}$  for about one-half (21 of 40) of the wells, as indicated by the median value of 470  $\mu\text{S}/\text{cm}$  (table 7). The other 19 wells had specific conductance values in the range of about 500 to 1,890  $\mu\text{S}/\text{cm}$  (table 14). Generally, water from wells located in Missouri had the smallest specific conductance values, and overall, Kansas had the largest. However, the largest specific conductance (1,890  $\mu\text{S}/\text{cm}$ ) was determined in water from well 33 in Oklahoma (table 14, fig. 4).

The pH of water is a measure of the activity of the hydrogen ion and indicates the degree of acidity or alkalinity of a solution. A pH of less than 7.0 standard units is considered acidic, and a pH greater than 7.0 standard units is considered alkaline. The pH of water from sampled wells in the study area had a median value of 7.56 standard units (table 7). USEPA has established an SDWR range of 6.5 to 8.5 standard units (U.S. Environmental Protection Agency, 2006) in drinking

water, and water from all sampled wells was within this guideline.

Oxygen enters ground water through recharge of oxygen-enriched surface or meteoric water that percolates down through the unsaturated zone where it may react with oxidizable material encountered along the flow path of the water. The main reacting compounds are organic material and reduced inorganic minerals such as pyrite and siderite (Hem, 1992). Water from most of the 37 wells for which dissolved oxygen content was determined was relatively oxygen poor as indicated by a median dissolved oxygen concentration of 0.16 mg/L (table 7). Six wells had no measurable dissolved oxygen content (less than 0.01 mg/L), 24 wells had dissolved oxygen concentrations that ranged from 0.01 to 0.28 mg/L, and the remaining 7 wells had dissolved oxygen concentrations that ranged from 1.4 to 2.0 mg/L (table 14). Because of the large depths of the wells sampled in this study (table 3), confined conditions, and potential for flow paths of tens of miles or more, the small concentrations of dissolved oxygen in ground water were not unexpected.

Turbidity refers to the cloudiness of water and is caused by suspended matter and other factors (Anderson, 2005). Turbidity is measured by quantifying the amount of light scattered by particles in the water and can be measured in nephelometric turbidity units (NTUs). Turbidity has no health effects, but it can interfere with disinfection and provide a medium for microbial growth. The USEPA established an MCL of 5 NTU (U.S. Environmental Protection Agency, 2006). The turbidity of water in the wells sampled generally was small as indicated by a median value of 0.20 NTU (table 7). However, three wells (1, 5, and 9; fig. 4) exceeded the water-quality standard

**Table 7.** Statistical summary and U.S. Environmental Protection Agency (2006) drinking-water standards for physical properties measured or analyzed in ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.

[ $\mu\text{S}/\text{cm}$ , microsiemens per centimeter at 25°C; °C, degrees Celsius; mg/L, milligrams per liter; NTU, nephelometric turbidity units; SHE, relative to standard hydrogen electrode; mV, millivolts;  $\text{CaCO}_3$ , calcium carbonate; --, not applicable; MCL, Maximum Contaminant Level; SDWR, Secondary Drinking-Water Regulation]

Physical property (unit of measurement)	Number of samples	Minimum	Percentile			Maximum	Drinking-water standard
			25	50 (median)	75		
Specific conductance ( $\mu\text{S}/\text{cm}$ )	40	236	334	470	913	1,890	--
pH (standard units)	40	6.84	7.35	7.56	7.75	8.15	6.5–8.5 (SDWR)
Water temperature (°C)	40	15.3	18.2	19.5	21.1	23.9	--
Dissolved oxygen (mg/L)	37	<.01	.05	.16	.56	2.0	--
Turbidity (NTU)	31	0.08	0.13	0.20	0.46	25	5 (MCL)
Oxidation-reduction (redox) potential, SHE (mV)	32	-110	-80	40	80	380	--
Alkalinity as $\text{CaCO}_3$ (mg/L)	40	110	140	160	240	290	--

of 5 NTU with turbidities of 15, 5.8, and 25 NTU, respectively (table 14).

Redox (oxidation-reduction) potential is a measure of the intensity of oxidizing or reducing conditions within a system such as water. Positive potentials indicate that the water is relatively oxidizing, and negative potentials indicate that the water is relatively reducing (Hem, 1992). Redox potential (also called Eh) was measured for water from 32 of the 40 wells sampled for this study. Redox potential relative to a standard hydrogen electrode ranged from -110 (well 7) to 380 (well 18) mV (millivolts), with a median value of 40 mV (tables 7 and 14). Some water-quality constituents such as arsenic, iron, and selenium are sensitive to the redox environment, and any change to the redox potential in an environment potentially could cause these constituents to dissolve into solution from surrounding aquifer material or to precipitate out of solution. Both situations eventually could affect the permeability of the aquifer in addition to releasing potentially harmful constituents such as arsenic to the formation water.

## Dissolved Solids and Major Ions

Dissolved solids are an important indicator of water quality and, in uncontaminated ground water, are the result of natural dissolution of rocks and minerals. Dissolved solids also are an important indicator of the suitability of water for drinking, irrigation, and industrial use. The major constituents of dissolved solids in ground-water samples from the study

area are the cations (positively charged ions) calcium, magnesium, sodium, and potassium, and the anions (negatively charged ions) bicarbonate, sulfate, chloride, fluoride, bromide, and silica.

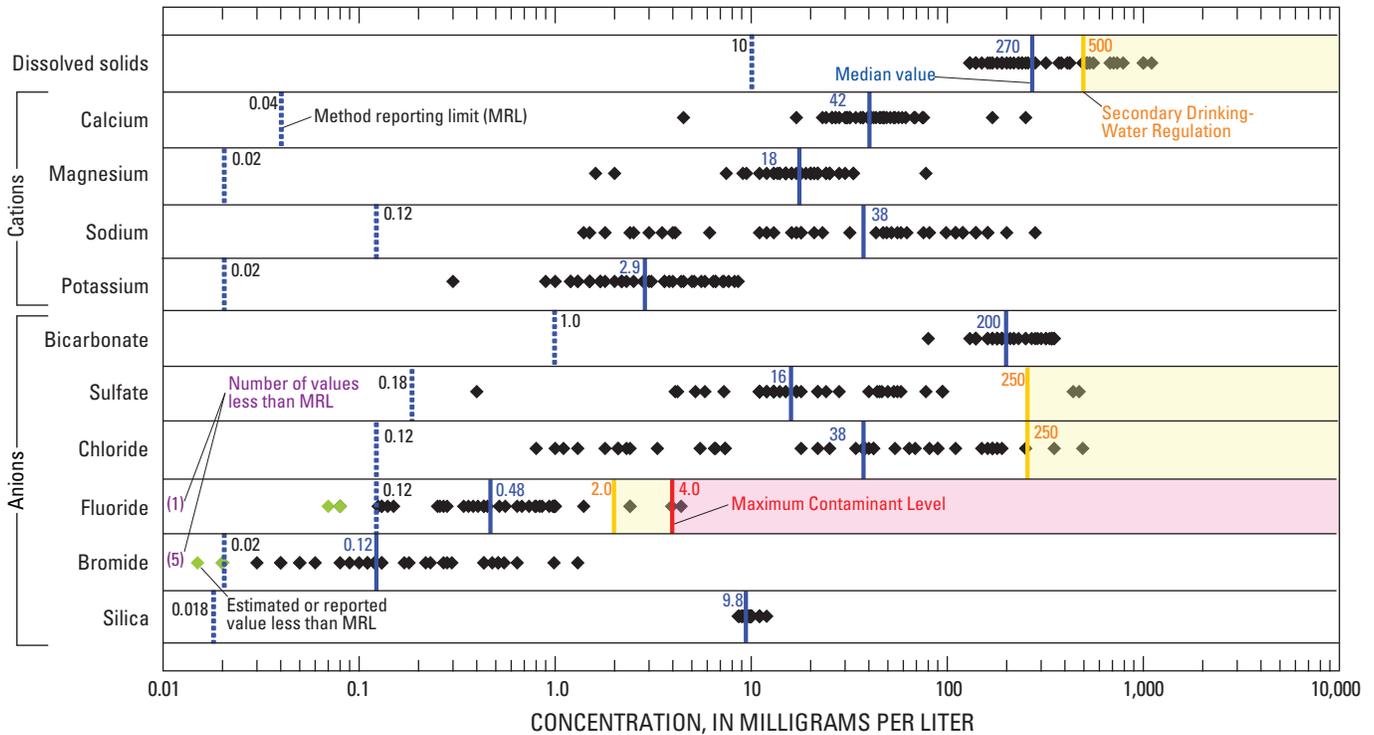
Large concentrations of dissolved solids are undesirable in water supplies because of objectionable taste in drinking water and limitations for industrial uses (American Public Health Association and others, 1998). The USEPA has established a 500-mg/L SDWR for dissolved solids in drinking water (U.S. Environmental Protection Agency, 2006). Concentrations of dissolved solids from the 40 sampled water-supply wells ranged from 130 (wells 24 and 25) to 1,100 mg/L (well 31), with a median value of 270 mg/L (tables 8 and 15, fig. 5). Water from about one-fourth of the wells (1, 2, 3, 5, 9, 12, 20, 31, 33, 36, and 40) exceeded the 500-mg/L SDWR for dissolved solids. The majority of these wells were located in Kansas (fig. 6).

The largest dissolved-solids concentrations determined during this investigation probably are related to a general transition from freshwater to saline water in the Ozark aquifer in an east-to-west trend across the study area (Macfarlane and Hathaway, 1987; Imes and Davis, 1991; Imes and Emmett, 1994). This increase in dissolved solids is a vestige of the original connate “formation” water (Jorgensen and others, 1996) and may reach concentrations as large as 10,000 mg/L along the western boundary of the study area (Imes and Emmett, 1994). This artifact of ancient seawater also is evident in a general shift in water type along an east-to-west

**Table 8.** Statistical summary and U.S. Environmental Protection Agency (2006) drinking-water standards for dissolved solids and major ions in ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.

[mg/L, milligrams per liter; --, not applicable; E, estimated; SDWR, Secondary Drinking-Water Regulation; MCL, Maximum Contaminant Level]

Dissolved solids or major ion (mg/L)	Number of samples	Minimum	Percentile			Maximum	Drinking-water standard
			25	50 (median)	75		
Dissolved solids	40	130	190	270	510	1,100	500 (SDWR)
Calcium	40	4.5	30	42	53	250	--
Magnesium	40	1.6	14	18	22	78	--
Sodium	40	1.4	9.8	38	100	403	--
Potassium	40	.3	1.6	2.9	5.3	8.6	--
Bicarbonate	40	130	170	200	290	350	--
Sulfate	40	.4	11	16	45	470	250 (SDWR)
Chloride	40	.8	5.0	38	95	490	250 (SDWR)
Fluoride	40	E.07	.26	.48	.94	4.4	4 (MCL), 2 (SDWR)
Bromide	40	E.01	.04	.12	.28	1.3	--
Silica	40	8.6	9.5	9.8	10	12	--



**Figure 5.** Method reporting limits, sample concentrations and median values, and drinking-water standards for dissolved solids and major ions detected in ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07. Drinking-water standards established by U.S. Environmental Protection Agency (2006).

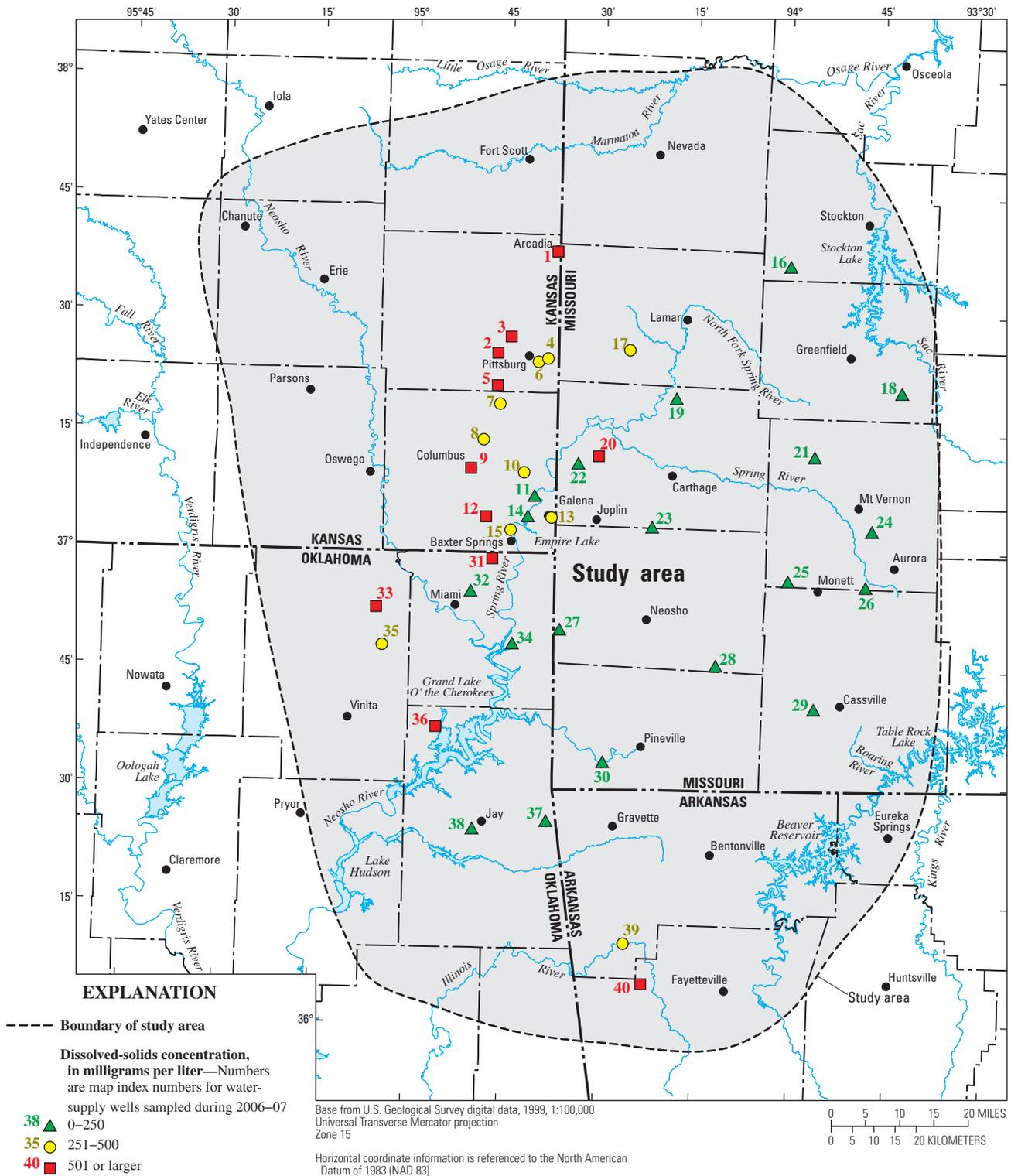
trend (fig. 6). Water from most sampled wells in Missouri is a calcium bicarbonate or calcium magnesium bicarbonate type (fig. 7), whereas water from wells in Kansas transitions to a sodium bicarbonate, sodium bicarbonate chloride, or sodium chloride type. The approximate dissolved-solids scale included in figure 7 was developed from a relation between the summation of major ions in milliequivalents per liter and dissolved-solids concentrations (fig. 8). Milliequivalents per liter is the measure of the concentration of a solute in solution calculated by dividing the concentration in milligrams per liter by the equivalent weight of the ion.

Chloride is present in natural water, but large concentrations can impart a salty taste to drinking water and may accelerate the corrosion of metals used in water-supply systems. The USEPA has established an SDWR of 250 mg/L for chloride in drinking water (U.S. Environmental Protection Agency, 2006). Chloride concentrations ranged among the sampled wells from 0.8 (well 24) to 490 mg/L (well 33), with a median concentration of 38 mg/L (tables 8 and 15, fig. 5). Water samples from wells 33 and 36 had chloride concentrations greater than the 250-mg/L SDWR (fig. 9, table 15). Because the chloride ion can comprise a large part of dissolved-solids concentrations, particularly in marine connate water, the chloride concentrations in water from sampled wells had a distributional pattern similar to that of dissolved solids (figs. 6 and

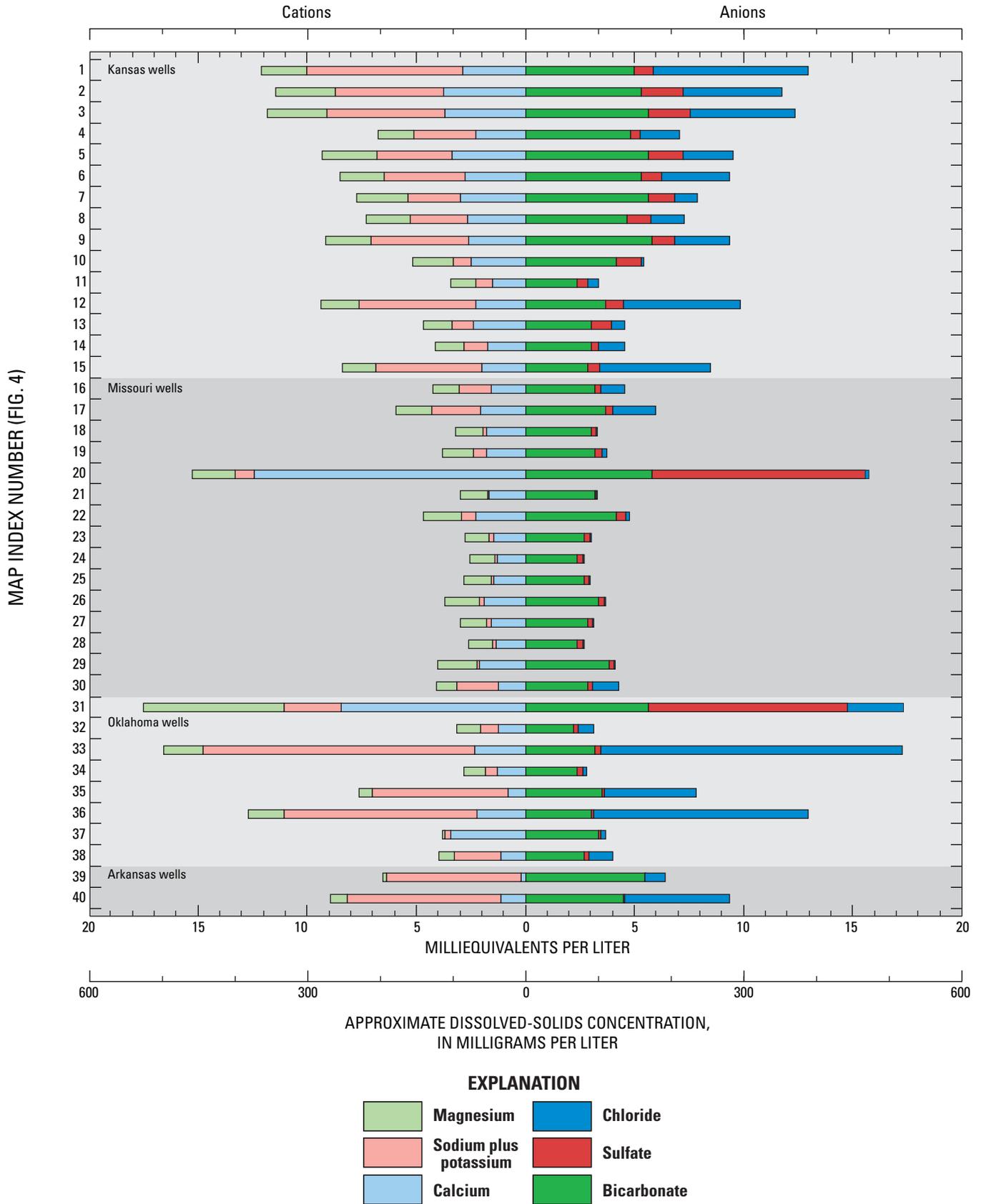
9). The smallest chloride concentrations were found in water from wells in the eastern part of the study area, and concentrations progressively increased in a westerly direction.

