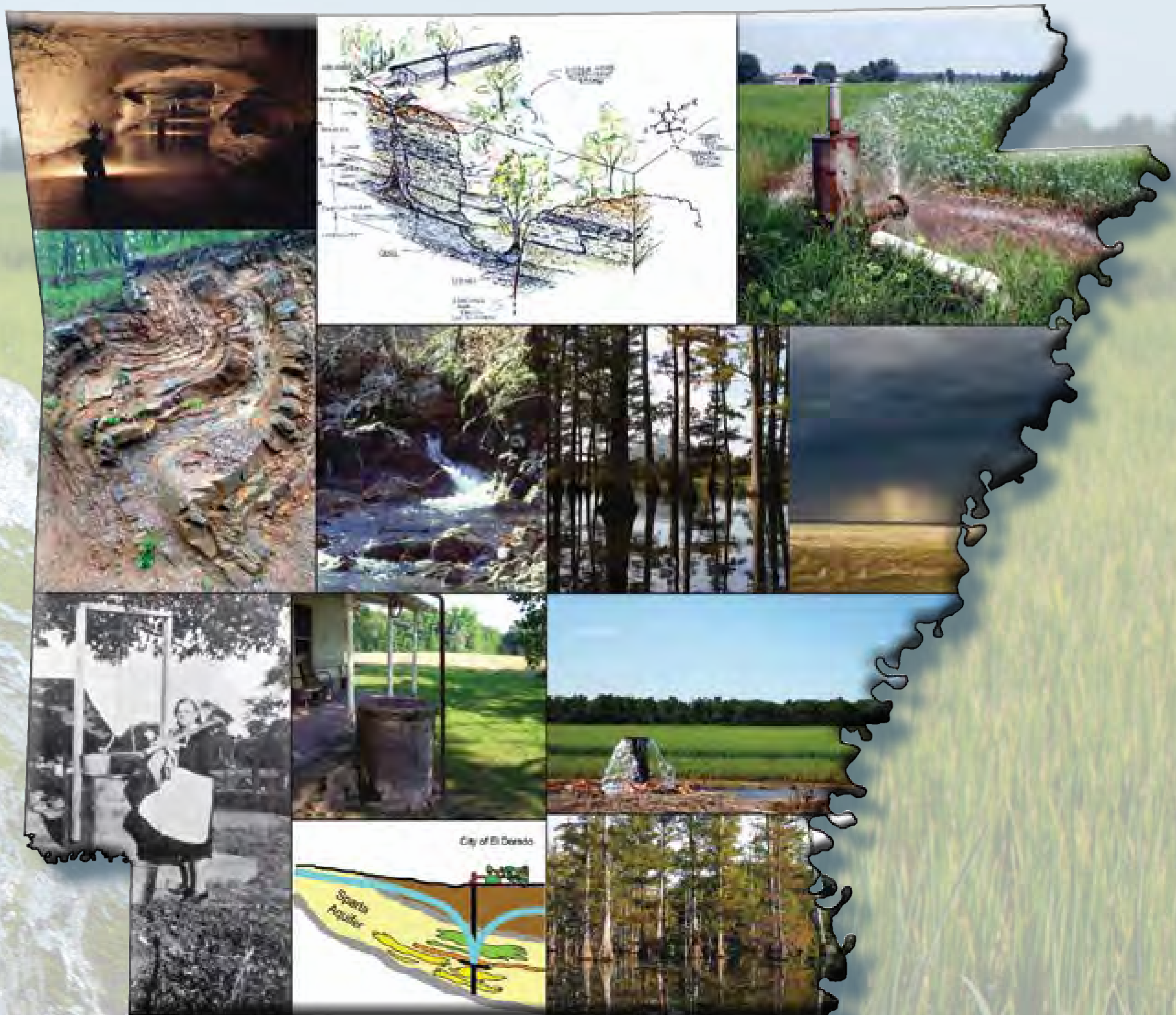
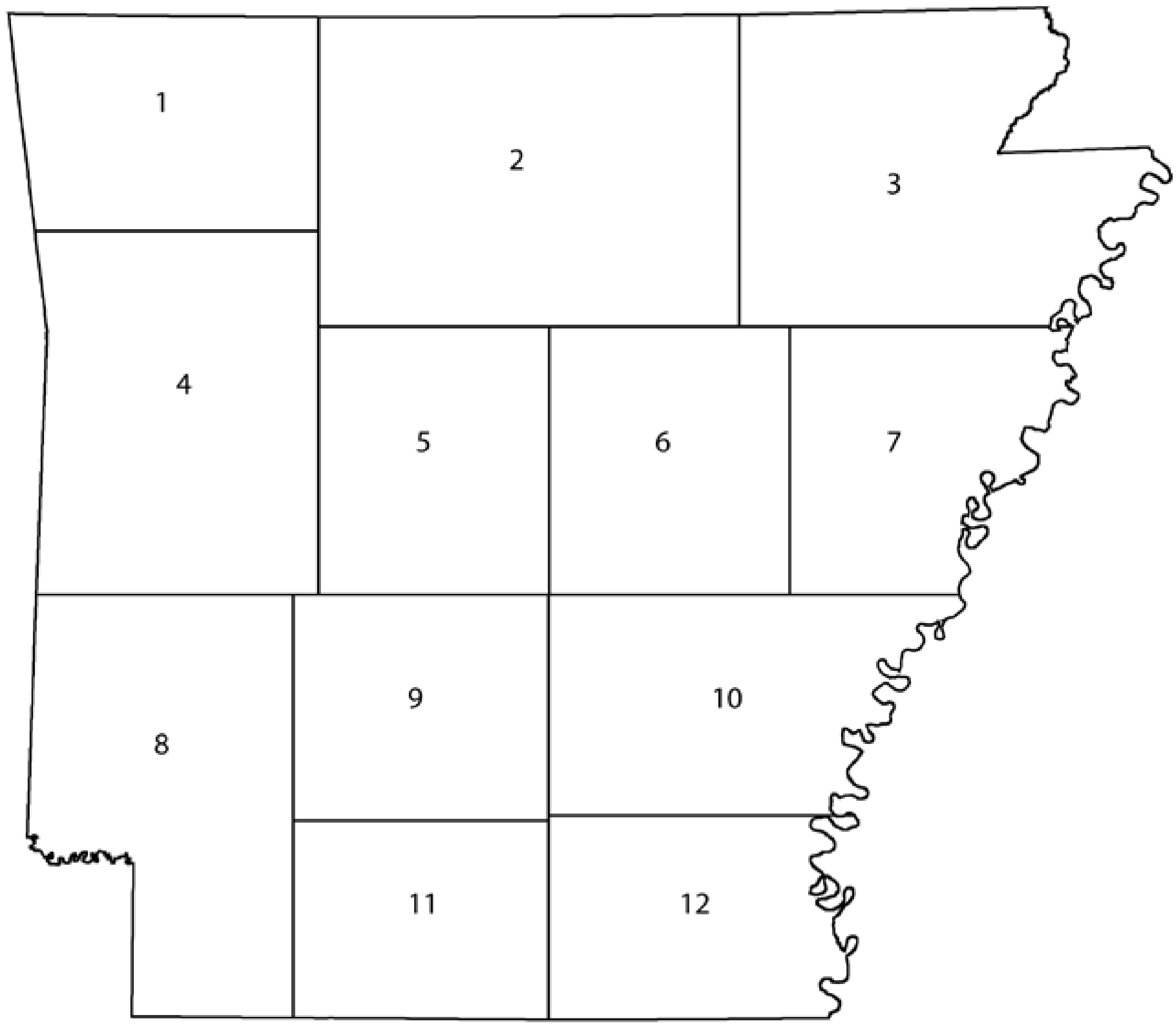
Prepared in cooperation with the Arkansas Natural Resources Commission

# Aquifers of Arkansas—Protection, Management, and Hydrologic and Geochemical Characteristics of Groundwater Resources in Arkansas




Scientific Investigations Report 2014–5149

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

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**U.S. Department of the Interior**
SALLY JEWELL, Secretary

**U.S. Geological Survey**
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In total, Jim probably read through the entire report, including figures and tables, on three different occasions. Although considering multiple reviewers for reviewing various sections of the report to reduce the burden on any one person, the authors decided for purpose of consistency that the report would benefit by the use of one outside peer review. Geoffrey Delin, regional Groundwater Specialist in Denver, Colorado, with extensive experience in groundwater studies, agreed to act as sole outside peer review for the report. Although busy with travel and other duties, Geoff used every free moment over a 5-month period to carefully review the text, tables, and figures and to provide valuable insight and thoughtful comments. Finally, our thanks to Keith Lucey for his thorough and insightful edits of the final draft report.

# Contents

## Figures

# Tables

# Conversion Factors

Inch/Pound to SI

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch (in.) | 2.54 | centimeter (cm) |
| inch (in.) | 25.4 | millimeter (mm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | Area | |
| acre | 4,047 | square meter ($m^2$) |
| acre | 0.4047 | hectare (ha) |
| acre | 0.4047 | square hectometer ($hm^2$) |
| acre | 0.004047 | square kilometer ($km^2$) |
| square mile ($mi^2$) | 259.0 | hectare (ha) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | Volume | |
| million gallons (Mgal) | 3,785 | cubic meter (m3) |
| acre-foot (acre-ft) | 1,233 | cubic meter (m3) |
| acre-foot (acre-ft) | 0.001233 | cubic hectometer ($hm^3$) |
| | Flow rate | |
| acre-foot per year (acre-ft/yr) | 1,233 | cubic meter per year ($m^3$/yr) |
| acre-foot per year (acre-ft/yr) | 0.001233 | cubic hectometer per year ($hm^3$/yr) |
| foot per second (ft/s) | 0.3048 | meter per second (m/s) |
| foot per day (ft/d) | 0.3048 | meter per day (m/d) |
| foot per year (ft/yr) | 0.3048 | meter per year (m/yr) |
| cubic foot per second ($ft^3$/s) | 0.02832 | cubic meter per second ($m^3$/s) |
| cubic foot per second per square mile [($ft^3$/s)/$mi^2$] | 0.01093 | cubic meter per second per square kilometer [($m^3$/s)/$km^2$] |
| cubic foot per day ($ft^3$/d) | 0.02832 | cubic meter per day ($m^3$/d) |
| gallon per minute (gal/min) | 0.06309 | liter per second (L/s) |
| gallon per day (gal/d) | 0.003785 | cubic meter per day ($m^3$/d) |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second ($m^3$/s) |
| inch per year (in/yr) | 25.4 | millimeter per year (mm/yr) |
| | Mass | |
| pound, avoirdupois (lb) | 0.4536 | kilogram (kg) |
| ton, short (2,000 lb) | 0.9072 | megagram (Mg) |
| | Radioactivity | |
| picocurie per liter (pCi/L) | 0.037 | becquerel per liter (Bq/L) |
| | Specific capacity | |
| gallon per minute per foot [(gal/min)/ft] | 0.2070 | liter per second per meter [(L/s)/m] |
| | Hydraulic conductivity | |
| foot per day (ft/d) | 0.3048 | meter per day (m/d) |
| | Hydraulic gradient | |
| foot per mile (ft/mi) | 0.1894 | meter per kilometer (m/km) |
| | Transmissivity* | |
| foot squared per day ($ft^2$/d) | 0.09290 | meter squared per day ($m^2$/d) |

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

°F=(1.8×°C)+32

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

°C=(°F-32)/1.8

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

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

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

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/ft^2$]ft. In this report, the mathematically reduced form, foot squared per day ($ft^2/d$), is used for convenience.

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

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

# Acronyms

| | |
|---|---|
| ADEQ | Arkansas Department of Environmental Quality |
| ADH | Arkansas Department of Health |
| AGS | Arkansas Geological Survey |
| AML | Abandoned Mine Land |
| ANRC | Arkansas Natural Resources Commission |
| AOGC | Arkansas Oil and Gas Commission |
| APCEC | Arkansas Pollution Control and Ecology Commission |
| ARWUDBS | Arkansas Water-Use Data Base System |
| ASPB | Arkansas State Plant Board |
| AWRC | Arkansas Water Resources Center |
| AWWCC | Arkansas Water Well Construction Commission |
| BMP | Best management practice |
| CERCLA | Comprehensive Environmental Response Compensation and Liability Act |
| CFR | Code of Federal Regulations |
| CWA | Clean Water Act |
| EARCS | Eastern Arkansas Region Comprehensive Study |
| EPA | U.S. Environmental Protection Agency |
| FIFRA | Federal Insecticide, Fungicide, and Rodenticide Act |
| GPS | Global Positioning System |
| GPWUA | Grand Prairie Water Users Association |
| HWD | Hazardous Waste Division |
| Koc | Organic carbon partition coefficient |
| MCL | Maximum contaminant level |
| NEPA | National Environmental Policy Act |
| NPDES | National Pollutant Discharge Elimination System |
| NPL | National Priority List |
| NPS | Nonpoint source |
| NRCS | Natural Resources Conservation Service |
| NWIS | National Water Information System |
| RASA | Regional Aquifer-System Analysis |
| RATFA | Remedial Action Trust Fund Act |
| RCRA | Resource Conservation and Recovery Act |
| SDWA | Safe Drinking Water Act |
| SMCRA | Surface Mining Control and Reclamation Act |
| SMRD | Surface Mining and Reclamation Division |
| SWAP | Source Water Assessment Programs |
| SWMD | Solid Waste Management Division |
| UCWCB | Union County Water Conservation Board |
| UIC | Underground injection control |
| USACE | U.S. Army Corps of Engineers |
| USDA | U.S. Department of Agriculture |
| USGS | U.S. Geological Survey |
| UST | Underground storage tanks |
| WHPP | Wellhead Protection Program |

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## Abstract

Sixteen aquifers in Arkansas that currently serve or have served as sources of water supply are described with respect to existing groundwater protection and management programs, geology, hydrologic characteristics, water use, water levels, deductive analysis, projections of hydrologic conditions, and water quality. State and Federal protection and management programs are described according to regulatory oversight, management strategies, and ambient groundwater-monitoring programs that currently (2013) are in place for assessing and protecting groundwater resources throughout the State.

Physical attributes, groundwater geochemistry, and groundwater quality are described for each of the 16 aquifers of the State. Information in regard to the hydrology and geochemistry of each of the aquifers is summarized from about 550 historical and recent publications. Additionally, more than 8,000 sites with groundwater-quality data were obtained from the U.S. Geological Survey National Water Information System and the Arkansas Department of Environmental Quality databases and entered into a spatial database to investigate distribution and trends in chemical constituents for each of the aquifers.

The 16 aquifers of the State were divided into two major physiographic regions of the State: the Coastal Plain Province (referred to as Coastal Plain) of eastern and southern Arkansas, which includes 11 of the 16 aquifers, and the Interior Highlands Division (referred to as Interior Highlands) of western Arkansas, which includes the remaining 5 aquifers. The 11 aquifers in the Coastal Plain consist of various geologic units that are Cenozoic in age and consist primarily of Cretaceous, Tertiary, and Quaternary sands, gravels, silts, and clays. Groundwater in the Coastal Plain represents one of the most valuable natural resources in the State, driving the economic engines of agriculture, while also supplying abundant water for commercial, industrial, and public-supply use. In terms of age from youngest to oldest, the aquifers of the Coastal Plain include Quaternary alluvial aquifers, including the Mississippi River Valley alluvial aquifer (the most important aquifer in Arkansas in terms of volume of use and economic benefits), the Jackson Group (a regional confining unit that served for decades as an important source of domestic supply), and the Cockfield, Sparta, Cane River, Carrizo, Wilcox, Nacatoch, Ozan, Tokio, and Trinity aquifers. The Mississippi River Valley alluvial aquifer accounts for approximately 94 percent of all groundwater used in the State, and the aquifer is used primarily for irrigation purposes. The Sparta aquifer is the second most important aquifer in terms of use, and the aquifer was used in the past dominantly as a source of public and industrial supply, although increasing irrigation use is occurring because of critically declining water levels in the Mississippi River Valley alluvial aquifer. Other aquifers of the Coastal Plain generally are used as important local sources of domestic, industrial, and public supply, in addition to other minor uses. Water quality generally is good for all aquifers of the Coastal Plain, except for elevated iron concentrations and localized areas of high salinity. The high salinity results from intrusion from underlying formations, evapotranspiration processes in areas of low recharge, and inadequate flushing in downgradient areas of residual salinity from deposition in marine environments. Trends in the spatial distribution of individual chemical constituents are related to position along the flow path for most aquifers of the Coastal Plain. These trends include elevated iron and nitrate concentrations with lower pH values and dissolved solids in groundwater from the outcrop areas, transitioning to lower iron and nitrate (related to changes in redox) and higher pH and dissolved solids (dominantly from the dissolution of carbonate minerals) in groundwater downgradient from outcrop areas. Groundwater generally trended from a calcium- to a sodium-bicarbonate water type with increasing cation exchange along the flow path.

The Interior Highlands of western Arkansas has less reported groundwater use than other areas of the State, reflecting a combination of factors. These factors include prevalent and increasing use of surface water, less intensive agricultural uses, lower population and industry densities,

[1]U.S. Geological Survey.

[2]Arkansas Natural Resources Commission.

[3]FTN Associates, Ltd.

lesser potential yield of the resource, and lack of detailed reporting. The overall low yields of aquifers of the Interior Highlands result in domestic supply as the dominant use, with minor industrial, public, and commercial-supply use. Where greater volumes are required for growth of population and industry, surface water is the greatest supplier of water needs in the Interior Highlands. The various aquifers of the Interior Highlands generally occur in shallow, fractured, well-indurated, structurally modified bedrock of this mountainous region of the State, as compared to the relatively flat-lying, unconsolidated sediments of the Coastal Plain. In terms of age from youngest to oldest, the aquifers of the Interior Highlands include: the Arkansas River Valley alluvial aquifer, the Ouachita Mountains aquifer, the Western Interior Plains confining system, the Springfield Plateau aquifer, and the Ozark aquifer. Spatial trends in groundwater geochemistry in the Interior Highlands differ greatly from trends noted for aquifers of the Coastal Plain. In the Coastal Plain, the prevalence of long regional flow paths results in regionally predictable and mappable geochemical changes along the flow paths. In the Interior Highlands, short, topographically controlled flow paths (from hilltops to valleys) within small watersheds represent the predominant groundwater-flow system. As such, dense data coverage from numerous wells would be required to effectively characterize these groundwater basins and define small-scale geochemical changes along any given flow path for aquifers of the Interior Highlands. Changes in geochemistry generally were related to rock type and residence time along individual flow paths. Dominant changes in geochemistry for the Ouachita Mountains aquifer and the Western Interior Plains confining system are attributed to rock/water interaction and changes in redox zonation along the flow path. In these areas, groundwater evolves along flow paths from a calcium- to a sodium-bicarbonate water type with increasing reducing conditions resulting in denitrification, elevated iron and manganese concentrations, and production of methane in the more geochemically evolved and strongest reducing conditions. In the Ozark and Springfield Plateau aquifers, rapid influx of surface-derived contaminants, especially nitrogen, coupled with few to no attenuation processes was attributed to the karst landscape developed on Mississippian- and Ordovician-age carbonate rocks of the Ozark Plateaus. Increasing nitrate concentrations are related to increasing agricultural land use, and areas of mature karst development result in higher nitrate concentrations than areas with less karst features.

# Introduction

Groundwater is vitally important to the State of Arkansas. A total of approximately 11,450 million gallons per day (Mgal/d) of water was used in Arkansas in 2010, and approximately 7,873 Mgal/d (69 percent) was from a groundwater source. Irrigation water use accounts for the largest groundwater withdrawals, resulting in 94 percent of the total groundwater used in Arkansas. Total groundwater use has increased from approximately 892 Mgal/d in 1960 (Stephens and Halberg, 1961) to approximately 7,873 Mgal/d in 2010, an increase of 774 percent. Of 2010 groundwater use, about 94 percent is from the Mississippi River Valley alluvial aquifer. Recent scenarios of sustainable water levels for the Mississippi River Valley alluvial aquifer indicate that only 45 to 50 percent of current (2013) withdrawals from this aquifer are sustainable (Clark and others, 2013). These estimates of sustainable yield compare closely with earlier optimization models (Czarnecki and others, 2003a), which indicated that the sustainable yield from the Mississippi River Valley alluvial aquifer was equal to the amount of water withdrawn during the late 1970s and early 1980s, although use has continued to grow since this earlier time period. Similarly, model scenarios using water levels and pumping rates from the Sparta aquifer indicate that less than 60 percent of withdrawals from the Sparta aquifer are sustainable (McKee and others, 2004). These increasingly large withdrawals of groundwater have caused substantial declines in water levels in areas of greatest pumping. Such withdrawals can adversely affect aquifers and water users, with reliance on alternate water sources becoming an increasing necessity.

The Arkansas Natural Resources Commission (ANRC) received statutory authority and was charged by the State of Arkansas to develop the Arkansas Water Plan in 1969 (Ark. Code Ann. Sec. 15–22–503). The plan provides a comprehensive planning process for the conservation, development, and protection of the State's water resources, with a goal of long-term sustainable use for the health, well-being, environmental, and economic benefit to the State of Arkansas. This plan was to be used by all State agencies, commissions, and political subdivisions in all matters pertaining to the discharge of their respective duties and responsibilities as they may affect the State's water resources. The first Arkansas Water Plan was published in 1975. In 1985, the Arkansas General Assembly enacted Ark. Code Ann. Sec. 15–22–301, which broadened the powers of the ANRC's planning responsibilities to include (1) an inventory of the State's water resources; (2) the determination of the current needs and the projection of future needs of all water uses in the State; and (3) the determination of whether excess surface water existed that might be put to beneficial use. From this statute, an updated State Water Plan was required, which resulted in the 1990 update. These plans were instrumental in shaping Arkansas' water policy and providing needed guidance with respect to developing and protecting the State's water resources.

The 1990 plan contained eight basin reports with an executive summary document (http://anrc.ark.org/divisions/water-resources-management/arkansas-water-plan). An important outcome of the 1990 plan was the motivation behind the development of Act 154 of 1991, the Arkansas

Groundwater Protection and Management Act. This Act outlined the State's role in groundwater planning, provided authority to the ANRC to delineate critical groundwater areas, and gave the ANRC limited authority to allocate groundwater within those areas under specific conditions. Though the authority to limit groundwater use was extremely restricted, it represented the first such authority in the State. The State Water Plan and associated legal authority have provided valuable assistance to the State with respect to the conservation and protection of groundwater in Arkansas. It has been successful in promoting conservation, education, and a conjunctive use strategy relying on sustainable groundwater use and excess surface water. This policy is helping the State move towards conjunctive and sustainable water use. A major outcome from the 1990 State Water Plan and resulting Arkansas Groundwater Protection and Management Act was the implementation of use of excess surface water by major industrial users in Union County, Ark. Industries in this area of the State previously had used groundwater from the Sparta aquifer, which had shown severe water-level declines and was designated as a critical groundwater area. Since the switch to surface-water use in this area, water levels in the Sparta aquifer have increased more than 80 ft (T.P. Schrader, U.S. Geological Survey, oral commun., 2013).

In 2011, the ANRC recognized the need to update the Arkansas Water Plan. With more than two decades passing since the publication of the 1990 State Water Plan, groundwater use has shifted by various demands, total groundwater use has increased, new data and information have been developed, and new water issues have emerged. The ANRC recognized the need for a detailed groundwater summary that would be independent of past summaries included in individual basin reports. Suggested changes included documenting changes over time in groundwater use and water levels, in addition to documenting spatial and temporal trends in groundwater quality for all the State's aquifers. The purpose of the comprehensive groundwater report was to (1) establish a clear identification of all Federal, State, and local entities with water resources authority; (2) identify stakeholders and critical groundwater issues and needs of the State; (3) collect all existing water-use and water-level data and document changes over time; (4) identify shifts in groundwater use related to changes in population, changes in land use, changes in water needs, and other criteria; and (5) collect all available groundwater-quality data to identify areas with poor water quality and define spatial and temporal changes as affected by natural and anthropogenic sources.

Water managers, planners, regulators, and groundwater users, as well as the institutions charged with the protection and management or with a vital interest in groundwater in Arkansas, have long recognized the importance of groundwater as a resource supporting life, health, and the economy in the State. These entities have expended great effort in collecting data, characterizing, and understanding this important resource. Abundant data, data reports, and interpretive reports are available from these efforts; however, no comprehensive synthesis and intellectual resource compendium has been compiled in regard to the State's aquifers. The current large-scale task of updating the Arkansas State Water Plan has highlighted the need for such a compendium and has provided the framework to address this need.

Various meetings between the ANRC, U.S. Geological Survey (USGS), and other stakeholders established the need for a comprehensive source of groundwater information by State and local authorities, water-resources managers and planners, and the public. Therefore, the USGS, in cooperation with the ANRC, compiled a compendium to aid in addressing these concerns and to cover all aspects of the groundwater resources of Arkansas including status and changes in water law and policy, water rights, water use, water quality, water quantity, water levels, and stream-aquifer interaction.

## Purpose and Scope

The purpose of this report is to provide a compilation of geologic, hydrologic, and water-quality data for all major and minor aquifers in the State and to describe the geologic framework, overall use by category, current and past water-level information, and general water quality associated with each aquifer. The purpose also is to provide a comprehensive reference of the collective studies of groundwater in Arkansas and to develop an intellectual resource compendium on groundwater. Review of available data and interpretive studies was performed for each aquifer identified as currently being or having been used as sources of water supply, resulting in the identification and summary descriptions of 16 aquifers within the State of Arkansas. This report provides a general encyclopedic reference of the state of knowledge on aquifers in Arkansas to support water management, planning, development, academic, and legislative needs. The geographic scope for this study and level of data collection were confined to the boundaries of the State of Arkansas, though some discussion extends to adjacent States for aquifer systems that are of regional importance and cross State boundaries.

# Methods

Water-use data referenced in this report were derived from numerous historical reports, the 5-year USGS water-use reports, and the Arkansas Water-Use Data Base System (ARWUDBS). The water-use data from the 5-year water-use reports (1960–2005) (Stephens and Halberg, 1961; Halberg and Stephens, 1966; Halberg, 1972, 1977; Holland, 1981, 1987, 1993, 1999, 2004, 2007) were compiled into a Microsoft Access database. The 2010 water-use report was not published at the time of this writing (2013), and the 2010 water-use data were compiled from the ARWUDBS and placed into the Microsoft Access database. This allowed querying by county, year, or use category. On occasion, conflicting water-use values were found between ARWUDBS, the 5-year water-use reports, and the historical reports. When there was conflict between the historical reports and the 5-year water-use reports, the values were taken from the 5-year water-use report. ARWUDBS was assumed to be more up-to-date than the 5-year water-use reports, and values from ARWUDBS were used when a conflict between ARWUDBS and the 5-year water-use report occurred; any changes from the 5-year water-use reports were footnoted in the appropriate water-use table. Inventories of public-water supplies, municipal websites, and oral or written communication with the Arkansas Department of Health (ADH) were used to determine the public-supply source or duration of groundwater use by municipalities. Potentiometric-surface maps and water-level data were provided by the USGS.

Groundwater-quality data from approximately 8,000 sites in Arkansas were used to produce statistical analyses and spatial-distribution maps for selected chemical constituents associated with 16 aquifers. Approximately 7,000 water-quality data were extracted from the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2013b). Data were extracted irrespective of collection date and included field data (pH, specific conductance), major ions (calcium, magnesium, sodium, potassium, chloride, sulfate, and bicarbonate), select trace metals (iron, manganese, and arsenic), hardness, and dissolved solids. Approximately 1,000 sites with groundwater-quality data were extracted from the Arkansas Department of Environmental Quality (ADEQ) database (Roger Miller, Arkansas Department of Environmental Quality, written commun., 2012). The ADEQ operates a water-quality laboratory; groundwater samples collected by the ADEQ Water Division are analyzed by U.S. Environmental Protection Agency (EPA) approved methods with data stored in an internal database at their Little Rock office. The ADEQ additionally has participated in the USGS Standard Reference Sample project (http://bqs.usgs.gov/) for numerous years, which evaluates and improves the performance of participating laboratories. Multiple State and Federal agencies, university libraries, and archives additionally were searched for relevant data and interpretive reports; about 550 publications are referenced herein with summaries of important data, results, and interpretations included in this report.

Water type was determined by converting all major-ion weight concentrations to equivalent concentrations (milligrams per liter [mg/L] to milliequivalent per liter [meq/L]). In this manner, each cation or anion was calculated as a percent of the total cations and anions, respectively. Major cations and anions are those comprising more than 50 percent of the total cations and anions in milliequivalents per liter, respectively. Where no one cation or anion constitutes more than 50 percent of the total cations and anions, respectively, then a mixed water type was assigned using the dominant (ions with the highest percentage of the total cations and anions in milliequivalents per liter) cations and anions.

Water-quality requirements by various users can vary widely depending on the intended use (industrial, public supply, irrigation or other uses). In assessing general water quality for this report, water-quality data were compared to the EPA Federal drinking-water standards (U.S. Environmental Protection Agency, 2009). These standards address a wide array of inorganic and organic constituents. Because only inorganic constituents serving as important indicators of general water quality were reviewed for this report, drinking-water standards were only discussed for these constituents. The Federal drinking-water standards are threefold and include mandatory and recommended standards. Federal maximum contaminant levels (MCLs) are enforceable (for public and community supply systems) and are based on adverse health effects. Federal lifetime health advisories are nonregulatory estimates of acceptable drinking-water levels for a chemical substance based on health effects information (often leads to development of MCLs). Federal secondary drinking-water regulations are nonenforceable guidelines regarding cosmetic effects (such as tooth or skin discoloration) or aesthetic effects (such as taste, odor, or color) of drinking water (U.S. Environmental Protection Agency, 2009). MCLs, lifetime health advisories, and secondary drinking-water regulations for the constituents reviewed in this report are found in table 1. Detailed information for all primary and secondary drinking-water standards can be found at http://water.epa.gov/drink/contaminants/index.cfm.

**Table 1.** Primary and secondary drinking water regulations for selected constituents and characteristics.

[NA, not applicable; mg/L, milligrams per liter; mg/d, milligrams per day]

| Constituents and characteristics | Maximum contaminant levels | Lifetime health advisories | Secondary regulations |
|---|---|---|---|
| pH | NA | NA | 6.5–8.5 |
| Dissolved solids | NA | NA | 500 mg/L |
| Sodium[1] | NA | NA | 30–60 mg/L |
| Chloride | NA | NA | 250 mg/L |
| Sulfate | NA | NA | 250 mg/L |
| Iron | NA | NA | 0.3 mg/L |
| Manganese | NA | 0.3 mg/L[2] | 0.05 |
| Arsenic | 0.01 mg/L | 0.002 mg/L[3] | NA |

[1]Health-based drinking water advisory of 20 mg/L for individuals on a 500 mg/d restricted sodium diet.

[2]Dietary manganese. The lifetime health advisory includes a threefold modifying factor for increased bioavailability from drinking water.

[3]Based at $10^{-4}$ cancer risk.

# Groundwater Protection and Management Programs

There are three main components of groundwater protection and management: (1) ensuring the available quantity necessary for the various uses, (2) protecting and restoring groundwater quality, and (3) ambient monitoring of groundwater quality on a continuous basis. State water-resources protection authority is generally divided among various State agencies. The ADEQ has primary water-quality protection authority, and the ADH has authority over public drinking-water-supply programs. The ANRC has comprehensive planning and water-quantity authority and is responsible for protection of diminishing groundwater supplies in areas where agricultural, public, and industrial needs have placed unsustainable demands on production capacities of certain aquifers. The broad scope of groundwater protection and management activities requires a multiagency approach to address groundwater quantity and quality issues. This section presents a summary of water law, policy, and regulatory programs that have evolved and the role that various Federal and State agencies have taken to address groundwater protection and management in the State of Arkansas.

## Groundwater Quality Protection and Restoration

There are numerous potential and actual sources of groundwater contamination in the State, both natural and manmade. Arkansas Department of Environmental Quality (2012) identified the 10 major sources of contamination in Arkansas to be animal feedlots, fertilizers, pesticides, underground storage tanks, surface impoundments, landfills, septic systems, hazardous wastes sites, saltwater intrusion, and spills. It is difficult to define which sources have the greatest effect on groundwater quality because each source varies in areal extent and degree of alteration of groundwater quality. For example, a point source, such as a landfill, may result in severe impact to groundwater with numerous organic chemicals exceeding safe drinking-water standards, but the areal extent of the plume may be limited with no offsite migration and no known groundwater users at risk. On the other hand, contamination from nonpoint sources, such as agricultural activities, may be areally extensive with minimal effect on the use of the groundwater for drinking-water supply or other purposes. Point-source prevention programs are almost entirely established as regulatory programs and are administered primarily by ADEQ. Most nonpoint sources are related to agriculture and other land-use activities and commonly are addressed by joint efforts of several agencies, with lead oversight relegated to the ANRC.

Despite the threat to groundwater resources, no Federal or State statute comprehensively addresses groundwater protection. There are currently only patchworks of law at the Federal and State levels that address groundwater protection. The EPA has been designated by Congress to be the primary Federal agency responsible for groundwater protection; however, there is no comprehensive Federal groundwater law comparable to the legislation addressing surface-water pollution. Instead, the EPA enforces requirements of a myriad of Federal laws having provisions that protect groundwater quality. These laws include among others: the Safe Drinking Water Act (SDWA) of 1974 (42 USC §300f *et seq.*[and the following]) and amendments; the Resource Conservation and Recovery Act (RCRA) of 1976 (42 USC §6901 *et seq.*); and the Comprehensive Environmental Response Compensation and Liability Act (CERCLA) of 1980 (42 USC §9601 *et seq*.) and amendments. The Clean Water Act (CWA) of 1972 (33 USC §1251 *et seq*.), including the 1977 amendments, is the primary Federal law in the United States that governs the discharge of pollutants into the Nation's waters. The CWA's primary regulatory mechanism is the National Pollutant Discharge Elimination System (NPDES), which requires permits to be issued for discharges of any pollutant or combination of pollutants into navigable waters. Certain sections specifically address groundwater, but it is unclear whether the CWA's pollution-control provisions apply to groundwater. Some provisions of the CWA clearly apply to groundwater. For example, Section 106 provides for regional monitoring of surface water and groundwater; and Section 304 provides for development of specific water-quality criteria, which would include groundwater quality (Quatrochi, 1996).

Act 472 of 1949, the Arkansas Water and Air Pollution Control Act, codified as Arkansas Code Annotated (ACA §8–4–101 *et seq*.), defines groundwater as a part of "waters of the state" that are subject to protection. This act is the primary statute providing authority to State agencies for the regulation of various programs that protect human health and the environment; however, Act 472 of 1949 does not contain reporting requirements for groundwater contamination nor does it contain numerical standards or other guidance for monitoring or remediating groundwater contamination. ADEQ is the State's delegated authority responsible for implementing various EPA programs and enforces environmental policies set by the Arkansas Pollution Control and Ecology Commission (APCEC); however, other State agencies also have authority to enact rules and regulations that address groundwater protection. Restoring aquifers to beneficial use and minimizing human exposure to contaminants can be very costly when protection mechanisms have failed or were not in place. Most remedial activities are the responsibility of ADEQ.

## Groundwater Contamination Prevention Programs

There are a number of potential threats to groundwater drinking-water supplies from point and nonpoint sources of contamination. This section describes various State programs initiated with the intended purpose of preventing potential contamination of drinking water and its sources.

## Wellhead Protection

Originally, the Federal SDWA focused primarily on treatment as the means of providing safe drinking water at the tap. The law was amended in 1986 and 1996 and required many actions to protect drinking water and its sources. The amendments of 1986 specified that certain program activities, such as delineation, contaminant-source inventory, and source-management plans, be incorporated into state Wellhead Protection Programs (WHPP). Implementation of Arkansas' WHPP began in the early 1990s. The WHPP is a voluntary program that is maintained by the public water systems and local communities with technical assistance and guidance provided by the ADH. The goal of the program is to develop strategies and methods for managing a wellhead protection area for groundwater sources of public supply.

The 1996 amendments greatly enhanced the existing law by recognizing source-water protection of all public drinking-water supplies (surface and groundwater). States were asked to develop and implement Source Water Assessment Programs (SWAPs) to evaluate the vulnerability of public drinking-water systems to possible sources of contamination throughout the State and use this information as a management tool for the benefit and protection of public water systems. In Arkansas, the WHPP is now part of the SWAP. Arkansas' SWAP includes delineating the source-water assessment areas, conducting contaminant source inventories, determining the susceptibility of each public water supply source to contamination from the inventoried sources, and releasing the results of the assessments to the public (Arkansas Department of Health, 2009). Those systems that are considered vulnerable are advised to take action through community education programs or by passing city ordinances to protect water sources.

## Water Well Construction

The Arkansas Water Well Construction Commission (AWWCC) regulates the development of groundwater supplies to provide safe water for public consumption, and Act 855 of 2003 (ACA §17–50–401 *et seq*.) provides a means of holding persons who violate Arkansas law regarding water-well construction accountable for their actions. AWWCC licenses water-well contractors and registers drillers, pump installers, and their apprentices.

The rules and regulations of the Arkansas Water Well Construction Commission (2011) provide minimum standards for the construction and abandonment of water wells (that is, water supply, geothermal, and monitoring) so that groundwater is protected from contamination. Water-well contractors must file a well-completion report for each well. Well-completion data are maintained in an ANRC database that is linked to the USGS water-use database (http://water.usgs.gov/watuse/). Water-well records also may be obtained from Arkansas Geological Survey (AGS), which has over 145,000 water-well construction records on file by county and township/range that date from the early 1970s.

Administrative and investigative functions are carried out by ANRC. ANRC responds to complaints from the public about water-well construction, as well as inspecting wells for violations of the rules and regulations. ANRC also works closely with ADH and its Environmental Health Specialist in each county and conducts well inspections in each county. These inspections are to ensure the protection of groundwater through compliance with the rules and regulations established by the ANRC.

## Pesticide Management

The Arkansas State Plant Board (ASPB) is the lead agency for implementing the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) of 1996 (7 USC §136 *et seq*.). The ASPB has been monitoring groundwater since 2004 using an EPA-approved Pesticide Management Plan that allows the agency to work with ADH to determine actions to be taken in the event pesticide contamination is confirmed (Arkansas State Plant Board, 2013). ASPB also developed the Arkansas Agricultural Abandoned Pesticide Program as a way for farmers to safely and properly dispose of unused pesticides. This program is conducted in cooperation with ASPB, the University of Arkansas Cooperative Extension Service, the Arkansas Farm Bureau, ANRC, and ADEQ. Representatives from these agencies comprise the Abandoned Pesticide Advisory Board. The Abandoned Pesticide Advisory Board selects counties for collection events and has a goal of holding at least one collection event in every county in Arkansas. The Advisory Board uses priority watersheds as a guiding principle when selecting counties for pesticide collections. The pesticide collections began in 2005 in northeastern Arkansas; by the spring of 2009, at least one collection had been held in each county in eastern Arkansas. By the spring of 2011, the Abandoned Pesticide Program had collected over 744,000 pounds of unwanted pesticides from Arkansas farmers in 55 different counties (Arkansas State Plant Board, 2013). The pesticide collections are paid for by the pesticide manufacturers through a fee added to the registration of each agricultural pesticide used in Arkansas. There is no cost to the farmer, and participation in the program is anonymous.

## State Nonpoint Source Program

Potential sources of nonpoint source (NPS) pollution in groundwater include excess fertilizers, chemicals, and animal wastes from row-crop agriculture, residential and urban areas, pastures, and concentrated animal feeding operations. ANRC is responsible for developing and implementing the State's NPS program (Arkansas Natural Resources Commission, 1999). This program is a cooperative effort of many local, State, and Federal agencies; regional and local entities; nonprofit organizations; and watershed groups. The program promotes voluntary action to improve water quality. Projects may include implementation of best management programs

(BMPs), demonstrations of effective techniques, technical assistance, education, and monitoring. ANRC's NPS program is supported by grant funds under Section 319 of the CWA.

## Oversight of Public Water-Supply Systems

The SDWA was passed by Congress in 1974 to protect public health by regulating the Nation's drinking-water supply. The SDWA authorizes the EPA to set national health-based standards that protect against naturally occurring and manmade contaminants in drinking water. The EPA, States, and public water systems work together to ensure that these standards are met.

The ADH has primary enforcement responsibility and provides oversight of public water systems throughout the State. ADH reviews new water-system facility construction, inspects water-system facilities, troubleshoots water-treatment and distribution problems, investigates complaints, and collects and analyzes samples to determine water quality. ADH enacts rules to ensure that public water systems adhere to EPA regulations (Arkansas State Board of Health, 2012b) enacted under the authority of Act 96 of 1913 as amended (ACA §20–7–109). These rules and regulations incorporate the Federal National Primary Drinking Water Regulations found in Title 40 of the Code of Federal Regulations (40 CFR) parts 141, 142, and 143 (U.S. Environmental Protection Agency, 2001).

Monitoring the quality of drinking water is a joint responsibility of ADH and the State's public water-supply systems. According to ADH (Bradley Jones, Arkansas Department of Health, oral commun., 2013), Arkansas has over 1,190 individual groundwater wells used for public drinking-water supply. Statewide, there are about 710 community public drinking-water systems, of which about 690 use groundwater as their only water source. These groundwater systems serve more than 870,000 residents. Additionally, there are about 35 facilities defined by the SDWA as noncommunity, nontransient public water systems that rely on groundwater. These smaller facilities include schools, daycare centers, and businesses. There are also about 375 transient noncommunity public systems such as restaurants, churches, community centers, and campgrounds that use groundwater.

## National Environmental Policy Act

The National Environmental Policy Act (NEPA) of 1969 (42 USC §4321 *et seq.*) and amendments require that all actions sponsored, funded, permitted, or approved by Federal agencies undergo planning to ensure that environmental considerations (including impacts to groundwater) are given due weight in project decision making. NEPA has procedural requirements for all Federal government agencies to prepare environmental assessments (EAS) and environmental impact statements (EISs).

## Permit Programs

Protecting groundwater is accomplished through issuance of permits, inspections, as well as continuous monitoring and enforcement of the regulations. ADEQ and other State agencies issue many types of permits for activities that can have a negative effect on groundwater quality. Permits can establish limits for specific chemicals or groups of pollutants or can require BMPs designed to reduce release of pollutants to surface and groundwater resources.

### Underground Injection Control

Part C of the SDWA of 1977 required the EPA to establish regulations for the disposal of wastewaters in underground reservoirs. The Underground Injection Control (UIC) program is responsible for regulating the construction, operation, permitting, and closure of injection wells constructed for underground storage or disposal of wastewater. Arkansas was given primary enforcement authority to administer the UIC program in 1982. There are three classes of underground injection wells in Arkansas—Class I, Class II, and Class V (U.S. Environmental Protection Agency, 1984). ADEQ has the authority to regulate Class I and V wells (excluding bromine-related, spent-brine disposal wells). The Arkansas Oil and Gas Commission (AOGC) has State primacy to regulate Class II wells and shares enforcement authority with ADEQ of the Class V bromine-disposal wells as recognized in a Memorandum of Understanding between ADEQ, AOGC, and EPA. Corresponding Federal regulations found in 40 CFR parts 144, 145, and 146 provide performance standards for location, design, installation, construction, and maintenance of permitted facilities. ADEQ issues UIC permits pursuant to APCEC Regulation 17 (Arkansas Pollution Control and Ecology Commission, 2005). AOGC issues Class II well permits under General Rule H, General Rules and Regulations (Arkansas Oil and Gas Commission, 2013).

Class I wells inject hazardous and nonhazardous wastes into saline formations found at depths between 2,500 and 8,700 ft below ground surface. Class I requirements stipulate that a facility be able to demonstrate that injected waste will not impact groundwater (or surface water) for 10,000 years. There are 14 operating Class I wells in Arkansas: 4 hazardous and 10 nonhazardous wells (Linda Hanson, Arkansas Department of Environmental Quality, oral commun., 2013). Four of the wells are "shut-in," meaning the wells are not currently injecting fluids.

Class II wells are the primary means of disposal for energy and production wastes and include enhanced oil-recovery injection wells and saltwater disposal wells. Most of the injected fluid is saltwater (brine), which is brought to the surface in the process of producing oil and gas. In addition, brine and other fluids, like diesel fuel, are injected to enhance oil and gas production. There are approximately 28 Class II commercial disposal wells and over 500 noncommercial, producer-owned Class II disposal wells in Arkansas (State

Review of Oil and Natural Gas Environmental Regulations, 2012).

Class V wells are shallow, subsurface treatment and disposal systems such as air conditioning return-flow wells, cooling water return-flow wells, drainage wells for stormwater runoff, dry wells, recharge wells, saltwater intrusion barrier wells, septic systems for multiple dwellings, subsidence-control wells, geothermal wells, solution-mining wells, spent-brine, return-flow wells, in-situ recovery, motor-vehicle waste disposal, and wells used in experimental technology. Large-capacity cesspools are also Class V wells, but they are banned in Arkansas under authority of the ADH. There are approximately 136 Class V wells that are permitted by ADEQ and 74 bromine wells permitted by AOGC (Linda Hanson, Arkansas Department of Environmental Quality, oral commun., 2013; Rex Robertson, Arkansas Oil and Gas Commission, oral commun., 2013).

### Hazardous Waste

The ADEQ's Hazardous Waste Division (HWD) implements Arkansas' RCRA Subtitle C waste-management program governing the management and disposition of hazardous wastes, used oils, and universal wastes and administers the State's hazardous waste program under authority of the Arkansas Hazardous Waste Management Act 406 of 1979, as amended (ACA §8–7–02 *et seq*.) The HWD received delegation of the Federal RCRA hazardous waste-management program from the EPA. State and Federal hazardous waste-management regulations and requirements are merged into a single reference document, APCEC Regulation 23 (Arkansas Pollution Control and Ecology Commission, 2012a).

The HWD relies on record keeping to maintain a "cradle-to-grave" tracking system for all generated hazardous wastes. Proper management and pollution-prevention techniques are designed to ensure against contamination of groundwater. If there is improper management of hazardous wastes, the program requires that actions be taken to remedy the situation and to restore, to the extent possible, quality of the affected groundwater. A strong oversight and enforcement effort are maintained to provide high visibility as a deterrent against future violations. Certain permitted facilities that are used to manage hazardous wastes have specific construction criteria designed to protect groundwater quality. Permit conditions for these facilities include the requirement for groundwater monitoring that meets the requirements of APCEC Regulation 23.

### Solid Waste

Nonhazardous landfills are subject to Federal regulation under Subtitle D of RCRA, 40 CFR, parts 258 and 257. ADEQ's Solid Waste Management Division (SWMD) regulates the management and disposal of nonhazardous wastes through adoption of Subtitle D and by implementing rules and regulations in APCEC Regulation 22 (Arkansas Pollution Control and Ecology Commission, 2008), which came into effect in 1993 and was adopted pursuant to the Arkansas Solid Waste Management Act.

Permits are required for various classes of landfills. Class 1 landfills include all municipal solid waste landfill units. These landfills can accept household wastes, commercial wastes, and approved industrial wastes. Class 3 landfills accept commercial, industrial, and special solid wastes, and Class 4 landfills accept construction and demolition debris and other nonputrescible wastes. The solid waste program permitting requirements for facilities accepting wastes are directed at protecting groundwater and surface water, while assuring the safe management and disposal of wastes. Permitting requirements for Class I landfills and most Class 3 landfills include liners and leachate-collection/treatment systems, groundwater-monitoring systems, and other environmental protection systems that protect groundwater. At a minimum, semiannual reports are submitted by facilities required to monitor groundwater. If constituents in groundwater around the landfill exceed the EPA MCLs for drinking-water supplies, corrective action is required to bring the facility into compliance. A Post-Closure Trust Fund pays for corrective action needed after closure of landfills. The SWMD currently (2013) evaluates environmental monitoring data for one closed landfill.

### Waste Utilization

Pursuant to Act 472 of 1949, as amended, ADEQ has the power to issue permits "to prevent, control or abate pollution." Therefore, any waste-disposal system that does not discharge directly into the waters of the State must be operated under the terms and conditions of a no-discharge water permit. An example of a no-discharge permit is a UIC well permit. Other no-discharge permits are required for land application, land farming, and subsurface disposal of water-treatment-plant residuals, and industrial and animal wastes.

Permit procedures for liquid animal waste-management systems are described in APCEC Regulation 5 enacted in May 2012 (Arkansas Pollution Control and Ecology Commission, 2012b). An objective of the regulation is to control nutrients from confined animal operations with such systems. Obtaining a permit requires, among other conditions, an approved waste-management plan that is prepared by Natural Resource Conservation Service (NRCS), the University of Arkansas Cooperative Extension Service, a Certified Nutrient Management Planner, a water-quality technician from ANRC, or a professional engineer. By limiting the amount of nutrients applied to those actually required by crops, excess amounts of nutrients can be controlled and surface water and groundwater protected.

### Onsite Sewage Disposal Systems

The ADH administers the Arkansas State Board of Health Rules and Regulations pertaining to onsite wastewater systems (Arkansas State Board of Health, 2012a). These regulations were enacted under the authority of Act 402 of 1977 and established minimum standards for the design and construction of individual sewage disposal systems, including alternate and experimental sewage system applications and subdivision systems. Onsite wastewater-system permits are required for operation, and the systems must be installed by licensed contractors. These systems typically are designed by ADH Designated Representatives and approved by local health units. There are approximately 400,000 onsite wastewater systems in Arkansas (Renae Mites, Arkansas Department of Health, oral commun., 2013).

### Mining

The Surface Mining and Reclamation Division (SMRD) of ADEQ regulates surface mining and reclamation, which includes the coal program and the noncoal program. The Surface Mining Control and Reclamation Act of 1977 (SMCRA) established performance standards for coal mining operations for the express purpose of protecting society and the environment from the adverse effects of surface coal mining operations and to ensure reclamation of mine sites. States were charged with submitting a State program covering surface coal mining and reclamation operations. As such, the Arkansas Surface Coal Mining and Reclamation Act, Act 134 of 1979, authorized the State to develop, adopt, issue, and amend rules and regulations pertaining to surface coal mining and reclamation operations. Active coal mines must comply with APCEC Regulation 20 (Arkansas Pollution Control and Ecology Commission, 2002). Regulation 20 has a groundwater protection clause requiring mine operators to control or prevent the discharge of acid mine drainage into groundwater systems.

Act 827 of 1991, as amended, deals with the reclamation of land affected by the mining of noncoal minerals, such as bauxite, clay, and sand and gravel, using open-cut mining methods. A 1999 amendment authorized the regulation of soil and shale pits with some exemptions based on the size of the pit and the distance from adjacent property lines. APCEC Regulation 15, the Arkansas Open Cut Mining and Land Reclamation (Arkansas Pollution Control and Ecology Commission, 2012c), set performance standards that must be followed during mining and the process of reclaiming land to a beneficial use. Act 1166 of 1997 provided a regulatory framework for the operation, reclamation, and safe closure of new stone quarries and any land purchased or leased for a quarry.

### Oil and Gas Production

Arkansas has a long history of oil and gas production beginning in the early 1900s. In 2012, there were about 7,000 oil-production wells in southern Arkansas and about 4,000 gas-production wells in northern Arkansas; however, since 2004, the majority of gas production has occurred in north-central Arkansas, where gas-production is being developed at a rate of about 700–900 wells per year (State Review of Oil and Natural Gas Environmental Regulations, 2012) through the use of horizontal drilling and hydraulic fracturing.

Oil and gas exploration and production, as well as hydraulic fracturing, is regulated by the AOGC. This authority was given to AOGC in Subtitle 6, Title 15 of the Arkansas Code. Regulations describing requirements for oil and gas well development activities, including hydraulic fracturing and use of Class II UIC wells, have been adopted under the authority of these statutes. Storage of saltwater prior to injection in Class II UIC wells is regulated by ADEQ under APCEC Regulation 1 (Arkansas Pollution Control and Ecology Commission, 1993).

Concerns by local citizens and citizen groups on the potential environmental effects of gas production resulted in more stringent State regulations. For example, AOGC General Rule B–19 was among the first rules in the Nation to require public disclosure of the chemicals used in hydraulic fracturing operations; AOGC General Rule B–26 governs the siting, construction, and operation of pits and tanks used for the holding or storage of well fluids; AOGC General Rules B–17, B–26, and B–34 address spill prevention and cleanup; and AOGC General Rule–19 has production casing requirements specific to the Fayetteville Shale that are the first line of defense in protecting groundwater during hydraulic fracturing operations (Arkansas Oil and Gas Commission, 2013).

Responsibilities for water use and disposal related to hydraulic fracturing for gas production are through various State programs. The use of surface water for makeup water is governed by regulations administered by ANRC. The AOGC and ADEQ respond to complaints of water-well contamination, and AOGC has adopted joint standards with ADEQ. The inclusion of multiuse reserve pits in the rules (General Rule B–17 [Arkansas Oil and Gas Commission, 2013] and APCEC Regulation 34 [Arkansas Pollution Control and Ecology Commission, 2011a]) encourages reuse and recycling of return flow waters from gas-production operations for hydraulic fracturing purposes. The ADH regulates sources of ionizing radiation including naturally occurring radioactive materials (NORM). A produced water or effluent concentration of greater than or equal to 60 picocuries per liter (pCi/L) for combined radium-226 and radium-228 would be subject to ADH regulations. Owners/operators would be required to notify the ADH as part of the ADH's NORM General Licensee registration process. Regulatory efforts are coordinated with the Arkansas Department of Environmental Quality and the Arkansas Oil and Gas Commission (Bevill Bernard, Arkansas Department of Health, written commun., 2014).

### Stormwater

Urban stormwater discharges are generated by runoff from paved surfaces including streets, parking lots, and other impervious areas (for example, buildings) during rainfall and snow events, which often contain pollutants in quantities that could adversely affect water quality. Most urban and industrial stormwater discharges are considered point sources and therefore require coverage by a NPDES permit under APCEC Regulation 2 (Arkansas Pollution Control and Ecology Commission, 2011b). The primary method to control stormwater discharges is through use of BMPs. There are a variety of traditional and low-impact BMPs, including retention and detention ponds, biofilters, grassed filter strips, porous pavement, wetlands, and others. BMPs are especially important in northern Arkansas because stormwater can discharge directly through karst features into aquifers.

## Groundwater Remediation and Restoration

Remediation of groundwater contaminated by anthropogenic sources often is required to restore groundwater to its previous uses. Numerous sites in Arkansas have been investigated or remediated under voluntary actions, through enforcement, or under hazardous waste permits. Most cleanups are overseen by ADEQ, but if radiological materials are involved, ADH will lead the cleanup effort. This section describes some of the programs through which groundwater remediation is managed in Arkansas.

### Groundwater Remediation Level Interim Policy

The goal of groundwater remediation in Arkansas is to protect, enhance, and restore, to the extent technically and economically feasible, groundwater conditions to the maximum beneficial use, while maintaining conditions that are protective of human health and the environment (Ellen Carpenter, Arkansas Department of Environmental Quality, oral commun., 2005). It is the policy of ADEQ that until final regulations are enacted by APCEC specific to the establishment of groundwater cleanup standards, cleanup levels or goals will be established on a case-by-case basis in a consistent manner. The process includes full characterization of the contaminant plume, source-control measures, BMPs to control migration of the plume, and a groundwater cleanup strategy. Preliminary remediation goals are established after an evaluation of risks to human health and the environment; consideration is given to the current and reasonably anticipated future land use, including groundwater usage. Because many citizens drink groundwater and use it in their homes, ADEQ currently classifies all groundwater in Arkansas as a potential source of drinking water. It is not necessary for groundwater to be defined as an aquifer (that is, a saturated permeable geologic formation that can produce a significant quantity of water) in order to be protected. Thus, final groundwater remediation levels are the existing Federal MCLs. Institutional controls, such as deed restrictions or city ordinances, are used with source controls to minimize the potential for human exposure to contamination by limiting groundwater use.

### Federal and State Programs for Hazardous Waste Sites

The Federal “Superfund” program, authorized by CERCLA, was established to identify, prioritize, and clean up hazardous wastes sites posing threats to human health and the environment. Sites identified under the Superfund program are placed on the National Priority List (NPL). In 2013, there were 14 NPL sites in Arkansas (U.S. Environmental Protection Agency, 2013). ADEQ HWD ensures that State requirements are met during investigation and cleanup of sites designated under this Federal “Superfund” program. ADEQ’s HWD administers a similar cleanup program for abandoned hazardous wastes sites under authority of the Remedial Action Trust Fund Act (RATFA) of 1985. The Arkansas RATFA State Priority List identifies those hazardous substance sites for which expenditures to investigate and remediate are authorized.

### Brownfields Program

Arkansas Voluntary Cleanup Act (Act 1042 of 1997, as amended) established the Brownfields Program and provides a streamlined process for the remediation and redevelopment of abandoned industrial or commercial properties that are contaminated or are perceived to be contaminated with hazardous constituents. ADEQ hopes to encourage the development of Brownfields as a sustainable land-use policy as an alternative to new development of Greenfields, or pristine properties, in the State of Arkansas. In December 2000, the EPA and ADEQ entered into a Memorandum of Agreement to support ADEQ’s Brownfields Program and define the roles and responsibilities of EPA Region 6 and ADEQ. The rules and requirements of the program are outlined in APCEC Regulation No. 29 (Arkansas Pollution Control and Ecology Commission, 2006). Upon successful completion of the Brownfields Program, participants are provided limitations on liability for the eligible property.

### Elective Site Cleanup Program

The ADEQ administers an Elective Site Cleanup Program, which allows responsible parties to enter into an agreement with ADEQ for cleanup of sites. The Elective Site Cleanup Program does not offer a release of liability but does offer participants a means to address historic contamination on their site without penalty and with known objectives. ADEQ is working to promote the Elective Site Cleanup Program in order to maximize cleanups of sites within the State. There is also a number of sites undergoing voluntary cleanup through Consent Administrative Orders.

### Abandoned Mine Lands

The SMCRA created an Abandoned Mine Land (AML) fund to pay for the cleanup of mine lands abandoned before the passage of the statute in 1977. The law was amended in 1990 to allow funds to be spent on the reclamation of mines abandoned after 1977. The trust fund is financed by a fee assessed on every ton of coal mined in the country. A portion of AML fees are distributed to States with an approved reclamation program to fund reclamation activities. The SMRD currently uses state-of-the-art surveying and computer-aided design systems to perform the functions necessary to produce reclamation plans for the AML sites in Arkansas.

### Underground Storage Tanks

The ADEQ Regulated Storage Tank Division drafts, administers, and enforces State regulations pertaining to underground storage tanks (USTs) as prescribed by 40 CFR 280, as well as aboveground petroleum storage tanks. There are approximately 13,000 regulated storage tanks located at over 5,600 active facilities across the State (Arkansas Department of Environmental Quality, 2012). These tanks are located primarily at retail gasoline and diesel sales facilities but may also include bulk petroleum storage facilities, private fleet-fueling facilities, and emergency generating stations. Prior to the mid-1980s, USTs had been regulated in a fragmented fashion by the Federal government through various environmental statutes. When studies revealed growing problems with a large number of tank systems, along with an alarming potential for future problems, the U.S. Congress mandated changes that were initiated by the States (U.S. Environmental Protection Agency, 1988). These standards focused on new tank system installation standards (for example, secondary containment), existing tank upgrades, registration requirements, closure requirements, and corrective action requirements. The controlling regulation for regulated storage tanks in Arkansas is the APCEC Regulation 12 (Arkansas Pollution Control and Ecology Commission, 2009).

The number of confirmed releases in Arkansas peaked in 2001 and has slowly declined since that time (Arkansas Department of Environmental Quality, 2012). Releases from USTs are required to be investigated, and those with groundwater impacts are required to have owners define the vertical and horizontal extent of contamination. Once defined, a Corrective Action Plan is implemented to mitigate the impact of contamination. The effectiveness of remediation normally is evaluated through groundwater monitoring.

## Groundwater Quantity and Use

Water law traditionally has been concerned with the quantity of water available for all shared uses. The development and management of groundwater resources in Arkansas takes place within a framework of common law, legislative law, and administrative policy. Arkansas is a water-rich State with a mean annual precipitation of 48 inches in the north and 56 inches in the south (Kleiss and others, 2000; Pugh and Westerman, 2014). However, long-term unsustainable water use for industry, public supply, and the agricultural economy of eastern Arkansas has resulted in groundwater depletion issues, and groundwater policy has emerged in response to these events.

### Reasonable Use/Correlative Rights Doctrine

A water right, as defined by law, is not legal title to the water but the legal right to use it in a manner dictated by State law. In Arkansas, groundwater is generally subject to the same treatment given to surface water in case law as early as 1882 and conforms to the riparian doctrine, or rights system, which is recognized in Eastern States. This concept holds that the riparian owner, that is, the property owner of land overlying a groundwater source of water, has the right to withdraw and use beneficially the water and shares this right equally with other riparian owners. Additionally, water withdrawals are limited to what is determined to be reasonable in comparison with other riparian owners. All riparian owners have equal right to use reasonable amounts of groundwater, but this right may vary with time and is subject to modification; for example, as new users exert their rights to the water (Arkansas Natural Resources Commission, 2011).

Disputes over groundwater generally have been resolved according to a reasonable use test. There were two early cases in Arkansas that dealt with the question of the right to use groundwater:

1. In 1957, the Arkansas Supreme Court applied the riparian rights concept of reasonable use to groundwater use in *Jones* v. *Oz-Ark-Val Poultry Co.* (Looney, 1990; Arkansas Natural Resources Commission, 2011). This case was a conflict between industrial use and domestic use of groundwater. The court recognized that under State law domestic use is given the highest priority, and the right to use groundwater is a correlative right among property owners in which each has the right to a reasonable amount up to the full extent of the water use need, if the supply is sufficient such that other users are not adversely impacted. Thus, groundwater is subject to the reasonable use/correlative rights doctrine, which includes the concept of shared reductions in time of allocation.

2. In 1975, the court again addressed the reasonable use doctrine and the right to use groundwater when it dealt with the right to transfer water away from a “riparian land” in groundwater cases. In *Lingo* v. *City of Jacksonville* (Looney, 1990; Arkansas Natural Resources Commission, 2011), the court indicated that it would be permissible for a riparian owner to remove groundwater and either use it or sell it away from the tract of land from which it was pumped, if this use did not injure the common supply of the riparian owners.

### Statutory Water Laws and Policy

One of the first documented water-resources reports was published in 1939 by the Arkansas State Planning Board (Arkansas State Planning Board, 1939). This report is one of the first documents to identify a groundwater depletion problem in the Grand Prairie and to suggest a study of augmenting groundwater in the rice producing area with a diversion and importation of surface water. Importantly, the report called for the establishment of a permanent Water Resources Commission. In 1957, Arkansas began to move away from traditional case-by-case adjudication of water rights, and the General Assembly passed legislation creating a State agency with the responsibility to resolve water conflicts. Specifically, this agency, a predecessor to ANRC, had the authority to allocate available stream water during periods of shortage (Act 81 of 1957, ACA §15–22–201 *et seq*.), but Act 81 excluded any control over groundwater (Mack, 1963). Prior to 1957, bills had been introduced to the legislature to "facilitate the conservation of groundwater" by encouraging surface-water developments and to make the filing of water-well logs mandatory, but these bills did not pass or were withdrawn (Mack, 1963; McGuiness, 1951).

The ANRC serves as the State's primary water-resources planning and management agency with authority to develop the State Water Plan and other appropriate policy documents. The agency's groundwater policy has evolved over the past few years in response to substantial groundwater-level declines observed in eastern and southern parts of the State. In general, the policy, as outlined by the 1975 and 1990 water plans, is to provide for the unmet water demand through the practices of conservation, education, and the use of excess surface water in a conjunctive-use pumping strategy to protect groundwater resources. Although implementation of the policy, especially with respect to use of excess surface water, has progressed slowly and groundwater levels continue to decline throughout much of the State, regulation of groundwater withdrawals has been reserved as a last resort for groundwater resource protection (D. Todd Fugitt, Arkansas Natural Resources Commission, oral commun., 2013). However, various pieces of legislation were passed to establish a comprehensive groundwater-protection program as outlined in ANRC's Rules and Regulations, Title IV, "Rules for the Protection and Management of Groundwater" (Arkansas Natural Resources Commission, 2005) that encourages the conservation of groundwater while protecting the beneficial use of aquifers for future generations. Key legislation includes:

1. Act 1051 of 1985 (ACA §15–22–301 *et seq*.) requires all groundwater users to report water usage to ANRC. As ANRC is charged with the duty to make various determinations concerning water supply and demand, it is important that the agency has some mechanism for receiving water-use information. Domestic uses of groundwater having a potential flow rate of less than 50,000 gallons per day are exempt from reporting. The quantity, location, type of use, and name of the user must be registered on an annual basis with the Commission. The quantity used must be reported by March 1 of the following year. In 2009, there were approximately 49,558 registered wells reported in the State. Of this total, 48,599 (98.1 percent) were agricultural wells, most of which were used for irrigation and were located primarily in eastern Arkansas. The remaining 959 reported wells were used predominately for commercial, industrial, and public water supply purposes (Arkansas Natural Resources Commission, 2012a).
2. Act 154 of 1991, the Arkansas Ground Water Protection and Management Act, was an outcome of the 1990 Arkansas Water Plan, which attempted to address some of the deficiencies in the law with regard to groundwater, especially groundwater depletion. The act provided ANRC with authority to designate critical groundwater areas and provided a process for initiation of regulation limiting groundwater withdrawals in these areas. The legislation also authorized ANRC to develop a groundwater-classification system and groundwater-quality standards, set groundwater rights, establish water-use registration fees, and establish a mechanism for local groundwater management, but little guidance is provided as to what may be included in a regulatory program (Looney, 1995). The law mandated that ANRC evaluate the condition of the State's aquifers on a biennial basis and make recommendations concerning safe yields and critical groundwater areas. The ANRC works with the USGS, the U.S. Department of Agriculture (USDA)-NRCS, and the AGS to monitor water levels and water quality in a network of over 1,200 wells statewide to evaluate the State's groundwater resources.
3. Act 1426 of 2001 (ACA §15–22–903 *et seq*.), an amendment to the Arkansas Ground Water Protection and Management Act, requires individuals with nondomestic water wells in certain aquifers to install meters to accurately compute water usage.

## Critical Groundwater Area Designation

Pumping from the most productive aquifers in Arkansas—the Mississippi River Valley alluvial and Sparta aquifers—has led to declining water levels, reduced well yields, and the deterioration of the water quality in areas throughout the Coastal Plain of eastern and southern Arkansas. These aquifers are the principal sources of water for irrigation, industrial, and public drinking-water supplies in this region. Since enactment of the Arkansas Ground Water Protection and Management Act, ANRC has designated three critical groundwater areas (fig. 1) in Arkansas.

The South Arkansas critical groundwater area is composed of the Sparta aquifer in Bradley, Calhoun, Columbia, Ouachita, and Union Counties. Since the 1996 designation, education, conservation, and development and usage of excess surface water have caused water levels within the areas to stabilize or rise (Arkansas Natural Resources Commission, 2013a) in the Sparta aquifer.

The Grand Prairie critical groundwater area, designated in 1998, includes the Mississippi River Valley alluvial and Sparta aquifers within Arkansas, Jefferson, and Prairie Counties as well as parts of Lonoke, Pulaski, and White Counties. Water-level data from this area continue to show declines (Arkansas Natural Resources Commission, 2013a).

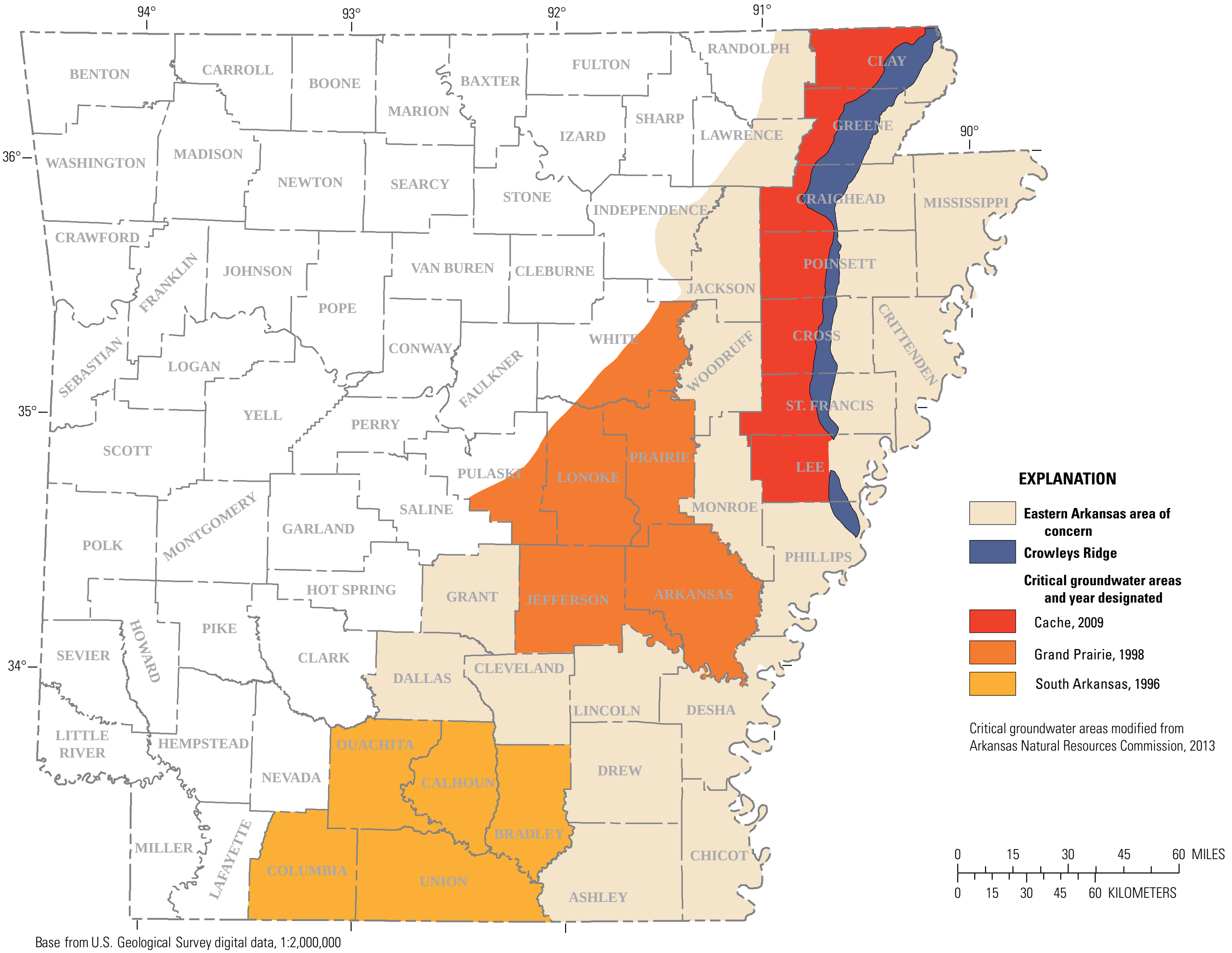



**Figure 1.** Location of critical groundwater areas in eastern Arkansas and counties referenced in this report.

The Cache critical groundwater area, designated in 2009, includes the Mississippi River Valley alluvial and Sparta aquifers within parts of Clay, Craighead, Cross, Greene, Lee, Poinsett, and St. Francis Counties lying west of Crowleys Ridge. Water-level data from this area continue to show declines (Arkansas Natural Resources Commission, 2013a).

Specific criteria used in designating a critical groundwater area include water levels declining at a rate of 1 foot per year (ft/yr) or more, water levels declining below the top of a confined aquifer or below the 50-percent saturated thickness for an unconfined aquifer, and groundwater-quality degradation. Water-level data collected by the ANRC, the USGS, and the USDA-NRCS suggest that there are additional areas throughout the State experiencing substantial water-level declines that may qualify for future critical groundwater area designation (Arkansas Natural Resources Commission, 2012a).

The designation of a critical groundwater area allows Federal, State, and local groups to work together in providing a managed and protected resource for current and future water users by focusing on conservation and education. Critical area designation also allows Federal and State agencies to focus cost-share and tax incentives for conservation projects within those areas. Critical area designation does not involve regulation of water use or well drilling but is a proactive process, which focuses on the prevention and mitigation of problems associated with groundwater-level declines and groundwater-quality degradation. The most effective tools in use by the State are education programs, conservation tax incentives, and the development of alternative surface-water supplies and a conjunctive-use strategy.

The Arkansas Groundwater Protection and Management Act also provides a process for the initiation of a regulation limiting groundwater withdrawals in critical groundwater areas. ANRC must determine if implementation of a regulatory program is necessary and, if determined, follow administrative procedures, which include public hearings in the affected counties. Once ANRC has made a declaration of necessity, a regulatory program may be implemented through a system based on the issuance of water rights. Groundwater rights would be prioritized by the type of usage: sustaining life, maintaining health, and increasing wealth. To date, ANRC has not sought regulatory authority in any of the designated areas (Arkansas Natural Resources Commission, 2011).

An important goal of Arkansas water users, water planners, and water-policy managers is achieving long-term, effective, fair, and equitable uses of the State's limited groundwater resources. Water-resources policies and programs focus on conjunctive use of the State's groundwater and surface-water resources at optimized levels that are sustainable while providing the maximum amount of water possible to support life, health, and commerce. This sustainable yield conjunctive-use strategy is supported using water budget and groundwater model approaches. ANRC and other State water planners advocate sustainable-yield groundwater protection as a means of achieving the specific goals of preventing broad, long-term groundwater-level declines, assuring long-term viability of aquifers to provide necessary yields, preventing litigation, providing groundwater supplies for drought, preventing groundwater-quality degradation, protecting riparian rights, and providing courts with an objective means for determining reasonable and unreasonable uses. While the definition of sustainable yield can be subject to interpretation, Arkansas water policy has tended to follow a deferred perennial yield strategy, which accepts that current groundwater levels or levels defined by the critical groundwater area designation are reasonable or are at least acceptable. Groundwater-level monitoring data, groundwater-budget studies, and groundwater-modeling efforts show that for broad areas of several important aquifers in the State, rates of groundwater usage are not sustainable (Arkansas Natural Resources Commission, 2013a), and collaborative conservation efforts by ANRC, industry, municipalities, and local community networks are the primary tools in developing solutions in these areas.

## Groundwater and Climate Variation

Numerous factors affect changes in groundwater levels and the volume of stored water in Arkansas' aquifers. Prior to extensive mining of groundwater to meet the increasing water-supply demands from industrial, commercial, public, irrigation, and other uses, groundwater levels and volume of water stored in the State's aquifers were primarily dependent on precipitation patterns and stream stage coupled with recharge characteristics of surficial sediments in the aquifer outcrop and subcrop (any area where an aquifer is covered by unconsolidated deposits) areas. Because of these relations, long-term changes in climate controlling spatiotemporal patterns in precipitation, drought, and evapotranspiration can have a substantial influence on groundwater discharge and recharge (Hanson and others, 2004). To understand and define the long-term changes, research needs to address the effects of natural climate patterns on interannual to multidecadal timescales; a lack of understanding of climate patterns on these timescales is a major obstacle to the reliable characterization of global climate trends resulting from human activities (Ghil, 2002). State water planners and managers must understand the nature and potential magnitude of changes in climate—whether natural or human-induced—and evolving water needs and prepare for any contingency resulting from varying weather patterns to ensure the health of people and the viability of State commerce. Although difficulties can arise in establishing Arkansas policy because of the uncertainty in predicting long-term trends in climate patterns in the State, various studies have been conducted to establish historical patterns of the effects of precipitation on groundwater levels and to predict potential effects of long-term climate trends on available groundwater resources in the State. As such, ANRC and other State water planners and managers are aware of potential effects on water resources from varying climate trends and are conducting studies for improving the understanding of these effects on aquifers in Arkansas.