Sodium and chloride represents a large fraction of the dissolved minerals in marine connate water. Because of this, sodium concentrations tended to be large in ground-water samples with large chloride concentrations (table 15). Sodium concentrations ranged from 1.4 (well 24) to 403 mg/L (well 6), with a median concentration of 38 mg/L (table 8). USEPA has not established an SDWR or MCL for sodium in drinking water but has listed a health-based advisory level (HAL) of 20 mg/L for individuals on a 500 milligrams per day (mg/d) restricted sodium diet (U.S. Environmental Protection Agency, 2006). Water samples from 23 wells had concentrations that exceeded this advisory level (table 15). All but 2 (wells 10 and 11) of the 15 wells sampled in Kansas yielded samples with sodium concentrations exceeding 20 mg/L, whereas only three wells (wells 16, 17, and 30) located in the upgradient part of the study area (Missouri) had sodium concentrations exceeding 20 mg/L (table 15).

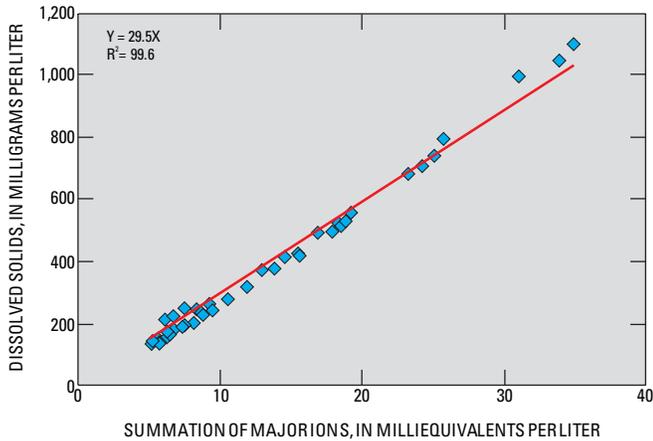
Macfarlane and Hathaway (1987) defined the upgradient boundary of the transition zone from freshwater to saline as the western edge of the Mississippian outcrop belt west of the Missouri and Kansas State line. Natural sources of sulfate in water include the weathering or dissolution of sulfur-bearing



**Figure 6.** Distribution of dissolved-solids concentrations in ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.



**Figure 7.** Major ion composition of ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–2007.



**Figure 8.** Relation between summation of major ions and dissolved solids in ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.

minerals, such as pyrite and gypsum, volcanic discharges to the atmosphere, and biologic and biochemical processes (Hem, 1992). Large concentrations of sulfate in drinking water may cause laxative effects. USEPA has established an SDWR of 250 mg/L for sulfate in drinking water (U.S. Environmental Protection Agency, 2006). Sulfate concentrations ranged from 0.4 (well 39) to 470 mg/L (well 20), with a median concentration of 16 mg/L (tables 8 and 15). Water samples from wells 20 and 31 had sulfate concentrations larger than the 250-mg/L SDWR (fig. 10, table 15). Sulfate concentrations generally were largest in samples from wells located in the western part of the study area (fig. 10). The sulfate measured in well 20 is essentially the same sulfate concentration that it exhibited when that well was drilled. No other nearby water-supply wells have this problem, but several nearby wells do have somewhat elevated sulfate concentrations (Jim Vandike, U.S. Geological Survey, written commun., 2009). The elevated sulfate concentrations may be caused by a deposit a couple of miles to the southeast where there is a major mineralized breccia zone that has considerable vertical extent and may have breached the confining unit (Jim Vandike, U.S. Geological Survey, written commun., 2009). A noticeable hydrogen-sulfide odor was evident in well water at the time of sampling increased in intensity in the downgradient direction (away from recharge areas in Missouri). The most noticeable hydrogen-sulfide odor occurred in wells along and west of the Kansas State line.

Fluoride is present in natural water at a concentration usually smaller than 1.0 mg/L and is the result of weathering of fluorine-containing minerals such as fluorite or apatite. More advanced animals incorporate fluoride into bone and teeth tissues (Hem, 1992). However, excessive fluoride concentrations in drinking water can cause dental or skeletal fluorosis, and in response, the USEPA established two

regulatory levels for fluoride in drinking water—an SDWR of 2.0 mg/L and an MCL of 4.0 mg/L (U.S. Environmental Protection Agency, 2006). Fluoride concentrations in ground-water samples collected during this investigation generally were less than 1.0 mg/L, with a median concentration of 0.48 mg/L (table 8, fig. 5). However, samples from seven wells had fluoride concentrations of 1.0 mg/L or larger, and concentrations ranged from 1.0 (wells 8 and 36) to 4.4 mg/L (well 39) (table 15). Fluoride concentrations in samples from wells 33, 35, 39, and 40 exceeded the 2.0-mg/L SDWR, whereas the concentration in the sample from well 39 was the only sample concentration to exceed the 4.0-mg/L MCL (fig. 5).

Concentrations of magnesium, potassium, bromide, and silica generally were small in water from sampled wells relative to other major ions (fig. 5, table 8). The USEPA has not established drinking-water standards for these four ions.

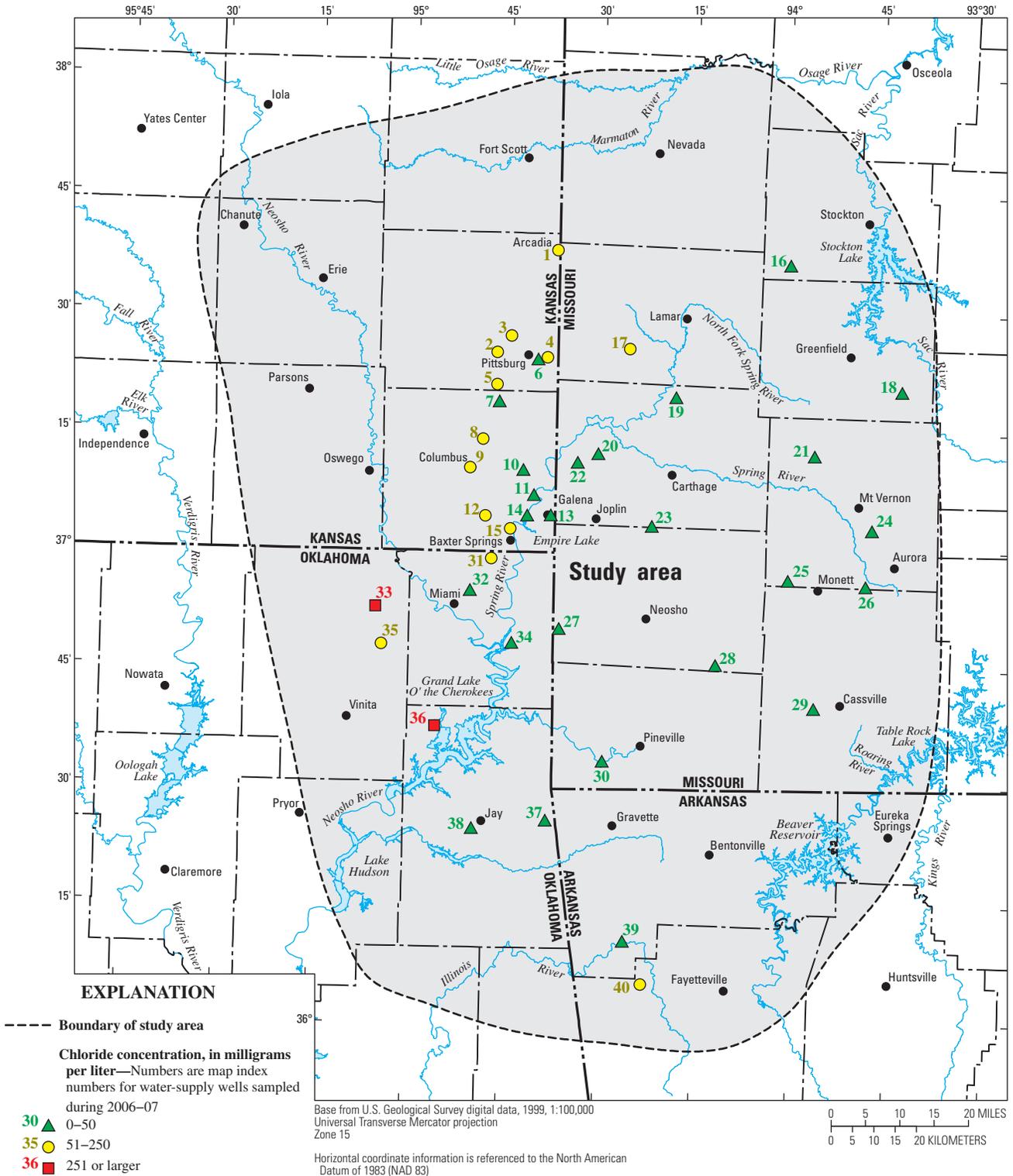
## Nutrients

Nutrients, which contain the elements nitrogen and phosphorus, are essential for the growth and reproduction of plants. Compounds of nitrogen and phosphorus contained in synthetic fertilizers and manure, commonly are applied to cropland and some pastures to stimulate plant growth and increase crop yields and hay production. Synthetic fertilizers include anhydrous ammonia, ammonium nitrate, urea and mono- and diammonium phosphates. Other sources of nutrients include human waste, nitrogen-containing organic compounds, and industrial waste. Recharge water in areas where nutrients are applied or disposed on the land surface can leach nutrients and infiltrate into the ground-water system and potentially contaminate drinking-water sources. Large concentrations of nutrients (particularly nitrates) in drinking water may be physiologically damaging to humans.

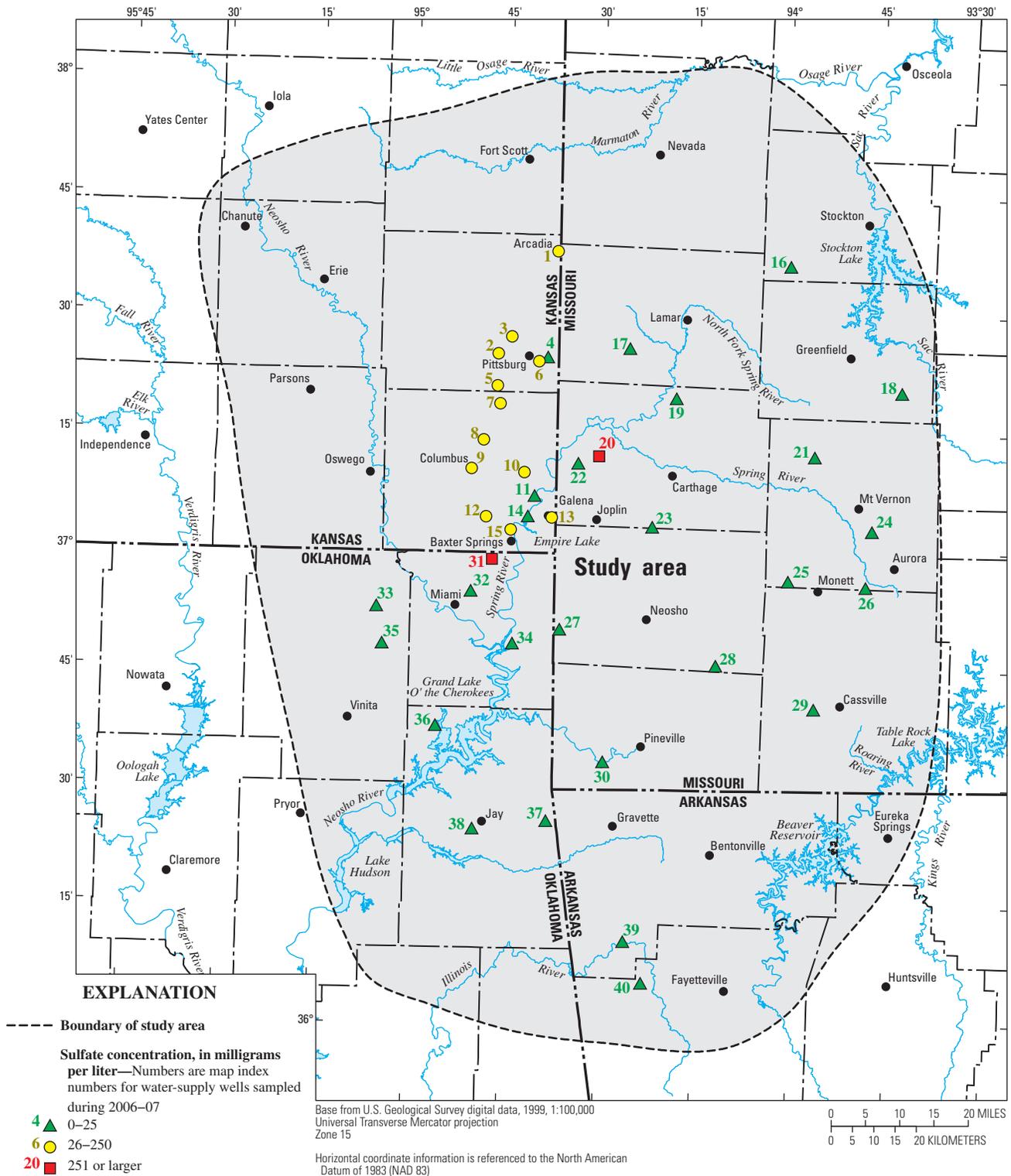
Concentrations of nitrite, nitrite plus nitrate, ammonia, total nitrogen, phosphorus, and orthophosphate, were determined in ground water from the 40 water-supply wells sampled during the investigation described in this report. Generally, nutrient concentrations in water from the 40 wells were small (table 16 in the “Supplemental Information” section at the back of this report) and always less than drinking-water standards.

Nitrite and nitrate are inorganic ions produced during various stages of the nitrogen cycle. In oxygenated natural water, nitrite typically is oxidized to nitrate (U.S. Environmental Protection Agency, 1986); thus, nitrate will tend to predominate. Nitrite and nitrate usually occur in relatively small concentrations in uncontaminated water. Mueller and Helsel (1996) estimated a national average background concentration of nitrate in ground water of 2.0 mg/L as nitrogen, which indicates that concentrations larger than 2.0 mg/L may result from contamination from human activities.

Human health-based regulations have been established for nitrate concentrations in drinking water because of the potential adverse health effects on infants. Consumption of drinking water with nitrate concentrations larger than



**Figure 9.** Distribution of chloride concentrations in ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.

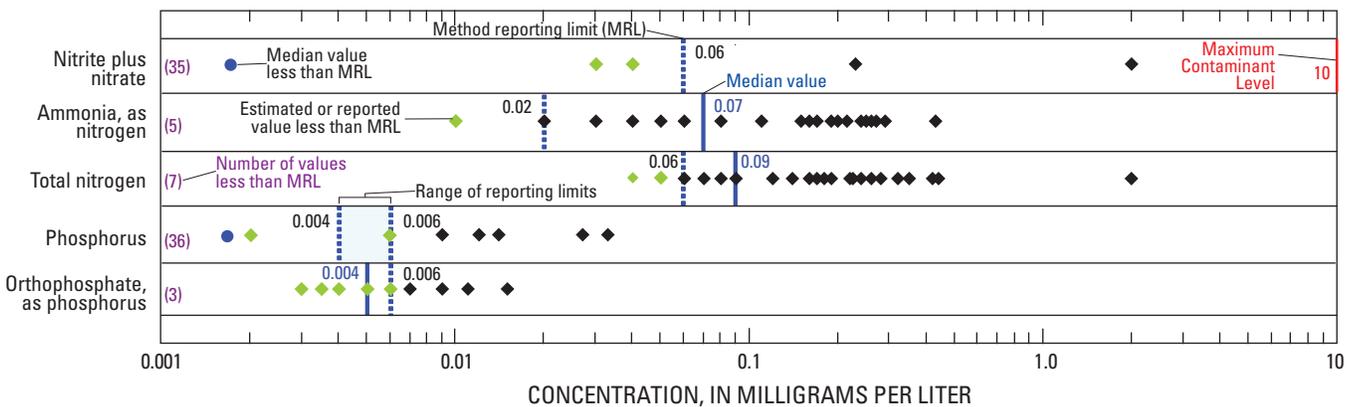


**Figure 10.** Distribution of sulfate concentrations in ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.

**Table 9.** Statistical summary and U.S. Environmental Protection Agency (2006) drinking-water standards for nutrients in ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–2007.

[mg/L, milligrams per liter; E, estimated; --, not applicable; <, less than; MCL, Maximum Contaminant Level]

Nutrient (mg/L)	Number of samples	Minimum	Percentile			Maximum	Drinking-water standard
			25	50 (median)	75		
Nitrite, as nitrogen	40	E.001	<.002	<.002	<.002	.002	1 (MCL)
Nitrite plus nitrate, as nitrogen	40	E.03	<.06	<.06	<.06	2.0	10 (MCL)
Ammonia, as nitrogen	40	E0.01	0.028	0.070	0.19	0.43	--
Total nitrogen	40	E.04	<.06	.09	.23	2.0	--
Phosphorus	40	E.002	<.004	<.006	<.006	.033	--
Orthophosphate, as phosphorus	40	E.003	.004	.004	.005	.015	--



**Figure 11.** Method reporting limits, sample concentrations and median values, and drinking-water standards for nutrients detected in ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07. Drinking-water standards established by U.S. Environmental Protection Agency (2006).

10 mg/L can cause methemoglobinemia (blue-baby syndrome) in infants, a sometimes fatal illness related to the impairment of the oxygen-carrying ability of the blood (U.S. Environmental Protection Agency, 1986). Accordingly, an MCL of 10 mg/L of nitrate as nitrogen has been established by the USEPA (U.S. Environmental Protection Agency, 2006).