Various studies have documented the effects of short-term climate trends on groundwater levels in the State. Czarnecki and Schrader (2013) compared groundwater-level fluctuations in wells completed in the Mississippi River Valley alluvial aquifer to variability in annual precipitation from 2004 through 2010, which included some of the wettest and driest years on record for Arkansas. The wettest year on record for Arkansas occurred in 2009 with 81.79 inches of precipitation compared to an average precipitation (2004 through 2010) of 47.1 in/yr. In contrast, 2005 and 2010 were the 7th and 14th driest years on record (1878 to 2010) with 34.55 and 36.52 in/yr, respectively. Drier conditions between 2004 and 2008 led to an average decline in groundwater levels of 1.62 ft, whereas wetter conditions between 2006 and 2010 led to an average rise in groundwater levels of 1.36 ft (Czarnecki and Schrader, 2013).

Kresse and Huetter (1999) compared precipitation amounts to water levels from six wells completed in the Mississippi River Valley alluvial aquifer in Jefferson County for the period between 1955 and 1994. Average precipitation in Jefferson County for this period was 48.5 inches, which compares closely with the average of 47.1 from Czarnecki and Schrader (2013). Several years of lesser and greater (relative to the average) precipitation resulted in decreases and increases, respectively, in groundwater levels for the six wells. Two of the six wells were within a well-defined cone of depression in the Grand Prairie region, whereas four wells were outside this cone of depression; the four wells outside the cone of depression showed the greatest variation in water levels. For example, from 1976 through 1978, precipitation ranged from approximately 6 to 10 inches below average, during which time water levels in the four wells outside the cone of depression had water-level decreases ranging from approximately 5.5 to 7.0 inches. The year 1980 had an annual precipitation amount approximately 20 inches above average, and the same four wells exhibited water-level increases ranging from approximately 1.0 to 4.0 inches despite steadily increasing irrigation use in the area. The two wells within the cone of depression showed a minor water-level increase of approximately 0.5 inch in one well and only a diminution of a long-term decreasing water-level trend in the other well in 1980. These studies demonstrate a strong influence on water levels from changes in annual precipitation within short temporal scales, an important indicator of the effects of climate variability. Inspection of these data also shows that climate has considerably lesser control on water levels in areas where stress on the aquifer is great, and most of the water is being removed from storage.

Long-term climate trends can affect the hydrologic cycle in many ways. Components of the hydrologic cycle that may be affected include atmospheric water vapor content, precipitation and evapotranspiration patterns, snow cover and melting of ice and glaciers, soil temperature and moisture, and surface runoff and streamflow (Bates and others, 2008). Potential hydrologic effects of long-term climate trends have been well documented, although relatively little research has been conducted on effects of climate trends on groundwater (Holman, 2006). Anthropogenic factors, such as reduction in streamflow, lowering of the water table, and removal of water from storage through groundwater pumping complicates quantification of the effects of changing climate on groundwater (Kundzewicz and others, 2007). Clark and others (2013) used a frequency analysis of hydroclimate data and global climate model results to improve understanding of aquifer hydrologic response in the Mississippi embayment. Although temperatures in the Mississippi embayment are projected to increase slightly (1–1.5 degrees Celsius [°C]) and precipitation to decrease slightly (approximately 5 percent) over the next two decades, model simulations from Clark and others (2013) showed little difference between drier climate or wetter climate model scenarios in terms of percent groundwater-level change. The lack of difference in the two scenarios was attributed to the fact that the greatest change in the overall groundwater budget in the Mississippi embayment was primarily the result of the magnitude of groundwater removed from storage, with changes in net recharge having negligible effects. It should be noted, however, that such models evaluate groundwater flow on large regional scales and do not provide robust evaluation of groundwater flow and water levels at local scales caused by small-scale variation in recharge and pumping. The studies by Kresse and Huetter (1999) and Clark and others (2013) suggest that reduced recharge from changing climate trends may show little effect on water levels in wells within cones of depression or in areas where pumping is removing large quantities of water from storage but will affect more strongly water levels in wells outside of these areas that show large water-level responses to local precipitation on short time scales.

## Monitoring and Assessment of Groundwater

Monitoring of groundwater is conducted by numerous Federal and State agencies and universities in Arkansas. Groundwater monitoring includes mandated monitoring at regulated sites, which has been previously discussed, short-term research-oriented monitoring, and ambient monitoring. Mandated monitoring by regulatory agencies (for example, ADEQ) is a valuable resource but often is limited by a reduced number of constituents. Additionally, this monitoring often is associated with contaminated sites and cannot be used to describe natural or background groundwater geochemistry.

A substantial amount of groundwater research has been conducted by the University of Arkansas in Fayetteville. Although this research has resulted in scientific data and information that can be used to understand, manage, and protect water resources within Arkansas, most of the resulting data and reports are not available online. Hardcopy reports, theses, and journal articles are available at the Arkansas Water Resources Center (AWRC) technical library, which can be accessed at http://www.uark.edu/depts/awrc/index.html.

There are numerous ambient monitoring programs as well as site-specific studies related to assessment of groundwater quantity and quality issues. Many of the studies involve cooperative efforts by the USGS, ANRC, ADEQ, and other Federal and State agencies. Groundwater monitoring is not limited to water quality, as there is a substantial ongoing effort in the State to monitor and evaluate water levels, especially in critical groundwater areas. Data collection sites primarily include existing irrigation and domestic wells and a few public water-supply wells. Some monitoring wells have been installed by ANRC and USGS to serve as data-collection points in specific aquifers. Groundwater-quality monitoring activities in Arkansas are funded in large part by EPA grants under Sections 106 and 319 of the Clean Water Act. Funding for some conservation-monitoring programs has been made through the NRCS. The following subsections document some of the ongoing groundwater-monitoring programs in Arkansas.

## Arkansas Department of Health

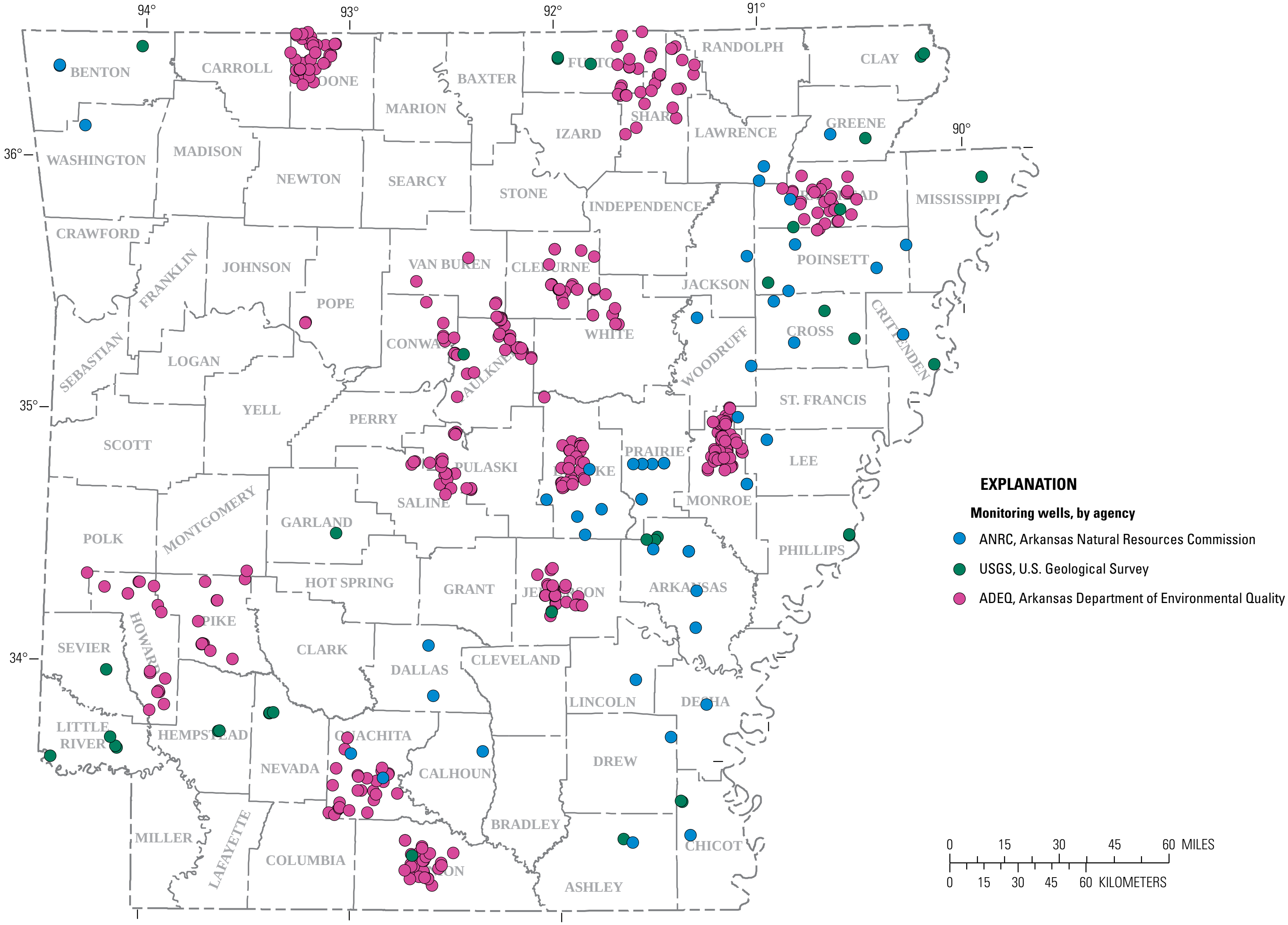
The ADH currently (2013) maintains a database of approximately 1,300 wells that are sampled every 3 years for inorganic, organic (for example, pesticides, herbicides, volatile organic compounds, and semi-volatile organic compounds), and radiological contaminants. However, treated water predominantly is sampled, which does not necessarily reflect the natural chemistry of groundwater (Arkansas Department of Health, 2013). Nitrate is monitored on at least an annual basis, total coliform sampling is conducted monthly, and trihalomethanes and byproducts of disinfection are monitored on a quarterly or annual basis depending on the source and the population served by the system. Additionally, raw water from groundwater wells that may be directly influenced by surface waters is sampled weekly for bacteriological testing and other parameters as required by the SDWA.

## Arkansas Department of Environmental Quality

The ADEQ has developed an ambient groundwater-monitoring program to help assess the quality of groundwater in various aquifers throughout the State (fig. 2). The program, begun in 1986 as part of ADEQ's responsibilities in administering its Groundwater Protection Strategy (Arkansas Department of Environmental Quality, 1996), currently (2013) includes 11 areas selected for monitoring, with sampling conducted from multiple wells in each area on a 3-year rotational basis. These areas were chosen as high risk localities on the basis of local contamination threats and aquifer vulnerabilities. These data are used to document trends and changes in water quality over time. The monitoring program currently (2013) consists of approximately 250 well and spring sites. Samples are analyzed for a full suite of inorganic constituents, including major cations, anions, and trace metals; in addition, semivolatile and volatile organic analyses are performed on samples in areas where industry, landfills, and other facilities store, manufacture, or dispose of organic chemicals. In areas with row-crop agriculture, samples commonly are analyzed for pesticides. Published reports for each area of the State are produced following each sampling event (Arkansas Department of Environmental Quality, 2013d). Data are accessible through various ADEQ publications and in the EPA's STORET database. Summaries of monitoring results are presented in the State 305(b) report, which is published in accordance with Section 106(e) of the Clean Water Act (Arkansas Department of Environmental Quality, 2012).

## Arkansas State Plant Board

The goal of ASPB's groundwater monitoring program is to prevent the State's groundwater from being polluted by agricultural chemicals and to respond appropriately if pollution is found. ASPB recognizes that preserving groundwater quality is less costly and more ecologically sound than restoring groundwater to its natural state, a process that may not be technically or economically viable (Arkansas State Plant Board, 2013). The groundwater monitoring program is a voluntary program that offers laboratory testing of groundwater samples from agricultural wells to help ensure that producers and applicators are using pesticides in accordance with label directions to protect and preserve groundwater. ASPB monitors groundwater in areas that may be considered vulnerable to agricultural pesticide contamination based on area use patterns and the concentration of agricultural production land in the vicinity. Since inception of the groundwater-sampling program in 2004, ASPB has sampled 271 wells in 30 counties. Results are summarized in annual reports. These reports and all sample results can be found on the ASPB Web site (Arkansas State Plant Board, 2013).




Base from U.S. Geological Survey digital data, 1:2,000,000

**Figure 2.** Location of ambient groundwater-quality monitoring sites in Arkansas.

### Arkansas Natural Resources Commission

The ANRC sponsors groundwater monitoring in six groundwater study areas within the State. Water-level monitoring is a cooperative program with ANRC, USGS, NRCS, and local water-resources agencies. Each spring approximately 700 wells are monitored in the Mississippi River Valley alluvial aquifer resulting in the largest number of water-level measurements for an aquifer in the State. This number varies from year to year depending on available resources. There are approximately 300 wells that are monitored for water levels in the Sparta aquifer. A monitoring schedule has been established to obtain data from the Mississippi River Valley alluvial aquifer and the Sparta aquifer on an annual basis. These measurements are made each spring to minimize the effects of seasonal pumping for irrigation. The drawdown that results from seasonal pumping is determined by the NRCS and ANRC by taking measurements of the alluvial aquifer in the spring and fall. Additionally, hydrogeologic data are collected statewide; however, resources are focused on study areas where water-level declines and water-quality degradation have been observed historically. Results of assessments are published annually by ANRC in the Arkansas Groundwater Protection and Management Report (Arkansas Natural Resources Commission, 2012a). Long-term water-level data collected over a 25-year period indicate that there are areas of the State experiencing groundwater withdrawals of such magnitude that demand on the aquifer exceeds the sustainable yield, resulting in consistently falling groundwater levels and the development of depressions in the potentiometric surfaces of the Mississippi River Valley alluvial and Sparta aquifers (Arkansas Natural Resources Commission, 2013a).

### U.S. Geological Survey

The USGS, in cooperation with State, Federal, and other local governmental agencies, collects a large amount of data each year pertaining to the groundwater resources of Arkansas. The USGS samples 24 wells (or springs) in 14 aquifers (fig. 2) on a 5-year rotational basis for a variety of constituents including nutrients, metals, radioactivity, organics, and selected primary and secondary drinking-water constituents. USGS also participates in a cooperative program to measure groundwater levels for seven aquifers in Arkansas on a rotating basis with water levels from over 600 available Mississippi River Valley alluvial and Sparta aquifer wells being measured on a 2-year rotation (Arkansas Natural Resources Commission, 2011). USGS also measures specific conductance and groundwater levels continuously at 23 (as of 2013) real-time stations (fig. 2). These data, accumulated since 1969, constitute a part of the USGS' National Water Information System (NWIS), a database for developing an improved understanding of the water resources of the State. The NWISWeb database provides access to groundwater levels and water-quality data at sites throughout the State. This Web service provides methods for retrieving daily data, such as water levels and other real-time data (U.S. Geological Survey, 2013b). The wells monitored by USGS are in a constant state of flux depending on cooperator needs and funding and are not differentiated on figure 2, which only depicts total wells monitored by the USGS in 2013. For a current list of water-quality and continuous water-level monitoring sites see http://ar.water.usgs.gov/.

## Overview of Aquifers of Arkansas

Prior to any discussion of aquifers, defining the frequently used terms is useful and important to the reader. Groundwater generally is defined as any water under the surface of the ground (Freeze and Cherry, 1979; Fetter, 1988), which creates little confusion on the part of the scientific community, regulators, and the general public. The term "aquifer," however, is not such a simple term, is often hotly debated, and can lead to problems in applying regulations pertaining to required monitoring and remediation of impacted aquifers (Skinner, 1984). Various definitions are found for the term "aquifer." Fetter (1988) defines an aquifer as "… a geologic unit that can store and transmit water at rates fast enough to supply reasonable amounts to wells." Freeze and Cherry (1979) define an aquifer as "… a saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients." Freeze and Cherry (1979) also provide an alternative definition widely used in the water-well industry "… is permeable enough to yield economic quantities of water to wells." The above definitions all have qualitative descriptors, such as "reasonable amounts," "significant quantities," and "economic quantities," which only serve to create further confusion.

Less permeable geologic units that restrict the vertical movement of groundwater between aquifers are referred to as "confining units." Fetter (1988) defines a confining unit as "A body of material of low hydraulic conductivity that is stratigraphically adjacent to one or more aquifers. It may lie above or below the aquifer." Where a stratigraphic unit of regional extent restricts the vertical movement of groundwater from underlying or overlying aquifers, these units often are assigned a formal name of "confining unit."

A problem that arises from strict application of these terms is that local use may be at variance with regional hydrologic perception and designations for various hydrogeologic units. An example that highlights the importance of the discussion of "aquifers" and "confining units" is found in the nomenclature associated with the correlation of stratigraphic geologic units and regional hydrologeologic units in the Ozark Plateaus in northern Arkansas. The Springfield Plateau aquifer is a regional aquifer across parts of Arkansas, Oklahoma, Kansas, and Missouri and is confined by less permeable shale and sandstone rocks of upper Mississippian to Pennsylvanian age, collectively referred to as the Western Interior Plains confining system (Imes and Emmett, 1994). Although regionally serving as an upper confining system for the underlying more porous and permeable Springfield Plateau aquifer, the formations constituting this confining system are important local sources of domestic supply. The aquifer typically yields less than 10 gallons per minute (gal/min) and upwards to 20–50 gal/min and often serves as the only source of water across large areas of the Boston Mountains in Arkansas (fig. 3). Regionally, however, the relatively low permeability of these strata impedes vertical flow of water into the underlying and more hydrologically productive formations of the Springfield Plateau aquifer.

For this report, although the regional hydrogeologic nomenclature often is applied for the hydrogeologic formations of importance to the State, the designation of aquifer is implied for any formation or group of formations that have served or currently serve as important local or regional water supplies for any use. A review of the history of groundwater use in Arkansas identified 16 distinct formations or groups of formations that historically and currently serve as aquifers (fig. 3). For this report, aquifers are grouped into the Coastal Plain Province and the Interior Highlands Division physiographic regions of the State (referred to as Coastal Plain and Interior Highlands, respectively, in the remainder of this report). Aquifers of the Coastal Plain generally are characterized by unconsolidated sediments with higher porosity and greater yields compared to aquifers in the Interior Highlands, which generally are characterized by fractured bedrock with low secondary porosity and lesser yields (see “Geologic Setting” in the next section for additional information on the differing geology in these two regions of the State). These 16 aquifers, the formation(s) hosting the aquifers, and the number of sites with available groundwater-quality data are listed in table 2.

A review of table 2 reveals a large variation and a disparity in the number of sites with water-quality data available, which reflects the attention focused on the Mississippi River Valley alluvial aquifer relative to other aquifers over the years that often was based on economic value or importance as a regional public-supply source. For example, the Mississippi River Valley alluvial aquifer in the Coastal Plain, used almost solely for irrigation supply, accounted for more than 94 percent of all groundwater withdrawn in Arkansas and 62 percent of total combined groundwater and surface-water withdrawals in the State for 2010. Therefore, this aquifer is monitored more extensively than other aquifers and included 4,061 sites (as of 2013) with some form of water-quality data. The Sparta aquifer long has been an important source of public-supply water and has in recent years become an important source of irrigation supply as groundwater levels have declined in the Mississippi River Valley alluvial aquifer in certain areas of the State. In keeping with this importance, the database for the Sparta aquifer includes 1,626 sites with associated water-quality data. Although of local importance to families relying on groundwater as a source of domestic supply, other aquifers are of less importance from a regional perspective and have a limited number of sites with water-quality data. An exception to this pattern is the large number of water-quality sites associated with the Arkansas River Valley alluvial aquifer. A monitoring program by the Arkansas Geological Commission (now known as Arkansas Geological Survey), the U.S. Army Corps of Engineers, and the USGS, between 1957 and 1972, collected abundant water-level and limited water-quality data prior to and after completion of the lock and dam system in 1969 on the Arkansas River. These data were input into the USGS NWIS database (U.S. Geological Survey, 2013b).

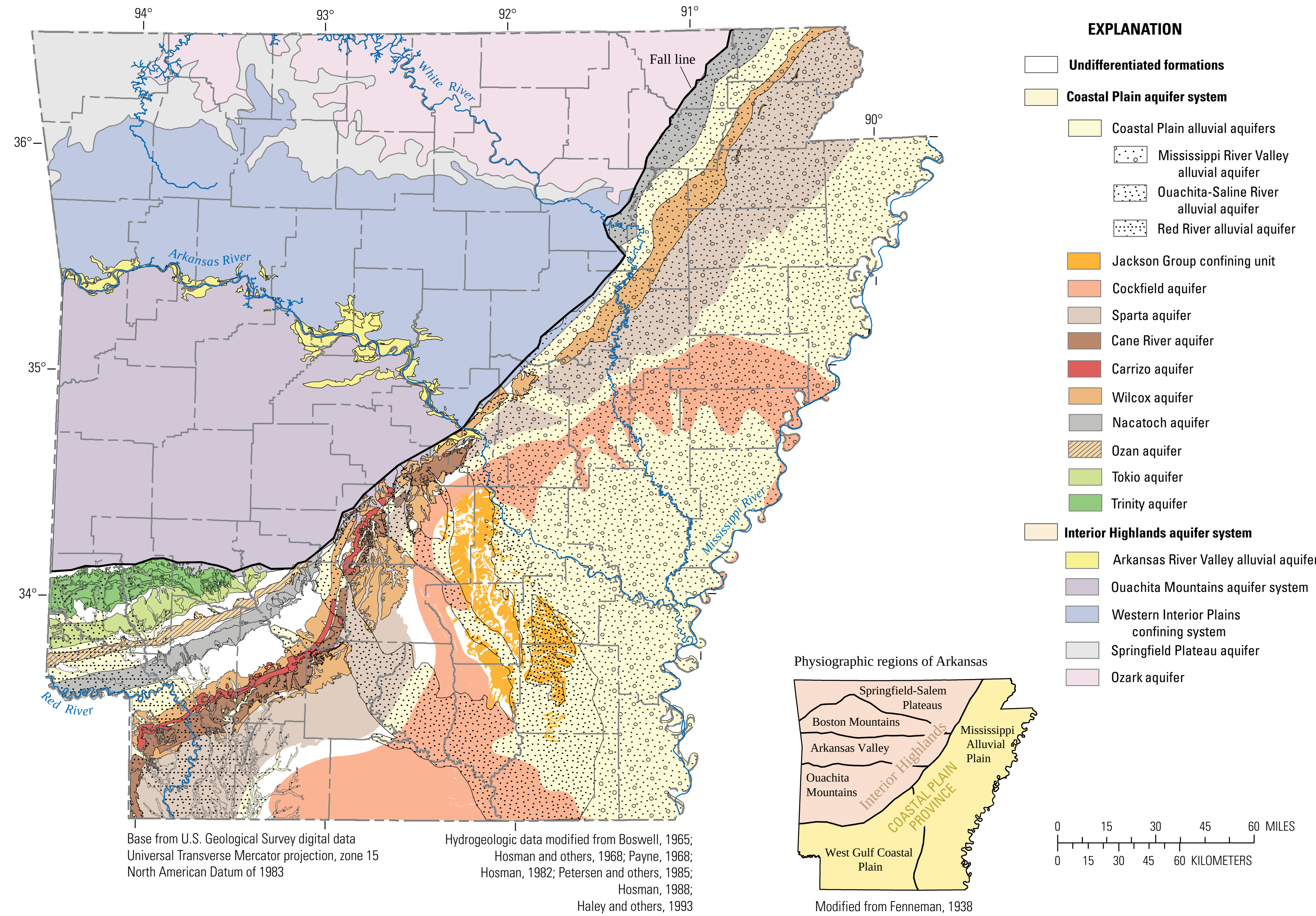



**Figure 3.** Combined outcrop, subcrop areas, and physiographic regions for the 16 aquifers serving as major and minor sources of groundwater supplies throughout Arkansas.

**Table 2.** Nomenclature, geologic age, use, and number of sites with groundwater-quality data for the 16 major and minor aquifers in Arkansas.

| Major division | Province | Section | Formation or group of formations | Geologic age | Hydrogeologic unit name | Aquifer code | Aquifer use[1] | Water-quality sites |
|---|---|---|---|---|---|---|---|---|
| Atlantic Plain | Coastal Plain | Mississippi Alluvial Plain and West Gulf Coastal Plain | Coastal Plain Alluvium | Quaternary | Mississippi River Valley, Ouachita-Saline, and Red River alluvial aquifers | 110ALVM, 112ALVM 112VLTR, 112TRRC | IR, ps, in | 4,061 |
| | | | Jackson Group | Tertiary | Vicksburg-Jackson confining unit | 124JCKS | D | 68 |
| | | | Cockfield Formation | Tertiary | Cockfield aquifer | 124CCKF | IN, IR, ps | 257 |
| | | | Sparta Sand | Tertiary | Sparta aquifer | 12405MP, 124SPRT, 124MMPS | IR, PS, IN | 1,626 |
| | | | Cane River Formation | Tertiary | Cane River aquifer | 124CRVR, 124CANR | PS, d | 45 |
| | | | Carrizo Sand | Tertiary | Carrizo aquifer | 124CRRZ | D | 12 |
| | | | Wilcox Group | Tertiary | Wilcox aquifer | 124WLCX, 124WL-CXG | PS, ir, in | 170 |
| | | | Nacatoch Sand | Cretaceous | Nacatoch aquifer | 211NCTC | PS | 143 |
| | | West Gulf Coastal Plain | Ozan Formation | Cretaceous | Ozan aquifer | 212OZAN | D | 14 |
| | | | Tokio Formation | Cretaceous | Tokio aquifer | 212TOKO | PS, in | 165 |
| | | | Trinity Group | Cretaceous | Trinity aquifer | 218TRNT | PS, in | 38 |
| Interior Highlands | Ouachita Province | Arkansas Valley | Arkansas River Valley Alluvium | Quaternary | Arkansas River Valley alluvial aquifer | 110ALVM, 110TRRC 112TRRC | PS, IR, d | 680 |
| | | Ouachita Mountains | Collier Shale through Boggy Formation[2] | Cambrian through Pennsylvanian | Ouachita Mountains aquifer | 325HRSR, 325MCAL 326ATOK, 328JKFK 330ARKS, 330HSPG 330STNL, 350MSRM 361PKCK, 364BGFK | D | 162 |
| | Ozark Plateaus | Boston Mountains | Moorefield Formation through McAlester Formation[3] | Mississippian and Pennsylvanian | Western Interior Plains Confining System | 325HRSR, 325MCAL 326ATKN, 326ATOK 328BLYD, 328CNHL 328JKFK, 3331BSVL 331MFLD, 331PTKN | D | 287 |
| | | Springfield-Salem Plateaus | Boone Formation | Mississippian | Springfield Plateau aquifer | 330BOON | D, ps | 95 |
| | | | Van Buren Formation through Clifty Limestone[4] | Ordovician through Devonian | Ozark aquifer | 361FRVL, 364EVRN 364JCHM, 364STPR 367CTJF, 367CTTR 368PWLL, 371POTS 367RBDX, 367GNTR | PS, d | 131 |

[1]IR, irrigation; PS, public supply; IN, industrial; D, domestic. Listed in order of highest use by volume. Primary use in capital letters; secondary use in small caps.

[2]Collier Shale, Crystal Mountain Sandstone, Mazarn Shale, Blakely Sandstone, Womble Shale, Bigfork Chert, Polk Creek Shale, Blaylock Sandstone, Missouri Mountain Shale, Arkansas Novaculite, Hot Springs Sandstone, Stanley Shale, Jackfork Sandstone, Johns Valley Shale, Atoka Formation, Hartshorne Sandstone, McAlester Formation, Savanna Formation, and Boggy Formation.

[3]Moorefield Formation, Batesville Sandstone, Fayetteville Shale, Pitkin Limestone, Hale Formation, Bloyd Formation, Atoka Formation, Hartshorne Sandstone, and McAlester Formation.

[4]Van Buren Formation, Gasconade Formation, Roubidoux Formation, Jefferson City Dolomite, Cotter Dolomite, Powell Dolomite, Smithville Formation, Everton Formation, St. Peter Sandstone, Joachim Dolomite, Plattin Limestone, Kimmswick Limestone, Fernvale Limestone, Cason Shale, Brassfield Limestone, St. Clair Limestone, Lafferty Limestone, Penters Chert, and Clifty Limestone.

## Geologic Setting

The Coastal Plain Province, which includes the Mississippi Alluvial Plain and West Gulf Coastal Plain physiographic sections (fig. 3), is underlain by Mesozoic and Cenozoic sedimentary deposits (table 3) (McFarland, 2004). These sedimentary deposits represent the cyclic transgression and regression of Mesozoic and Cenozoic seas that followed extensive continental inundation by inland seas that extended from Central America to New England (Manger, 1983; Arthur and Taylor, 1998). The Mississippi River defines the eastern border of Arkansas and falls roughly along the axis of the Mississippi embayment, a south-plunging, asymmetrical geosyncline with the dip of the beds being steeper on the western side of the Mississippi embayment in the Coastal Plain. The Mississippi embayment is a result of downwarping and rifting related to the Ouachita orogeny, which formed a deep basin for subsequent sedimentation (Hosman, 1996). The Mississippi embayment represents an extension of the Coastal Plain into the continental interior (Manger, 1983).

**Table 3.** Stratigraphic column and correlated geohydrologic units of the Coastal Plain Province in southern and eastern Arkansas.

<table>
<tr><th colspan="3">Time-stratigraphic unit</th><th rowspan="2">Group</th><th rowspan="2" colspan="2">Formation</th><th rowspan="2">Regional geohydrologic unit</th></tr>
<tr><th>Era</th><th>System</th><th>Series</th></tr>
<tr><td rowspan="11">Cenozoic</td><td rowspan="2">Quaternary</td><td>Holocene</td><td rowspan="2"></td><td colspan="2">Alluvium</td><td rowspan="2">Mississippi River Valley, Ouachita-Saline River, and Red River alluvial aquifers[1]</td></tr>
<tr><td>Pleistocene</td><td colspan="2">Terrace deposits</td></tr>
<tr><td rowspan="9">Tertiary</td><td rowspan="7">Eocene</td><td>Jackson</td><td colspan="2">Jackson Group</td><td>Vicksburg-Jackson confining unit[1]</td></tr>
<tr><td rowspan="5">Claiborne</td><td colspan="2">Cockfield Formation</td><td>Upper Claiborne aquifer[1]</td></tr>
<tr><td colspan="2">Cook Mountain Formation</td><td>Middle Claiborne confining unit[1]</td></tr>
<tr><td>Sparta Sand</td><td rowspan="3">Memphis Sand[3]</td><td>Middle Claiborne aquifer[1,2]</td></tr>
<tr><td>Cane River Formation</td><td>Lower Claiborne confining unit[1]</td></tr>
<tr><td>Carrizo Sand</td><td>Lower Claiborne aquifer[1]</td></tr>
<tr><td>Wilcox</td><td colspan="2">undifferentiated</td><td>Upper, middle, and lower Wilcox aquifers[1]</td></tr>
<tr><td rowspan="2">Paleocene</td><td rowspan="2">Midway</td><td colspan="2">Porters Creek Clay</td><td rowspan="2">Midway confining unit[1]</td></tr>
<tr><td colspan="2">Clayton Formation</td></tr>
<tr><td rowspan="17">Mesozoic</td><td rowspan="17">Cretaceous</td><td rowspan="11">Upper</td><td rowspan="11"></td><td colspan="2">Arkadelphi Marl</td><td></td></tr>
<tr><td colspan="2">Nacatoch Sand</td><td>McNary - Nacatoch aquifer[4]</td></tr>
<tr><td colspan="2">Saratoga Chalk</td><td rowspan="5"></td></tr>
<tr><td colspan="2">Marlbrook Marl</td></tr>
<tr><td colspan="2">Annona Chalk</td></tr>
<tr><td colspan="2">Ozan Formation</td></tr>
<tr><td colspan="2">Brownstone Marl</td></tr>
<tr><td colspan="2">Tokio Formation</td><td rowspan="2">Tokio - Woodbine aquifer[4]</td></tr>
<tr><td colspan="2">Woodbine Formation</td></tr>
<tr><td rowspan="8">Lower</td><td rowspan="2"></td><td colspan="2">Kiamichi Shale</td><td rowspan="2"></td></tr>
<tr><td colspan="2">Goodland Limestone</td></tr>
<tr><td rowspan="6">Trinity</td><td colspan="2">Paluxy Sand</td><td rowspan="6">Trinity aquifer[4]</td></tr>
<tr><td colspan="2">De Queen Limestone</td></tr>
<tr><td colspan="2">Holly Creek Formation</td></tr>
<tr><td colspan="2">Dierks Limestone</td></tr>
<tr><td colspan="2">Delight Sand</td></tr>
<tr><td colspan="2">Pike Gravel</td></tr>
</table>

[1]Modified from Hart and others (2008).

[2]North of 35°N latitude, the Lower Claiborne confining unit and Lower Claiborne aquifer are undifferentiated and referred to regionally as the middle Claiborne aquifer (Hart and others, 2008).

[3]North of 35°N latitude, the Sparta Sand, Cane River Formation, and Carrizo Sand are undifferentiated and refered to regionally as the Memphis Sand (Counts, 1957; Hosman and others, 1968; Payne, 1972; Petersen and others, 1985; Hart and others, 2008).

[4]Modified from Renken (1998).

Downwarping and downfaulting proceeded further as a response to the weight of sediment accumulation enabling further accommodation of a very thick sequence of Mesozoic through modern sediments (Hosman, 1996).

While the oldest sediments exposed at the surface in the Coastal Plain are Cretaceous in age, Jurassic-age sediments have been encountered in the subsurface (Manger, 1983; Clark and Hart, 2009). Strata of Mesozoic and Cenozoic ages rest on an erosional surface developed on underlying Paleozoic rocks (Manger, 1983). The Cretaceous sedimentary deposits exposed in the West Gulf Coastal Plain of southwestern Arkansas represent shallow and often restricted (hypersaline) marine environments (McFarland, 2004). Toward the axis of the Mississippi embayment, these deposits were covered by Cenozoic deposits consisting of Tertiary marginal marine and continental deposits with a veneer of Quaternary terrace and alluvial deposits. The veneer of Quaternary terrace and alluvial deposits dominate eastern Arkansas with minor exposures of Tertiary units (Hosman and others, 1968; Hosman, 1982, 1996; Manger, 1983; McFarland, 2004; Clark and others, 2011b). The Cenozoic deposits constitute the main water-bearing units of importance within the Mississippi embayment (Clark and others, 2011b)

The strata of Mesozoic and Cenozoic age found at the surface in Arkansas are poorly cemented and indurated and therefore are soft and easily eroded, resulting in a relatively flat terrain with some low hills. The Mississippi River has eroded a broad valley into the Tertiary deposits filling the Mississippi embayment and leaving Crowleys Ridge as a prominent erosional remnant. Crowleys Ridge comprises Tertiary deposits capped by Quaternary loess (Manger, 1983; McFarland, 2004).

Sedimentary Paleozoic-age rocks are exposed over most of western Arkansas. This area is part of the Interior Highlands, which is subdivided into two provinces: the Ouachita Province and Ozark Plateaus Province. The sedimentary rocks of the Ouachita Mountains physiographic section consist of a thick sequence of shale, chert, sandstone, conglomerates, novaculite, and volcanic tuff deposited during the Paleozoic Era (table 4) within an elongate, subsiding

**Table 4.** Stratigraphic column and correlated geohydrologic units of the Ouachita Mountains Region, Arkansas.

| Time-stratigraphic unit | | Series | Formation | Regional geohydrologic unit[1] |
|---|---|---|---|---|
| Era | System | | | |
| Cenozoic | Quaternary | Holocene | Alluvium | |
| | | Pleistocene | Terrace Deposits | |
| Paleozoic | Pennsylvanian | Des Moinesian | Boggy Formation | Ouachita Mountains aquifer |
| | | | Savanna Formation | |
| | | | McAlester Formation | |
| | | | Hartshorne Sandstone | |
| | | Atokan | Atoka Formatioin | |
| | | Morrowan | Johns Valley Shale | |
| | | | Jackfork Sandstone | |
| | | | Stanley Shale | |
| | Mississippian | | Hot Springs Sandstone | |
| | | | Arkansas Novaculite | |
| | Devonian | Middle and Upper | | |
| | Sillurian | | Missouri Mountain Shale | |
| | | | Blaylock Sandstone | |
| | Ordovician | Upper | Polk Creek Shale | |
| | | Middle | Bigfork Chert | |
| | | Lower | Womble Shale | |
| | | | Blakely Sandstone | |
| | | | Mazarn Shale | |
| | | | Crystal Mountain Sandstone | |
| | Cambrian | | Collier Shale | |

[1]Modified from Renken (1998).

trough (Renken, 1998). Deposition from the Ordovician through the early Mississippian times represents “starved basin” conditions in which deposition was extremely slow. These sediments are overlain by late-Mississippian and early-Pennsylvanian sediments that were a result of very rapid deposition into a subsiding trough (Manger, 1983). The Ouachita Mountains are true geosynclinal mountains formed from strata deposited in deep water settings and uplifted and deformed by the compressional events associated with continental collision. The general structure of the Ouachita Mountains is a broad uplift with complex folds and numerous complex faults (Manger, 1983; McFarland, 2004). Sediments of the Ouachita Mountains are well indurated and generally well cemented as a result of deep burial, intense compression, and complex diagenetic history (Renken, 1998). The Arkansas Valley physiographic section comprises Quaternary-age alluvial deposits that filled a synclinorium generally lying between dipping rocks of the Boston Mountains to the north and the highly folded rocks of the Ouachita Mountains to the south, although these deposits are assigned to the Ouachita Province by Renken (1998).

The Ozark Plateaus consist of sedimentary strata that dip radially away from the core of the Ozark dome, which is located in southeastern Missouri (Manger, 1983). The Ozark Plateaus (table 5) are divided two physiographic sections: the Boston Mountains and the Springfield-Salem Plateaus (fig. 3). The Salem Plateau is characterized by outcropping Ordovician-age sedimentary rocks, which constitute the Ozark aquifer (table 5). These rocks crop out over much of north-central and northeastern Arkansas and consist mainly of karsted limestones and dolostones with some sandstone and shale. The Springfield Plateau is characterized by the outcrop of the Mississippian-age Boone Formation, which comprises karsted limestone interbedded with chert. The Boone Formation constitutes the Springfield Plateau aquifer (table 5). The Springfield Plateau aquifer is separated from the underlying Ozark aquifer by the Chattanooga Shale, which is the primary unit of the Ozark confining unit. Locally, the Ozark confining unit is absent and the Springfield Plateau aquifer rests unconformably on rocks of the Ozark aquifer. The Boston Mountains are characterized by outcropping Pennsylvanian-age sedimentary rocks that constitute the Western Interior Plains confining system, which overlies the Springfield Plateau aquifer (table 5). The rocks of the Boston Mountains are composed mainly of sandstones and shales, with some limestone units occurring near the base. The Ozark Plateaus have experienced extensive erosion and have deeply dissected stream valleys throughout. Sedimentary rocks of the Ozark Plateaus generally are nearly flat lying and dip toward the south. Gentle, low-amplitude folds have been observed in the Ozark Plateaus. A majority of the faults in the Ozark Plateaus are normal, with displacement generally occurring downward on the southern side. Rocks of the Ozark Plateaus were deposited on a relatively shallow continental shelf that was exposed at numerous times during the Paleozoic resulting in erosional surfaces throughout the stratigraphic sequence (Manger, 1983; Imes and Emmett, 1994; Renken, 1998; McFarland, 2004).

**Table 5.** Stratigraphic column and correlated geohydrologic units of the Ozark Plateaus Province in northern Arkansas.

| Time-stratigraphic unit | | Formation | Regional geohydologic unit[1] |
|---|---|---|---|
| Era | System | | |
| Paleozoic | Pennsylvanian | McAlester Formation<br>Hartshorne Sandstone<br>Atoka Formation<br>Bloyd Shale<br>Hale Formation | Western Interior Plains confining system |
| | Mississippian | Pitkin Limestone<br>Fayetteville Shale<br>Batesville Sandstone<br>Moorefield Formation | |
| | | Boone Formation<br>St. Joe Limestone Member | Springfield Plateau aquifer |
| | Devonian | Chattanooga Shale | Ozark confining unit |
| | | Clifty Limestone<br>Penters Chert | Upper Ozark aquifer |
| | Silurian | Lafferty Limestone<br>St. Clair Limestone<br>Brassfield Limestone | |
| | Ordovician | Cason Shale<br>Fernvale Limestone<br>Kimmswick Limestone<br>Plattin Limestone<br>Joachim Dolomite<br>St. Peter Sandstone<br>Everton Formation<br>Smithville Formation<br>Powell Dolomite<br>Cotter Dolomite<br>Jefferson City Dolomite | |
| | | Roubidoux Formation<br>Gasconade Dolomite<br>Gunter Sandstone Member | Lower Ozark aquifer |
| | | Van Buren Formation | |
| | Cambrian | Eminence Dolomite<br>Potosi Dolomite | |
| | | Doe Run Dolomite<br>Derby Dolomite<br>Davis Formation | St. Francois confining unit |
| | | Bonneterre Formation<br>Reagan Sandstone<br>Lamotte Sandstone | St. Francois aquifer |
| Precambrian | Precambrian | Precambrian intrusive and volcanic igneous rocks | Basement confining unit |

[1]Modified from Imes and Emmet (1994).

## Groundwater Use in Arkansas

Arkansas traditionally has been considered a water-rich State with a mean annual precipitation of 48 inches in the north and 56 inches in the south (Kleiss and others, 2000; Pugh and Westerman, 2014). This precipitation is the primary input for the State's water budget that includes the groundwater and surface-water systems; associated ecosystems; interception and uptake by vegetation; runoff plus direct input into streams, lakes, and other surface water bodies; and infiltration through soil and rock to the water table. Evapotranspiration processes redistribute water back into the atmosphere to renew this important part of the hydrologic cycle. Predevelopment groundwater levels reflect equilibrium between the natural filling of groundwater reservoirs by infiltration of precipitation and eventual discharge of groundwater as base flow to streams or springs. Historical and increasing demands on groundwater have changed this natural balance, have highlighted the fact that the resource is not without limit, and have necessitated the review of water use and water-use reporting requirements for groundwater throughout the State. Arkansas is the fourth largest user of groundwater in the Nation (Kenny and others, 2009). Groundwater use is extremely important for the State as groundwater irrigation is critical to agriculture—the keystone in the economy (McGraw and others, 2012). Irrigation accounts for the highest percentage of groundwater use in Arkansas (Holland, 2007), especially for rice production that requires large volumes of water during its growing season. Other groundwater uses in Arkansas include public supply, domestic rural self supply, commercial, industrial, mining, livestock, aquaculture, and duck hunting, as well as its use as an important source of base flow to surface-water bodies.

### Reporting and Registration

Since 1950, the USGS has conducted a water-use inventory by State every 5 years. From 1960 to 1985, the water-use inventory was conducted at the county level by computing aggregated estimates. Data were compiled from multiple Federal, State, and local sources. Many estimates of water use were based on multipliers of water requirements by type of use. Other early methods of data collection used surveys sent to known industrial, commercial, and public-supply entities; completion of the surveys was less than complete and not always accurate.

Data collection first began on a site-specific basis for surface-water withdrawals for irrigation in 1969. Surveys in 1980 and 1984 collected information on the amount of water used by industrial facilities (Arkansas Industrial Development Commission, 1980; Harrington and Childers, 1985). An inventory of public-water suppliers was completed in 1985. Beginning in 1987, water-use data-collection forms were mailed directly to industrial, commercial, and public-supply water users, which resulted in improved reporting (Baker, 1990).

In 1985, ANRC and USGS began collecting annual site-specific water-use information for all groundwater wells with a potential pumping rate more than 50,000 gal/d or surface-water users that withdraw more than 1 acre-foot per year (acre-ft/yr) (in accordance with Arkansas Act 1051 of 1985). Domestic users were exempted from the requirement to register their wells. ANRC in conjunction with the USGS created the Arkansas Water-Use Data Base System (ARWUDBS) to register, store, and conduct queries from Arkansas water-use data. Data from this system are available from the USGS, Little Rock, Ark. To generate a more complete water-use dataset, an annual $10 fee per well or relift (pumping from surface water) has been assessed by ANRC. Failure to comply with water-use registration requirements by ANRC results in a fine for the water user or well owner. Failure to comply after 2 years can result in the user's loss of water rights. Metering of the sustaining aquifers (Sparta, Cockfield, Cane River, Carrizo, Wilcox, Nacatoch, Roubidoux, and Gunter) was required in new wells after September 2001 and in all wells after September 2006 (Arkansas Natural Resources Commission, 2013b).

The 1985 water-use compilation represents the first site-specific, water-use data effort for the State. As such, the 1985 water-use data were likely underestimated, as the many thousands of water users needed time to comply with the new reporting requirements. The 1985 data possibly were underestimated by as much as 50 percent (Baker, 1990). The underestimation problems decreased by 1988 as more water users moved into compliance. Because agricultural users may not know exactly how much water is used in any particular year, they also report the type, acreage, and water-application rate of various crops. The reported acreage after 1988 was more accurate than the estimated acreage used in early water-use compilations (Baker, 1990). More information on the transition to the site-specific database can be found in Baker (1990).

Water-use data are reported through several avenues. In 2002, an interactive website was established for use in the Conservation District offices in 29 counties in eastern Arkansas because most irrigation use occurs in these counties. Agricultural users can verbally report their water use to trained personnel at a County Conservation District office or mail the registration form to ANRC. More information on the Arkansas water-use database can be found in National Research Council (2002).

### Categories of Water Use

The USGS water-use reporting program has changed its definition of categories through the years. Estimated groundwater use for Arkansas by category is shown in table 6. In the 1950 and 1955 compilations, only five categories were considered at the State level (rural, public, industrial, irrigation, and water power). In 1960, county-level estimates were reported but did not give water-use values for Jefferson and Ouachita Counties. Also in 1960, rural estimates were

**Table 6.** Groundwater use by category for Arkansas from published reports.

[Units are million gallons per day. Data marked with "--" indicates data were not published for that year and category]

| Year | Aquaculture[1] | Commercial[2] | Domestic[3] | Duck hunting[4] | Electric[5] | Industrial | Irrigation | Livestock[3] | Mining[2] | Public supply[6] | Total | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1938 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | **320** | Arkansas Water Study Commission, 1956 |
| 1945 | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | **525** | Baker, 1955 |
| 1950 | -- | -- | 35 | -- | -- | 65 | 678 | -- | -- | 35 | **813** | MacKichan, 1951 |
| 1952 | -- | -- | 35 | -- | -- | 70 | 720 | -- | -- | 40 | **865** | Baker, 1955 |
| 1955 | -- | -- | 24 | -- | -- | 121 | 790 | -- | -- | 28 | **963** | MacKichan, 1957 |
| 1960[7] | -- | -- | 26.08 | -- | -- | 101.75 | 712.75 | 18.57 | -- | 33.15 | [7]**892.3** | Stephens and Halberg, 1961 |
| 1965 | 103.51 | -- | 31.32 | 0.48 | 5.94 | 73.88 | 949.35 | 12.54 | -- | 53.71 | **1,230.73** | Halberg and Stephens, 1966 |
| 1970 | 212.18 | -- | 48.8 | 0.28 | 4.14 | 114.6 | 1,063.9 | 16.27 | -- | 70.85 | **1,531.16** | Halberg, 1972 |
| 1975 | 229.65 | -- | 46.15 | 1.26 | 2.45 | 105.76 | 2,033.3 | 28.53 | -- | 88.91 | **2,536.01** | Halberg, 1977 |
| 1980 | 284.88 | -- | 56.88 | 5.36 | 3.06 | 90.83 | 3,481.4 | 22 | -- | 109.97 | **4,054.38** | Holland, 1981 |
| 1981 | 233 | -- | 55 | -- | 2.37 | 92.7 | 3,760 | 23 | -- | 104 | **4,300** | Hall and Holland, 1984 |
| 1982 | 237.52 | -- | 55.64 | -- | 5.24 | 82.99 | 3,386.6 | 21.37 | -- | 99.19 | **3,890** | Holland and Hall, 1986 |
| 1985 | --[8] | 6.03 | 60.42 | -- | 1.09 | 64.01 | 3,332.7 | [8]241.95 | 1.03 | 104.49 | **3,811.72** | Holland, 1987 |
| 1990 | 98.53 | 14.31 | 50.61 | -- | 2.43 | 98.92 | 4,296.2 | 26.43 | 1.82 | 118.95 | **4,708.2** | Holland, 1993 |
| 1995 | 228.25 | 0.39 | 37.61 | -- | 5.15 | 107.95 | 4,925.7 | 15.43 | 0.00 | 135.11 | **5,455.59** | Holland, 1999 |
| 2000 | 187.35 | 3.85 | 31.22 | -- | 2.92 | 67.07 | 6,506.5 | 15.46 | 0.21 | 138.02 | **6,952.25** | Holland, 2004 |
| 2005 | 245.82 | 3.16 | 17.83 | 81.14 | 0.93 | 65.75 | 6,942.2 | 15.53 | 0.24 | 137.69 | **7,510.29** | Holland, 2007 |
| 2010 | 181.14 | 0.95 | 13.26 | 80.43 | 4.28 | 61.17 | 7,367.75 | 27.1 | 0.18 | 133.66 | **7,873.75** | unpublished data |

[1]Aquaculture was not reported prior to 1965. The 1970 water-use report used the term fish and minnow farms.

[2]Commerical and mining categories were lumped into the industrial category prior to 1985.

[3]In the 1950 and 1955 water-use reports, a"rural" category included both domestic supply and livestock use. For this report, "rural" use is displayed under the domestic category.

[4]Water use for wildlife impoundments was reported from 1965 through 1980 and included water withdrawn for migratory waterfowl. This category was not reported separately from 1985 to 2000; however, this type of use continued and, if reported, would have been combined into the irrigation category. Duck hunting was reinstated as a use category in the 2005 water-use report.

[5]In 1950, 1955, and 1960 water-use reports, the electric category included nonconsumptive use of hydroelectric power and was removed from this summary.

[6]The 1950 water-use report used the term municipal supply.

[7]Groundwater use was not reported for Jefferson and Ouachita Counties in 1960.

[8]In the 1985 water-use report, aquaculture was combined into the livestock category.

divided into rural domestic and rural livestock. Beginning in 1965, county-level groundwater use was reported by aquifer, as well as for wildlife impoundments for migratory waterfowl and aquaculture. Additional water-use compilations were completed for 1981 and 1982 (Hall and Holland, 1984; Holland and Hall, 1986). Mining and commercial use were divided into separate categories in 1985 (Holland, 1987). Data for aquaculture were combined with the livestock category in 1985.

Early reports did not separate water consumed by hydroelectric processes from nonconsumptive uses, and the amount of water stored behind dams was included in these early estimates; therefore, the total amount of water used was unrepresentatively high for 1950, 1955, and 1960 and was not included in the summary shown in table 6. More information on how the categories in the national program have changed through the years is found at U.S. Geological Survey (2013a).

## Statewide Groundwater Use

All counties in Arkansas report some groundwater use (Terrance W. Holland, U.S. Geological Survey, written commun., 2013). The largest groundwater use occurs in eastern Arkansas, where row-crop agriculture is prevalent, widespread, and the largest user of groundwater. The counties with the largest groundwater use since 1960 are Arkansas, Lonoke, and Poinsett. Since 2005, the greatest water use has been in Poinsett County. Water use has increased steadily in Arkansas since the earliest reported estimates (fig. 4; table 6). Irrigation is consistently the largest water use in the State (94 percent of groundwater use in 2010), and groundwater use for irrigation increased more than tenfold from 1950 to 2010. The second largest use of groundwater has been aquaculture because use has been heavily dependent on commercial demand. Duck hunting, a very important recreation and tourist industry in central and eastern Arkansas, has incomplete records, but groundwater use for flooding of fields and woodlands for seasonal habitat has increased over the years. Livestock agriculture is important in many counties; however, the most change in water use for that category can be attributed to differences in reporting requirements. Groundwater-use changes in the livestock, industrial, commercial, and mining categories are mostly because of the changes in reporting. More detailed discussions on reporting by category are in the following sections.

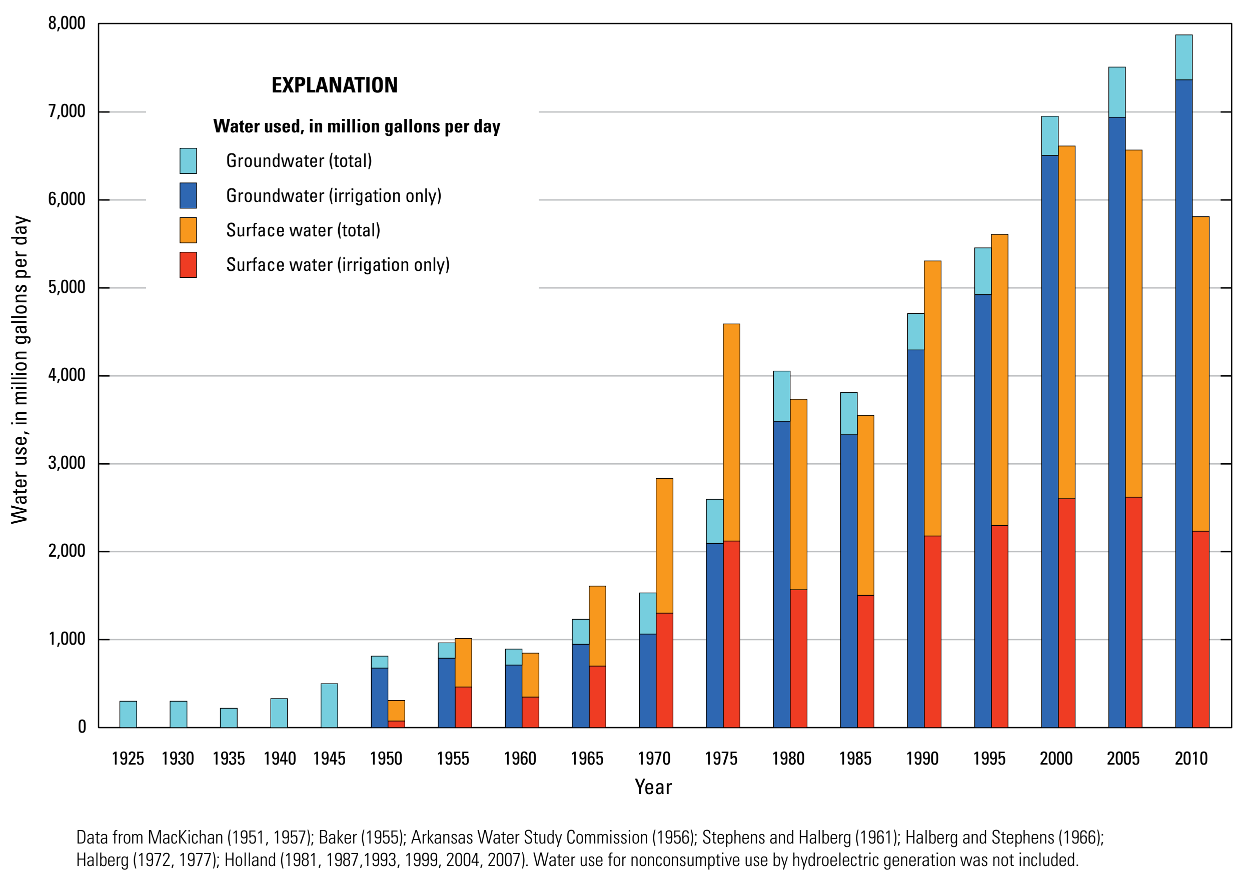



**Figure 4.** Total and irrigation use from groundwater and surface-water sources in Arkansas from 1925 to 2010.

### Irrigation

The irrigation-use category comprises water applied for crop or pasture and includes lawns at parks and golf courses. Other onfarm applications for this category include water used for preirrigation, frost protection, chemical application, weed control, field preparation, crop cooling, harvesting, dust suppression, leaching of salts from the root zone, microirrigation, and sprinkler irrigation. Estimates of conveyance loss (leakage from an irrigation ditch, canal, or pipe) were included in previous water-use reports but were not reported beginning in 2000 (U.S. Geological Survey, 2013a).

Row-crop agriculture consistently has been the leading driver in Arkansas' economy. One in every six jobs was related to agriculture in 2010 (McGraw and others, 2012). Arkansas is the Nation's leading producer of rice and ranks third in the Nation in cotton production and ninth in soybean production (U.S. Department of Agriculture, 2011; McGraw and others, 2012). Other important agricultural commodities in Arkansas are wheat, grain sorghum, and pecans.

Irrigation use is dependent on many factors, including the types of crops, management practices, climatic conditions, market factors, and Congressional controls. Soybeans account for the most acreage planted and harvested (U.S. Department of Agriculture, 2011), but rice uses the most water per acre. Most rice farmers inundate their fields with 3–6 inches of standing water during the growing season (April to September). Every county in Arkansas has reported rice acreage, but the lowlands of eastern Arkansas generally have been the largest producers (Engler and others, 1963). In 2011, 22 counties, primarily in eastern Arkansas, grew rice (U.S. Department of Agriculture, 2012).

Groundwater use for irrigation by county is shown in table 7 for 1960–2010. Use also was calculated at the State level for 1950 and 1955. Irrigation has consistently been the largest use of groundwater since official USGS inventories began in 1950 (table 6). Farmers began to increasingly depend upon irrigation in the 1970s for watering other traditionally dryland crops such as corn, soybeans, and cotton. From 1970 to 1975, groundwater use for irrigation increased by 91 percent. Use was fairly steady in the 1980s, then again increased 28 percent from 1985 to 1990 and again increased another 32 percent from 1995 to 2000 (fig. 4; table 7). Statewide irrigation use has increased over 930 percent from 1960 to 2010. Generally, the counties with irrigated rice acreage coincide with the greatest groundwater usage. Arkansas County was the largest groundwater user for irrigation from 1960 to 1970 and 1990 to 2000. Poinsett County was the largest groundwater user and harvested the most acres of rice in the State in the 1980s and since 2000 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

The Mississippi River Valley alluvial aquifer is the primary source of irrigation water in Arkansas. The Mississippi River Valley alluvial aquifer supplied approximately 7,050 Mgal/d, 96 percent of irrigation water used in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). In an effort to reduce groundwater pumping for irrigation, many farmers initiated water-conservation practices, including tailwater recovery systems, polypipe irrigation, precision land grading (land-leveling), and planting of less water-intensive crops. Research has demonstrated substantial reductions in water use from many of these practices (Vories and others, 2005; Smith and others, 2007). The decline of water use in Arkansas County since 2000 has been attributed to enactment of these measures (Czarnecki and Schrader, 2013).

### Public Supply

The public-supply water-use category represents water withdrawn by municipalities or rural-water associations and delivered to domestic, commercial, industrial, and thermoelectric power uses. Public or private systems that deliver water to a minimum of 25 people or have a minimum of 15 service connections are required to report their water-use data to ANRC (Holland, 2007). Water used for firefighting, street washing, flushing of water lines, and filling of swimming pools is included in this category.

Around the late 1800s, Arkansans obtained drinking water from groundwater supplies except for the cities of Little Rock and Newport (fig. 5), which were located near the Arkansas and White Rivers, respectively (Veatch, 1906). Comparison of groundwater use for public supply with increasing population through 2010 is illustrated in figure 6. Groundwater withdrawals for public supply stabilized at about 135 Mgal/d from 1995 to 2010 (tables 6 and 8). Surface-water use surpassed groundwater use for public supply beginning in 1955 (fig. 6). The proportion of surface water used for public supply gradually increased to become much more than that of groundwater; as of 2010, surface-water use for public supply was more than twice that of groundwater. The increased use of surface water is attributed to the availability of surface water—construction of several reservoirs and river intakes occurred throughout the twentieth century and other major surface-water diversions are currently (2013) in construction—as well as an increasing population in northwestern Arkansas, which predominantly uses surface water. As of 2012, only 36 percent of Arkansans receive their drinking water from public-supplied groundwater sources (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

**Table 7.** Groundwater use for irrigation supply by counties and years in Arkansas.

[Counties shown are only those with published data. Data from Stephens and Halberg (1961); Halberg and Stephens (1966); Halberg (1972, 1977); Holland and Hall (1986); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1960 | 1965 | 1970 | 1975 | 1980 | 1982 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Arkansas | 108.72 | 125.97 | 130.93 | 153.26 | 229.88 | 318.99 | 214.23 | 419.02 | 450.93 | 616.45 | 470.15 | 531.61 |
| Ashley | 9.83 | 14.32 | 17.94 | 35.15 | 89.19 | 75.00 | 60.61 | 67.29 | 69.11 | 97.84 | 124.86 | 119.92 |
| Baxter | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 |
| Benton | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.12 | 0.07 | 0.00 |
| Bradley | 0.00 | 0.00 | 0.00 | 0.01 | 0.40 | 0.58 | 0.28 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 |
| Calhoun | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.01 | 0.00 |
| Carroll | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.89 | 0.00 |
| Chicot | 13.37 | 11.67 | 19.98 | 42.45 | 63.91 | 67.86 | 72.05 | 106.60 | 120.77 | 127.79 | 190.70 | 154.68 |
| Clark | 0.00 | 0.00 | 0.00 | 0.00 | 0.79 | 0.89 | 1.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Clay | 17.73 | 19.50 | 17.89 | 58.61 | 148.16 | 141.76 | 174.37 | 195.48 | 169.76 | 263.06 | 466.08 | 396.83 |
| Cleburne | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.13 |
| Cleveland | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 |
| Columbia | 0.00 | 0.00 | 0.00 | 0.00 | 0.07 | 0.04 | 0.06 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Conway | 0.14 | 0.21 | 0.40 | 1.19 | 3.50 | 2.82 | 1.84 | 0.70 | 0.67 | 1.30 | 1.94 | 1.02 |
| Craighead | 28.64 | 47.26 | 59.04 | 138.72 | 215.17 | 200.35 | 196.46 | 228.97 | 305.31 | 337.08 | 350.76 | 357.60 |
| Crawford | 0.00 | 1.08 | 1.49 | 0.71 | 3.88 | 2.98 | 3.68 | 0.06 | 0.02 | 0.10 | 0.05 | 0.66 |
| Crittenden | 10.82 | 25.29 | 27.62 | 35.96 | 77.91 | 53.21 | 110.20 | 59.10 | 102.33 | 119.42 | 148.94 | 210.11 |
| Cross | 53.39 | 67.00 | 80.12 | 164.71 | 220.35 | 237.56 | 255.25 | 335.35 | 281.05 | 408.64 | 596.40 | 519.14 |
| Dallas | 0.00 | 0.00 | 0.00 | 0.00 | 0.22 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Desha | 24.36 | 39.00 | 69.09 | 113.53 | 131.42 | 103.16 | 106.45 | 207.07 | 216.50 | 310.95 | 284.37 | 354.73 |
| Drew | 6.32 | 7.07 | 14.01 | 22.66 | 44.01 | 43.61 | 40.13 | 36.03 | 54.65 | 51.42 | 74.25 | 31.98 |
| Faulkner | 0.91 | 0.00 | 0.00 | 0.23 | 0.43 | 0.31 | 0.29 | 0.63 | 0.35 | 0.73 | 1.11 | 1.00 |
| Franklin | 0.00 | 0.08 | 0.00 | 0.00 | 1.13 | 0.50 | 0.32 | 0.26 | 0.07 | 0.00 | 0.00 | 0.06 |
| Fulton | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.13 | 0.00 |
| Grant | 0.03 | 0.09 | 0.10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 | 0.00 | 0.00 | 0.23 | 3.16 |
| Greene | 7.87 | 12.82 | 11.64 | 2.33 | 131.90 | 79.18 | 124.25 | 105.79 | 147.09 | 154.89 | 206.17 | 338.79 |
| Hempstead | 0.00 | 0.00 | 0.00 | 0.00 | 0.74 | 1.00 | 1.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Hot Spring | 0.00 | 0.00 | 0.00 | 0.03 | 0.27 | 0.06 | 0.34 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Howard | 0.00 | 0.00 | 0.00 | 0.00 | 0.09 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Independence | 1.50 | 2.05 | 3.76 | 6.93 | 17.34 | 23.05 | 31.65 | 7.59 | 16.50 | 33.62 | 40.43 | 55.96 |
| Izard | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 | 0.02 | 0.03 | 0.00 | 0.00 | 0.00 | 0.40 | 0.00 |
| Jackson | 52.55 | 48.73 | 50.69 | 153.59 | 206.88 | 211.05 | 197.66 | 265.97 | 275.32 | 360.55 | 369.86 | 414.93 |
| Jefferson | --[1] | 41.03 | 45.54 | 100.94 | 147.62 | 123.87 | 123.56 | 153.56 | 282.40 | 413.34 | 215.58 | 229.39 |
| Johnson | 0.00 | 0.31 | 0.93 | 1.19 | 2.56 | 2.18 | 2.43 | 0.43 | 0.30 | 0.56 | 0.03 | 0.00 |
| Lafayette | 2.45 | 3.87 | 3.22 | 11.31 | 19.04 | 16.54 | 14.67 | 0.00 | 20.62 | 9.12 | 28.42 | 19.08 |

**Table 7.** Groundwater use for irrigation supply by counties and years in Arkansas.—Continued

[Counties shown are only those with published data. Data from Stephens and Halberg (1961); Halberg and Stephens (1966); Halberg (1972, 1977); Holland and Hall (1986); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1960 | 1965 | 1970 | 1975 | 1980 | 1982 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lawrence | 19.61 | 15.69 | 18.75 | 70.82 | 150.84 | 155.83 | 150.34 | 212.49 | 257.44 | 294.63 | 220.77 | 178.47 |
| Lee | 12.29 | 24.14 | 20.42 | 39.27 | 117.12 | 131.94 | 96.33 | 163.68 | 157.63 | 233.75 | 254.71 | 294.74 |
| Lincoln | 17.19 | 23.51 | 51.84 | 70.76 | 87.35 | 90.13 | 84.62 | 107.52 | 128.34 | 167.34 | 177.81 | 194.51 |
| Little River | 0.58 | 0.60 | 0.98 | 0.30 | 3.35 | 2.35 | 1.04 | 1.41 | 0.00 | 0.00 | 3.19 | 2.86 |
| Logan | 0.04 | 0.16 | 0.18 | 0.18 | 0.93 | 1.61 | 1.51 | 0.98 | 0.37 | 0.23 | 0.28 | 0.25 |
| Lonoke | 92.28 | 100.69 | 104.06 | 158.74 | 246.85 | 198.32 | 201.36 | 232.75 | 234.09 | 334.01 | 355.84 | 308.98 |
| Miller | 1.45 | 1.50 | 1.78 | 0.98 | 0.81 | 3.49 | 17.76 | 6.86 | 9.28 | 6.38 | 9.75 | 5.67 |
| Mississippi | 3.46 | 3.74 | 3.70 | 4.84 | 29.93 | 27.81 | 48.28 | 98.01 | 132.05 | 178.05 | 270.57 | 362.30 |
| Monroe | 31.11 | 52.28 | 39.39 | 74.49 | 125.55 | 117.09 | 114.40 | 173.59 | 177.81 | 233.74 | 269.62 | 262.39 |
| Nevada | 0.00 | 0.00 | 0.00 | 0.00 | 0.26 | 0.22 | 0.49 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Newton | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.01 | 0.00 | 0.00 |
| Ouachita | --[1] | 0.00 | 0.00 | 0.00 | 0.02 | 0.02 | 0.22 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Perry | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Phillips | 13.99 | 13.33 | 12.01 | 15.11 | 77.28 | 65.56 | 71.63 | 115.20 | 132.32 | 198.07 | 204.31 | 260.01 |
| Pike | 0.00 | 0.00 | 0.00 | 0.00 | 0.58 | 0.83 | 0.98 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| Poinsett | 52.33 | 85.18 | 98.12 | 175.89 | 303.20 | 334.86 | 296.76 | 394.52 | 430.98 | 581.70 | 671.27 | 837.34 |
| Polk | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Pope | 0.00 | 0.41 | 0.51 | 1.85 | 2.57 | 2.03 | 3.88 | 2.05 | 1.09 | 0.87 | 1.34 | 0.58 |
| Prairie | 51.51 | 67.52 | 56.32 | 119.69 | 157.32 | 149.44 | 147.17 | 193.56 | 190.56 | 226.51 | 218.68 | 207.66 |
| Pulaski | 5.37 | 5.57 | 8.16 | 13.50 | 23.30 | 20.68 | 22.19 | 17.59 | 13.52 | 20.43 | 20.76 | 20.03 |
| Randolph | 3.16 | 2.97 | 3.09 | 17.89 | 41.88 | 42.72 | 41.08 | 50.67 | 59.17 | 85.45 | 101.46 | 110.56 |
| Saline | 0.00 | 0.00 | 0.00 | 0.00 | 0.07 | 0.24 | 0.04 | 0.34 | 0.00 | 0.03 | 0.02 | 0.00 |
| Sebastian | 0.00 | 0.00 | 0.01 | 0.01 | 0.61 | 0.53 | 1.03 | 0.06 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sevier | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Sharp | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| St. Francis | 37.45 | 30.17 | 46.34 | 99.30 | 137.28 | 131.05 | 106.97 | 155.85 | 181.65 | 245.51 | 285.34 | 336.36 |
| Stone | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.32 | 0.07 |
| Van Buren | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.02 | 0.02 | 0.00 | 0.00 | 0.00 | 0.21 | 0.00 |
| Washington | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 | 0.00 | 0.00 |
| White | 1.42 | 1.83 | 2.10 | 10.90 | 49.36 | 43.92 | 47.43 | 39.02 | 55.81 | 45.62 | 41.57 | 31.83 |
| Woodruff | 30.64 | 52.30 | 41.18 | 114.34 | 165.68 | 157.50 | 140.68 | 138.94 | 249.82 | 347.09 | 262.50 | 212.36 |
| Yell | 0.24 | 0.40 | 0.53 | 0.96 | 2.34 | 1.86 | 3.62 | 1.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Total** | **712.75** | **949.35** | **1,063.91** | **2,033.33** | **3,481.41** | **3,386.61** | **3,332.74** | **4,296.15** | **4,925.70** | **6,506.46** | **6,942.16** | **7,367.76** |

[1]Data not reported from Jefferson and Ouachita Counties in 1960.

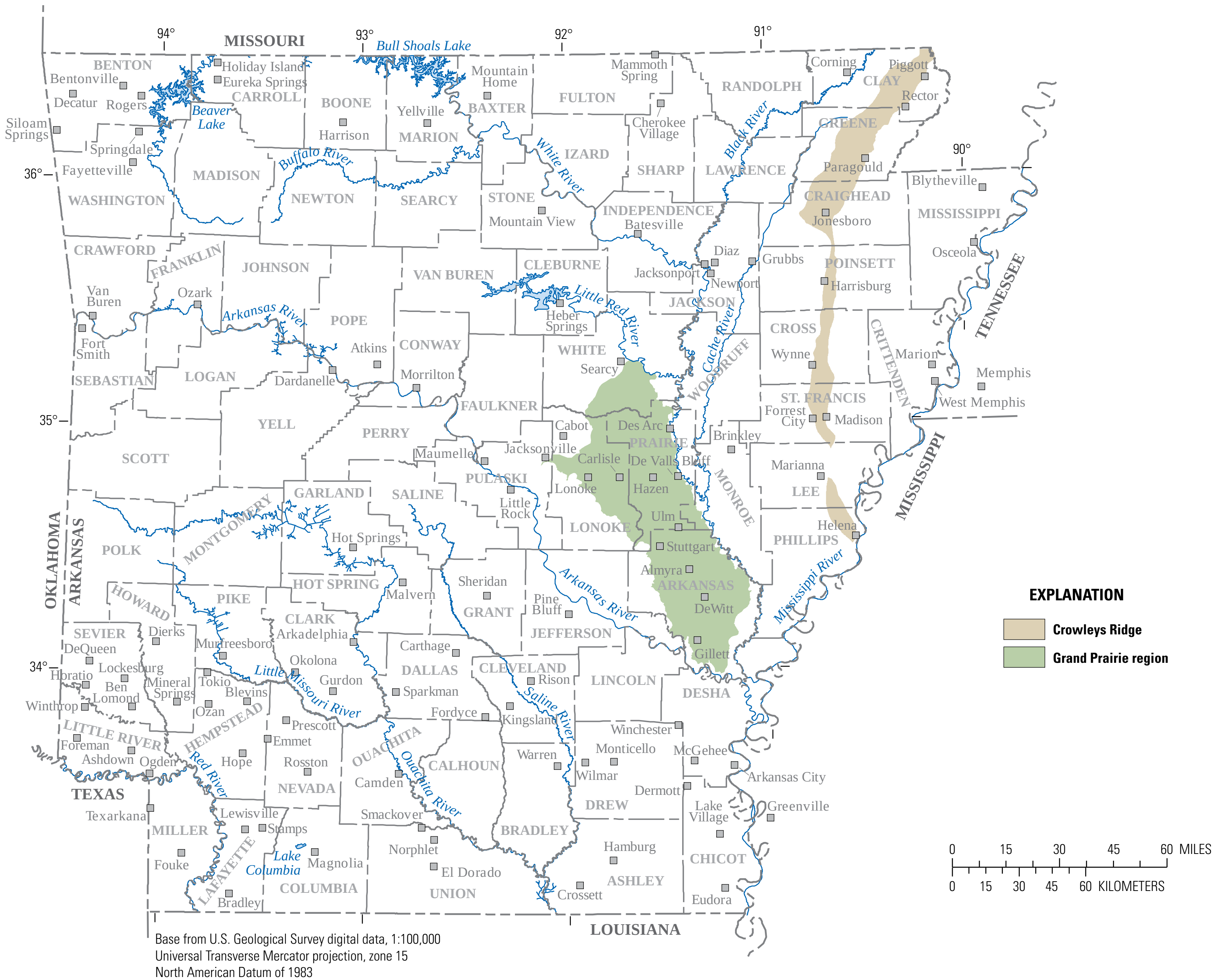
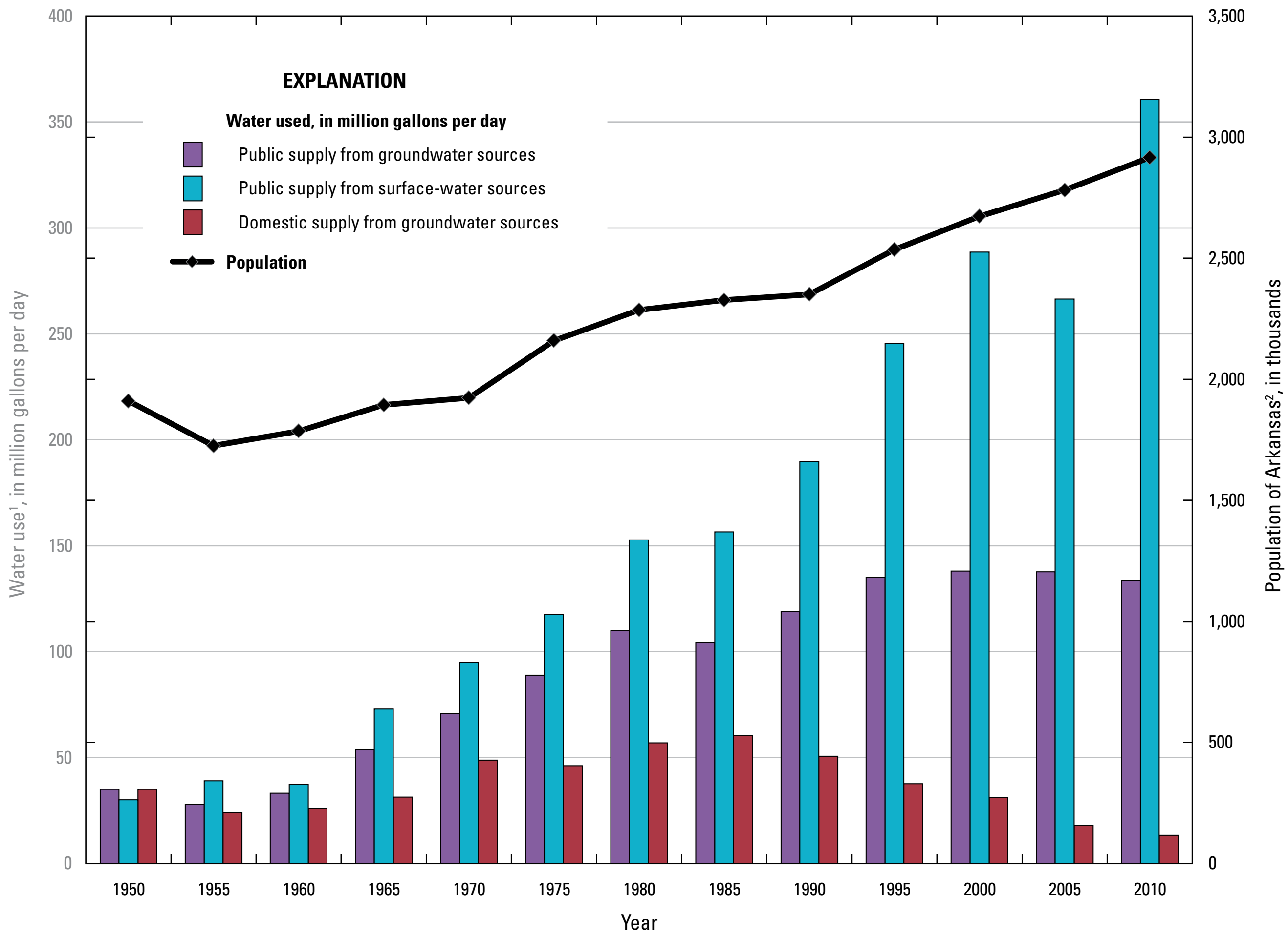



**Figure 5.** Location of Arkansas cities and major rivers referenced in this report.




[1]Water use data from MacKichan (1951, 1957); Baker (1955); Stephens and Halberg (1961); Halberg and Stephens (1966); Halberg (1972, 1977); Holland (1981, 1987, 1993, 1999, 2004, 2007).

[2]Annual population for Arkansas from www.census.gov.

**Figure 6.** Surface-water and groundwater use for domestic and public supply and population of Arkansas from 1950 to 2010.

**Table 8.** Groundwater use for public supply by counties and years in Arkansas.

[Counties shown are only those with published data. Data from Stephens and Halberg (1961); Halberg and Stephens (1966); Halberg (1972, 1977); Holland and Hall (1986); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1960 | 1965 | 1970 | 1975 | 1980 | 1982 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Arkansas | 1.04 | 1.66 | 2.14 | 2.98 | 4.02 | 3.43 | 3.49 | 4.18 | 4.74 | 4.86 | 6.02 | 4.83 |
| Ashley | 0.82 | 0.93 | 1.43 | 1.65 | 2.27 | 2.21 | 2.09 | 2.25 | 2.75 | 2.18 | 2.12 | 1.75 |
| Baxter | 0.20 | 0.34 | 0.46 | 0.38 | 0.55 | 0.46 | 0.46 | 0.53 | 0.71 | 0.81 | 0.53 | 0.50 |
| Benton | 0.89 | 2.36 | 2.00 | 1.78 | 0.43 | 0.43 | 0.43 | 4.30 | 0.77 | 0.88 | 1.10 | 4.62 |
| Boone | 0.61 | 0.02 | 0.05 | 1.94 | 1.98 | 1.67 | 1.22 | 0.64 | 0.50 | 0.83 | 0.88 | 0.90 |
| Bradley | 0.40 | 0.74 | 0.64 | 0.69 | 0.98 | 0.87 | 0.99 | 0.96 | 1.14 | 1.11 | 1.22 | 1.32 |
| Calhoun | 0.11 | 0.12 | 0.13 | 0.20 | 0.31 | 0.28 | 0.28 | 0.40 | 0.86 | 0.32 | 0.40 | 0.56 |
| Carroll | 0.07 | 0.55 | 1.11 | 1.42 | 1.46 | 1.75 | 1.75 | 0.46 | 0.54 | 0.55 | 0.90 | 0.80 |
| Chicot | 0.65 | 0.79 | 0.73 | 0.98 | 1.76 | 1.75 | 1.68 | 1.55 | 2.28 | 1.74 | 1.82 | 1.81 |
| Clark | 0.18 | 0.20 | 0.02 | 0.22 | 0.48 | 0.42 | 0.42 | 0.31 | 0.21 | 0.06 | 0.07 | 0.06 |
| Clay | 0.49 | 0.58 | 0.86 | 0.97 | 1.42 | 1.15 | 1.09 | 1.61 | 1.60 | 1.83 | 1.42 | 1.68 |
| Cleburne | 0.00 | 0.02 | 0.05 | 0.05 | 0.12 | 0.13 | 0.13 | 0.12 | 0.15 | 0.06 | 0.08 | 0.00 |
| Cleveland | 0.06 | 0.11 | 0.14 | 0.15 | 0.41 | 0.43 | 0.43 | 0.80 | 1.03 | 1.33 | 0.54 | 1.00 |
| Columbia | 1.03 | 1.48 | 1.82 | 1.93 | 2.66 | 2.71 | 3.00 | 3.12 | 4.18 | 0.63 | 1.38 | 1.34 |
| Conway | 0.53 | 1.02 | 1.07 | 1.29 | 1.39 | 1.12 | 1.12 | 0.15 | 0.24 | 0.00 | 0.00 | 0.00 |
| Craighead | 1.65 | 3.08 | 4.38 | 5.46 | 7.44 | 6.77 | 6.90 | 8.70 | 11.90 | 13.76 | 13.52 | 15.27 |
| Crawford | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Crittenden | 1.97 | 2.16 | 3.54 | 4.76 | 5.79 | 5.23 | 6.03 | 7.70 | 9.52 | 16.28 | 8.47 | 6.69 |
| Cross | 0.51 | 0.61 | 1.06 | 1.39 | 2.20 | 2.07 | 2.02 | 1.16 | 2.95 | 1.79 | 2.44 | 2.63 |
| Dallas | 0.45 | 0.50 | 0.63 | 0.59 | 0.76 | 0.83 | 0.85 | 0.92 | 0.85 | 0.84 | 1.34 | 0.76 |
| Desha | 0.65 | 0.78 | 0.85 | 1.38 | 1.35 | 1.35 | 4.22 | 5.82 | 2.28 | 1.88 | 2.18 | 1.07 |
| Drew | 0.38 | 1.02 | 2.06 | 2.51 | 2.82 | 2.67 | 2.79 | 2.02 | 2.04 | 3.03 | 2.78 | 3.14 |
| Faulkner | 0.00 | 0.02 | 0.09 | 0.32 | 0.84 | 0.82 | 0.82 | 1.80 | 1.30 | 0.16 | 0.52 | 2.74 |
| Franklin | 0.15 | 0.52 | 1.26 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fulton | 0.08 | 0.12 | 0.16 | 0.29 | 0.38 | 0.34 | 0.34 | 0.67 | 0.41 | 0.03 | 1.28 | 1.55 |
| Garland | 0.01 | 0.01 | 0.01 | 0.34 | 0.13 | 0.13 | 0.13 | 0.10 | 0.13 | 0.19 | 0.13 | 0.00 |
| Grant | 0.15 | 0.31 | 0.80 | 1.11 | 1.30 | 1.29 | 1.04 | 1.33 | 1.80 | 1.20 | 2.03 | 1.47 |
| Greene | 0.84 | 1.12 | 1.90 | 1.87 | 2.99 | 2.77 | 2.33 | 2.92 | 3.43 | 4.17 | 4.23 | 4.36 |
| Hempstead | 0.83 | 1.08 | 1.04 | 2.25 | 2.56 | 2.14 | 1.91 | 0.19 | 1.87 | 4.01 | 2.65 | 2.37 |
| Hot Spring | 0.00 | 0.00 | 0.00 | 0.00 | 0.08 | 0.09 | 0.09 | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 |
| Howard | 0.05 | 0.35 | 0.06 | 0.05 | 0.12 | 0.14 | 0.14 | 0.42 | 0.18 | 0.13 | 0.01 | 0.00 |
| Independence | 0.04 | 0.04 | 0.10 | 0.59 | 1.17 | 1.13 | 1.13 | 1.24 | 1.06 | 0.82 | 0.87 | 0.69 |
| Izard | 0.14 | 0.11 | 0.17 | 0.64 | 1.22 | 1.13 | 0.86 | 0.99 | 1.86 | 1.84 | 1.01 | 0.93 |
| Jackson | 0.81 | 0.87 | 0.89 | 1.16 | 1.32 | 1.60 | 1.66 | 1.38 | 1.89 | 1.96 | 1.52 | 1.59 |
| Jefferson | --[1] | 5.40 | 7.83 | 8.86 | 11.63 | 10.93 | 10.97 | 10.98 | 16.54 | 15.98 | 14.25 | 13.14 |
| Johnson | 0.00 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lafayette | 0.33 | 0.36 | 0.38 | 1.04 | 0.80 | 0.87 | 0.96 | 1.14 | 0.94 | 0.85 | 0.92 | 0.93 |
| Lawrence | 0.39 | 0.71 | 0.86 | 1.20 | 1.28 | 1.34 | 1.43 | 1.37 | 1.52 | 1.94 | 1.61 | 1.15 |

**Table 8.** Groundwater use for public supply by counties and years in Arkansas.—Continued

[Counties shown are only those with published data. Data from Stephens and Halberg (1961); Halberg and Stephens (1966); Halberg (1972, 1977); Holland and Hall (1986); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1960 | 1965 | 1970 | 1975 | 1980 | 1982 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lee | 0.50 | 0.56 | 0.59 | 0.98 | 1.40 | 1.38 | 1.31 | 1.27 | 1.96 | 1.27 | 0.99 | 1.73 |
| Lincoln | 0.23 | 0.29 | 0.42 | 0.59 | 0.88 | 0.85 | 0.85 | 0.88 | 1.30 | 1.71 | 1.04 | 1.48 |
| Little River | 0.25 | 0.31 | 0.49 | 0.81 | 0.89 | 0.87 | 0.97 | 0.89 | 1.05 | 0.65 | 0.61 | 0.56 |
| Logan | 0.00 | 0.04 | 0.11 | 0.15 | 0.10 | 0.09 | 0.09 | 0.11 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lonoke | 0.69 | 0.74 | 1.38 | 2.10 | 2.54 | 2.08 | 2.34 | 1.92 | 3.01 | 3.14 | 6.49 | 7.27 |
| Madison | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.02 | 0.02 | 0.30 | 0.31 | 0.01 | 0.00 | 0.00 |
| Marion | 0.02 | 0.08 | 0.19 | 0.41 | 0.56 | 0.51 | 0.50 | 0.45 | 0.02 | 0.02 | 0.03 | 0.00 |
| Miller | 0.00 | 0.00 | 0.05 | 0.10 | 0.20 | 0.21 | 0.21 | 0.10 | 0.10 | 0.22 | 0.25 | 0.10 |
| Mississippi | 3.02 | 3.85 | 4.83 | 5.38 | 7.09 | 4.64 | 5.05 | 9.42 | 9.03 | 7.49 | 4.05 | 7.19 |
| Monroe | 0.73 | 0.74 | 0.81 | 0.97 | 1.25 | 1.30 | 1.41 | 1.64 | 1.80 | 1.74 | 1.49 | 1.33 |
| Montgomery | 0.03 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.30 | 0.03 | 0.00 |
| Nevada | 0.28 | 0.32 | 0.43 | 0.47 | 0.63 | 0.61 | 0.56 | 0.07 | 0.10 | 0.24 | 0.15 | 0.09 |
| Newton | 0.00 | 0.00 | 0.03 | 0.08 | 0.10 | 0.09 | 0.09 | 0.22 | 0.20 | 0.27 | 0.97 | 0.97 |
| Ouachita | --[1] | 0.23 | 0.52 | 0.77 | 0.98 | 0.91 | 0.91 | 0.39 | 0.53 | 1.24 | 0.97 | 1.16 |
| Perry | 0.00 | 0.03 | 0.05 | 0.07 | 0.10 | 0.10 | 0.10 | 0.09 | 0.09 | 0.00 | 0.01 | 0.01 |
| Phillips | 1.86 | 2.60 | 3.12 | 3.12 | 3.41 | 3.41 | 3.27 | 3.42 | 4.53 | 4.46 | 3.70 | 3.17 |
| Pike | 0.10 | 0.36 | 0.54 | 0.03 | 0.06 | 0.06 | 0.06 | 0.07 | 0.10 | 0.05 | 0.05 | 0.05 |
| Poinsett | 0.86 | 1.29 | 1.79 | 3.51 | 2.83 | 2.55 | 2.53 | 3.52 | 3.37 | 2.80 | 5.12 | 2.86 |
| Polk | 0.00 | 0.00 | 0.03 | 0.11 | 0.22 | 0.20 | 0.20 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Pope | 0.12 | 0.21 | 0.45 | 0.43 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Prairie | 0.26 | 0.33 | 0.41 | 0.51 | 0.87 | 0.86 | 0.80 | 0.79 | 0.83 | 0.82 | 0.79 | 0.77 |
| Pulaski | 2.20 | 3.17 | 3.76 | 4.19 | 3.38 | 1.58 | 1.81 | 4.18 | 3.74 | 4.97 | 4.56 | 3.72 |
| Randolph | 0.00 | 0.00 | 0.06 | 0.10 | 0.16 | 0.21 | 0.21 | 0.18 | 0.19 | 0.15 | 0.33 | 0.11 |
| Saline | 0.04 | 0.07 | 0.23 | 0.64 | 0.75 | 0.69 | 1.43 | 2.01 | 1.62 | 1.65 | 1.63 | 4.50 |
| Scott | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.69 | 0.00 |
| Searcy | 0.11 | 0.11 | 0.17 | 0.15 | 0.25 | 0.23 | 0.24 | 0.17 | 0.17 | 0.45 | 0.00 | 1.31 |
| Sebastian | 0.03 | 0.08 | 0.10 | 0.08 | 0.09 | 0.13 | 0.13 | 0.00 | 0.00 | 0.00 | 0.20 | 0.00 |
| Sevier | 0.30 | 0.95 | 0.12 | 0.16 | 0.20 | 0.18 | 0.18 | 0.16 | 0.25 | 1.30 | 1.15 | 0.29 |
| Sharp | 0.05 | 0.09 | 0.98 | 1.05 | 1.42 | 1.10 | 1.30 | 0.75 | 0.75 | 0.79 | 3.80 | 0.78 |
| St. Francis | 0.69 | 1.42 | 1.88 | 2.55 | 2.93 | 2.62 | 3.04 | 2.96 | 3.65 | 4.10 | 5.18 | 4.99 |
| Stone | 0.05 | 0.09 | 0.00 | 0.00 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.28 |
| Union | 2.39 | 3.79 | 4.35 | 5.04 | 7.88 | 7.17 | 7.45 | 7.85 | 8.90 | 8.00 | 8.44 | 5.34 |
| Van Buren | 0.00 | 0.00 | 0.10 | 0.02 | 0.04 | 0.04 | 0.04 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 |
| Washington | 0.92 | 0.25 | 0.13 | 0.31 | 0.02 | 0.02 | 0.02 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| White | 0.43 | 0.33 | 0.28 | 0.30 | 0.55 | 0.49 | 0.49 | 0.78 | 0.88 | 0.88 | 0.75 | 0.04 |
| Woodruff | 0.28 | 0.48 | 0.74 | 0.72 | 0.80 | 0.73 | 0.73 | 0.81 | 0.96 | 1.02 | 0.96 | 1.88 |
| Yell | 0.20 | 0.74 | 0.98 | 0.56 | 0.93 | 0.88 | 0.93 | 1.27 | 1.47 | 0.20 | 2.00 | 0.00 |
| **Total** | **33.15** | **53.71** | **70.85** | **88.91** | **109.97** | **99.19** | **104.49** | **118.95** | **135.11** | **138.02** | **137.69** | **133.66** |

[1]Data not reported from Jefferson and Ouachita Counties in 1960.

The largest population centers served by groundwater are in central and northeastern Arkansas (fig. 7). The largest population center served by groundwater in 2010 was Jonesboro (Craighead County) (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Other large groundwater users for public supply are the cities of Stuttgart (Arkansas County), Pine Bluff (Jefferson County), and El Dorado (Union County), which all withdraw from the Sparta aquifer. West Memphis (Crittenden County), Blytheville (Mississippi County), and Paragould (Greene County) are the largest public-supply users of the Wilcox aquifer. The largest withdrawal for public supply from the Cockfield aquifer is the town of Crossett (Ashley County).

Eastern Arkansas relies heavily on groundwater for public supply, tapping many aquifers including the Sparta, Wilcox, Mississippi River Valley alluvial, Cockfield, and Nacatoch aquifers. The Sparta aquifer is the predominant source of public supply in southern Arkansas, serving as the drinking-water source for over 120 municipalities. The second-highest amount of groundwater withdrawn for public supply comes from the Wilcox aquifer in the area east of Crowleys Ridge and west of the Mississippi River, which serves 35 municipalities, whereas west of Crowleys Ridge, the Mississippi River Valley alluvial aquifer serves over 70 municipalities. In southeastern Arkansas, the Cockfield aquifer supplies municipalities in Ashley, Bradley, and Chicot Counties. In far northeastern Arkansas, the Nacatoch aquifer supplies eastern Clay and northeastern Greene Counties (fig. 5).

Groundwater in central Arkansas primarily was obtained from the Arkansas River Valley alluvial aquifer. The city of Little Rock obtained groundwater solely from wells prior to 1915 and then mixed groundwater with water from the Arkansas River until 1926, when groundwater was abandoned because of taste and odor problems (University of Arkansas at Little Rock Water Study Task Force, 2000). Currently (2013), surface water is the primary public-supply source in western Arkansas, whereas groundwater is predominantly used in eastern Arkansas (fig. 7).

The Ozark aquifer is the primary high-yield, water-bearing aquifer in the Ozark Plateaus but requires deep drilling to median depths of approximately 1,300 ft to reach the high-producing deeper formations in the aquifer. Insufficient yields from shallower formations limit groundwater use in the Ozark Plateaus. Many municipalities have had trouble providing water to their populations because of low-yield wells, water-quality issues (including the common occurrence of radium), uncertainty of obtaining a good producing well, and the expense of drilling deep wells (Albin, 1965; Lamonds, 1972; Imes and Emmet, 1994); therefore, this area relies more on surface water for public supply (Brahana and others, 1993). Surface-water reservoirs were built in many areas in central and western Arkansas in the 1960s and 1970s. Beaver Lake in northwestern Arkansas (fig. 5), constructed in the 1960s, supplies more water than any other surface-water body in the State. The counties of Benton, Boone, Carroll, Madison, and Washington are supplied by the lake (Beaver Water District, 2010), which allowed many municipalities in northwestern Arkansas to switch from groundwater to surface-water sources. Construction of infrastructure needed to distribute water from Bull Shoals Lake to users in Boone, Newton, and Searcy Counties also is underway (Ozark Mountain Regional Public Water Authority, 2013).

Southwestern Arkansas traditionally has used groundwater from multiple aquifers. The towns of Hope (Hempstead County) and Prescott (Nevada County) withdrew from the Nacatoch and Tokio aquifers. Hope supplements its groundwater supply with surface water, while Prescott currently (2013) only uses the Little Missouri River. The towns of Ashdown, Foreman (Little River County), and Texarkana (Miller County) used the Red River alluvial aquifer for public supply; these cities now rely on surface water (Southwest Arkansas Water District, 2013). Many cities in Lafayette County have public-supply wells completed in the Cane River Formation. The Trinity aquifer supplied many cities in Sevier County as well as Murfreesboro (Pike County) and Mineral Springs (Howard County). Horatio and Lockesburg (Sevier County) still use the Trinity aquifer, Murfreesboro now uses the Little Missouri River, and Mineral Springs uses the Tokio aquifer.

### Domestic (Self-Supplied)

Domestic water use is for household purposes such as drinking, food preparation, bathing, washing clothes and dishes, flushing toilets, as well as watering lawns and gardens. Most water used for domestic purposes is provided by public suppliers, yet approximately 1 percent of Arkansas' population supplies their own water (Holland, 2007). The domestic-use category is calculated by applying an application rate to the rural population not serviced by public-supply systems. The rural population not serviced by public-supply systems is calculated for each county by subtracting the population served by public suppliers, which is obtained when the supplier reports its water use, from the population of the county obtained through census data. In early reports, the domestic population was split into populations with and without running water. The application rates used to estimate domestic use has changed over the reporting periods, increasing from 50 gal/d per person in 1965 to 80–97 gal/d per person in 2010 (Halberg and Stephens, 1966; Terrance W. Holland, U.S. Geological Survey, written commun., 2013).

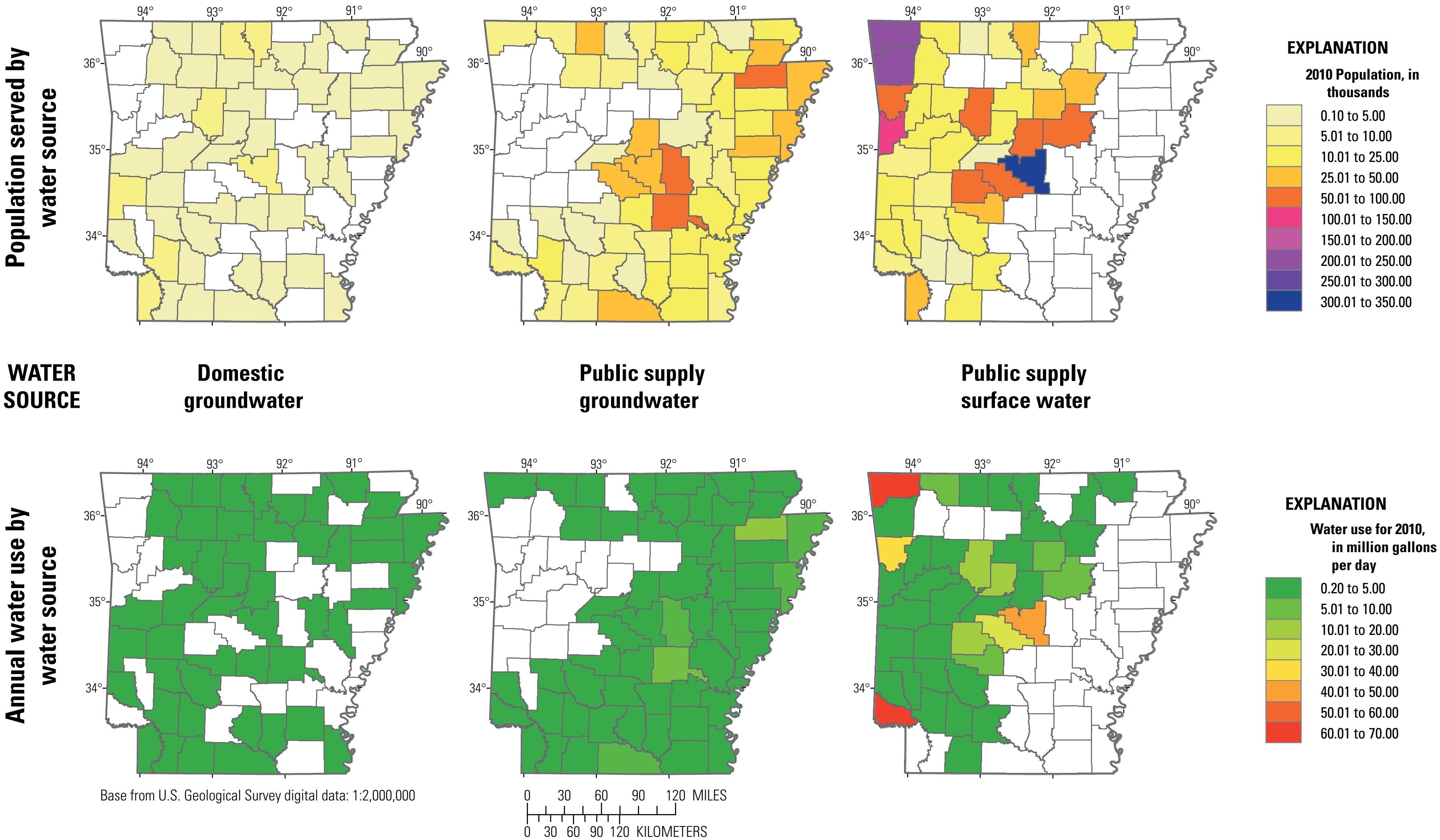



**Figure 7.** Population, in thousands, by water source (domestic groundwater, public supply groundwater or public supply surface water) and water use, in million of gallons per day, by water source in Arkansas, 2010.

Estimated domestic groundwater use in Arkansas increased with increasing population prior to 1985 (fig. 6). Domestic use increased by 23 percent between 1975 and 1980 reporting years (table 6) because of a drought in 1980. Domestic groundwater use peaked in 1985 and has been decreasing ever since. These decreases resulted largely from expansion of public-supply systems sourcing from large surface-water reservoirs into areas that previously relied on groundwater. Domestic use was reported in all 75 Arkansas counties from 1960 to 1985 and also in 1995. The number of counties reporting domestic use dropped from 71 in 2000 to 48 in 2010 (table 9). The largest populations with self-supplied groundwater sources are in southwestern and northwestern Arkansas (fig. 7). Rural residents in Miller County used the most domestic groundwater in 2010 (0.75 Mgal/d); Pope and Baxter Counties were second in the use of domestic groundwater (0.73 Mgal/d).

Almost all aquifers in the State provide some water for domestic use. The Mississippi River Valley alluvial aquifer is the primary source for domestic supply in eastern Arkansas; whereas east of Crowleys Ridge some have tapped the Wilcox aquifer. Many of the aquifers used in southern Arkansas for public supply are also used for domestic supply: Cane River, Carrizo, Cockfield, Red River alluvium, Tokio, and Trinity aquifers. The depth required to reach the Sparta aquifer results in limited domestic use of that aquifer. Domestic users in Clark County often tap the Ozan aquifer. Domestic users in parts of eastern Arkansas use groundwater from the Jackson Group. Domestic users in northern Arkansas use the Springfield Plateau and Ozark aquifers.

### Commercial

The commercial (self-supplied) category includes consumptive water use by schools, restaurants, grocery stores, gas stations, hotels, parks, office buildings, recreation areas, and government facilities (including military sites). Prior to 1985, commercial use was included with the industrial water-use category. In 1990 and 1995, fish hatcheries were included in this category, whereas from 1965 to 1980 and since 2000, fish hatcheries were included in the aquaculture category (U.S. Geological Survey, 2013a).

Most withdrawals for commercial use have been small (less than 0.05 Mgal/d; table 10), and many are seasonal. This is especially true for school district wells and recreational areas such as Federal, State, local, and private parks that primarily use water during peak times in the summer. Most commercial withdrawals are from the Mississippi River Valley alluvial aquifer, but several other aquifers also provide water for this use. Poinsett County had the most commercial groundwater use in 2010 (0.48 Mgal/d).

**Table 9.** Groundwater use for domestic supply by counties and years in Arkansas.

[Counties shown are only those with published data. Data from Stephens and Halberg (1961); Halberg and Stephens (1966); Halberg (1972, 1977); Holland and Hall (1986); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1960 | 1965 | 1970 | 1975 | 1980 | 1982 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Arkansas | 0.32 | 0.32 | 0.50 | 0.26 | 0.34 | 0.34 | 0.29 | 0.36 | 0.28 | 0.17 | 0.18 | 0.00 |
| Ashley | 0.48 | 0.53 | 0.54 | 0.62 | 0.66 | 0.85 | 0.69 | 0.44 | 0.38 | 0.57 | 0.18 | 0.00 |
| Baxter | 0.24 | 0.26 | 0.72 | 0.66 | 1.06 | 1.14 | 1.32 | 1.60 | 0.85 | 0.93 | 0.66 | 0.73 |
| Benton | 0.69 | 0.81 | 1.38 | 1.63 | 2.32 | 2.35 | 2.79 | 2.21 | 3.21 | 0.40 | 0.51 | 0.00 |
| Boone | 0.32 | 0.37 | 0.65 | 0.68 | 0.93 | 1.01 | 1.13 | 0.33 | 0.38 | 0.58 | 0.49 | 0.41 |
| Bradley | 0.25 | 0.26 | 0.37 | 0.15 | 0.20 | 0.19 | 0.17 | 0.28 | 0.19 | 0.23 | 0.05 | 0.09 |
| Calhoun | 0.15 | 0.16 | 0.24 | 0.24 | 0.22 | 0.23 | 0.24 | 0.11 | 0.12 | 0.19 | 0.10 | 0.05 |
| Carroll | 0.23 | 0.29 | 0.48 | 0.58 | 0.60 | 0.63 | 0.75 | 0.56 | 0.49 | 0.99 | 0.30 | 0.57 |
| Chicot | 0.29 | 0.38 | 0.49 | 0.38 | 0.44 | 0.47 | 0.44 | 0.37 | 0.22 | 0.00 | 0.18 | 0.18 |
| Clark | 0.34 | 0.38 | 0.48 | 0.57 | 0.50 | 0.47 | 0.47 | 0.53 | 0.29 | 0.12 | 0.07 | 0.32 |
| Clay | 0.48 | 0.53 | 0.64 | 0.64 | 0.78 | 0.76 | 0.73 | 0.09 | 0.10 | 0.00 | 0.00 | 0.00 |
| Cleburne | 0.23 | 0.26 | 0.49 | 0.32 | 0.22 | 0.19 | 0.14 | 0.44 | 0.10 | 0.01 | 0.09 | 0.00 |
| Cleveland | 0.20 | 0.21 | 0.36 | 0.39 | 0.43 | 0.45 | 0.47 | 0.11 | 0.01 | 0.00 | 0.07 | 0.00 |
| Columbia | 0.43 | 0.51 | 0.74 | 0.73 | 0.75 | 0.80 | 0.83 | 0.24 | 0.24 | 0.16 | 0.06 | 0.07 |
| Conway | 0.30 | 0.37 | 0.62 | 0.53 | 0.69 | 0.68 | 0.71 | 0.47 | 0.23 | 0.29 | 0.18 | 0.18 |
| Craighead | 0.78 | 0.84 | 1.31 | 1.05 | 0.42 | 0.22 | 0.25 | 1.91 | 0.60 | 0.47 | 0.46 | 0.44 |
| Crawford | 0.40 | 0.52 | 0.75 | 0.68 | 1.07 | 1.18 | 1.44 | 1.11 | 0.32 | 0.03 | 0.65 | 0.00 |
| Crittenden | 0.79 | 0.77 | 1.02 | 0.47 | 0.68 | 0.71 | 0.77 | 0.43 | 0.05 | 0.07 | 0.18 | 0.16 |
| Cross | 0.45 | 0.45 | 0.72 | 0.46 | 0.46 | 0.49 | 0.49 | 0.08 | 0.01 | 0.01 | 0.00 | 0.00 |
| Dallas | 0.20 | 0.20 | 0.27 | 0.19 | 0.35 | 0.34 | 0.34 | 0.35 | 0.24 | 0.27 | 0.11 | 0.00 |
| Desha | 0.39 | 0.45 | 0.50 | 0.35 | 0.48 | 0.48 | 0.43 | 0.40 | 0.08 | 0.31 | 0.00 | 0.00 |
| Drew | 0.33 | 0.39 | 0.60 | 0.47 | 0.68 | 0.38 | 0.40 | 0.01 | 0.34 | 0.07 | 0.07 | 0.11 |
| Faulkner | 0.49 | 0.61 | 1.04 | 1.24 | 1.69 | 1.82 | 2.21 | 1.88 | 1.88 | 0.54 | 0.47 | 0.40 |
| Franklin | 0.24 | 0.25 | 0.44 | 0.51 | 0.58 | 0.60 | 0.66 | 0.35 | 0.32 | 0.01 | 0.00 | 0.00 |
| Fulton | 0.17 | 0.20 | 0.36 | 0.45 | 0.47 | 0.48 | 0.52 | 0.58 | 0.63 | 0.69 | 0.09 | 0.00 |
| Garland | 0.62 | 0.58 | 0.74 | 1.00 | 1.17 | 1.22 | 1.52 | 2.03 | 1.28 | 0.88 | 0.07 | 0.00 |
| Grant | 0.21 | 0.23 | 0.43 | 0.27 | 0.25 | 0.24 | 0.28 | 0.11 | 0.26 | 0.41 | 0.12 | 0.10 |
| Greene | 0.49 | 0.51 | 0.86 | 0.98 | 0.98 | 1.01 | 1.08 | 0.94 | 1.05 | 0.05 | 0.05 | 0.32 |
| Hempstead | 0.35 | 0.42 | 0.66 | 0.67 | 1.08 | 1.08 | 1.08 | 0.90 | 0.94 | 0.90 | 0.78 | 0.49 |
| Hot Spring | 0.41 | 0.47 | 0.93 | 0.93 | 0.71 | 0.78 | 0.85 | 0.59 | 0.30 | 0.52 | 0.16 | 0.30 |
| Howard | 0.18 | 0.18 | 0.36 | 0.47 | 0.55 | 0.56 | 0.59 | 0.53 | 0.25 | 0.25 | 0.05 | 0.00 |
| Independence | 0.44 | 0.50 | 0.88 | 0.18 | 0.92 | 1.06 | 1.13 | 0.66 | 0.46 | 0.51 | 0.17 | 0.34 |
| Izard | 0.18 | 0.20 | 0.33 | 0.37 | 0.41 | 0.42 | 0.43 | 0.40 | 0.32 | 0.23 | 0.14 | 0.16 |
| Jackson | 0.48 | 0.50 | 0.66 | 0.66 | 0.36 | 0.36 | 0.33 | 0.25 | 0.25 | 0.28 | 0.14 | 0.18 |
| Jefferson | --[1] | 1.18 | 1.19 | 0.60 | 0.48 | 0.47 | 0.43 | 0.00 | 0.04 | 0.02 | 0.12 | 0.03 |
| Johnson | 0.25 | 0.29 | 0.48 | 0.59 | 0.84 | 0.92 | 0.99 | 0.03 | 0.33 | 0.51 | 0.00 | 0.06 |
| Lafayette | 0.21 | 0.23 | 0.35 | 0.28 | 0.35 | 0.35 | 0.34 | 0.35 | 0.31 | 0.25 | 0.19 | 0.16 |
| Lawrence | 0.38 | 0.41 | 0.53 | 0.56 | 0.62 | 0.68 | 0.67 | 0.36 | 0.04 | 0.01 | 0.00 | 0.00 |
| Lee | 0.54 | 0.65 | 0.88 | 0.50 | 0.71 | 0.44 | 0.41 | 0.11 | 0.10 | 0.23 | 0.01 | 0.00 |

**Table 9.** Groundwater use for domestic supply by counties and years in Arkansas.—Continued

[Counties shown are only those with published data. Data from Stephens and Halberg (1961); Halberg and Stephens (1966); Halberg (1972, 1977); Holland and Hall (1986); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1960 | 1965 | 1970 | 1975 | 1980 | 1982 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lincoln | 0.37 | 0.44 | 0.60 | 0.34 | 0.15 | 0.14 | 0.15 | 0.12 | 0.01 | 0.01 | 0.00 | 0.00 |
| Little River | 0.19 | 0.21 | 0.41 | 0.34 | 0.68 | 0.70 | 0.73 | 0.51 | 0.60 | 0.59 | 0.10 | 0.00 |
| Logan | 0.34 | 0.40 | 0.55 | 0.60 | 0.87 | 0.91 | 0.97 | 1.10 | 0.73 | 0.88 | 0.86 | 0.00 |
| Lonoke | 0.55 | 0.59 | 0.90 | 1.03 | 1.42 | 1.50 | 1.72 | 1.10 | 1.55 | 1.38 | 0.55 | 0.00 |
| Madison | 0.27 | 0.33 | 0.58 | 0.63 | 0.76 | 0.77 | 0.85 | 0.54 | 0.79 | 1.03 | 0.60 | 0.39 |
| Marion | 0.17 | 0.19 | 0.28 | 0.44 | 0.54 | 0.59 | 0.65 | 0.59 | 0.13 | 0.02 | 0.61 | 0.67 |
| Miller | 0.40 | 0.43 | 0.52 | 0.60 | 0.93 | 1.02 | 1.05 | 1.28 | 0.01 | 0.14 | 0.72 | 0.75 |
| Mississippi | 0.19 | 1.42 | 1.13 | 0.80 | 0.79 | 0.69 | 0.66 | 0.35 | 0.01 | 0.08 | 0.00 | 0.11 |
| Monroe | 0.32 | 0.39 | 0.45 | 0.40 | 0.24 | 0.23 | 0.18 | 0.13 | 0.02 | 0.04 | 0.00 | 0.30 |
| Montgomery | 0.15 | 0.18 | 0.33 | 0.37 | 0.54 | 0.53 | 0.57 | 0.42 | 0.51 | 0.47 | 0.47 | 0.04 |
| Nevada | 0.24 | 0.23 | 0.40 | 0.41 | 0.55 | 0.55 | 0.55 | 0.38 | 0.41 | 0.38 | 0.25 | 0.19 |
| Newton | 0.20 | 0.24 | 0.38 | 0.46 | 0.50 | 0.59 | 0.64 | 0.41 | 0.44 | 0.49 | 0.06 | 0.05 |
| Ouachita | --[1] | 0.44 | 0.77 | 0.62 | 0.27 | 0.08 | 0.30 | 0.85 | 0.28 | 0.48 | 0.06 | 0.00 |
| Perry | 0.14 | 0.16 | 0.30 | 0.35 | 0.40 | 0.42 | 0.46 | 0.38 | 0.33 | 0.66 | 0.32 | 0.36 |
| Phillips | 0.72 | 0.71 | 0.67 | 0.48 | 0.52 | 0.51 | 0.44 | 0.29 | 0.11 | 0.05 | 0.00 | 0.00 |
| Pike | 0.18 | 0.20 | 0.45 | 0.43 | 0.56 | 0.55 | 0.56 | 0.51 | 0.55 | 0.45 | 0.23 | 0.26 |
| Poinsett | 0.65 | 0.75 | 0.84 | 0.70 | 0.32 | 0.25 | 0.21 | 0.29 | 0.23 | 0.34 | 0.16 | 0.16 |
| Polk | 0.28 | 0.29 | 0.60 | 0.65 | 0.89 | 0.91 | 0.94 | 0.79 | 0.76 | 0.74 | 0.83 | 0.66 |
| Pope | 0.71 | 0.41 | 0.94 | 1.05 | 1.58 | 1.61 | 1.84 | 1.55 | 1.77 | 1.35 | 0.27 | 0.73 |
| Prairie | 0.25 | 0.27 | 0.41 | 0.30 | 0.10 | 0.10 | 0.09 | 0.31 | 0.11 | 0.13 | 0.18 | 0.14 |
| Pulaski | 0.14 | 0.18 | 2.31 | 1.80 | 5.80 | 3.93 | 4.67 | 7.44 | 0.08 | 1.11 | 0.00 | 0.54 |
| Randolph | 0.29 | 0.32 | 0.50 | 0.67 | 0.73 | 0.69 | 0.71 | 0.76 | 0.54 | 0.31 | 0.49 | 0.44 |
| Saline | 0.60 | 0.61 | 1.14 | 0.94 | 1.84 | 1.80 | 1.99 | 1.21 | 2.26 | 1.59 | 0.57 | 0.00 |
| Scott | 0.19 | 0.24 | 0.42 | 0.47 | 0.62 | 0.62 | 0.68 | 0.64 | 0.70 | 0.66 | 0.36 | 0.36 |
| Searcy | 0.22 | 0.27 | 0.41 | 0.44 | 0.56 | 0.59 | 0.59 | 0.45 | 0.23 | 0.16 | 0.07 | 0.04 |
| Sebastian | 0.02 | 0.41 | 0.43 | 1.97 | 0.89 | 0.86 | 1.10 | 0.32 | 0.22 | 0.10 | 0.51 | 0.00 |
| Sevier | 0.21 | 0.22 | 0.41 | 0.47 | 0.63 | 0.65 | 0.66 | 0.57 | 0.70 | 0.68 | 0.27 | 0.29 |
| Sharp | 0.16 | 0.16 | 0.17 | 0.11 | 0.39 | 0.40 | 0.47 | 0.14 | 0.08 | 0.00 | 0.27 | 0.26 |
| St. Francis | 0.70 | 0.70 | 1.01 | 0.83 | 0.48 | 0.49 | 0.51 | 0.80 | 0.31 | 0.13 | 0.18 | 0.03 |
| Stone | 0.18 | 0.18 | 0.36 | 0.45 | 0.57 | 0.55 | 0.61 | 0.67 | 0.27 | 0.45 | 0.00 | 0.06 |
| Union | 0.61 | 0.65 | 0.76 | 0.41 | 0.35 | 0.33 | 0.38 | 0.26 | 0.27 | 0.63 | 0.66 | 0.43 |
| Van Buren | 0.22 | 0.26 | 0.40 | 0.25 | 0.52 | 0.57 | 0.64 | 0.77 | 0.49 | 0.01 | 0.04 | 0.11 |
| Washington | 1.10 | 0.78 | 1.70 | 1.95 | 2.20 | 2.31 | 2.67 | 1.38 | 2.97 | 1.40 | 0.18 | 0.00 |
| White | 0.62 | 0.74 | 1.33 | 1.16 | 1.22 | 1.28 | 1.35 | 0.52 | 1.04 | 1.57 | 0.73 | 0.00 |
| Woodruff | 0.30 | 0.34 | 0.39 | 0.24 | 0.30 | 0.28 | 0.27 | 0.24 | 0.20 | 0.03 | 0.08 | 0.00 |
| Yell | 0.27 | 0.31 | 0.56 | 0.68 | 0.72 | 0.79 | 0.75 | 0.04 | 0.41 | 0.52 | 0.00 | 0.04 |
| **Total** | **26.08** | **31.32** | **48.80** | **46.15** | **56.88** | **55.64** | **60.42** | **50.61** | **37.61** | **31.23** | **17.83** | **13.26** |

[1]Data not reported from Jefferson and Ouachita Counties in 1960.

**Table 10.** Groundwater use for commercial supply by counties and years in Arkansas.

[Commercial and mining categories were lumped into the industrial category prior to 1985. Counties shown are only those with published data. Data from Holland (1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|
| Arkansas | 0.05 | 0.63 | 0.00 | 0.91 | 0.18 | 0.00 |
| Baxter | 0.31 | 0.00 | 0.00 | 0.07 | 0.00 | 0.00 |
| Benton | 0.45 | 0.24 | 0.00 | 0.02 | 0.00 | 0.00 |
| Boone | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Bradley | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Carroll | 0.00 | 0.00 | 0.00 | 0.07 | 0.10 | 0.05 |
| Clark | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Clay | 0.00 | 0.14 | 0.00 | 0.00 | 1.97 | 0.00 |
| Cleburne | 0.43 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Columbia | 0.10 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 |
| Conway | 0.05 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 |
| Craighead | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 |
| Crittenden | 0.00 | 0.00 | 0.00 | 1.07 | 0.00 | 0.00 |
| Cross | 0.00 | 0.00 | 0.00 | 0.05 | 0.00 | 0.00 |
| Franklin | 0.11 | 0.13 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fulton | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 |
| Garland | 0.40 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 |
| Greene | 0.12 | 0.00 | 0.07 | 0.07 | 0.14 | 0.09 |
| Hempstead | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| Hot Spring | 0.18 | 0.01 | 0.01 | 0.01 | 0.00 | 0.03 |
| Howard | 0.00 | 0.34 | 0.00 | 0.01 | 0.00 | 0.00 |
| Independence | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Jefferson | 0.89 | 0.94 | 0.00 | 0.00 | 0.00 | 0.00 |
| Johnson | 0.00 | 0.30 | 0.00 | 0.01 | 0.00 | 0.00 |
| Lawrence | 0.00 | 0.00 | 0.00 | 0.00 | 0.24 | 0.00 |
| Lincoln | 0.33 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Little River | 0.20 | 0.00 | 0.00 | 0.04 | 0.06 | 0.08 |
| Logan | 0.03 | 1.05 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lonoke | 0.01 | 0.00 | 0.00 | 0.30 | 0.00 | 0.00 |
| Madison | 0.15 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 |
| Marion | 0.32 | 0.00 | 0.00 | 0.04 | 0.00 | 0.00 |
| Miller | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| Mississippi | 0.65 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Monroe | 0.00 | 0.00 | 0.01 | 0.33 | 0.00 | 0.00 |
| Montgomery | 0.20 | 0.00 | 0.00 | 0.02 | 0.00 | 0.06 |
| Nevada | 0.02 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Newton | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Perry | 0.15 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Phillips | 0.00 | 0.00 | 0.00 | 0.08 | 0.00 | 0.02 |
| Pike | 0.18 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| Poinsett | 0.02 | 2.51 | 0.16 | 0.51 | 0.19 | 0.48 |
| Polk | 0.08 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 |
| Pope | 0.16 | 8.00 | 0.10 | 0.04 | 0.10 | 0.02 |
| Pulaski | 0.11 | 0.00 | 0.00 | 0.01 | 0.12 | 0.03 |
| Randolph | 0.03 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Scott | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Searcy | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Stone | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 |
| Washington | 0.08 | 0.00 | 0.02 | 0.03 | 0.03 | 0.00 |
| Yell | 0.20 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| **Total** | **6.03** | **14.31** | **0.39** | **3.85** | **3.16** | **0.95** |

## Industrial

The industrial water-use category includes water used for fabrication, processing, washing, and cooling in facilities that manufacture products. Prior to 1985, water used in commercial and mining operations was included in the industrial category. From 1985 to 1995, this category also included water provided by public suppliers to industrial users. As of the 2000 report, the industrial category refers to "self-supplied" industrial water use. Large decreases in water use are noted from 1982 to 1985 and from 1995 to 2000 and corresponded to the two changes in reporting (table 11).

Early industrial groundwater users in the State were railroads, ice companies, and lumber and paper mills (Veatch, 1906). Arkansas is home to a diversity of industries including pulp and paper mills, food processors, oil refineries, and chemical plants. Most industrial groundwater use occurs in southern Arkansas. The majority of groundwater use is from the Sparta aquifer, with lesser amounts from the Mississippi River Valley alluvial, Cockfield, Wilcox, and Nacatoch aquifers. For the last decade, paper mills were the largest user of groundwater for industrial purposes (Terrance W. Holland, U.S. Geological Survey, written commun., 2013).

Jefferson County consistently has reported the most industrial groundwater withdrawals in the State. Industrial groundwater use in Jefferson County in 2010 was 35.35 Mgal/d, a 17-percent decrease from 2005 (table 11). In Jefferson County, 80 to 95 percent of groundwater comes from the Sparta aquifer and the remainder from the Mississippi River Valley alluvial aquifer. Industrial growth in Jefferson County has been centered in Pine Bluff.

Union County has several industrial facilities that withdraw groundwater from the Sparta aquifer, with chemical and oil companies as the larger users. In response to decreasing water levels in the Sparta aquifer, multiple conservation measures were initiated to reduce reliance on groundwater. For example, a nationally recognized conservation effort was initiated in Union County involving the Union County Water Conservation Board, local industries, businesses, community leaders, ANRC, and USGS. As a result, Union County decreased its use of groundwater, which resulted in rising groundwater levels in the Sparta aquifer (see "Sparta Aquifer" section for further information).

The Cockfield aquifer is the primary source of water for pulp and sawmilling industries in Ashley County. The Wilcox aquifer is tapped in Mississippi and Greene Counties for various industrial processing including plastic, fertilizer, and steel production, among others. Smaller withdrawals are made from the Ozark, Tokio, Nacatoch, and other aquifers within the State for numerous local industries.

Reporting changes were a main factor in the trends in use for the industrial category. Industrial groundwater use peaked in 1955 (table 6), but use may have been greater in 1960; Jefferson County, the county with the most industrial groundwater use, was not reported (tables 6 and 11). If the industrial use for Pine Bluff (Jefferson County) in 1958 that was reported by Bedinger and others (1960) as 33.55 Mgal/d had been included, then total use for the State would have been estimated at 135 Mgal/d. Industrial use decreased by about 45 percent from 1960 to 1965 because use in Ashley County fell from 28.24 to 7.47 Mgal/d after the construction of a lake to supply a paper company with water (Encyclopedia of Arkansas, 2013; U.S. Army Corps of Engineers, 2013a). Statewide use increased 55 percent from 1965 to 1970 to 114.6 Mgal/d. After commercial and mining categories were separated from the industrial category in 1985, industrial use decreased to 64.01 Mgal/d. Use again increased by approximately 35–40 Mgal/d in 1990 and 1995 because of another change in reporting; public-supply deliveries to industry were included in this category from 1985 to 1995. (In 1985, changes in reporting to ARWUDBS were assumed to counteract increases in use because of the additional public-supply deliveries to industry.) Industrial groundwater use has stabilized between 60 and 70 Mgal/d since 2000.

**Table 11.** Groundwater use for industrial supply by counties and years in Arkansas.

[Counties shown are only those with published data. Commercial and mining categories were lumped into the industrial category prior to 1985. Data from Stephens and Halberg (1961); Halberg and Stephens (1966); Halberg (1972, 1977); Holland and Hall (1986); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1960 | 1965 | 1970 | 1975 | 1980 | 1982 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Arkansas | 8.86 | 0.00 | 0.05 | 0.01 | 0.09 | 0.10 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ashley | 28.24 | 7.47 | 9.21 | 10.67 | 10.03 | 10.04 | 9.96 | 3.80 | 7.50 | 8.73 | 6.20 | 8.40 |
| Baxter | 0.01 | 0.07 | 0.25 | 0.28 | 0.14 | 0.23 | 0.08 | 0.00 | 0.00 | 0.00 | 0.61 | 0.00 |
| Benton | 2.10 | 0.11 | 0.30 | 0.70 | 0.15 | 0.08 | 0.08 | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 |
| Boone | 0.00 | 0.01 | 1.65 | 0.00 | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Bradley | 0.20 | 0.38 | 0.53 | 0.53 | 0.45 | 0.44 | 0.44 | 0.00 | 0.00 | 0.37 | 0.46 | 0.52 |
| Calhoun | 0.00 | 0.03 | 0.00 | 0.21 | 0.51 | 0.37 | 0.01 | 0.00 | 0.00 | 0.06 | 0.00 | 0.01 |
| Carroll | 0.01 | 0.00 | 0.01 | 0.01 | 0.05 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Chicot | 0.01 | 0.02 | 0.01 | 0.03 | 0.45 | 0.03 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Clark | 0.00 | 0.05 | 0.24 | 0.12 | 0.51 | 0.19 | 0.05 | 0.00 | 0.54 | 0.23 | 0.27 | 0.14 |
| Clay | 0.62 | 0.00 | 0.00 | 0.01 | 0.70 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Cleburne | 0.01 | 0.04 | 0.12 | 0.09 | 0.13 | 0.22 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Cleveland | 0.36 | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Columbia | 0.17 | 1.12 | 3.17 | 3.23 | 2.87 | 2.97 | 3.17 | 1.63 | 1.55 | 2.05 | 2.08 | 7.94 |
| Conway | 0.22 | 0.02 | 5.40 | 5.02 | 0.06 | 0.03 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Craighead | 0.68 | 0.19 | 0.72 | 0.30 | 0.46 | 0.10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Crawford | 0.78 | 0.00 | 0.01 | 0.00 | 0.03 | 0.03 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Crittenden | 0.19 | 0.07 | 0.05 | 0.01 | 0.17 | 0.02 | 0.00 | 0.11 | 0.20 | 0.19 | 0.30 | 0.24 |
| Cross | 1.05 | 0.00 | 1.22 | 1.60 | 0.30 | 0.33 | 0.25 | 0.00 | 0.00 | 0.17 | 0.40 | 0.41 |
| Dallas | 0.01 | 0.00 | 0.00 | 0.06 | 0.14 | 0.14 | 0.13 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Desha | 1.70 | 0.00 | 0.01 | 0.03 | 0.97 | 0.88 | 1.98 | 1.69 | 6.14 | 2.92 | 3.19 | 3.24 |
| Drew | 0.23 | 0.13 | 0.20 | 0.01 | 0.01 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Faulkner | 0.10 | 0.00 | 0.01 | 0.00 | 0.03 | 0.07 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Franklin | 0.04 | 0.00 | 0.07 | 0.19 | 0.19 | 0.15 | 0.06 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fulton | 1.30 | 0.00 | 0.00 | 0.00 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Garland | 0.36 | 0.34 | 0.35 | 0.74 | 0.51 | 0.59 | 0.40 | 0.25 | 0.00 | 0.03 | 0.06 | 0.00 |
| Grant | 0.42 | 0.00 | 0.11 | 0.10 | 0.07 | 0.04 | 0.07 | 0.08 | 0.00 | 0.23 | 0.15 | 0.26 |
| Greene | 0.14 | 0.12 | 0.15 | 0.45 | 0.17 | 0.13 | 0.01 | 0.00 | 0.37 | 0.29 | 0.00 | 0.11 |
| Hempstead | 0.00 | 0.01 | 0.04 | 0.01 | 0.01 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Hot Spring | 0.35 | 0.08 | 0.62 | 0.15 | 0.22 | 0.11 | 0.02 | 0.21 | 0.14 | 0.01 | 0.00 | 0.00 |
| Howard | 0.00 | 0.27 | 0.35 | 0.72 | 0.49 | 0.26 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Independence | 0.25 | 0.00 | 0.03 | 0.04 | 0.09 | 0.13 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Izard | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Jackson | 1.26 | 1.01 | 0.41 | 2.06 | 0.79 | 0.74 | 0.74 | 0.00 | 0.00 | 0.00 | 0.00 | 0.18 |
| Jefferson | --[1] | 38.96 | 51.23 | 44.83 | 45.45 | 39.79 | 30.09 | 84.65 | 75.56 | 37.13 | 42.54 | 35.35 |
| Johnson | 0.22 | 0.01 | 0.02 | 0.03 | 0.10 | 0.08 | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lafayette | 2.24 | 0.56 | 0.71 | 0.20 | 0.19 | 0.20 | 0.14 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| Lawrence | 1.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lee | 0.16 | 0.02 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

**Table 11.** Groundwater use for industrial supply by counties and years in Arkansas.—Continued

[Counties shown are only those with published data. Commercial and mining categories were lumped into the industrial category prior to 1985. Data from Stephens and Halberg (1961); Halberg and Stephens (1966); Halberg (1972, 1977); Holland and Hall (1986); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1960 | 1965 | 1970 | 1975 | 1980 | 1982 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lincoln | 0.61 | 0.03 | 0.19 | 0.34 | 0.40 | 0.38 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Little River | 0.03 | 0.34 | 1.41 | 1.28 | 0.47 | 0.25 | 0.27 | 0.00 | 0.00 | 0.24 | 0.24 | 0.00 |
| Logan | 0.00 | 0.01 | 0.16 | 0.01 | 0.04 | 0.05 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lonoke | 5.92 | 0.00 | 0.82 | 0.52 | 1.28 | 1.09 | 1.08 | 0.00 | 0.97 | 0.81 | 0.59 | 0.74 |
| Madison | 0.00 | 0.00 | 0.01 | 0.00 | 0.01 | 0.04 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Marion | 0.07 | 0.07 | 0.04 | 0.08 | 0.22 | 0.19 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Miller | 0.05 | 0.08 | 0.40 | 0.21 | 0.23 | 0.19 | 0.16 | 0.00 | 0.00 | 0.00 | 0.00 | 0.14 |
| Mississippi | 0.88 | 2.88 | 6.96 | 7.33 | 3.80 | 4.39 | 1.73 | 2.75 | 7.65 | 2.66 | 2.16 | 1.67 |
| Monroe | 1.11 | 0.01 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Montgomery | 0.00 | 0.05 | 0.06 | 0.06 | 0.10 | 0.11 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Nevada | 0.00 | 0.00 | 0.39 | 0.13 | 0.04 | 0.04 | 0.03 | 0.00 | 0.00 | 0.01 | 0.17 | 0.00 |
| Newton | 0.00 | 0.00 | 0.04 | 0.12 | 0.17 | 0.12 | 0.12 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ouachita | --[1] | 1.75 | 5.94 | 2.84 | 2.64 | 2.49 | 2.26 | 0.00 | 0.79 | 0.81 | 0.00 | 0.00 |
| Perry | 0.02 | 0.00 | 0.03 | 0.02 | 0.02 | 0.09 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Phillips | 0.13 | 1.19 | 5.37 | 5.07 | 2.44 | 2.36 | 2.36 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| Pike | 0.24 | 0.07 | 0.12 | 0.15 | 0.27 | 0.12 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Poinsett | 0.47 | 0.00 | 0.29 | 0.35 | 0.43 | 0.21 | 0.14 | 0.00 | 0.00 | 0.11 | 0.00 | 0.00 |
| Polk | 0.25 | 0.33 | 0.10 | 0.33 | 0.03 | 0.03 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Pope | 0.52 | 0.05 | 0.02 | 0.04 | 0.47 | 0.23 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Prairie | 1.09 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Pulaski | 6.73 | 0.00 | 0.00 | 0.74 | 0.71 | 0.99 | 0.52 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Randolph | 0.00 | 0.02 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Saline | 0.00 | 0.01 | 0.01 | 0.18 | 0.27 | 0.07 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Scott | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Searcy | 0.09 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sebastian | 0.00 | 0.00 | 0.05 | 0.04 | 0.05 | 0.05 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sevier | 0.22 | 0.00 | 0.00 | 0.00 | 0.12 | 0.12 | 0.05 | 1.03 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sharp | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.66 | 0.00 | 0.00 |
| St. Francis | 0.55 | 0.68 | 0.30 | 0.37 | 0.31 | 0.11 | 0.01 | 0.00 | 0.00 | 0.07 | 0.00 | 0.00 |
| Stone | 0.00 | 0.01 | 0.01 | 0.03 | 0.05 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Union | 28.62 | 15.12 | 14.38 | 12.47 | 8.20 | 9.64 | 6.02 | 2.72 | 6.41 | 9.23 | 6.33 | 1.75 |
| Van Buren | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Washington | 0.00 | 0.00 | 0.01 | 0.02 | 0.03 | 0.04 | 0.07 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| White | 0.15 | 0.04 | 0.05 | 0.05 | 0.04 | 0.03 | 0.01 | 0.00 | 0.00 | 0.04 | 0.00 | 0.00 |
| Woodruff | 0.66 | 0.02 | 0.13 | 0.03 | 0.02 | 0.00 | 0.00 | 0.00 | 0.12 | 0.00 | 0.00 | 0.00 |
| Yell | 0.04 | 0.03 | 0.03 | 0.46 | 1.26 | 0.89 | 1.14 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 |
| **Total** | **101.75** | **73.88** | **114.60** | **105.76** | **90.83** | **82.99** | **64.01** | **98.92** | **107.95** | **67.07** | **65.75** | **61.17** |

[1]Data not reported from Jefferson and Ouachita Counties in 1960.

## Mining

Water use in the mining category is defined as water used for coal, sand, and gravel operations, and additionally includes saline withdrawals from oil and natural gas wells. Water use in this category dominantly is for drilling and washing processes associated with mining operations. Prior to the development of the ARWUDBS in the 1980s, water-use estimates for mining operations were obtained from the Arkansas Geological Commission (now Arkansas Geological Survey) and were included in the industrial category.

Groundwater use for mining has been minimal in Arkansas with maximum use in 1990 of 1.82 Mgal/d (table 12); use for any one county has not been more than 0.5 Mgal/d. Use for this category has averaged 0.21 Mgal/d since 2000. Users in Polk County (0.07 Mgal/d) withdrew the most groundwater for mining purposes in 2010. Recently, Arkansas has seen an increase in natural gas development in the Fayetteville Shale; however, most water use for this development has been from surface-water sources (Terrance W. Holland, U.S. Geological Survey, written commun., 2013).

**Table 12.** Groundwater use for mining supply by counties and years in Arkansas.

[Counties shown are only those with published data. Data from Holland (1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|
| Ashley | 0.00 | 0.18 | 0.00 | 0.00 | 0.00 | 0.00 |
| Benton | 0.01 | 0.00 | 0.00 | 0.04 | 0.00 | 0.02 |
| Calhoun | 0.00 | 0.18 | 0.00 | 0.00 | 0.00 | 0.00 |
| Clark | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Conway | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 |
| Craighead | 0.00 | 0.18 | 0.00 | 0.06 | 0.08 | 0.02 |
| Crittenden | 0.02 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 |
| Cross | 0.00 | 0.18 | 0.00 | 0.00 | 0.00 | 0.00 |
| Desha | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Franklin | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Garland | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Greene | 0.00 | 0.00 | 0.00 | 0.02 | 0.07 | 0.02 |
| Hempstead | 0.02 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 |
| Hot Spring | 0.01 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 |
| Howard | 0.46 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Independence | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Izard | 0.01 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 |
| Jackson | 0.00 | 0.18 | 0.00 | 0.00 | 0.00 | 0.00 |
| Jefferson | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 |
| Johnson | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Little River | 0.25 | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 |
| Logan | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lonoke | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 |
| Miller | 0.02 | 0.18 | 0.00 | 0.00 | 0.00 | 0.00 |
| Poinsett | 0.00 | 0.18 | 0.00 | 0.06 | 0.08 | 0.04 |
| Polk | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.07 |
| Pope | 0.01 | 0.18 | 0.00 | 0.00 | 0.00 | 0.00 |
| Randolph | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Saline | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sebastian | 0.03 | 0.22 | 0.00 | 0.00 | 0.00 | 0.00 |
| White | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Total** | **1.03** | **1.82** | **0.00** | **0.21** | **0.24** | **0.18** |

## Aquaculture (Fish and Minnow Farming)

The aquaculture category represents water use associated with fish hatcheries and the farming of aquatic organisms including fish, shellfish, and algae. In reports from 1965 to 1980, withdrawals in this category were reported as "fish and minnow farming." This included the National Fish Hatcheries in Baxter, Clay (now a State hatchery), Cleburne, and Fulton Counties. Water use at trout hatcheries was considered negligible in 1980 and thus was not reported (tables 6 and 13). In 1990 and 1995, fish hatcheries were included in the commercial category. Fish-hatchery water use has been included in the aquaculture category since 2000. From 1965 to 1985, water-use data for aquaculture were derived by multiplying aquaculture acreage by an application rate. Application rates were developed by the Arkansas Game and Fish Commission, the USDA Soil Conservation Service (now the USDA Natural Resources Conservation Service), and the U.S. Bureau of Sport Fisheries and Wildlife at Stuttgart (Halberg and Stephens, 1966; Halberg, 1972, 1977; Holland, 1981). Catfish and minnow ponds use an application rate of 7–8.9 acre-ft, and rough ponds as well as fishing ponds use a 3-acre-ft application rate. After 1985, water use for fish farming was reported and registered in ARWUDBS.

Aquaculture is an important industry in Arkansas. Multiple counties in southeastern Arkansas began aquaculture in the 1960s (Broom and Reed, 1973; Kaliba and Engle, 2006). Goldfish farming reportedly began in Lonoke County as early as the 1940s (Engle, 2012). Arkansas leads the Nation in the production of baitfish (Kaliba and Engle, 2006; Stone and Selden, 2006), and the world's largest producer of baitfish is located in Lonoke County. Other commonly grown aquaculture crops are bass, carp, catfish, crayfish, and koi. Fish commonly are raised in large ponds surrounded by earthen berms filled with groundwater. Approximately 98 percent of all withdrawals for aquaculture are from the Mississippi River Valley alluvial aquifer (Terrance W. Holland, U.S. Geological Survey, written commun., 2013). Some aquaculture wells in Chicot County reach the Cockfield aquifer, whereas wells in Arkansas and Lonoke County are completed in the Sparta aquifer. Historically, trout production was of local importance in the Ozark Plateaus of northern Arkansas. Trout require very high-quality, low-temperature water. Springs of the Springfield Plateau and Ozark aquifers provide an abundant source of suitable water, and hundreds of trout farms have operated in Arkansas over the years. Lower market prices and problems of nutrient enrichment and sediment—associated with poultry and livestock production and development (Adamski and others, 1995)—have forced many of the trout farms to close. Currently (2013), only two large trout farms are known to be active, one north of Harrison (Boone County) and one near Yellville (Marion County).

**Table 13.** Groundwater use for aquaculture supply by counties and years in Arkansas.

[Counties shown are only those with published data. Data for 1985 were combined with the livestock category and are not shown. Data from Halberg and Stephens (1966); Halberg (1972, 1977); Holland and Hall (1986); Holland (1981, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1965 | 1970 | 1975 | 1980 | 1982 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|
| Arkansas | 2.70 | 3.86 | 3.81 | 12.05 | 10.09 | 0.76 | 23.34 | 8.88 | 8.26 | 0.64 |
| Ashley | 0.27 | 6.55 | 5.46 | 8.33 | 6.75 | 2.75 | 13.80 | 0.00 | 22.91 | 8.82 |
| Baxter | 0.01 | 0.07 | 0.05 | 0.00 | 0.50 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Benton | 0.77 | 0.91 | 5.54 | 0.61 | 0.50 | 0.20 | 0.36 | 0.00 | 0.07 | 0.00 |
| Boone | 0.03 | 0.05 | 1.87 | 0.11 | 0.09 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Bradley | 0.34 | 0.21 | 0.07 | 0.07 | 0.07 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Chicot | 0.00 | 3.48 | 3.54 | 4.34 | 3.56 | 12.89 | 32.42 | 44.67 | 56.79 | 46.78 |
| Clark | 0.00 | 0.01 | 0.00 | 1.34 | 1.09 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Clay | 1.94 | 0.13 | 0.64 | 1.37 | 1.11 | 0.95 | 0.77 | 0.00 | 1.52 | 0.92 |
| Cleburne | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Cleveland | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Columbia | 0.00 | 0.29 | 0.17 | 1.10 | 0.89 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Conway | 0.80 | 1.16 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Craighead | 0.64 | 0.75 | 0.32 | 0.15 | 0.13 | 0.23 | 0.05 | 1.23 | 0.16 | 0.23 |
| Crawford | 0.00 | 0.15 | 0.06 | 0.02 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Crittenden | 0.30 | 0.98 | 1.21 | 4.13 | 3.37 | 0.00 | 0.00 | 0.07 | 1.50 | 0.82 |
| Cross | 0.49 | 2.51 | 1.68 | 3.43 | 2.80 | 0.55 | 0.82 | 0.00 | 0.02 | 0.02 |
| Dallas | 0.00 | 0.19 | 0.47 | 0.14 | 0.12 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Desha | 6.01 | 11.82 | 11.26 | 14.15 | 11.49 | 3.30 | 12.63 | 12.83 | 9.67 | 10.68 |
| Drew | 1.14 | 8.53 | 9.54 | 1.11 | 0.91 | 0.31 | 0.79 | 0.98 | 0.03 | 0.29 |
| Faulkner | 0.00 | 1.84 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

**Table 13.** Groundwater use for aquaculture supply by counties and years in Arkansas.—Continued

[Counties shown are only those with published data. Data for 1985 were combined with the livestock category and are not shown. Data from Halberg and Stephens (1966); Halberg (1972, 1977); Holland and Hall (1986); Holland (1981, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1965 | 1970 | 1975 | 1980 | 1982 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|
| Franklin | 0.14 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fulton | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.13 | 0.00 |
| Garland | 0.00 | 0.33 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Grant | 0.06 | 0.26 | 0.13 | 0.17 | 0.14 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Greene | 2.42 | 6.48 | 4.65 | 7.92 | 6.42 | 11.96 | 0.00 | 0.02 | 12.91 | 12.42 |
| Hempstead | 0.21 | 0.25 | 0.00 | 0.02 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Hot Spring | 0.12 | 1.84 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Howard | 0.00 | 0.11 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Independence | 0.00 | 0.94 | 0.15 | 0.10 | 0.08 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Izard | 0.00 | 0.01 | 0.00 | 0.05 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Jackson | 5.72 | 7.28 | 7.11 | 3.40 | 2.76 | 1.95 | 6.61 | 1.74 | 3.40 | 2.20 |
| Jefferson | 0.22 | 5.33 | 5.33 | 7.24 | 6.25 | 3.00 | 7.36 | 4.65 | 2.03 | 0.25 |
| Johnson | 0.18 | 0.00 | 0.00 | 0.03 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lafayette | 0.62 | 0.92 | 0.61 | 0.65 | 0.53 | 0.00 | 1.52 | 0.02 | 4.49 | 3.28 |
| Lawrence | 1.03 | 4.58 | 4.52 | 1.30 | 1.06 | 0.17 | 0.06 | 0.00 | 0.26 | 0.00 |
| Lee | 0.00 | 0.37 | 0.33 | 0.27 | 0.27 | 0.74 | 4.70 | 0.14 | 3.64 | 3.86 |
| Lincoln | 2.19 | 17.31 | 13.01 | 1.22 | 1.04 | 2.48 | 2.92 | 0.00 | 3.89 | 1.07 |
| Little River | 0.00 | 0.06 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| Logan | 0.00 | 0.29 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lonoke | 53.66 | 70.33 | 95.15 | 123.04 | 102.56 | 32.31 | 66.63 | 57.36 | 56.60 | 41.44 |
| Madison | 0.21 | 0.19 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Marion | 0.03 | 0.00 | 3.46 | 3.97 | 3.21 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Miller | 0.00 | 0.29 | 0.29 | 0.40 | 0.32 | 0.02 | 0.45 | 0.00 | 0.35 | 0.00 |
| Mississippi | 0.00 | 1.19 | 0.94 | 2.50 | 2.02 | 0.00 | 0.00 | 0.08 | 0.98 | 0.84 |
| Monroe | 2.87 | 6.05 | 6.70 | 39.80 | 33.15 | 3.96 | 0.00 | 0.00 | 13.38 | 13.80 |
| Montgomery | 0.00 | 0.09 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Newton | 0.03 | 0.01 | 1.73 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ouachita | 0.00 | 0.28 | 0.10 | 0.04 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Perry | 0.00 | 1.71 | 0.25 | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 |
| Phillips | 0.41 | 1.37 | 0.26 | 0.04 | 0.04 | 0.02 | 0.00 | 2.80 | 0.02 | 0.05 |
| Pike | 0.00 | 0.08 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| Poinsett | 0.35 | 1.59 | 0.96 | 3.24 | 2.66 | 5.59 | 11.51 | 0.17 | 4.72 | 2.78 |
| Polk | 0.21 | 0.22 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Pope | 0.00 | 0.30 | 0.00 | 0.00 | 0.00 | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 |
| Prairie | 8.44 | 21.43 | 21.14 | 29.30 | 24.86 | 12.83 | 33.21 | 42.87 | 32.89 | 29.12 |
| Pulaski | 0.92 | 2.76 | 2.09 | 1.25 | 1.05 | 0.24 | 0.48 | 0.17 | 0.09 | 0.05 |
| Randolph | 0.00 | 0.48 | 0.27 | 0.44 | 0.35 | 0.05 | 0.01 | 0.00 | 0.00 | 0.00 |
| Saline | 1.07 | 0.29 | 0.08 | 0.10 | 0.08 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Scott | 0.00 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sebastian | 0.21 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sevier | 0.04 | 0.07 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sharp | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| St. Francis | 0.42 | 2.82 | 1.46 | 0.45 | 0.40 | 0.01 | 3.47 | 2.80 | 2.33 | 0.57 |
| Stone | 0.00 | 0.01 | 0.04 | 0.02 | 0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Union | 0.00 | 0.03 | 0.00 | 0.10 | 0.08 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Washington | 0.26 | 0.17 | 3.46 | 3.97 | 3.21 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| White | 1.04 | 2.56 | 2.69 | 0.85 | 0.76 | 0.40 | 1.03 | 1.19 | 0.27 | 0.21 |
| Woodruff | 4.94 | 7.03 | 7.02 | 0.55 | 0.61 | 0.78 | 3.31 | 4.67 | 2.50 | 0.00 |
| Yell | 0.00 | 0.91 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Total** | **103.50** | **212.18** | **229.65** | **284.88** | **237.54** | **98.53** | **228.25** | **187.35** | **245.82** | **181.14** |

Aquaculture was the second largest category of water use in Arkansas in 2010 (table 6). Because data for aquaculture were combined with data for livestock for 1985, aquaculture groundwater use for the State in 1985 was assumed to be approximately 220 Mgal/d. Reports for 1990 and 1995 also included fish farming in the livestock category (Holland, 1993, 1999); data for 1990 and 1995 shown in table 6 were extracted from ARWUDBS instead of the published 5-year reports (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

Statewide, the peak of groundwater use for aquaculture occurred in 1980 at 284.88 Mgal/d. Lonoke or Chicot Counties generally have had the greatest withdrawals with 41.44 and 46.78 Mgal/d, respectively, being used in 2010 (table 13). At times, production in the State has been limited because of a lack of fish processing facilities; increases in water-use rates were seen after the installation of fish processing facilities. In Chicot County, increases in water-use rates for aquaculture were noted in 1980 and again in 1990 after two catfish processing facilities were constructed (Kaliba and Engle, 2006). Aquaculture production rates, and thus water use, since have declined because of foreign imports of catfish and other species (Stone and Selden, 1991).

### Duck Hunting (Wildlife Impoundments)

Withdrawals for duck hunting provide habitat for migratory waterfowl. Duck hunters, particularly in the Grand Prairie region, withdraw water to provide habitat for migrating ducks. This category was reported as “Wildlife Impoundments” from 1965 to 1980 (table 6). Withdrawals for this practice were reported in the irrigation category from 1985 to 2003, and the “Duck Hunting” category was reinstated for the 2005 compilation (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Accounting for this water use is extremely important because duck hunting occurs in the winter when recharge to the aquifers is the greatest (Holland, 2007).