Nitrite and nitrite plus nitrate (hereinafter referred to as nitrate) concentrations generally were less than method reporting limits but were detected in water samples from 9 wells (table 16, fig. 11). Nitrate concentrations in water from the 40 sampled wells ranged from an estimated 0.03 (wells 1, 2, 5, and 25) to 2.0 mg/L (well 37), with a median concentration of less than 0.06 mg/L (table 9). All nitrate concentrations were substantially less than the established MCL of 10 mg/L. Additionally, all determined nitrate concentrations were equal to or substantially less than the 2.0-mg/L national average background concentration reported in Mueller and Helsel (1996).

Total phosphorus and orthophosphate as phosphorus typically were present only in small concentrations in water

from the 40 sampled wells (table 16, fig. 11). Total phosphorus was detected only in water from eight wells. Total phosphorus concentrations in water from the 40 wells ranged from an estimated 0.002 (wells 3 and 7) to 0.033 mg/L (well 25), with a median concentration of less than 0.006 mg/L (table 9). Concentrations of orthophosphate as phosphorus ranged from an estimated 0.003 (wells 5, 16, 18, and 34) to 0.015 mg/L (well 37), with a median concentration of an estimated 0.004 mg/L (table 9). Most of the phosphorus in water from the 40 sampled wells was in the form of orthophosphate-phosphorus on the basis of similarities in concentrations (table 16).

Water from 90 percent of sampled wells had small reportable concentrations of ammonia with a range from an estimated 0.01 (well 25) to 0.43 mg/L (well 33) and a median concentration of 0.07 mg/L (table 9, fig. 11). Ammonia is the dominant nitrogen-containing nutrient in sampled wells in the Ozark aquifer and represents most of the total nitrogen as indicated in the similarities between ammonia and total nitrogen concentrations (table 16, fig. 11). The dominance of ammonia

among nitrogen nutrient species is a result of anaerobic conditions within the aquifer. Dissolved oxygen concentrations in water from most wells were small (0.56 mg/L at the 75th percentile; table 7). Under anaerobic conditions, ammonia-nitrogen accumulation occurs because of the suppression of nitrification (formation of nitrate ion) (Canter, 1996).

The similarity between ammonia and total nitrogen concentrations (fig. 11) indicates that concentrations of organic nitrogen in water from Ozark wells are small and that contamination of the Ozark aquifer from surface nitrogen is not evident.

## Trace Elements

Trace elements normally occur in natural water in small concentrations even though some are naturally abundant. For example, aluminum is the one of the most abundant elements in the rock of the Earth's crust; however, it rarely occurs in solution in natural water in concentrations greater than a few hundred micrograms per liter (Hem, 1992). The occurrence in ground water of most of the trace elements listed in table 13 (in the "Supplemental Information" at the back of this report) typically results from natural physical and chemical processes. Physical processes include those associated with origin and mineral composition, ground-water flow paths, and depositional characteristics of sediment in the aquifer. Chemical processes include the interaction of water, oxygen, carbon dioxide, and other acidic components that cause the chemical breakdown or dissolution of minerals containing trace elements (Brickler and Jones, 1995). Generally, the occurrence and chemical speciation of trace elements in ground water are determined by (1) hydrogen ion availability (defined by pH); (2) the presence and concentrations of inorganic ligands such as carbonate, sulfate, sulfide, and chloride; (3) the presence and concentrations of organic complexing agents (primarily humic and fulvic acids); (4) free electron availability (redox potential); and (5) the ionic strength (specific conductance) and cation distribution of the water (Allard, 1995).

Concentrations of 24 trace elements (table 13) were determined in water from wells sampled during this investigation. Trace elements were of particular concern because the historic use of the Tri-State Mining District for production of lead and zinc ores provided the opportunity for water to be contaminated by trace elements associated with these ores. Lead and zinc were the most economically important trace elements associated with the minerals mined in the Tri-State District (Pope, 2005).

Most trace elements in ground water analyzed during this investigation were present in concentrations less than water-quality standards. In fact, many trace constituents frequently were not detected or were detected in small concentrations (table 17, fig. 12). Seventeen trace elements (antimony, arsenic, beryllium, cadmium, chromium, cobalt, copper, lead, mercury, molybdenum, nickel, selenium, silver, thallium, uranium, vanadium, and zinc) had median concentrations less than 1.0 µg/L and were not detected in about 70 percent of the

samples (tables 10 and 17, fig. 12). Silver was not detected in any of the wells. Six constituents had median concentrations greater than 1.0 µg/L—barium, boron, iron, lithium, manganese, and strontium. Additionally, nine trace elements had a maximum concentration greater than 5.0 µg/L—barium, boron, iron, lithium, manganese, molybdenum, strontium, and zinc. Iron, lead, and manganese were the only trace elements found in concentrations that exceeded USEPA drinking-water criteria.

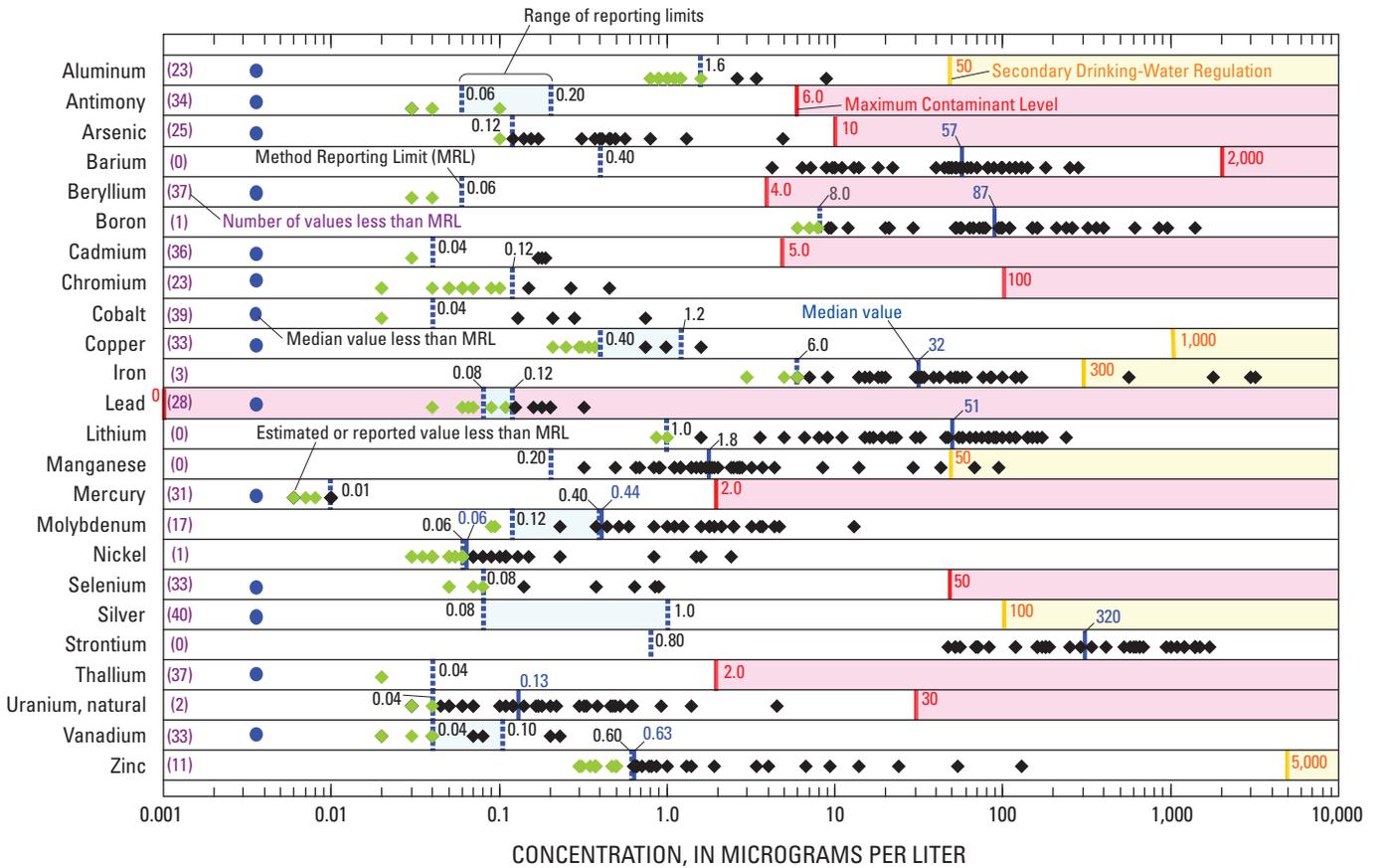
Iron concentrations in water from sampled wells ranged from an estimated 3.0 to 3,200 µg/L, with a median value of 32 µg/L (table 10). Iron is essential to the growth of plants and animals, but when present in large concentrations, precipitates of red oxyhydroxide can form and cause staining of laundry or plumbing fixtures (Hem, 1992). Therefore, iron is an undesirable impurity in water used for domestic or industrial purposes. The USEPA established an SDWR of 300 µg/L for iron in drinking water (U.S. Environmental Protection Agency, 2006). Water from wells 5, 20, 21, and 31 exceeded the SDWR with iron concentrations of 560, 3,200, 1,800, and 3,000 µg/L, respectively (table 17).

Lead was not detected in water from most wells. Where it was detected, it was present at concentrations less than 1.0 µg/L (table 17). The USEPA established two standards for lead in drinking water—an Action Level (AL) of 15 µg/L and a Maximum Contaminant Level Goal (MCLG) of 0 µg/L. An Action Level is defined as, "...the concentration of a contaminant which, if exceeded, triggers treatment or other requirements which a water system must follow..." (U.S. Environmental Protection Agency, 2006). An MCLG is a non-enforceable goal for a contaminant set at a level at which no known or anticipated adverse health effects are expected and which allows a margin of safety (U.S. Environmental Protection Agency, 2006). Concentrations of lead were substantially smaller than the AL. Twelve wells (2, 3, 4, 6, 7, 10, 13, 14, 18, 22, 37, and 39) had measurable lead concentrations and, thus, exceeded the MCLG (table 17).

Manganese concentrations ranged from 0.32 to 95 µg/L and had a median value of 1.8 µg/L (table 10). Manganese is an objectionable impurity in water supplies because of staining from black manganese oxide deposits (Hem, 1992). The USEPA established an SDWR of 50 µg/L for manganese in drinking water (U.S. Environmental Protection Agency, 2006). Water from wells 20 and 21 exceeded the SDWR with manganese concentrations of 95 and 68 µg/L (table 17), respectively.

## Potential Effect of Mining on Water Quality

One ground-water-quality concern in the study area is that past lead and zinc mining in the Tri-State Mining District may be a source of trace-element contamination for the Ozark aquifer. As previously discussed in the "Geology" and "Geohydrology" sections of this report, mining was conducted



**Figure 12.** Method reporting limits, sample concentrations and median values, and drinking-water standards for trace elements detected in ground water from 40 water-supply wells completed in Ozark aquifer, northeastern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07. Drinking-water standards established by U.S. Environmental Protection Agency (2006).

in some of the Mississippian-age rock formations that compose the Springfield Plateau aquifer (figs. 1 and 3; table 1). The Springfield Plateau aquifer is mostly unconfined in the study area and receives direct precipitation recharge. Therefore, water in the Springfield Plateau aquifer might well be a younger age (time since recharge) relative to water in the underlying, confined Ozark aquifer in the study area, which primarily occurs as a result of recharge and lateral migration from unconfined areas in the Ozark Plateaus east of the study area (fig. 1). The presence of younger water and elevated concentrations of trace elements such as iron and lead in the Ozark aquifer may be indicative of movement of Springfield Plateau aquifer water into the Ozark aquifer and the possibility of surface contamination or may be from poor quality mine water.

Water from a water-supply well in Galena, Kansas (well 13, fig. 4), does show younger water characteristics relative to other sampled Ozark aquifer wells as evidenced by isotope analysis. Tritium radioactivity (in picocuries per liter, pCi/L) was largest in water from well 13 among the 11 wells sampled for tritium (table 17). The 4.7 pCi/L tritium concen-

tration in water from well 13 was about five times larger than the second largest concentration (well 6, 1.0 pCi/L).

The 4.7 pCi/L tritium concentration determined in water from well 13 falls within the range (2.6 to 12.8 pCi/L) indicating ground water containing a mixture of submodern and recent (since 1952) recharge (Clark and Fritz, 1997, p. 185). Because tritium concentrations in water from the other 10 wells sampled in the Ozark aquifer were relatively small and within the range (less than 2.6 pCi/L) indicating recharge prior to 1952, it is probable that the mixed recharge water from well 13 is the result of a downward movement of younger water from the Springfield Plateau aquifer. This downward movement could occur through cracks or fissures in the Ozark confining unit that separates the Springfield Plateau and Ozark aquifers (fig. 3), water-supply wells open to both the Springfield Plateau and Ozark aquifers, poorly constructed or abandoned wells, or as a result of historic lead-and-zinc mining activities (exploratory drill holes or water-supply wells). Further evidence of mixed recharge water is indicated in the <sup>14</sup>C results for well 13 (table 17). Water from well 13 had the largest percentage of modern <sup>14</sup>C (0.13 percent) of any of the Ozark aquifer wells sampled.

**32 Quality Characteristics of Ground Water in the Ozark Aquifer of Arkansas, Kansas, Missouri, and Oklahoma, 2006–07**
**Table 10.** Statistical summary and U.S. Environmental Protection Agency (2006) drinking-water standards for trace elements in ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.

[µg/L, micrograms per liter; E, estimated; --, not applicable; <, less than; SDWR, Secondary Drinking-Water Regulation; MCL, Maximum Contaminant Level; AL, Action Level; MCLG, Maximum Contaminant Level Goal]

Trace element (µg/L)	Number of samples	Minimum	Percentile			Maximum	Drinking-water standard
			25	50 (median)	75		
Aluminum	40	E0.8	1.0	<1.6	<1.6	8.9	50 to 200 (SDWR)
Antimony	40	E.03	<.06	<.06	<.20	<.10	6 (MCL)
Arsenic	40	E.10	<.12	<.12	.38	4.9	10 (MCL)
Barium	40	4.2	21	57	102	280	2,000 (MCL)
Beryllium	40	E.03	<.06	<.06	<.06	<.06	4 (MCL)
Boron	40	E6.0	27	87	220	1,400	--
Cadmium	40	E.03	<.04	<.04	<.04	<.40	5 (MCL)
Chromium	40	E.02	.07	<.12	<.12	.45	100 (MCL)
Cobalt	40	E.02	<.04	<.04	<.04	.75	--
Copper	40	E.21	<.40	<.40	<.40	1.6	1,000 (SDWR)
Iron	40	E3.0	13	32	78	3,200	300 (SDWR) 15 (AL)
Lead	40	E.04	.09	<.12	<.12	<1.2	0 (MCLG)
Lithium	40	E.86	16	51	94	240	--
Manganese	40	.31	1.2	1.8	2.7	95	50 (SDWR)
Mercury	40	E.006	<.01	<.01	<.01	.01	2 (MCL)
Molybdenum	40	E.09	.38	.44	1.8	13	--
Nickel	40	E.03	.04	.06	.11	2.4	--
Selenium	40	E.04	<.08	<.08	<.08	.90	50 (MCL)
Silver	39	<.1	<.1	<.1	<.2	<1.0	100 (SDWR)
Strontium	40	47	150	320	950	1,700	--
Thallium	40	E.02	<.04	<.04	<.04	<.40	2 (MCL)
Uranium	40	E.03	.05	.13	.34	4.5	30 (MCL)
Vanadium	40	E.02	<.04	.04	<.10	.23	--
Zinc	40	E.30	.50	.63	1.3	130	5,000 (SDWR)

**Table 11.** Physical property and chemical-constituent determinations that exceed U.S. Environmental Protection Agency (2006) drinking-water standards in ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.

[NTU, nephelometric turbidity units; MCL, Maximum Contaminant Level; mg/L, milligrams per liter; SDWR, Secondary Drinking-Water Regulation; µg/L, micrograms per liter; MCLG, Maximum Contaminant Level Goal]

Property or constituent	Total number of wells that exceed drinking-water standards (map index number, fig. 4)	Drinking-water standard
Physical property		
Turbidity	3 (1, 5, 9)	5.0 NTU (MCL)
Dissolved solids and major ions		
Dissolved solids	11 (1, 2, 3, 5, 9, 12, 20, 31, 33, 36, 40)	500 mg/L (SDWR)
Sulfate	2 (20, 31)	250 mg/L (SDWR)
Chloride	2 (33, 36)	250 mg/L (SDWR)
Fluoride	1 (39)	4 mg/L (MCL)
	3 (33, 35, 40)	2 mg/L (SDWR)
Trace elements		
Iron	4 (5, 20, 21, 31)	300 µg/L (SDWR)
Lead	12 (2, 3, 4, 6, 7, 10, 13, 14, 18, 22, 37, 39)	0 µg/L (MCLG)
Manganese	2 (20, 21)	50 µg/L (SDWR)

Macfarlane and Hathaway (1987) noted larger concentrations of sulfate in water from the Ozark aquifer in the Tri-State mining areas and speculated that the additional sulfate could have come from oxidized sulfides in the overlying Springfield Plateau aquifer. Well numbers 20 and 31 had elevated concentrations of sulfate (table 15).

Galena, Kansas, was the center of lead-and-zinc mining in southeastern Kansas beginning about 1876 and lasting until about 1925 when major production activities shifted to the Baxter Springs (fig. 4) area (Gibson, 1972). Nearly all mining in the Tri-State District used room-and-pillar methods in geologic formations of the Springfield Plateau aquifer, and once the mines were abandoned, these rooms filled with ground water. Previous investigations have determined that mine-associated water had large specific conductance and sulfate concentrations and is contaminated with sulfate and trace elements and such as cadmium, lead, zinc, and others (Haworth and others, 1904; Bailey, 1911; Barks, 1977; Playton and others, 1980; Spruill, 1987; Parkhurst, 1988; and DeHay,

2003). Therefore, the occurrence of these trace elements and sulfate in water from the Ozark aquifer may be an indication of the movement of contaminated water through one or a combination of the previously mentioned flow paths.

Water from well 13 also had large concentrations of copper (0.74 µg/L), lead (0.20 µg/L), and zinc (54 µg/L) relative to water from most of the other sampled Ozark aquifer wells. In fact, the concentrations of lead and zinc in water from well 13 were the second largest concentrations of lead and zinc among the 40 wells sampled (table 17). These results, in conjunction with the mixed-age recharge characteristics for well 13, indicate the possibility that contaminated water in the Springfield Plateau aquifer has migrated downward to the Ozark aquifer and potentially compromised the use of the aquifer for public supply, at least on a local scale in the mined areas. The water chemistry from well 20 (table 15) also may be affected by mining activities as indicated by large calcium and sulfate concentrations.