The expansion of duck hunting was coincidental with increased rice agriculture in eastern and southern Arkansas. Reports of the area being good for commercial game hunters began around the 1920s. Cleared rice fields provide food, water, and a natural wintering habitat for migratory waterfowl in an area close to the Mississippi Flyway (a migratory flight pattern for birds flying south from Canada and the northern States). Duck (hunting) clubs have formed in many areas, and fallow cropland is flooded with water from irrigation wells to provide habitat to attract ducks. Approximately 22 percent of rice fields are flooded for migratory bird habitat following the rice harvest (Wilson and Branson, 2002). Arkansas, particularly in the Grand Prairie region, is an international duck hunting destination, and many farmers supplement income from growing crops by leasing land for duck hunting (Bowman and Wright, 1999).

The majority of water used for duck hunting has been withdrawn from the Mississippi River Valley alluvial aquifer; however, in the Grand Prairie region, groundwater is now being removed from the Sparta aquifer to flood fields for hunting with 1–2 percent of the water used statewide for duck hunting being withdrawn from the Sparta aquifer (Terrance W. Holland, U.S. Geological Survey, written commun., 2013). Groundwater use for this category has increased approximately 166 percent from 1965 to 2010 (table 14). Most groundwater withdrawn for duck hunting was in the Grand Prairie region, and Arkansas County reported the most water used for this category in 2005 and 2010.

### Livestock

The livestock water-use category includes water consumed by stock and poultry including feedlots, dairy farming, and other needs in the production of animal crops. The amount of water used generally falls beneath the reporting threshold, so only a small amount of livestock use is reported to ARWUDBS. Most use in this category is estimated by multiplying the water requirements of a type of animal (for example dairy cows, hogs, poultry) by the livestock production values from the USDA. More information on this calculation can be found in Holland (2007).

In 1985, this category was called Agriculture (non-irrigation). Groundwater use reported for this category was erroneously high in 1985 (table 6) because the national USGS water-use reporting program combined the categories of aquaculture and livestock. Livestock use for 1985 was assumed to be similar to that in 1982 and 1990, between 21 and 26 Mgal/d. The 1990 and 1995 reports also included fish farming in the livestock category (Holland, 1993, 1999); however, data for 1990 and 1995 shown in table 15 were extracted from ARWUDBS (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

All counties have reported groundwater use for livestock (table 15). Nationally, Arkansas produced the second most broilers (chickens), the fourth most turkeys, and the tenth most eggs in 2012 (University of Arkansas Division of Agriculture, 2013). The poultry industry primarily is located in northwestern Arkansas, the location for many national poultry producers. Benton and Washington Counties were the largest groundwater users for livestock (excluding data in 1985). Groundwater use for livestock has remained relatively stable since 1995, at around 15 Mgal/d, until a change in reporting in 2010 caused increased usage in Lee, Lonoke, Mississippi, Poinsett, and White Counties.

**Table 14.** Groundwater use for wildlife impoundments (1965–80) and duck hunting (2005–10) supply by counties and years in Arkansas.

[Counties shown are only those with published data. Data from Halberg and Stephens (1966); Halberg (1972, 1977); Holland (1981, 2007). Units are million gallons per day]

| County | 1965 | 1970 | 1975 | 1980 | 2005 | 2010 |
|---|---|---|---|---|---|---|
| Arkansas | 0.08 | 0.08 | 0.04 | 0.00 | 24.67 | 22.84 |
| Baxter | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Clay | 0.15 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Crittenden | 0.00 | 0.00 | 0.00 | 0.00 | 0.12 | 0.84 |
| Cross | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.21 |
| Dallas | 0.00 | 0.00 | 0.25 | 0.00 | 0.31 | 0.00 |
| Desha | 0.00 | 0.00 | 0.00 | 0.00 | 4.91 | 1.68 |
| Drew | 0.00 | 0.00 | 0.00 | 0.00 | 0.20 | 0.40 |
| Independence | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 |
| Jackson | 0.00 | 0.00 | 0.00 | 0.00 | 8.18 | 3.79 |
| Jefferson | 0.00 | 0.00 | 0.00 | 0.00 | 5.14 | 4.55 |
| Lafayette | 0.00 | 0.00 | 0.00 | 0.00 | 4.62 | 2.83 |
| Lawrence | 0.00 | 0.00 | 0.00 | 0.00 | 0.22 | 0.00 |
| Lee | 0.00 | 0.00 | 0.00 | 0.00 | 7.42 | 7.90 |
| Lincoln | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 | 0.00 |
| Little River | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 |
| Lonoke | 0.00 | 0.00 | 0.00 | 0.00 | 3.65 | 2.68 |
| Miller | 0.00 | 0.00 | 0.00 | 0.00 | 5.00 | 2.40 |
| Mississippi | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 |
| Monroe | 0.00 | 0.00 | 0.00 | 0.00 | 5.54 | 18.90 |
| Phillips | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 | 0.02 |
| Poinsett | 0.00 | 0.00 | 0.00 | 5.36 | 0.75 | 2.86 |
| Pope | 0.19 | 0.19 | 0.96 | 0.00 | 0.00 | 0.00 |
| Prairie | 0.00 | 0.00 | 0.00 | 0.00 | 1.01 | 2.35 |
| Pulaski | 0.00 | 0.00 | 0.00 | 0.00 | 0.80 | 0.43 |
| Randolph | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.26 |
| St. Francis | 0.00 | 0.00 | 0.00 | 0.00 | 2.68 | 4.99 |
| White | 0.00 | 0.00 | 0.00 | 0.00 | 4.88 | 0.00 |
| Woodruff | 0.00 | 0.00 | 0.00 | 0.00 | 0.95 | 0.48 |
| **Total** | **0.48** | **0.28** | **1.26** | **5.36** | **81.14** | **80.43** |

**Table 15.** Groundwater use for livestock supply by counties and years in Arkansas.

[Counties shown are only those with published data. Data from Stephens and Halberg (1961); Halberg and Stephens (1966); Halberg (1972, 1977); Holland and Hall (1986); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1960 | 1965 | 1970 | 1975 | 1980 | 1982 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Arkansas | 0.15 | 0.11 | 0.08 | 0.16 | 0.08 | 0.03 | 3.67 | 0.01 | 0.03 | 0.03 | 0.02 | 0.66 |
| Ashley | 0.19 | 0.11 | 0.10 | 0.22 | 0.09 | 0.05 | 5.27 | 0.08 | 0.04 | 0.04 | 0.03 | 0.03 |
| Baxter | 0.14 | 0.05 | 0.05 | 0.26 | 0.07 | 0.07 | 0.14 | 0.07 | 0.14 | 0.14 | 0.15 | 0.14 |
| Benton | 1.42 | 1.06 | 1.38 | 2.04 | 2.10 | 1.82 | 3.00 | 2.02 | 0.98 | 1.03 | 1.12 | 0.98 |
| Boone | 0.13 | 0.11 | 0.65 | 0.66 | 0.16 | 0.16 | 0.31 | 0.22 | 0.46 | 0.46 | 0.54 | 0.48 |
| Bradley | 0.09 | 0.06 | 0.37 | 0.18 | 0.13 | 0.14 | 0.28 | 0.12 | 0.05 | 0.05 | 0.05 | 0.05 |
| Calhoun | 0.08 | 0.04 | 0.06 | 0.08 | 0.04 | 0.04 | 0.02 | 0.02 | 0.04 | 0.04 | 0.02 | 0.01 |
| Carroll | 0.38 | 0.21 | 0.31 | 0.69 | 0.20 | 0.29 | 0.32 | 0.42 | 0.58 | 0.58 | 0.68 | 0.67 |
| Chicot | 0.47 | 0.18 | 0.21 | 0.39 | 0.12 | 0.06 | 3.59 | 0.07 | 0.06 | 0.06 | 0.04 | 0.09 |
| Clark | 0.20 | 0.16 | 0.21 | 0.34 | 0.17 | 0.14 | 1.15 | 0.16 | 0.13 | 0.13 | 0.10 | 0.09 |
| Clay | 0.12 | 0.14 | 0.20 | 0.27 | 0.12 | 0.09 | 1.18 | 0.11 | 0.04 | 0.04 | 0.06 | 0.09 |
| Cleburne | 0.12 | 0.15 | 0.24 | 0.39 | 0.56 | 0.54 | 0.52 | 0.67 | 0.95 | 0.95 | 0.24 | 0.24 |
| Cleveland | 0.22 | 0.08 | 0.12 | 0.14 | 0.15 | 0.14 | 0.19 | 0.32 | 0.10 | 0.11 | 0.12 | 0.16 |
| Columbia | 0.19 | 0.12 | 0.18 | 0.39 | 0.31 | 0.21 | 1.14 | 0.24 | 0.12 | 0.12 | 0.12 | 0.12 |
| Conway | 0.24 | 0.23 | 0.24 | 0.49 | 0.54 | 0.51 | 0.59 | 0.56 | 0.33 | 0.33 | 0.39 | 0.46 |
| Craighead | 0.28 | 0.14 | 0.14 | 0.17 | 0.12 | 0.12 | 0.21 | 0.07 | 0.05 | 0.05 | 0.05 | 0.08 |
| Crawford | 0.20 | 0.18 | 0.27 | 0.36 | 0.46 | 0.45 | 0.46 | 0.45 | 0.25 | 0.25 | 0.24 | 0.21 |
| Crittenden | 0.21 | 0.10 | 0.08 | 0.07 | 0.06 | 0.02 | 3.38 | 0.02 | 0.01 | 0.01 | 0.00 | 0.06 |
| Cross | 0.21 | 0.17 | 0.14 | 0.16 | 0.13 | 0.08 | 2.89 | 0.07 | 0.04 | 0.04 | 0.03 | 0.94 |
| Dallas | 0.08 | 0.05 | 0.06 | 0.08 | 0.04 | 0.04 | 0.14 | 0.04 | 0.04 | 0.04 | 0.02 | 0.02 |
| Desha | 0.37 | 0.10 | 0.08 | 0.23 | 0.07 | 0.06 | 21.62 | 0.04 | 0.04 | 0.04 | 0.02 | 0.01 |
| Drew | 0.19 | 0.12 | 0.12 | 0.35 | 0.11 | 0.10 | 1.00 | 0.28 | 0.08 | 0.08 | 0.07 | 0.13 |
| Faulkner | 0.23 | 0.27 | 0.29 | 0.50 | 0.31 | 0.38 | 0.38 | 0.38 | 0.37 | 0.37 | 0.30 | 0.24 |
| Franklin | 0.22 | 0.24 | 0.31 | 0.54 | 0.25 | 0.56 | 0.54 | 0.67 | 0.36 | 0.36 | 0.40 | 0.37 |
| Fulton | 0.10 | 0.06 | 0.06 | 0.39 | 0.11 | 0.13 | 0.08 | 0.15 | 0.25 | 0.25 | 0.33 | 0.34 |
| Garland | 0.16 | 0.12 | 0.10 | 0.13 | 0.08 | 0.13 | 0.08 | 0.06 | 0.10 | 0.10 | 0.06 | 0.05 |
| Grant | 0.09 | 0.06 | 0.07 | 0.12 | 0.09 | 0.08 | 0.23 | 0.06 | 0.08 | 0.08 | 0.07 | 0.13 |
| Greene | 0.06 | 0.18 | 0.19 | 0.23 | 0.27 | 0.10 | 7.67 | 0.12 | 0.06 | 0.06 | 0.06 | 0.56 |
| Hempstead | 0.43 | 0.33 | 0.53 | 0.83 | 0.77 | 0.73 | 0.76 | 0.99 | 0.38 | 0.38 | 0.58 | 0.55 |
| Hot Spring | 0.17 | 0.15 | 0.15 | 0.19 | 0.11 | 0.15 | 0.11 | 0.00 | 0.12 | 0.12 | 0.11 | 0.11 |
| Howard | 0.45 | 0.28 | 0.40 | 0.68 | 0.91 | 0.80 | 0.89 | 0.98 | 0.34 | 0.33 | 0.44 | 0.54 |
| Independence | 0.68 | 0.21 | 0.27 | 0.65 | 0.21 | 0.39 | 0.39 | 0.37 | 0.31 | 0.31 | 0.35 | 0.53 |
| Izard | 0.15 | 0.07 | 0.10 | 0.29 | 0.12 | 0.12 | 0.15 | 0.13 | 0.22 | 0.22 | 0.24 | 0.21 |
| Jackson | 0.12 | 0.10 | 0.10 | 0.21 | 0.14 | 0.05 | 2.80 | 0.06 | 0.03 | 0.03 | 0.02 | 0.05 |
| Jefferson | --[1] | 0.10 | 0.14 | 0.24 | 0.12 | 0.10 | 6.33 | 0.08 | 0.04 | 0.04 | 0.04 | 0.05 |
| Johnson | 0.30 | 0.17 | 0.20 | 0.35 | 0.34 | 0.32 | 0.44 | 0.55 | 0.26 | 0.25 | 0.29 | 0.29 |
| Lafayette | 0.14 | 0.12 | 0.21 | 0.36 | 0.31 | 0.33 | 0.92 | 0.51 | 0.23 | 0.23 | 0.26 | 0.22 |
| Lawrence | 0.07 | 0.05 | 0.05 | 0.25 | 0.06 | 0.06 | 1.10 | 0.22 | 0.14 | 0.14 | 0.17 | 0.14 |

**Table 15.** Groundwater use for livestock supply by counties and years in Arkansas.—Continued

[Counties shown are only those with published data. Data from Stephens and Halberg (1961); Halberg and Stephens (1966); Halberg (1972, 1977); Holland and Hall (1986); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1960 | 1965 | 1970 | 1975 | 1980 | 1982 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lee | 0.30 | 0.18 | 0.13 | 0.23 | 0.12 | 0.06 | 0.30 | 0.04 | 0.02 | 0.02 | 0.02 | 1.21 |
| Lincoln | 0.18 | 0.11 | 0.12 | 0.21 | 0.16 | 0.15 | 1.19 | 0.52 | 0.11 | 0.11 | 0.10 | 0.22 |
| Little River | 0.17 | 0.16 | 0.21 | 0.43 | 0.24 | 0.19 | 0.23 | 0.24 | 0.23 | 0.23 | 0.23 | 0.24 |
| Logan | 0.39 | 0.35 | 0.38 | 0.69 | 0.65 | 0.65 | 0.63 | 0.71 | 0.43 | 0.43 | 0.51 | 0.46 |
| Lonoke | 0.25 | 0.19 | 0.26 | 0.51 | 0.30 | 0.17 | 92.36 | 0.35 | 0.14 | 0.14 | 0.12 | 1.17 |
| Madison | 0.60 | 0.27 | 0.38 | 0.80 | 0.37 | 0.44 | 0.46 | 0.43 | 0.52 | 0.52 | 0.55 | 0.54 |
| Marion | 0.06 | 0.06 | 0.06 | 0.33 | 0.09 | 0.08 | 3.28 | 0.06 | 0.18 | 0.18 | 0.19 | 0.17 |
| Miller | 0.22 | 0.21 | 0.30 | 0.59 | 0.48 | 0.43 | 0.88 | 0.38 | 0.22 | 0.22 | 0.21 | 0.18 |
| Mississippi | 0.20 | 0.12 | 0.10 | 0.08 | 0.07 | 0.06 | 2.05 | 0.02 | 0.01 | 0.01 | 0.00 | 1.10 |
| Monroe | 0.07 | 0.03 | 0.03 | 0.06 | 0.02 | 0.01 | 8.75 | 0.01 | 0.01 | 0.01 | 0.01 | 0.29 |
| Montgomery | 0.15 | 0.12 | 0.15 | 0.20 | 0.29 | 0.27 | 0.34 | 0.33 | 0.17 | 0.17 | 0.20 | 0.16 |
| Nevada | 0.19 | 0.16 | 0.26 | 0.46 | 0.35 | 0.45 | 0.34 | 0.34 | 0.14 | 0.14 | 0.16 | 0.15 |
| Newton | 0.05 | 0.04 | 0.04 | 0.19 | 0.06 | 0.05 | 0.04 | 0.00 | 0.13 | 0.13 | 0.14 | 0.13 |
| Ouachita | --[1] | 0.07 | 0.13 | 0.16 | 0.14 | 0.12 | 0.13 | 0.12 | 0.07 | 0.07 | 0.05 | 0.08 |
| Perry | 0.11 | 0.10 | 0.12 | 0.17 | 0.19 | 0.18 | 0.27 | 0.88 | 0.15 | 0.15 | 0.13 | 0.12 |
| Phillips | 0.30 | 0.08 | 0.08 | 0.14 | 0.11 | 0.03 | 0.07 | 0.04 | 0.02 | 0.02 | 0.01 | 0.12 |
| Pike | 0.19 | 0.16 | 0.25 | 0.37 | 0.40 | 0.39 | 0.51 | 0.69 | 0.20 | 0.20 | 0.18 | 0.34 |
| Poinsett | 0.17 | 0.06 | 0.06 | 0.09 | 0.12 | 0.09 | 2.69 | 0.02 | 0.02 | 0.02 | 0.02 | 1.53 |
| Polk | 0.16 | 0.16 | 0.28 | 0.51 | 0.70 | 0.77 | 0.88 | 0.84 | 0.28 | 0.28 | 0.33 | 0.42 |
| Pope | 0.56 | 0.29 | 0.38 | 0.58 | 0.60 | 0.82 | 0.80 | 1.15 | 0.37 | 0.37 | 0.38 | 0.39 |
| Prairie | 0.12 | 0.09 | 0.09 | 0.15 | 0.08 | 0.04 | 41.99 | 0.09 | 0.05 | 0.05 | 0.03 | 0.03 |
| Pulaski | 0.20 | 0.17 | 0.14 | 0.34 | 0.11 | 0.10 | 1.11 | 0.03 | 0.09 | 0.09 | 0.06 | 0.85 |
| Randolph | 0.06 | 0.05 | 0.06 | 0.33 | 0.06 | 0.08 | 0.43 | 0.45 | 0.19 | 0.19 | 0.23 | 0.22 |
| Saline | 0.15 | 0.10 | 0.10 | 0.17 | 0.09 | 0.07 | 0.16 | 0.07 | 0.08 | 0.08 | 0.07 | 0.05 |
| Scott | 0.16 | 0.18 | 0.20 | 0.35 | 0.43 | 0.38 | 0.54 | 0.67 | 0.28 | 0.28 | 0.30 | 0.24 |
| Searcy | 0.07 | 0.06 | 0.04 | 0.36 | 0.10 | 0.10 | 0.08 | 0.11 | 0.22 | 0.22 | 0.22 | 0.19 |
| Sebastian | 0.34 | 0.21 | 0.20 | 0.44 | 0.34 | 0.30 | 0.27 | 0.36 | 0.21 | 0.21 | 0.23 | 0.24 |
| Sevier | 0.29 | 0.17 | 0.24 | 0.53 | 0.64 | 0.66 | 0.66 | 1.01 | 0.37 | 0.37 | 0.32 | 0.37 |
| Sharp | 0.08 | 0.04 | 0.05 | 0.24 | 0.07 | 0.07 | 0.08 | 0.06 | 0.18 | 0.18 | 0.24 | 0.25 |
| St. Francis | 0.25 | 0.20 | 0.16 | 0.16 | 0.16 | 0.05 | 0.34 | 0.04 | 0.02 | 0.02 | 0.02 | 0.03 |
| Stone | 0.18 | 0.08 | 0.10 | 0.33 | 0.19 | 0.17 | 0.20 | 0.21 | 0.21 | 0.21 | 0.25 | 0.26 |
| Union | 0.16 | 0.11 | 0.11 | 0.15 | 0.21 | 0.34 | 0.46 | 0.36 | 0.12 | 0.12 | 0.12 | 0.12 |
| Van Buren | 0.16 | 0.06 | 0.12 | 0.31 | 0.14 | 0.11 | 0.13 | 0.11 | 0.22 | 0.22 | 0.16 | 0.14 |
| Washington | 1.85 | 1.15 | 1.41 | 2.01 | 2.52 | 2.63 | 2.83 | 2.67 | 1.04 | 1.04 | 1.14 | 1.09 |
| White | 0.40 | 0.34 | 0.52 | 0.83 | 0.43 | 0.48 | 1.19 | 0.70 | 0.45 | 0.45 | 0.39 | 3.37 |
| Woodruff | 0.09 | 0.05 | 0.05 | 0.11 | 0.05 | 0.02 | 0.50 | 0.01 | 0.02 | 0.01 | 0.01 | 0.12 |
| Yell | 0.64 | 0.38 | 0.50 | 0.84 | 0.89 | 0.86 | 0.84 | 0.92 | 0.41 | 0.41 | 0.37 | 0.41 |
| **Total** | **18.57** | **12.54** | **16.27** | **28.53** | **22.00** | **21.37** | **241.95** | **26.43** | **15.43** | **15.46** | **15.53** | **27.10** |

[1]Data not reported from Jefferson and Ouachita Counties in 1960.

### Electric

The electric water-use category includes water consumed by thermoelectric power generation from fossil fuels, geothermal, nuclear, or thermoelectric power. Most water used for this purpose was derived from surface water; less than 1 percent of water used in Arkansas for thermoelectric power generation was pumped from groundwater sources (Holland, 2007). Independence County was the largest user of groundwater for electric use with 1.20 Mgal/d used in 2010 (table 16).

## Groundwater Discharge to Surface-Water Bodies

In addition to benefits gained from the pumping of groundwater for various uses, groundwater naturally discharges to surface-water bodies (springs, streams, wetlands, lakes, and other water bodies on the land surface), which support many processes, activities, and standard uses. Before human development of groundwater resources, the terminus of all groundwater flow paths was discharge to surface-water bodies. Groundwater provides a relatively stable input of water to surface-water bodies. Conversely, surface runoff from precipitation often provides a discontinuous or "flashy" source of water to surface-water bodies. Important aquatic species and aquatic ecosystems have evolved to depend on groundwater discharge to streams, wetlands, and lakes, particularly during dry seasons and drought (National Wildlife Federation, 2014). Humans rely on the continuity of groundwater contribution to stream base flow to maintain typical surface-water uses during dry season and drought. Discharging groundwater also moderates the temperature of surface-water bodies and affects water quality. In recent decades, groundwater discharge to streams and wetlands has decreased significantly because of groundwater pumping (Brahana and Mesko, 1988; Williamson and others, 1990; Arthur and Taylor, 1998).

The reduction of groundwater discharge to surface-water bodies, particularly during dry periods, has had a strong deleterious effect on many important aquatic species and aquatic ecosystems. Human water uses, including irrigation, industry, public supply, recreational use, fishing, and water-fowl hunting, also have been adversely affected. As such, streamflow depletions by groundwater pumping have become an important water-resource management issue as a result of the negative effects that the reduced flows have on aquatic ecosystems, the availability of surface water for drinking and other needs, and the quality and aesthetic value of streams (Stanton and others, 2010; Barlow and Leake, 2012). Stream base flow from groundwater is an important criterion that water regulators and planners consider when evaluating conjunctive use, water allotment, and sustainable yield needs in the State.

Groundwater contributions to streams, wetlands, lakes, and associated ecosystems provide considerable benefit, although perhaps difficult to quantify. Historically, benefits from natural processes that occur in natural, healthy aquatic ecosystems—such as clean water for drinking and other uses, decomposition of wastes, and amelioration of

**Table 16.** Groundwater use for electric supply by counties and years in Arkansas.

[Counties shown are only those with published data. Data from Halberg and Stephens (1966); Halberg (1972, 1977); Holland and Hall (1986); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1965 | 1970 | 1975 | 1980 | 1982 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Craighead | 0.31 | 0.18 | 0.06 | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Franklin | 0.02 | 0.03 | 0.04 | 0.00 | 0.00 | 0.00 | 0.00 | 0.20 | 0.02 | 0.00 | 0.05 |
| Independence | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.53 | 0.47 | 0.00 | 1.20 |
| Jefferson | 0.00 | 0.00 | 0.00 | 0.00 | 1.87 | 0.00 | 0.02 | 1.74 | 0.63 | 0.00 | 1.12 |
| Lafayette | 1.80 | 1.15 | 1.09 | 1.68 | 1.39 | 1.06 | 1.20 | 1.12 | 0.90 | 0.50 | 0.35 |
| Little River | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.35 |
| Mississippi | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.62 |
| Phillips | 0.72 | 0.72 | 0.23 | 0.05 | 0.12 | 0.00 | 1.19 | 1.51 | 0.42 | 0.43 | 0.34 |
| Pulaski | 2.98 | 1.63 | 0.76 | 1.03 | 1.48 | 0.03 | 0.02 | 0.00 | 0.00 | 0.00 | 0.19 |
| St. Francis | 0.11 | 0.38 | 0.25 | 0.03 | 0.04 | 0.00 | 0.00 | 0.00 | 0.36 | 0.00 | 0.00 |
| Woodruff | 0.00 | 0.05 | 0.02 | 0.22 | 0.32 | 0.00 | 0.00 | 0.05 | 0.12 | 0.00 | 0.06 |
| **Total** | **5.94** | **4.14** | **2.45** | **3.06** | **5.23** | **1.09** | **2.43** | **5.15** | **2.92** | **0.93** | **4.28** |

contaminants—were often overlooked and were not assessed and quantified in terms of economic benefit. Within the last decade, however, the benefits that are supplied by ecosystems have been recognized and assessed in terms of economic benefit. These benefits have been termed “ecosystem services,” and defined as any positive benefit that wildlife or ecosystems provide to people (National Wildlife Federation, 2014). Ecosystem services are now a market-oriented objective recognized by Federal agencies, including the EPA and the USDA, and were included in the Food, Conservation, and Energy Act of 2008 (122 Stat. 923). The USDA has set policy for agriculture and forestry programs in providing environmental offsets and in developing economic accounting practices and procedures for quantifying environmental goods and services (U.S. Department of Agriculture, 2006). The USDA’s goal is to enhance fish and wildlife habitat maintenance, pollution protection, surface-water runoff, floodwater management, water sustainability, and cultural benefits. The advent of practical economic accounting procedures to quantify and incorporate groundwater remunerative benefits into resource analysis, planning, and allocation is a significant advancement of water-resource management.

The scale of interchange of water between the surface and subsurface environments is considerable for every aquifer system in Arkansas where these environments are hydraulically connected. The degree of connectivity is shown by direct observation, hydraulic-head distributions, water-quality conditions, water-balance analyses, groundwater-flow model results, and other approaches (for example, Hines, 1975; Ludwig, 1992). Data in many of the surface-water hydrology and groundwater hydrology studies in the State corroborate the importance of surface-water/groundwater interaction by way of physical and chemical hydrology results. Several studies in the State have been conducted with objectives specifically addressing characterization of surface-water/groundwater interaction. Mesko and Imes (1995) conducted regional groundwater-flow simulations linking simulations of two regional-scale models—the Ozark Plateaus aquifer-system model (Imes and Emmett, 1994) and the Mississippi embayment aquifer system model (Brahana and Mesko, 1988). They noted that historical hydrogeological data indicated the potential for groundwater to move from the Ozark Plateaus aquifer system beneath the Fall Line (escarpment between the Interior Highlands and the Coastal Plain; fig. 3) and discharge to overlying embayment aquifers or directly to streams. The quantity of water moving under the Fall Line was estimated using simulations from the Ozark Plateaus aquifer system and the Mississippi embayment aquifer system models. Simulation results indicated that the rate of groundwater movement from the Ozark Plateaus aquifer system under the Fall Line was 650–800 cubic feet per second ($ft^3/s$) more than rate of recharge on the embayment side of the Fall Line. The results indicated that the most likely alternative discharge for this water was determined to be discharge to embayment streams. To determine if these differences in simulated groundwater flow could be explained by discharge as base flow to streams, low-flow seepage measurements were made on the Black River and its major tributaries in 1987. The seepage data indicated that groundwater did contribute substantial flow to the streams, indicating a total groundwater contribution of more than 1,500 $ft^3/s$, a total stream loss of about 500 $ft^3/s$, and a net gain of approximately 1,000 $ft^3/s$, which is an average gain of 2.6 cubic foot per second per mile ($ft^3/s/mi$) for measured streams. The hydrologic measurement results were in agreement with model results and illustrated the scale and importance of groundwater contribution to streamflow.

Freiwald (1987) conducted extensive groundwater discharge gain and loss measurements on eight streams and their tributaries representative of streams across the Ozark Plateaus in northern Arkansas. Study results illustrated the importance of groundwater contribution to streams in maintaining flow and affecting water quality. The study was designed to identify the relative importance of gaining and losing sections of typical Ozark streams and to characterize the degree of surface-water/groundwater interaction in this karst area. Three streams were shown to be gaining—receiving groundwater—throughout their reaches; the remaining five streams were shown to be gaining streams through the majority of their reaches. Groundwater contributed measurable and substantial streamflow in 51 of 61 measured reaches. Losing sections—where water moves from a stream into groundwater—tended to be relatively short in length. Results indicated that lithology and the presence of faults were strong controls on the degree of interchange between the groundwater and surface-water environments. Stream reaches that received larger inputs of groundwater tended to lie in or near Mississippian-age, carbonate-rock outcrop areas; stream reaches where water moved into the groundwater environment were typically associated with fault zones. Groundwater also had a substantial influence on stream-water quality causing a notable increase in specific conductance and affecting moderation of stream temperature.

Grosz and others (1988) quantified the degree of surface-water/groundwater interaction on the Little Red River by conducting detailed monitoring of stream discharge at multiple stations from Searcy to the confluence with the White River. They also conducted detailed monitoring of groundwater levels near the river at 19 piezometers. The study was conducted to obtain information needed for streamflow allocation planning. Comparison of surface and groundwater levels indicated that the Little Red River gained groundwater during summer and fall dry periods and lost flow to groundwater during periods of high flow. Minimum groundwater contribution to the Little Red River was estimated at 200–300 $ft^3/s$ during low-flow periods. This base-flow component was noted to be a critical resource locally for supporting agricultural irrigation during summer months.

The studies by Freiwald (1987) and Grosz and others (1988) highlight the importance of groundwater base flow in providing streamflow during times of limited surface-water availability, which can affect ecosystem viability. The benefits of groundwater contributions to surface water often have been overlooked; however, surface-water/groundwater interaction is recognized as an important part of ecosystem services, which not only defines the critical influence and benefits of groundwater, but provides an accounting mechanism for quantifying economic impact.

# Aquifers of the Coastal Plain

Groundwater in the Coastal Plain of Arkansas represents one of the most valuable natural resources in the State, driving the economic engines of agriculture, while also supplying abundant water for commercial, industrial, and public-water supply. Aquifers in the Coastal Plain consist of various geologic units that are Cenozoic and Mesozoic in age and consist primarily of Cretaceous, Tertiary, and Quaternary sands, gravels, silts, and clays (table 3). Depositional processes resulted in a stratigraphy represented by alternating accumulations of fine-grained materials, which impede flow and serve as confining units, and coarse-grained sands and gravels serving as aquifers. Decades of surface and subsurface mapping combined with careful geologic interpretation using a myriad of methods (age-dating, laboratory analysis, grain-sorting, geophysical analysis) categorized and described various formations, their inherent hydrologic characteristics, and importance as groundwater resources.

Results of these activities were documented in county or multicounty investigations describing the extent and importance of these groundwater resources on local and regional scales. The reader should refer to figure 5 for locations of cities and counties discussed in this section. The following sections list and discuss 11 aquifers that have served or are currently in use as important sources of water supply throughout the Coastal Plain of southern and eastern Arkansas. Each of these aquifers is described with respect to the depositional history of the formation, hydrologic characteristics, water use, water levels and water-level declines where significant, applied management tools for predicting flow patterns and sustainable use of aquifers, and local and regional water quality. Many of the aquifers are widely recognized, have long regional flow paths, serve as sources of water supply for multiple uses, have boundaries extending throughout neighboring States, and have water-use values in the millions of gallons per day. Other aquifers have a limited extent, serve solely as local sources of water, and often lack hydrologic and geochemical data but are nonetheless important sources of water to local entities in Arkansas that otherwise would have no other source of water.

In terms of age from youngest to oldest, the aquifers of the Coastal Plain are discussed in the following order: Quaternary alluvial aquifers, which include the Mississippi River Valley alluvial aquifer (the most important aquifer in Arkansas in terms of volume of use and economic benefits) and minor alluvial aquifers, Jackson Group (a regional confining unit that served for years as an important source of domestic supply), Cockfield, Sparta, Cane River, Carrizo, Wilcox, Nacatoch, Ozan, Tokio, and Trinity aquifers.

## Quaternary Alluvial Aquifers

### Mississippi River Valley Alluvial Aquifer

Although all of Arkansas' aquifers are important as water-supply sources locally or regionally, in terms of the volume of use, economic importance to the State, support of ecosystems, as well as abundant use for public, domestic, commercial, and industrial supply, the Mississippi River Valley alluvial aquifer must be considered the most important aquifer and one of the more important natural resources in Arkansas. The fertile soils overlying the Mississippi River Valley alluvial aquifer had long been recognized by explorers into eastern Arkansas. According to an early report by Nuttall (1821), "…rice has been tried on a small scale and found to answer every expectation. Under the influence of a climate mild as the South of Europe, and a soil equal to that of Kentucky, wealth will ere long flow, no doubt, to the banks of the Arkansa." Also, President Theodore Roosevelt was quoted by The New York Times (1907) while on a tour of the Mississippi River Valley area: "The Mississippi Valley is a magnificent empire in size and fertility... In wealth of natural resources, no kingdom of Europe can compare with the Mississippi Valley… [It] is politically and commercially more important than any other valley on the face of the globe."

The potential for this projected wealth from an agricultural perspective only was realized with the advent of irrigation, and the Mississippi River Valley alluvial aquifer ultimately proved to be the most important source of irrigation water in the Mississippi embayment. The Mississippi River Valley alluvial aquifer has long been cited as the most important water-bearing formation from an economic standpoint for northeastern Arkansas (Stephenson and Crider, 1916). With the expansion of irrigation for agriculture over the years, together with the advent of many municipalities and industries drilling deeper to obtain better-quality water, the Mississippi River Valley alluvial aquifer (commonly referred to by most Arkansans as simply the "alluvial aquifer") has transitioned to primarily being a source of irrigation supply. The following sections provide an overview of the geologic setting, groundwater use, water-level trends, planning and management tools, and water quality for the Mississippi River Valley alluvial aquifer of eastern Arkansas.

## Geologic Setting

The Mississippi River Valley alluvial aquifer is the uppermost aquifer in eastern Arkansas and comprises unconsolidated clastic sediments—sand, gravel, silt, and clay—deposited in river and river-proximal environments. The aquifer is a part of and contained within the Mississippi embayment (fig. 8). The Mississippi embayment lies within a syncline that plunges south toward the Gulf of Mexico with the axis roughly along the present day Mississippi River (Hart and others, 2008). This structural feature was formed through extension of the North American continental plate and began infilling with sediment beginning during the Jurassic period. In a large part of eastern Arkansas, the Mississippi embayment was blanketed with alluvial sediment during the Quaternary period, resulting in formation of the aptly named Quaternary alluvium. The Mississippi embayment extends across parts of Alabama, Arkansas, Illinois, Kentucky, Louisiana, Mississippi, Missouri, and Tennessee, covering an area of approximately 160,000 square miles ($mi^2$) (Cushing and others, 1964; Williamson and others, 1990; Arthur and Taylor, 1998). The Mississippi River Valley alluvial aquifer covers an area of approximately 32,000 $mi^2$ within the Mississippi embayment, and approximately 54 percent of this aquifer is located in eastern Arkansas (Pugh and others, 1997).

The Mississippi River Valley alluvial aquifer is composed of unconsolidated materials ranging from clay and silt in the upper part and grading downward to coarse sand and gravel at the base (Hosman and Weiss, 1991). The aquifer effectively can be divided into two distinct units based on lithologies: a lower unit that contains the primary aquifer consisting of coarse sands and gravels derived from alluvial and terrace deposits that coarsen downward (herein referred to as the "Mississippi River Valley alluvial aquifer"), and an upper unit that consists of fine sand, silt, and clay that serves as a confining unit of varying competency (herein referred to as the "Mississippi River Valley confining unit"), which is of local importance as a lower-yield aquifer primarily for domestic use.

The importance of the Mississippi River Valley alluvial aquifer is reflected in the long-term interest in its geology. Veatch (1906) and Stephenson and Crider (1916) reported on Quaternary deposits of southern Arkansas and northern Louisiana. Fisk (1944) described alluvial sediments as part of geologic investigations along the Mississippi River Valley by the U.S. Army Corps of Engineers. Krinitzsky and Wire (1964) added to the work of Fisk with additional information on groundwater conditions. Cushing and others (1964) gave a basic description of Quaternary aquifers, with Boswell and others (1968) providing greater detail and applying the name "Mississippi River Valley alluvial aquifer" to the sediments underlying the alluvial plain. Ackerman (1989a) applied the term "Mississippi River Valley confining unit" to the fine-grained materials that overlie the coarser lower unit of the Mississippi River Valley alluvial aquifer.

Virtually all of the landforms and associated sediments within the Mississippi River Valley are the direct result of fluvial processes. The dominant controls influencing the fluvial processes and resulting surface geology of the Lower Mississippi Valley were glaciation, climate, relative sea level, tectonism, and subsidence (Saucier, 1994). The resulting landforms that occupy the area and influence the hydrology of the Mississippi River Valley alluvial aquifer for the present investigation are valley-train, meanderbelt, and backswamp deposits.

Because of the consistency of sediment supply, the low-relief character of the area, and the wandering nature of streams shifting their positions across the landscape through time, the geology of the Mississippi River Valley alluvial aquifer at the regional scale is relatively consistent throughout its range. For a thorough review of the geography, regional geologic framework, and stratigraphy and lithology within the Lower Mississippi Valley, the reader is directed to Saucier (1994); additional detail is provided in the smaller-scale studies and is summarized in the discussion below.

The Mississippi River Valley alluvium is the uppermost, surficial formation extending across a large area of the Mississippi embayment and unconformably overlies, in various areas, the Jackson Group, the Cockfield Formation, the Cook Mountain Formation, the Sparta Sand, the Cane River Formation, the Carizzo Sand, the Wilcox Group, the Midway Group, the Arkadelphia Marl, the Nacatoch Sand, and older Paleozoic units (Cushing and others, 1964; Boswell and others, 1968; Hosman and others, 1968; Broom and Reed, 1973; Ackerman, 1996). The lateral boundary of the Mississippi River Valley alluvial aquifer is seen at the peripheral areas of the embayment where the contact of the base of the alluvial aquifer with older, underlying units is exposed. To the west, this boundary closely parallels the "Fall Line," the boundary with the Interior Highlands defined by greater topographic relief and outcrop of Paleozoic rock in the Interior Highlands (fig. 9). The Fall Line has been cited as "one of the most strongly marked physiographic and cultural lines on the surface of the globe" (McGee, 1888). The term "Fall Line" originally referred to the "fall line of rivers," and was defined as the upper limit of navigation and the lower limit of water power, and often marked by waterfalls or points where rivers changed from rapid and turbulent to becoming broad and slow moving (Hill, 1888). The importance of the Fall Line from a hydrological standpoint is that this transitional zone between the Interior Highlands and the Coastal Plain has been noted as an area of upwelling of deep-sourced, high salinity groundwater from Paleozoic rocks of the Interior Highlands (see "Occurrence, Distribution, and Sources of Elevated Chloride Concentrations" section). Crowleys Ridge, a structural high and erosional remnant of Tertiary-age units, physically divides the Mississippi River Valley alluvial aquifer in the northern part of eastern Arkansas (fig. 8). No deposition of Quaternary alluvium occurred on Crowleys Ridge (Ackerman, 1996).

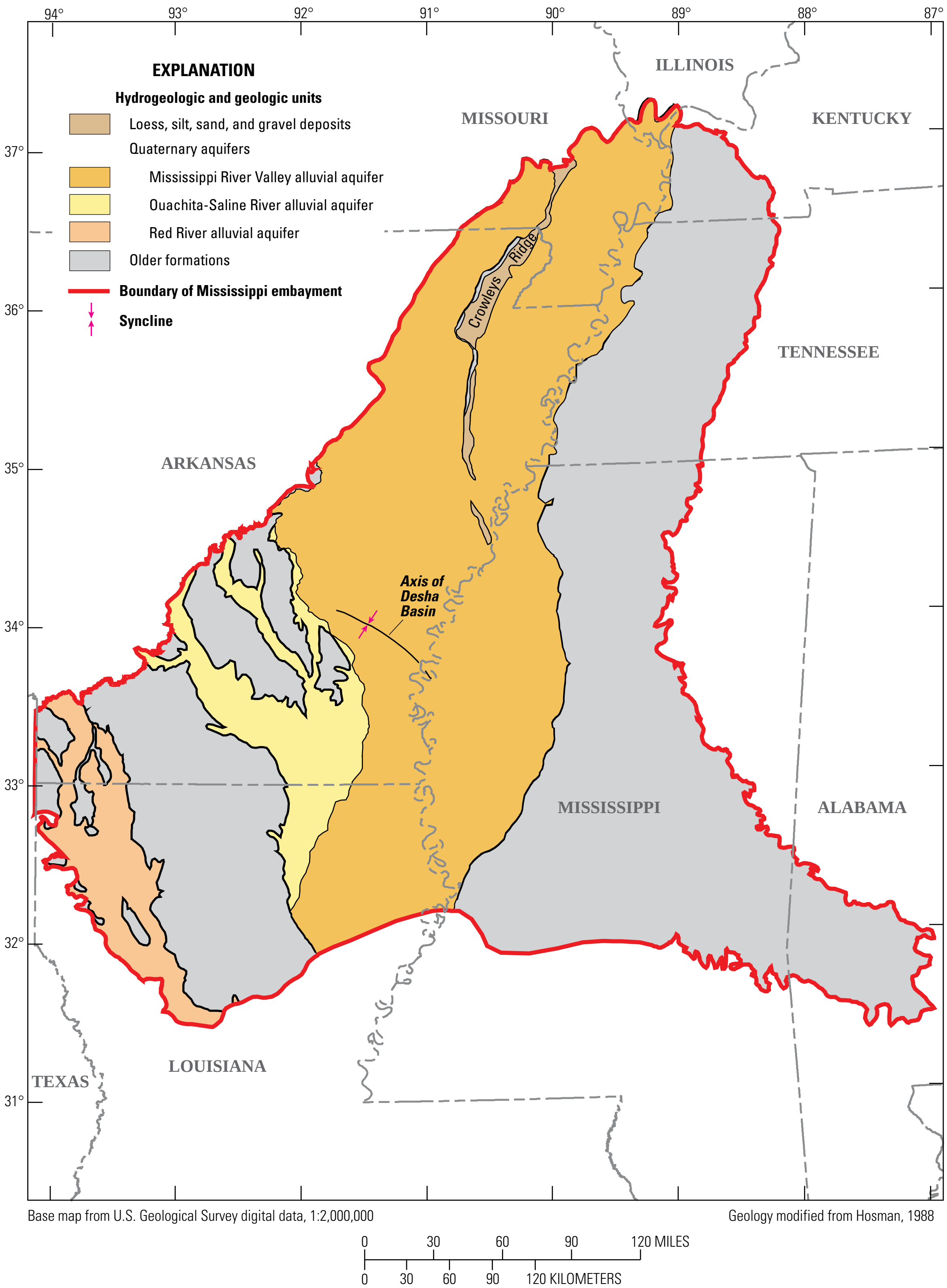



**Figure 8.** Extent of the Mississippi embayment with location of Quaternary aquifers.

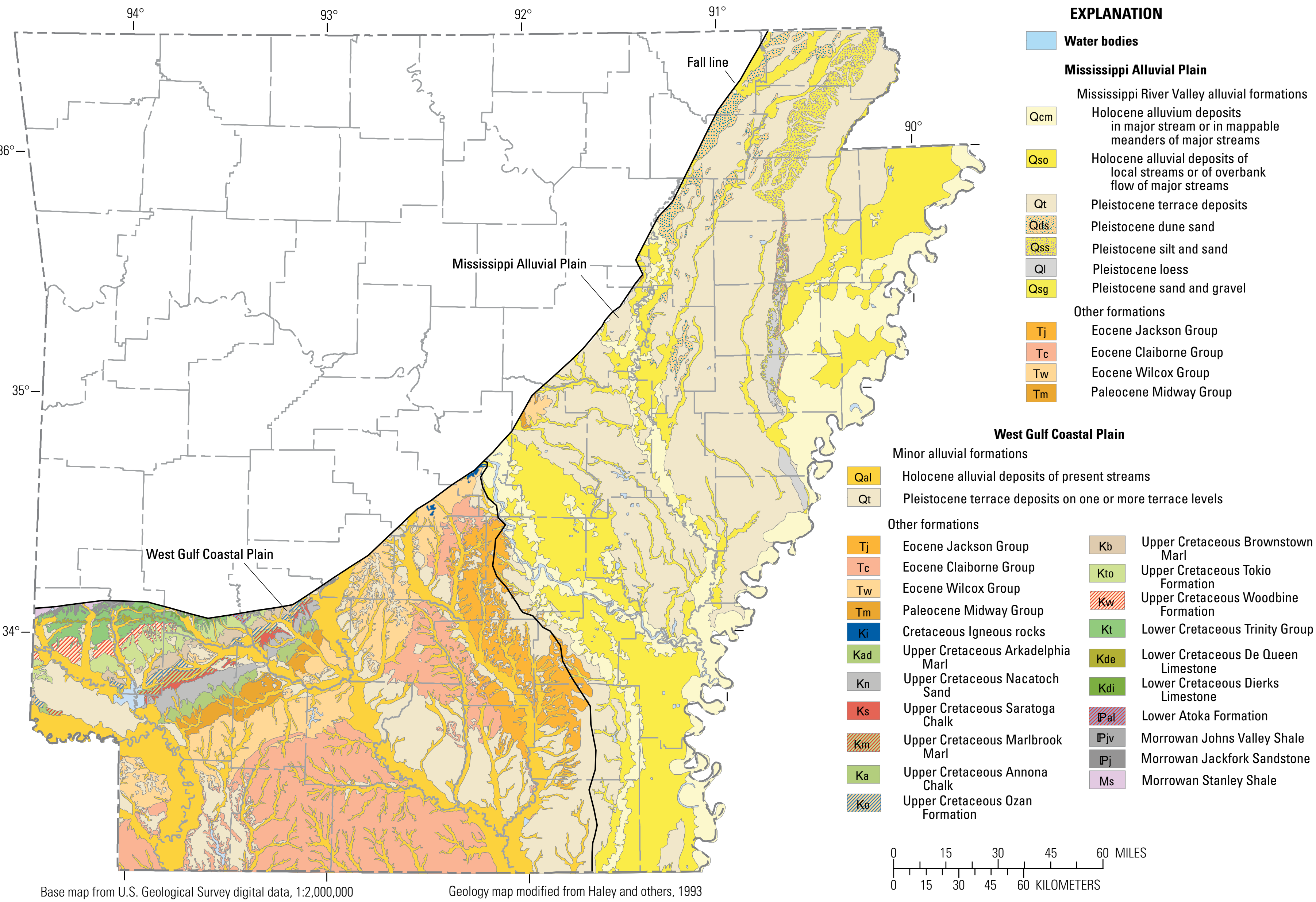



**Figure 9.** Surface geology of the West Gulf Coastal Plain and Mississippi Alluvial Plain in southern and eastern Arkansas.

The lower unit of the Mississippi River Valley alluvial aquifer comprises alluvium and terrace deposits consisting of a coarse-sand matrix with varying amounts of gravel; the base of the aquifer is predominately gravel in some areas. The gravels generally coarsen northward and with depth; the maximum grain size can be as large as 8 inches to the north and 3 inches to the south (Fisk, 1947; Ackerman, 1996). The gravel is mostly chert, but other lithologies including quartz, sandstone, and igneous rock also are present as a result of diverse sediment origin (Cushing and others, 1964; Boswell and others, 1968; Broom and Reed, 1973; Stanton and Clark, 2003). The basal coarse sand and gravel are overlain by fine-grained sand and lenses of clay, silt, or sandy silt (Ackerman, 1996). The basal gravel may be absent in some areas, notably in the immediate vicinity of the Fall Line, and clay layers occur locally in the lower unit of the aquifer (Halberg and Reed, 1964). The lower unit of the Mississippi River Valley alluvial aquifer generally ranges in thickness between 0 and 140 ft with an average thickness of 100 ft and decreases in thickness to the south (Ackerman, 1996; Pugh and others, 1997). Thicker sequences as much as 160 ft occur at two locations in Poinsett County on opposite sides of Crowleys Ridge, in western Clay County, and in Greene County (Pugh and others, 1997). The large range in thickness is a result of the deposition on an irregular erosional surface underlying the Mississippi River Valley alluvial aquifer (Broom and Reed, 1973; Broom and Lyford, 1981; Ackerman, 1996). The basal gravel typically is thicker where the total thickness of the alluvium is the greatest (Sumner and Wasson, 1990).

The environments of deposition for the Mississippi River Valley alluvium controlled the spatial distribution of the varying hydraulic characteristics of the aquifer. As the glacial periods of the Pleistocene waned and sea level rose, regional stream gradients decreased and aggradation of sediments occurred. The depositional processes were complex, with alluvium being deposited, eroded, dissected, reworked, and redeposited into terraces as flow conditions changed and local gradients changed with sediment aggradation (Boswell and others, 1968). The sediment was deposited by braided stream, meander belt, backswamp, and valley outwash plain depositional processes (Fisk, 1944, 1947; Krinitzsky and Wire, 1964; Ackerman, 1996). Deposition of the Mississippi River Valley confining unit occurred predominantly under lower hydrodynamic energy deposition conditions of the backswamp and channel-fill environments, resulting in a mantling deposition of fines that reduced the relief of the land surface (Gonthier and Mahon, 1993). The coarser-grained, high-yield lower unit of the Mississippi River Valley alluvial aquifer is characterized by valley-train (or braided-stream) deposits originating from high-discharge streams carrying coarse-grained glacial outwash fed by meltwater of receding glaciers. Valley-train deposits are represented as wide, frequently branching channels separating irregular braid bars and interfluve areas.

With the onset of the Holocene, depositional processes switched from bedload-dominated braided streams to suspended-load dominated meandering streams that remain today. Meander-belt deposits include natural levees and point bars, both of which are very permeable and provide favorable recharge pathways into the Mississippi River Valley alluvial aquifer (Bedinger and Reed, 1961; Bedinger and Jeffery, 1964). Backswamps are meander-belt proximal environments characterized by low-relief, shallow, and poorly drained areas associated with overbank flooding that generally includes massive sequences of fine-grained silts and clays (Saucier, 1994). Channel-fill deposits are abandoned channels, such as oxbow lakes, that typically fill with fine-grained sediments. Backswamp and channel-fill deposits are characterized by materials of low permeability that are poor avenues for aquifer recharge (Bedinger and Reed, 1961; Bedinger and Jeffery, 1964). Backswamp deposits occupy parts of Jefferson, Lincoln, and large parts of Desha Counties; these deposits are a major influence on groundwater flow and geochemical evolution in the study area (Kresse and Clark, 2008).

The Mississippi River Valley confining unit generally thickens from north to south; however, the thickness of the confining unit varies greatly and is absent in many areas. Where present, the confining unit ranges up to 150 ft in thickness; however, areas of absent and thin zones are common across the extent of the confining unit. Trends in thickness were controlled by depositional processes, and areas of equal thickness tend to parallel major stream channels. The Mississippi River Valley confining unit is relatively thick, consistently more than 50 ft, in the Grand Prairie region, which is bounded by two major rivers. The confining unit is absent in areas of Craighead and Poinsett Counties. “Clay plugs,” local anomalously thicker clay deposits, occur and may be 50–100 ft thicker than the adjacent areas. In other areas, the confining unit is present as infilled oxbow lakes or meander channels and is therefore much thicker locally (Broom and Lyford, 1981; Ackerman, 1989a, 1996; Gonthier and Mahon, 1993). In some areas, modern rivers have reworked the upper part of the alluvial fill materials. Stanton and Clark (2003) showed a confining-unit thickness ranging from 0 to 60 ft south of the Arkansas River.

### Hydrologic Characteristics

During predevelopment time, the Mississippi River Valley alluvial aquifer was confined where the upper confining clay layer was present; in these areas, the potentiometric surface was at or above the top of the aquifer (Ackerman, 1996). As groundwater development increased, widespread pumping caused regional declines in water levels to below the clay layer across much of the aquifer’s extent, converting the aquifer to an unconfined condition. Dewatering the aquifer can lead to subsidence and a permanent loss of storage (Konikow, 2013). Clays present in the aquifer and the confining layer average approximately 50 percent smectite (Scott and others, 2000), a type of clay that is highly susceptible to compaction. Dewatering of the alluvial aquifer and overlying clay layer can lead to irreversible compaction and subsidence, reducing the water-yielding capacity of more clay-rich layers and reducing the ability of precipitation to move through the clay layer and recharge the aquifer. Aquifers and confining units containing substantial amounts of fine-grained materials, as the Mississippi River Valley alluvial aquifer does, are most susceptible to compaction. Marshall (2005) used high-precision static and kinematic Global Positioning System (GPS) to document land subsidence of 0.67 in/yr near the area of the largest observed water-level declines in the Grand Prairie.

The Mississippi River Valley alluvial aquifer in some areas is hydraulically connected to underlying Tertiary aquifers. The degree of hydraulic connection is dependent on the grain size and permeability of the aquifers, the composition of sediments near the contact of the aquifers, and the head differences between aquifers (Hosman and Weiss, 1991). Even where the Mississippi River Valley alluvial aquifer is in contact with underlying aquifers, the permeability contrast between the higher hydraulic conductivity alluvial aquifer and the lower hydraulic conductivity of underlying aquifers allows the aquifers to be differentiated (Ackerman, 1996).

Aquifer-test data for the Mississippi River Valley alluvial aquifer are found in numerous countywide reports dating back to the mid-1950s. Ranges in yields and other hydrologic characteristics are controlled by the thickness, sediment size and distribution, and other physical characteristics of the producing zone. Reported yields throughout the Mississippi River Valley alluvial aquifer in eastern Arkansas ranged from 400 to 3,000 gal/min (Onellion and Criner, 1955; Counts, 1957; Lamonds and others, 1969; Hines and others, 1972; Broom and Reed, 1973). Boswell and others (1968) reported yields throughout the Mississippi embayment by State, with a maximum yield of 5,000 gal/min for Arkansas. Yields of 2,000 gal/min were cited as common, which was the most commonly reported yield cited in the earlier countywide reports.

Hydraulic conductivity values for the Mississippi River Valley alluvial aquifer ranged from 60 to 390 feet per day (ft/d) (Halberg and Reed, 1964; Boswell and others, 1968; Broom and Lyford, 1981). Ackerman (1996) listed hydraulic conductivity values ranging from 120 to 390 ft/d with a geometric mean of 210 ft/d. Krinitzsky and Wire (1964), reporting on the Mississippi River Valley alluvial aquifer in the lower Mississippi Valley, listed hydraulic conductivity values from 38 tests ranging from 120 to 390 ft/d with a geometric mean of 210 ft/d. Although data from Ackerman (1996) and Krinitzsky and Wire (1964) included values from other States, the similar range in hydraulic conductivity values reflects the uniform geologic character of the aquifer throughout the lower Mississippi Valley. Multiple investigations have observed that the hydraulic conductivity is larger at the base of the aquifer and decreases upward as average sediment size decreases (Broom and Lyford, 1981; Ackerman, 1989a, 1989b, 1990; Mahon and Ludwig, 1990; Mahon and Poynter, 1993).

Transmissivity values ranged from 5,200 to 64,900 foot squared per day ($ft^2/d$) for the Mississippi River Valley alluvial aquifer in Arkansas (Halberg and Reed, 1964; Boswell and others, 1968; Lamonds and others, 1969; Broom and Reed, 1973; Broom and Lyford, 1981). Storage coefficients—dimensionless values describing the volume of water released per area of aquifer and depth of drawdown—ranged from 0.0004 to 0.08 (Halberg and Reed, 1964; Boswell and others, 1968; Lamonds and others, 1969; Broom and Reed, 1973; Broom and Lyford, 1981), which reflects unconfined and confined conditions in the aquifer. A review of 75 reported storage coefficients (Ackerman, 1996) for the Mississippi embayment, mostly from Arkansas, revealed a range from 0.15 to 0.0009, with 16 values between 0.05 and 0.15, 34 between 0.001 and 0.01, and 25 values between 0.0001 and 0.0009. Specific capacities ranged from 18 to 90 gallons per minute per foot [(gal/min)/ft] of drawdown (Boswell and others, 1968; Lamonds and others, 1969).

A summary of aquifer-test data in Arkansas, which included aquifer-test data collected since 1995, and data separated for the Mississippi River Valley alluvial aquifer by Holocene-age alluvium and Pleistocene-age terrace deposits were presented by Pugh (2008a). Pugh also reported transmissivity values that ranged from 450 to 160,000 $ft^2/d$ (median of 24,000 $ft^2/d$) and specific-capacity values that ranged from 0.06 to 3,200 (gal/min)/ft (median of 171 (gal/min)/ft) for the Holocene alluvium. For wells completed in Pleistocene terrace deposits, Pugh (2008a) reported transmissivity values that ranged from 325 to 43,000 $ft^2/d$ (median of 18,200 $ft^2/d$) and specific-capacity values that ranged from 2.02 to 723 (gal/min)/ft (median of 160 (gal/min)/ft).

Little research has focused on the hydrologic characteristics of the Mississippi River Valley confining unit. Ackerman (1996) conducted laboratory analyses of samples taken from the confining unit; these samples were found to be in the clay to silty sand texture range and exhibited hydraulic conductivity values ranging from 0.0001 to 0.5 ft/d (values consistent with those reported for that range of grain sizes of samples by Freeze and Cherry [1979]). Yields for domestic wells completed in the Mississippi River Valley confining unit ranged from less than 5 to 100 gal/min or more, depending upon grain size and depth of wells.

### Sources of Recharge

Determining and quantifying sources of recharge is important to managing the valuable resource provided by the Mississippi River Valley alluvial aquifer, especially for accurately modeling flow and predicting sustainable pumping rates from continued irrigation use. The principal source of recharge to the Mississippi River Valley alluvial aquifer is precipitation. The Mississippi embayment experiences a mean annual precipitation of 48 and 56 inches in the northern and southern parts of the State, respectively (Kleiss and others, 2000; Pugh and Westerman, 2014). While no study has been conducted to quantify actual recharge rates across the aquifer, calibrated Mississippi River Valley alluvial aquifer groundwater models constrain recharge values and use recharge rates of 0.8–2.6 in/yr (about 1.5–5 percent of total precipitation) to simulate recharge from precipitation (Mahon and Poynter, 1993; Ackerman, 1996; Arthur, 2001; Stanton and Clark, 2003). These models, however, integrated locally low and high values of recharge and represented average recharge rates across large regional areas of the Mississippi River Valley alluvial aquifer. Kresse and Clark (2008) applied a chloride mass balance method using chloride concentrations in precipitation and groundwater to show recharge values from about 0.07 in/yr to 7.8 in/yr in areas of Mississippi River Valley backswamp and channel deposits, respectively, south of the Arkansas River.

The Mississippi River Valley alluvial aquifer receives abundant recharge where the impermeable clay layer is very thin or absent; where the clay layer is present, vertical infiltration from the surface is impeded, and recharge by lateral flow from adjacent areas is more important (Onellion, 1956; Bedinger and Reed, 1961; Bedinger and Jeffery, 1964; Boswell and others, 1968; Whitfield, 1975). Recharge rates are related to grain size and the hydraulic characteristics of sediment present at the surface; the type of sediment is, in turn, controlled by the environment of deposition. Point-bar, channel, and natural-levee deposits are composed of coarser sediments that are highly permeable and support higher recharge rates. Overbank and backswamp deposits are fine-grained sediments deposited in low-energy environments removed from main river channels, are less permeable, and impede recharge (Bedinger and Reed, 1961; Kresse and Clark, 2008). The complex depositional history of the alluvial aquifer has resulted in highly variable surface geology and therefore highly variable zones of recharge.

Recharge to the Mississippi River Valley alluvial aquifer also may occur through streambeds, as suggested by hydraulic gradients near the rivers (Bedinger and Reed, 1961). However, the pervasive presence of low-permeable fine sediments in some lowland river bottoms can reduce effectiveness of river-derived recharge. A recent study using groundwater chemistry from alluvial wells south of the Arkansas River suggests that an important component of the recharge to the Mississippi River Valley alluvial aquifer may be infiltration of precipitation through coarse channel deposits near the river rather than from the river itself (Kresse and Clark, 2008). Therefore, the high hydraulic gradients near rivers may be more strongly affected by precipitation-induced, higher water levels in the coarser deposits next to the river. Upward flow from underlying aquifers can contribute to recharge; however, the recharge would likely not be substantial because of the higher hydraulic conductivity of the lower part of the alluvial aquifer in contrast to the lower hydraulic conductivity of underlying aquifers and associated confining units (Ackerman, 1996).

### Groundwater Flow

The Mississippi River Valley alluvial aquifer contains regional and local flow systems. Regionally, groundwater flow tends to follow the topographic gradient (albeit very low) with movement generally from the topographically higher areas in the northern and western parts of the Mississippi embayment to the topographically lower areas in the southern and eastern parts of the embayment. This regional pattern is locally inflected near streams acting as drains to the aquifer and in areas of high withdrawals (Schrader, 2006a). Groundwater flow paths can range from tens to hundreds of miles before intersecting major rivers such as the Mississippi, Arkansas, or White Rivers.

Crowleys Ridge is a barrier to groundwater movement (Boswell and others, 1968) in the northeastern part of the State. Potentiometric-surface maps (Joseph, 1999; Reed, 2004; Schrader, 2001b, 2006a, 2008a, 2010) in this area reveal a head difference of 20–30 ft on opposite sides of Crowleys Ridge, which indicates that even in areas where groundwater throughflow would be most likely, Crowleys Ridge serves as a hydraulic barrier. Water levels from wells on the ridge generally are higher than those of the alluvial aquifer, indicating that the ridge is not part of the alluvial aquifer flow system (Reed, 2003; Gillip and Czarnecki, 2009). For more information about the effects of Crowleys Ridge on potentiometric surfaces, see the section titled “Water Level Trends.”

The Mississippi River Valley alluvial aquifer is in hydraulic connection with numerous rivers that are incised into the alluvium. Many rivers may have been gaining flow from the aquifer prior to development, but as groundwater levels declined regionally in response to withdrawals from the aquifer, the head differences were reversed, and the more common condition is for the rivers to lose water to the aquifer (Ackerman, 1989a). Hunrichs (1983) noted that water levels were below some rivers in southeastern Arkansas, and some of these rivers were no longer perennial streams for parts of their length. The degree of hydraulic connection between streams and the Mississippi River Valley alluvial aquifer in Arkansas is dependent on the hydraulic conductivity of the riverbed materials, the hydraulic gradient between the two water bodies, and the extent to which the river is incised into the aquifer (Ackerman, 1996; Barlow and Leake, 2012).

The Mississippi River serves as a hydrologic flow boundary for the Mississippi River Valley alluvial aquifer at the eastern extent of the aquifer in Arkansas. The river is incised through the entire thickness of the aquifer along many reaches (Whitfield, 1975; Ackerman, 1989a) and recharges the alluvial aquifer for most of the year. The stage of the river controls groundwater levels and flow in an area adjacent to the river. The Arkansas and White Rivers incise a part of the alluvial aquifer, serve as hydrologic flow boundaries, and appear to be hydraulically well connected as shown by a strong correlation between river stage and local potentiometric heads (Freiwald and Grosz, 1988; Ackerman, 1996).

Rivers in the Mississippi Alluvial Plain were considered primary groundwater-discharge locations during predevelopment time. Many of these rivers transitioned to important sources of recharge to the Mississippi River Valley alluvial aquifer as groundwater levels decreased, reversing the river-aquifer head relation at the scale of groundwater-level mapping activities. As a result, several numerical models in the past two decades were developed using river-package simulations; results indicated that rivers are volumetrically important sources of recharge to the aquifer (Mahon and Ludwig, 1990; Mahon and Poynter, 1993; Reed, 2003; McKee and Clark, 2003; Stanton and Clark, 2003). Reed (2003) depicted flow from model cells along the Arkansas River into the Mississippi River Valley alluvial aquifer throughout much of Jefferson County in southeastern Arkansas. Stanton and Clark (2003) also depicted river model cells in southeastern Arkansas as a primary source of recharge to the aquifer. From a standpoint of logical analysis, the large volume of available water in the river, the hydrologic boundary created by the river, and groundwater-level data showing gradients of flow away from the river strongly suggested that flow was moving from the river into the aquifer.

Prior to the installation of the lock and dam system in 1967, the Arkansas River acted as a drain for excess groundwater flow for most of the year (Bedinger and Reed, 1961). Previous publications identified a groundwater divide between the water moving into the river and water moving away from the river. Although wells near the river exhibited higher water levels during high river stage, this effect was diminished exponentially away from the river and was small beyond a distance of approximately 2 miles (mi) (Bedinger and Reed, 1961; Bedinger and Jeffery, 1964; Krinitzsky and Wire, 1964; Freiwald and Grosz, 1988; Ackerman, 1996). Bedinger and Jeffery (1964) stated that correlations of stage and water levels for wells greater than 2 mi from the river were "… probably more apparent than real, is caused by local recharge from precipitation coincident with river-stage changes." As such, earlier analysis of the connectivity between the Arkansas River and the Mississippi River Valley alluvial aquifer recognized the effects of bank storage and the limited effects of river-water infiltration into the aquifer at distances greater than 1–2 mi.

While very strong corollary evidence supported the concept of the hydraulic connectivity of rivers and the alluvial aquifer, questions regarding the volume and rate of water leaking from rivers have yet to be answered. The earlier interpretation of bank storage and the degree of hydraulic connection between the Arkansas River and the Mississippi River Valley alluvial aquifer changed with construction of lock and dam channelization along the river in the 1960s. Resulting higher river stage and higher groundwater gradients near the river implied continual direct flow from the river to the aquifer. The available data led to definitive statements that the Arkansas River contributed appreciable water to the aquifer under observed head conditions. The difficult, unaddressed, and long-standing debate in hydrogeology has centered on the question of how much water passes through streambeds in systems that carry an abundant load of fine-grained material. Although many streams are in hydraulic connection with an aquifer, flow rates are impeded by fine stream-bottom sediments and by migration of clay and silt into the aquifer matrix. Barlow and Leake (2012) noted that thick, silty streambeds (such as that of the Arkansas River) will tend to reduce the rate of flow between a stream and aquifer, while simultaneously increasing the hydraulic gradient between the two water bodies. Additionally, the clay-rich Mississippi River Valley confining unit ranges up to 100 ft in thickness, whereas the Arkansas River typically has channel depths of less than 30 ft, further restricting the hydraulic connection between the river and the aquifer in many places.

Kresse and Clark (2008) conducted a study to determine the source of elevated chloride concentrations in the Mississippi River Valley alluvial aquifer in southeastern Arkansas (see "Occurrence, Distribution, and Sources of Elevated Chloride Concentrations" section). Their study used maps of chloride concentrations, bromide-chloride ratios, and other methods to show a correlation of elevated chloride concentrations in backswamp areas at greater distances from river channels, which suggested that evaporation in these areas accounted for the elevated chloride concentrations. Additionally, higher chloride concentrations in the Arkansas River relative to low concentrations in channel deposits proximal to the river suggested that influx of water from the Arkansas River may be relatively small, and that infiltration of precipitation through coarse-grained channel and natural-levee deposits proximal to the river may be the primary avenue for recharge to the Mississippi River Valley alluvial aquifer (Kresse and Clark, 2008). While these findings may seem to contradict river-package modeling studies (referenced above) conducted in the Mississippi River Valley alluvial aquifer, this certainly is not the case. The discretization and resolution of these models simply support the statement that a certain amount of water moves into the aquifer near a given river. While models are effective at estimating the amount of water entering the aquifer near the river, the models do not necessarily differentiate between direct leakage from rivers and infiltration of precipitation into deposits that are proximal to and intimately associated with the current river channel. Geochemical data provide a valuable aid in determining the source and volumetric relation of recharge water into the Mississippi River Valley alluvial aquifer. Determination of an accurate rate of flow from a river into the aquifer requires labor- and cost-intensive methods, including a dense network of observation wells or streambed piezometers, seepage meters, direct measurement of streamflow at various locations, measurements of temperature in the stream and streambed, analysis of geochemical tracers, physical aquifer and river-bottom hydraulic characteristics, and geophysical studies of the stream-aquifer system (Barlow and Leake, 2012). Alternatively, the very different chemistries of river water and rainfall make the exercise of distinguishing these sources possible using a less demanding approach. A geochemical approach provides strong evidence of the dominant recharge source and the relative contribution of direct channel recharge compared with infiltration of rainfall through permeable, river-proximal channel deposits.

## Water Use

The Mississippi River Valley alluvial aquifer is extremely important in terms of total water use in Arkansas. The State ranks fourth nationally in groundwater use (Kenny and others, 2009); in 2010, 94 percent of all groundwater use in Arkansas was from the Mississippi River Valley alluvial aquifer. Over 47,000 wells reported approximately 7,400 Mgal/d of use from the Mississippi River Valley alluvial aquifer as of 2010 (fig. 10). The economy of eastern Arkansas is heavily reliant on agriculture, and water from the Mississippi River Valley alluvial aquifer drives agricultural production. Locally, industry depends on the aquifer, and a recent trend of increasing water use is the flooding of agricultural fields to provide duck habitat to improve hunting.

Water-use rates for the Mississippi River Valley alluvial aquifer have increased steadily from 1965 to 2010 (fig. 11). The majority of the increase is attributed to irrigation, which has increased consistently over time for all reported water-use data (fig. 4). In 1965, the average water use by county from the Mississippi River Valley alluvial aquifer was 22.69 Mgal/d; by 2010, the average use had increased to 148.64 Mgal/d per county. Data from 2010 show 21 counties where reported water-use rates were less than 5 Mgal/d (but above 0), highlighting the fact that water-use increases have been focused within specific counties—areas where agricultural use is important (table 17). Since 1965, the greatest increase in use from the Mississippi River Valley alluvial aquifer was observed in Mississippi County (fig. 12; table 17).

Counties in the intensively farmed area of the Grand Prairie (Arkansas, Lonoke, and Prairie) historically had the highest groundwater use rates until 1985 (fig. 11), when water use began to substantially increase in counties in northeastern Arkansas. Lonoke County had the most withdrawals from 1965 to 1985, with rice irrigation being the primary use of the water. From 1990 to 2010, Poinsett County was the largest user, primarily for rice irrigation (98 percent). Jefferson County had the largest water withdrawals for industrial purposes (5.94 Mgal/d) in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

The following sections focus on the categories of water use from the Mississippi River Valley alluvial aquifer. The section “Overview of Aquifers of Arkansas” gives details on the inclusion of particular withdrawals and the definition of the water-use categories. For more information on the categories of water use, refer to “Groundwater Use in Arkansas” in the “Overview of Aquifers of Arkansas” section.

### Agriculture and Irrigation Use

Arkansas is the Nation’s leading rice producer (McGraw and others, 2012). Rice is a water-intensive crop, and traditional rice farming, as practiced in Arkansas, requires flooded paddies. Supplemental irrigation application rates for rice in Arkansas were estimated at 1.6 to 2.0 acre-ft during the growing season, which typically lasts from April to September (Engler and others, 1945, 1963; Bedinger and Reed, 1961). Current estimates place irrigation application rates as much as 3.3 acre-ft during a dry year, with average rates of 2.5 acre-ft depending on soil type, water-application methods, and degree of management (Henry and others, 2013). With expansion of rice agriculture, farmers also began to irrigate other crops, thus increasing groundwater use. Arkansas’ economy greatly benefits from irrigation and the Mississippi River Valley alluvial aquifer is the greatest source of irrigation water supply.

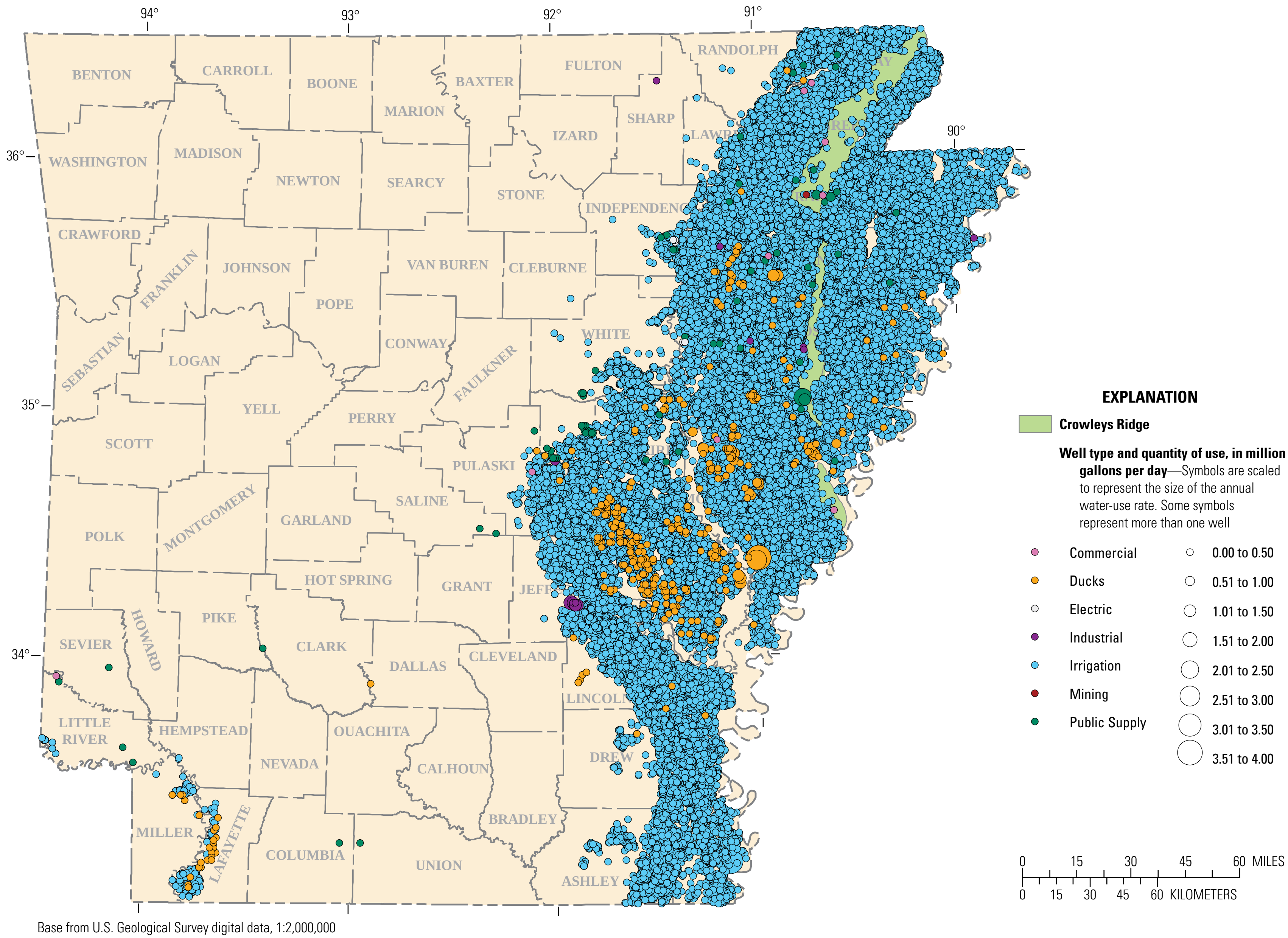



**Figure 10.** Wells with reported water use from the alluvial aquifers in the Coastal Plain in Arkansas, 2010.

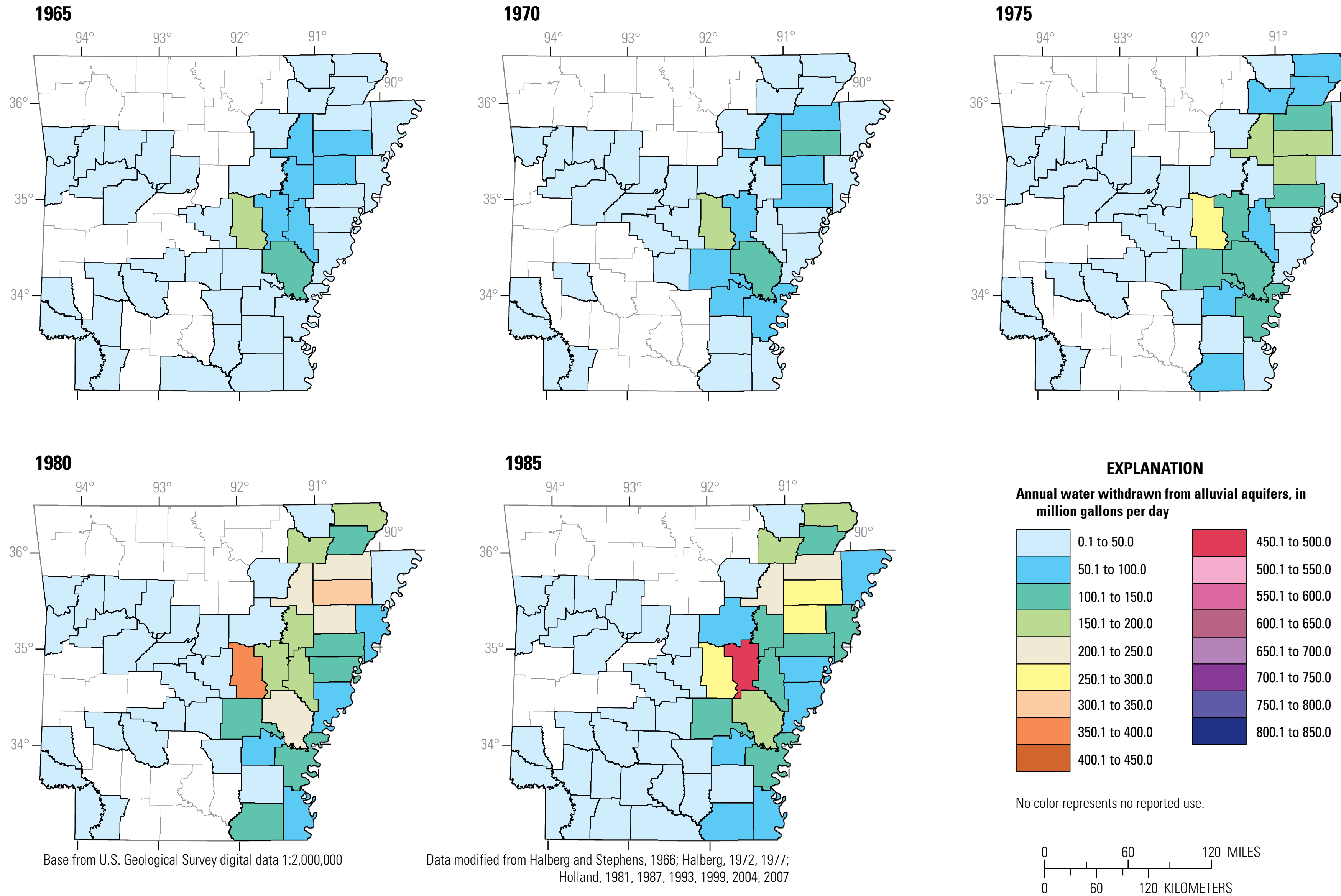



**Figure 11.** Water use from alluvial aquifers in Arkansas from 1965 to 2010.

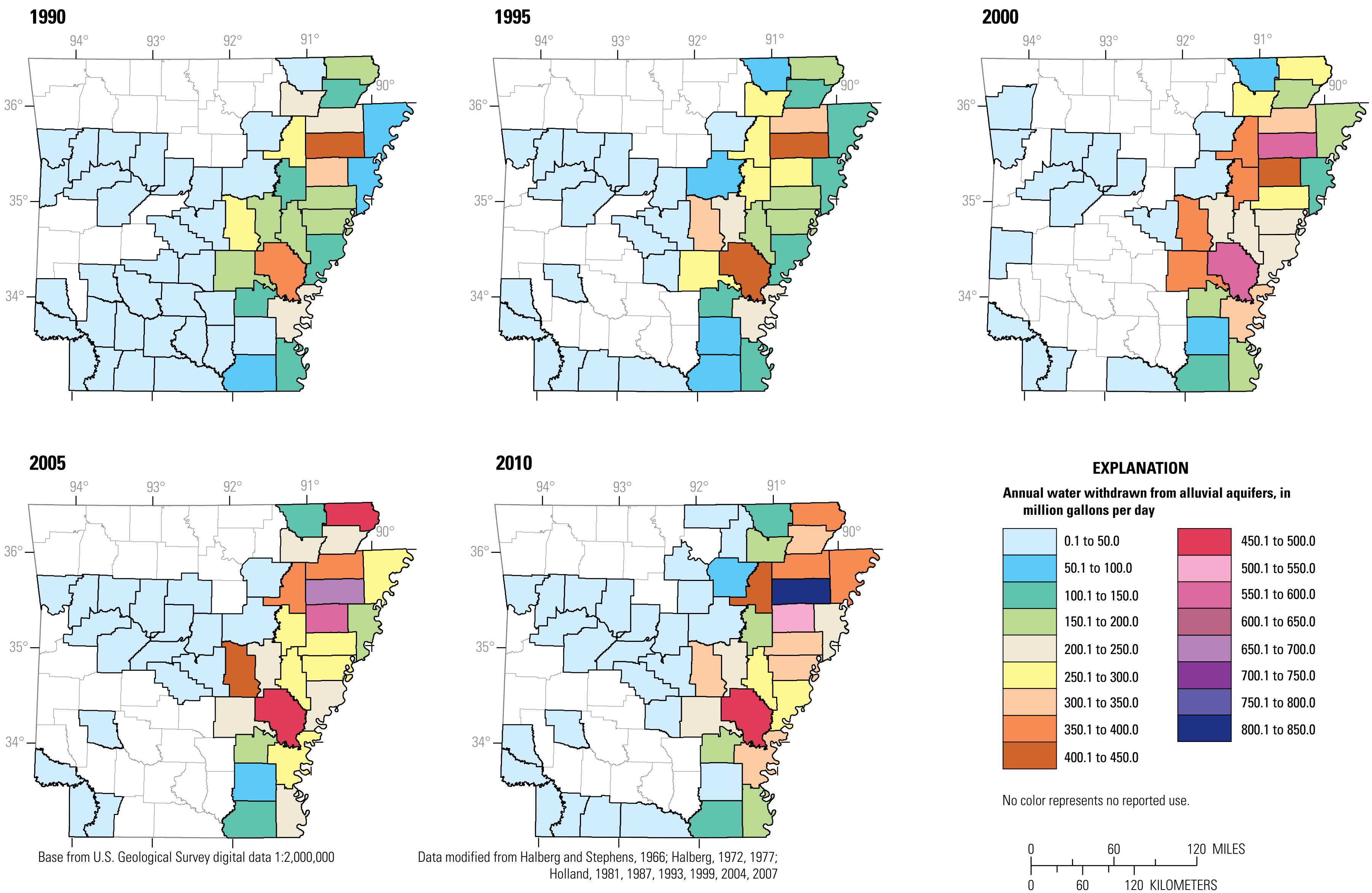



**Figure 11.** Water use from alluvial aquifers in Arkansas from 1965 to 2010.—Continued

**Table 17.** Water use from alluvial aquifers in Arkansas, 1965–2010.

[Data from Halberg and Stephens (1966); Halberg, (1972, 1977); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1965 | 1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|
| Arkansas | 113.45 | 117.38 | 136.27 | 209.49 | 185.07 | 356.97 | 402.63 | 567.33 | 472.97 | 496.36 |
| Ashley | 22.80 | 35.38 | 53.27 | 109.56 | 77.43 | 74.35 | 90.77 | 105.78 | 148.13 | 128.34 |
| Bradley | 0.34 | 0.00 | 0.00 | 0.00 | 0.56 | 0.36 | 0.37 | 0.00 | 0.00 | 0.00 |
| Calhoun | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 | 0.03 | 0.04 | 0.00 | 0.00 | 0.00 |
| Chicot | 12.19 | 23.94 | 46.61 | 69.19 | 75.71 | 116.48 | 149.52 | 172.84 | 247.08 | 200.76 |
| Clark | 0.12 | 0.09 | 0.13 | 0.35 | 2.17 | 0.70 | 0.82 | 0.00 | 0.00 | 0.00 |
| Clay | 22.13 | 19.04 | 60.33 | 150.50 | 175.87 | 196.40 | 170.55 | 260.94 | 466.06 | 360.50 |
| Cleburne | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.37 |
| Cleveland | 0.04 | 0.02 | 0.02 | 0.03 | 0.19 | 0.22 | 0.06 | 0.00 | 0.00 | 0.00 |
| Columbia | 0.00 | 0.00 | 0.00 | 0.00 | 1.20 | 0.73 | 0.85 | 0.00 | 0.00 | 0.04 |
| Conway | 2.10 | 8.06 | 7.53 | 5.44 | 4.19 | 1.64 | 1.26 | 1.94 | 2.51 | 1.53 |
| Craighead | 48.82 | 65.87 | 145.27 | 222.57 | 202.84 | 237.55 | 314.73 | 329.12 | 350.08 | 355.18 |
| Crawford | 1.18 | 1.71 | 0.84 | 2.51 | 4.15 | 1.00 | 0.37 | 0.38 | 0.94 | 0.87 |
| Crittenden | 26.37 | 29.68 | 38.16 | 78.98 | 113.68 | 62.33 | 104.26 | 130.06 | 151.42 | 210.75 |
| Cross | 67.96 | 85.37 | 169.61 | 226.34 | 261.00 | 337.39 | 284.87 | 406.53 | 592.27 | 508.98 |
| Dallas | 0.00 | 0.00 | 0.00 | 0.00 | 0.27 | 0.24 | 0.20 | 0.00 | 0.00 | 0.00 |
| Desha | 45.11 | 81.13 | 114.04 | 146.27 | 128.62 | 211.71 | 230.54 | 324.84 | 297.34 | 340.72 |
| Drew | 8.51 | 22.51 | 32.10 | 43.60 | 41.08 | 35.94 | 53.85 | 54.70 | 74.58 | 31.34 |
| Faulkner | 0.00 | 1.93 | 0.36 | 0.53 | 0.67 | 0.78 | 0.66 | 0.00 | 2.22 | 4.50 |
| Franklin | 0.76 | 1.32 | 0.27 | 0.24 | 0.96 | 0.71 | 0.47 | 0.00 | 0.39 | 0.46 |
| Fulton | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| Grant | 0.11 | 0.11 | 0.12 | 0.13 | 0.23 | 0.23 | 0.30 | 0.00 | 0.00 | 3.39 |
| Greene | 15.75 | 18.64 | 67.93 | 138.96 | 131.79 | 118.15 | 147.51 | 152.45 | 217.60 | 350.19 |
| Hempstead | 0.26 | 0.00 | 0.00 | 0.00 | 1.81 | 0.80 | 1.21 | 0.00 | 0.00 | 0.00 |
| Hot Spring | 0.04 | 0.13 | 0.14 | 0.15 | 0.46 | 0.22 | 0.04 | 0.00 | 0.00 | 0.00 |
| Independence | 2.17 | 5.29 | 7.67 | 16.85 | 32.57 | 7.74 | 14.71 | 35.74 | 41.84 | 57.58 |
| Jackson | 56.87 | 60.03 | 164.79 | 212.89 | 203.53 | 269.79 | 284.10 | 363.38 | 382.70 | 415.50 |
| Jefferson | 42.01 | 51.60 | 106.79 | 141.14 | 133.97 | 174.73 | 264.74 | 377.74 | 227.36 | 237.47 |
| Johnson | 0.60 | 0.97 | 1.25 | 2.24 | 2.87 | 0.90 | 0.61 | 1.33 | 0.32 | 0.35 |
| Lafayette | 4.61 | 4.37 | 12.19 | 18.88 | 16.62 | 2.97 | 23.01 | 11.00 | 38.31 | 23.89 |
| Lawrence | 17.72 | 25.54 | 77.02 | 154.11 | 153.69 | 212.39 | 256.61 | 290.65 | 222.20 | 178.65 |
| Lee | 25.44 | 21.80 | 40.32 | 116.73 | 96.60 | 162.52 | 161.12 | 234.23 | 265.86 | 305.40 |
| Lincoln | 25.88 | 69.24 | 83.92 | 88.74 | 86.06 | 110.40 | 131.35 | 167.16 | 181.67 | 193.96 |
| Little River | 1.42 | 3.52 | 3.17 | 5.57 | 3.22 | 2.70 | 1.64 | 1.76 | 4.43 | 4.12 |
| Logan | 0.31 | 0.54 | 0.29 | 0.25 | 0.33 | 0.20 | 0.08 | 1.54 | 1.65 | 0.71 |

**Table 17.** Water use from alluvial aquifers in Arkansas, 1965–2010.—Continued

[Data from Halberg and Stephens (1966); Halberg, (1972, 1977); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1965 | 1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|
| Lonoke | 155.46 | 177.03 | 257.15 | 374.13 | 293.84 | 263.65 | 300.26 | 373.11 | 413.08 | 343.87 |
| Miller | 1.71 | 2.41 | 1.74 | 3.86 | 18.77 | 8.13 | 9.26 | 6.92 | 16.14 | 9.08 |
| Mississippi | 5.19 | 7.51 | 8.48 | 19.44 | 50.36 | 93.68 | 126.29 | 185.78 | 271.19 | 364.73 |
| Monroe | 56.08 | 45.97 | 81.80 | 165.21 | 124.11 | 178.60 | 177.85 | 235.69 | 288.33 | 293.58 |
| Nevada | 0.00 | 0.00 | 0.00 | 0.00 | 0.83 | 0.33 | 0.27 | 0.00 | 0.00 | 0.00 |
| Ouachita | 0.00 | 0.00 | 0.00 | 0.00 | 0.36 | 0.13 | 0.15 | 0.00 | 0.00 | 0.00 |
| Perry | 0.00 | 1.74 | 0.28 | 0.24 | 0.00 | 0.00 | 0.00 | 0.00 | 0.46 | 0.49 |
| Phillips | 14.44 | 14.15 | 16.85 | 78.01 | 71.76 | 110.89 | 128.81 | 204.45 | 204.37 | 261.19 |
| Pike | 0.42 | 0.56 | 0.03 | 0.06 | 0.98 | 0.35 | 0.24 | 0.00 | 0.47 | 0.64 |
| Poinsett | 86.18 | 100.50 | 177.68 | 308.86 | 299.77 | 403.22 | 442.51 | 583.84 | 678.17 | 841.44 |
| Polk | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.03 | 0.00 | 0.00 |
| Pope | 1.02 | 1.49 | 3.25 | 3.45 | 6.53 | 10.59 | 2.73 | 2.32 | 1.55 | 0.71 |
| Prairie | 69.90 | 70.76 | 125.79 | 166.49 | 469.56 | 185.00 | 200.04 | 242.73 | 247.57 | 214.65 |
| Pulaski | 12.78 | 16.80 | 21.69 | 33.50 | 29.54 | 28.66 | 18.01 | 26.35 | 26.24 | 15.27 |
| Randolph | 3.16 | 3.98 | 18.85 | 42.41 | 42.05 | 49.54 | 57.09 | 85.88 | 102.26 | 111.24 |
| Saline | 0.00 | 0.15 | 0.12 | 0.20 | 0.20 | 0.20 | 0.24 | 0.00 | 0.98 | 1.32 |
| Sebastian | 0.21 | 0.12 | 0.17 | 0.15 | 1.07 | 0.40 | 0.18 | 0.00 | 0.00 | 0.24 |
| Sevier | 0.17 | 0.03 | 0.04 | 0.05 | 0.04 | 0.33 | 0.16 | 0.00 | 0.00 | 0.11 |
| Sharp | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| St. Francis | 32.79 | 52.26 | 104.25 | 140.71 | 110.90 | 159.66 | 189.10 | 252.22 | 295.34 | 345.96 |
| Stone | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.07 |
| Union | 0.05 | 0.00 | 0.00 | 0.00 | 0.46 | 0.36 | 0.47 | 0.01 | 0.00 | 0.05 |
| Van Buren | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.41 | 0.00 |
| Washington | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 |
| White | 3.55 | 5.42 | 14.43 | 47.20 | 50.50 | 41.42 | 59.21 | 48.32 | 48.05 | 34.22 |
| Woodruff | 58.00 | 49.47 | 22.39 | 166.97 | 142.37 | 140.78 | 254.48 | 351.46 | 265.79 | 182.48 |
| Yell | 0.47 | 2.52 | 2.15 | 3.75 | 5.96 | 0.58 | 0.41 | 1.16 | 2.37 | 0.45 |
| **Total** | **1,066.65** | **1,308.08** | **2,227.55** | **3,716.93** | **3,859.39** | **4,375.77** | **5,061.61** | **6,592.72** | **7,252.70** | **7,433.72** |

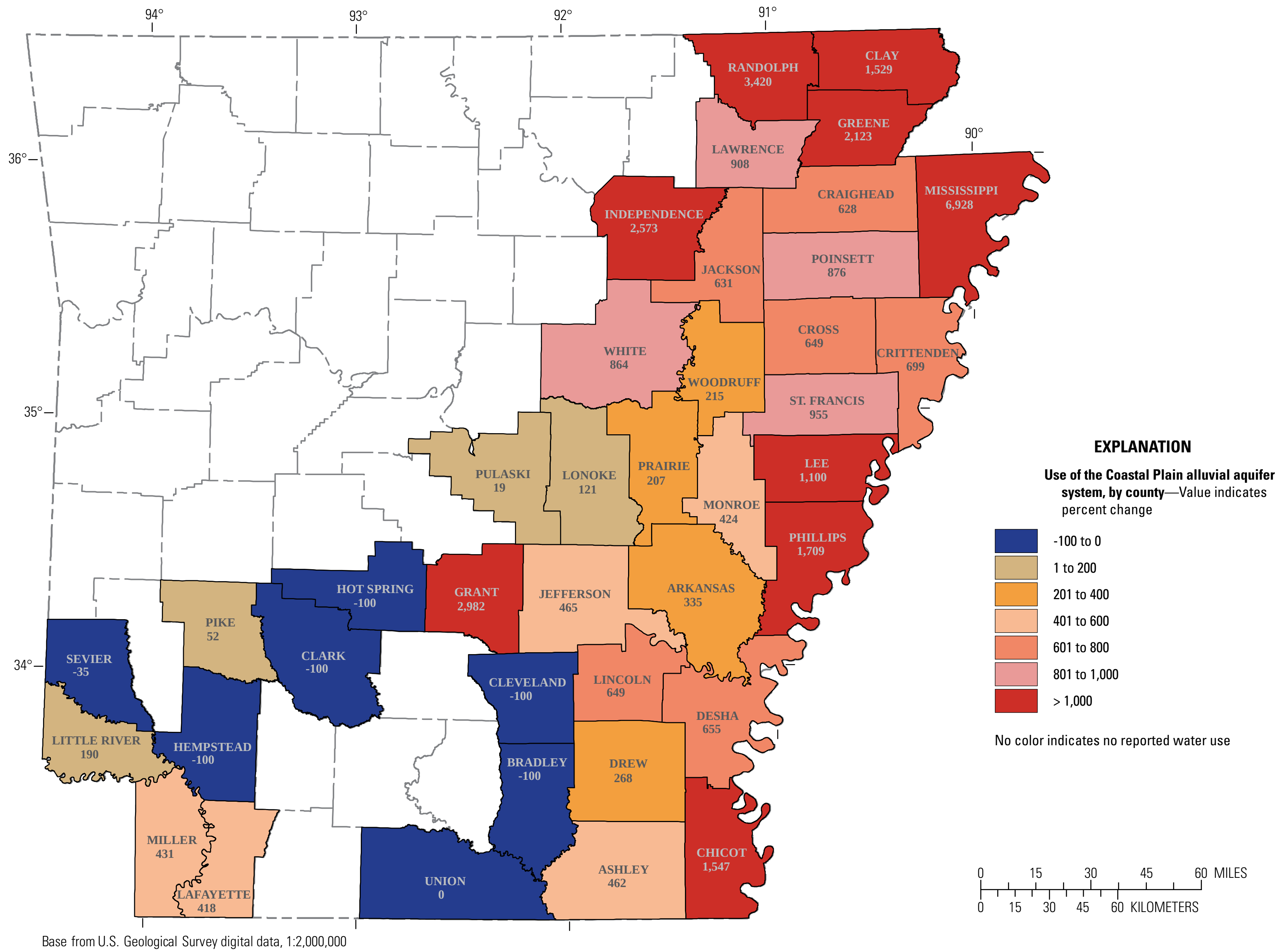



**Figure 12.** Change in percentage of water use from the alluvial aquifers in the Coastal Plain alluvial aquifer system in Arkansas from 1965 to 2010.

The earliest wells completed in eastern Arkansas were predominantly in the Mississippi River Valley alluvial aquifer and supplied domestic and livestock requirements (Veatch, 1906). Withdrawal of groundwater from the aquifer for agriculture started just before the turn of the 20th century in the Grand Prairie for irrigation of rice and, to a lesser extent, soybeans. In most areas, the aquifer is high-yielding and capable of producing hundreds to thousands of gallons per minute and making it very well suited for agricultural supply. Rice farming began in 1897 on 3 acres in Lonoke County by a single farmer (Stephenson and Crider, 1916). Soils of the Grand Prairie did not drain well and were underlain by an extensive clay layer, which was perfect for flooding of fields. Early rice production efforts were successful, and rice agriculture quickly expanded. Commercial rice farming began on 70 acres in 1904 in Lonoke County and was present throughout the Grand Prairie region by 1910 (Stephenson and Crider, 1916; Engler and others, 1945, 1963; Baker, 1955; Sniegocki, 1964; Gates, 2005). With the introduction and expansion of rice production in the Grand Prairie region, water use increased dramatically (fig. 13). Economic rice production required irrigation, and farmers in the Grand Prairie relied heavily on the Mississippi River Valley alluvial aquifer. The entirety of the 1906 rice crop, some 4,000 acres, was reported as being irrigated with groundwater (Engler and others, 1945). By 1916, Arkansas County had more than 250 rice irrigation wells (Stephenson and Crider, 1916). Early farmers in the Grand Prairie area called the groundwater resources “limitless” and “inexhaustible” (Gates, 2005); however, the poorly drained soils that provided such optimum conditions for rice production also restricted recharge to the aquifer, and considerable water-level declines were noted during the early history of irrigation as rice production expanded (Engler and others, 1945).

Rice cultivation spread quickly to the rest of eastern Arkansas because of many factors. Rice commanded high

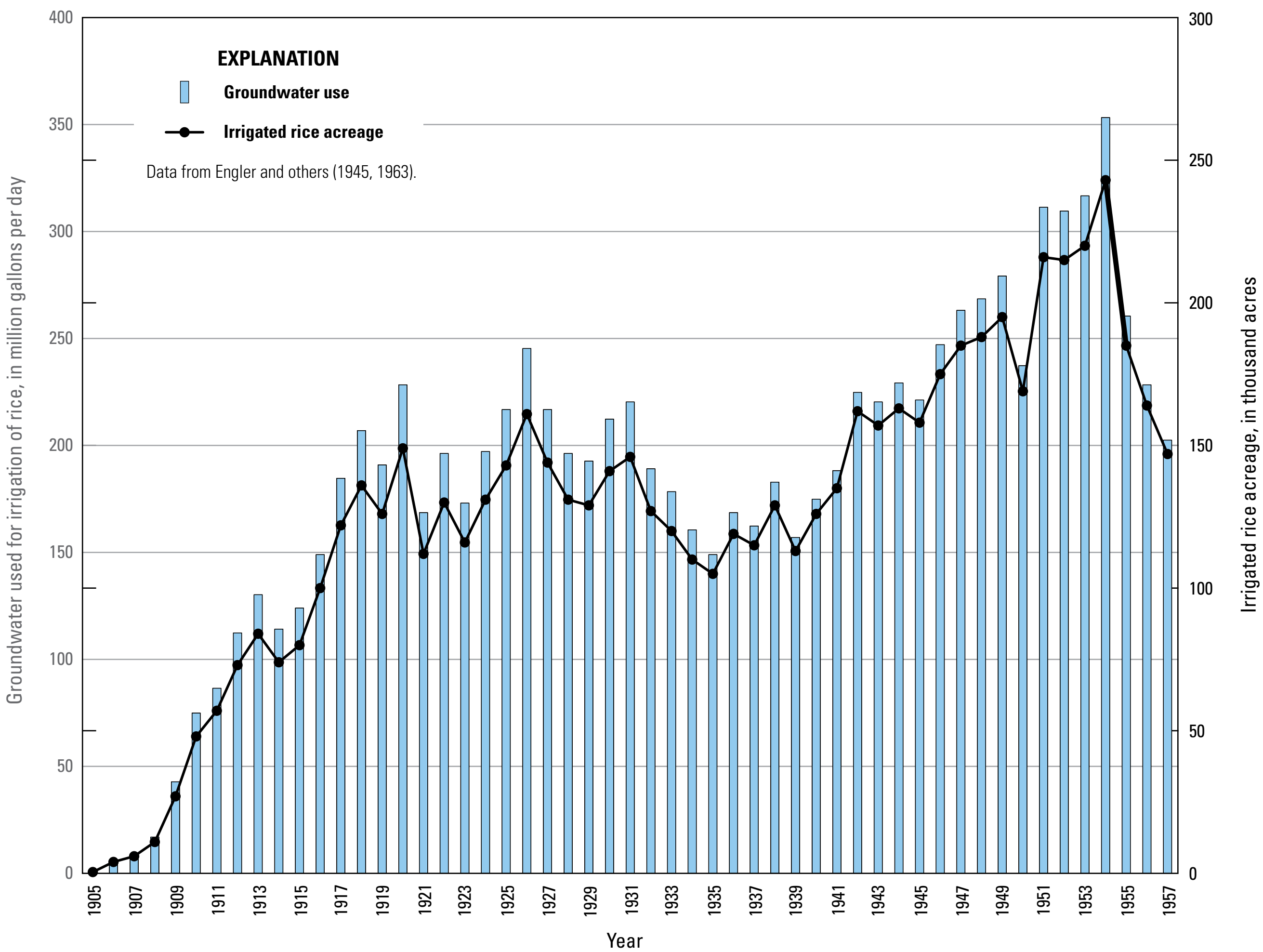



**Figure 13.** Rice acreage and corresponding irrigation water use from Mississippi River Valley alluvial aquifer in the Grand Prairie region of Arkansas, 1905–57.

market prices nationally with little regional or national competition, and drillers offered “water or no pay” discounts to farmers looking to make the expensive investment of a rice well (Gates, 2005). Farmers saw a use for swampy lands and clay-rich soils that were unable to economically produce other crops. By 1912, 13 counties grew rice: Arkansas, Clay, Craighead, Cross, Jefferson, Lawrence, Lee, Lonoke, Monroe, Poinsett, Prairie, St. Francis, and Woodruff. Acreage of rice grew rapidly across the State: 189,000 acres were documented by 1938 and approximately 600,000 acres in 1954 (fig. 14).

Natural and economic factors affecting other crops influenced the growth of rice agriculture throughout this period. Rice production increased through the early part of the 20th century (fig. 13). With this boom in rice production and resulting irrigation, groundwater withdrawals reached a peak in 1920 (Engler and others, 1945, 1963; Rosencrantz, 1946) but declined the following year as rice acreage dropped as a result of market excess. Cotton, a dryland crop that conventionally relied on precipitation rather than irrigation to meet crop-water requirements, was traditionally grown in the Mississippi River Delta; however, the drought of 1930–31 resulted in a poor cotton harvest causing economic hardship for growers. As a result, more farmers turned to rice and installed groundwater wells—a controlled and predictable water source.

Government and politics were a large factor affecting the increasing acreage of rice and therefore widespread and increasing use of the Mississippi River Valley alluvial aquifer in Arkansas. Many farmers in the northern Delta region switched from dryland cotton to irrigated rice production when the Agricultural Adjustment Act of 1933 placed controls on the amount of cotton produced (Williams, 2012). However, rice acreage in the Grand Prairie region were reduced during the Great Depression years when crop prices decreased (Chowdhury, 2002). Rice production and groundwater use increased again in the beginning of the 1940s during World War II, resulting in increased demands on domestic food production, and then dropped dramatically in the mid-1950s when Congress placed acreage controls on rice (fig. 13) (Broom and Reed, 1973; Broom and Lyford, 1981; Chowdhury, 2002).

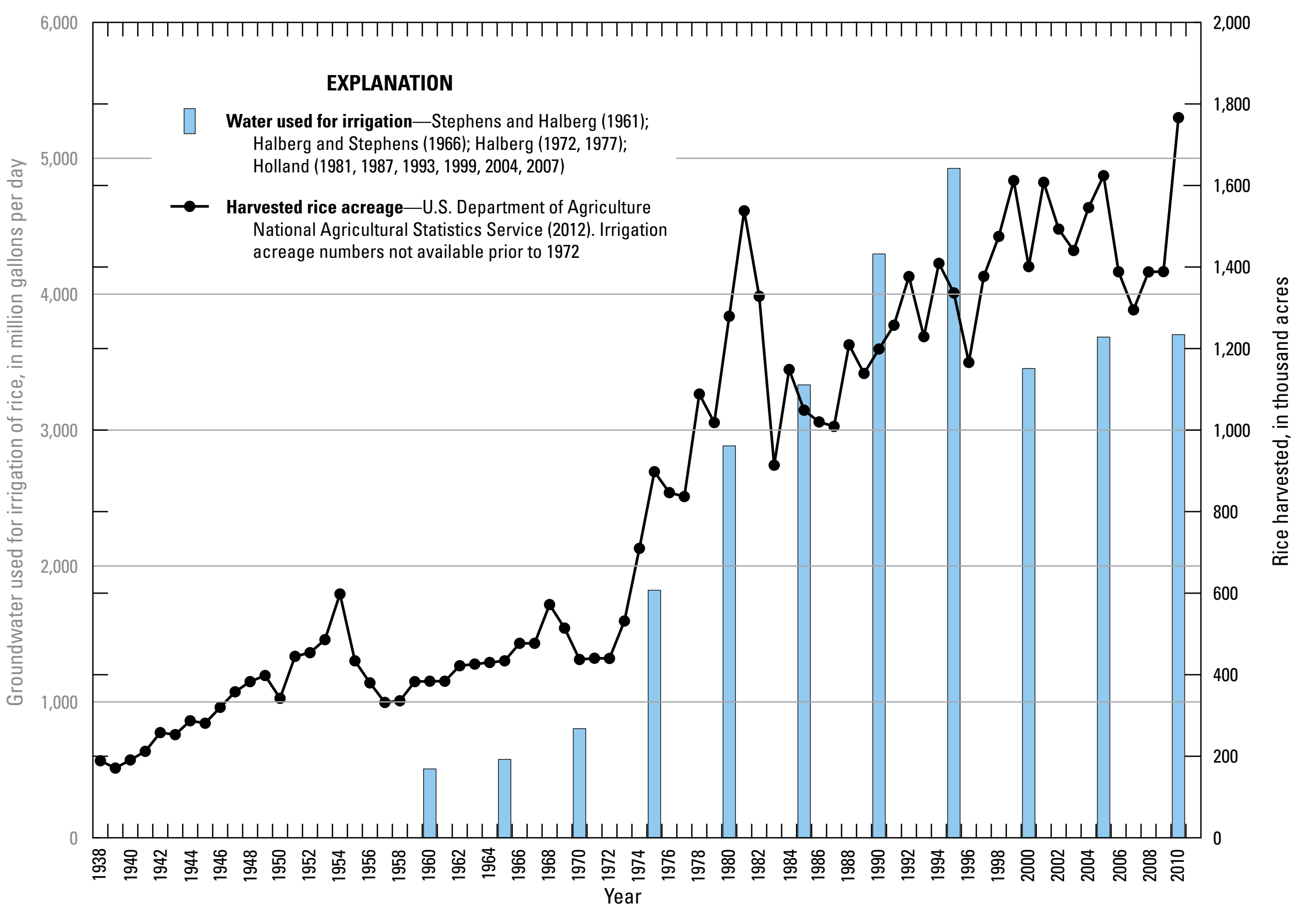



**Figure 14.** Acres of rice harvested and groundwater use for irrigation of rice in Arkansas.

After World War II, broad availability of affordable farm tractors and earth-moving equipment coincided with increased rice production and irrigation in southern and eastern Arkansas. Previously, much of this area remained undeveloped because of high water levels, the prevalence of wetlands and swampy soils, and extensive forest. Availability of machinery that could clear marsh and forest, ditch and drain wetlands, and create farmland changed the economics of farming in the area and changed the face of the land (Williams, 2012). During this time, rice wells were installed in areas where rice previously could not be grown. In Ashley County, irrigation wells produced 8 Mgal/d during rice growing season in 1947, whereas 5 years earlier, no rice irrigation was reported for that county (Hewitt and others, 1949). Similarly, Desha and Lincoln Counties had approximately 6 rice wells in 1946 that increased to 400 wells with a combined use of 45 Mgal/d by 1956 (Bedinger and Reed, 1961). Rice production began in Chicot County in 1946; by 1956, 12 Mgal/d was being pumped for irrigation (Onellion and Criner, 1955). Rice irrigation in Drew County resulted in the withdrawal of 12 Mgal/d from the aquifer in 1955 (Onellion, 1956). Wells in Mississippi County withdrew 2.2 Mgal/d in 1957 for rice irrigation (Ryling, 1960).

Another large and rapid increase in rice acreage and irrigation demand occurred when rice acreage controls were removed in 1975 with the Rice Production Act of 1975 (fig. 14). Farmers were allowed to produce in excess of their acreage allotment for the first time in 20 years (Chowdhury, 2002). Reported water use from the Mississippi River Valley alluvial aquifer for the irrigation use category approximately doubled between 1970 and 1975 (fig. 14; table 17).

Farmers began to increasingly depend upon irrigation in the 1970s for other historically dryland crops such as corn, soybeans, and cotton (figs. 15 and 16). Drought in the early 1980s increased agricultural demands on groundwater and caused dramatic declines in water levels (Mahon and Poynter, 1993). Use of groundwater for irrigation increased by more than 1,000 Mgal/d from 1975 to 1985 (table 7). Irrigation of corn from the Mississippi River Valley alluvial aquifer increased from approximately 110 Mgal/d in 2000 to a

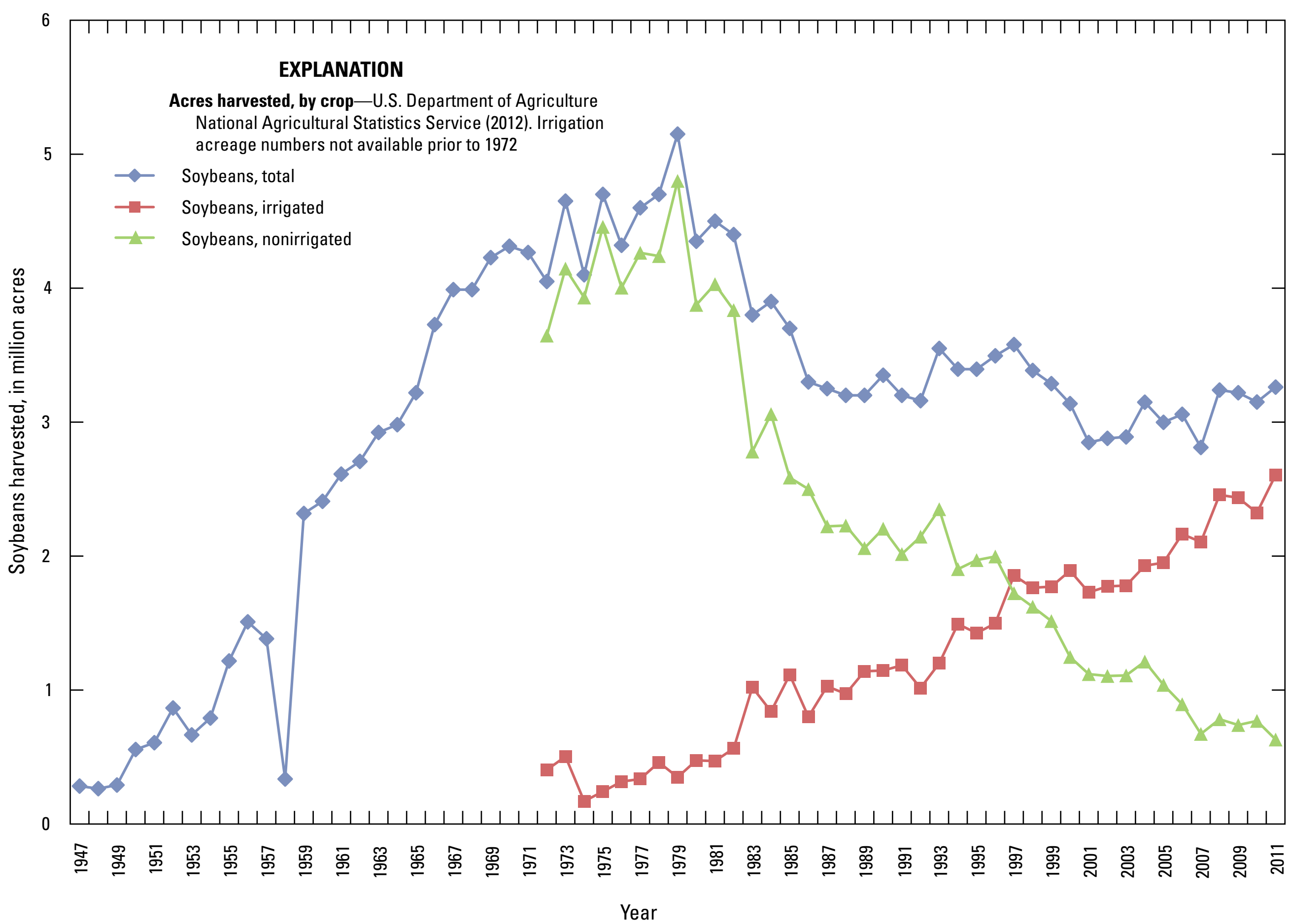



**Figure 15.** Acres harvested of irrigated and nonirrigated soybeans for Arkansas.

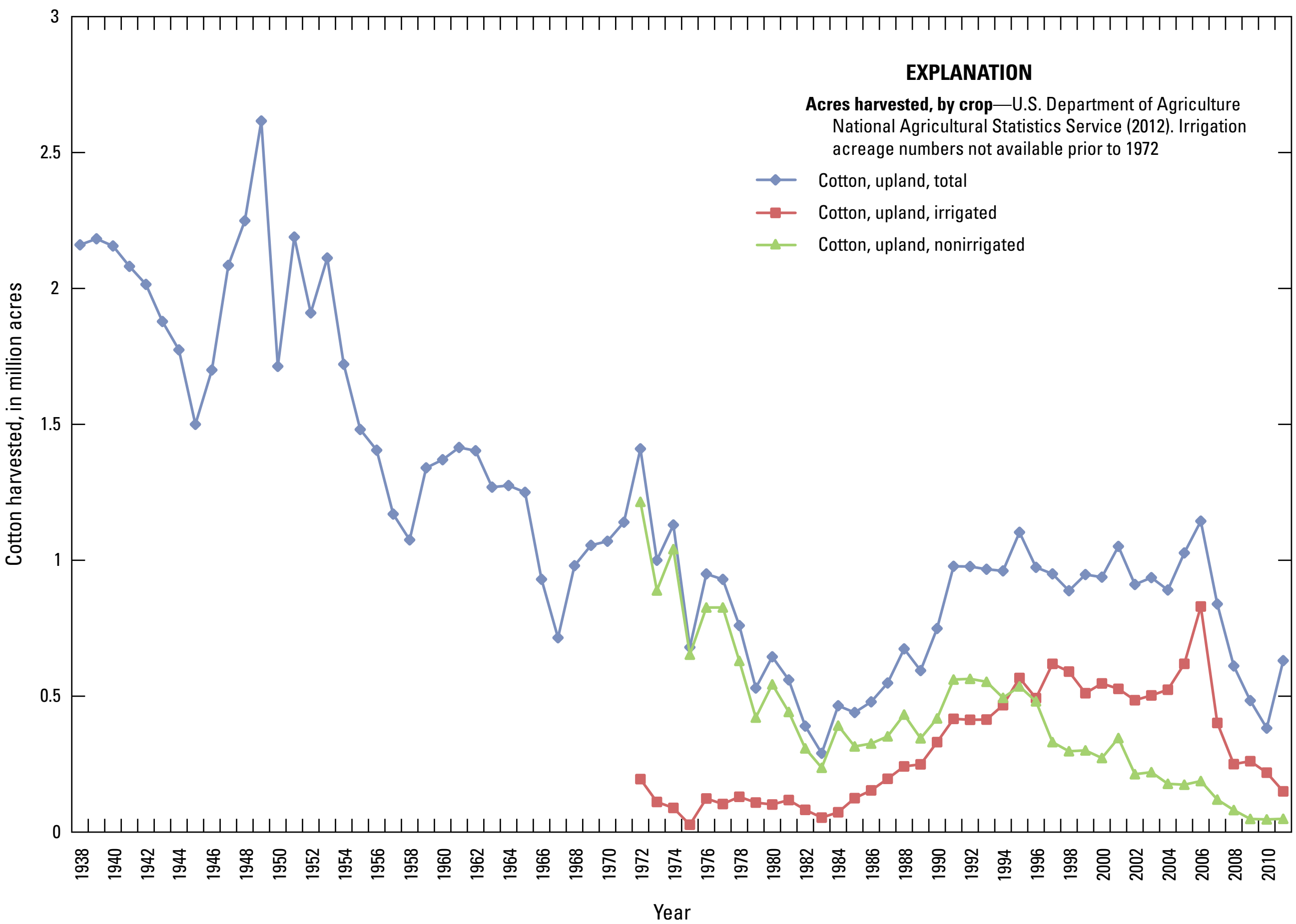



**Figure 16.** Acres harvested of irrigated and nonirrigated cotton for Arkansas.

maximum around 430 Mgal/d in 2007 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Corn irrigation decreased to 300 Mgal/d in 2010. This increase of corn agriculture coincided with the increased demand of corn for biofuels. Irrigated soybean acreage increased from 170,000 acres to 2.6 million acres from 1974 to 2011 (fig. 15).

In 2010, 7,050 Mgal/d was withdrawn in eastern Arkansas to irrigate approximately 3.2 million acres (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Approximately 1.7 million of those acres were planted in rice, a slight increase from 1.6 million acres in 2005 (fig. 14). Approximately half of the water used from the Mississippi River Valley alluvial aquifer in 2010 was for rice irrigation (Terrance W. Holland, U.S. Geological Survey, written commun., 2013). Poinsett County reported the largest use of the alluvial aquifer for irrigation in 2010 (data not shown), which accounted for 11 percent of all groundwater pumped in the State for irrigation use.

### Aquaculture Use

Aquaculture—mainly baitfish and catfish production—is an important industry in Arkansas relying heavily on groundwater withdrawal from the Mississippi River Valley alluvial aquifer. Arkansas leads the Nation in production of baitfish (Kaliba and Engle, 2006; Stone and Selden, 2006). In 2010, 97 percent of water used for aquaculture was withdrawn from the Mississippi River Valley alluvial aquifer (Terrance W. Holland, U.S. Geological Survey, written commun., 2013). Substantial groundwater withdrawals were from Lonoke and Chicot Counties.

The first aquaculture farms in Arkansas were built in Lonoke in the 1940s to raise goldfish (Engle, 2012; Arkansas Agriculture Department, 2013). Multiple counties in southeastern Arkansas began aquaculture in the 1960s (Broom and Reed, 1973; Kaliba and Engle, 2006). Halberg and Reed (1964) estimated that 11 Mgal/d were used to refill commercial ponds in an area of northeastern Arkansas including Cross, Lee, Lonoke, Monroe, Prairie, St. Francis, and Woodruff Counties. In 1970, there were over 3,000 acres of fish farms in Desha and Lincoln Counties (Broom and Reed, 1973).

Aquaculture peaked in the 1980s. Growth and continuity of aquaculture in Arkansas has been limited by the lack of processing facilities and more recently by competition from imported fish. In Chicot County, increases in water-use rates for aquaculture were seen in 1980 and again in 1990 (table 13) after two catfish processing facilities were installed (Kaliba and Engle, 2006). Recently, water use and aquaculture production rates have declined because of foreign imports of catfish and other species (Stone and Selden, 2006; Bell, 2010).

### Duck Hunting Use

Arkansas has been an acknowledged duck hunting destination since presettlement times (Arkansas Game and Fish Commission, 1998). Ducks and geese began using land cleared for rice fields as stopping points on their winter migration route. As farmers recognized the off-season economic potential of leasing land for duck hunting, fields were flooded to provide improved stopover habitat. Water-use reporting did not have a separate category for duck hunting until 2005, so determining any trends in water use because of duck hunting is difficult with the limited period of record. Fields not in production during the off-season are flooded using irrigation wells. Many areas where water-level declines are an issue, such as the Grand Prairie, continue this practice of flooding to create duck habitat. The largest use in this category was in Arkansas and Monroe Counties in 2010 (table 14).

### Public-Supply Use

Until the mid-20th century, all municipalities in eastern Arkansas were supplied by groundwater from the Mississippi River Valley alluvial aquifer where it was present (Stephenson and Crider, 1916; Hale and others, 1947; Engler and others, 1963). Even where it was not the primary source of water, many towns frequently had additional emergency wells completed in the Mississippi River Valley alluvial aquifer (Stephenson and Crider, 1916; Hale and others, 1947). Water-quality issues related to the Mississippi River Valley alluvial aquifer, especially elevated iron concentrations, forced some towns to find other sources.

Declining water levels in the Mississippi River Valley alluvial aquifer also forced many municipalities to find other water sources, and the Sparta aquifer is currently the primary drinking-water source in the Grand Prairie region (fig. 5). Three Mississippi River Valley alluvial aquifer wells originally were used by the city of Stuttgart (Arkansas County), and two Mississippi River Valley alluvial aquifer wells each for the cities of Carlisle, Lonoke (both Lonoke County), and Hazen (Prairie County) (Stephenson and others, 1916; Engler and others, 1945). Stuttgart first tapped the Sparta aquifer because of declining water levels in the Mississippi River Valley alluvial aquifer and completed its first well into the Sparta aquifer by 1947 (Hale and others, 1947; Engler and others, 1963). Around the early 1960s, the cities of DeWitt and Gillett (Arkansas County) drilled their primary drinking-water wells deeper into the Sparta aquifer (Engler and others, 1963). Stuttgart currently has six wells completed in the Sparta aquifer; its three Mississippi River Valley alluvial aquifer wells are currently (2013) inactive (Lyle Godfrey, Arkansas Department of Health, written commun., 2012).

A combined public-supply use of 1.87 Mgal/d was reported in 1960 from the Mississippi River Valley alluvial aquifer for Brinkley (Monroe County), DeValls Bluff, Des Arc, and Hazen (Prairie County), Forrest City (St. Francis County), and Carlisle and Lonoke (Lonoke County) (Halberg and Reed, 1964). Currently (2013), Carlisle, DeValls Bluff, Forrest City, and Hazen continue to use the Mississippi River Valley alluvial aquifer as a sole source. Forrest City is the largest public-supply user of the aquifer, pumping 3.82 Mgal/d in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Des Arc still pumps from its alluvial wells but added a well completed in the Sparta aquifer in 2004. Brinkley and Lonoke now use the Sparta aquifer.

Public supply accounted for less than 1 percent of all groundwater use in 2010, but the Mississippi River Valley alluvial aquifer ranks as the third highest-use aquifer for public supply in Arkansas after the Sparta and the Wilcox aquifers. More than 50 municipalities use wells completed in the Mississippi River Valley alluvial aquifer as their public-supply source (fig. 10). Lonoke County (primarily the cities of Cabot and Jacksonville) used the largest amount of alluvial water for public supply from 2000 to 2010.

Other municipalities using the Mississippi River Valley alluvial aquifer are in northeastern Arkansas near Crowleys Ridge. All municipalities in Jackson County use the Mississippi River Valley alluvial aquifer, which accounted for 0.81 Mgal/d in 1963 (Albin and others, 1967a) and steadily increased to 1.59 Mgal/d by 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). The city of Newport originally pumped water from the White River until 1930, when two wells were drilled into the Mississippi River Valley alluvial aquifer (Stephenson and Crider, 1916; Hale, 1926; Hale and others, 1947). Newport had seven Mississippi River Valley alluvial aquifer wells in 2010 and supplied water to the cities of Grubbs, Diaz, and Jacksonport (all Jackson County). The city of Jonesboro (Craighead County) is another major user, withdrawing 2.06 Mgal/d in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012); Jonesboro also has wells completed in the Sparta aquifer. Although cities east of Crowleys Ridge tap the Wilcox aquifer, a few smaller communities use the Mississippi River Valley alluvial aquifer.

### Domestic Use

Since predevelopment, the Mississippi River Valley alluvial aquifer has been the primary source of domestic water supply in eastern Arkansas (Stephenson and Crider, 1916; Onellion and Criner, 1955; Halberg and Reed, 1964; Albin and others, 1967a; Lamonds, 1969; Plebuch and Hines, 1969; Broom and Lyford, 1981). Engler and others (1963) noted that all of the estimated 43,000 homes in the Grand Prairie relied on wells completed in the Mississippi River Valley alluvial aquifer, using about the same amount of water as three rice irrigation wells. More recently, domestic supply is an important, but lesser in terms of volume, use of the Mississippi River Valley alluvial aquifer. Domestic supply use has decreased as smaller communities formed rural water associations to provide water. Domestic use was less than 1 percent of total withdrawals from the Mississippi River Valley alluvial aquifer in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

### Industrial Use

The earliest industrial use of the Mississippi River Valley alluvial aquifer was primarily for railroads, ice companies, cotton gins, and rice mills (Purdue, 1905; Veatch, 1906; Stephenson and Crider, 1916; Engler and others, 1963), but predominant industrial use since that time has been for lumber and paper industries. Many lumber mills and paper factories were present across the State, though somewhat transient in the early part of the century, and it was not uncommon for withdrawals to occur for only a short time as changes took place in operation and production (Mahon and Poynter, 1993). Facilities in Pine Bluff (Jefferson County) and in Crossett (Ashley County) produce wood and paper products. In Ashley County, pumping from the Mississippi River Valley alluvial aquifer began around 1900 for sawmills and related paper and wood products. Recorded use for wood-products related industries in Crossett was 0.2 Mgal/d in 1902, which steadily increased over the years: 0.9 Mgal/d in 1920, 2 Mgal/d in 1925, 10.5 Mgal/d in 1940, 12 Mgal/d in 1946, and 16 Mgal/d in 1947 (Hewitt and others, 1949). The Saline River was dammed in 1963 to construct a lake and provide a new water source for the paper industry in Ashley County (Encyclopedia of Arkansas, 2013; U.S. Army Corps of Engineers, 2013a), which reduced Ashley County's industrial consumption of groundwater from 28.24 Mgal/d in 1960 to 7.47 Mgal/d in 1965 (table 11). Records from the ARWUDBS indicate that from the mid-1980s to present, all current industrial wells in Ashley County tap the Cockfield aquifer (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

Many wells were drilled in the 1930s and 1940s in Jefferson County for ice companies and railroads (Klein and others, 1950). Also, the Pine Bluff Arsenal drilled four wells into the Mississippi River Valley alluvial aquifer in 1942 (Klein and others, 1950). These wells were used intermittently, depending on production, and pumped a combined 1.1 Mgal/d in 1947 but were unused in 1948. Another eight wells in the Pine Bluff area were used for industrial purposes with an estimated use of 0.3 Mgal/d (Klein and others, 1950). A paper-products company was the only industrial user in Jefferson County in 2010, pumping 6.45 Mgal/d (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Many other companies use the Mississippi River Valley alluvial aquifer, withdrawing an additional 1.32 Mgal/d in 2010 for a variety of manufacturing processes.

### Water Level Trends

Prior to widespread agricultural irrigation in the Grand Prairie region, the Mississippi River Valley alluvial aquifer was confined (Engler and others, 1963). The Mississippi River Valley confining unit that overlies the Mississippi River Valley alluvial aquifer is a clay-rich unit that is typically about 40–100 ft thick and is a primary reason that the region is suitable for rice agriculture by holding water to inundate the rice plants. However, this clay layer also impedes vertical flow, restricts recharge, and in predevelopment time served as a confining unit for the underlying Mississippi River Valley alluvial aquifer. As groundwater withdrawals increased, water levels in many parts of the Mississippi River Valley alluvial aquifer declined below the clay layer, and the aquifer transitioned to an unconfined condition. In some areas of the Grand Prairie, water levels were below the base of the clay layer, and withdrawals were recognized as unsustainable, with the aquifer being in danger of depletion as early as 1929 (Engler and others, 1945; Counts and Engler, 1954; Baker, 1955; Plebuch, 1962; Albin and others, 1967a, b). In extensive areas of the Mississippi River Valley alluvial aquifer, declines of water levels have resulted in: (1) unconfined conditions (that is, the upper section of the aquifer is now unsaturated) and (2) reductions in hydraulic pressure, saturated thickness, amount of water stored, lateral flow within the aquifer, and base flow to streams throughout most of its extent in Arkansas (Czarnecki and others, 2012).

In extensive areas of eastern Arkansas, water was withdrawn from the Mississippi River Valley alluvial aquifer at rates that exceeded recharge; therefore, those rates could not be sustained indefinitely. This water-budget imbalance resulted in regional water-level declines, formation of extensive cones of depression, reduction of water in storage, and decreases in individual well yields. In some areas, water levels have declined such that water cannot be pumped at rates needed to support demand, particularly for irrigation (Czarnecki and Schrader, 2013). In addition, deeper wells were required into underlying formations (including the Sparta, Cockfield, and Wilcox aquifers) to reach water (Mahon and Poynter, 1993). Furthermore, excessive dewatering of an aquifer can lead to irreversible compaction of the aquifer (subsidence), reducing its water-yielding capacity or ability to be recharged (Konikow, 2013).

Because of the economic importance of the aquifer and concerns regarding depletion, multiple investigations focused on water levels in the Mississippi River Valley alluvial aquifer in eastern Arkansas (Engler and others, 1945, 1963; Plebuch, 1962; Albin and others, 1967b; Broom and Reed, 1973; Arkansas Geological Commission, 1980; Edds and Fitzpatrick, 1984a; Plafcan, 1985, 1986, 1987; Plafcan and Edds, 1986; Plafcan and Fugitt, 1987; Ackerman, 1989b; Plafcan and Remsing, 1989; Westerfield, 1989, 1990; Westerfield and Baxter, 1990a, 1990b, 1990c; Westerfield and Touschner, 1991, 1992, 1993; Mahon and Poynter, 1993; Westerfield and Gonthier, 1993; Westerfield and Poynter, 1993, 1994; Stanton and others, 1998; Joseph, 1999; Schrader, 2001b, 2006a, 2008a, 2010; Reed, 2004). Water-level surfaces, represented by potentiometric contours from predevelopment through 2008, constructed from multiple studies are shown in figure 17. Predevelopment-water levels for the Mississippi River Valley alluvial aquifer typically were reported as near land surface (within 20 ft) and sloped gently from the northwest to southeast mirroring topography. As groundwater irrigation spread across eastern Arkansas, groundwater withdrawals exceeded recharge and water levels declined. Changes in water levels were seen as early as 1929, when the first water-level map of the area was created from water levels measured in the Grand Prairie region (Engler and others, 1945). Water levels rose slightly in the mid-1960s during a period of congressional controls on rice acreage. When the controls were removed in 1975, water levels again declined.

Sustained heavy pumping from wells for extensive periods resulted in substantial, long-term, and widespread water-level declines in parts of eastern Arkansas; cones of depression formed and expanded in many areas. A cone of depression appeared early in the pumping history of the Grand Prairie region, grew to encompass Arkansas County, and continued growing in a northwestern direction into Lonoke and Prairie Counties, becoming a major regional depression (fig. 17). Another cone of depression developed on the western side of Crowleys Ridge (fig. 17). The two cones of depression were hypothesized as eventually coalescing if withdrawals continued at unsustainable rates as defined by Westerfield (1990). On the eastern side of Crowleys Ridge, water levels do not reflect declines west of the ridge as a result of hypothesized recharge from the Mississippi River. Intermittent large industrial withdrawals have caused intermittent depressions in Ashley County. For more discussion on recent changes in water levels in the Mississippi River Valley alluvial aquifer see Schrader (2006a, 2008a, 2010).

Rates of water-level declines by county over an approximately 20-year period are included in four reports from 2004 through 2010 (Reed, 2004; Schrader, 2006a, 2008a, 2010). A compilation of these 20-year summary statistics for water levels in the Mississippi River Valley alluvial aquifer are shown in table 18. Although substantial overlap occurs for each approximate 20-year period, in addition to the varying number of wells measured in each county, inspection of the data provides valuable information on effects of pumping over time for each of the counties. Generally, water-level declines for each county increased in each reporting period. For example, Cross County had mean annual declines in water levels about 1 ft or more in all periods. The largest mean annual decline, 1.21 ft/yr, was an average of water levels in eight wells in Lonoke County from 1984 to 2008. A rise in water levels was seen in a single well in Independence County for all study periods as well as in wells in White County for a couple of time periods (table 18).

### Grand Prairie

In the Grand Prairie, withdrawals for rice irrigation had exceeded natural recharge rates as evidenced by considerable water-level declines (Engler and others, 1963). Water levels in the Mississippi River Valley alluvial aquifer began to decline after 1910, although groundwater pumping for irrigation in this region only began around 1905 (Thompson, 1936). From 1910 to 1929, water levels in Grand Prairie wells had a net decline ranging from a minimum of 10 ft to more than 35 ft (Engler and others, 1945). The largest declines averaged 1.5 ft/yr. Thompson (1931) noted the development of a cone of depression that encompassed a majority of Arkansas County, at an estimated 130 ft above National Geodetic Vertical Datum of 1929 (NGVD 29) (hereinafter all altitudes refer to feet above NGVD 29). The largest declines during this period were seen in Arkansas County from southeast of Stuttgart to Almyra and in Lonoke County northeast of Ulm to Lonoke (Engler and others, 1945, 1963).

With increasing irrigation, water-level declines averaged 1 ft/yr resulting in many shallow wells going dry by 1930 (Engler and others, 1963). Water levels in Arkansas County continued to decrease, with the cone of depression enlarging to the northwest into southern Prairie County by 1938 (Counts and Engler, 1945). As shown in the potentiometric surfaces in figs. 17*B* and 17*C*, the surface at the center of the depression in Arkansas dropped 10 ft (to the 120-ft contour) from 1929 to 1938. The largest declines during this period were between Stuttgart and Almyra (Engler and others, 1945) because a smaller cone of depression developed at the 110-ft contour (fig. 17*C*).

Declines continued from 1938 to 1953 with water levels dropping more than 20 ft between Lonoke to Des Arc and south to DeValls Bluff (Counts and Engler, 1954). Water levels at Stuttgart dropped an additional 30 ft during this time, for a total decline of 60 ft since 1910 (Baker, 1955). From 1953 to 1961, the depression expanded in a northwesterly direction, and water-level declines as much as 9 ft were noted in a line from Stuttgart to Lonoke (Plebuch, 1962). Also, the contours in central to northern Prairie County and some areas between Crowleys Ridge and the White River shifted southward (Plebuch, 1962). For example, the 1953 surface shows the 160-ft contour through northern Prairie County (fig. 17*E*); the 160-ft contour is shown in central Prairie County in the 1961 surface (fig. 17*F*).

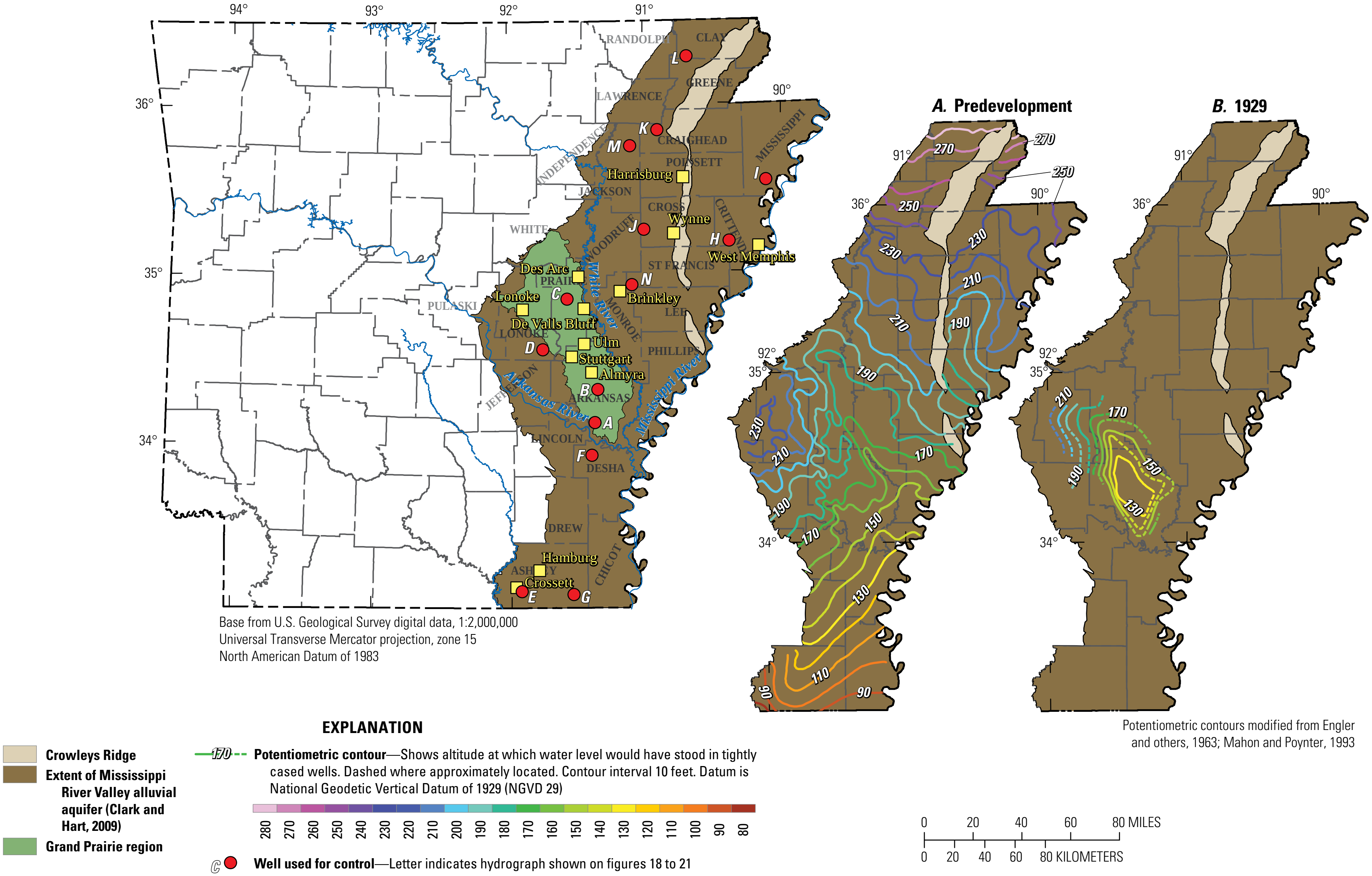



**Figure 17.** Selected potentiometric contours of water levels for selected time periods in the Mississippi River Valley alluvial aquifer in Arkansas. *A*, predevelopment; *B*, 1929; *C*, 1938; *D*, 1944; *E*, 1953 and 1955; *F*, 1961 and 1962; *G*, 1965; *H*, 1972; *I*, 1980; *J*, 1992; *K*, 1998; *L*, 2004; *M*, 2006; and *N*, 2008.

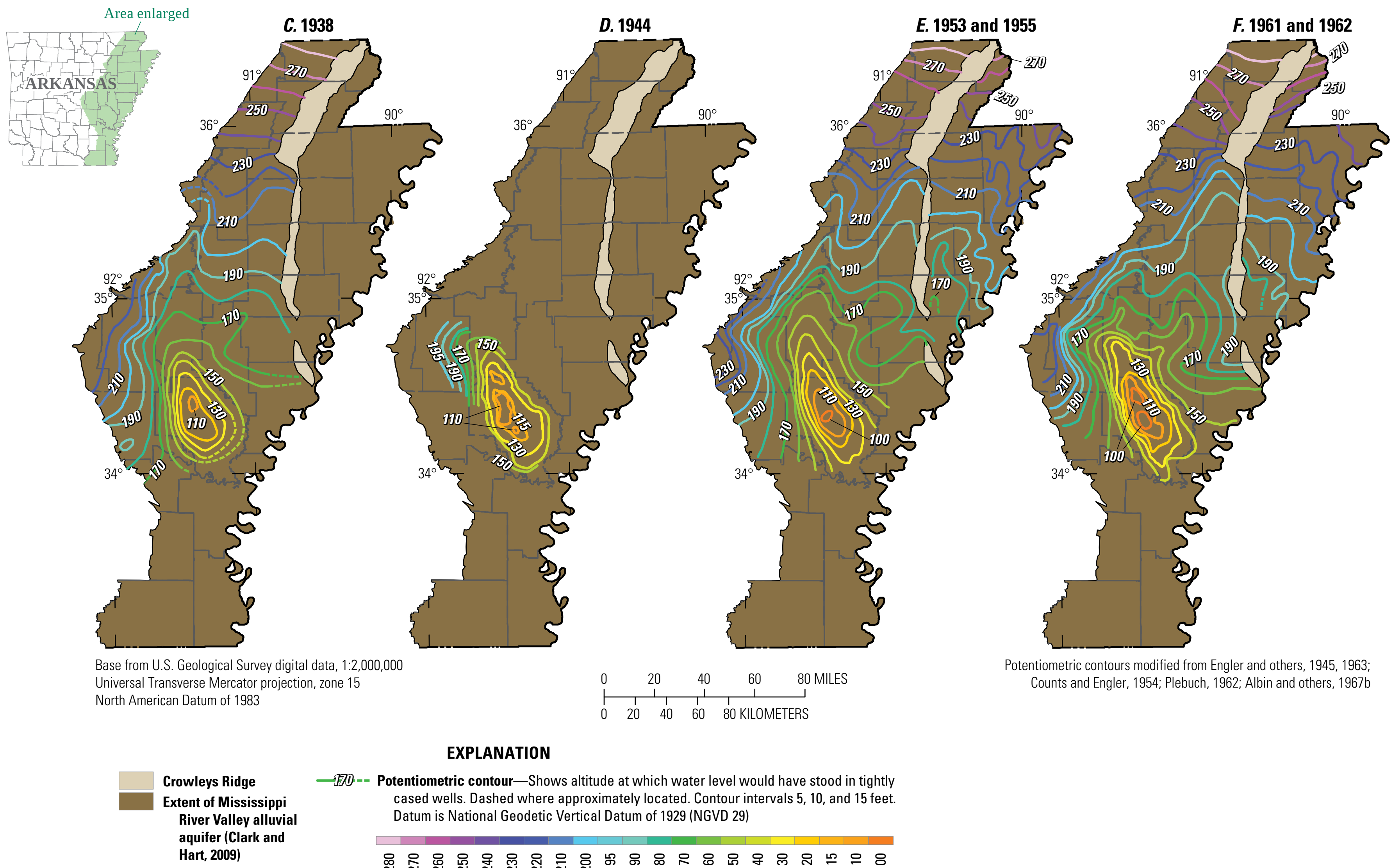



**Figure 17.** Selected potentiometric contours of water levels for selected time periods in the Mississippi River Valley alluvial aquifer in Arkansas. *A*, predevelopment; *B*, 1929; *C*, 1938; *D*, 1944; *E*, 1953 and 1955; *F*, 1961 and 1962; *G*, 1965; *H*, 1972; *I*, 1980; *J*, 1992; *K*, 1998; *L*, 2004; *M*, 2006; and *N*, 2008.—Continued

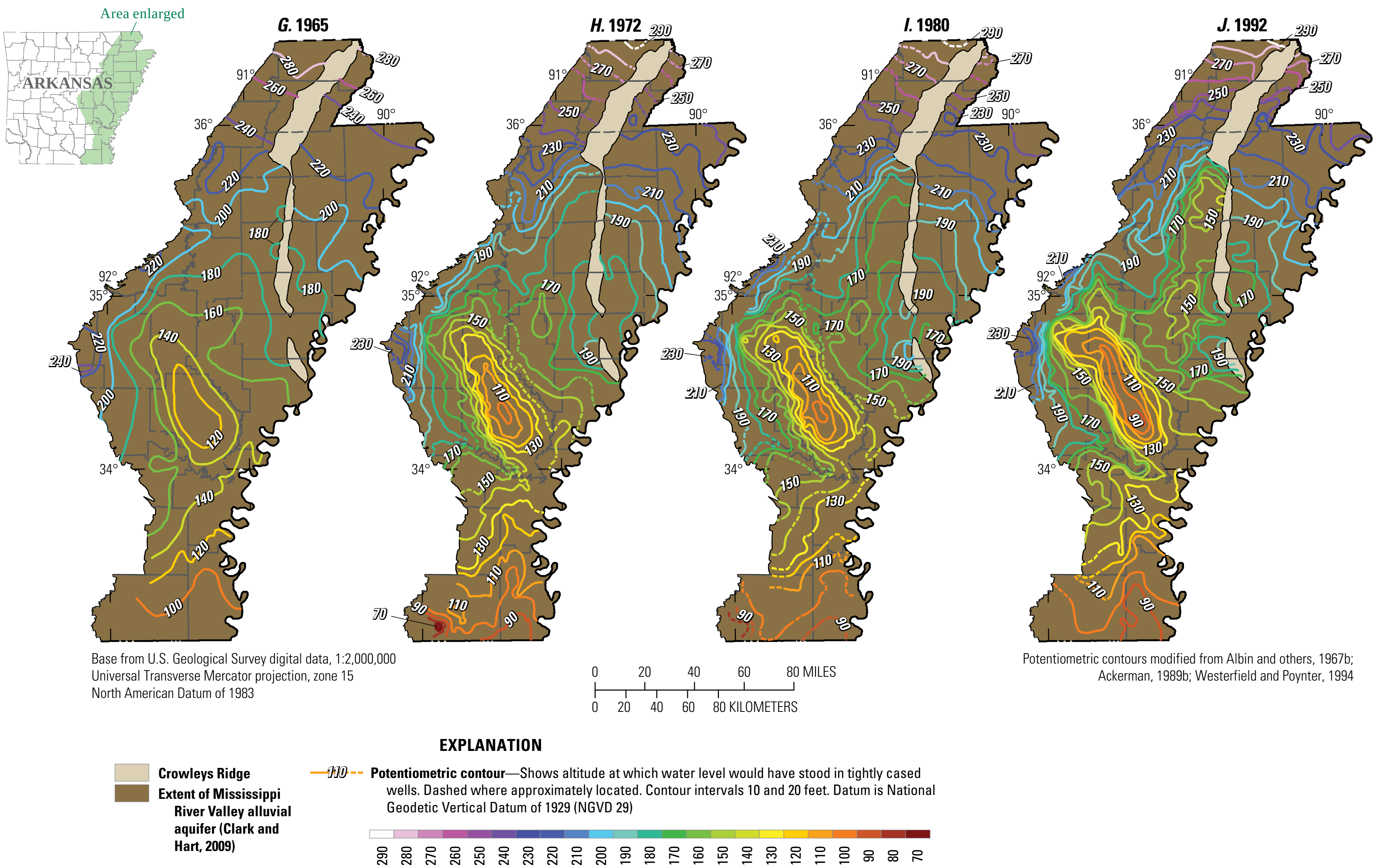



**Figure 17.** Selected potentiometric contours of water levels for selected time periods in the Mississippi River Valley alluvial aquifer in Arkansas. *A*, predevelopment; *B*, 1929; *C*, 1938; *D*, 1944; *E*, 1953 and 1955; *F*, 1961 and 1962; *G*, 1965; *H*, 1972; *I*, 1980; *J*, 1992; *K*, 1998; *L*, 2004; *M*, 2006; and *N*, 2008.—Continued

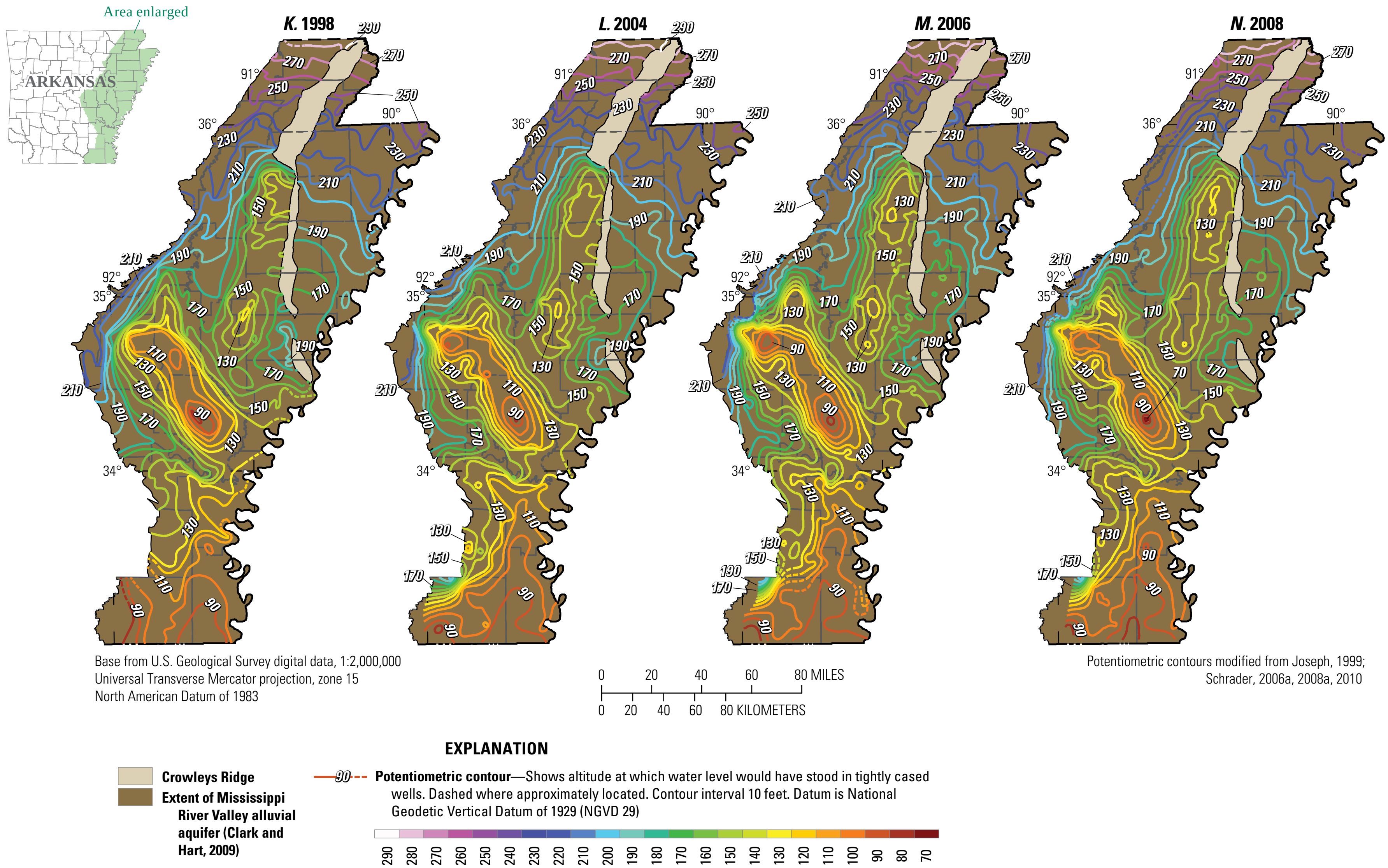



**Figure 17.** Selected potentiometric contours of water levels for selected time periods in the Mississippi River Valley alluvial aquifer in Arkansas. *A*, predevelopment; *B*, 1929; *C*, 1938; *D*, 1944; *E*, 1953 and 1955; *F*, 1961 and 1962; *G*, 1965; *H*, 1972; *I*, 1980; *J*, 1992; *K*, 1998; *L*, 2004; *M*, 2006; and *N*, 2008.—Continued

**Table 18.** Range, mean, and median of annual rise-decline in water level by county for wells in the Mississippi River Valley alluvial aquifer.