## Summary of Regulatory Exceedances

The water from wells sampled during this investigation exceeded enforceable MCL standards in only four measurements or determinations (table 11). USEPA set an MCL of 5 NTU (nephelometric turbidity units) for turbidity in drinking water. Water from wells 1, 5, and 9 exceeded this standard with turbidities of 15, 5.8, and 25 NTU, respectively (table 14 in the “Supplemental Information” section at the back of this report). Additionally, water from well 39 exceeded the 4.0-mg/L MCL for fluoride with a concentration of 4.4 mg/L (table 15).

Nonenforceable SDWR and MCLG drinking-water standards were exceeded in water from sampled wells in a total of 36 water-quality constituent determinations (table 11). Concentrations of dissolved solids in water from wells 1, 2, 3, 5, 9, 12, 20, 31, 33, 36, and 40 exceeded the 500-mg/L SDWR with concentrations that ranged from 510 to 1,100 mg/L (table 15). Concentrations of sulfate in water from wells 20 and 31 exceeded the 250-mg/L SDWR with concentrations of 470 and 440 mg/L, respectively, and concentrations of chloride in water from well 33 and 36 exceeded the 250-mg/L SDWR with concentrations of 490 and 350 mg/L, respectively (table 15). An SDWR of 2.0 mg/L for fluoride was exceeded in water from wells 33, 35, and 40 with concentrations of 2.4, 3.9, and 2.4 mg/L, respectively (table 15).

Three trace elements (iron, lead, and manganese) exceeded nonenforceable drinking-water-quality standards in water from some wells (tables 11 and 17). Concentrations of iron were larger than the SDWR of 300 µg/L in wells 5, 20, 21, and 31 with concentrations that ranged from 560 to 3,200 µg/L. Lead usually was not detected in the water from sampled wells but was detected in concentrations that ranged from 0.04 (estimate) to 0.32 µg/L in 12 wells (2, 3, 4, 6, 7, 10, 13, 14, 18, 22, 37, and 39), which exceeded the MCLG of 0 µg/L. Concentrations of manganese exceeded the 50-µg/L SDWR in water from wells 20 and 21 with concentrations of 95 and 68 µg/L, respectively.

## Flow-Path Evolution

The previous discussion of spatial distribution of water-quality characteristics in this report indicates a general evolution in water quality for some major ions in an east-to-west direction across the study area. In an attempt to examine this evolution in more detail, 11 of the 40 selected water-supply wells were evaluated on the basis of their location along two generalized ground-water flow paths. Five wells (26, 25, 23, 13, and 12; fig. 13) were selected to define water-quality evolution along a westerly trending ground-water flow path originating from a potentiometric high in Missouri, and six wells (24, 21, 19, 17, 6, and 2; fig. 13) were selected to represent a northwesterly trending flow path originating from the same general potentiometric high in Missouri as the westerly trending flow path. The westerly trending flow path tracks past the

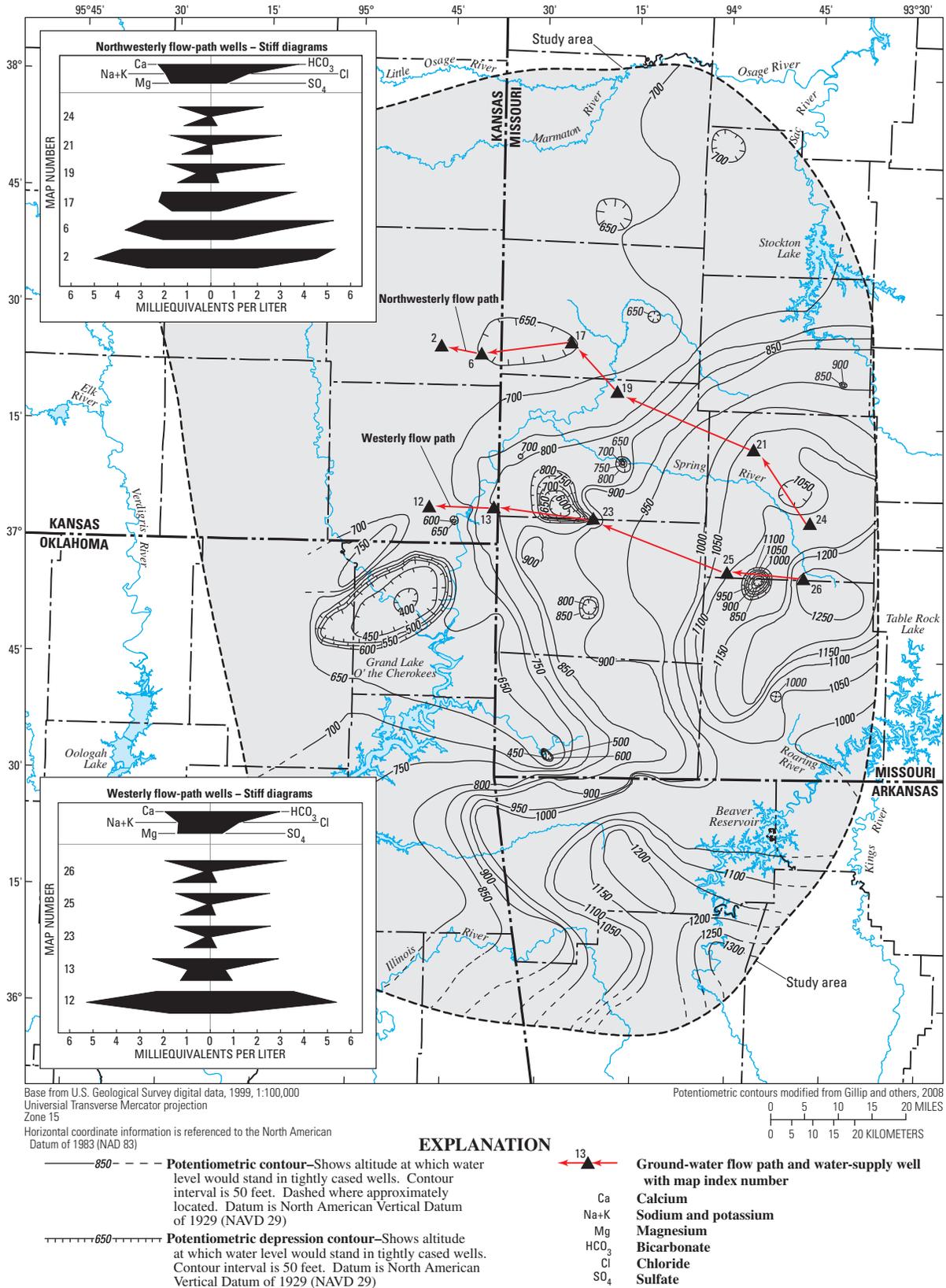
major pumping center at Joplin, Missouri, and subsequently through Galena, Kansas (well 13; fig. 4). The northwesterly flow path tracks through the major pumping center at Pittsburg, Kansas (well 6; fig. 4).

Analyses of stable isotopes in water have been used to identify source, age, and mixing characteristics of ground water (Clark and Fritz, 1997). Stable isotopes are isotopes that do not radioactively decay. In nature, isotopic variations occur because substances (such as water, minerals, and gases) preferentially concentrate one isotope over another or because organisms can metabolize one isotope more efficiently than another. Natural isotope variations, therefore, can arise from numerous common chemical and physical processes, such as cooling of hydrothermal fluids during mineral deposition, the evaporation or condensation of water, mixing of two or more sources of water, or the metabolic activity of organisms (Seal, 2008).

The stable isotopes with relatively low atomic mass, such as carbon, hydrogen, oxygen, and sulfur, are the most biogeochemically active elements and display wide ranges in isotopic abundance. However, other elements with relatively large atomic masses, such as strontium, also have isotopic ratios that may be useful indicators of water-rock interactions and as tracers for ground-water movement (Clark and Fritz, 1997).

Water from all 11 flow-path wells was collected and analyzed for selected stable isotopes (table 13 in the “Supplemental Information” section at the back of this report). Results of analyses of stable isotopes are presented in table 17 at the back of this report. Analytical results are presented as a ratio of the two most abundant isotopes of individual elements relative to the isotopic ratio of a known standard and expressed in delta ( $\delta$ ) notation in per thousand parts or permil (‰) of the heavier isotope (for example,  $\delta^{18}\text{O}$ ). Isotope reference standards are the Vienna Standard Mean Ocean Water (VSMOW) for hydrogen ( $^2\text{H}/^1\text{H}$ ) and oxygen ( $^{18}\text{O}/^{16}\text{O}$ ) isotope ratios, the Vienna Pee Dee Belemnite (VPDB) for carbon ( $^{13}\text{C}/^{12}\text{C}$ ), and the Cañon Diablo Troilite (CDT) for sulfur isotopes ( $^{34}\text{S}/^{32}\text{S}$ ). The isotopic ratio of strontium-87 ( $^{87}\text{Sr}$ ) to strontium-86 ( $^{86}\text{Sr}$ ) is an absolute ratio in sampled water. A positive  $\delta$  value means that the sample contains more of the heavy isotope than the standard; a negative  $\delta$  value means that the sample contains less of the heavy isotope than the standard. For example, a  $\delta^{18}\text{O}$  value of -7.0 permil means that there are 7 parts per thousand or 0.7 percent less  $^{18}\text{O}$  in the sample relative to the standard (Kendall and Caldwell, 1998).

The origin of most fresh ground water is atmospheric precipitation that infiltrated where it fell or accumulated in streams and lakes and then seeped into the ground (Bouwer, 1978). It has been estimated that for the contiguous United States about 25 percent of the precipitation that falls becomes ground water (Nace, 1960). Ground water that was recently of atmospheric origin is referred to as meteoric water, whereas water that has been in the subsurface since sediment deposition is called connate water (Bouwer, 1978). Meteoric and connate water may have substantially different isotopic sig-



**Figure 13.** Potentiometric surface of Ozark aquifer, spring 2006, and water-supply wells completed in Ozark aquifer delineating two ground-water flow paths, and stiff diagrams showing results of water-quality analyses, fall 2006, and identification of water types.

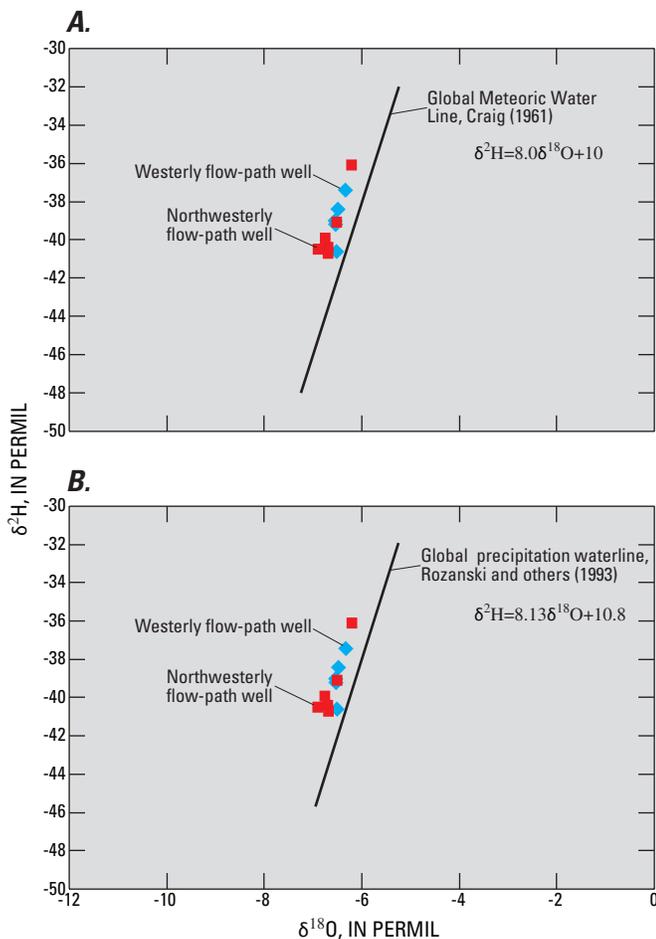
natures owing to the climate, temperature, and geography in which the water was precipitated (Kendall and Coplen, 2001).

Results of stable isotope analyses of ground water from 11 flow-path wells seem to indicate that water in the Ozark aquifer is of post-Pleistocene meteoric origin. The relation between  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  isotopes in water from the flow-path wells is similar to the Global Meteoric Water Line (GMWL) developed by Craig (1961) from worldwide fresh surface water (fig. 14A). A waterline is an equation for a relation between hydrogen and oxygen isotope ratios in natural terrestrial water that is expressed as a worldwide average. Craig's line, in reality, is an average of many local and regional meteoric waterlines, which differ from the global line due to varying climatic and geographic characteristics (Clark and Fritz, 1997). The relation between  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  among the flow-path wells also is similar to the global precipitation relation developed by Rozanski and others (1993) using weighted mean annual precipitation values from monitoring stations in the International Atomic Energy Agency's global network for isotopes in precipitation (fig. 14B). The global precipitation

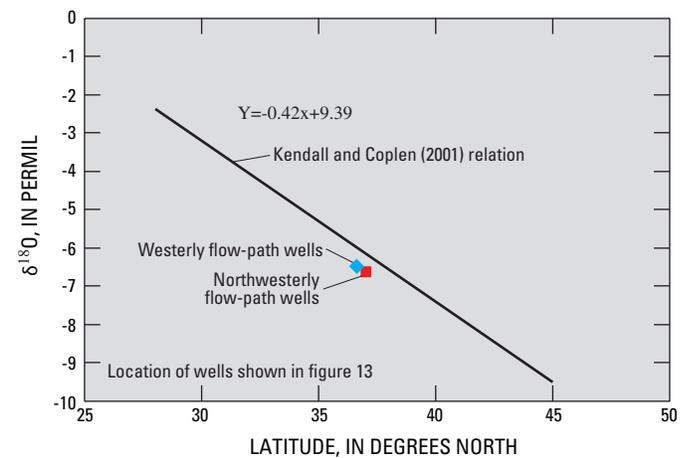
waterline of Rozanski and others (1993) consisted of a later refinement of the GMWL originally presented by Craig (1961). If ground-water  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values plot near the global precipitation waterline, the water is likely of meteoric origin (that is, derived from precipitation without subsequent modification). If the values do not plot along a waterline, the water has been affected by some physical or chemical process prior to recharge or during the movement of the ground water through the aquifer (Harvey, 2001).

Further evidence of a meteoric source for water in the Ozark aquifer comes from a comparison of  $\delta^{18}\text{O}$  results from the 11 flow-path wells to a relation presented by Kendall and Coplen (2001). Kendall and Coplen (2001) developed a relation between the latitude (in degrees North) of 391 sampling sites and  $\delta^{18}\text{O}$ -isotope values in river water of the United States. Kendall and Coplen (2001) used river water as a surrogate for isotopic characteristics of local and regional precipitation. They further segregated the sampling sites into eastern and western sites with the 97th meridian as the dividing line and developed separate latitude/  $\delta^{18}\text{O}$  relations for each half of the United States. All Ozark aquifer flow-path wells are located east of the 97th meridian. Average latitudes were calculated for wells located along both the westerly and northwesterly flow paths, plotted in relation to the average  $\delta^{18}\text{O}$  values for each flow path, and displayed on a graph of the Kendall and Coplen (2001) relation (fig. 15). Ozark aquifer results are similar to Kendall and Coplen (2001) results, which indicate that water from the flow-path wells is of meteoric origin.

The chemistry and isotopes of carbon in ground water provide insight in understanding ground-water quality, fate of contaminants, and interpretation of ground-water age (Clark



**Figure 14.** Relation between  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  stable isotopes in ground water from 11 flow-path wells completed in Ozark aquifer of southeastern Kansas and southwestern Missouri, 2006.



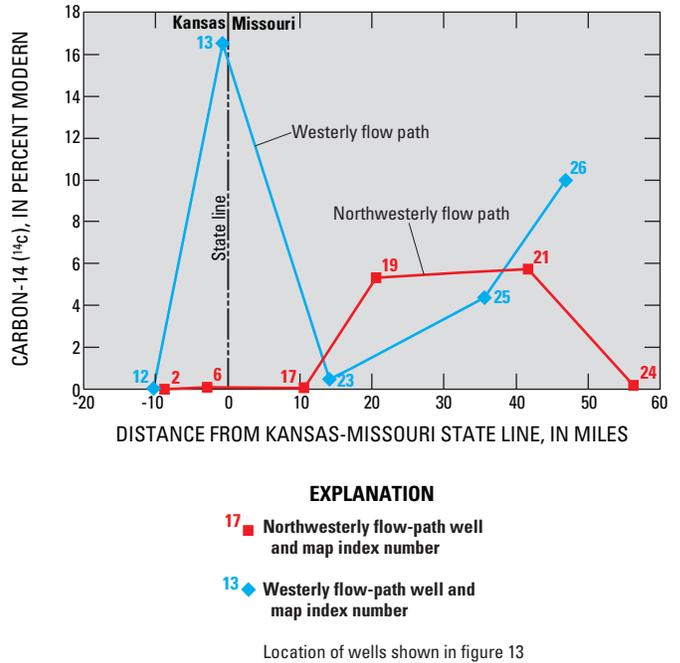
**Figure 15.** Relation of sampling-site latitudes and  $\delta^{18}\text{O}$  isotope values from 391 river-water sampling sites in eastern United States (Kendall and Coplen, 2001) to average latitudes and  $\delta^{18}\text{O}$  isotope values in ground water from 11 flow-path wells completed in Ozark aquifer of southeastern Kansas and southwestern Missouri, 2006.

and Fritz, 1997). Carbon may enter the ground-water system as carbon dioxide (CO<sub>2</sub>) dissolved in precipitation or picked up in the soil profile as dissolved inorganic carbon (DIC) through infiltration. CO<sub>2</sub> can be converted to organic carbon through the process of plant photosynthesis and subsequently transported from the unsaturated zone in recharge areas to the water table and confined aquifer systems in the form of dissolved organic carbon (DOC). The stable carbon-isotope ratio <sup>13</sup>C/<sup>12</sup>C (δ<sup>13</sup>C) and the radionuclide <sup>14</sup>C were determined on the DIC component of ground water collected from the 11 flow-path wells sampled during the investigation described in this report.

The δ<sup>13</sup>C values for the westerly flow-path wells ranged from -6.95 (well 23) to -8.85 permil (well 26) and from -7.14 (well 19) to -9.71 permil (well 21) for the northwesterly flow-path wells (fig. 13, table 17). All of these values are within the expected range for ground-water DIC (Clark and Fritz, 1997). These values probably are affected by the dolomite (calcium magnesium carbonate) makeup of the Ozark aquifer system. Soil CO<sub>2</sub> for the ecosystem overlying the Ozark aquifer generally would have δ<sup>13</sup>C values of about -23 permil (Clark and Fritz, 1997), but as infiltrating water dissolves CO<sub>2</sub> and some of it hydrates and dissociates into bicarbonate (HCO<sub>3</sub><sup>-</sup>) and carbonate (CO<sub>3</sub><sup>2-</sup>), different isotope-fractionation factors develop. As recharge water moves through the soil profile and into the aquifer system, it encounters carbonate minerals (calcite and dolomite) enriched with <sup>13</sup>C (larger, less negative δ<sup>13</sup>C values) close to the reference VPDB value of about 0 permil. Recharge water subsequently dissolves carbonate minerals, which provides a diluting (enriching) effect on δ<sup>13</sup>C values. The generally -7 to -9 permil δ<sup>13</sup>C values determined in water DIC from the flow-path wells indicate that the Ozark aquifer is reacting as a “closed” system. Within this system, δ<sup>13</sup>C evolution is the result of dilution from the more <sup>13</sup>C-enriched carbonate minerals common in the aquifer formations (table 1) and not as an “open” system receiving continual inputs, relative to the flow path, from the large reservoir of DIC in the unsaturated zone with reduced <sup>13</sup>C composition.

Analytical results of DIC <sup>14</sup>C in water from the 11 flow-path wells generally showed an east-to-west downward trend in <sup>14</sup>C activity (fig. 16) along the two flow paths. Along the westerly flow path, the downward trend was interrupted by a spike in <sup>14</sup>C in water from well 13. This particular activity value was discussed previously in the “Spatial Distribution” section of this report and probably is the result of downward leakage of newer water through the confining unit in the mined areas in and around Galena, Kansas. With the exception of the small <sup>14</sup>C activity at well 24 (the first well in the northwesterly flow path sequence), a downward trend is evident in water from wells along the northwesterly flow path. The reason for the small <sup>14</sup>C activity in water from well 24 is not known.

Downward trends in <sup>14</sup>C activity and, therefore, increasing age in ground water along the two flow paths would indicate the occurrence of one or more of three processes: (1) ground water is aging as a result of residence time along the flow path, (2) <sup>14</sup>C is being lost through exchange with the



**Figure 16.** Carbon-14 (<sup>14</sup>C) activity in ground water from 11 flow-path wells completed in Ozark aquifer of southeastern Kansas and southwestern Missouri, 2006.

mineral matrix of the aquifer formations, or (3) <sup>14</sup>C activity is being diluted by dissolution of DIC “dead” carbon (carbon so old that it has lost all <sup>14</sup>C activity) from the carbonate formations through which it flows. The possibility that <sup>14</sup>C results determined during this investigation provide reliable age estimates for recharged water probably is not a viable conclusion. The <sup>14</sup>C pmC values determined from the sampled wells indicate age estimates of at least 25,000 years BP (before present) (Stuiver and Polach, 1977). These estimates probably are erroneously old on the basis of previously presented information. The δ<sup>2</sup>H/ δ<sup>18</sup>O relation developed for the flow-path wells indicated an isotopic signature similar to the modern GMWL (Craig, 1961) and the global precipitation relation developed by Rozanski and others (1993) (fig. 14). Water with an age in excess of 25,000 years BP would place it at the maximum of the last major glacial period in North America (the Wisconsin), and the δ<sup>2</sup>H/ δ<sup>18</sup>O-relational signature of precipitation (and ultimately recharge water) during this much colder climate would be substantially different from the current GMWL because isotopic fractionation is, in part, thermally driven. Additionally, δ<sup>13</sup>C values for DIC in water from the flow-path wells indicated a mixture of DIC from recharge water and DIC containing “dead” carbon from carbonate minerals. The downward trend in <sup>14</sup>C activity indicated in figure 16 probably is the result of a loss of <sup>14</sup>C through a matrix exchange between the DIC in recharged water and the carbonate minerals in the aquifer matrix and matrix diffusion of <sup>14</sup>C into dead-end pores of the aquifer material (Maloszewski and Zuber, 1991), and a simple dilution by non-<sup>14</sup>C-containing DIC from dissolution

of the carbonate minerals deposited hundreds of millions of years ago.

The result of  $^{14}\text{C}$  data is ambiguous at best, at least within the scope of the reconnaissance investigation described in this report. The small detections of tritium in water from the flow-path wells (table 17) coupled with other stable-isotope data indicate that ground water along the two selected flow paths is more than about 60 years old but substantially less than the 25,000 years BP as indicated by the  $^{14}\text{C}$  data. The spikes in  $^{14}\text{C}$  and  $^3\text{H}$  in well 13 indicated that there was possible leakage of younger ground water into the lower Ozark aquifer. This may be caused by cracks and fissures in the confining unit that separates the upper and lower parts of the aquifer.

Strontium (Sr) is a fairly common element in natural water as a divalent cation with reaction chemistry similar to that of calcium and can replace calcium or potassium in some minerals. The minerals strontianite (strontium carbonate) and celestite (strontium sulfate) are common in sediment. The strontium-to-calcium ratio in most limestone is less than 1:1,000, although fossils in the limestone tend to be enriched in strontium. The strontium concentration in most natural water does not approach the solubility limit of either strontianite or celestite (Hem, 1992). In ground-water systems, the concentration of strontium is dependent upon the initial concentration in recharge water but, more importantly, the contact time (flow-path residence time) with the mineral matrix and composition of the formations through which the water flows. Therefore, along a ground-water flow path in a carbonate-dominated system, increasing concentrations of strontium would be expected as  $\text{Sr}^{+2}$  trends toward geochemical equilibrium with strontium minerals. Strontium concentrations in

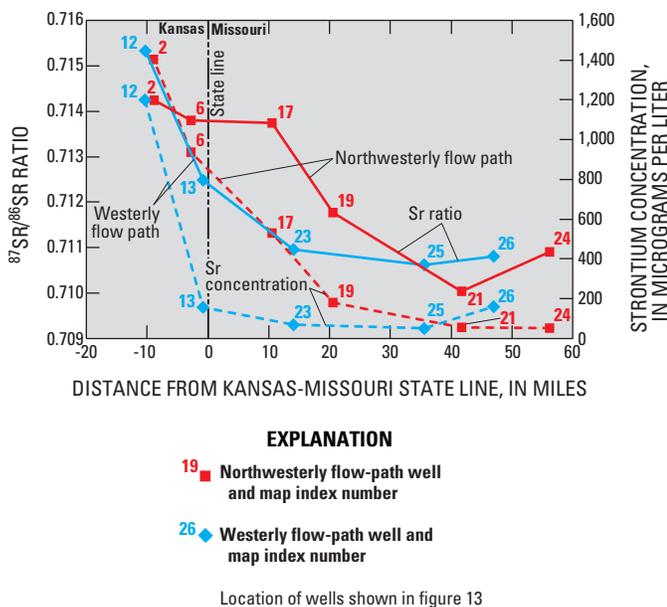
water from wells along the westerly and northwesterly flow paths in the Ozark aquifer generally increase with distance from recharge areas in the east (fig. 17).

Strontium has four stable, naturally occurring isotopes— $^{84}\text{Sr}$  (0.56 percent),  $^{86}\text{Sr}$  (9.86 percent),  $^{87}\text{Sr}$  (7.00 percent), and  $^{88}\text{Sr}$  (82.58 percent) (Kendall and others, 1995). The isotope ratio  $^{87}\text{Sr}/^{86}\text{Sr}$  can be a useful indicator of water-rock interaction, as a tracer for ground-water movement, and in determining the origin of salinity (Clark and Fritz, 1997). The isotopic composition of strontium in ground water depends on the chemistry of recharge, host rock geochemistry and water-rock interactions in ground-water systems, the residence time of ground water in the aquifer, and the mixing of different ground water (Ma and Liu, 1999). The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio in minerals and rock ranges from about 0.7 to greater than 4.0 (Faure and Powell, 1972). In water from wells of the two selected flow paths in the Ozark aquifer,  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios ranged from 0.71061 (well 25) to 0.71532 (well 12) for the westerly flow path and 0.71002 (well 21) to 0.71424 (well 2) for the northwesterly flow path (table 17). Generally, however, strontium-isotopic ratios increased in a downgradient (increasing ground-water age) direction along both flow paths (fig. 17).

The generally upward trend in  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios along ground-water flow paths is the result of subtle mineralogical controls such as the integration of more  $^{87}\text{Sr}$  from the dissolution of strontium-bearing minerals such as K-feldspar, biotite, and muscovite. Also, the longer ground water is in contact with the mineral matrix of the aquifer, the larger the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio as the water approaches equilibrium with the isotope ratio of the aquifer mineral matrix.

Although an east-to-west upward trend in  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios along Ozark aquifer flow paths might be expected, a sudden or abrupt change in the trend might be an indication of ground water with different geochemical characteristics mixing with flow-path water. Such an abrupt change in  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio between two successive wells is evident in ratios from the westerly flow path between wells 13 and 12 (fig. 17). The increase in  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios between wells 13 and 12 represents 60 percent of the increase for the entire flow path from well 25 (the flow-path point where increase starts) to well 12. The increase in  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios between wells 13 and 12 is supported by a 650-percent increase in  $\text{Sr}^{+2}$  concentration from well 13 to well 12, far greater than any other segment along either flow path. It is believed that the abrupt change in  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios and increase in  $\text{Sr}^{+2}$  concentrations is the result of the proximity of the formation water being pushed from the system by westerly flowing freshwater. Well 12 is located within the transition zone between fresh and saline water identified by Macfarlane and others (1981) and Macfarlane and Hathaway (1987). Although water from wells along the northwesterly flow path do not display similar abrupt changes in  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios and Sr concentrations, end-member values are similar for both flow paths, which probably indicates a transitional shift toward salinity along both flow paths.

The east-to-west transition from fresh-to-saline water along both flow paths also is evident in a shift in water type



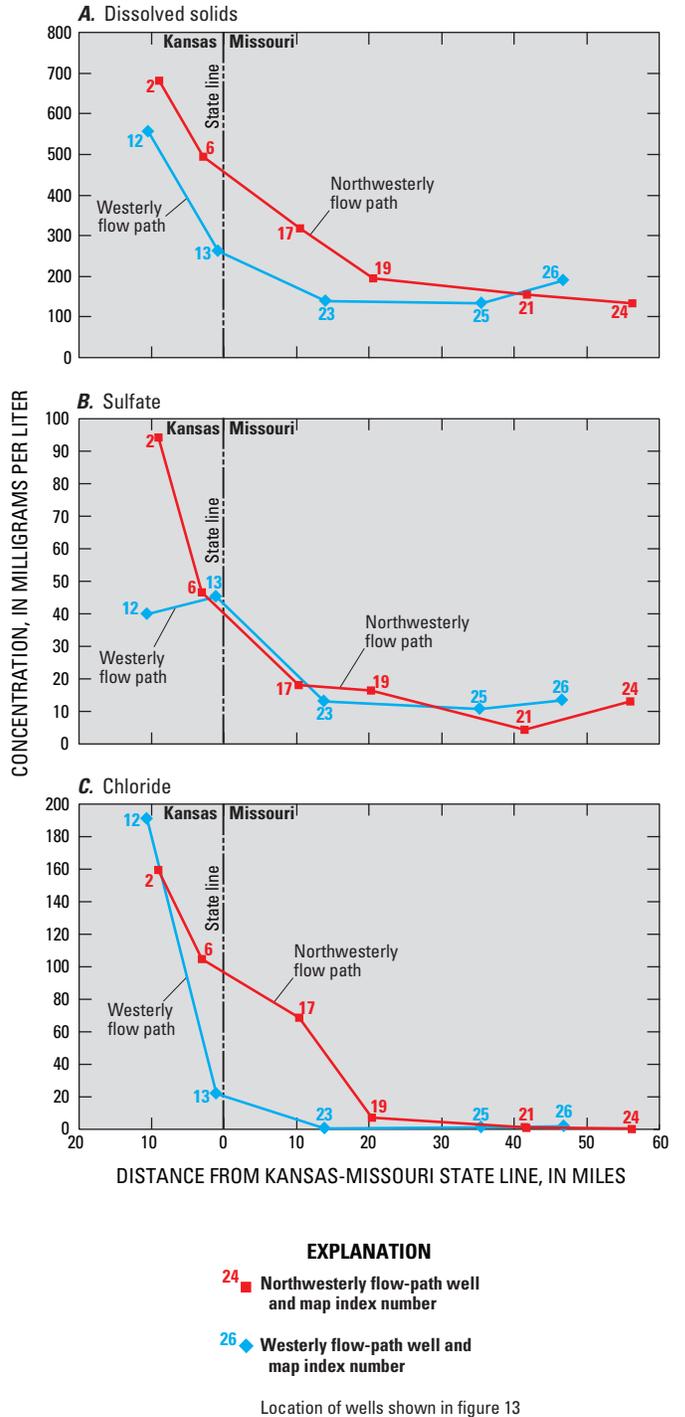
**Figure 17.** Strontium (Sr) concentrations and  $^{87}\text{Sr}/^{86}\text{Sr}$  isotope ratios in ground water from 11 flow-path wells completed in Ozark aquifer of southeastern Kansas and southwestern Missouri, 2006.

and composition along the flow paths. Ground water at the start of both flow paths is a calcium magnesium bicarbonate type and transitions to a sodium calcium bicarbonate type along the northwesterly flow path and to a sodium calcium chloride bicarbonate type along the westerly flow path (fig. 13) although the transition is much more abrupt (between wells 13 and 12) for the westerly flow path than for the more gradually evolving northwesterly flow path. These results mirror the Sr concentrations and <sup>87</sup>Sr/<sup>86</sup>Sr ratios previously presented as demonstrated by flow-path evolution in concentrations of dissolved solids, sulfate, and chloride along the two flow paths (fig. 18).

A summary of selected major ions indicates substantial evolution in ion concentrations over the entire flow-path lengths, first well to last well (table 12). Increases in ionic concentrations ranged from 10 percent for bicarbonate along the westerly flow path to approximately 20,000 percent for chloride along the northwesterly flow path. Although substantial increases in major-ion concentrations occurred over the approximately 60-mi lengths of both flow paths, the largest part of the increase occurred within about the last 20 to 25 mi (from about 10 to 15 mi east of the Kansas-Missouri State line). For example, all of the effective increase in concentrations for dissolved solids, sulfate, and chloride, along the westerly flow path (shown in figure 18) occurred starting at about 13 mi east of the State line (well 23). Similarly, the increase in concentrations for dissolved solids, sulfate, and chloride, from well 17 (about 10 mi east of the State line) to well 2 along the northwesterly flow path represent 65, 94, and 57 percent, respectively, of the total increase for the entire length of the flow path. The general water-quality analysis is that the water quality in the Kansas part of the Ozark aquifer is degraded compared to the Missouri part.

**Vertical Variability**

Geophysical and well-bore flow information and depth-dependent water samples were collected at Pittsburg, Kansas, city well 10 (PCW-10) during June through August 2007 using methods and procedures previously described in the “Methods of Investigations” section of this report. Total depth of this Ozark aquifer well was 1,050 ft bls with the pump at 350 ft bls and casing to 550 ft bls. This information is used to evaluate vertical ground-water flow accretion and variability in water-quality characteristics. Flow accretion and water-quality sampling were conducted under pumping conditions of 1,900 to 2,300 gal/min. Prior to the collection of water-quality samples, this well had been pumped continuously for about 7 days at



**Figure 18.** Dissolved-solids, sulfate, and chloride concentrations in ground water from 11 flow-path wells completed in Ozark aquifer of southeastern Kansas and southwestern Missouri, 2006.

**Table 12.** Concentrations of dissolved solids and selected major ions and overall percentage change along westerly and northwesterly ground-water flow paths in Ozark aquifer of southeastern Kansas and southwestern Missouri, 2006.

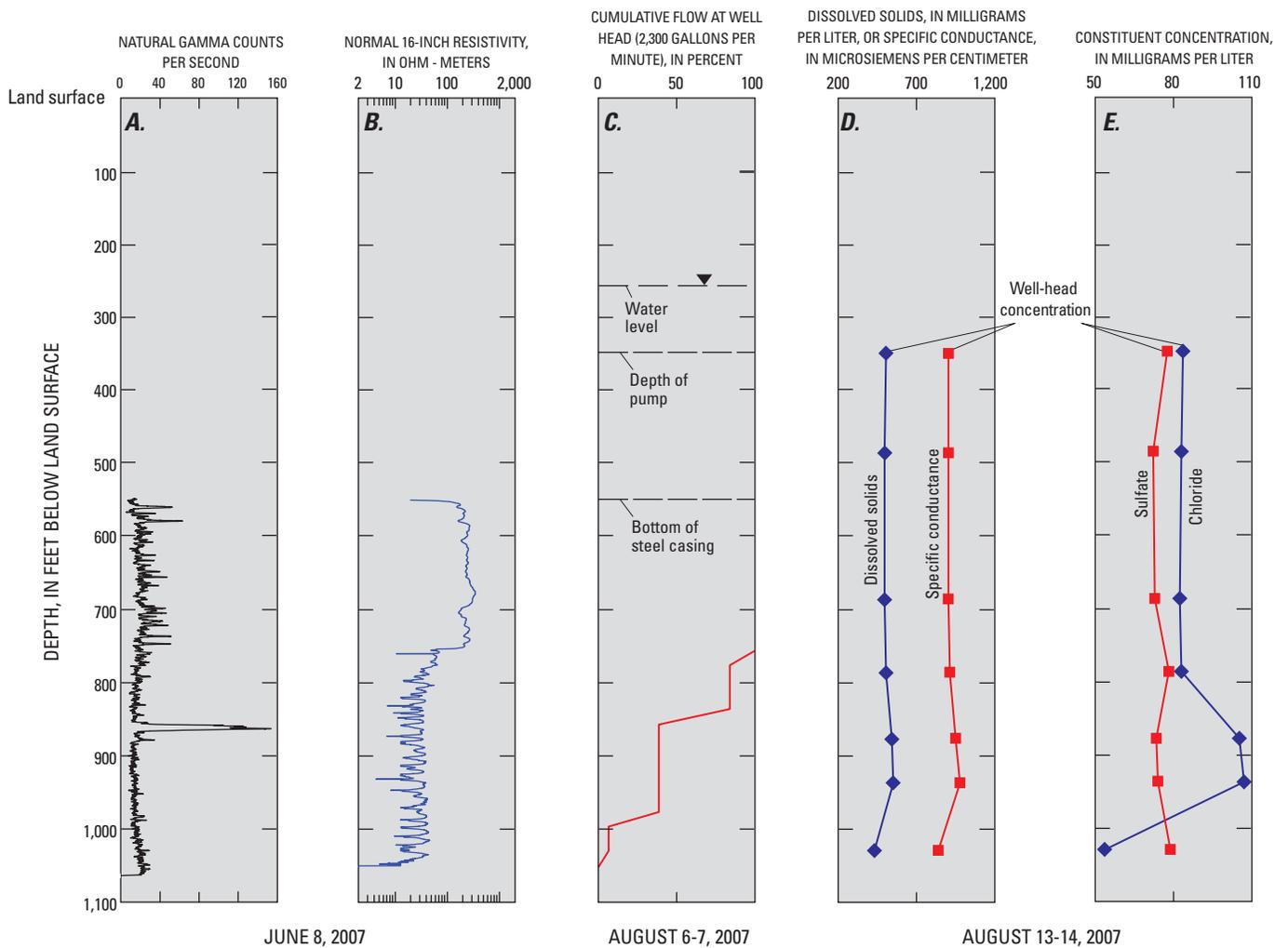
[mg/L, milligrams per liter]

Constituent	Starting concentration, first well (mg/L)	Ending concentration, last well (mg/L)	Overall change (percent)
Westerly flow path			
Dissolved solids	190	560	190
Calcium	39	46	18
Magnesium	19	21	11
Sodium	4.1	120	2,800
Bicarbonate	200	220	10
Sulfate	13	40	210
Chloride	1.8	190	10,000
Northwesterly flow path			
Dissolved solids	130	680	420
Calcium	27	76	180
Magnesium	14	33	140
Sodium	1.4	110	7,800
Bicarbonate	140	320	130
Sulfate	13	94	620
Chloride	.8	160	20,000

the lesser flow rate. Analytical results of water-quality samples are presented in table 18 in the “Supplemental Information” section at the back of this report.