[Annual rise or decline in water level for each well is calculated using linear regression; negative value indicates decline; positive value indicates rise; Shaded values indicate that the county had a decline greater than 1 foot/year; >, greater than]

| County | Number of wells 1977–2002[1] | Range of annual rise/decline in water level (feet/year) 1977–2002[1] | Median annual rise/decline in water 1977–2002[1] | Number of wells 1980–2004[2] | Range of annual rise/decline in water level (feet/year) 1980–2004[2] | Mean annual rise/decline in water 1980–2004[2] | Median annual rise/decline in water 1980–2004[2] | Number of wells 1982–2006[3] | Range of annual rise/decline in water level (feet/year) 1982–2006[3] | Mean annual rise/decline in water 1982–2006[3] | Median annual rise/decline in water 1982–2006[3] | Number of wells 1984–2008[4] | Range of annual rise/decline in water level (feet/year) 1984–2008[4] | Mean annual rise/decline in water 1984–2008[4] | Median annual rise/decline in water 1984–2008[4] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Arkansas | 27 | -0.66 to 0.84 | -0.11 | 28 | -0.69 to 0.84 | -0.1 | -0.13 | 27 | -0.80 to 0.77 | -0.12 | -0.15 | 30 | -0.95 to 0.58 | -0.19 | -0.24 |
| Ashley | 6 | -0.33 to 0.02 | -0.18 | 7 | -0.37 to 0.11 | -0.14 | -0.15 | 9 | -0.33 to 0.11 | -0.14 | -0.18 | 10 | -4.86 to 0.11 | -0.69 | -0.29 |
| Chicot | 2 | -0.47 to -0.07 | -0.27 | 2 | -0.47 to -0.11 | -0.29 | -0.29 | 3 | -0.40 to -0.11 | -0.26 | -0.26 | 7 | -1.06 to 0.00 | -0.39 | -0.37 |
| Clay | 6 | -0.51 to 0.18 | -0.16 | 4 | -0.55 to 0.03 | -0.29 | -0.33 | 7 | -0.55 to -0.01 | -0.21 | -0.15 | 7 | -0.99 to 0.00 | -0.37 | -0.37 |
| Craighead | 5 | -1.1 to -0.01 | -0.11 | 4 | -1.05 to -0.02 | -0.48 | -0.42 | 5 | -0.99 to 0.18 | -0.37 | -0.18 | 6 | -0.99 to 0.00 | -0.41 | -0.27 |
| Crittenden | 4 | -0.51 to -0.04 | -0.37 | 4 | -0.55 to -0.11 | -0.37 | -0.42 | 6 | -0.62 to -0.15 | -0.37 | -0.35 | 5 | -0.69 to -0.18 | -0.41 | -0.37 |
| Cross | 5 | -1.13 to -0.29 | -0.99 | 5 | -1.1 to -0.33 | -0.88 | -1.02 | 5 | -1.24 to -0.33 | -0.94 | -1.02 | 7 | -3.18 to -0.26 | -1.15 | -1.06 |
| Desha | 5 | -0.8 to -0.04 | -0.26 | 4 | -0.77 to -0.26 | -0.55 | -0.58 | 5 | -0.80 to -0.07 | -0.5 | -0.62 | 6 | -1.13 to -0.11 | -0.69 | -0.75 |
| Drew | 2 | -0.11 to -0.02 | -0.06 | 1 | -0.151 | -0.151 | -0.151 | 4 | -0.29 to -0.15 | -0.24 | -0.26 | 4 | -0.37 to -0.18 | -0.3 | -0.33 |
| Greene | 4 | -0.8 to -0.01 | -0.6 | 4 | -0.77 to -0.03 | -0.46 | -0.53 | 5 | -0.73 to -0.11 | -0.53 | -0.66 | 4 | -0.80 to -0.15 | -0.48 | -0.49 |
| Independence | 1 | 0.00 | 0.00 | 1 | 0.04 | 0.04 | 0.04 | 1 | 0.07 | 0.07 | 0.07 | 1 | 0.18 | 0.18 | 0.18 |
| Jackson | 4 | -0.88 to -0.25 | -0.66 | 4 | -0.84 to -0.26 | -0.65 | -0.75 | 5 | -0.84 to -0.29 | -0.68 | -0.77 | 5 | -0.91 to -0.37 | -0.72 | -0.77 |
| Jefferson | 6 | -0.69 to -0.07 | -0.22 | 6 | -0.69 to -0.11 | -0.29 | -0.24 | 6 | -0.69 to -0.18 | -0.32 | -0.24 | 7 | -0.69 to 0.00 | -0.31 | -0.26 |
| Lee | 4 | -0.62 to -0.29 | -0.55 | 4 | -0.65 to -0.29 | -0.51 | -0.55 | 5 | -0.58 to -0.26 | -0.49 | -0.55 | 5 | -0.69 to -0.37 | -0.58 | -0.62 |
| Lincoln | 3 | -0.37 to 0.69 | -0.15 | 2 | -0.44 to -0.18 | -0.31 | -0.31 | 3 | -0.84 to -0.33 | -0.57 | -0.55 | 4 | -1.02 to -0.44 | -0.77 | -0.8 |

**Table 18.** Range, mean, and median of annual rise-decline in water level by county for wells in the Mississippi River Valley alluvial aquifer.—Continued

[Annual rise or decline in water level for each well is calculated using linear regression; negative value indicates decline; positive value indicates rise; Shaded values indicate that the county had a decline greater than 1 foot/year; >, greater than]

| County | Number of wells 1977–2002[1] | Range of annual rise/decline in water level (feet/year) 1977–2002[1] | Median annual rise/decline in water 1977–2002[1] | Number of wells 1980–2004[2] | Range of annual rise/decline in water level (feet/year) 1980–2004[2] | Mean annual rise/decline in water 1980–2004[2] | Median annual rise/decline in water 1980–2004[2] | Number of wells 1982–2006[3] | Range of annual rise/decline in water level (feet/year) 1982–2006[3] | Mean annual rise/decline in water 1982–2006[3] | Median annual rise/decline in water 1982–2006[3] | Number of wells 1984–2008[4] | Range of annual rise/decline in water level (feet/year) 1984–2008[4] | Mean annual rise/decline in water 1984–2008[4] | Median annual rise/decline in water 1984–2008[4] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lonoke | 6 | -1.35 to 0.44 | -0.6 | 4 | -1.21 to -0.51 | -0.79 | -0.73 | 5 | -1.06 to -0.51 | -0.8 | -0.88 | 8 | -2.74 to -0.47 | -1.21 | -0.93 |
| Mississippi | 9 | -0.11 to 0.02 | -0.07 | 9 | -0.15 to 0 | -0.06 | -0.07 | 8 | -0.22 to 0.00 | -0.09 | -0.09 | 8 | -0.33 to 0.02 | -0.09 | -0.07 |
| Monroe | 8 | -0.51 to -0.03 | -0.26 | 6 | -0.58 to -0.03 | -0.31 | -0.29 | 8 | -0.55 to -0.01 | -0.28 | -0.27 | 9 | -0.69 to -0.04 | -0.34 | -0.33 |
| Phillips | 3 | -0.26 to -0.07 | -0.11 | 3 | -0.29 to -0.11 | -0.19 | -0.18 | 3 | -0.29 to -0.07 | -0.18 | -0.18 | 3 | -0.33 to -0.04 | -0.22 | -0.29 |
| Poinsett | 5 | -1.42 to -0.03 | -0.33 | 5 | -1.35 to -0.02 | -0.53 | -0.33 | 5 | -1.28 to 0.03 | -0.37 | -0.18 | 5 | -1.28 to 0.11 | -0.38 | -0.18 |
| Prairie | 10 | -0.84 to 0.48 | -0.18 | 9 | -0.73 to 0.29 | -0.29 | -0.29 | 10 | -0.66 to 0.00 | -0.31 | -0.29 | 11 | -0.95 to 0.22 | -0.38 | -0.33 |
| Pulaski | 1 | -0.26 | -0.26 | | | | | 1 | -0.33 | -0.33 | -0.33 | 1 | -0.29 | -0.29 | -0.29 |
| Randolph | 1 | -0.18 | -0.18 | 2 | -0.18 to -0.04 | -0.11 | -0.11 | 1 | -0.26 | -0.26 | -0.26 | 2 | -0.26 to -0.07 | -0.16 | -0.16 |
| St. Francis | 8 | -0.91 to -0.07 | -0.54 | 7 | -0.91 to -0.07 | -0.56 | -0.69 | 7 | -0.95 to -0.04 | -0.56 | -0.62 | 7 | -0.95 to -0.03 | -0.58 | -0.69 |
| White | 3 | -0.33 to 0.22 | -0.22 | 4 | -0.22 to 0.22 | -0.03 | -0.06 | 3 | 0.11 to 0.29 | 0.19 | 0.18 | 6 | -0.37 to 0.26 | 0.11 | 0.18 |
| Woodruff | 5 | -0.51 to >0.00 | -0.07 | 5 | -0.55 to 0 | -0.17 | -0.07 | 5 | -0.58 to 0.00 | -0.19 | -0.11 | 5 | -0.66 to 0.01 | -0.19 | -0.15 |

[1]Data from Reed (2004); mean for 1977–2002 not available.

[2]Data from Schrader (2006a).

[3]Data from Schrader (2008a).

[4]Data from Schrader (2010).

Comparison of the 1961 and 1965 potentiometric-surface contours shows water-level gains in some areas (figs. 17*F* and 17*G*; Plebuch, 1962; Albin and others, 1967b). This was attributed to a reduction in groundwater pumping because of congressional controls on rice acreage that went into effect in 1955 (Chowdhury, 2002; Broom and Lyford, 1981; Broom and Reed, 1973). Consequently, the cone of the depression surrounding the Grand Prairie was not as deep in 1965 (120-ft contour) as in 1960 (100-ft contours) (Albin and others, 1967b). Potentiometric surfaces for areas east of Crowleys Ridge also reflected increases in water levels between 1955 and 1962 (Plebuch, 1962).

Water use increased as rice-acreage controls were removed in 1975 (fig. 14), and water-level declines continued to 2008 (Schrader, 2010). A smaller cone of depression appeared on the border of Monroe and St. Francis Counties in 1972 at the 160-ft contour (fig. 17*H*) and continued to deepen and expand horizontally (Ackerman, 1989b). Two smaller cones of depression appeared on the border of Lonoke and Prairie Counties around 1980 (fig. 17*I*; Ackerman, 1989b); these enlarged and eventually coalesced with the cone of depression in Arkansas County by 1992 (fig. 17*J*). The cone of depression in the Grand Prairie currently (2013) continues to extend to the northwest and decline vertically in Arkansas and Prairie Counties between the Arkansas and White Rivers (T.P. Schrader, U.S. Geological Survey, oral commun., 2013). In the 2008 surface, two distinct cones of depression were seen at the 70-ft contour in central Arkansas County and at the 100-ft contour in eastern Lonoke County (fig. 17*N*).

Well hydrographs (fig. 18) provide another valuable tool for the evaluation of water-level declines in the Grand Prairie area. A well near the Arkansas River (well A; location of well shown in fig. 17) shows little to no effects from large-scale pumping. Wells B, C, and D (figs. 17 and 18) were located inside the depression in Arkansas, Prairie, and Lonoke Counties, respectively, and reflect declines associated with the combined large-scale withdrawals, low recharge, and an expanding cone of depression. The largest declines are noted in well B in Arkansas County near the center of the cone of depression (figs. 17 and 18).

#### Grand Prairie Area Demonstration Project and Bayou Meto Project

Public concern about declining water levels in the Mississippi River Valley alluvial aquifer has been present since the 1920s (Engler and others, 1945, 1964; Sniegocki, 1964; Gates, 2005). A major drought in the early 1980s caused massive crop failures and renewed concerns of declining water levels. As a result, numerous groundwater studies were instigated (Bryant and others, 1985), and water-conservation efforts were introduced to address the declines. ANRC designated the Grand Prairie area as a critical groundwater area for Sparta and Mississippi River Valley alluvial aquifers in 1998 (fig. 1; Arkansas Natural Resources Commission, 1996). This designation included all of Arkansas, Jefferson, and Prairie Counties with parts of Lonoke, Pulaski, and White Counties included in the extent of the Sparta aquifer.

Surface-water diversions currently are planned (2013) for the White and Arkansas Rivers to provide irrigation water and decrease the dependence on both the Mississippi River Valley alluvial and Sparta aquifers in the Grand Prairie region. The Grand Prairie Area Demonstration Project will supply users in Arkansas and Prairie Counties with water from the White River; the Bayou Meto Project will deliver surface water from the Arkansas River to farmland in Lonoke, Prairie, Jefferson, and Arkansas Counties. These projects were initially proposed to the U.S. Army Corps of Engineers in 1930 as result of concern over rapidly falling water levels and were authorized by the Flood Control Act of 1950 (Truman, 1949) but delayed for years because of political and environmental concerns, lawsuits, and other delays (Tacker and others, 2010). Construction of onfarm features (surface-water reservoirs and tail-water recovery systems) was initiated in the fall of 2000, with over $38 million in contracts administered by the NRCS using project funds and non-Federal cost-share funds provided by the farmers. Over 250 onfarm reservoirs have been completed as a part of the project (Arkansas Natural Resources Commission, 2012b). For the Grand Prairie Area Demonstration Project, construction of the DeValls Bluff pumping station on the White River began in 2005, and its completion was expected in late 2013 (Arkansas Natural Resources Commission, 2012b; U.S. Army Corps of Engineers, 2013b). Completion of two of the four pumping stations on the Arkansas River in the Bayou Meto Basin also was expected in late 2013 (Arkansas Natural Resources Commission, 2012b). The Grand Prairie Area Demonstration Project is projected to begin operation in June 2016 (Dennis Carmen, National Resources Conservation Service, oral commun., 2013).

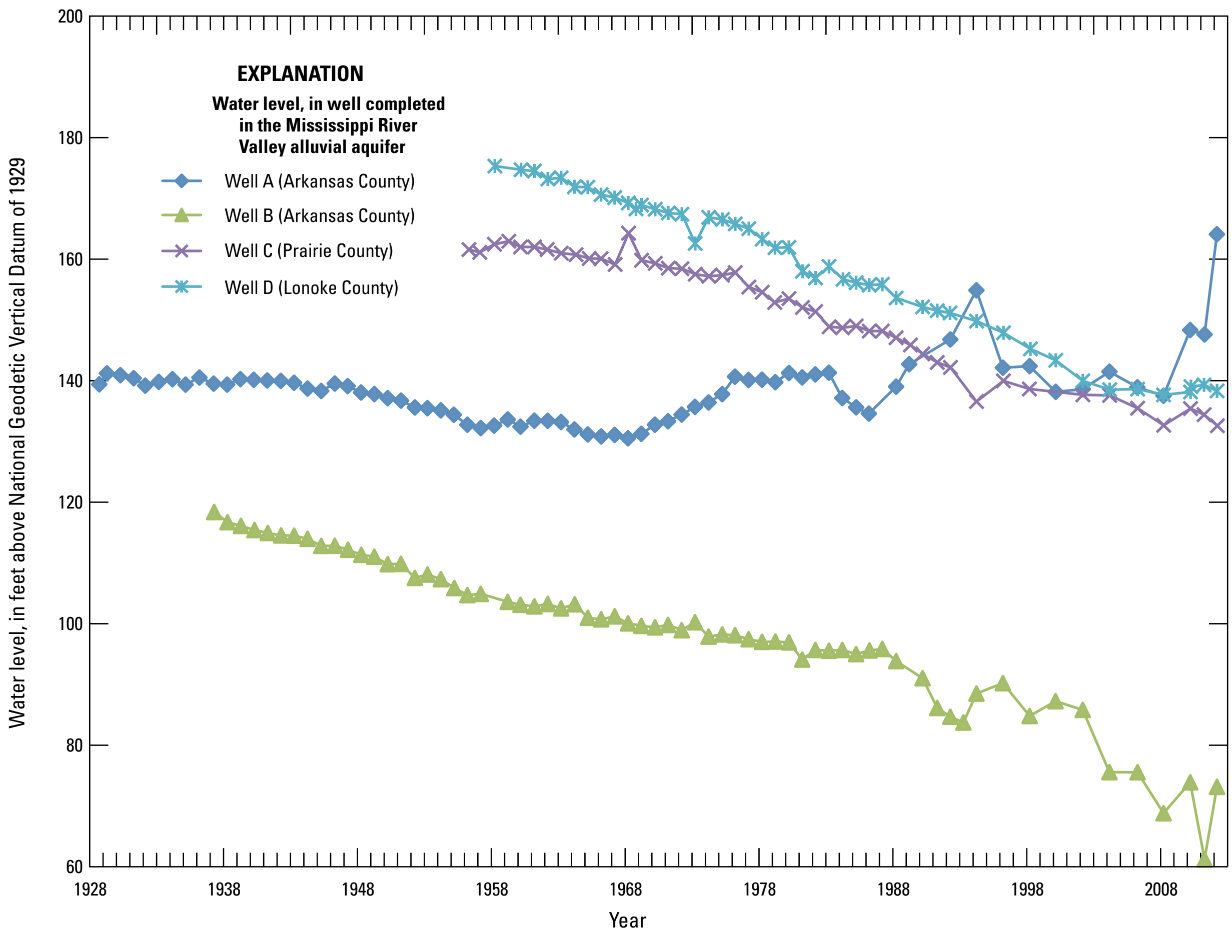



**Figure 18.** Hydrograph of water levels in wells completed in Mississippi River Valley alluvial aquifer in the Grand Prairie region of Arkansas.

### West of Crowleys Ridge

Crowleys Ridge serves as a hydraulic divide for the Mississippi River Valley alluvial aquifer in northeastern Arkansas; water levels can be dramatically different on each side of the ridge. During the 1950s and 1960s, water levels rose in areas east of Crowleys Ridge and declined west of Crowleys Ridge (Albin and others, 1967b; figs. 17*E* and 17*F*). ANRC established the Mississippi River Valley alluvial aquifer west of Crowleys Ridge as a critical groundwater area in 2009 (fig. 1; Arkansas Natural Resources Commission, 2009).

The earliest postdevelopment-potentiometric surface for this area was created using 1938 water levels (fig. 17*C*). The majority of the aquifer west of Crowleys Ridge experienced declines of 10 ft or less from 1938 to 1953, a time when rice acreage tripled (Counts and Engler, 1954; Baker, 1955). Some areas in western Craighead, Poinsett, Greene, and eastern Lawrence and Jackson Counties showed water-level rises over that period attributed to recharge from the Cache River (Counts and Engler, 1954). By the 1950s, water-level declines were observed in wells in areas west of Crowleys Ridge in Craighead, Poinsett, and Cross Counties (Plebuch, 1962). The average decline rate west of Crowleys Ridge was 1 ft/yr; the greatest decline was 16 ft/yr in northwestern Cross County. Further to the west in Randolph and Lawrence Counties, pumpage did not affect water levels during this time period (Lamonds and others, 1969).

Two cones of depression formed at the 180-ft contour adjacent to the western side of Crowleys Ridge in Cross and Poinsett Counties between 1961 and 1965 (fig. 17*F* and 17*G*; Albin and others, 1967b); each had closed potentiometric contours (indicating cones of depression) in 1965 at the 180-ft contour near Harrisburg (Poinsett County) and north of Wynne (Cross County), respectively. These two cones of depression did not appear on the 1972 or 1980 water-level surface maps (figs. 17*H* and 17*I*; Ackerman, 1989b). These depressions reappeared, having expanded and coalesced in the 1983 and later maps (not shown in fig. 17; Edds and Fitzpatrick, 1984; Plafcan and Edds, 1986), and the depression had deepened to the 160-ft contour in 1983 (Edds and Fitzpatrick, 1984).

A cone of depression in the Mississippi River Valley alluvial aquifer appeared near Brinkley (northeastern Monroe County) in 1972 with closure at the 160-ft contour (fig. 17*H*; Ackerman, 1989b). The depression had expanded to the north and east by 1992 (fig. 17*J*; Westerfield and Poynter, 1993) and to the south following the border of Monroe and Lee Counties by 1996 (not shown in fig. 17; Stanton and others, 1998). Between 2000 and 2002 (both years not shown in fig. 17), the 150-ft potentiometric contour in western St. Francis County expanded to central Monroe and western Lee Counties and coalesced with the cone of depression that stretched across Cross, Poinsett, and southern Craighead Counties (Schrader 2001b; Reed, 2004). Closure in the bottom of the original depression had dropped to the 140-ft contour by 2002, and dual cones at the 130-ft contours were observed by 2006 (Reed, 2004; Schrader, 2008a). Only one of these cones was noted in the 2008 potentiometric surface (Schrader, 2010).

By 1994 (not shown in fig. 17), the closed 160-ft contour had expanded to include parts of Craighead, Cross, Lee, Monroe, Poinsett, St. Francis, and Woodruff Counties (Stanton and others, 1998); most of Cross and Poinsett Counties, west of Crowleys Ridge, had water levels at or below the 160-ft contour (Stanton and others, 1998). By 2000, water levels across most of those two counties had declined to the 150-ft contour (Schrader, 2001b). From 1994 to 2004, the seven-county area of Craighead, Cross, Lee, Monroe, Poinsett, St. Francis, and Woodruff experienced water-level declines of at least 10 ft, from the 160-ft contour in 1994 to the 150-ft contour in 2004 (Schrader, 2006a). As of 2008, each of those seven counties had areas with water levels within the 140-ft contour (Schrader, 2010).

In Clay (well L), Craighead (well K), and Jackson (well M) Counties, water levels dropped quickly after the controls on rice acreage were removed with the Rice Control Act of 1975 (fig. 19; location of wells shown in fig. 17). Water levels for wells in Cross (J) and St. Francis (well N) Counties have steadily decreased since measurements first were recorded (fig. 19).

### East of Crowleys Ridge

The earliest potentiometric surface for the area east of Crowleys Ridge was created using 1955 water-level measurements (fig. 17*E*). Water levels in the Mississippi River Valley alluvial aquifer east of Crowleys Ridge reportedly have been influenced by the Mississippi River (Ryling, 1960; Plebuch, 1961; Albin and others, 1967b). After a drought in the 1950s, a rise in water levels east of Crowleys Ridge between 1955 and 1962 was attributed to a decrease in pumpage (Plebuch, 1962); however, the 200-ft contour shifted south of West Memphis (Crittenden County) most likely because of pumping by that city for public supply. Water levels for a well in Crittenden County (well H) have declined steadily since the 1980s, with a total decline of roughly 20 ft (fig. 20; location of wells shown in fig. 17). Water-level declines in a Mississippi County well (well I) are less drastic and started later in the 1990s; water levels have fallen approximately 8 ft and have since rebounded from a minimum in 1998. Water levels in both wells declined after the drought of 1980 (fig. 20) (Neely, 1991).

A cone of depression in the Mississippi River Valley alluvial aquifer potentiometric surface was first documented east of Crowleys Ridge in Greene County in 1972 at the 230-ft closure (fig. 17*H*; Ackerman, 1989b). This depression was seen in the 1980 (fig. 17*I*), 1982, and 1984 surfaces (Edds and Fitzpatrick, 1984; Plafcan and Edds, 1986) and was enclosed by the 220-ft contour in 1992 (Westerfield and Poytner, 1993). The cone expanded horizontally through 2002 (Stanton and others, 1998; Joseph, 1999; Schrader, 2001b; Reed, 2004) and has since contracted in the surfaces constructed for 2004–8 (Schrader, 2006a, 2008a, 2010).

The largest cone of depression east of Crowleys Ridge is in eastern St. Francis County. It was originally enclosed at the 170-ft contour in 1984 (not shown in fig. 17; Plafcan and Edds, 1986). The 1992 surface (fig. 17*J*) showed this depression still at the 170-ft contour and had reached the eastern side of Crowleys Ridge. Around 2004 (fig. 17*L*), the cone expanded southward into Lee County below the southern point of Crowleys Ridge and coalesced with the cone of depression on the western side of Crowleys Ridge. Other depressions east of Crowleys Ridge include eastern Clay County, seen in 2002 (Reed, 2004), and on the eastern border of Craighead and Mississippi Counties, seen in 2006 and 2008 (figs. 17*M* and 17*N*).

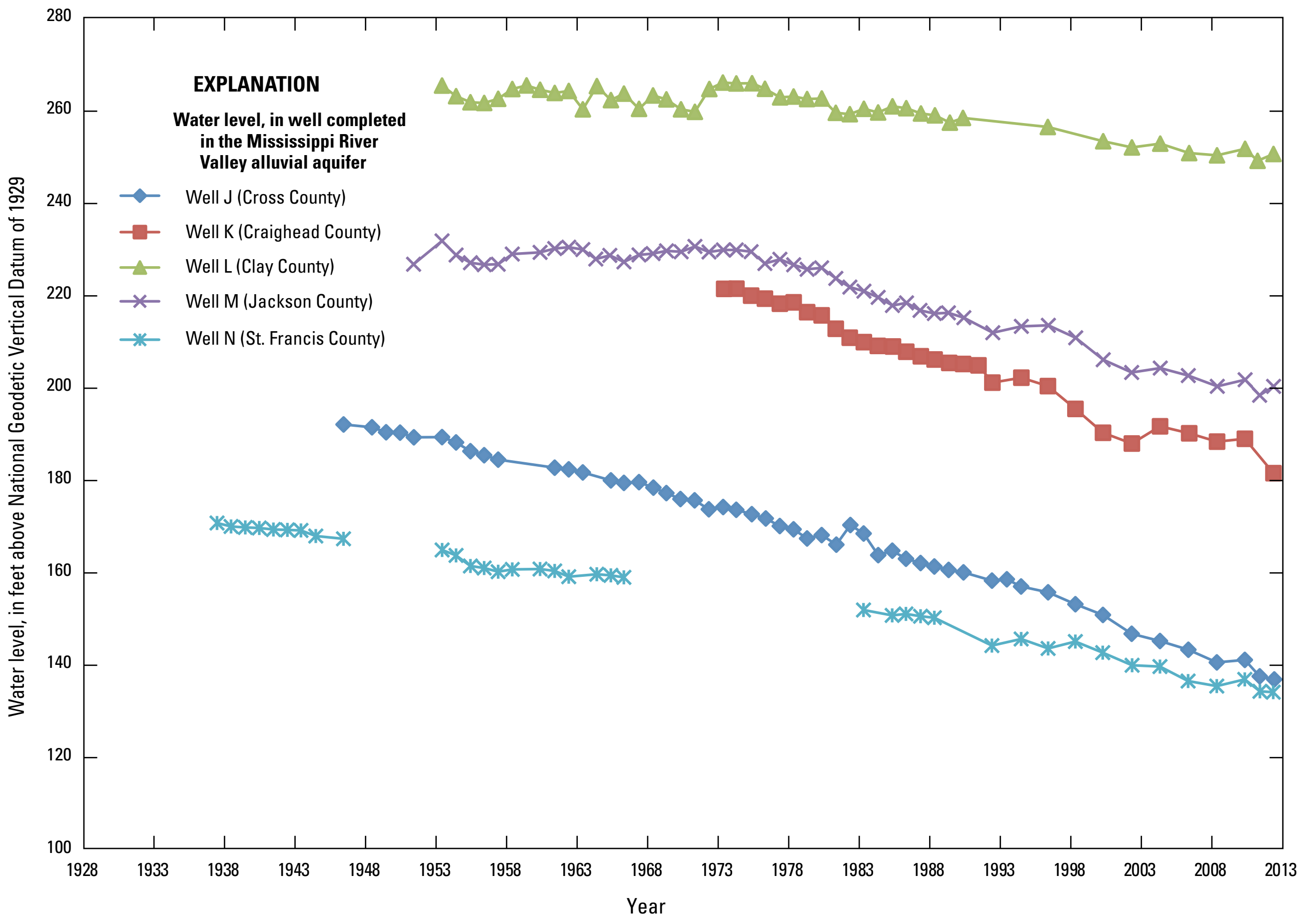



**Figure 19.** Hydrographs of water levels in wells completed in the Mississippi River Valley alluvial aquifer west of Crowleys Ridge in northeastern Arkansas.

## Southeastern Arkansas

Mapping efforts of the potentiometric surface did not include southern Arkansas until 1965. Publications from the 1950s and 1960s reported declines in water levels in these areas because of seasonal agricultural pumpage (Hewitt and others, 1949; Onellion and Criner, 1955; Bedinger and Reed, 1961). In Drew County, the water level in one well had dropped 15 ft from 1939 to 1955 (Onellion, 1956). Even though water-level declines were noted in this area, cones of depression were not documented until mapping of the 1972 potentiometric surface indicated a cone of depression in Ashley County, south of Crossett (fig. 17*H*).

Multiple cones of depressions have developed in southeastern Arkansas in the Mississippi River Valley alluvial aquifer potentiometric surface: eastern Lincoln and northwestern Desha Counties, on the border of Desha and Chicot Counties, central Drew County, and on the border of Ashley and Chicot Counties (fig. 17). Mapping of the 2000 potentiometric surface revealed a depression in northeastern Lincoln County and on the border of Ashley and Chicot Counties (not shown in fig. 17; Schrader, 2001b). Another cone of depression, enclosed at the 130-ft contour, was noted in central Drew County in the 2002 potentiometric-surface map (Reed, 2004). These cones of depression continued to expand as shown on the 2008 potentiometric-surface map (fig. 17*N*).

Depressions in the Mississippi River Valley alluvial aquifer potentiometric surface developed in Ashley County near industrial paper and forestry operations in the vicinity of Crossett (fig. 17). Steady declines were seen from 1925 to 1947, with a total water-level decline of 26 ft (Hewitt and others, 1949). As of 1970, two cones of depression had appeared in Ashley County (Broom and Reed, 1973): one near a paper factory in Crossett and the other near logging and forestry operations northeast of Hamburg. The 1972 map (fig. 17*H*) shows these two depressions with closure at the 70-ft and 110-ft contours. Only the western depression appears again in the 2004 surface (fig. 17*L*), although water-use rates of Ashley County increased over 460 percent from 1965 to 2010 (fig. 12). The effects of the large industrial groundwater withdrawals on water levels may not be represented accurately because of Crossett being located at the edge of the Mississippi River Valley alluvial aquifer’s extent.

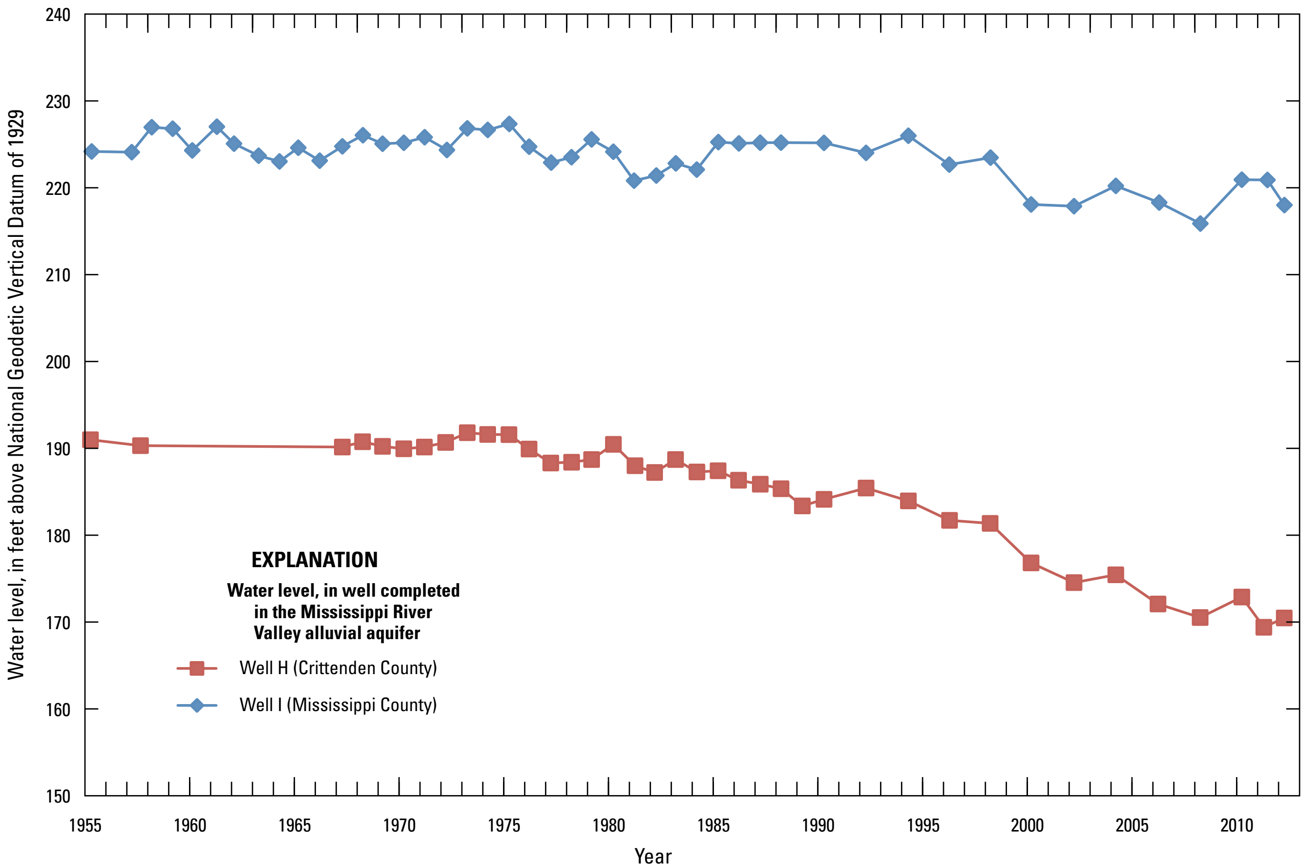



**Figure 20.** Hydrographs of water levels in wells completed in the Mississippi River Valley alluvial aquifer east of Crowleys Ridge in northeastern Arkansas.

Water levels for three wells in southeastern Arkansas are shown in figure 21 (locations of wells shown in fig. 17). Well E in Ashley County declined in the 1960s and rose following the creation of a surface-water source in the early 1970s. Water levels in well G in Ashley County declined after 1975 in response to increased use; water use increased 178 percent from 1975 to 2005 (table 17). Water levels generally stabilized in well G from 2000 through 2010 and declined by approximately 6 ft from 2010 to 2012. Water levels in well F in Desha County steadily declined after 1975 in response to increased use; water use increased approximately 200 percent from 1975 to 2010 (table 17).

## Deductive Analyses, Projections of Aquifer Conditions, and Sustainable Use

Groundwater often is overlooked in the scheme of water management and protection because of the lack of direct observations leading to a limited understanding of groundwater behavior. This combined with the expansive scale and broadly distributed nature of groundwater flow and the fact that groundwater moves very slowly in most systems—often on time scales beyond the practical constraints of direct human observation and experimentation—necessitates development and use of secondary approaches to understanding groundwater that are somewhat different than those applied to surface water. Important questions that groundwater managers and groundwater scientists may pose include: How accurate and representative are our water-use and hydraulic parameter measurements? How much water is stored in a given aquifer? At what rate can water be produced? Where does groundwater flow, and what are the sources and outlets? What is a sustainable long-term yield, or how long will the aquifer produce water if that yield rate is exceeded? How will aquifer yields and groundwater flow paths be affected by natural or human-induced changes? These and other more specific questions can be addressed effectively by digital simulations of groundwater aquifers—groundwater-flow models.

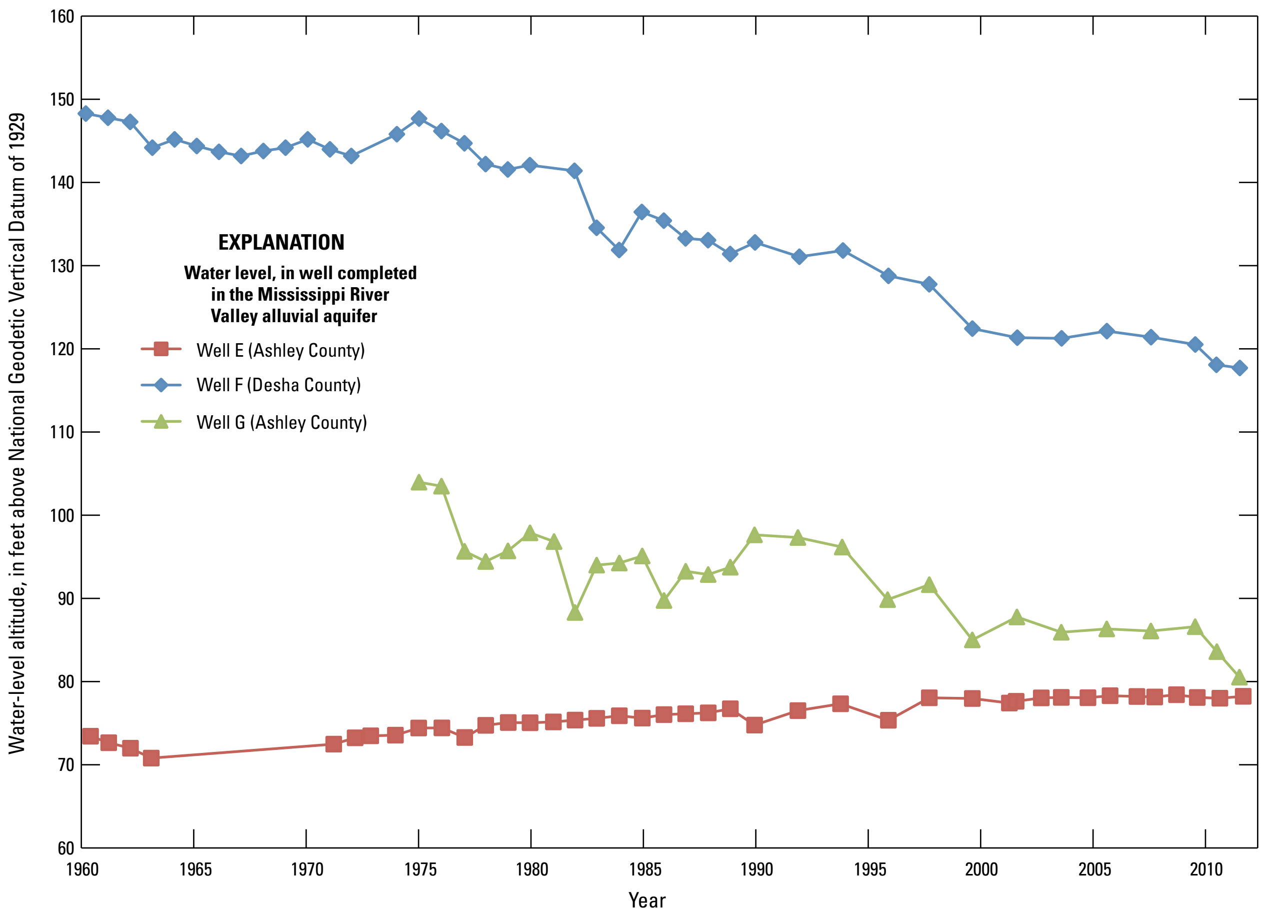



**Figure 21.** Hydrographs of water levels in wells completed in the Mississippi River Valley alluvial aquifer in southeastern Arkansas.

Groundwater-flow models simulate the physical processes using the governing equation for groundwater flow and the ancillary equations describing conditions at system boundaries. The appeal and utility of a groundwater-flow model are derived from the ability of a model to take a large and complex dataset describing hydraulic characteristics, hydraulic stresses, hydrogeologic framework, and boundary conditions and, to the degree possible given certain data constraints, accurately represent a complex natural groundwater system. A major limitation of any model is derived from the absolute necessity to input a large, complex, and accurate dataset to achieve usable results. Because of this, the construction of a groundwater-flow model is time-consuming, labor and data intensive, and expensive; however, the importance of groundwater resources, effective management of those resources, and the utility of groundwater-flow models in understanding and predicting groundwater behavior has made the model a tool of great value, warranting the investments that water managers in Arkansas have made in developing and maintaining groundwater models for water management.

### Results of Groundwater-Flow Simulation Models

Griffis (1972) developed one of the first groundwater-flow models in the State—a digital simulation of the Mississippi River Valley alluvial aquifer in the Grand Prairie (fig. 22). The flow model was used to project future water-level declines under then-current pumping rates, to determine the reduction in withdrawals necessary to abate water-level declines, and to explore the feasibility of artificial-recharge scenarios for the alluvial aquifer. The artificial-recharge scenarios tested by the model included installation of recharge wells and dredging or other modification to improve aquifer connectivity with Bayou Meto. Results of the study determined that a reduction in pumpage of approximately 50 percent was necessary to stabilize water levels at the target 1959 water-level surface. Artificial recharge at Bayou Meto was shown to be ineffective. Recharge wells placed in the model at the center of the cone of depression were found to moderate declines; however, Griffis (1972) noted that economic factors and technical problems involved in operating recharge wells would have to be resolved to make that approach feasible.

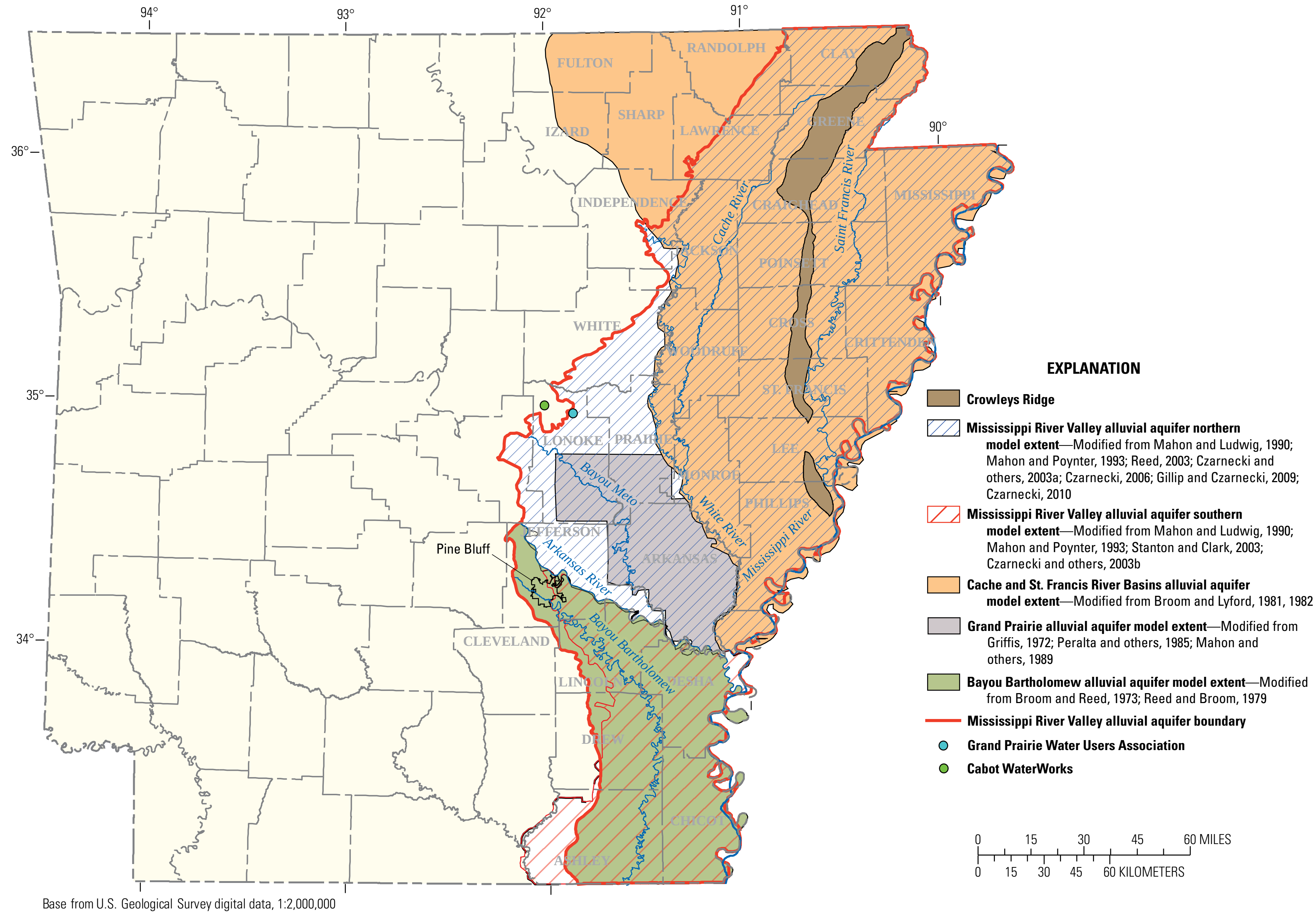



**Figure 22.** Areal extents for all groundwater flow-simulation models conducted in the Mississippi River Valley alluvial aquifer in eastern Arkansas.

Broom and Reed (1973) conducted a study of the Mississippi River Valley alluvial aquifer in the Bayou Bartholomew watershed (fig. 22) to project the hydrologic responses to stresses from ongoing water development. Scenario development stresses included construction of flood-control levees on the Arkansas and Mississippi Rivers; damming; land-use change; drainage-canal construction; and groundwater pumpage for irrigation, fish farming, and manufacturing. The study included development of an electrical analog model of groundwater flow. Reported results of the study included basic hydrogeological characteristics of the system used for model parameterization and assessment of aquifer recharge. Recharge to the aquifer in the modeled area was estimated at 161,000 acre-ft for the year 1970, with analog results indicating some 70 percent of recharge occurring at or near the stream. In a second phase of the Bayou Bartholomew study, Reed and Broom (1979) developed linked, unsaturated-zone groundwater and surface-water models in a calibrated, numerical simulation of the aquifer-river system using a finite-difference equation approach. The model provided projections of water-level changes resulting from changes in rate and distribution of groundwater pumpage and changes in stream and reservoir stage.

Broom and Lyford (1981) developed a digital model of the Mississippi River Valley alluvial aquifer in the Cache and St. Francis River Basins with the goal of estimating the capability of the aquifer to provide water for rice irrigation through the year 2000 (fig. 22). Model results indicated that by 1978 the total groundwater pumpage of 1,460,000 acre-ft/yr comprised water provided from aquifer storage at the rate of 540,000 acre-ft/yr, water captured from streamflow at a rate of approximately 430,000 acre-ft/yr, and water from recharge to the aquifer at a rate of 490,000 acre-ft/yr. The 1978 pumping rate of 1,460,000 acre-ft/yr was determined to exceed the rates needed to sustain minimum water levels throughout Poinsett, Craighead, and Cross Counties west of Crowleys Ridge by 110,000 acre-ft/yr. Even a reduced pumping rate of 1,350,000 acre-ft/yr beginning in 1991 was projected to result in an aquifer saturated thickness west of Crowleys Ridge of less than 50 ft in most of Poinsett and Craighead Counties and a substantial part of Cross County by the end of 2000. By 2000, the rate of water removal from aquifer storage was projected to approach 490,000 acre-ft/yr, and the rate of streamflow capture would be about 860,000 acre-ft/yr.

Peralta and others (1985) developed a groundwater-flow model for the Mississippi River Valley alluvial aquifer in the Grand Prairie of east-central Arkansas with approximately the same model area as that used by Griffis (1972) and incorporated improvements, including use of the MODFLOW modeling package and more comprehensive water-use, aquifer-characteristics, and boundary datasets. Objectives of the Peralta and others (1985) modeling study were to project groundwater levels and aquifer saturated thickness through 1993, determine where rice irrigation would become infeasible, and determine future effects of declining water levels on cost of pumping groundwater. Model results projected groundwater-level declines as much as 28 ft during 1983–93 and areas where well yields were less than 500 gal/min would increase from 54 mi$^2$ to as much as 171 mi$^2$.

Mahon and Ludwig (1990) developed a calibrated groundwater-flow model of the Mississippi River Valley alluvial aquifer covering all or part of 23 counties of eastern Arkansas located north of the Arkansas River (fig. 22) as part of the Eastern Arkansas Region Comprehensive Study (EARCS); a multiagency investigation that began in 1985 with the U.S. Army Corps of Engineers (USACE), the NRCS, the ANRC, the USGS, and the University of Arkansas. The goals of the modeling effort were to evaluate the potential effects of developing hydraulic structures for supplying irrigation water from surface sources for use in areas of potential groundwater deficiency and to aid ANRC in predicting and designating critical areas—areas where projected groundwater withdrawals would result in rates of groundwater-level decline or decreases in aquifer saturated thickness that are designated as requiring focused water management. Pumpage projections input into the model were based on projected water needs according to two scenarios: (1) without conservation measures—continuing 1990 current withdrawals, and (2) with conservation measures that decreased 1990 withdrawals by about 30 percent by the year 2040. Model results indicated that without conservation measures, saturated thickness would decrease to less than 20 ft over an area of 3,800 mi$^2$; whereas with conservations measures and reduced withdrawals, saturated thickness would decrease to less than 20 ft in a 2,300-mi$^2$ area. Three principal areas of concern were determined based on these simulations: the Grand Prairie area and areas to the east and to the west of Crowleys Ridge. The modeling results highlighted the critical nature of water-level declines in the Mississippi River Valley alluvial aquifer and supported ANRC in developing the critical groundwater area designation (See description of critical groundwater area designation in the section on "Groundwater Protection and Management Programs" for more information on this program.).

Water-level declines in the Mississippi River Valley alluvial aquifer through the 1980s called greater attention to an important and threatened resource and showed the need to better understand the flow system. Mahon and Poynter (1993) developed a regional groundwater-flow model using a 1-mi$^2$ cell size that was more finely discretized than any model previously constructed for the aquifer (fig. 22). Because of the size of the area and computing time constraints, two models were developed for the eastern Arkansas study area with the Arkansas River dividing the study area into a north model area and a south model area. Because pumping distribution in time and space is a key element in understanding aquifer behavior and response, and the historical pumping database was recognized as limited and potentially inaccurate, a primary goal of the modeling effort was estimating historical pumping distribution. The north and south models were used to investigate three different spatial and temporal pumpage scenarios to generate an estimated representative pumping distribution. The results of Mahon and Poynter (1993), and the primary objective of the modeling effort, highlight the importance of ongoing water-use monitoring and maintenance of an accurate water-use database in the effective planning, management, and protection of groundwater resources.

An improved understanding of the Mississippi River Valley alluvial aquifer in Arkansas was advanced by modeling conducted as part of the USGS Gulf Coast Regional Aquifer-System Analysis (RASA) model investigations (Williamson and others, 1990), which covered 290,000 $mi^2$ in parts of Alabama, Arkansas, Florida, Illinois, Kentucky, Mississippi, Missouri, Tennessee, Texas, and all of Louisiana (fig. 23). Regionwide model results identified the important factors controlling regional flow prior to development as being topography, outcrop patterns, and geometry of aquifers and confining units; interestingly, geologic structure and variation in rainfall patterns, while locally important, were found to be minor influences at a regional scale. The databases and the modeling framework, as well as programing, served as the basis for more detailed analysis of subregions across the Gulf Coast regional aquifer system; several of the embayment models referenced herein were derived from or benefitted in some fashion from the RASA model. Ackerman (1989a, 1989b, 1990, 1996) added greater detail to the RASA databases and model and developed a three-layer regional model simulating the Mississippi River Valley alluvial aquifer in Arkansas (as well as the aquifer's extents into Louisiana, Mississippi, Tennessee, Missouri, and Kentucky) with the goal of understanding regional flow paths, aquifer fluxes, and effects of development. Ackerman (1989b) described the regional hydrogeology of the Mississippi River Valley alluvial aquifer in greater detail than previous studies and documented the aquifer properties database development, model parameterization, development, and calibration; described simulation of predevelopment groundwater flow system conditions; and described changes in aquifer conditions after onset of development, focusing on the year 1972. Ackerman (1989b) also summarized predevelopment conditions as follows: original unperturbed groundwater levels mirrored topography with flow paths moving from high areas to low areas with rivers acting as major drains and flow lines intersecting river basin axes; recharge was quantified and important sources were determined as originating from rainfall and leakage from underlying aquifers. Changes in the system with onset of groundwater development were as follows: flow lines shifted and moved water to regional pumping centers with pumpage replacing drainage to rivers as the major water sink; recharge from rivers increased with many reaches of major rivers becoming losing streams; recharge from rainfall moving through the clay layer increased; and discharge to underlying aquifers increased as those aquifers were also developed. Average recharge to the aquifer was quantified at approximately 0.8 in/yr.

Carrying the work further, Ackerman (1996) ran scenarios on the model documented in the Ackerman (1989b) report and explored the potential for future development in terms of flow components; stress on the aquifer because of development of large-scale pumpage for agricultural water use; direction, distribution, and quantity of flow; and changes in saturated thickness. These simulations were carried through the year 2022. Simulation results at 1985 pumping rates showed widespread water-level declines to less than 75 ft of saturated thickness across much of the area north of the Arkansas River and west of Crowleys Ridge; part of this area could not sustain the 1985 pumping rate, with saturated thickness decreasing to less than 25 ft. A second scenario, exploring the possibility of expanded groundwater development, incorporated increased pumping rates of 1.2 Mgal/d per a 25-$mi^2$ area above 1985 rates and showed a severe reduction in saturated thickness to less than 50 ft across most of the area between the Arkansas and White Rivers and a large part of the area immediately west of Crowleys Ridge. The areas with greatest potential for development of additional pumpage were outside of Arkansas (northwestern Mississippi and southeastern Missouri); only a small area south of the Arkansas River exhibited potential for increased withdrawals.

Stanton and Clark (2003) updated and recalibrated the Mahon and Poynter (1993) "south model" (fig. 22) using data available through 1998. The goals of the modeling effort were to determine potential effects of three different groundwater withdrawal management strategies and to simulate water-level declines resulting from projected groundwater withdrawals for the period 1998–2049. The scenarios entailed (1) continuation of 1997 pumping rates, (2) extrapolation of the observed trend of increasing water use, and (3) withdrawal reduction in an area where USACE was planning surface-water diversion to reduce demands on groundwater. Model results were evaluated using the ANRC critical groundwater area designation criterion for maintaining a 50-percent saturated formation thickness. Scenario 1 resulted in substantial water-level declines centered in Desha and Ashley Counties with an area of 81 $mi^2$ dropping below 50 percent saturated thickness by 2049; Scenario 2 resulted in 92 $mi^2$ of the aquifer being depleted in the model (as indicated by dry cells) in Desha, Lincoln, and Ashley Counties by 2049; and Scenario 3 resulted in saturated thickness decreasing below 50 percent in an area of 374 $mi^2$, and the aquifer was projected to be depleted across an area of 64 $mi^2$ by 2049. Model results highlighted the unsustainable nature of withdrawal rates in the modeled area and showed the improvements to groundwater conditions that would be brought about by importation of surface water.

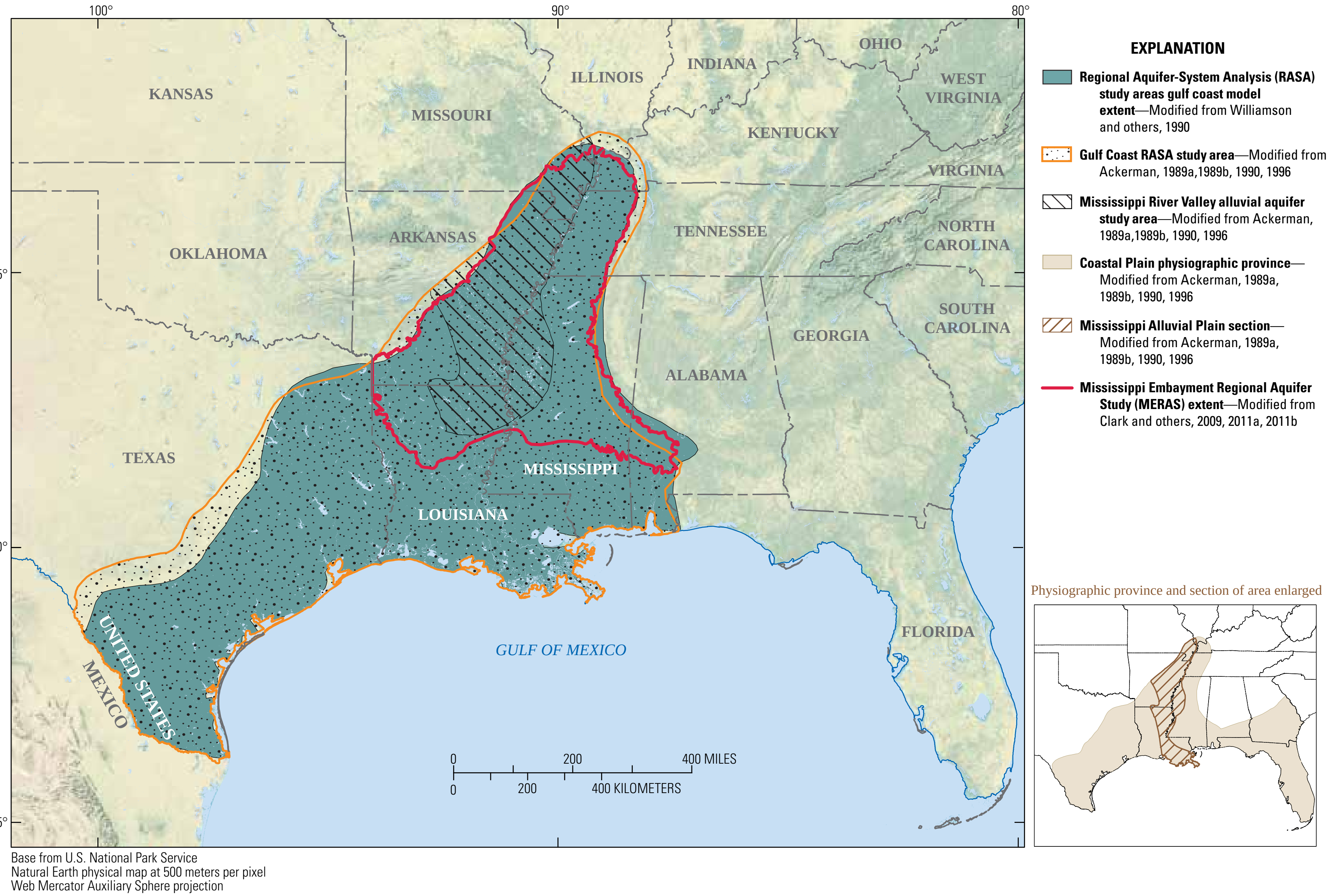



**Figure 23.** Spatial extent of the Mississippi Embayment Regional Aquifer-System Analysis study including the Mississippi River Valley alluvial aquifer study area.

Reed (2003) updated and recalibrated the Mahon and Poynter (1993) "north model" (fig. 22) using data available through 1998. The goal of the modeling effort was to simulate water-level declines resulting from projected groundwater withdrawals through the year 2049. Model simulations explored three different groundwater management scenarios: (1) continuation of 1997 pumping rates, (2) extrapolation of the observed trend of increasing water use, and (3) withdrawal reduction in two areas of the Grand Prairie where the USACE was planning surface-water diversion to reduce demands on groundwater (U.S. Army Corps of Engineers, 2007, 2013b). Scenario 3 used a conservative assumption that the USACE diversion would provide 12 million cubic feet per day (Mft$^3$/d), by 2049; the USACE had stated that the diversion effort possibly could provide as much as 76 Mft$^3$/d (U.S. Army Corps of Engineers, 2013b). Model results were evaluated using the ANRC critical groundwater area designation criterion for maintaining a 50-percent saturated formation thickness. All three model scenarios projected extreme water-level declines—large areas of decreases to less than 50 percent saturated thickness and broad areas of aquifer depletion. The most seriously affected areas were projected to be in the Grand Prairie area between the Arkansas River and White River and west of Crowleys Ridge along the Cache River. Those areas of the aquifer were projected to have depleted areas of approximately 400 mi$^2$ under Scenario 1 by 2049 and depleted areas of 1,300 mi$^2$ under Scenario 2. Two diversion projects proposed by the USACE in the Scenario 3 simulation reduced pumping rates to 90 percent of the observed water-use rates in the Grand Prairie; however, model results indicated that the reduction in withdrawal would do little to decrease the extreme water-level declines and depletion of the aquifer. The depleted area of the aquifer in the area supplied by the surface-water diversion was reduced by approximately 60 mi$^2$ as compared to Scenario 2. Model results indicated that at 1997 withdrawal rates, water was being withdrawn from the aquifer at rates more than could be sustained for the long term.

Czarnecki (2006a) conducted model scenarios using the Reed (2003) revision of the Mahon and Poynter (1993) alluvial aquifer north model (fig. 22) to address the concerns of ANRC and the Grand Prairie Water Users Association (GPWUA) regarding a planned increase in groundwater withdrawals for public supply. The GPWUA proposed an additional well that increased pumpage from the aquifer from 576,000 gal/d to 2,016,000 gal/d. The ANRC's broad water-management responsibilities required understanding and predicting long-term effects of the proposed increase in withdrawals prior to issuing a well permit. Groundwater simulations were conducted to determine flow and water-level changes from 2005 through 2049, with scenarios comparing simulated water levels with and without the proposed increase in withdrawals. Pumping from wells owned by Cabot WaterWorks, located about 2 mi from the proposed GPWUA wells, also was added to the model. The model simulations showed that pumping the additional 2,016,000 gal/d combined with the 2,224,754 gal/d pumping from the Cabot WaterWorks wells would result in the development of a cone of depression. A simulated maximum water-level decline of about 8.5 ft occurred over the 45-year model simulation, with about 3.3 ft of the decline attributed to the proposed well; however, the additional withdrawal was shown not to cause water levels to decline below the 50-percent aquifer saturation criterion.

Continuing the work supporting water-management planning and municipal growth in Lonoke County, Czarnecki (2007) conducted additional model scenarios using the Reed (2003) alluvial aquifer north model to address the concerns of ANRC and Cabot WaterWorks regarding the planned increase in groundwater withdrawals for public supply. The ANRC again needed to better understand and project long-term effects of the proposed increase in withdrawals prior to issuing a well permit. Sixteen groundwater-flow scenarios were conducted to determine flow and water-level changes from 2007 through 2049 for the proposed increase in groundwater withdrawals from a 2004 rate of 2.24 Mgal/d to between 4.8 and 8.0 Mgal/d by 2049. Ten of the 16 scenarios included potential pumping from proposed new GPWUA wells that would be located about 2 mi from the nearest Cabot WaterWorks wells. Eight scenarios addressed reduced pumping rates associated with the Grand Prairie Area Demonstration Project (U.S. Army Corps of Engineers, 2007, 2013b). Projected water-level declines for the baseline pumping rate of 4.8 Mgal/d from the Cabot WaterWorks wells ranged from 15 to 25 ft; increasing pumping rates to 8.0 Mgal/d resulted in water-level declines ranging from about 15 to 40 ft. Model results indicated that water-level declines would continue beyond 2049 with continued pumping. All scenarios with increased pumping rates resulted in aquifer depletion as indicated by the occurrence of dry cells in the model, even for scenarios where the USACE Grand Prairie surface-water diversion decreased regional demand on the Mississippi River Valley alluvial aquifer. Pumping rates of 8.0 Mgal/d resulted in water levels falling below 50 percent of aquifer saturated thickness.

Gillip and Czarnecki (2009) updated the north alluvial model (Reed, 2003) using water-level and water-use data from 1998 through 2005 and conducted two scenarios exploring the sustainability of then-current and potential water-use patterns. The first scenario incorporated reported 2005 water use applied as a constant value through 2049; the second scenario incorporated the 2005 water-use rate with an annual 2-percent increase through 2049. The first scenario showed that the 2005 water-use rate resulted in a 779-mi$^2$ area of aquifer depletion by 2049 as indicated by dry cells in the model. Water-use increases of 2 percent annually (more than doubling groundwater withdrawal in the aquifer by 2049) resulted in a 2,910 mi$^2$ area of depletion as indicated by dry cells. Most areas of aquifer depletion were in the Grand Prairie and Cache River areas. The second scenario also resulted in dry cells east of Crowleys Ridge. The model results highlighted the unsustainable nature of groundwater withdrawals in the Grand Prairie, Cache, and Crowleys Ridge areas.

Long-term monitoring of aquifer conditions by ANRC showed decreases in saturated thickness and rates of water-level declines in an area west of Crowleys Ridge that included western parts of Clay, Greene, Craighead, Poinsett, Cross, St. Francis, and Lee Counties, indicating that the future viability of groundwater in that area was threatened. The need for focused management and protection of groundwater led to designation of the Cache critical groundwater area for the Mississippi River Valley alluvial and Sparta aquifers in 2009. To assist ANRC in understanding aquifer conditions and behavior and to support improved management of groundwater, Czarnecki (2010) applied particle-tracking, groundwater-flow vectors, and zone-budget analyses using the updated Mississippi River Valley alluvial aquifer model of Gillip and Czarnecki (2009), focusing on the Cache critical groundwater area (figs. 1 and 22). Three scenarios applying differing pumping conditions were simulated to determine the effect of pumping in Jackson and Woodruff Counties on groundwater levels west of Crowleys Ridge. Scenario 1 was a baseline scenario in which the 2005 pumping rate was applied through 2050 without change; pumping rates prior to 2005 were varied according to reported or previously modeled water use. Scenario 2 applied a zero pumping rate in Jackson and Woodruff Counties from 1998 to 2050—a reduction of pumping within the model of about 10 percent; the objective was not to test a feasible pumping management strategy but to determine the broader effect of pumping concentrated in those two counties on the surrounding areas. Scenario 3 applied a pumping rate of 50 percent of the reported 2005 pumping rate in Jackson and Woodruff Counties from 1998 to 2050. Comparison of model scenario results showed that the reduction in pumping applied in Scenario 2 resulted in nearly a 30-percent reduction in aquifer depletion, as indicated by dry model cells, compared to the Scenario 1 baseline. Zone-budget analyses showed that reduction of pumping in Scenarios 2 and 3 resulted in more groundwater flow into the Cache critical groundwater area and more flow to rivers. Water-level difference maps based on model results showed that decreasing pumping rates in Scenario 1 improved water levels by 60–80 ft, mostly in Jackson and Woodruff Counties but also over parts of western Cross and Poinsett Counties. Water-level difference maps for Scenario 3 showed water-level increases of 20–40 ft in Jackson and Woodruff Counties as compared to Scenario 1. Model results highlighted the wide-scale importance of managing pumping in the intensive pumping centers in Jackson and Woodruff Counties.

### Optimization and Sustainable Yield

Optimization modeling is an extension of numerical simulation of groundwater flow incorporating (1) specific water-management objectives; for example, providing specific minimum water supply for prioritized users (generally referred to in modeling terminology as the objective function), (2) managed withdrawal rates at wells and river locations (referred to as decision variables), and (3) maintenance of specific aquifer (or surface-water) conditions; for example, maintaining defined water levels or percent saturation for groundwater or minimum streamflows (referred to as constraints)—surface-water flow also may be integrated to achieve conjunctive-use analysis. Such modeling can support optimized use of water resources and maintain key indexes of aquifer and surface-water conditions. These extended modeling approaches also can be used to determine long-term, sustainable groundwater yields as defined by water managers and water policy. Groundwater modeling that focuses on optimization of use, conjunctive use, and maintenance of constraints necessary for sustainable or safe yield use of groundwater has been an important tool for Arkansas water users, water managers, and water-policy planners in achieving effective, fair, and equitable use of this limited resource.

Arkansas' water-resources policy and programs have moved forward with the goal of conjunctive use of the State's groundwater and surface-water resources at optimized levels that are sustainable. This sustained-yield conjunctive-use strategy has been supported by using groundwater models developed largely through the ANRC/USGS cooperative program. ANRC and other State water planners have advocated sustainable yield groundwater protection as a means of achieving specific goals such as preventing groundwater-level declines, assuring long-term viability of aquifers to provide certain yields, preventing litigation, providing groundwater supplies for drought, preventing groundwater-quality degradation, protecting riparian rights, and providing courts with an objective means for determining reasonable and unreasonable use. Arkansas' water policy has tended to follow a deferred perennial yield strategy, which accepts that current groundwater levels or levels defined by the critical groundwater area designation are reasonable or, at least, acceptable. The alternative view of requiring the complete recovery of Arkansas' aquifers to predevelopment levels is viewed as being difficult to achieve under increasing water requirements for irrigation use. For the Mississippi River Valley alluvial aquifer, water users and planners noted early in the history of development that rates of usage were not sustainable; for example, Klein and others (1950) stated that in "… the Grand Prairie region as a whole, the present pumpage is roughly twice the rate of recharge." Once the unsustainable nature of withdrawals from the Mississippi River Valley alluvial aquifer was recognized in the Grand Prairie in the 1920s, hydrologists, geologists, and engineers began to estimate the sustainable yield (often referred to as safe yield) of the aquifer. One of the earliest estimates of safe yield is from a USGS press release by Thompson (1931) in which he estimated the sustainable yield for the Grand Prairie from the Mississippi River Valley alluvial aquifer at less than 177,000 acre-ft/yr, with unmet demand at that time of 340,000 acre-ft/yr or more. Engler (1958) documented withdrawals from the aquifer of approximately 200,000 acre-ft/yr and commented that volume exceeded sustainable levels by about 50,000 acre-ft/yr.

Mahon and others (1989) and Peralta and others (1992, 1995) developed groundwater optimization models based upon the calibrated Mississippi River Valley alluvial-aquifer groundwater-flow model of Mahon and Ludwig (1990) with the goal of determining optimal sustained groundwater yield and conjunctive water-use strategies for east-central to northeastern Arkansas, based on a 50-year projected water demand from 1990 to 2039. Simulations were designed to maximize total annual allocation of surface-water resources and sustainable groundwater yield for a 13,000-$mi^2$ area of the Mississippi River Valley alluvial aquifer (fig. 22), using a sequential steady-state modeling approach incorporating increased potential water demand. Five model scenarios were simulated: (1) two incorporating pumpage based on meeting growing public and irrigation water use, (2) two incorporating decreased pumpage based on the potential of implementing conservation measures, and (3) one based on a steady rate of groundwater pumping in all cells through time. The model results indicated that the groundwater pumping strategies employed were sustainable; however, total water demand in the area could not be met in any of the model scenarios. The authors concluded that "Possibly the most appropriate future scenario is the one in which public and industrial demand is always satisfied, and farmers must utilize improved water conservation measures. Implementation of this scenario satisfies Arkansas' priority of use hierarchy" (Peralta and others, 1995).

Czarnecki and others (2003a, b) conducted conjunctive-use optimization of the Mississippi River Valley alluvial aquifer of northeastern (Czarnecki and others, 2003a) and southeastern (Czarnecki and others, 2003b) Arkansas (fig. 22) using the groundwater models of Reed (2003) and Stanton and Clark (2003) as platforms to estimate sustainable yield from the alluvial aquifer and from surface water. The goals of these optimization modeling studies were to: (1) estimate maximum groundwater withdrawal rates for 1997, (2) estimate maximum potential withdrawal rates from stream locations, (3) maintain groundwater levels at or above specified levels, and (4) maintain streamflow at or above specified rates. For the optimization model, groundwater levels were constrained above 50 percent of aquifer thickness or 30 ft above the bottom of the aquifer, whichever resulted in the higher groundwater level. Streamflows for most streams incorporated in the model were not allowed to drop below minimum flows specified by ANRC; these streamflow constraints generally were specified at river cells based on average 7-day low flows with 10-year recurrence intervals. Because groundwater sustainable yield is dependent upon the pumping limit specified for each managed well in the model, multiples of 100 percent, 150 percent, and 200 percent of individual well 1997 pumping rates were used to set the upper pumping limit, and optimization estimates were determined for each of those pumping limits.

Setting an upper limit on individual well pumping rates was important because wells located proximal to recharge sources such as rivers are effective in intercepting flow, so as the withdrawal rate limit for individual wells is increased, wells located a distance from recharge sources receive less groundwater and are removed as pumping wells, and the total number of wells decreases (although the total amount withdrawn increases). The optimization model showed that if no limits were placed on groundwater withdrawals, all of the withdrawals would come from wells adjacent to sources of water within the model (Czarnecki and others, 2003a). Although overall optimized withdrawal would be largest for such a scenario, the distribution of wells would be unacceptable from a management and farmowner standpoint because nearly all of the water production would come from wells that are proximal to rivers. Optimization results (Czarnecki and others, 2003a) indicated that the sustainable yield from groundwater for the study area, with 1997 withdrawals rates set as an index and upper limit, was 360 $Mft^3/d$, approximately 57 percent of the 1997 withdrawal rate. For the Bayou Meto irrigation project and the Grand Prairie irrigation project areas (U.S. Army Corps of Engineers, 2007, 2013b) within the larger alluvial north model, the sustainable yields determined by optimization were 18.1 $Mft^3/d$ (35 percent of 1997 withdrawals) for the Bayou Meto area and 9.1 $Mft^3/d$ (30 percent of 1997 withdrawals) for the Grand Prairie area. Groundwater sustainable yield for the entire north model area increased to 445 $Mft^3/d$—70 percent of the amount withdrawn in 1997—if the upper withdrawal limit was increased to 150 percent of the 1997 rate. Groundwater sustainable yield increased to 526 $Mft^3$ /d—83 percent of the amount withdrawn in 1997—if the upper withdrawal limit was increased to 200 percent of the 1997 rate. Using a specified upper withdrawal limit of 100 percent of the 1997 withdrawal rate for individual wells, Czarnecki and others (2003b) estimated a groundwater sustainable yield for the entire alluvial south model study area of 70.3 $Mft^3/d$—a value representing 96 percent of the amount withdrawn in 1997 (73.5 $Mft^3/d$). Groundwater sustainable yield increased to 80.6 $Mft^3/d$—110 percent of the amount withdrawn in 1997—if the upper withdrawal limit was increased to 150 percent of the 1997 rate. Groundwater sustainable yield increased to 110.2 $Mft^3/d$—150 percent of the amount withdrawn in 1997—if the upper withdrawal limit was increased to 200 percent of the 1997 rate. These optimization studies pointed out that the then-current (2003) demand on the alluvial aquifer was unsustainable in the alluvial north model area, but that some potential addition capacity existed in the alluvial south model area.