Nearly all ground-water flow into the borehole of city well PCW-10 occurred below the 750-ft bls level in the well with the majority of flow (77 percent) entering from two relatively thin layers (837–857 and 977–997 ft bls; fig. 19C). These water-contributing zones generally corresponded to smaller but undulating resistivity (relative to upper formations, fig. 19B) and fairly consistent natural gamma counts (fig. 19A), which generally indicate undifferentiated formations. The exception to the gamma data was a thin layer around 860 ft bls that may represent a shale formation (fig. 19A).

Water quality in city well PCW-10 was determined within the flow-accretion zone previously discussed (fig. 19C). For the most part, water quality changed only minimally from the deepest sample to the well-head sample with the exception of chloride that doubled in concentration from about 50 to 100 mg/L between 1,050 bls and second and third samples (just below and just above 900 ft bls) (fig. 19E). Subsequent inflow to the well above 800 ft bls reduced chloride concentration to about 80 mg/L and, thereafter, remained fairly consistent up to and including the 350 ft bls well-head sample. There does not seem to be much evidence of substantially quality-degraded water upwelling from geologic formations below the well. The chloride concentrations in the two relatively thin



**Figure 19.** Selected results of geophysical logging, well-bore flow accretion, and depth-dependent water-quality sampling at Pittsburg, Kansas, city well 10, June–August 2007, showing vertical variability in ground-water flow and water quality.

layers near 900 ft bls were higher compared to the shallower samples above 800 ft bls, which may indicate that water below 800 ft bls is more saline.

## Summary

The Ozark aquifer is part of the regionally important Ozark Plateaus aquifer system that occurs in parts of Arkansas, Kansas, Missouri, and Oklahoma. The Ozark aquifer is a source of freshwater for municipal, domestic, industrial, and irrigation uses, and as such, an interstate concern exists for the long-term sustainability of the resource and protection of the aquifer from water-quality degradation. Water quality in supply wells completed in the Ozark aquifer potentially could be degraded with increased water demand from a growing population. Increases in pumping capacity at major population centers along the Kansas-Missouri State line or in northeastern Oklahoma may lower water levels in the Ozark aquifer such that, locally, the natural east-to-west flow gradient reverses and saline water from the western part of the aquifer migrates toward the pumping centers. Additionally, upwelling of saline water from lower geologic strata may be possible at the pumping centers. Lower water levels in the Ozark aquifer will increase the hydraulic gradient between an overlying aquifer system (Springfield Plateau aquifer) and the Ozark aquifer. This increased gradient may draw highly mineralized or contaminated water in the Springfield Plateau aquifer through areas where the intervening confining unit is thinner or more permeable or through older or abandoned wells or mining-related exploratory drill holes that are open to both the Springfield Plateau and Ozark aquifers.

Because of quantity and quality concerns with the Ozark aquifer, the State of Kansas in 2004 issued a moratorium on new appropriations from the Ozark aquifer in Kansas with the exclusion of domestic supplies, requests for less than 5 acre-ft of water per year, or temporary and term permits. In 2005, the U.S. Geological Survey entered into a cooperative agreement with the Kansas Water Office to develop a regional ground-water flow model of the Ozark and Springfield Plateau aquifers in northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma (the study area) and to conduct an assessment of current water-quality conditions within the Ozark aquifer. In 2006 and 2007, water-quality samples were collected from 40 water-supply wells completed in the Ozark aquifer and spatially distributed throughout the study area. The purpose of this report is to present the results of the water-quality assessment as part of this combined effort.

Water samples from the 40 water-supply wells were analyzed for physical properties, dissolved solids and major ions, nutrients, trace elements, and selected isotopes of selected elements. Many of the constituents in these water-quality samples are regulated in drinking-water supplies by the U.S.

Environmental Protection Agency (USEPA) and, as such, were evaluated on the basis of these regulatory criteria.

Physical properties measured at the time of sample collection included specific conductance, pH, water temperature, turbidity, dissolved oxygen, and reduction-oxidation (redox) potential. Specific conductance of water from the sampled wells was less than 500  $\mu\text{S}/\text{cm}$  (microsiemens per centimeter at 25°C) for about one-half (21 of 40) of the wells, as indicated by the median value of 470  $\mu\text{S}/\text{cm}$ . The other 19 wells had specific conductance values in the range of about 500 to 1,890  $\mu\text{S}/\text{cm}$ . Generally, water from wells located in Missouri had the smallest specific conductance values, and overall, Kansas had the largest. The pH of water from sampled wells in the study area had a median value of 7.56 standard units. USEPA has established a Secondary Drinking-Water Standard (SDWR) range of 6.5 to 8.5 standard units, and water from all sampled wells was within this guideline. Dissolved-oxygen concentrations in water from most wells were small as indicated by a median dissolved-oxygen concentration of 0.16 mg/L (milligrams per liter). Six wells had no measurable dissolved oxygen (less than 0.01 mg/L), 24 wells had dissolved-oxygen concentrations between 0.01 and 0.28 mg/L, and the remaining seven wells had dissolved-oxygen concentrations between 1.4 and 2.0 mg/L. The turbidity of water from the wells generally was small as indicated by a median value of 0.20 NTU (nephelometric turbidity units). However, water from three wells exceeded the USEPA Maximum Contaminant Level (MCL) of 5 NTU with turbidity values of 5.8 to 25 NTU. Redox (oxidation-reduction) potential was measured for water from 32 of the 40 wells sampled for this study. Redox potential relative to a standard hydrogen electrode ranged from -110 to 380 mV (millivolts), with a median value of 40 mV.

Concentrations of dissolved solids from the 40 sampled water-supply wells ranged from 130 to 1,100 mg/L, with a median value of 270 mg/L. Water from about one-fourth of the wells exceeded the USEPA 500-mg/L SDWR for dissolved solids. The majority of these wells were located in Kansas. The largest dissolved-solids concentrations determined during this investigation probably are related to a general transition from freshwater to saline water in the Ozark aquifer in an east-to-west trend across the study area. Water from most sampled wells in Missouri is a calcium bicarbonate or calcium magnesium bicarbonate type, whereas water from wells in Kansas transitions to a sodium bicarbonate, sodium bicarbonate chloride, or sodium chloride type.

Chloride concentrations ranged among the sampled wells from 0.8 to 490 mg/L, with a median concentration of 38 mg/L. Water from two wells exceeded the 250-mg/L SDWR for chloride. The smallest chloride concentrations were found in water from wells in the eastern part of the study area, and concentrations progressively increased in a westerly direction.

Sodium concentrations ranged from 1.4 to 403 mg/L, with a median concentration of 38 mg/L. USEPA has not established an SDWR or MCL for sodium in drinking water

but has listed a health-based advisory level (HAL) of 20 mg/L for individuals on a 500 mg/d restricted sodium diet. Water samples from 23 wells had concentrations that exceeded this advisory level. All but 2 of the 15 wells sampled in Kansas yielded samples with sodium concentrations greater than 20 mg/L, whereas only three wells located in the upgradient part of the study area (Missouri) had sodium concentrations greater than 20 mg/L.

Sulfate concentrations ranged from 0.4 to 470 mg/L, with a median concentration of 16 mg/L. Water from two wells had sulfate concentrations larger than the 250-mg/L USEPA SDWR. Sulfate concentrations generally were largest in samples from wells located in the western part of the study area.

Fluoride concentrations in ground-water samples collected during this investigation generally were less than 1.0 mg/L, with a median concentration of 0.48 mg/L. However, samples from seven wells had fluoride concentrations of 1.0 mg/L or larger, and concentrations ranged from 1.0 to 4.4 mg/L. Fluoride concentrations in samples from four wells exceeded the 2.0-mg/L USEPA SDWR, whereas the concentration in water from one well exceeded the 4.0-mg/L MCL.

Concentrations of magnesium, potassium, bromide, and silica generally were small in water from sampled wells relative to other major ions. The USEPA has not established drinking-water standards for these four ions.

Generally, nutrient concentrations in water from the 40 wells were small. Nitrite and nitrite plus nitrate concentrations generally were less than method reporting limits but were detected in water from nine wells. Nitrite plus nitrate concentrations in water from the 40 sampled wells ranged from an estimated 0.03 to 2.0 mg/L, with a median concentration of less than 0.06 mg/L. Additionally, all determined nitrate concentrations were equal to or substantially less than the 2.0-mg/L national average background concentration for ground water.

Total phosphorus and orthophosphate as phosphorus typically were present only in small concentrations in water from the 40 sampled wells. Total phosphorus was detected only in water from eight wells. Total phosphorus concentrations in water from the 40 wells ranged from an estimated 0.002 to 0.033 mg/L, with a median concentration of less than 0.006 mg/L. Concentrations of orthophosphate as phosphorus ranged from an estimated 0.003 to 0.015 mg/L, with a median concentration of an estimated 0.004 mg/L. Most of the phosphorus in water from the 40 sampled wells was in the form of orthophosphate as phosphorus. Water from 90 percent of sampled wells had small reportable concentrations of ammonia with a range from an estimated 0.01 to 0.43 mg/L and a median concentration of 0.07 mg/L. Ammonia is the dominant nitrogen-containing nutrient in sampled wells in the Ozark aquifer and represents most of the total nitrogen.

Most trace elements in ground water analyzed during this investigation were present in concentrations less than water-quality standards. In fact, many trace constituents frequently were not detected or detected in small concentrations. Seventeen elements (antimony, arsenic, beryllium, cadmium,

chromium, cobalt, copper, lead, mercury, molybdenum, nickel, selenium, silver, thallium, uranium, vanadium, and zinc) had median concentrations less than 1.0 µg/L (micrograms per liter) and were not detected in about 70 percent of the samples. Silver was not detected in any of the wells. Seven constituents had median concentrations greater than 1.0 µg/L—aluminum, barium, boron, iron, lithium, manganese, and strontium. Additionally, nine trace elements had a maximum concentration greater than 5.0 µg/L—aluminum, barium, boron, iron, lithium, manganese, molybdenum, strontium, and zinc. Iron, lead, and manganese were the only trace elements found in concentrations that exceeded USEPA drinking-water criteria. Iron concentrations ranged from an estimated 3.0 to 3,200 µg/L, with a median value of 32 µg/L. Water from four wells exceeded the 300-µg/L USEPA SDWR for iron. Lead was not detected in water from most wells. Where it was detected, lead was present at concentrations less than 1.0 µg/L, substantially less than the USEPA Action Level of 15 µg/L; however, 12 wells had measurable lead concentrations that exceeded the USEPA MCLG of 0 µg/L. Manganese concentrations ranged from 0.32 to 95 µg/L, with a median value of 1.8 µg/L, and water from two wells exceeded the USEPA SDWR of 50 µg/L.

Analyses of relations between the stable-isotopes  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  in water from 11 wells along two selected ground-water flow paths indicate that Ozark aquifer water is of a “recent” meteoric source because of similarity to the established Global Meteoric Water Line and a global precipitation relation. Results of tritium analyses indicate that ground water probably was recharged more than 60 years ago; however,  $^{14}\text{C}$  results are ambiguous at best and an upper age limit could not be determined. Results of  $^{87}\text{Sr}/^{86}\text{Sr}$ -isotope ratios indicate that, along at least one of the flow paths, mixing of saline water from the western part of the study area may be occurring in a transitional area near the Kansas-Missouri State line. Analyses of major-ion results also indicate a transition from freshwater to saline water along both flow paths. Generally, ground water along flow paths evolves from a calcium magnesium bicarbonate type to a sodium calcium bicarbonate or a sodium calcium chloride bicarbonate type. However, much of this evolution occurs within the last 20 to 25 mi of the 60-mi flow paths as it approaches the transition zone near the Kansas-Missouri State line. The general water-quality analysis is that the water in the Kansas part of the Ozark aquifer is degraded compared to the Missouri part.

Additionally, analysis of  $^3\text{H}$  and  $^{14}\text{C}$  indicated that there was possible leakage of younger ground water into the lower Ozark aquifer. This may be caused by cracks or fissures in the intervening confining unity, poorly constructed or abandoned wells, or a result of historic mining activities.

Geophysical and well-bore flow information and depth-dependent water samples were collected at Pittsburg, Kansas, city well 10 (PCW-10) during June through August 2007 to evaluate vertical ground-water flow accretion and variability in water-quality characteristics. Flow accretion and water-quality sampling were conducted under pumping conditions

of 1,900 to 2,300 gal/min. Nearly all ground-water flow into the borehole of city well PCW-10 occurred below the 750-ft depth with the majority of flow (77 percent) entering from two relatively thin layers (837–857 and 977–997 ft bls). For the most part, water quality changed little from the deepest sample to the well-head sample. There is not much evidence of substantially quality-degraded water upwelling from geologic formations below the well. However, more saline water may exist below the bottom of the well.

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## Supplemental Information

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**Table 13.** Water-quality properties or constituents analyzed in ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.

[ $\mu\text{S}/\text{cm}$ , microsiemens per centimeter;  $^{\circ}\text{C}$ , degrees Celsius; NTU, nephelometric turbidity units;  $\text{mg}/\text{L}$ , milligrams per liter; mV, millivolts, relative to standard hydrogen electrode; --, not applicable;  $\text{CaCO}_3$ , calcium carbonate; USGS, U.S. Geological Survey; SC, schedule code; C, carbon;  $\delta$ , del; H, hydrogen; permil, ratio per thousand parts; pCi/L, picocuries per liter; O, oxygen; pct, percent; Sr, strontium; S, sulfur]

Constituent (unit of measurement)	Analytical method reporting limit	Constituent	Analytical method reporting limit
Physical properties			
Specific conductance ( $\mu\text{S}/\text{cm}$ )	2.6	pH (standard units)	.01
Water temperature ( $^{\circ}\text{C}$ )	.1	Turbidity (NTU)	0.05
Dissolved oxygen ( $\text{mg}/\text{L}$ )	0.01	Oxidation-reduction (redox) potential (mV)	--
Alkalinity (as $\text{CaCO}_3$ )	1.0		
Dissolved solids and major ions, USGS SC2750, in milligrams per liter			
Dissolved solids	10	Calcium	.04
Magnesium	.02	Sodium	.12
Potassium	.02	Bicarbonate	1.0
Carbonate	.10	Sulfate	.18
Chloride	.12	Fluoride	.12
Bromide	.02	Silica	.018
Nutrients, USGS SC2752, filtered, in milligrams per liter			
Nitrite, as nitrogen	.002	Nitrite plus nitrate, as nitrogen	.06
Ammonia, as nitrogen	.02	Total nitrogen	.06
Phosphorus	0.004–0.006	Orthophosphate, as phosphorus	.006
Trace elements, USGS SC2710, USGS SC2750, and mercury, USGS LC2707, filtered, in micrograms per liter			
Aluminum	1.6	Antimony	0.06–0.20
Arsenic	.12	Barium	.40
Beryllium	.06	Boron	8.0
Cadmium	.04	Chromium	.12
Cobalt	.04	Copper	0.40–1.2
Iron	6.0	Lead	0.08–0.12
Lithium	1.0	Manganese	.20
Mercury	.01	Molybdenum	0.12–0.40
Nickel	.06	Selenium	.08
Silver	0.08–1.0	Strontium	.80
Thallium	.04	Uranium, natural	.04
Vanadium	0.04–0.10	Zinc	.60
Isotopes (units or reporting limits)			
$\delta^{13}\text{C}$	permil	$^{14}\text{C}$ count	pct modern
$\delta^2\text{H}$	permil	Tritium	.04 pCi/L
$\delta^{18}\text{O}$	permil	$\delta^{34}\text{S}$	permil
$^{87}\text{Sr}/^{86}\text{Sr}$	ratio		

**Table 14.** Results of measurements or analysis of physical properties in ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.