Czarnecki (2006b) used the optimization model of Czarnecki and others (2003b) to analyze potential management effects on the alluvial aquifer of surface-water diversions for irrigation proposed for Bayou Meto and the White River by USACE (U.S. Army Corps of Engineers, 2007, 2013b) and for a potential industrial water-supply well in the alluvial aquifer for a paper mill in Pine Bluff (Jefferson County). The study explored the effects on sustainable yield of four water-management alternatives, represented in the model by applying different sets of constraints on groundwater levels and surface-water withdrawals that were being considered by ANRC. Scenario 1 was a baseline scenario in which surface-water withdrawal was allowed from all 11 rivers—including the Arkansas and White Rivers—for the Bayou Meto and Grand Prairie irrigation project areas (U.S. Army Corps of Engineers, 2007), while maintaining groundwater levels above the 50-percent saturated thickness of the aquifer. Scenario 2 evaluated the effect of lowering the water-level constraint to a minimum 30 ft aquifer saturated thickness. Scenario 3 evaluated the effect of the USACE Bayou Meto or Grand Prairie irrigation projects (U.S. Army Corps of Engineers, 2007, 2013b) if water from the White River or Bayou Meto was not used to augment the alluvial aquifer that is used for irrigation; however, withdrawals from other rivers were allowed. Scenario 4 evaluated the combination of conditions for Scenarios 2 and 3. Additional simulations explored the effects of the potential industrial supply well near Pine Bluff. Optimization modeling for the baseline scenario, Scenario 1, as compared to the differing management alternatives represented by Scenarios 2, 3, and 4, showed increases in estimated sustainable yield of groundwater of approximately 7 percent, 7 percent, and 13 percent, respectively. The proposed industrial supply well in Pine Bluff was simulated as pumping 30 Mgal/d for a period of 50 years. Model results showed development of a cone of depression and a maximum water-level decline of about 40 ft; however, this degree of decline held water levels well above a 50-percent saturated thickness for that location. A pumping rate of 38.9 Mgal/d resulted in model cells going dry, indicating aquifer depletion.

Czarnecki (2008) used the optimization model of Czarnecki and others (2003a) coupled with the alluvial aquifer north model to analyze potential management effects of three different water-management alternatives on the sustainable yield from the Mississippi River Valley alluvial aquifer. The model scenarios to test the management alternatives were (1) changing the upper limits of groundwater pumping to maintain a degree of sustainable pumping at all model cells representing wells that reported pumping during 1997, (2) assessing the effects on the alluvial aquifer associated with establishing minimum flow rates accommodating average spring floods and habitat requirements for select aquatic species, and (3) assessing the effects on the alluvial aquifer that would occur if the Melinda Head Cut Structure, a flood-control structure designed to prevent the White River from altering course to flow into the Arkansas River, failed and river stage was altered on the lower White River. Scenario 1 results indicated that as the upper limit of groundwater withdrawal was reduced first to 75, then 50, and finally 25 percent of the 1997 groundwater withdrawal rates, a spatial expansion of sustainable pumping sites was observed. Sustainable groundwater yield for the model area increased by 13,864,017 $ft^3/d$ over the baseline scenario for a groundwater withdrawal rate set at 75 percent of the 1997 withdrawal rate. For Scenario 2, a streamflow rate of 5,097,600,000 $ft^3/d$ was reported to be necessary for protection of paddlefish spawning. Scenario 3 results showed that decreasing White River stage at the Melinda Head Cut Structure caused declines in the sustainable yield of groundwater in the region. Model simulations of 20-, 30-, and 40-ft groundwater-level declines decreased sustainable yield by approximately 7,000,000 $ft^3/d$, 11,000,000 $ft^3/d$, and 14,000,000 $ft^3/d$, respectively. The study emphasized the finding that the weighting of various management constraints changed resultant estimations of sustainable yield and no single and unique value of sustainable yield from groundwater or surface water existed as those constraints were varied.

### Mississippi Embayment Regional Aquifer Study

The USGS in cooperation with other Federal, State, local governments, and the private sector studied regional groundwater-flow systems across the conterminous United States as part of a national assessment of groundwater availability conducted from 2004 to 2012, which continued as the WaterSmart Program (Reilly and others, 2008). The Mississippi Embayment Regional Aquifer Study (MERAS) component of the larger assessment covered the extent of the Mississippi embayment including eastern Arkansas (fig. 23). A numerical groundwater-flow model was developed to explore the effects of human activities and climate variability on groundwater levels, changes in aquifer storage, and flow between groundwater and surface-water bodies.

The MERAS model was constructed of 13 hydrogeologic layers over 78,000 $mi^2$ representing multiple aquifers, including the Mississippi River Valley alluvial aquifer and the Sparta aquifer. MERAS simulations showed that groundwater-level declines of more than 100 ft occurred across 216 $mi^2$ in the Mississippi River Valley alluvial aquifer from 1870 to 2007 with the greatest expanse of groundwater-level decline occurring in Arkansas. Declines of more than 100 ft in the Mississippi River Valley alluvial aquifer are substantial because the total thickness of the aquifer rarely exceeds 200 ft. Cumulative groundwater withdrawals from 1870 to 2007 from the Mississippi River Valley alluvial aquifer exceeded 280 million acre-ft. Cumulative change in storage within all the aquifers simulated in the MERAS model showed a drastic misbalance between withdrawal and recharge to the aquifers, with model results indicating a net depletion of 140 million acre-ft. The amount of water removed from storage over the history of pumping is about 26 percent of the total amount stored in the Mississippi River Valley alluvial aquifer. This overdraft of water volume being removed from the aquifer system, greatly outweighing what is recharging the aquifers, has important consequences for sustainability and long-term use and management of the aquifers. The importance of the MERAS model lies not only in the published results of Clark and Hart (2009) and Clark and others (2011b) but from the future utility of the existing model as an evolving tool that can be updated to address the new and continuing questions and issues arising from changing human activities, changing natural conditions, and changing water-policy environment that challenge water managers and water stakeholders. The tools and databases integral to the MERAS model include a database of over 2,600 geophysical logs used in the construction of the hydrogeologic framework (Hart and Clark, 2008).

The MERAS model represents the current state-of-the-art in modeling tools for aquifers of eastern Arkansas. Since the initial development of the MERAS model, two revisions were implemented in 2013 (Clark and others, 2013) to continually improve upon the ability to accurately simulate groundwater flow. The MERAS model has been utilized in three States to provide scenarios of future conditions or proposed conservation measures and continues to provide information through adaptive scenario analyses with regard to projected groundwater demand.

Three scenarios have been recently completed that evaluate potential future conditions in eastern Arkansas: (1) simulation of previously optimized pumping values in the Mississippi River Valley alluvial and the Sparta aquifers, (2) simulation of long-term effects of pumping at average recent rates, and (3) simulation of constraints on drawdown for most pumping wells (Clark and others, 2013). The results of scenario 1 indicated large drawdowns throughout the area of the alluvial aquifer, regardless of the substitution of the optimized pumping values from earlier model simulations. The results of scenario 2 also indicated large areas of water-level decline, to below half the saturated thickness, throughout the aquifer. The results of scenario 3 reveal some effects from the inclusion of multiple aquifers in a single simulation. The initial configuration resulted in water levels well below the defined drawdown constraint and some areas of aquifer depletion in east-central Arkansas. An additional, derivative simulation of scenario 3 was configured to apply the same drawdown constraints from the Mississippi River Valley alluvial aquifer wells to the Sparta aquifer wells in the depleted area. This configuration did not produce depleted areas within the Mississippi River Valley alluvial aquifer and resulted in some similar patterns of limited pumping from the original scenario 3 optimization results (fig. 24).

These simulations offer vitally important management information by indicating that even with limited pumping in the Mississippi River Valley alluvial aquifer, water levels may continue to decline in some areas as a result of pumping in the underlying Sparta aquifer, highlighting the connectivity of these important aquifers. These simulations indicate the need to further evaluate the groundwater resource as a single, fully integrated and connected system because pumping from one aquifer may affect water levels in another. Additionally, some scenarios pointed to new areas of groundwater-level decline that are not currently considered problematic. While simulations can provide information only with respect to the inputs and generalized assumptions, the results indicate and highlight areas of future concern that have only recently begun to show declines in water level.

Most large-scale groundwater-flow models discussed herein were used in rearward looking or deductive testing and determination of basic model parameter inputs—hydraulic conductivity, storage, recharge, stream interaction, boundary effects, and water use. This effort in estimating and verifying these basic data is a strong indication that although Arkansas maintains some of the most advanced and comprehensive groundwater monitoring and water-use monitoring programs in the Nation, these data sometimes are insufficient at needed scales to effectively satisfy water management, planning, and protection needs. This highlights the importance of widescale and long-term groundwater monitoring. For some of the modeling projects, such deductive testing was an important objective, whereas in the remaining models, deductive testing was a necessary phase before conducting projections of aquifer conditions. Deductive analyses are an important component of modeling, particularly for estimating conditions in the model for time periods when monitoring was sparse and input datasets based on monitoring data were sparse or nonexistent, enabling minimizing of model error for projections. Projections using groundwater-flow and optimization models are state-of-the-art for forecasting future conditions in aquifer systems and providing robust, quantitative, and statistically defensible results for guiding protection and management of valuable groundwater resources. Model results for the analyses that have been conducted in Arkansas are consistent in one important facet—quantifying the difference between desired increased water use to support a growing and vibrant population and economy and the actuality of the finite resource available in any aquifer. These results call attention to the critical importance of effective and equitable management and apportionment of this shared resource.

## Water Quality

The quality of groundwater from the Mississippi River Valley alluvial aquifer is generally good compared to the EPA primary drinking-water standards (U.S. Environmental Protection Agency, 2009). Certain common water-quality characteristics of the aquifer limit its use for domestic, industrial, and public supply purposes and have resulted in irrigation as the dominant use of the aquifer. Concentrations of hardness, iron, and manganese frequently exceed secondary drinking-water regulations that address problems of staining, scale formation, and objectionable taste. Localized areas contain elevated concentrations of chloride that can adversely affect crops including soybeans and rice. Concentrations of arsenic in deeper parts (lower unit) of the Mississippi River Valley alluvial aquifer exceed the EPA primary drinking-water standards; however, domestic wells are completed in the arsenic-free shallower part (upper unit) of the aquifer. Because irrigation is the main use of the aquifer, the occurrence of arsenic does not present obstacles to use of groundwater for this purpose. Localized areas of poor water quality result from natural sources including microbial-mediated changes in reduction/oxidation (redox) conditions, basic rock/water interactions, or upwelling of high salinity water from underlying formations.

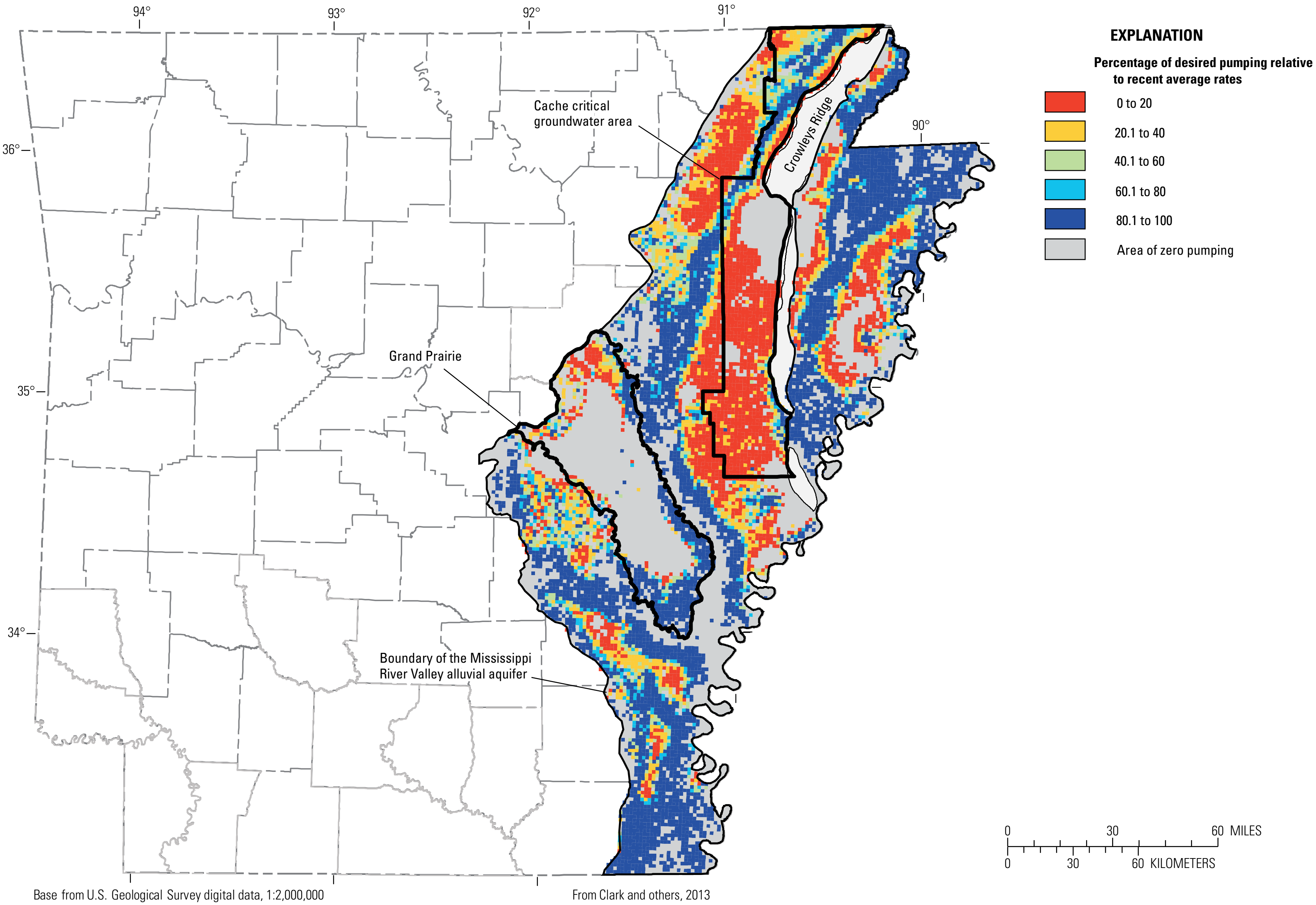



**Figure 24.** Percentage of recent average annual pumping from the Mississippi River Valley alluvial aquifer with reductions for surface-water diversions simulated in scenario 3 of Clark and others (2013).

Because row-crop agriculture is the dominant land use in eastern Arkansas, use of pesticides and fertilizers is the most prevalent and ubiquitous anthropogenic threat to groundwater quality in the shallow alluvial aquifer. Local sources of contamination exist in urban settings (for example, USTs, pesticides and fertilizers, small industry, and other sources); however, contaminant plumes normally are present at small local scales and do not affect large regional areas.

### General Geochemistry and Water Type

Groundwater from the alluvial deposits of the Coastal Plain, which includes the extent of the Mississippi River Valley alluvial aquifer, is dominantly a calcium-bicarbonate water type; sodium, magnesium, chloride, sulfate, silica, and iron comprise the remaining major (by weight) ions in solution (fig. 25; table 19). Most of the samples collected from wells in the Coastal Plain are predominantly from the Mississippi River Valley alluvial aquifer (greater than 90 percent), and therefore statistical analyses in table 19 are considered representative of the aquifer. Most constituents generally show a wide variability in concentration based on residence time of groundwater along a flow path—the longer the flow path, the more time allowed for mineral dissolution and rock/water interactions that affect the chemical composition of groundwater. Constituent variability also is affected locally by anthropogenic sources or upwelling of high-salinity water from underlying formations. The following sections provide more detailed information related to general water quality and a discussion of the occurrence, sources, and distribution of constituents that contribute to localized or ubiquitous water-quality concerns throughout the extent of the Mississippi River Valley alluvial aquifer in eastern Arkansas. It should be noted that in some of the figures, some sites appear to be outside of the Coastal Plain. This is a result of the scale for the physiographic province boundaries (line representing the Fall Line), and the fact that where major streams (for example, the White River) enter the Coastal Plain, the line does not follow some of the thicker deposits upstream (that is, it is difficult to define an exact boundary where deposits from one stream extend upstream from those of the Mississippi Alluvial Plain deposits). All wells were completed in alluvial deposits considered belonging to and assigned to the Coastal Plain alluvium.

Groundwater-quality data for the Mississippi River Valley alluvial aquifer are available in many publications that describe general inorganic groundwater chemistry for various locations in the State. Several earlier reports were part of a statewide assessment of groundwater resources by counties that began in the late 1940s (Hewitt and others, 1949: Klein and others, 1950; Onellion and Criner, 1955; Onellion, 1956; Counts, 1957; Ryling, 1960; Bedinger and Reed, 1961; Plebuch, 1961; Halberg and Reed, 1964; Sniegocki, 1964; Albin and others, 1967a; Lamonds and others, 1969; Hines and others, 1972; Ludwig, 1973). Other assessments focused on groundwater quality in particular areas of concern or groundwater resources in major basins within eastern Arkansas (Broom and Reed, 1973; Broom and Lyford, 1981; Fitzpatrick, 1985; Morris and Bush, 1986; Kilpatrick and Ludwig, 1990b; Leidy and Morris, 1990a). A large regional groundwater-quality assessment of the Mississippi embayment in Mississippi, Louisiana, Arkansas, Missouri, Tennessee, and Kentucky was performed as part of the National Water-Quality Assessment (NAWQA) Program, and findings were summarized in Kleiss and others (2000) and Gonthier (2003). The ADEQ conducts groundwater-quality monitoring on a rotating 3-year schedule for several areas in eastern Arkansas and has published summary reports of the data (Van Schaik and Kresse, 1994, 1995, 1996; Kresse and others, 1997; Kresse and Huetter, 1999). Most of these groundwater studies typically covered one to three counties. These reports provided basic descriptive statistics on chemical constituents including major ions, trace metals, and nutrients with little to no discussion of processes that affected the occurrence, source, and distribution of various chemical constituents.

The first detailed assessment of processes controlling inorganic chemistry of groundwater in the Mississippi River Valley alluvial aquifer is found in Kresse and Fazio (2002). This study collected groundwater-quality samples from 118 wells in southeastern Arkansas and developed a conceptual model for the evolution of the groundwater geochemistry of the Mississippi River Valley alluvial aquifer. Previous reports (listed above) had noted the dominantly calcium-bicarbonate water type and the elevated iron and manganese concentrations in groundwater from the aquifer. Kresse and others (1997) provided evidence for cation exchange along a flow path driving the transition of a calcium-bicarbonate to a sodium-bicarbonate water type, in addition to providing evidence for gypsum dissolution contributing calcium and sulfate. Kresse and Fazio (2002) added to the work of Kresse and others (1997) and used analyses of rainwater, shallow groundwater, and deep groundwater to develop a conceptual geochemical model that accounted for the varying chemistry and water types. They showed that young, shallow groundwater (within the upper 10 ft of the vertical-flow dominated saturated zone) chemistry was explained as rainwater that was concentrated through evapotranspiration, sufficiently elevating magnesium, potassium, chloride, sulfate, and nitrogen concentrations. Most of the calcium and bicarbonate resulted from carbonate mineral dissolution in the unsaturated and upper saturated zones. High sodium-chloride ratios were explained by calcium-sodium cation exchange increasing groundwater sodium concentrations relative to chloride. The clay-rich upper unit of the aquifer provides abundant exchange capacity (Kresse and Fazio, 2002).

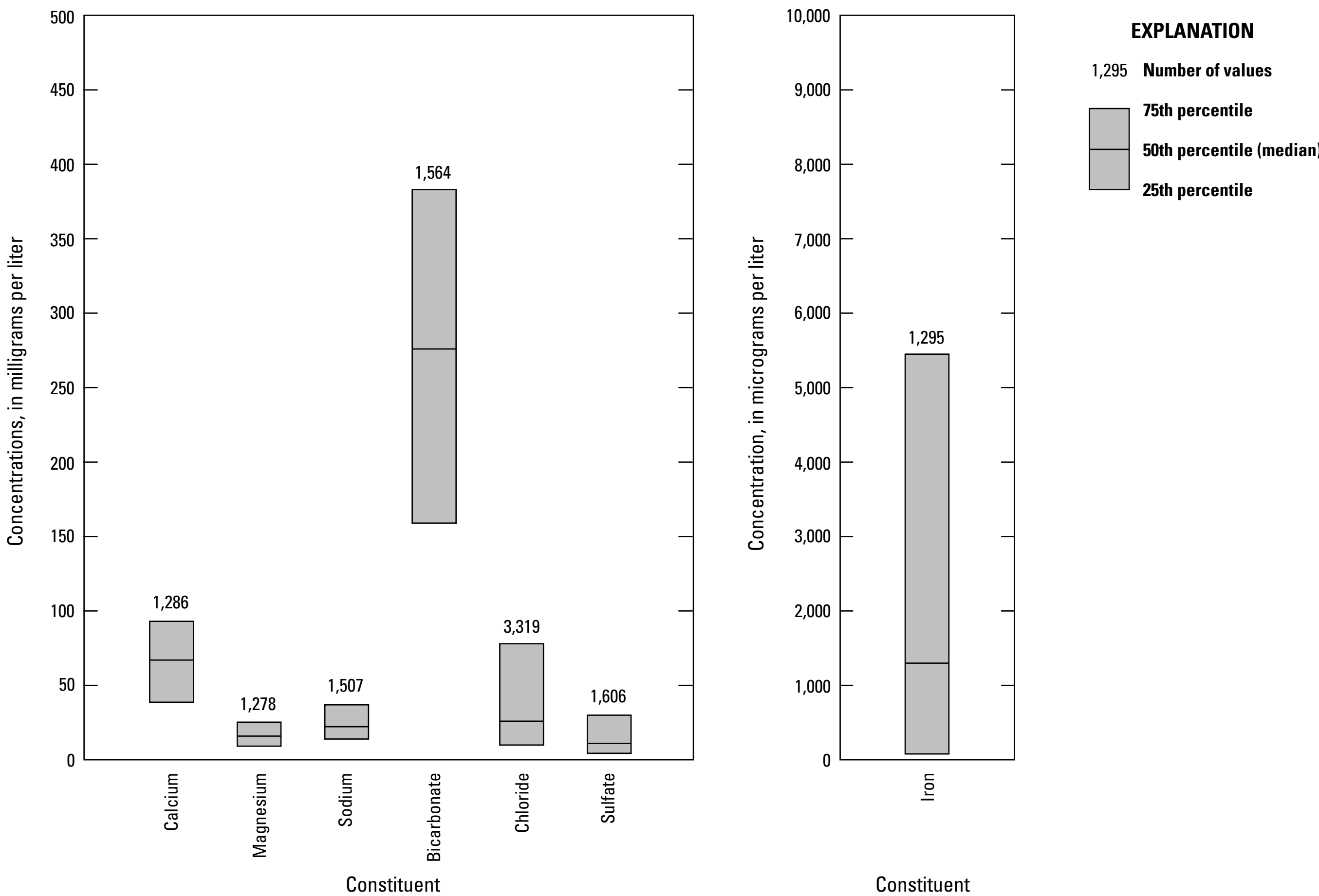



**Figure 25.** Interquartile range of selected chemical constituents in groundwater from alluvial deposits in the Coastal Plain of southern and eastern Arkansas.

**Table 19.** Descriptive statistics for selected chemical constituents in groundwater from alluvial deposits in the Coastal Plain Province of southern and eastern Arkansas.

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

| Constituent or characteristic | Minimum | Median | Maximum | Standard deviation | Number of wells |
|---|---|---|---|---|---|
| Calcium (mg/L) | 0.1 | 65 | 659 | 47.3 | 1,286 |
| Magnesium (mg/L) | 0.03 | 16 | 663 | 22.8 | 1,278 |
| Sodium (mg/L) | 0.23 | 22 | 771 | 61 | 1,507 |
| Potassium (mg/L) | 0.08 | 1.8 | 54 | 2.8 | 1,314 |
| Bicarbonate (mg/L) | 2.0 | 276 | 830 | 151 | 1,564 |
| Chloride (mg/L) | 0.12 | 23 | 7,150 | 237 | 3,319 |
| Sulfate (mg/L) | 0.1 | 11 | 1,200 | 64 | 1,606 |
| Silica (mg/L) | 1.2 | 31 | 667 | 23 | 912 |
| Nitrate (mg/L as nitrogen) | 0.002 | 0.09 | 228 | 7.9 | 1,444 |
| Dissolved solids (mg/L) | 28 | 320 | 3,435 | 292 | 1,267 |
| Iron (µg/L) | 0.05 | 1,200 | 109,000 | 6,812 | 1,295 |
| Manganese (µg/L) | 0.13 | 413 | 25,000 | 1,010 | 785 |
| Arsenic (µg/L) | 0.03 | 2.09 | 80 | 8.8 | 527 |
| Hardness (mg/L as calcium carbonate) | 1.05 | 220 | 4,380 | 215 | 1,415 |
| Specific conductance (µS/cm) | 7 | 596 | 10,200 | 550 | 3,789 |
| pH (standard units) | 4.2 | 7.2 | 9.4 | 0.6 | 2,141 |

Groundwater samples from irrigation wells completed in the lower, high-yield basal unit of the Mississippi River Valley alluvial aquifer provided a chemical composition representative of deeper, older waters. Kresse and Fazio (2002) conducted a graphical analysis of various constituents along a continuum of increasing residence time in the aquifer, represented by increasing dissolved-solids concentrations. This analysis was used to delineate evolution of groundwater chemistry in the deeper, horizontal-flow dominated part of the aquifer. Geochemical trends for individual chemical constituents with increasing dissolved-solids concentrations revealed two populations. The first population of data values, ranging from less than 100 to 350 milligrams per liter (mg/L) dissolved solids, evolved toward a strongly calcium-bicarbonate water type with calcium and bicarbonate comprising over 65 and 95 percent of the total cations and anions in milliequivalents per liter, respectively. Values for pH simultaneously increased within this population from approximately 5.9 to 7.4, reflecting the consumption of hydrogen ions with the dissolution of carbonate material. For the second population of data values, calcium and bicarbonate percentages decreased with increasing dissolved-solids concentrations. This population was characterized by increasing sodium, chloride, and sulfate concentrations, and decreasing pH values at dissolved-solids concentrations from 350 to 746 mg/L. Calculation of saturation indices demonstrated that groundwater in the first population was undersaturated with respect to calcite, whereas groundwater in the second population was supersaturated with respect to calcite. No mechanism was proposed for the evolution of higher salinity groundwater represented by the second population. A later study (described in greater detail in the next section) investigated elevated arsenic concentrations in southeastern Arkansas (Kresse and Fazio, 2003). That study revealed a predictable spatial distribution for the water types and groundwater chemistry trends in the alluvial aquifer described by Kresse and Fazio (2002) based on geomorphology and stratigraphy in southeastern Arkansas.

### Source of Elevated Trace Metals

Trace metals, particularly iron, manganese, and arsenic, occur in elevated concentrations in large areas of the Mississippi River Valley alluvial aquifer. Concentrations exceeding secondary drinking-water regulations (related to taste and staining) for iron (0.3 mg/L or 300 µg/L) and manganese (0.05 mg/L or 50 µg/L) (table 1) are common throughout the Mississippi River Valley alluvial aquifer and present problems to farmers because of fouling of irrigation well pumps and screens. Elevated concentrations of these metals have been mentioned by nearly every author reporting on groundwater quality in the alluvial aquifer; however, the large database accumulated for this study, together with spatial analysis of individual constituents within a geographical information system, revealed a trend in the distribution of iron concentrations (fig. 26) that could benefit users requiring large amounts of water (for example, public supply) with little treatment expense. Large areas of low (less than 300 µg/L) iron concentrations are located in the northern part of the aquifer, in addition to isolated areas in the southern part of the aquifer.

A limited attempt at investigating relations of iron (and other constituents) to other spatial attributes (for example, soils, geology, geomorphology) for this report revealed a general relation with the geomorphology of the Mississippi embayment; however, a detailed assessment of sources and processes accounting for the spatial distribution of dissolved iron concentrations was outside the scope of this report. Box plots (fig. 27) of selected constituents were constructed using an overlay method within a geographical information system to categorize individual sites by percentage of various geomorphological units as mapped by Saucier (1994). Providing explanations for differences in concentrations of various constituents related to geomorphology were outside of the scope of this report, especially for areas north of the Arkansas River. For areas south of the Arkansas River, reports are available that describe the relation of various chemical constituents to area geomorphology. These reports, discussed in the following paragraphs, illuminate the effects of depositional processes forming the resulting geomorphology on geochemical evolution of groundwater throughout the Mississippi River Valley alluvial aquifer.

Kresse and Fazio (2003) provided the first comprehensive study addressing the source and distribution of trace metals in the Mississippi River Valley alluvial aquifer, which aided in understanding the overall evolution of geochemistry in the aquifer. Their study was prompted by a lowering of the Federal MCL for arsenic from 50 µg/L to 10 µg/L in 2001 (U.S. Environmental Protection Agency, 2001). Kresse and Fazio (2002) reported that 21 of 118 irrigation wells sampled in southeastern Arkansas had arsenic concentrations exceeding 10 µg/L. They hypothesized that inorganic arsenic was the source of these elevated concentrations based on statistically significant differences between groundwater in older Pleistocene terrace deposits, with lower concentrations of iron, arsenic, barium, and manganese, and younger Holocene deposits with elevated concentrations of these metals. Gonthier (2003) compared groundwater chemistry from 25 wells completed in the Holocene alluvium to 29 wells completed in Pleistocene valley train deposits and also noted significantly higher concentrations of metals in groundwater from the Holocene relative to that from the Pleistocene deposits. Kresse and Fazio (2003) further investigated the occurrence and source of arsenic in groundwater throughout Arkansas and employed regression analyses to show correlations between redox-sensitive constituents (ammonia, nitrate, iron, manganese, phosphorus, barium, and arsenic) and total organic carbon for groundwater from the Mississippi River Valley alluvial aquifer.

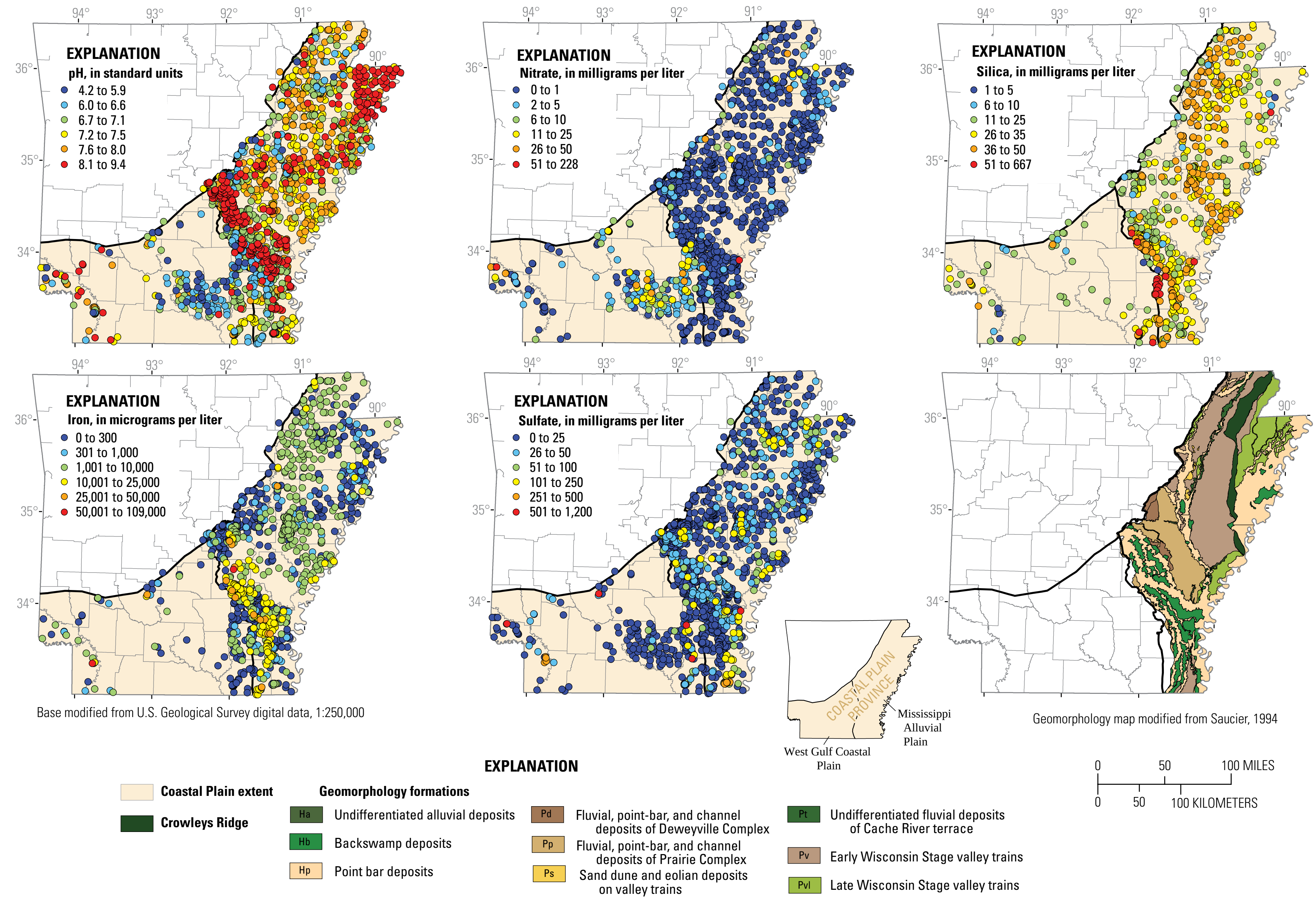



**Figure 26.** Spatial distribution of selected chemical constituents in groundwater from alluvial deposits in the Coastal Plain of southern and eastern Arkansas.

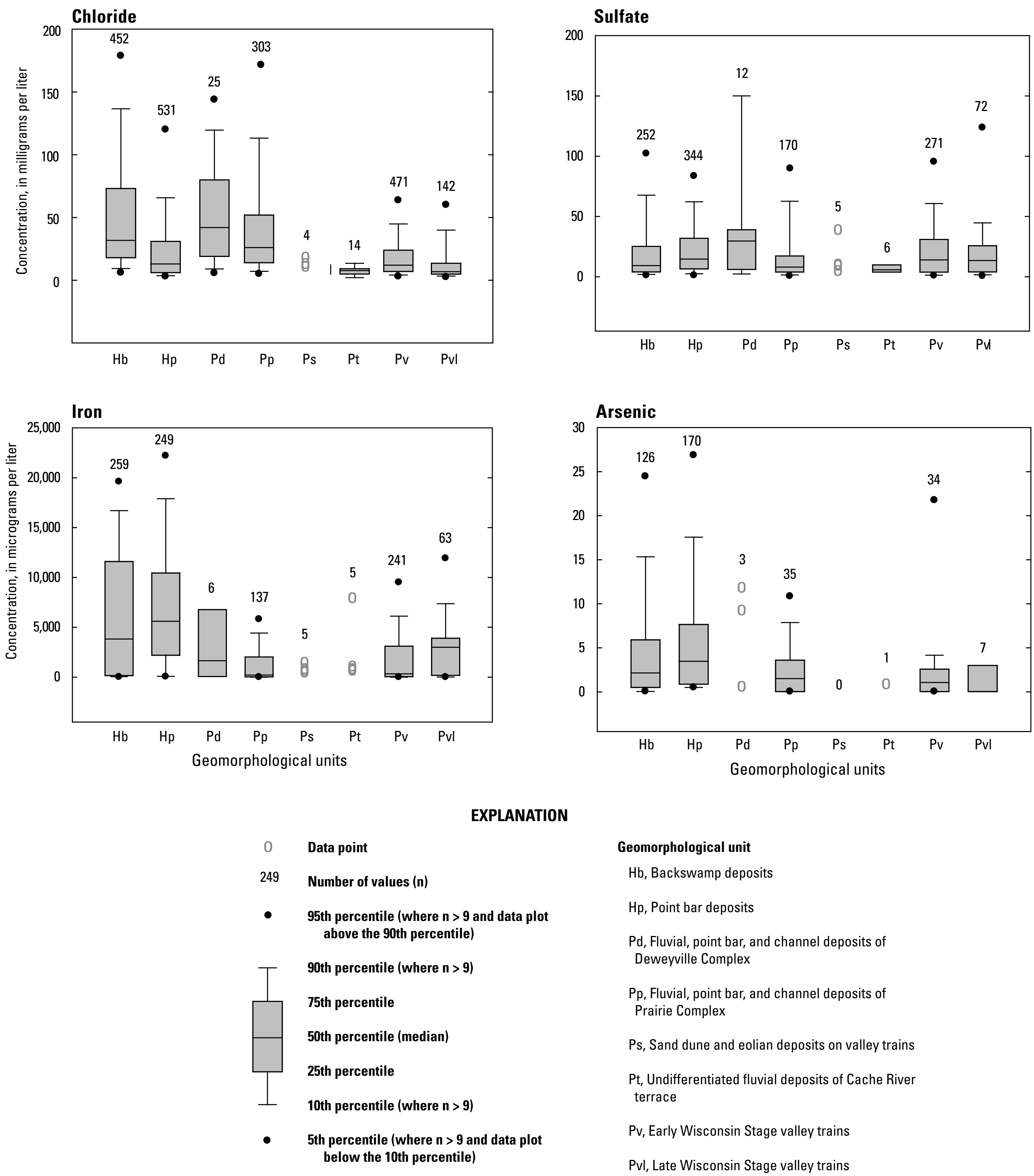



**Figure 27.** Selected chemical constituents in groundwater from alluvial deposits as related to geomorphological units in the Mississippi Alluvial Plain of eastern Arkansas.

Numerous correlations by Kresse and Fazio (2003) indicated an inorganic source of arsenic rather than past use of arsenical pesticides. Inverse relations were noted for comparisons of iron, manganese, and arsenic to nitrate concentrations. When concentrations of iron and manganese exceeded 0.5 mg/L, nitrate concentrations were less than 0.5 mg/L as nitrogen (N). Similarly, when nitrate concentrations were greater than 0.1 mg/L as N, arsenic concentrations were less than 5 µg/L, and when nitrate concentrations were less than 0.1 mg/L, arsenic concentrations ranged upward to 50 µg/L with 21 samples that exceeded 10 µg/L. These correlations tended to rule out arsenical pesticides as the source of arsenic because iron, manganese, and arsenic did not occur in the shallow groundwater with low dissolved solids but only occurred in groundwater along a deep, longer flow path with higher dissolved-solids concentrations.

Arsenic additionally correlated more closely with increases in iron, manganese, barium, total organic carbon, and total phosphorus. These correlations indicated reductive dissolution of iron oxyhydroxide coatings on sand particles as the source of elevated arsenic (and other redox sensitive constituents) in the Mississippi River Valley alluvial aquifer, as had been described for groundwater in alluvial deposits across the globe (Nickson and others, 2000; McArthur and others, 2001; Mueller and others, 2001; Hon and others, 2002). Kresse and Fazio (2003) noted that arsenic and iron concentrations were noted to increase simultaneously up to iron concentrations of approximately 12,000 µg/L; at that point, arsenic concentrations decreased as iron concentrations continued to increase. Similar to the two groupings noted from Kresse and Fazio (2002), iron and arsenic concentrations showed abrupt decreases for dissolved-solids concentrations greater than 350 mg/L. Because iron and arsenic concentrations decreased with concomitant increases in sulfate concentrations, formation of arsenic-containing iron sulfides under sulfate-reducing conditions was interpreted as accounting for the loss of arsenic and iron. Subsequent studies in elevated arsenic zones in southeastern Arkansas employed five-step sequential extraction of sediments, inverse geochemical modeling, surface complexation modeling, X-ray diffraction analysis, arsenic speciation, and other investigative techniques. These studies confirmed reductive dissolution of iron oxyhydroxides as the source of elevated arsenic. The studies also confirmed that reduction of sulfate with coprecipitation of arsenic and sulfide is an important limiting process controlling the concentration of arsenic in solution (Sharif and others, 2008a, b, 2011).

The above studies also identified redox processes as an important limiting control for dissolved nitrate concentrations in the Mississippi River Valley alluvial aquifer. Despite extensive application of nitrogen fertilizers for crops in eastern Arkansas, nitrate concentrations in the aquifer are relatively low. The median concentration of nitrate was 0.02 mg/L for 118 irrigation well samples from Kresse and Fazio (2002), 0.05 mg/L for 77 irrigation well samples from Kresse and others (1997), and 0.09 mg/L for 1,444 samples compiled for this report (table 19). Steele and others (1994) noted that groundwater from shallow alluvial wells (less than 50 ft deep) had median nitrate concentrations of 2.94 mg/L, whereas deep wells (more than 50 ft deep) had median concentrations of 0.13 mg/L. In a redox zonation, nitrate follows oxygen as the next most energetic electron acceptor. Virtually all dissolved nitrate in deeper sections of the Mississippi River Valley alluvial aquifer had been reduced to dinitrogen prior to reduction of manganese and iron oxides. Together with the inverse correlation of nitrate with iron and arsenic (Kresse and Fazio, 2003), abundant evidence is available to indicate that iron and other trace metals should be present in low concentrations in shallow, young, oxygenated waters and more elevated in deeper, older, reduced groundwater in the Mississippi River Valley alluvial aquifer. Several historical reports cited soft water and low iron concentrations in shallow wells completed in the Mississippi River Valley alluvial aquifer (Ryling, 1960; Plebuch, 1961; Steele and others, 1994).

### Occurrence, Distribution, and Sources of Elevated Chloride Concentrations

High chloride concentrations are a common problem limiting use of the Mississippi River Valley alluvial aquifer in some areas of Arkansas. The median chloride concentration for 3,319 samples compiled for this report was 23 mg/L. The distribution of chloride concentrations in groundwater from alluvial deposits in the Coastal Plain, including the extent of the Mississippi River Valley alluvial aquifer, was plotted to investigate areas of high salinity (fig. 28). The Arkansas River physically divides the alluvial aquifer into northern and southern parts and serves as a hydrologic boundary. This boundary also was applied to the north and south alluvial aquifer groundwater-flow models (described in section “Results of Groundwater-Flow Simulation Models”). For this report, areas of high salinity are discussed separately for the Mississippi River Valley alluvial aquifer north and south of the Arkansas River. Changes in lithostratigraphy, geomorphology, and underlying formations north and south of the Arkansas River have resulted in differing sources for high-salinity water. Various publications have addressed these problems separately for site-specific areas.

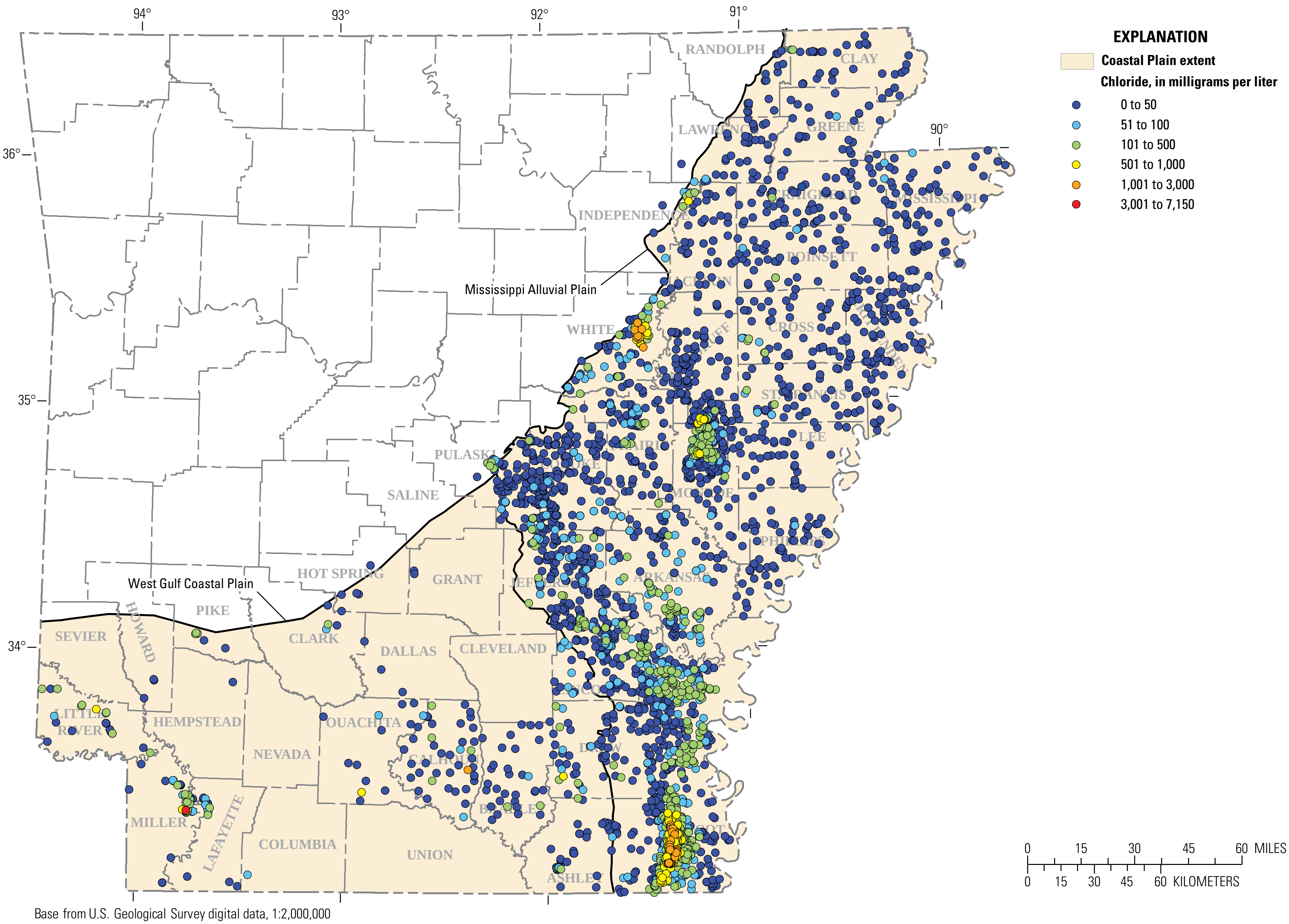



**Figure 28.** Distribution of chloride concentrations in groundwater from alluvial deposits of the Coastal Plain in Arkansas.

Chloride concentrations often are correlated with greater concentrations of dissolved solids. Such a correlation was shown by Kresse and Fazio (2002) for the Mississippi River Valley alluvial aquifer in southeastern Arkansas as discussed in the previous section. The EPA established a secondary drinking-water regulation for chloride of 250 mg/L based on aesthetic qualities including taste (table 1; U.S. Environmental Protection Agency, 2009). Elevated chloride concentrations also can affect various crops, thus presenting problems to farmers in eastern Arkansas. Problems encountered in the use of high-salinity waters for irrigation can be acute, such as burning of foliage, and chronic, including a reduction in the plant's ability to uptake water as a result of increased soil osmotic pressure (McFarland and others, 1998). Additionally, high sodium concentrations (often associated with high chloride concentrations) can result in soil structure deterioration and reduced water infiltration rates (Cardon and Mortvedt, 2001; Gilmour, 2000). Salinity also has been shown to suppress nutrient uptake and other metabolic processes, limiting growth and crop yields (Pulley and Beyrouty, 1996), and has affected a substantial amount of rice acreage in Arkansas (Wilson and others, 1997). For this reason, groundwater that contains chloride concentrations exceeding 100 mg/L is not recommended for rice production (Tacker and others, 1994), although some farmers are able to apply novel irrigation management approaches to economically produce rice and other crops with water containing higher concentrations of chloride. For this report, a practical definition of elevated chloride concentration is set at 100 mg/L as was established in Kresse and Clark (2008).

Numerous reports describe the occurrence of elevated chlorides in southeastern Arkansas. Onellion and Criner (1955) showed chloride concentrations as high as 1,490 mg/L in southwestern Chicot County. Klein and others (1950), Bedinger and Reed (1961), Bedinger and Jeffery (1964), and Broom and Reed (1973) reported elevated chloride concentrations in Jefferson, Lincoln, and Desha Counties but did little to identify the source of elevated chloride except to comment on proximity to the Arkansas River, which often contained elevated chloride concentrations. Fitzpatrick (1985) reported high salinity concentrations in the Mississippi River Valley alluvial aquifer of southeastern Arkansas (south of the Arkansas River). Elevated chloride concentrations were attributed to several possible sources: (1) upward flow from underlying, high-salinity Tertiary aquifers; (2) influx of water from the Arkansas River (in the area of Desha and Lincoln Counties); (3) upward migration of deep reservoir brines from abandoned oil and gas wells; and (4) migration of deep brine upfaults (in Chicot County), although no direct evidence was presented to validate or refute these potential sources. Fitzpatrick (1985) showed chloride concentrations as high as 360 mg/L in Desha and Lincoln Counties, corresponding to the area described in Bedinger and Reed (1961), and a maximum chloride concentration of 1,360 mg/L in Chicot County. Kresse and others (1997) sampled 77 wells in parts of southeastern Arkansas, including Jefferson, Lincoln, and Desha Counties, and noted that 5 groundwater samples exceeded 100 mg/L with a maximum concentration of 184 mg/L. They compared chloride concentrations from their study in eastern Arkansas to older datasets from Klein and others (1950) for Jefferson County and Bedinger and Reed (1961) for Desha and Lincoln Counties. Based on isoconcentration maps for all studies and comparison of mean chloride concentrations between the datasets, Kresse and others (1997) concluded that little change had occurred over time in the occurrence, areal distribution, and concentration of chloride in groundwater from this area. Kresse and Fazio (2002) collected 118 groundwater samples from irrigation wells in the Bayou Bartholomew watershed in southeastern Arkansas and noted 4 samples that exceeded 100 mg/L in Jefferson and Lincoln Counties. They hypothesized several potential sources of salinity including (1) infiltration from the Arkansas River, (2) low recharge rates through overlying clays leading to high residence time and minimal flushing, (3) downward percolation of irrigation water enriched in salts by evapotranspiration, and (4) upward flow of high-salinity water from underlying Tertiary aquifers.

Kresse and Clark (2008) provided the first study specifically designed to elucidate the sources of saline (more than 1,000 mg/L dissolved solids) water in the Mississippi River Valley alluvial aquifer in the Bayou Bartholomew watershed of southeastern Arkansas. They defined two separate areas that each exhibited elevated chloride concentrations derived from distinct sources: Area I, which comprised most of Jefferson, Lincoln, and Desha Counties, and Area II, which is mostly in Chicot County (fig. 29).

Previous studies provided numerous explanations for the elevated chloride concentrations in Area I, including upwelling of poor quality water from underlying Tertiary aquifers or influx of high-salinity water from the Arkansas River (Bedinger and Reed, 1961; Bedinger and Jeffery, 1964, Broom and Reed, 1973; Fitzpatrick, 1985). Kresse and Clark (2008) documented low chloride concentrations in the underlying Cockfield and Sparta aquifers in Area I to rule out upwelling from underlying Tertiary aquifers. Spatial correlations between geomorphological landforms and chloride concentrations were used to show that a concentration of dissolved solids from rainwater through evapotranspiration in areas of low-permeable, clay-dominated backswamp deposits was the most likely source of elevated chloride concentrations in Area I. Lower chloride concentrations were consistently noted in groundwater from high-permeable, coarse channel deposits of the Arkansas River and Bayou Bartholomew. This relation was demonstrated best for Desha County, which had the largest amounts of data (fig. 30). Interestingly, Kresse and Clark (2008) noted that the lowest chloride concentrations were from wells near the Arkansas River, providing strong evidence that infiltration of river water was not a likely source.

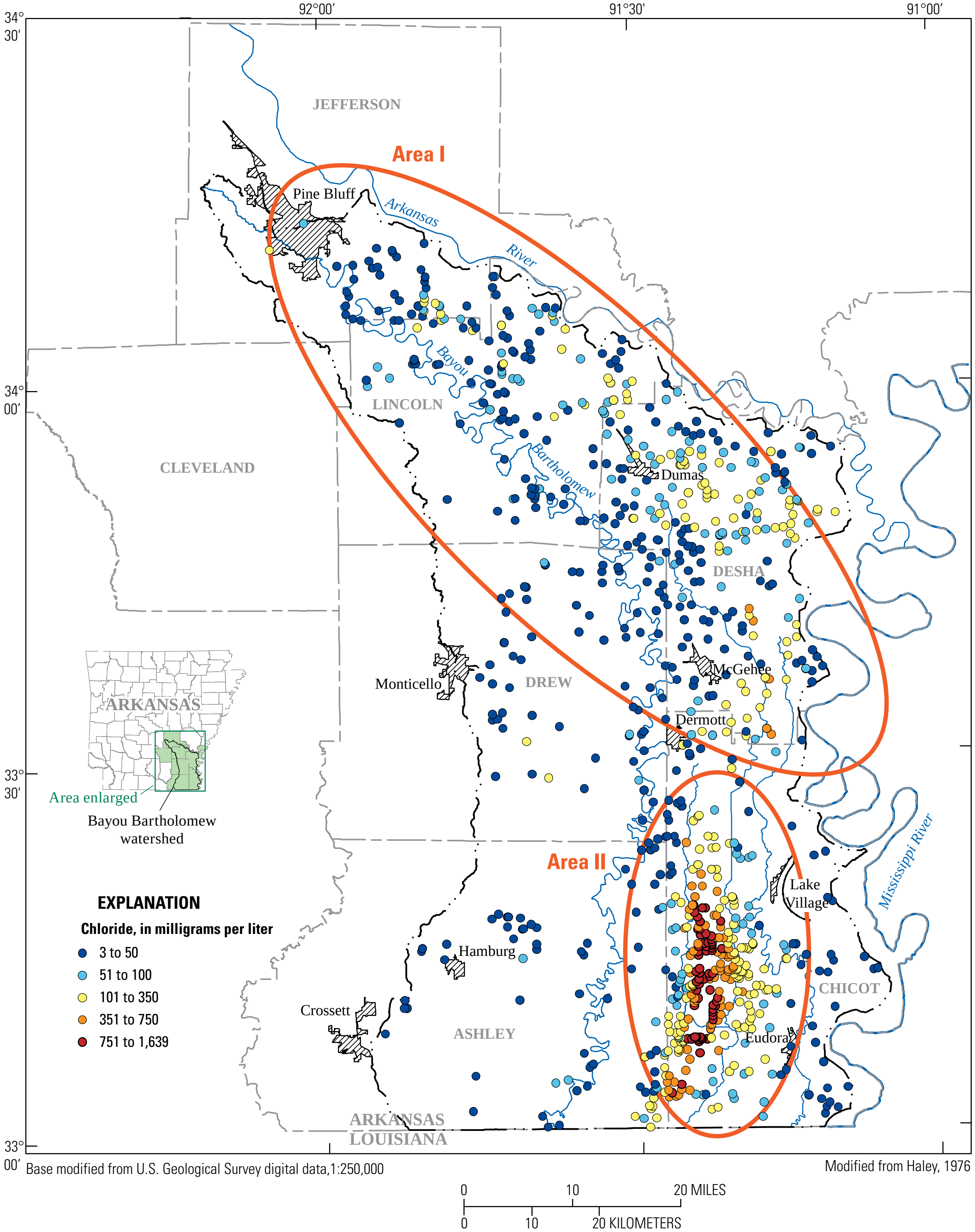



**Figure 29.** Distribution of chloride concentrations in groundwater from the Mississippi River Valley alluvial aquifer in Bayou Bartholomew watershed of southeastern Arkansas (from Kresse and Clark, 2008).

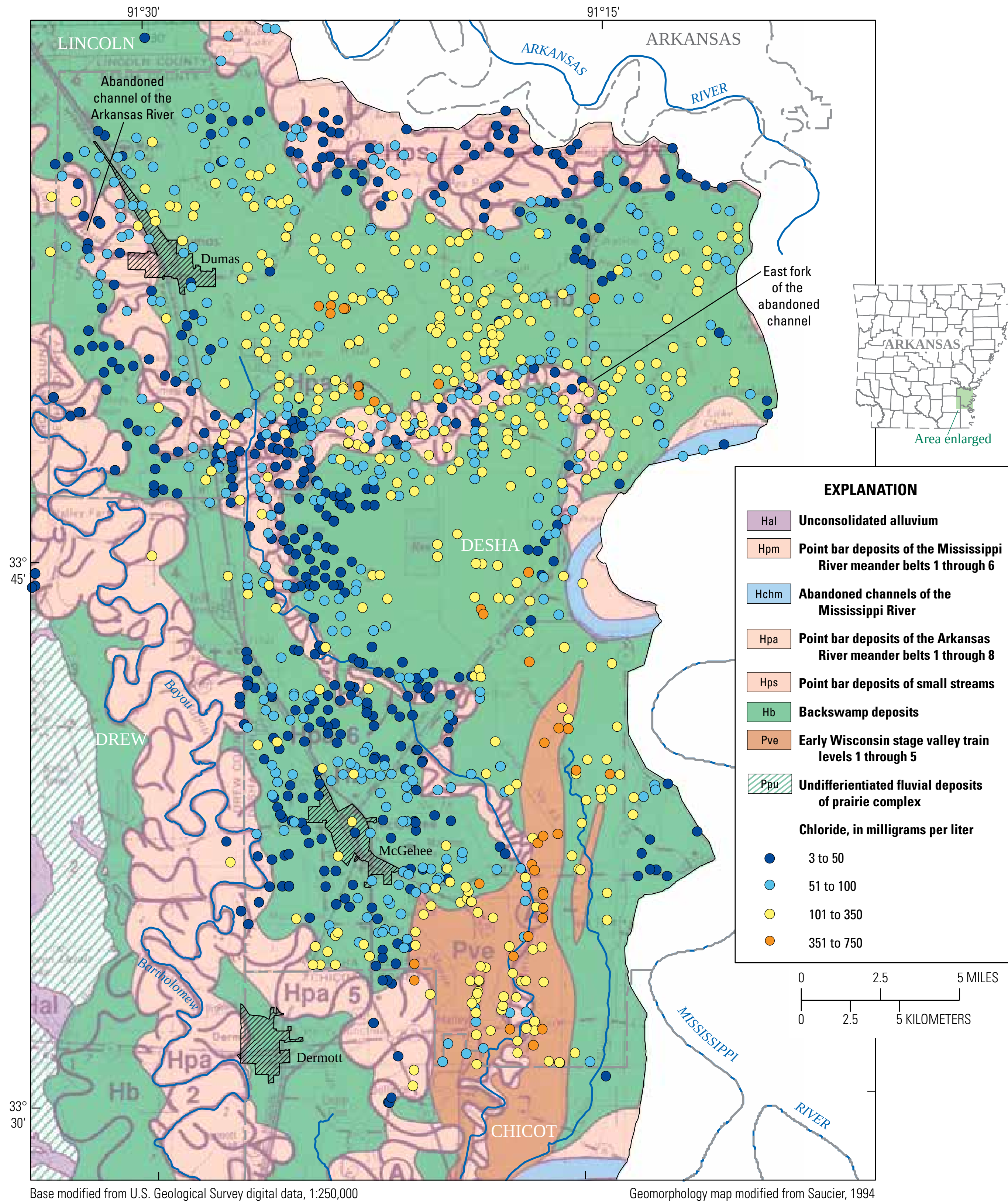



**Figure 30.** Distribution of chloride concentrations in groundwater from the Mississippi River Valley alluvial aquifer overlain onto a map of Quaternary geomorphological landforms (from Kresse and Clark, 2008).

In Area II (fig. 29), Kresse and Clark (2008) ruled out upwelling of saline water in Tertiary aquifers and abandoned oil and gas wells as a source of the salinity problem. They used (1) mixing curves developed from bromide-chloride ratios from the Mississippi River Valley alluvial and Tertiary aquifers as well as brine water from the Smackover Formation of Jurassic age, (2) chloride isoconcentration maps for the Mississippi River Valley alluvial and Tertiary aquifers, and (3) dates of early oil exploration wells. Evidence, including elongation of the zone of elevated chloride concentrations in the alluvial aquifer, suggested that the most likely source of chloride was brine water from the Smackover Formation moving up the intersection of two mapped wrench faults (Zimmerman, 1992) in the vicinity of Area II. At least one of the faults was described as extending into the Smackover Formation and was listed as having been active as late as the Pleistocene or Holocene Periods (Zimmerman, 1992). Trend analysis of the data indicated that no changes occurred in the concentration or spatial distribution of chloride concentrations in Area I or Area II from the earliest sampling periods in the early 1950s through 1995. This finding is similar to Kresse and others (1997), which concluded that little to no change had occurred over time in the occurrence, areal distribution, and concentration of chloride in southeastern Arkansas.

Kresse and Clark's (2008) demonstration of the lithostratigraphic and geomorphologic control on chloride concentration distribution in southeastern Arkansas provided additional information on trace metal occurrence and distribution, particularly elevated arsenic concentrations. Whereas chloride and sulfate concentrations were found to be elevated in the backswamp deposits, arsenic concentrations were lower in these deposits. Similarly, when chloride and sulfate concentrations were lower in the channel deposits, groundwater in these deposits contained elevated levels of arsenic (fig. 31). Inspection of the relation of arsenic to sulfate and chloride for data collected for this report revealed inverse correlations supporting lack of arsenic in groundwater regimes with elevated chloride and sulfate concentrations. Kresse and Fazio (2002, 2003) noted that elevated concentrations of chloride correlated with elevated levels of sulfate. Several studies (Kresse and Fazio, 2003; Sharif and others, 2008a, b, 2011) hypothesize that reduction of sulfate was a controlling factor for elevated arsenic concentrations as a result of coprecipitation of arsenic in iron-sulfide minerals. Sharif and others (2008b) noted that clay-layer thickness correlated with sulfate concentration and inversely correlated with arsenic concentrations. This, together with an inspection of the geomorphology of the area, indicates that areas of increased confining clay layer thickness are observed in backswamp environment areas. Relatively small infiltration rates have minimally exceeded evaporation in the backswamp areas over thousands of years (Sharif and others, 2008b) that has led to increases in concentrations of chloride and sulfate delivered with rainwater in these areas and has resulted in a dominantly sulfate reduction groundwater system (Sharif and others, 2008b). This type of groundwater system controls concentrations of soluble arsenic previously liberated by reductive dissolution of iron oxyhydroxides.

Areas of high salinity have been documented in areas north of the Arkansas River, though no definitive sources have been identified to explain their occurrence. An area of high salinity groundwater was noted near Brinkley (Monroe County; fig. 28) where a well with a chloride concentration of 22 mg/L in the late 1940s increased to 800 mg/L by 1982. Morris and Bush (1986) described a 56-$mi^2$ area affected by saltwater intrusion that was attributed to upward leakage from deeper formations. Based on results of sampling from 217 wells, Morris and Bush (1986) identified two separate areas of high concentrations of chloride: (1) an area about 1.5 mi north of Brinkley (centered near the well initially identified as problematic in the late 1940s) and exhibiting groundwater chloride concentrations as much as 960 mg/L, and (2) an area approximately 6 mi southwest of Brinkley with chloride concentrations exceeding 400 mg/L. Morris and Bush (1986) hypothesized three transport pathways to potentially explain upward migration of high salinity water: (1) upward influx of high concentrations of chloride water from the Sparta Sand in areas where the confining layer is thin, (2) upward migration along as yet unmapped faults, or (3) movement of saltwater from the Nacatoch Sand upward into the Sparta and Mississippi River Valley alluvial aquifers through abandoned oil- and gas-test boreholes. Although Morris and Bush (1986) characterized the areal distribution of high-chloride concentrations and addressed immediate concerns, no followup study has been completed to definitively explain the source of the chloride.

In White County (fig. 28), 30 groundwater samples had chloride concentrations exceeding 100 mg/L, and 9 samples exceeded 1,000 mg/L, with a maximum concentration of 3,000 mg/L (Counts, 1957). This area reportedly had a rice crop that was killed by the high salinity water during a season when little surface water was available for mixing with the groundwater. Discussions with local residents revealed that several wells completed for domestic supplies yielded water so salty that the wells were abandoned (Counts, 1957). Counts (1957) conducted field tests for chloride on domestic and stock wells in the area and produced a chloride map that showed a high-chloride area of approximately 20 $mi^2$ with concentrations exceeding 1,000 mg/L. An anecdotal note best relating the degree of salinity is found in Counts (1957), who described the use of the shallow, high-salinity groundwater for salt production during the Civil War when water from dug wells was boiled to evaporation for salt. Saltwater was encountered in the Nacatoch Sand and in Paleozoic Formations in the area (Counts, 1957), and unmapped faults may exist that allow migration of water from these deeper formations into the Mississippi River Valley alluvial aquifer. Data compiled for this report revealed elevated chloride concentrations at various locations along the western extent of the Mississippi Alluvial Plain from Pulaski to Clay County (fig. 28). This finding suggests upwelling from high-salinity water at depth (possibly from Paleozoic formations) occurs along the transition (the Fall Line) from the Interior Highlands into the Coastal Plain, thus adding support to the theories proposed by Counts (1957) for elevated salinity in this area.

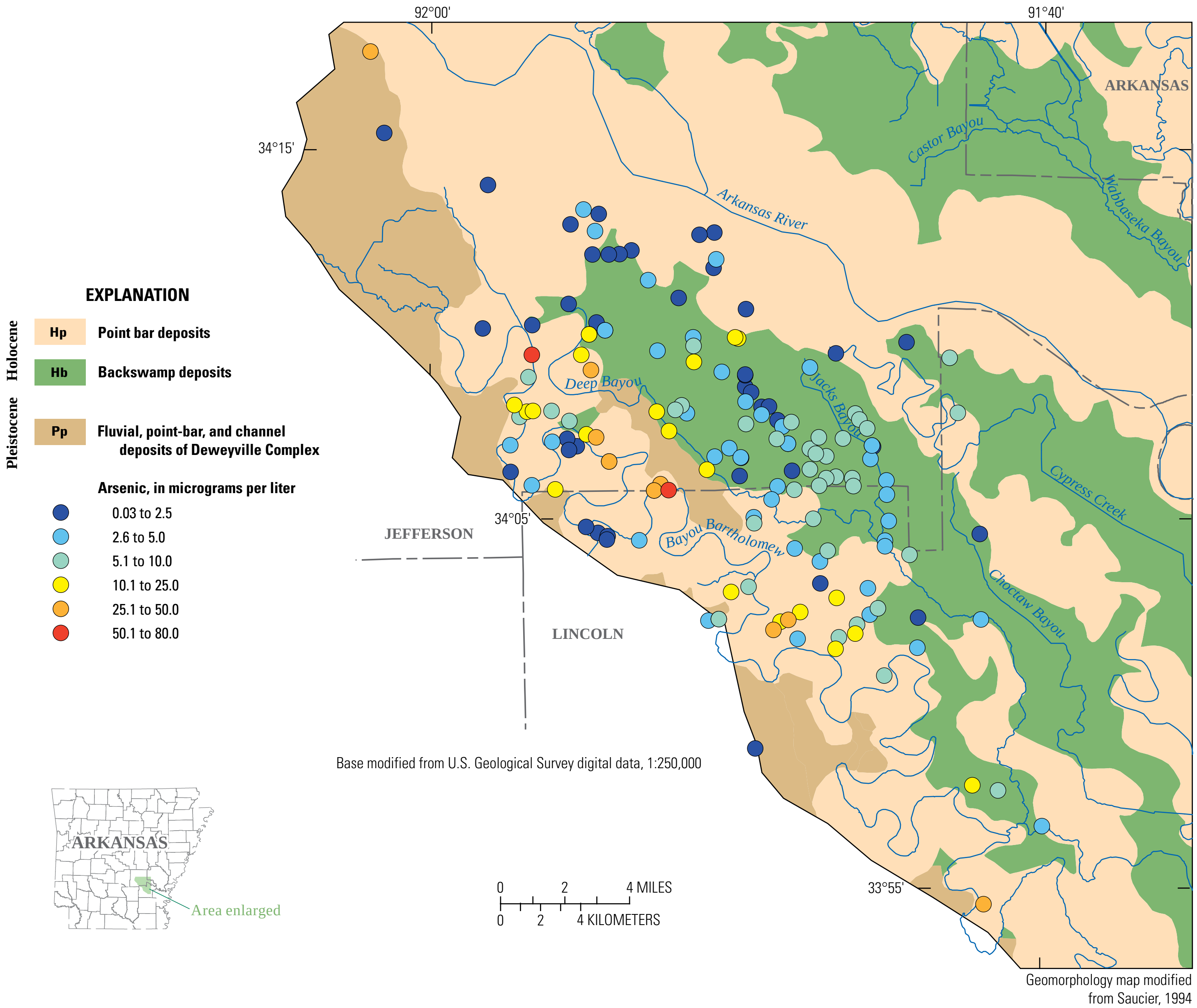



**Figure 31.** Distribution of arsenic concentrations in groundwater from the Mississippi River Valley alluvial aquifer overlain onto a map of Quaternary geomorphological landforms.

### Temporal Trends in Chloride Concentrations

A common concern regarding areas of high salinity in the Mississippi River Valley alluvial aquifer is the potential for these affected areas to expand under natural conditions or in response to pumping. Some of these concerns have been addressed in a few studies, which also have documented low groundwater velocities of approximately 0.25 ft/d in the Mississippi River Valley alluvial aquifer (Counts, 1957; Broom and Lyford, 1981; Mahon and Ludwig, 1990; Kresse and Van Schaik, 1996). Results of these studies demonstrated that consistent and detailed monitoring over time may be required to note (1) substantial changes in the spatial distribution of high-salinity groundwater in the aquifer and (2) zones of higher-velocity movement caused by preferential flow associated with faults, fractures, lithofacies changes, and focused pumping stress.

Recent studies have indicated little to no change in the spatial distribution of high-salinity groundwater in southeastern Arkansas. In Jefferson County, groundwater collected in 1996 with a mean chloride concentration of 35 mg/L (Kresse and others, 1997) was similar to the mean concentration of 39 mg/L that was documented in 1948–49 (Klein and others, 1950). In Desha County, a mean chloride concentration in 1996 of 62 mg/L (Kresse and others, 1997) was only slightly higher than the mean of 56 mg/L in 1952 (Bedinger and Reed, 1961). A chloride isoconcentration map for parts of Lincoln and Desha Counties (Klein and others, 1950) was similar to the map produced from the 1996 data for the same region (Kresse and others, 1997).

Kresse and Clark (2008) used chloride data collected from 1946 to 1959 compared to data collected after 1980 to identify spatial differences and temporal trends in Jefferson, Lincoln, and Desha Counties. A strong similarity was noted between these two time periods with greater chloride concentrations observed in backswamp deposits and lower concentrations in the active and abandoned channel point-bar deposits. Additionally, comparisons of sites in close proximity between the two time periods showed little difference in chloride concentrations. Kresse and Clark (2008) explained the lack of change over time as being controlled by (1) low groundwater velocities, (2) relatively consistent water levels over time, and (3) no large, regional pumping centers. As a result of the low diffusion- and dispersion-driven flux rates for groundwater in the Mississippi River Valley alluvial aquifer in southeastern Arkansas, any substantial changes in the occurrence and distribution of higher salinity groundwater likely would be on decadal or larger timescales (Kresse and Clark, 2008). In Chicot County, chloride data from 217 sites from Kresse and others, (2000), 89 sites from Fitzpatrick (1985), and 89 sites from Criner (1955) were very similar in shape and extent, based on chloride isoconcentration maps (Kresse and Clark, 2008). This analysis showed no major changes over time in the occurrence and spatial distribution of chloride concentrations in Chicot County.

Groundwater data collected during three sampling periods in 1989, 1992, and 1995 for the affected area in northeastern Arkansas, as outlined in Morris and Bush (1986), was reported by Van Schaik and Kresse (1996). Seventeen of the 217 wells sampled by Morris and Bush (1986) were resampled by Van Schaik and Kresse (1996), with a stated goal of evaluating changes in groundwater quality over time and expansion in the area of high salinity. No temporal trend was noted for the three sampling events. Several wells showed no change, others showed only minor increases in chloride concentration, and others showed decreases in chloride concentrations. Generally, the two areas identified with the highest chloride concentrations by Van Schaik and Kresse (1996) were similar to those identified by Morris and Bush (1986). The well with the high concentration of 960 mg/L (Morris and Bush, 1986) had a chloride concentration of 830 mg/L in 1989 (Van Schaik and Kresse, 1996). No discernible expansion or contraction was noted for the affected area described in Morris and Bush (1986).

In addition to ongoing monitoring efforts by the ADEQ in some high-chloride areas, the USGS, in cooperation with the ANRC and the AGS, has an ongoing monitoring program that collects and reports values of specific conductance and chloride concentrations from selected wells in the Mississippi River Valley alluvial aquifer in eastern Arkansas (Stanton and others, 1998; Joseph, 1999; Schrader, 2001b, 2006a, 2008a, 2010; Reed, 2004). Results from the 2008 sampling period showed specific conductance values ranging from 111 microsiemens per centimeter (µS/cm) to 2,020 µS/cm for 60 alluvial wells (Schrader, 2010). Maximum specific conductance values observed in Arkansas, Chicot, Cross, Desha, Greene, and Lincoln Counties equaled or exceeded 1,000 µS/cm. A comparison of specific conductance histograms for 2006 and 2008 showed similarity in distribution shape, largest category, and mean values, indicating a minimal change in overall water quality. In summary, studies from 1946 through 2013 for the Mississippi River Valley alluvial aquifer show (1) little to no change in salinity trend and (2) stable water-quality conditions. Based on inspection of groundwater-quality data from continuously monitored wells in eastern Arkansas, new areas have not been identified with poor water quality.