[ $\mu\text{S}/\text{cm}$ , microsiemens per centimeter at 25 °C; °C, degrees Celsius; mg/L, milligrams per liter; NTU, nephelometric turbidity units; mV, millivolts;  $\text{CaCO}_3$ , milligrams per liter as calcium carbonate; P, primary; CR, concurrent replicate; <, less than; --, not determined]

Map index number (fig. 4)	Date of sample collection (month/day/year)	Time (24-hour)	Sample type	Specific conductance ( $\mu\text{S}/\text{cm}$ )	pH, field (standard units)	Water temperature (°C)	Dissolved oxygen (mg/L)	Turbidity (NTU)	Oxidation-reduction (redox) potential (mV relative to a standard hydrogen electrode)	Alkalinity as $\text{CaCO}_3$ (mg/L)
Kansas										
1	09/19/2006	0910	P	1,340	7.39	19.7	<0.01	15	-100	250
2	09/19/2006	1220	P	1,170	7.17	23.9	.15	.29	-100	270
3	09/19/2006	1050	P	1,220	7.19	22.7	.05	.16	-100	280
4	09/20/2006	0830	P	678	7.40	20.3	<.01	.18	-100	240
5	09/19/2006	1420	P	909	7.20	22.5	1.6	5.8	0	280
6	09/20/2006	0950	P	888	7.28	20.4	.05	.09	-100	260
6	09/20/2006	0955	CR	888	7.28	20.4	.05	.09	-100	260
7	09/20/2006	1215	P	723	7.23	22.2	.16	.51	-110	280
8	10/11/2006	1125	P	715	7.21	23.2	.21	.17	-70	230
9	09/21/2006	1110	P	872	7.35	21.6	1.4	25	-100	290
10	09/29/2006	1140	P	483	7.45	18.2	.16	.08	120	210
11	09/21/2006	1320	P	336	7.76	18.6	.19	.14	60	120
12	09/21/2006	0925	P	1,020	7.53	20.4	.16	.12	-100	180
13	09/22/2006	0915	P	445	7.56	19.5	.28	.22	130	150
14	09/29/2006	1330	P	456	7.75	19.5	.15	.28	60	150
15	09/22/2006	1110	P	926	7.68	19.7	.18	.21	80	140
Missouri										
16	05/29/2007	1550	P	437	7.59	19.7	.05	.10	50	150
17	12/13/2006	1130	P	571	7.49	21.3	.01	.44	-40	180
18	05/29/2007	1330	P	308	7.53	17.4	.26	.11	380	150
18	05/29/2007	1335	CR	308	7.53	17.4	.26	.11	--	--
19	12/13/2006	0920	P	338	7.55	19.1	<.01	.13	40	160
20	05/30/2007	1000	P	1,260	6.85	19.4	.23	.52	90	290
21	12/11/2006	1320	P	273	7.98	16.1	<.01	.73	-70	150
22	05/30/2007	0800	P	446	7.35	20.0	.11	.36	180	200
23	12/12/2006	1510	P	250	7.66	18.2	.02	.41	60	130
23	12/12/2006	1515	CR	250	7.66	18.2	.02	.41	60	130
24	12/11/2006	1610	P	236	7.76	15.3	<.01	3.7	60	110
25	12/12/2006	1120	P	253	7.72	17.7	.03	.15	180	130
26	12/12/2006	0820	P	328	7.49	15.7	<.01	.35	120	160
27	05/30/2007	1220	P	283	7.39	19.6	.07	.13	70	140
28	05/31/2007	0820	P	252	7.96	18.1	.06	.12	60	120
29	05/31/2007	1000	P	369	7.58	18.7	.10	.10	140	190
30	05/30/2007	1400	P	415	7.59	19.3	.10	.10	0	140
Oklahoma										
31	05/22/2007	1130	P	1,500	6.84	19.3	--	--	--	280
32	05/22/2007	1430	P	323	7.89	19.1	1.4	--	--	110
33	05/21/2007	1600	P	1,890	7.70	23.2	--	--	--	150
34	05/23/2007	1300	P	286	7.76	19.4	1.6	--	--	110
34	05/23/2007	1305	CR	286	7.76	19.4	1.6	--	--	110
35	05/23/2007	0930	P	809	7.99	22.9	1.8	--	--	170
36	05/24/2007	0900	P	1,390	7.70	21.5	2.0	--	--	150
37	05/24/2007	1500	P	377	7.15	16.9	--	--	--	170
38	05/24/2007	1300	P	412	7.94	21.0	2.0	--	--	130
Arkansas										
39	06/01/2007	1010	P	620	8.15	18.0	.16	.75	10	270
40	06/01/2007	1140	P	963	7.76	18.2	.16	.20	-60	220

**Table 15.** Results of dissolved solids and major ion analyses of ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.

[mg/L, milligrams per liter; primary; CR, concurrent replicate; &lt;, less than; E, estimated; --, not determined]

Map index number (fig. 6)	Date of sample collection (month/day/year)	Time (24-hour)	Sample type	Dissolved solids (mg/L)	Calcium (mg/L)	Mag-nesium (mg/L)	Sodium (mg/L)	Potassium (mg/L)	Bicarbon-ate (mg/L)
Kansas									
1	09/19/2006	0910	P	740	59	25	160	7.3	300
2	09/19/2006	1220	P	680	76	33	110	7.7	320
3	09/19/2006	1050	P	710	75	33	120	7.2	340
4	09/20/2006	0830	P	380	47	20	62	4.0	290
5	09/19/2006	1420	P	530	68	30	76	6.6	340
6	09/20/2006	0950	P	490	38	25	403	5.2	320
6	09/20/2006	0955	CR	500	56	25	81	5.1	320
7	09/20/2006	1215	P	420	61	28	52	5.6	340
8	10/11/2006	1125	P	410	54	24	58	5.0	280
9	09/21/2006	1110	P	510	53	25	99	6.6	350
10	09/29/2006	1140	P	280	51	22	17	3.6	250
11	09/21/2006	1320	P	180	31	14	16	2.2	140
12	09/21/2006	0925	P	560	46	21	120	5.8	220
13	09/22/2006	0915	P	260	49	16	21	2.0	180
14	09/29/2006	1330	P	230	36	16	23	2.3	180
15	09/22/2006	1110	P	490	41	18	110	3.8	170
Missouri									
16	05/29/2007	1550	P	230	32	15	32	2.8	190
17	12/13/2006	1130	P	320	42	20	49	3.6	220
18	05/29/2007	1330	P	170	37	15	2.5	1.2	180
18	05/29/2007	1335	CR	160	37	15	2.5	1.2	--
19	12/13/2006	0920	P	190	37	17	12	2.2	190
20	05/30/2007	1000	P	1,000	250	24	18	2.5	350
21	12/11/2006	1320	P	160	34	15	1.5	.9	190
22	05/30/2007	0800	P	240	47	21	13	3.0	250
23	12/12/2006	1510	P	140	30	13	3.5	1.5	160
23	12/12/2006	1515	CR	140	31	14	3.5	1.5	160
24	12/11/2006	1610	P	130	27	14	1.4	1.3	140
25	12/12/2006	1120	P	130	30	15	1.8	1.2	160
26	12/12/2006	0820	P	190	39	19	4.1	2.2	200
27	05/30/2007	1220	P	210	32	15	4.0	1.5	170
28	05/31/2007	0820	P	140	28	13	3.0	1.3	140
29	05/31/2007	1000	P	200	43	22	2.4	1.0	230
30	05/30/2007	1400	P	240	26	11	43	1.8	170
Oklahoma									
31	05/22/2007	1130	P	1,100	170	78	56	8.2	340
32	05/22/2007	1430	P	170	26	13	18	1.5	130
33	05/21/2007	1600	P	1,000	48	22	280	8.6	190
34	05/23/2007	1300	P	150	27	12	11	1.7	140
34	05/23/2007	1305	CR	150	27	12	11	1.7	140
35	05/23/2007	0930	P	420	17	7.5	140	4.5	210
36	05/24/2007	0900	P	790	45	20	200	6.4	180
37	05/24/2007	1500	P	250	69	1.6	6.1	.3	200
38	05/24/2007	1300	P	220	24	9.1	47	1.7	160
Arkansas									
39	06/01/2007	1010	P	370	4.5	2.0	140	3.1	330
40	06/01/2007	1140	P	520	23	9.5	160	4.4	270

**Table 15.** Results of dissolved solids and major ion analyses of ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.—Continued

[mg/L, milligrams per liter; primary; CR, concurrent replicate; &lt;, less than; E, estimated; --, not determined]

Map index number (fig. 6)	Date of sample collection (month/day/year)	Time (24-hour)	Sample type	Carbonate (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Fluoride (mg/L)	Bromide (mg/L)	Silica (mg/L)
Kansas									
1	09/19/2006	0910	P	<0.1	44	250	0.97	0.64	9.8
2	09/19/2006	1220	P	<.1	94	160	.83	.43	11
3	09/19/2006	1050	P	<.1	94	170	.79	.48	10
4	09/20/2006	0830	P	<.1	22	64	.64	.18	9.9
5	09/19/2006	1420	P	<.1	78	81	.93	.23	10
6	09/20/2006	0950	P	<.1	46	42	.69	.29	9.7
6	09/20/2006	0955	CR	<.1	47	110	.67	.30	9.7
7	09/20/2006	1215	P	<.1	58	37	.86	.12	10
8	10/11/2006	1125	P	<.1	53	54	1.0	.17	10
9	09/21/2006	1110	P	<.1	50	90	1.4	.27	10
10	09/29/2006	1140	P	<.1	56	3.3	.74	.10	8.7
11	09/21/2006	1320	P	<.1	24	18	.52	.06	9.1
12	09/21/2006	0925	P	<.1	40	190	.98	.55	9.8
13	09/22/2006	0915	P	<.1	45	22	.27	.09	9.0
14	09/29/2006	1330	P	<.1	17	42	.36	.12	9.5
15	09/22/2006	1110	P	<.1	28	180	.45	.51	8.9
Missouri									
16	05/29/2007	1550	P	.1	15	38	.43	.11	9.5
17	12/13/2006	1130	P	<.1	18	69	.56	.22	10
18	05/29/2007	1330	P	.2	11	2.4	.13	E.01	9.7
18	05/29/2007	1335	CR	--	11	2.4	.12	E.02	9.7
19	12/13/2006	0920	P	<.1	17	7.4	.38	.04	9.7
20	05/30/2007	1000	P	.2	470	5.5	.28	.05	11
21	12/11/2006	1320	P	<.1	4.2	1.1	E.07	<.02	9.8
22	05/30/2007	0800	P	.1	22	6.6	.43	.04	9.5
23	12/12/2006	1510	P	<.1	13	1.0	.14	E.01	9.2
23	12/12/2006	1515	CR	<.1	13	1.0	.14	<.02	9.1
24	12/11/2006	1610	P	<.1	13	.8	.13	<.02	8.9
25	12/12/2006	1120	P	<.1	11	1.3	E.08	<.02	9.9
26	12/12/2006	0820	P	<.1	13	1.8	.34	<.20	9.4
27	05/30/2007	1220	P	.2	11	2.1	.15	<.02	9.9
28	05/31/2007	0820	P	.2	13	2.3	.26	E.02	9.5
29	05/31/2007	1000	P	.2	11	2.1	<.10	E.02	9.3
30	05/30/2007	1400	P	.7	12	42	.80	.13	9.9
Oklahoma									
31	05/22/2007	1130	P	.2	440	90	.13	.28	10
32	05/22/2007	1430	P	.5	12	25	.25	.08	9.5
33	05/21/2007	1600	P	.8	13	490	2.4	1.3	11
34	05/23/2007	1300	P	.3	14	6.5	.40	.03	9.7
34	05/23/2007	1305	CR	.3	14	6.5	.41	.03	9.6
35	05/23/2007	0930	P	1.2	5.8	150	3.9	.43	11
36	05/24/2007	0900	P	1.0	5.2	350	1.0	.99	10
37	05/24/2007	1500	P	.2	7.3	7.4	E.08	.05	8.7
38	05/24/2007	1300	P	.3	11	40	.99	.13	12
Arkansas									
39	06/01/2007	1010	P	.8	.4	34	4.4	.11	8.6
40	06/01/2007	1140	P	.5	4.1	170	2.4	.51	10

**Table 16.** Results of nutrient analyses of ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.

[sample type: P, primary; CR, concurrent replicate. mg/L, milligrams per liter; N, nitrogen; P, phosphorus; &lt;, less than; E, estimated]

Map index number (fig. 4)	Date of sample collection (month/day/year)	Time (24-hour)	Sample type	Nitrite (mg/L as N)	Nitrite plus nitrate (mg/L as N)	Ammonia (mg/L as N)	Total nitrogen (nitrate + nitrite + ammonia + organic-N) (mg/L)	Total phosphorus (mg/L)	Orthophosphate (mg/L as P)
1	09/19/2006	0910	P	<0.002	E0.03	0.27	0.32	<0.004	E0.005
2	09/19/2006	1220	P	<.002	E.03	.26	.26	<.004	E.006
3	09/19/2006	1050	P	<.002	<.06	.24	.35	E.002	E.005
4	09/20/2006	0830	P	<.002	<.06	.17	.14	<.004	E.005
5	09/19/2006	1420	P	<.002	E.03	.20	.32	<.004	E.003
6	09/20/2006	0950	P	<.002	<.06	.21	.18	<.004	E.005
6	09/20/2006	0955	CR	<.002	<.06	.22	.18	<.004	E.005
7	09/20/2006	1215	P	<.002	<.06	.19	.22	E.002	E.006
8	10/11/2006	1125	P	<.002	<.06	.19	.42	<.006	E.005
9	09/21/2006	1110	P	<.002	<.06	.29	.32	<.004	E.005
10	09/29/2006	1140	P	<.002	<.06	.16	.17	<.004	<.006
11	09/21/2006	1320	P	<.002	<.06	.05	.07	.027	E.004
12	09/21/2006	0925	P	<.002	<.06	.25	.28	<.004	E.004
13	09/22/2006	0915	P	.002	E.04	.03	E.04	<.004	E.005
14	09/29/2006	1330	P	<.002	<.06	.06	.06	<.004	<.006
15	09/22/2006	1110	P	<.002	<.06	.11	.09	<.004	E.005
16	05/29/2007	1550	P	<.002	<.06	.08	.09	<.006	E.003
17	12/13/2006	1130	P	<.002	<.06	.11	.12	<.006	E.005
18	05/29/2007	1330	P	<.002	.24	<.02	.23	<.006	E.004
18	05/29/2007	1335	CR	<.002	.22	<.02	.22	<.006	E.003
19	12/13/2006	0920	P	<.002	<.06	.04	.07	<.006	E.004
20	05/30/2007	1000	P	E.001	<.06	E.02	<.06	.009	.009
21	12/11/2006	1320	P	<.002	<.06	.04	E.05	.012	.011
22	05/30/2007	0800	P	<.002	<.06	.04	<.06	<.006	E.004
23	12/12/2006	1510	P	<.002	<.06	E.02	E.05	<.006	E.004
23	12/12/2006	1515	CR	<.002	<.06	E.02	E.03	<.006	E.004
24	12/11/2006	1610	P	<.002	<.06	E.02	E.05	<.006	E.004
25	12/12/2006	1120	P	<.002	E.03	E.01	E.05	.033	E.004
26	12/12/2006	0820	P	<.002	<.06	.03	E.05	<.006	E.005
27	05/30/2007	1220	P	<.002	<.06	<.02	<.06	<.006	E.004
28	05/31/2007	0820	P	<.002	<.06	.03	<.06	<.006	E.004
29	05/31/2007	1000	P	<.002	<.06	<.02	<.06	<.006	E.005
30	05/30/2007	1400	P	<.002	<.06	.03	<.06	<.006	E.004
31	05/22/2007	1130	P	<.002	<.06	.08	.07	<.006	<.006
32	05/22/2007	1430	P	<.002	<.06	.02	E.04	<.006	E.004
33	05/21/2007	1600	P	<.002	<.06	.43	.44	<.006	E.004
34	05/23/2007	1300	P	<.002	<.06	E.02	<.06	<.006	E.003
34	05/23/2007	1305	CR	<.002	<.06	E.02	<.06	<.006	E.003
35	05/23/2007	0930	P	<.002	<.06	.24	.24	<.006	E.004
36	05/24/2007	0900	P	<.002	<.30	.16	.16	<.006	E.004
37	05/24/2007	1500	P	<.002	2.0	<.02	2.0	.014	.015
38	05/24/2007	1300	P	<.002	<.06	.05	.08	E.006	.007
39	06/01/2007	1010	P	<.002	<.06	.11	.19	<.006	E.004
40	06/01/2007	1140	P	<.002	<.06	.15	.16	<.006	E.004

**Table 17.** Results of selected trace element and stable isotope analyses of ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.

[ $\mu\text{g/L}$ , micrograms per liter; P, primary; CR, concurrent replicate; <, less than; E, estimated;  $\delta$ , del; permil, per thousand parts; C, carbon; H, hydrogen; O, oxygen; S, sulfur; Sr, strontium]

Map index number (fig. 4)	Date of sample collection (month/day/year)	Time (24-hour)	Sample type	Aluminum ( $\mu\text{g/L}$ )	Antimony ( $\mu\text{g/L}$ )	Arsenic ( $\mu\text{g/L}$ )	Barium ( $\mu\text{g/L}$ )	Beryllium ( $\mu\text{g/L}$ )	Boron ( $\mu\text{g/L}$ )	Cadmium ( $\mu\text{g/L}$ )	Chromium ( $\mu\text{g/L}$ )
1	09/19/2006	0910	P	<1.6	<0.20	<0.12	70	<0.06	360	<0.04	E0.07
2	09/19/2006	1220	P	<1.6	<.20	<.12	53	<.06	160	.17	E.02
3	09/19/2006	1050	P	E1.1	<.20	<.12	58	<.06	260	<.04	E.10
4	09/20/2006	0830	P	<1.6	<.20	<.12	250	<.06	76	<.04	E.05
5	09/19/2006	1420	P	E1.2	<.20	<.12	47	<.06	260	<.04	.15
6	09/20/2006	0950	P	<1.6	<.20	<.12	280	<.06	95	<.04	.45
6	09/20/2006	0955	CR	<1.6	<.20	<.12	280	<.06	99	<.04	E.08
7	09/20/2006	1215	P	<1.6	<.20	<.12	61	<.06	95	<.04	E.06
8	10/11/2006	1125	P	3.4	E.10	<.12	82	<.06	240	<.40	<.12
9	09/21/2006	1110	P	E1.2	<.20	.12	120	E.03	400	<.04	E.09
10	09/29/2006	1140	P	<1.6	<.20	<.12	65	<.06	110	<.04	E.07
11	09/21/2006	1320	P	E1.0	<.20	.46	140	<.06	67	<.04	E.06
12	09/21/2006	0925	P	<1.6	<.20	<.12	130	<.06	320	<.04	E.05
13	09/22/2006	0915	P	E.9	<.20	.79	98	<.06	73	<.04	E.06
14	09/29/2006	1330	P	<1.6	<.20	.40	56	<.06	64	<.04	E.02
15	09/22/2006	1110	P	<1.6	<.20	.17	52	<.06	150	<.04	E.04
16	05/29/2007	1550	P	E1.0	<.06	<.12	110	<.06	79	<.04	<.12
17	12/13/2006	1130	P	<1.6	<.06	<.12	40	<.06	150	<.04	<.12
18	05/29/2007	1330	P	<1.6	<.06	.15	100	<.06	9.5	<.04	<.12
18	05/29/2007	1335	CR	<1.6	<.06	.16	100	<.06	8.8	<.04	<.12
19	12/13/2006	0920	P	E.8	<.06	<.12	100	<.06	57	<.04	<.12
20	05/30/2007	1000	P	<1.6	<.06	.56	18	E.03	21	<.04	<.12
21	12/11/2006	1320	P	<1.6	<.06	1.3	120	<.06	E7.1	<.04	<.12
22	05/30/2007	0800	P	<1.6	<.06	.41	120	<.06	56	<.04	<.12
23	12/12/2006	1510	P	<1.6	<.06	.48	130	<.06	12	<.04	<.12
23	12/12/2006	1515	CR	<1.6	<.06	.51	130	<.06	12	<.04	<.12
24	12/11/2006	1610	P	<1.6	<.06	<.12	48	<.06	9.5	<.04	<.12
25	12/12/2006	1120	P	E1.0	E.03	.45	10	<.06	E7.9	<.04	E.07
26	12/12/2006	0820	P	<1.6	<.06	.14	50	<.06	29	<.04	<.12
27	05/30/2007	1220	P	E.9	E.03	.31	6.4	<.06	20	<.04	<.12
28	05/31/2007	0820	P	E.9	E.04	<.12	8.9	<.06	21	.18	<.12
29	05/31/2007	1000	P	E.9	E.04	.45	9.7	<.06	<8.0	.19	<.12
30	05/30/2007	1400	P	E1.2	<.06	<.12	7.2	<.06	110	<.04	<.12
31	05/22/2007	1130	P	<1.6	<.06	4.9	45	E.04	100	<.04	<.12
32	05/22/2007	1430	P	E1.0	<.06	<.12	13	<.06	53	<.04	<.12
33	05/21/2007	1600	P	E.8	<.06	<.12	180	<.06	960	<.04	E.06
34	05/23/2007	1300	P	<1.6	<.06	<.12	14	<.06	54	<.04	<.12
34	05/23/2007	1305	CR	E1.2	<.06	<.12	14	<.06	51	<.04	<.12
35	05/23/2007	0930	P	<1.6	<.06	<.12	81	<.06	850	<.04	<.12
36	05/24/2007	0900	P	2.6	<.06	E.10	88	<.06	210	<.04	<.12
37	05/24/2007	1500	P	E1.0	E.03	.37	50	<.06	E6.0	E.03	.45
38	05/24/2007	1300	P	8.9	<.06	<.12	22	<.06	160	<.04	<.12
39	06/01/2007	1010	P	E1.6	<.06	<.12	4.2	<.06	1,400	<.04	<.12
40	06/01/2007	1140	P	E1.1	<.06	<.12	11	<.06	610	<.04	<.12

**Table 17.** Results of selected trace element and stable isotope analyses of ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.—Continued[ $\mu\text{g/L}$ , micrograms per liter; P, primary; CR, concurrent replicate; <, less than; E, estimated;  $\delta$ , del; permil, per thousand parts; C, carbon; H, hydrogen; O, oxygen; S, sulfur; Sr, strontium]

Map index number (fig. 4)	Date of sample collection (month/day/year)	Time (24-hour)	Sample type	Cobalt ( $\mu\text{g/L}$ )	Copper ( $\mu\text{g/L}$ )	Iron ( $\mu\text{g/L}$ )	Lead ( $\mu\text{g/L}$ )	Lithium ( $\mu\text{g/L}$ )	Manganese ( $\mu\text{g/L}$ )	Mercury ( $\mu\text{g/L}$ )	Molybdenum ( $\mu\text{g/L}$ )
1	09/19/2006	0910	P	<0.04	<1.6	130	<0.08	140	29	<0.01	<0.40
2	09/19/2006	1220	P	<.04	<.40	15	.20	91	1.2	.01	<.40
3	09/19/2006	1050	P	E.02	<1.2	18	E.04	140	2.7	<.01	<.40
4	09/20/2006	0830	P	<.04	<.40	6.0	.18	64	1.2	<.01	<.40
5	09/19/2006	1420	P	<.04	<1.2	560	<.08	120	14	<.01	<.40
6	09/20/2006	0950	P	<.04	<.40	9.6	.13	91	4.8	<.01	<.40
6	09/20/2006	0955	CR	<.04	<.40	6.0	.12	92	1.6	E.006	<.40
7	09/20/2006	1215	P	<.04	<.40	76	.16	88	2.5	<.01	<.40
8	10/11/2006	1125	P	<.04	<.40	52	<1.2	83	4.4	<.01	.59
9	09/21/2006	1110	P	<.04	<.40	E3.0	<.08	110	1.9	<.01	<.40
10	09/29/2006	1140	P	<.04	<.40	42	.09	47	1.7	<.01	<.40
11	09/21/2006	1320	P	<.04	<.40	86	<.08	23	2.7	E.007	.84
12	09/21/2006	0925	P	<.04	<.40	16	<.08	100	2.8	<.01	<.40
13	09/22/2006	0915	P	.21	.74	49	.20	19	8.5	<.01	1.6
14	09/29/2006	1330	P	<.04	<.40	100	.32	22	3.2	<.01	1.8
15	09/22/2006	1110	P	<.04	<.40	84	<.08	69	3.7	<.01	1.0
16	05/29/2007	1550	P	<.04	<.40	120	<.12	32	1.4	<.01	1.9
17	12/13/2006	1130	P	<.04	<.40	120	<.12	46	2.4	.01	<.12
18	05/29/2007	1330	P	<.04	1.1	<6.0	E.07	6.8	.33	<.01	4.7
18	05/29/2007	1335	CR	<.04	.86	<6.0	E.06	6.3	.31	<.01	4.7
19	12/13/2006	0920	P	<.04	<.40	60	<.12	17	1.2	.01	.52
20	05/30/2007	1000	P	.75	E.21	3,200	<.12	81	95	<.01	.23
21	12/11/2006	1320	P	<.04	<.40	1,800	<.12	1.6	68	.01	1.1
22	05/30/2007	0800	P	<.04	E.34	14	E.11	30	1.8	<.01	1.8
23	12/12/2006	1510	P	<.04	<.40	52	<.12	7.9	1.8	E.009	1.2
23	12/12/2006	1515	CR	<.04	<.40	56	<.12	8.2	1.9	<.01	1.3
24	12/11/2006	1610	P	<.04	<.40	32	<.12	5.0	.65	<.01	2.1
25	12/12/2006	1120	P	<.04	<.40	E3.0	<.12	3.6	1.1	E.006	3.2
26	12/12/2006	0820	P	<.04	<.40	9.0	<.12	15	1.8	E.006	2.5
27	05/30/2007	1220	P	<.04	<.40	58	<.12	9.0	1.6	<.01	2.5
28	05/31/2007	0820	P	<.04	<.40	7.0	<.12	11	.90	<.01	3.7
29	05/31/2007	1000	P	<.04	E.31	33	<.12	E.86	.84	<.01	13
30	05/30/2007	1400	P	<.04	<.40	14	<.12	55	.91	<.01	<.12
31	05/22/2007	1130	P	.13	E.25	3,000	<.12	75	43	<.01	4.4
32	05/22/2007	1430	P	<.04	<.40	31	<.12	16	1.4	<.01	3.6
33	05/21/2007	1600	P	<.04	<.40	30	<.12	240	2.0	<.01	<.12
34	05/23/2007	1300	P	<.04	<.40	38	<.12	22	1.5	E.007	E.09
34	05/23/2007	1305	CR	<.04	<.40	39	<.12	21	1.5	E.009	E.10
35	05/23/2007	0930	P	<.04	<.40	6.0	<.12	160	.69	<.01	<.12
36	05/24/2007	0900	P	<.04	<.40	34	<.12	120	1.6	<.01	<.12
37	05/24/2007	1500	P	.28	1.6	<6.0	E.06	1.0	.49	E.006	.44
38	05/24/2007	1300	P	<.04	<.40	19	<.12	58	2.6	E.006	<.12
39	06/01/2007	1010	P	<.04	E.30	20	E.07	170	2.7	<.01	.38
40	06/01/2007	1140	P	<.04	E.37	E5.0	<.12	150	1.1	<.01	E.09

**Table 17.** Results of selected trace element and stable isotope analyses of ground water from 40 water-supply wells completed in Ozark aquifer, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma, 2006–07.—Continued

[µg/L, micrograms per liter; P, primary; CR, concurrent replicate; <, less than; E, estimated; δ, del; permil, per thousand parts; C, carbon; H, hydrogen; O, oxygen; S, sulfur; Sr, strontium]

Map index number (fig. 4)	Date of sample collection (month/day/year)	Time (24-hour)	Sample type	Nickel (µg/L)	Selenium (µg/L)	Silver (µg/L)	Strontium (µg/L)	Thallium (µg/L)	Uranium (natural) (µg/L)	Vanadium (µg/L)	Zinc (µg/L)
1	09/19/2006	0910	P	E0.04	<0.08	<0.8	1,400	<0.04	E0.03	<0.10	<0.60
2	09/19/2006	1220	P	.10	<.08	<.2	1,400	<.04	E.03	<.10	<.60
3	09/19/2006	1050	P	.15	<.08	<.2	1,500	<.04	.05	<.10	E.49
4	09/20/2006	0830	P	E.05	<.08	<.2	620	<.04	E.03	<.10	.66
5	09/19/2006	1420	P	.11	<.08	<.6	1,200	<.04	.06	<.10	<.60
6	09/20/2006	0950	P	E.04	E.06	<.2	940	<.04	.04	<.10	<.60
6	09/20/2006	0955	CR	E.03	.10	<.2	930	<.04	.05	<.10	<.60
7	09/20/2006	1215	P	E.05	<.08	<.2	1,000	E.02	.11	<.10	<.60
8	10/11/2006	1125	P	E.05	<.08	--	1,100	<.40	.12	<.04	<.60
9	09/21/2006	1110	P	E.04	<.08	<1.0	1,400	<.04	.17	<.10	.63
10	09/29/2006	1140	P	.23	<.08	<.2	690	<.04	.53	<.10	9.3
11	09/21/2006	1320	P	E.04	<.08	<.2	340	<.04	.32	<.10	.65
12	09/21/2006	0925	P	E.03	<.08	<.6	1,200	<.04	.07	<.10	E.37
13	09/22/2006	0915	P	.83	.38	<.2	160	<.04	.93	<.10	54
14	09/29/2006	1330	P	.11	<.08	<.2	180	<.04	.49	<.10	4.0
15	09/22/2006	1110	P	.06	<.08	<.2	650	<.04	.30	<.10	E.50
16	05/29/2007	1550	P	E.03	<.08	<.1	290	<.04	.18	<.04	<.60
17	12/13/2006	1130	P	.07	<.08	<.2	530	<.04	.14	<.04	<.60
18	05/29/2007	1330	P	.06	E.04	<.1	70	<.04	.37	E.02	<.60
18	05/29/2007	1335	CR	E.05	E.06	<.1	69	<.04	.40	E.02	<.60
19	12/13/2006	0920	P	E.04	<.08	<.1	180	<.04	.17	<.04	E.31
20	05/30/2007	1000	P	2.4	E.07	<.1	190	<.04	.62	<.04	14
21	12/11/2006	1320	P	E.04	<.08	<.1	56	<.04	.12	<.04	1.0
22	05/30/2007	0800	P	.07	<.08	<.1	160	<.04	.61	<.04	6.7
23	12/12/2006	1510	P	.08	<.08	<.1	71	<.04	.16	<.04	.74
23	12/12/2006	1515	CR	.08	<.08	<.1	70	<.04	.17	<.04	.83
24	12/11/2006	1610	P	E.04	<.08	<.1	52	<.04	.20	<.04	1.4
25	12/12/2006	1120	P	.06	.90	<.1	52	E.02	.46	.07	E.47
26	12/12/2006	0820	P	.06	<.08	<.1	160	<.04	.33	<.04	E.30
27	05/30/2007	1220	P	.06	<.08	<.1	71	<.04	.22	<.04	.81
28	05/31/2007	0820	P	.13	<.08	<.1	120	<.04	.10	<.04	1.3
29	05/31/2007	1000	P	E.04	<.08	<.1	47	<.04	4.5	<.04	.87
30	05/30/2007	1400	P	E.04	<.08	<.1	250	<.04	.07	E.03	E.35
31	05/22/2007	1130	P	1.5	<.08	<.1	410	<.04	.48	<.04	130
32	05/22/2007	1430	P	.11	<.08	<.1	170	<.04	.12	E.02	3.4
33	05/21/2007	1600	P	.11	E.05	<.1	1,700	<.04	<.04	.04	E.38
34	05/23/2007	1300	P	E.03	<.08	<.1	180	<.04	.04	<.04	E.32
34	05/23/2007	1305	CR	.08	<.08	<.1	180	<.04	.04	<.04	1.1
35	05/23/2007	0930	P	<.06	<.08	<.1	600	<.04	E.03	.08	1.9
36	05/24/2007	0900	P	.09	.14	<.1	1,400	<.04	E.03	.20	<.60
37	05/24/2007	1500	P	1.6	.85	<.1	83	<.04	1.4	.23	24
38	05/24/2007	1300	P	E.03	<.08	<.1	570	<.04	.06	E.02	E.30
39	06/01/2007	1010	P	.08	<.08	<.1	120	<.04	.05	<.04	.64
40	06/01/2007	1140	P	.06	.64	<.1	650	<.04	<.04	.04	E.37



**Table 18.** Results of measurements or analysis of physical properties and chemical analyses of depth-dependent ground-water samples collected under pumping conditions from Pittsburg, Kansas, city well 10, August 13–14, 2007.

[ $\mu\text{S}/\text{cm}$ , microsiemens per centimeter;  $^{\circ}\text{C}$ , degrees Celsius;  $\text{mg}/\text{L}$ , milligrams per liter; NTU, nephelometric turbidity units; mV, millivolts; SHE, standard hydrogen electrode;  $\text{CaCO}_3$ , calcium carbonate; E, estimated; <, less than; permil, per thousand parts; pCi/L, picocuries per liter; C, carbon; pct, percent;  $\delta$ , del; H, hydrogen; Sr, strontium; S, sulfur]

Constituent (unit of measurement)	Sampling depth, in feet below land surface						
	Well head	487	687	787	877	937	1030
Physical properties							
Specific conductance ( $\mu\text{S}/\text{cm}$ )	898	913	914	926	996	981	848
pH (standard units)	7.22	7.41	7.25	7.37	7.37	7.28	7.65
Water temperature ( $^{\circ}\text{C}$ )	21.1	---	---	---	---	---	---
Dissolved oxygen ( $\text{mg}/\text{L}$ )	5.4	---	---	---	---	---	---
Turbidity (NTU)	0.39	0.67	0.46	0.74	0.59	1.2	0.64
Oxidation-reduction (redox) potential, raw (mV)	-233	-220	-182	-208	-211	---	-162
Oxidation-reduction (redox) potential, SHE (mV)	-30	-30	10	-20	-20	---	30
Alkalinity, as $\text{CaCO}_3$	260	260	260	260	250	250	240
Dissolved solids and major ions, in milligrams per liter							
Dissolved solids	510	500	500	510	540	550	430
Calcium	67	68	69	71	71	74	69
Magnesium	29	29	29	30	30	31	31
Sodium	77	77	76	77	84	84	60
Potassium	5.6	5.8	5.9	5.9	5.6	5.9	4.5
Bicarbonate	310	320	320	320	300	310	290
Carbonate	.2	.2	.2	.1	.8	.3	0
Sulfate	78	72	73	78	73	74	79
Chloride	84	83	82	83	110	110	54
Fluoride	.65	.64	.65	.63	.62	.64	.56
Bromide	.24	.24	.24	.25	.29	.30	.17
Silica	10	10	11	10	11	11	10
Nutrients, in milligrams per liter							
Nitrite, as nitrogen	<.002	<.002	<.006	<.002	<.002	<.002	<.002
Nitrite plus nitrate, as nitrogen	<.06	<.06	<.06	<.06	<.06	<.06	<.06
Ammonia, as nitrogen	.21	.20	.20	.20	.18	.18	.14
Total nitrogen	.18	.20	.22	.20	.22	.21	.20
Phosphorus	<.006	<.006	<.006	<.006	<.006	<.006	<.006
Orthophosphate, as phosphorus	E.004	E.005	E.003	E.004	E.005	E.004	E.005
Trace elements, in micrograms per liter							
Aluminum	E1.4	5.0	E1.2	1.8	3.7	3.1	15
Antimony	<.06	<.06	<.06	<.06	<.06	<.06	<.06
Arsenic	<.12	<.12	<.12	<.12	<.12	<.12	<.12
Barium	130	130	130	120	96	94	44

**Table 18.** Results of measurements or analysis of physical properties and chemical analyses of depth-dependent ground-water samples collected under pumping conditions from Pittsburg, Kansas, city well 10, August 13–14, 2007.—Continued

[ $\mu\text{S}/\text{cm}$ , microsiemens per centimeter;  $^{\circ}\text{C}$ , degrees Celsius;  $\text{mg}/\text{L}$ , milligrams per liter; NTU, nephelometric turbidity units; mV, millivolts; SHE, standard hydrogen electrode;  $\text{CaCO}_3$ , calcium carbonate; E, estimated; <, less than; permil, per thousand parts; pCi/L, picocuries per liter; C, carbon; pct, percent;  $\delta$ , del; H, hydrogen; Sr, strontium; S, sulfur]

Constituent (unit of measurement)	Sampling depth, in feet below land surface						
	Well head	487	687	787	877	937	1030
Trace elements, in micrograms per liter—Continued							
Beryllium	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06
Boron	170	160	170	160	150	150	130
Cadmium	<.04	<.04	<.04	<.04	<.04	<.04	<.04
Chromium	<.12	E.06	E.06	<.12	E.08	E.10	E.08
Cobalt	E.03	E.03	E.03	E.03	E.03	E.03	E.03
Copper	<.40	<.40	E.23	<.40	E.20	.59	E.26
Iron	E6.0	6.0	E4.0	E5.0	E6.0	E3.0	100
Lead	<.12	<.12	E.06	E.10	E.06	0.12	E.07
Lithium	94	88	86	95	90	93	81
Manganese	1.5	1.7	1.5	1.3	1.8	1.8	2.7
Mercury	E.01	<.01	<.01	<.01	E.007	<.01	E.007
Molybdenum	<.12	<.12	<.12	<.12	<.12	<.12	<.12
Nickel	.32	.50	.47	.48	.54	.67	.59
Selenium	<.08	<.08	<.08	<.08	<.08	<.08	<.08
Silver	<.1	<.1	<.1	<.1	<.1	<.1	<.1
Strontium	940	890	900	940	880	670	860
Thallium	<.04	<.04	<.04	<.04	<.04	<.04	<.04
Uranium	.04	.04	.04	.04	.04	.04	.43
Vanadium	.09	.11	.10	.10	.14	.12	.08
Zinc	<.60	E.30	.77	1.2	.70	3.5	.62
Isotopes							
$\delta^{13}\text{C}$ (permil)	-9.08	---	---	---	---	-8.54	---
$^{14}\text{C}$ counting error (pct modern)	.05	---	---	---	---	.05	---
$^{14}\text{C}$ (pct modern)	0	---	---	---	---	.6	---
$\delta^2\text{H}$ (permil)	-42.0	---	---	---	---	-41.4	---
Tritium (pCi/L)	---	---	---	---	---	---	---
$\delta^{18}\text{O}$ (permil)	-6.76	---	---	---	---	-6.74	---
$\delta^{34}\text{S}$ (permil)	14.0	---	---	---	---	13.3	---
$^{87}\text{Sr}/^{86}\text{Sr}$ (ratio)	.71363	---	---	---	---	.71374	---

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