### Occurrence of Pesticides

The monitoring of pesticides in Arkansas gained increased attention in the early 1990s with Federal mandates to develop a State Management Plan for pesticide use (U.S. Environmental Protection Agency, 1994a, b). The ASPB enforces Federal pesticide regulations and maintains a groundwater monitoring program for pesticides in Arkansas (Arkansas State Plant Board, 2013). Prior to 2005, the AWRC conducted annual pesticide monitoring for the ASPB and published the results in various reports (Nichols and others, 1993, 1996; Steele and others, 1993, 1994). These reports provided pesticide detection location and concentration. Kresse and others (1997) sampled 77 irrigation wells in eastern Arkansas and conducted the first study in Arkansas to systematically isolate potential sources and transport pathways based on pesticide use and chemical behavior. Their study noted that the occurrence of pesticides in groundwater was unrelated to the amount of use on crop acreage; instead, pesticide occurrence was strongly correlated to leaching potential based on chemical characteristics including water solubility, organic carbon partition coefficient (Koc), and field half-life. Bentazon, with the highest solubility of any of the pesticides used in eastern Arkansas, accounted for the greatest percentage of detections (36.8 percent), although only the 14th most frequently used pesticide, followed by molinate (18.4 percent detection rate), and metolachlor (8.0 percent detection rate). These results were similar to findings of the AWRC (Nichols and others, 1993, 1996; Steele and others, 1993, 1994) and Gonthier (2003), which listed bentazon as the most frequently detected pesticide. All of the most frequently detected pesticides had water solubilities greater than 500 mg/L and Koc values less than 200 milliliters per gram (mL/g), indicating a high potential for leaching to groundwater (Kresse and others, 1997).

Kresse and Fazio (2002) sampled 118 irrigation wells completed in the Mississippi River Valley alluvial aquifer in the Bayou Bartholomew watershed in southeastern Arkansas, analyzing for 61 pesticides and pesticide byproducts. Pesticides were detected in 28 of the 118 samples (24 percent). Bentazon again was the most frequently detected pesticide and occurred in 19 of the 28 wells (55.9 percent of the total detections), followed by prometryn (8.8 percent), molinate (5.9 percent), and metolachlor (5.9 percent). Kresse and Fazio (2002) summarized rainfall amount and intensity, pesticide management practices, irrigation timing and rates, and temperature as factors that affect the migration potential for pesticides in the subsurface; however, chemical characteristics including adsorption, solubility, photo- and microbial degradation, and hydrolysis were cited as being the most critical factors in controlling the occurrence and types of pesticides detected in groundwater. Pesticide concentrations typically were three to five orders of magnitude lower than Federal drinking-water standards and health advisory limits (U.S. Environmental Protection Agency, 2009).

The ASPB has been collecting and analyzing water samples from irrigation wells for pesticides since 2005 (Arkansas State Plant Board, 2013). Review of these data revealed that 32 of the 219 wells (14.6 percent) had pesticide detections. This percent detection rate is close to that cited in Kresse and others (1997), which listed 47 pesticides detected in 335 (14.0 percent) irrigation wells sampled collectively by the ADEQ, the AWRC, and the USGS through 1996. In data published by the ASPB, 2,4-Dichlorophenoxyacetic acid (2,4-D) accounted for the largest percentage of pesticide detections (17 of 219 samples), bentazon accounted for the second largest number (12 of 219 samples), followed by metolachlor and quinclorac (each with 2 detections). 2,4-D is an herbicide used for control of broadleaf plants, is highly soluble with a water solubility of 900 mg/L (Agricultural Research Service, 2013), and is used on rice in eastern Arkansas (Jason Robertson, Arkansas State Plant Board, oral commun., 2013). Kresse and Fazio (2002) noted only one detection of 2,4-D in 118 irrigation-well samples; however, these samples were taken in counties south of the Arkansas River, where the ASPB similarly found no detections of 2,4-D. It is not known if this means that (1) 2,4-D is used to a greater degree in counties north of the river, (2) detection levels were lower in the ASPB study, or (3) the use of 2,4-D has increased since 2005. Such an analysis is outside the scope of this report.

In spite of the heavy use of pesticides on crops in eastern Arkansas and an average rate of detection of approximately 14 percent in sampled wells, pesticide concentrations are relatively low in comparison to Federal drinking-water standards. Kresse and Fazio (2002) listed pesticide concentrations ranging from 0.002 to 0.519 µg/L, which were approximately three to five orders of magnitude below listed MCLs and other health advisory standards (U.S. Environmental Protection Agency, 2009). Similarly, the ASPB works with the ADH to determine potential health effects for pesticides in groundwater. These agencies show an absence of any adverse health effects for groundwater from the alluvial aquifer sampled by the ASPB since 2005 (Arkansas State Plant Board, 2013). In summarizing the occurrence of pesticides in groundwater, findings from studies to date indicate that (1) chemical and physical characteristics of pesticides far exceed pesticide use as the overall controlling factor for occurrence of pesticides in groundwater, (2) transport of pesticides to groundwater appears to be predominantly the result of vertical infiltration through the unsaturated zone because of normal application practices, rather than through back-siphoning and other point-source related events, and (3) pesticide groundwater concentrations are very low compared to Federal drinking-water standards.

In summary, water-quality problems in the Mississippi River Valley alluvial aquifer generally are related to elevated concentrations of iron and manganese concentrations that are widespread throughout the aquifer. Salinity problems and elevated arsenic concentrations are found in isolated parts of the aquifer. Because the primary use of the alluvial aquifer is for irrigation, practical issues related to elevated iron and manganese concentrations primarily are fouling of pumps and well screens. Elevated concentrations of chloride potentially can affect crop yields. Arsenic concentrations exceeded primary drinking-water regulations in some areas, but this problem has only been documented in irrigation wells that are completed in the deeper basal zone; domestic wells are completed in the arsenic-free shallower part (upper unit) of the Mississippi River Valley alluvial aquifer. Pesticide monitoring since the early 1990s has resulted in approximately a 14-percent pesticide detection rate; however, pesticide concentrations typically are low and are three to five orders of magnitude lower than published MCLs and health advisory standards.

## Minor Alluvial Aquifers in Coastal Plain

The Mississippi River Valley alluvial aquifer is limited to the eastern one-third of Arkansas. However, smaller deposits of Quaternary alluvium from other streams in southern Arkansas also contain groundwater that provides an important source of water in the Coastal Plain. Within the West Gulf Coastal Plain in southern and southwestern Arkansas, the Red River and Ouachita River alluvial deposits are important sources of water.

The principal source of recharge to these alluvial aquifers is precipitation (Boswell and others, 1968). The Red and Ouachita Rivers are in hydraulic connection with the alluvium (Halberg and others, 1968; Ludwig, 1973); therefore, the rivers may act as discharge or recharge points for the aquifer.

Like the Quaternary alluvium of the Mississippi River Valley, the Quaternary alluvium of the Red River and Ouachita River Valleys are the result of Pleistocene and Quaternary erosion and deposition. As sea level rose, the gradient of the streams was reduced and aggradation of sediments began. The depositional processes were complex, and the alluvium was eroded, dissected, and terraced with changing flow conditions (Boswell and others, 1968). The smaller scale drainage of these basins is reflected in the thinner nature of the alluvium compared to that of the Mississippi River Valley.

### Red River Alluvial Aquifer

#### Hydrogeologic Setting

Groundwater contained in the Red River Valley alluvial deposits (hereinafter referred to as the “Red River alluvial aquifer”) is an important source of water in southern Arkansas. The Red River Valley alluvial and terrace deposits underlie an area of about 540 $mi^2$ in southwestern Arkansas (figs. 3 and 8) with a maximum thickness of 90 ft. The aquifer is comprised of a coarsening downward sequence of clay, silt, sand, and gravel, (Counts and others, 1955; Ludwig, 1973; Terry and others, 1986). Tait and others (1953) reported that in western Columbia County, the alluvial deposits of tributaries to the Red River are as thick as 80 ft and are comprised of silt and clay with a 5–10-ft thick layer of coarse sand or gravel at the base. Ludwig and Terry (1980) reported a thickness for the Red River alluvium of 75–200 ft, thickening to the south.

Various reports provide hydraulic characteristics for the Red River alluvial aquifer. Boswell and others (1968) reported an average specific yield of the Red River alluvial aquifer of 0.2. Ludwig (1973) reported on the Red River alluvial aquifer in the area of Hempstead, Lafayette, Little River, Miller, and Nevada Counties. Aquifer tests in the aquifer in Little River County yielded hydraulic conductivity values ranging from 147 to 201 ft/d, transmissivity values ranging from 3,877 to 13,369 $ft^2$/d, and storage coefficients ranging from 0.002 to 0.0002. Irrigation wells completed in the Red River alluvial aquifer were reported to yield between 200 and 1,200 gal/min. Ludwig (1973) estimated that wells in Little River County could yield as much as 750 gal/min, and wells in Miller and Lafayette Counties could yield as much as 1,500 gal/min. Counts and others (1955) reported well yields as high as 150 gal/min in Little River County and 400 gal/min in Miller County. Ludwig and Terry (1980) noted that the Red River and its tributaries do not fully penetrate the alluvial aquifer in Louisiana, and the same is likely in Arkansas. In general, groundwater flows in the direction of the Red River from the southwestern State border with Texas to the southern border with Louisiana. The 1968 potentiometric surface is available in Ludwig (1973).

#### Water Use

While many counties in southern Arkansas have reduced groundwater use and rely on surface water as the dominant or sole source of water supply, use of the Red River alluvial aquifer has increased in southwestern Arkansas. Water use from the Red River alluvial aquifer historically is included with the Mississippi River Valley alluvial aquifer (fig. 10; table 17); historic countywide use totals can be seen in figure 11. Increases in use occurred from 1965 to 2010 in Little River, Miller, and Lafayette Counties (fig. 12), and decreases occurred in Sevier and Hempstead Counties over the same period. No use has been recorded for Hempstead County since 1995, and only a slight amount of use (0.11 Mgal/d) was recorded for Sevier County in 2010 (table 17). Lafayette County generally used the greatest amount of water from the Red River alluvial aquifer. In 2010, there were over 240 wells registered in ARWUDBs, and use of the Red River alluvial aquifer was estimated to be about 31 Mgal/d—83 percent of which was for use as irrigation supply (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

Most irrigation use of the Red River alluvial aquifer occurs in southern Lafayette and northwestern Miller Counties (fig. 10). Irrigation pumpage from the aquifer was an estimated 6.9 Mgal/d in 1965 (Ludwig, 1973), which increased 277 percent to 26.0 Mgal/d in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Counts and others (1955) previously recorded 17 wells in Little River and Miller Counties, 2 of these were irrigation wells in Miller County that have since increased to 40 irrigation wells (fig. 10; Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Common crops in the area mirror crops grown in eastern Arkansas: rice, cotton, soybeans, and other minor crops. At one time, rice irrigation used as much as 50 percent of the water from the aquifer (Ludwig, 1973), but as of 2010, the percentage of irrigation water for rice production was about 12 percent (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

Duck hunting is quite common in southwestern Arkansas. Many crop-producing areas also flood fields for duck hunting. In 2010, 15 percent of the Red River alluvial aquifer’s total use was for duck hunting (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

Numerous towns throughout southwestern Arkansas used the Red River alluvial aquifer as a source of public supply in the late 1880s, but surface-water reservoirs were developed for this purpose beginning in the early 1900s (Hale, 1926). In 2010, only 0.24 Mgal/d was withdrawn for public-supply use from the aquifer in Little River and Sevier Counties (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). The availability of other water sources and water-quality issues in groundwater from the aquifer has restricted much of the domestic and industrial uses of the Red River alluvial aquifer (Ludwig, 1973). Surface water is now the predominant source of public-supply water in southwestern Arkansas.

#### Water Quality

Groundwater-quality data from the Red River alluvial aquifer for this report show pH values generally more than 7.0 and ranging upward to 9.4 (fig. 26). Most samples are strongly calcium-bicarbonate except as affected by salinity sources in Miller County (discussed below). Iron concentrations were mostly less than 1,000 µg/L throughout the extent of the aquifer (fig. 26). Nitrate concentrations dominantly were less than 1 mg/L except in western Little River County, where four wells had concentrations exceeding the MCL for nitrate of 10 mg/L.

The Red River alluvial aquifer in Miller County is another area of high salinity within the Coastal Plain (fig. 28). Several alluvial wells, mainly sampled in the early 1950s through the late 1960s, had reported chloride concentrations ranging upward to 7,150 mg/L, with seven samples from the USGS NWIS database having chloride concentrations exceeding 1,000 mg/L. Ludwig (1973) stated that chloride concentrations as high as 46,250 mg/L had been reported in Miller County; however, the highest chloride concentration included in the data from the Ludwig (1972) report was only 7,150 mg/L, similar to the highest concentration from data compiled for this report. The high chloride concentration in groundwater in Miller County was attributed to oil-field activity and more specifically to seepage from brine-storage pits. Approximately 60 million gallons (Mgal) of groundwater were estimated to have been contaminated based on the areal extent of contamination and the thickness and porosity of the aquifer (Ludwig, 1973).

### Ouachita-Saline Rivers Alluvial Aquifer

#### Hydrogeologic Setting

Locally, the alluvium of the Ouachita and Saline Rivers (hereinafter referred to as the "Ouachita-Saline Rivers alluvial aquifer") provides readily available groundwater (figs. 3 and 8). In Grant and Hot Spring Counties, alluvium of the Ouachita and Saline Rivers unconformably overlie Tertiary-age deposits. The alluvium is comprised of silt and beds of fine- to very fine-grained sand with some clay. Locally, the alluvium may contain coarse sand. The alluvium ranges from 0 to 40 ft in thickness in Grant and Hot Springs Counties (Halberg and others, 1968). In the area of Clark, Cleveland, and Dallas Counties, the alluvium of the Ouachita River is comprised of silt, clay, sand, and gravel that reach a maximum thickness of about 40 ft (Plebuch and Hines, 1969).

Groundwater in the Ouachita-Saline Rivers alluvial aquifer is unconfined. Where the sand is coarse, the alluvium may be in hydraulic connection with the rivers. Specific-capacity tests indicated an average 1.3 (gal/min)/ft drawdown and noted a maximum yield of 25 gal/min in Grant and Hot Spring Counties (Halberg and others, 1968).

Although the aquifer is thin in the area of Clark, Cleveland, and Dallas Counties, Plebuch and Hines (1969) report that two industrial wells south of Arkadelphia yielded 240 gal/min, with transmissivities of 1,997 and 1,765 $ft^2/d$ and storage coefficients of 0.0032 and 0.0038. A nearby well had a transmissivity of 400 $ft^2/d$, which indicates a wide variability for aquifer properties in the area. Groundwater in this area is under water-table conditions. In most locations, the aquifer is in hydraulic connection with Pleistocene-age alluvial deposits, and no distinction is made between the groundwater from all of these combined alluvial deposits.

#### Water Quality

Unlike the Red River alluvial aquifer, which is contained in alluvial deposits from only the Red River, alluvial deposits constituting the Ouachita-Saline Rivers alluvial aquifer are thin, restricted in areal extent, and incise older Pleistocene terrace deposits of the Mississippi River. Many historical reports refer to wells that are within these basins as being completed in the Ouachita-Saline Rivers alluvial aquifer, which often are actually completed in the older Pleistocene terrace deposits. Therefore, for purposes of this section of the report, water quality will be reported for groundwater within the alluvial deposits of the Ouachita River and Saline River Basins as the Ouachita-Saline Rivers alluvial aquifer without discriminating between these deposits (figs. 3 and 8). This situation is similar to the alluvial deposits of the Arkansas River between Little Rock and the Mississippi River being undistinguishable from, and referenced as part of, the Mississippi River Valley alluvial aquifer (see section on "Arkansas River Valley Alluvial Aquifer").

Kresse and Fazio (2002) compared groundwater-quality data from Pleistocene-age terrace and Holocene-age flood-plain deposits in southeastern Arkansas and noted significantly lower iron, manganese, barium, and arsenic concentrations in groundwater from the older Pleistocene-age terrace deposits, although mean and median concentrations of dissolved solids and pH values were similar for both deposits. Gonthier (2003) reported on groundwater quality throughout the Mississippi embayment, including Arkansas, and noted that barium, potassium, dissolved organic carbon, iron, ammonia, phosphorus, and dissolved-solids concentrations were greater in groundwater from Holocene alluvium than from Pleistocene valley trains. Kresse and Fazio (2003) also reported on the occurrence of elevated arsenic in the Mississippi River Valley alluvial aquifer of southeastern Arkansas and similarly found significantly lower concentrations of arsenic, barium, iron, manganese, boron, ammonia, total phosphorus, and total organic carbon in groundwater from the older Pleistocene-age terrace deposits compared to the younger, Holocene-age flood-plain deposits. Other researchers (Davies and Exley, 1992; Bangladesh Agricultural Development Corporation, 1992; British Geological Survey, 2001; Ravenscroft, 2003) attributed geochemical differences in alluvial deposits to extensive flushing through time to account for the lack of iron, arsenic, and other trace metals in older Pleistocene alluvial deposits, which could account for the differences in water quality for these deposits in Arkansas. Consequently, the geochemistry and general water quality of groundwater from the Ouachita-Saline Rivers alluvial aquifer might be expected to be similar to groundwater in the Pleistocene-age deposits of the Mississippi River Valley alluvial aquifer.

Although only limited trace-metal data were available, these data appear to support the discussion of water quality in wells completed in Pleistocene alluvial deposits in southeastern Arkansas. Arsenic concentrations in the Ouachita-Saline Rivers alluvial aquifer were less than 2.0 µg/L, most iron concentrations were less than 300 µg/L (fig. 26), all but four sulfate concentrations were below 25 mg/L (fig. 26), dissolved-solids concentrations generally were less than 250 mg/L, and all but one silica concentrations were less than 25 mg/L (fig. 26). Numerous wells completed in the Ouachita-Saline Rivers alluvial aquifer had nitrate concentrations more than 10 mg/L (fig. 26), particularly in Calhoun and Bradley Counties. Because most of the wells sampled in this area had well depths less than 30 ft, they possibly are shallow domestic wells, which are more vulnerable to surface sources of nitrate (for example, septic systems). Additionally, shallow groundwater is not under reducing conditions that are typical for groundwater from the deeper parts of the aquifer (see “Source of Elevated Trace Metals” in the section “Mississippi River Valley Alluvial Aquifer”).

## Jackson Group

The Jackson Group comprises an upper Tertiary-age (Late Eocene) sequence of largely unconsolidated clays with rare, interbedded siltstone and sandstone units. Because of the predominance of fine-grained sediments and overall low hydraulic conductivity, the Jackson Group is designated as a regional confining unit, although groundwater in deposits of the Jackson Group served in the past as an important source of water supply throughout a large part of southeastern Arkansas. Because the Jackson Group is composed of thick, clayey deposits that impede vertical flow of water, it is referred to regionally as part of the Vicksburg-Jackson confining unit (Arthur and Taylor, 1990; Hosman and Weiss, 1991; Renken, 1998). The Jackson Group is included in regional hydrogeologic framework models. It is listed as the Vicksburg-Jackson confining unit separating the Claiborne Group from Quaternary deposits in regional models of Clark and Hart (2009) and Arthur and Taylor (1998). The southern extent of the subcrop served as the western boundary of the Mississippi River Valley alluvial model of Ackerman (1996).

In spite of its designation as a regional confining system, groundwater contained in thin sandy sections of the Jackson Group served a large number of users through the 1990s, primarily as a source of domestic and small farm supply. Throughout southeastern Arkansas, this group of deposits can be considered a minor aquifer because of poor yields and lack of an economical supply for industrial, public, irrigation, and other important uses. In concert with low yields of groundwater from the Jackson Group, groundwater quality is some of the poorest of any aquifer in Arkansas.

### Hydrogeologic Setting

The Jackson Formation was named by Conrad (1856) for type exposures at Jackson, Miss. The Jackson epoch completed the main filling of the Mississippi embayment (Veatch, 1906), and the structure of the Jackson and Cockfield Formations is framed by basinal downwarp with maximum downwarping in Desha and Lincoln Counties (Broom and Reed, 1973; Spooner, 1935). The Jackson Group contains marine and nonmarine beds (Stephenson and Crider, 1916; Wilbert, 1953; Onellion and Criner, 1955). The exposures at Crowleys Ridge are of a nearshore marine origin and were deposited during the last transgression into Arkansas (Guccione and others, 1986). The Jackson Group deposits of Late Eocene age occur in the subsurface throughout eastern Arkansas (Bedinger and Reed 1961; Saucier, 1994; Kresse and Fazio, 2002).

The largest area of outcrop of the Jackson Group in Arkansas is located south of the Arkansas River (fig. 3) in Jefferson, Lincoln, Cleveland, Drew, and Bradley Counties. A very narrow outcrop (not shown at the scale of fig. 3) also occurs north of the Arkansas River at the base of Crowleys Ridge from northern St. Francis County to the termination of the ridge in Phillips County. The Jackson Group unconformably overlies the Claiborne Group and is unconformably overlain by Mississippi River Valley alluvial deposits (Stephenson and Crider, 1916; Fisk, 1944). The Jackson Group comprises a series of clays with variable abundances of fossils, gypsum, marls, carbonate lenses, and lignite (Veatch, 1906; Hosman and Weiss, 1991); sands units are a minor but important occurrence (Stephenson and Crider, 1916). The clays are typically light gray to dark greenish or blueish gray and, when oxidized, may be red, pink, yellow, and brown. The clays are thinly laminated and, in some areas, include cross-bedded, fine- to coarse-grained sand (Stephenson and Crider, 1916). Although undifferentiated in this report, the Jackson Group can be divided in southeastern Arkansas into the marine White Bluff Formation (Dall, 1898) comprising marl, sand, and clay, and the nonmarine Redfield

Formation (Wilbert, 1953) containing lignitic sediment. The Jackson Group is the uppermost unit in the Tertiary System and, when overlain by Quaternary alluvium, is a confining bed between the Claiborne Group and the Quaternary alluvium (Petersen and others, 1985; Hosman and Weiss, 1991).

In southeastern Arkansas, the outcropping Jackson Group forms a high-altitude zone referred to as the Monticello Ridge. Alluvial terraces overlap the Jackson Group and older deposits in most of Ashley County. The Jackson Group and clays of the upper Cockfield Formation generally function as confining strata at the base of the alluvial aquifer in this area. Along the Monticello Ridge, the Jackson may exceed 400 ft in thickness. In a few places in Chicot County, the Jackson Group is only a few feet thick; in some areas of Ashley County, the Jackson has been entirely eroded and alluvial deposits rest on the Cockfield Formation (Broom and Reed, 1973).

The Jackson Group is often difficult to distinguish from underlying formations. Where the underlying upper Claiborne Group (Cockfield Formation, Cook Mountain Formation) contains clay, these clays often are included as part of the Jackson Group (Hosman and Weiss, 1991). In Bradley, Calhoun, and Jefferson Counties, the upper part of the Cockfield contains substantial clay and is difficult to differentiate from clays of the Jackson Group without paleontological evaluation (Albin, 1964; Kresse and Huetter, 1999). In Bradley County, the Jackson Group is about 300 ft in thickness and consists mainly of gray, brown, and green silty clay and some lignite and was deposited under mostly marine conditions (Albin, 1964). The Jackson Group is divided into two distinct units in Arkansas: the White Bluff and Redfield Formations. In Grant County, the White Bluff Formation is composed of very fine clay and silty clay. Much of the Jackson Group is fossiliferous with hardened ferruginous layers locally. In some areas, very fine-grained sand interbedded with silt and silty clay occurs. The Redfield Formation in Grant County consists primarily of interbedded lignitic silts and clays with minor layers of fine sand (Halberg and others, 1968). The Jackson Group, as much as 200 ft in thickness, crops out in Cleveland County and consists of gray, brown, and green silty clay with some lignite and sand (Plebuch and Hines, 1969). In Chicot County, the Jackson Group consists of blue to gray clay, sandy clay, and thin beds of gray sand. The maximum thickness in Chicot County is 200 ft, and the Jackson Group serves as a confining bed for the Cockfield (Onellion and Criner, 1955).

Along the margins of the southern part of Crowleys Ridge, the Jackson Group overlies the Claiborne Group, is about 500 ft in thickness, and is composed of sandy clay, silt, and glauconitic, fossiliferous sandy clay (Guccione and others, 1964). In Monroe County, the undifferentiated Jackson Group underlies most of the area with an average thickness of about 30 ft and a range of thickness from near zero to about 50 ft. In this area, the Jackson Group consists of clay, silty clay, and minor amounts of silt and very fine-grained sand and acts as a confining unit between the Sparta aquifer and the Mississippi River Valley alluvial aquifer (Morris and Bush, 1986). Producing wells have not been identified in this area of the State. Discussions of deposits of the Jackson Group as a viable aquifer are confined to southeastern Arkansas.

Yields to hand-dug (less than 50 ft) and drilled wells (125–204 ft) in Grand and Hot Spring Counties are reported to be very small (Halberg and others, 1968). In parts of southeastern Arkansas, the Jackson Group generally does not yield water to wells in usable quantities (Broom and Reed, 1973). Plebuch and Hines (1969) reported small yields to domestic wells in Cleveland County with total water use of 0.04 Mgal/d in 1965 (Halberg and Stephens, 1966), and water levels ranged from 6 to 60 ft below land surface. The Jackson Group is not considered to be a source of water in Chicot County (Onellion and Criner, 1955).

## Water Use

Groundwater use from the Jackson Group was confined almost solely to a large area of exposed deposits south of the Arkansas River. Because of the extensive clay content of sediments constituting the Jackson Group, yields were low and thus were sufficient for only domestic and livestock supply. Plebuch and Hines (1969) reported that the aquifer "… yields only small amounts of water and is utilized only for domestic purposes." Halberg and others (1968) similarly reported low yields throughout much of the extent of the Jackson Group and stated that where larger supplies were needed, wells would have to be drilled into the underlying Cockfield or Sparta Sand Formations. Halberg and others (1968) did not provide values for the yields, but stated the formation was tapped primarily by hand-dug and shallow-drilled wells for domestic purposes. Kresse and Fazio (2002) reported that prior to 1960, a minimum of 90 wells in Drew and Lincoln Counties and 6 wells in Jefferson County were in use as sources for farm and domestic supply. Until the advent of public supply systems in Arkansas, which currently serve numerous large and small urban communities in addition to outlying rural areas, homeowners often had to rely on available shallow groundwater resources as a cost-effective supply of water. Public water-supply sources have replaced use of groundwater from the Jackson Group. Remaining operational wells located in 1999 and 2000 by Kresse and Fazio (2002) were used solely for watering gardens and other ancillary domestic purposes. Kresse and Fazio (2002) reported that most of the wells completed in the Jackson Group were less than 50 ft, with many less than 30 ft. Only four wells were found to be deeper than 50 ft, ranging upward to 150 ft below land surface.

Water-use data for the Jackson Group from 1965 to 1980 are shown in table 20. Water-use data were not collected for this aquifer after 1980. No well depths were available in the USGS NWIS database. The combined effects of poor yields, undesirable water quality, and available public supply have rendered the Jackson Group effectively obsolete as a viable water-supply source at the time of this report (2013).

**Table 20.** Water use from the Jackson Group in southeastern Arkansas, 1965–80.

[Counties shown are only those with published data. Data from Halberg and Stephens (1966); Halberg (1972, 1977); Holland (1981). Units are million gallons per day]

| County | 1965 | 1970 | 1975 | 1980 |
|---|---|---|---|---|
| Bradley | 0.01 | 0.05 | 0.02 | 0.02 |
| Cleveland | 0.04 | 0.03 | 0.06 | 0.08 |
| Drew | 0.12 | 0.33 | 0.26 | 0.48 |
| Grant | 0.06 | 0.02 | 0.01 | 0.01 |
| Jefferson | 0.21 | 0.06 | 0.03 | 0.04 |
| Lincoln | 0.27 | 0.12 | 0.07 | 0.07 |
| **Total** | **0.71** | **0.61** | **0.45** | **0.70** |

## Water Quality

Several historical reports discuss the poor quality of groundwater derived from deposits of the Jackson Group, highlighting elevated sulfate, iron, and dissolved solids. Klein and others (1950) showed sulfate concentrations exceeding 100 mg/L in 5 of 18 groundwater samples in Jefferson County and ranging upward to 243 mg/L; the groundwater ranged from a sodium-bicarbonate to a sodium-sulfate water type. Onellion (1956) cited numerous incidences of high sulfate concentrations (maximum concentration of 1,256 mg/L), frequent occurrence of elevated chloride, and appreciable dissolved solids in waters from the Jackson Group in Drew County. Bedinger and Reed (1961) discussed variation in the water quality (described as poor to fair) in groundwater samples from the Jackson Group in Lincoln County and stated that the water was high in sulfate, although less mineralized than groundwater in Drew County. Their data revealed a wide range in sulfate concentrations, with a maximum of 2,360 mg/L (Bedinger and Reed, 1961). Halberg and others (1968) reported on one groundwater sample from Grant County that was a dilute, sodium-sulfate water type, slightly acidic, and with high iron concentration—this sample additionally contained 1.7 mg/L sulfides as hydrogen sulfide. Plebuch and Hines (1969) also noted high sulfate concentrations resulting from the presence of gypsum throughout the formation and stated that high sulfate was the major complaint by domestic users from a list of complaints in regard to water quality. Four samples collected from wells in Cleveland County showed iron concentrations ranging from 0.24 to 37 mg/L, dissolved-solids concentrations ranging from 198 to 2,650 mg/L, and sulfate concentrations ranging from 37 to 1,030 mg/L (Plebuch and Hines, 1969). A well completed in the Jackson Group in the Bayou Bartholomew watershed had a sodium concentration of 243 mg/L (more than three times the maximum concentration for 118 Mississippi River Valley alluvial aquifer samples); the sulfate concentration in this well was 211 mg/L, and boron and zinc also were elevated with respect to all 118 Mississippi River Valley alluvial aquifer samples (Kresse and Fazio, 2002).

### General Geochemistry and Water Type

In spite of the lack of importance of the Jackson Group as a regional source of water supply, an inspection of the USGS NWIS database revealed 68 samples with associated groundwater-quality data. This is in large part a result of the earlier, countywide, water-assessment reports, which were conducted at a time when the Jackson Group was locally important as a source of shallow domestic groundwater.

Groundwater from the Jackson Group varies by water type but dominantly is a sodium- and calcium-sulfate water type with other mixed water types occurring in various areas of the aquifer. Unique to most aquifers in Arkansas, sulfate, rather than bicarbonate, was the dominant anion for most of the 51 samples with a complete major anion (bicarbonate, chloride, and sulfate) chemical analysis. Sulfate was the dominant anion in 27 of 51 samples and greater than 50 percent (as much as 94 percent) of the anions in 20 samples. Chloride was the dominant anion in 13 samples (greater than 50 percent in 10 samples). Bicarbonate was the dominant anion in 11 samples (greater than 50 percent for 8 samples). For 37 samples with a complete cation analysis, sodium was the dominant cation in 21 samples (greater than 50 percent in 16 of 37 samples). Calcium was the dominant cation in 14 samples (greater than 50 percent in only 4 of 37 samples).

Values of pH in 67 samples ranged from 2.9 to 8.0 with a median value of 6.5 (table 21). Twenty samples (30 percent) had pH values less than 5.0 and 40 (60 percent) had pH values less than 7.0, demonstrating the prevalence of strongly to slightly acidic water throughout the extent of the aquifer. Twelve of the samples with pH values less than 5.0 had specific conductance values of 2,000 µS/cm ranging up to 5,490 µS/cm; thus, the lowest pH values occurred at wells with the greatest specific conductance values (corresponding to higher dissolved-solids concentrations) (fig. 32*A*). This situation is contrary to most other aquifers in Arkansas that commonly show increasing pH values with increasing carbonate mineral dissolution and resultant increases in bicarbonate and dissolved-solids concentrations. The prevalence of low-pH values, high sulfate concentrations, and high dissolved-solids concentrations strongly suggests oxidation of pyrite as a dominant control on groundwater geochemistry in the Jackson Group. Oxidation of pyrite has been shown to be a common cause of low-pH, high-sulfate water (Nordstrom and others, 2000).

**Table 21.** Descriptive statistics for selected chemical constituents in groundwater from the Jackson Group in southeastern Arkansas.

[mg/L, milligrams per liter; µg/L, micrograms per liter; NA, not analyzed; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

| Constituent or characteristic | Minimum | Median | Maximum | Standard deviation | Number of wells |
|---|---|---|---|---|---|
| Calcium (mg/L) | 1.3 | 26 | 500 | 132 | 37 |
| Magnesium (mg/L) | 0.2 | 13 | 333 | 72.9 | 37 |
| Sodium (mg/L) | 2.3 | 57 | 618 | 140 | 37 |
| Potassium (mg/L) | 0.1 | 8.2 | 67 | 13.9 | 27 |
| Bicarbonate (mg/L) | 1.0 | 32 | 302 | 94 | 51 |
| Chloride (mg/L) | 2.5 | 35 | 845 | 155 | 67 |
| Sulfate (mg/L) | 0.6 | 110 | 3,080 | 717 | 67 |
| Silica (mg/L) | 3.1 | 37 | 100 | 22.6 | 16 |
| Nitrate (mg/L as nitrogen) | 0.01 | 0.54 | 38 | 7.89 | 63 |
| Dissolved solids (mg/L) | 11 | 443 | 5,330 | 1,080 | 35 |
| Iron (µg/L) | 0.05 | 100 | 19,000 | 3,870 | 61 |
| Manganese (µg/L) | 20 | 65 | 370 | 142 | 4 |
| Arsenic (µg/L) | NA | NA | NA | NA | NA |
| Hardness (mg/L as calcium carbonate) | 4.0 | 140 | 2,600 | 629 | 67 |
| Specific conductance (µS/cm) | 36 | 701 | 5,490 | 1,340 | 68 |
| pH (standard units) | 2.9 | 6.5 | 8.0 | 1.5 | 67 |

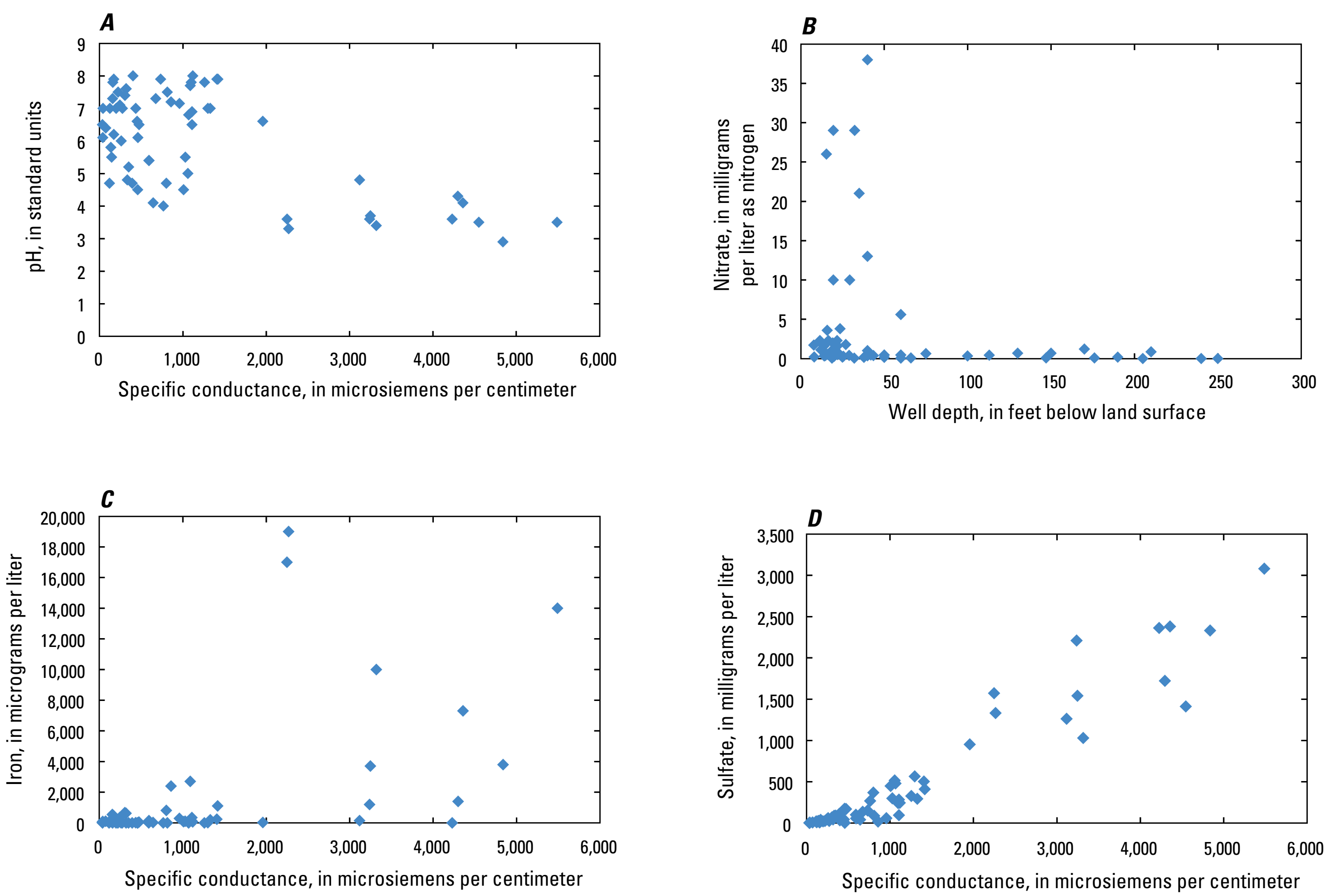



**Figure 32.** Graphs showing relation of *A*, specific conductance and pH; *B*, well depth and nitrate; *C*, specific conductance and iron; and *D*, specific conductance and sulfate in groundwater from Jackson Group in southeastern Arkansas.

## Nitrate

Nitrate concentrations for 63 samples ranged from 0.01 to 38 mg/L with a median concentration of 0.54 mg/L (table 21). Twenty-three sites had nitrate concentrations greater than or equal to 1.0 mg/L, and 8 of these sites had concentrations exceeding the Federal MCL of 10 mg/L (U.S. Environmental Protection Agency, 2009). Elevated nitrate concentrations generally were found in the more shallow wells. All but one well with nitrate concentrations greater than 1.0 mg/L had well depths of 40 ft or less below land surface—a strong indication of the increased vulnerability of shallow wells to surface sources of contamination (fig. 32*B*).

## Iron

Iron concentrations in 61 samples ranged from 0.05 to 19,000 µg/L with a median concentration of 100 µg/L (fig. 33; table 21). All iron concentrations greater than 3,000 µg/L occurred where specific conductance values were greater than 2,000 µS/cm (fig. 32*C*). Similarly, sulfate concentrations greater than 900 mg/L occurred where specific conductance values were greater than 2,000 µS/cm. There was a positive, linear relation between sulfate and specific conductance for specific conductance values greater than 1,000 µS/cm (fig. 32*D*). These relations, together with the trend of decreasing pH beyond a conductance of 2,000 µS/cm, adds supporting evidence identifying oxidation of pyrite as a principal source of the low-pH, high-sulfate, high-iron content found in groundwater in the Jackson Group. The greatest density of elevated (more than 1,000 µg/L) iron concentrations occurred in Drew County (fig. 34).

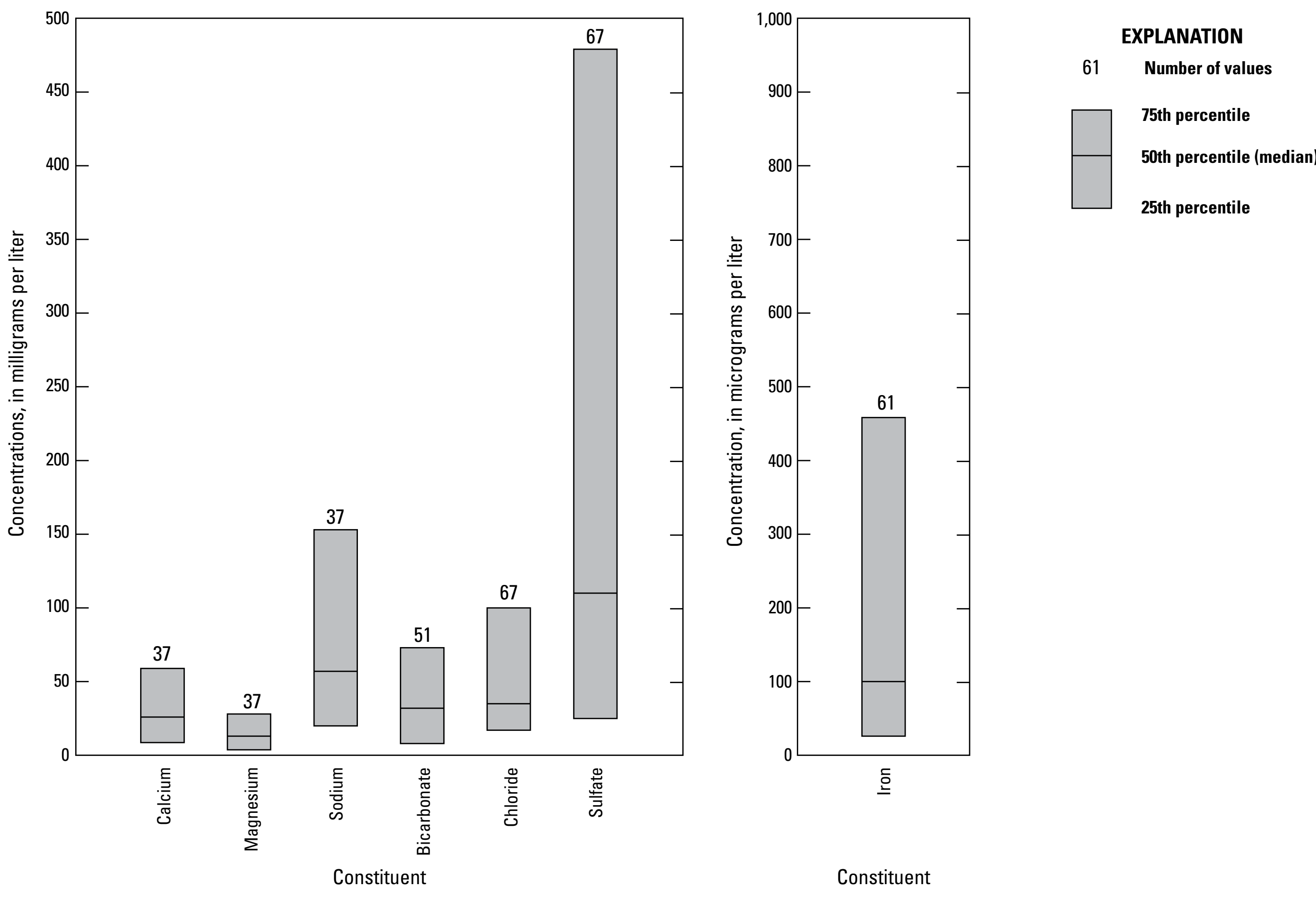



**Figure 33.** Interquartile range for selected chemical constituents in groundwater from the Jackson Group in southeastern Arkansas.

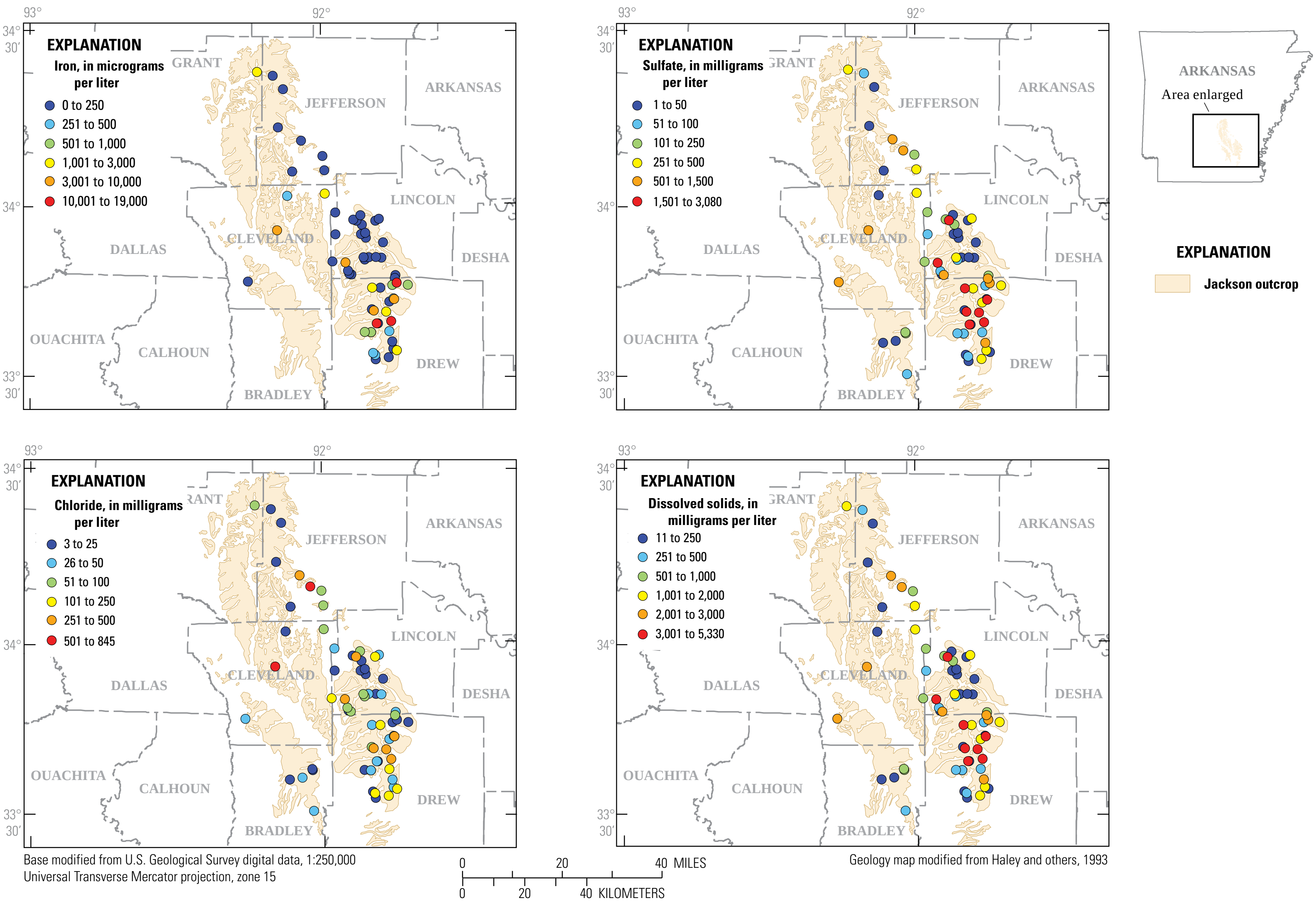



**Figure 34.** Spatial distribution of selected chemical constituents in groundwater from the Jackson Group in southeastern Arkansas.

### Sulfate

Sulfate concentrations, as mentioned above, can be elevated in groundwater from the Jackson Group. Sulfate data were available for 67 samples; concentrations ranged from 0.6 to 3,080 mg/L with a median of 110 mg/L (fig. 33; table 21). Twelve of the 67 samples had concentrations exceeding 1,000 mg/L, and 26 samples had concentrations exceeding the Federal secondary drinking-water regulation of 250 mg/L for sulfate (U.S. Environmental Agency, 2009). A spatial distribution of sulfate concentrations shows that the highest concentrations generally occurred in Drew County. Five of the seven samples with sulfate concentrations exceeding 1,500 mg/L were from wells in Drew County with the other two located in Lincoln County (fig. 34). Although these patterns suggest that some of the poorest quality of water is in the southern extent of the aquifer system, the fact that low sulfate concentrations also occur in this area indicates the lack of a clear spatial pattern for Jackson Group groundwater geochemistry. Most of the elevated sulfate concentrations, as noted above, appear to be the result of oxidation of pyrite. The abundance of clayey sediments and occurrence of lignite throughout the aquifer provide a setting for reducing conditions supporting formation of pyrite. Later infiltration of oxygenated water may be the source of redox changes that result in oxidation of pyrite and generation of low-pH, high-sulfate groundwater.

### Chloride

Chloride concentrations ranged from 2.5 to 845 mg/L with a median concentration of 35 mg/L (fig. 33; table 21). Nine of 67 samples with chloride data had concentrations that exceeded the Federal secondary drinking-water regulation of 250 mg/L. All but one chloride concentration were below 50 mg/L for specific conductance values of less than 500 µS/cm. Similar to trends noted for sulfate, chloride concentrations generally increased with increasing specific conductance. Chloride concentrations greater than 100 mg/L occurred almost solely in samples with specific conductance values greater than 850 µS/cm. Only 35 of the 67 samples had values for dissolved solids; 16 (46 percent) of these had concentrations that exceeded the secondary drinking-water regulation of 500 mg/L. A spatial distribution of dissolved-solids and chloride concentrations revealed a slightly greater concentration of relatively elevated concentrations in Drew County (fig. 34). However, only about half as many sites had available dissolved-solids data compared to sulfate and chloride (table 21), which resulted in too few analyses for making strong statements in regard to spatial trends.

The lack of a well-defined spatial pattern for chloride (and for other geochemical constituents) probably is related to the scale differences in regional and local groundwater flow paths. Many shallow aquifer systems, such as the fractured surficial bedrock aquifers of the Interior Highlands, do not have well-connected, regional flow paths but rather short, isolated flow paths with groundwater traveling locally from hilltops to valleys in small watersheds. Geochemical evolution for groundwater moving along a flow path within an aquifer is dependent on available reactive minerals, flow velocities affecting residence time, redox changes, and other rock/water interaction processes. The Jackson Group reflects this type of aquifer system because it is a shallow aquifer composed of clay and interbedded sand units that are not regionally extensive and it is not an adequate thickness to serve as a large yield aquifer for multiple uses. Hence, local flow patterns and local variation in permeability play an important role in geochemical evolution on a local scale that cannot be discerned from a regional-scale analysis.

In summary, groundwater from the Jackson Group has some of the poorest water quality of any aquifer in the State, especially in view of its extensive use in the past as a source of farm and domestic water supply. Sulfate concentrations are especially elevated in the aquifer; concentrations ranged upward to a maximum of 3,080 mg/L and 12 of 67 samples exceeded 1,000 mg/L. Additionally, most groundwater samples were of a calcium- and sodium-sulfate water type. Correlations of elevated sulfate concentrations to elevated iron concentrations and extremely low-pH groundwater strongly suggest that oxidation of pyrite in some regions of the aquifer contribute to this water type. Nitrate concentrations revealed an inverse correlation with well depth, reflecting increased vulnerability to surface sources of contamination. Residents previously using groundwater from the Jackson Group are now serviced by public-supply sources. The combined effects of poor yields, undesirable water quality, and available public supply have rendered the Jackson Group effectively obsolete as a viable water supply.

## Cockfield Aquifer

The Cockfield aquifer contains groundwater of high quality that is used throughout southeastern Arkansas. The Cockfield aquifer was described as a distinct and separate aquifer in an assessment of water resources of the Mississippi embayment by Hosman and others (1968); however, in later regional hydrogeologic framework analyses in the Mississippi embayment, the Cockfield Formation was included with undifferentiated sands of the underlying Cook Mountain Formation (middle Claiborne confining unit) and overlying Jackson Formation (Vicksburg-Jackson confining unit) as part of the upper Claiborne aquifer (Arthur and Taylor, 1990; Hosman and Weiss, 1991; Hart and others, 2008; Clark and Hart, 2009). Recent reports on groundwater use (Holland, 2007) and on potentiometric surfaces (Pugh, 2010) in Arkansas retain the common usage of “Cockfield aquifer.” For purposes of this report, the saturated part of the Cockfield Formation will be referred to as the Cockfield aquifer.

## Geologic Setting

The name Cockfield was first used by Vaughn (1895) to describe Eocene- (Tertiary) age beds in northwestern Louisiana (Payne, 1975). The Cockfield Formation is the uppermost and youngest formation of the Claiborne Group, which includes the Cockfield Formation, Cook Mountain Formation, Sparta Sand, Cane River Formation, and Carrizo Sand (table 3). The Cockfield Formation conformably overlies the Cook Mountain Formation and is unconformably overlain by the Jackson Group or Quaternary alluvium in Arkansas (Onellion and Criner, 1955; Hosman and others, 1968).

The Cockfield Formation generally consists of fine- to medium-grained sand in the basal part and silt, clay, and lignite in the upper part. The beds are discontinuous and contain carbonaceous material throughout (Hosman and others, 1968). The basal part of the overlying Jackson Group may contain beds of fine sand that are in contact with the Cockfield in south-central Arkansas. These sands are difficult to differentiate from the Cockfield Formation and are likely in hydraulic connection (Ackerman, 1987a; Pugh, 2010). The sand beds yielding the greatest amount of groundwater are located near the base of the formation (Pugh, 2010). Deposits of the formation are considered nonmarine in origin (Veatch, 1906) and were deposited as a result of the action of longshore currents and deltaic distributary channels within a nearshore marine environment (Lautier, 1981). The lower sand facies of the formation represent a delta front (Merrill and others, 1985), and the upper carbonaceous interbedded shale and sand facies represent a delta-plain depositional environment.

The Cockfield Formation is part of a north-northeast trending syncline, the Mississippi embayment, which plunges to the south-southwest, approximately centered beneath the Mississippi River (Hosman and others, 1968; Pugh, 2010). The formation dips southeast and toward the axis of the embayment (Hosman and others, 1968; Petersen and others, 1985). Similar to other Tertiary formations, the dip of the formation controls the regional direction of groundwater flow in the Cockfield aquifer. The formation crops out extensively over south-central Arkansas and is exposed over most of Union County as well as parts of Bradley, Cleveland, Dallas, Grant, and Saline Counties (Hosman and others, 1968; Hosman, 1982; Petersen and others, 1985). The formation has not been observed in outcrop or identified in the subsurface north of about latitude 35 degrees (Hosman and others, 1968).

Thickness of the Cockfield Formation near the outcrop generally ranges from 100 to 400 ft with a maximum thickness of approximately 700 ft. Considerable variability is noted in unit thickness and grain-size distribution across the outcrop area. In the southwestern part of the outcrop in Columbia County, the formation is composed of interbedded sand and clay with occasional thin beds of lignite with a maximum formation thickness of approximately 100 ft. Medium-grained sand beds are dominant in the formation and usually are thin and lenticular. Individual beds seldom exceed 20 ft in thickness (Tait and others, 1953). To the northeast in Union County, the formation is composed of interbedded, lenticular beds of lignitic sand and clay with a maximum formation thickness of 300 ft or more. Locally, the sand beds are as much as 100 ft thick and make up 50–75 percent of the formation's thickness (Broom and others, 1984). Further northeast into Cleveland County, the formation is as much as 200 ft in thickness and consists mainly of silt and lignitic clay with interbedded sand. The sand beds generally are relatively thin with locally thicker sand beds (Plebuch and Hines, 1969). In the northeast extent of the outcrop area in Jefferson County, the sand beds are discontinuous, and the formation contains a considerable amount of clay (Klein and others, 1950; Kresse and Huetter, 1999). The formation thickens considerably in the subsurface downdip from the outcrop area. In Chicot County, the formation ranges from 300 to 625 ft in thickness and consists of largely gray to white fine- to medium-grained sand containing some lignite, some gray to brown sandy and silty clay, and occasional thin beds of lignite. Sand beds may reach a continuous thickness of as much as 300 ft but in most places is interbedded with layers of clay (Onellion and Criner, 1955).

## Hydrologic Characteristics

Recharge to the Cockfield aquifer is from precipitation on the outcrop and leakage through the overlying Mississippi River Valley alluvial aquifer in the subcrop area (fig. 3). Surface water in the area of outcrop also is a potential recharge source (Hosman and others, 1968; Broom and others, 1984; Petersen and others, 1985). Discharge of groundwater is to rivers in outcrop areas, to vertically adjacent units where the Cockfield aquifer is confined, and to wells (Ackerman, 1987a; Pugh, 2010). In the outcrop area and where overlain by Quaternary alluvium, the aquifer is under water-table conditions. Where overlain by the Jackson Group, the aquifer is under confined conditions. In the confined part of the aquifer, the potentiometric surface can be near or above land surface (Ackerman, 1987a; Pugh 2010).

The degree of hydraulic connection between sands within the Cockfield aquifer is not known (Hosman and others, 1968; Broom and others, 1984). In and near the outcrop area, well depths generally are shallow (less than 200 ft), and yields of most wells are small, less than 30 gal/min. Downdip from the outcrop area, well depths can exceed 600 ft, and wells screening the full thickness of the aquifer often yield 100–500 gal/min (Westerfield, 1994; Pugh, 2010). Pugh (2010) summarized aquifer test data from the aquifer. Based on data from 11 sites, the average specific capacity was 5.36 (gal/min)/ft with a minimum of 0.15 (gal/min)/ft and a maximum of 23.7 (gal/min)/ft. Based on data from four sites, the average transmissivity was 3,330 $ft^2/d$ with a minimum of 325 $ft^2/d$ and a maximum of 6,280 $ft^2/d$). Based on data from one site, the storage coefficient was 0.00026. Pugh (2010) also reported that the aquifer commonly yields less than 100 gal/min to wells with a maximum of 750 gal/min. An aquifer test in Chicot County yielded a transmissivity of approximately 6,800 $ft^2/d$, a storage coefficient of 0.0008, and a hydraulic conductivity of approximately 110 ft/d (Hosman and others, 1965). The maximum reported well yield in Chicot County was 410 gal/min (Onellion and Criner, 1955). In Columbia County, only domestic wells tap the aquifer (Tait and others, 1953). In Jefferson County, the aquifer and the Jackson Group are undifferentiated, and the average well yield from the combined aquifers is 5 gal/min (Klein and others, 1950; Kresse, 1999). The aquifer is used mainly as a source of domestic water supplies in Dallas and Cleveland Counties; however, the town of Kingsland in Cleveland County used groundwater from the Cockfield Formation for public supply. Well yields more than 300 gal/min are reported in Cleveland County (Plebuch and Hines, 1969).

## Water Use

The Cockfield aquifer is an important source of groundwater throughout eastern Arkansas. There is widespread use of the aquifer for domestic purposes, and yields are high enough in some areas to supply public and industrial systems (Petersen and others, 1985; Joseph, 1998b; Yeatts, 2004). In 2010, more than 50 percent of use occurred in Ashley County for public and industrial supply (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). The general locations of 70 wells with reported use from the aquifer in 2010 are shown in figure 35.

The earliest reports of water use from the Cockfield aquifer documented domestic wells scattered across southern and eastern Arkansas, including communities in Chicot, Cleveland, Dallas, Desha, Drew, Jefferson, Phillips, and Union Counties (Veatch, 1906). Many of these communities later reported public supply from the aquifer. Municipalities in Chicot County primarily drew from the aquifer in the early part of the 19th century. Water use was reported in Lake Village as early as 1910 and in Eudora in 1916 (Hale, 1927; Onellion and Criner, 1955). Both municipalities continue their use of the aquifer (Lyle Godfrey, Arkansas Health Department, written commun., 2012).

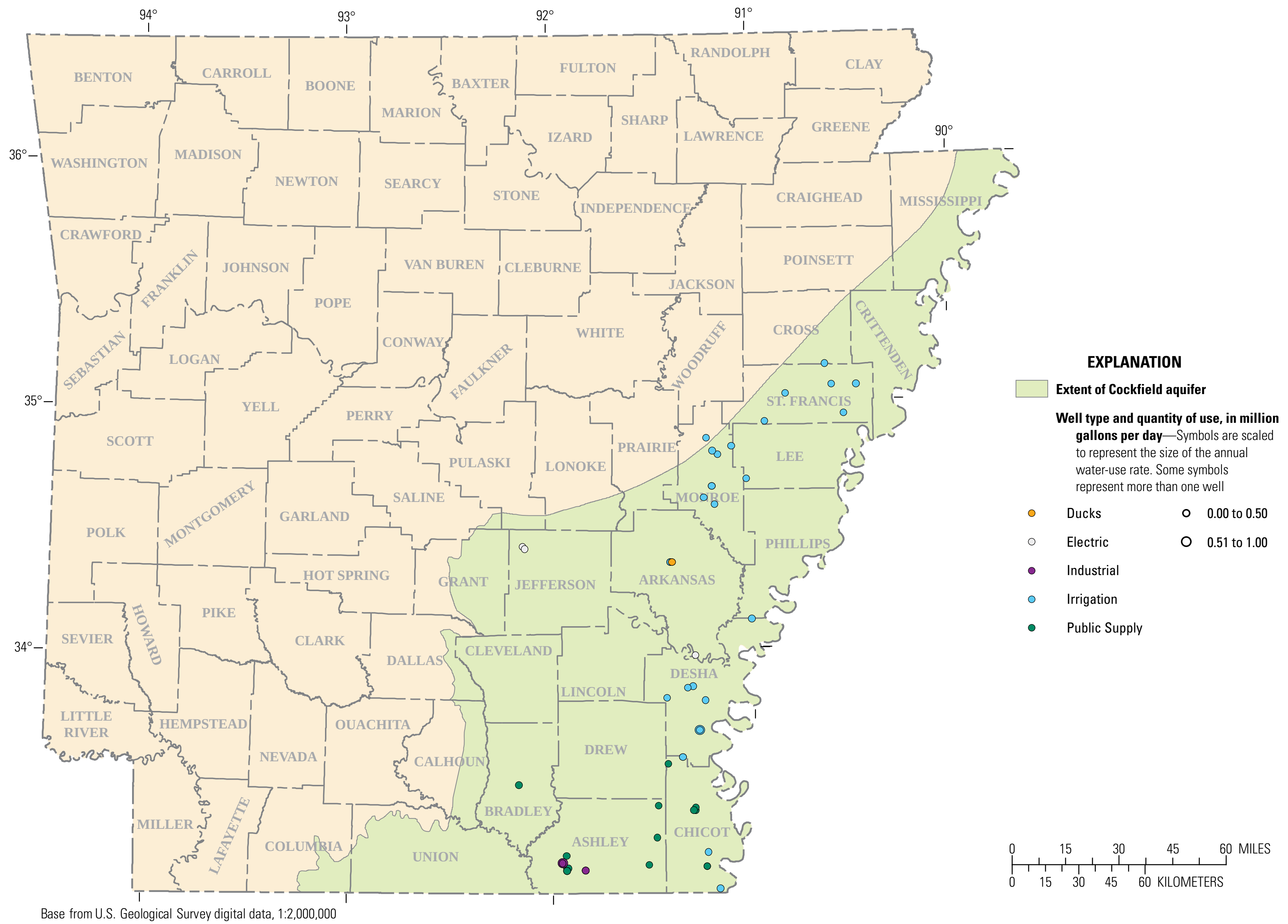



**Figure 35.** Wells with reported water use from the Cockfield aquifer in Arkansas, 2010.

Several municipalities using the Cockfield aquifer as their sole water-supply source eventually added other sources or changed their source with growing population and increasing water demands. Water use has correspondingly decreased in several counties (figs. 36 and 37; table 22) because many municipalities have switched their primary water supply from the Cockfield to the Sparta aquifer. McGehee (Desha County) used both the Sparta and Cockfield aquifers for a few decades in the middle part of the 1990s (Bedinger and Reed, 1961). Arkansas City (Desha County) and Kingsland (Cleveland County) were supplied solely by the Cockfield aquifer through the 1960s (Bedinger and Reed, 1961; Plebuch and Hines, 1969); however by the late 1970s, those three communities relied solely upon the Sparta aquifer for public supply (Lyle Godfrey, Arkansas Health Department, written commun., 2012). In Drew County, Wilmar and Winchester drilled wells into the Cockfield aquifer in 1902 and 1916, respectively, which were used until at least the 1950s (Onellion, 1956). Winchester currently (2013) uses the Sparta aquifer, while Wilmar taps the Cook Mountain Formation. Dermott (Desha County) began using the Cockfield aquifer in the 1920s and added the Sparta aquifer as a supplementary water source in 1960 (Lyle Godfrey, Arkansas Health Department, written commun., 2012).

Ashley County has been the greatest user of the Cockfield aquifer for public supply since ARWUDBS began and is the only county with increasing use of this aquifer (table 22). Water use from the Cockfield aquifer in Ashley County increased by more than 12,000 percent from 1965 to 2010 (fig. 37). Crossett used the Mississippi River Valley alluvial aquifer to provide public supply (Hale, 1926; Hewitt and others, 1949) from about 1900 until 1944, when the county began to share a well completed in the Cockfield aquifer with a lumber company. Three other Ashley County towns reported a cumulative use of approximately 0.065 Mgal/d for public supply in 1947 (Hewitt and others, 1949). Several public-supply wells were completed in the Cockfield aquifer near Crossett in the 1960s and 1970s, coinciding with an increase in use between 1965 and 1970 (Lyle Godfrey, Arkansas Health Department, written commun., 2012).

Public supply accounted for 17 percent of water pumped from the Cockfield aquifer in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). The aquifer ranks as the sixth highest-use aquifer for public supply in Arkansas after the Sparta, Wilcox, Mississippi River Valley alluvial, Arkansas River Valley alluvial, and lower Ozark aquifers. Ten municipalities use wells completed in the Cockfield aquifer for a source of public-supply water (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Ashley County used the largest amount from 2000 to 2010, with Crossett pumping a maximum of 1.26 Mgal/d in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Chicot County had the second highest rate of use for public supply in 2010, with Lake Village and Eudora using 0.83 and 0.51 Mgal/d, respectively in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

Rural domestic use from the Cockfield aquifer in south and south-central Arkansas has been locally important. Domestic users in Cleveland and Dallas Counties pumped a combined 0.12 Mgal/d in 1965 (Plebuch and Hines, 1969). Chicot County withdrew 0.5 Mgal/d for domestic use around the mid-1950s (Onellion and Criner, 1955). Cleveland and Dallas Counties together reported 0.12 Mgal/d in 1965 of domestic use (Plebuch and Hines, 1969). Ashley, Bradley, Calhoun, Columbia, Desha, Drew, Grant, and Lincoln Counties also used the Cockfield aquifer for domestic supply (Hewitt and others, 1949; Tait and others, 1953; Onellion, 1956; Bedinger and Reed, 1961; Albin, 1964; Halberg and others, 1968). Domestic use of the Cockfield aquifer continues to be locally important in southeastern Arkansas; however, domestic use is not reported to ARWUDBS and subsequently quantifiable data are not available.

Industrial use from the Cockfield aquifer has been locally important. During the oil boom of the early 1920s in southern Arkansas, large quantities of water were pumped from the Cockfield aquifer to supply water use for oil and gas exploration in Union County (Baker and others, 1948). In the city of El Dorado, Root Petroleum Company pumped 0.2 Mgal/d from 1921 to 1935 (Baker and others, 1948). El Dorado also relied on the Cockfield aquifer for public supply and reportedly pumped as much as 1.5 Mgal/d in the 1920s and 1930s (Baker and others, 1948). Public supply during this period increased greatly because of the population increase associated with petroleum production. Eventually, growing demand required other water sources, and El Dorado completed wells in the Sparta aquifer in 1935 (Baker and others, 1948). By the end of the 1940s, reliance on the Cockfield aquifer in southern Arkansas was decreasing as petroleum exploration and production declined. Since the 1940s, water supply in this area generally has been furnished from the Sparta aquifer and more recently from the Ouachita River (see “Sparta Aquifer” section).

Industrial use of the Cockfield aquifer is centered in Ashley County. As early as 1947, Ashley County reported 0.065 Mgal/d from the aquifer for paper and lumber mills (Hewitt and others 1949), constituting 5 percent of the total industrial water use for the county. The primary traditional source for industrial water use in Ashley County was the Mississippi River Valley alluvial aquifer; however, more recent water-use data from 1990 through 2010 have shown all industrial groundwater withdrawals were from the Cockfield aquifer (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Over 80 percent of the water used in Ashley County in 2010—8.40 Mgal/d—was for industrial purposes (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). A cone of depression surrounding Crossett was attributed to groundwater withdrawals (Pugh, 2010).

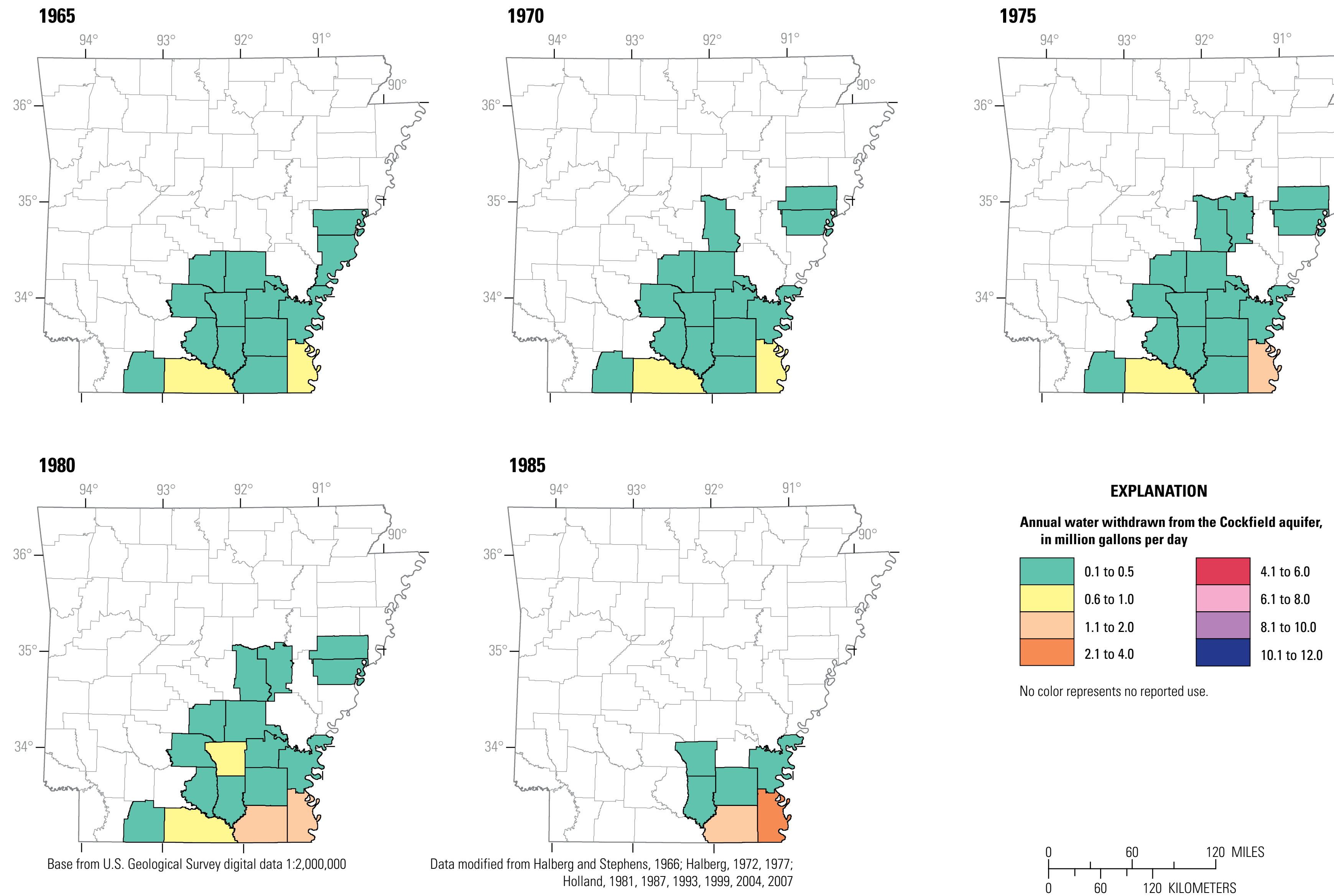



**Figure 36.** Water-use rates for the Cockfield aquifer in southeastern Arkansas from 1965 to 2010.

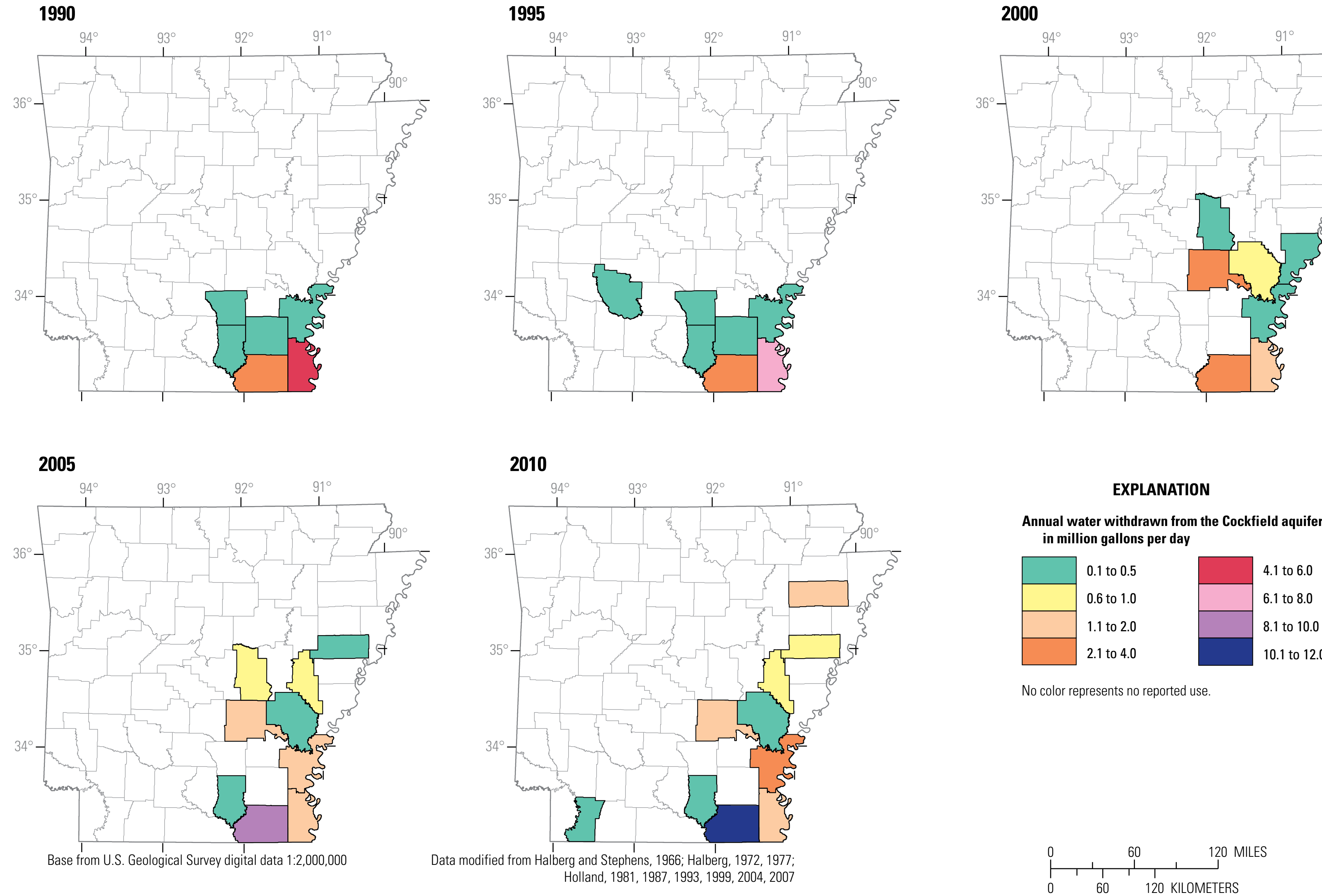



**Figure 36.** Water-use rates for the Cockfield aquifer in southeastern Arkansas from 1965 to 2010.—Continued

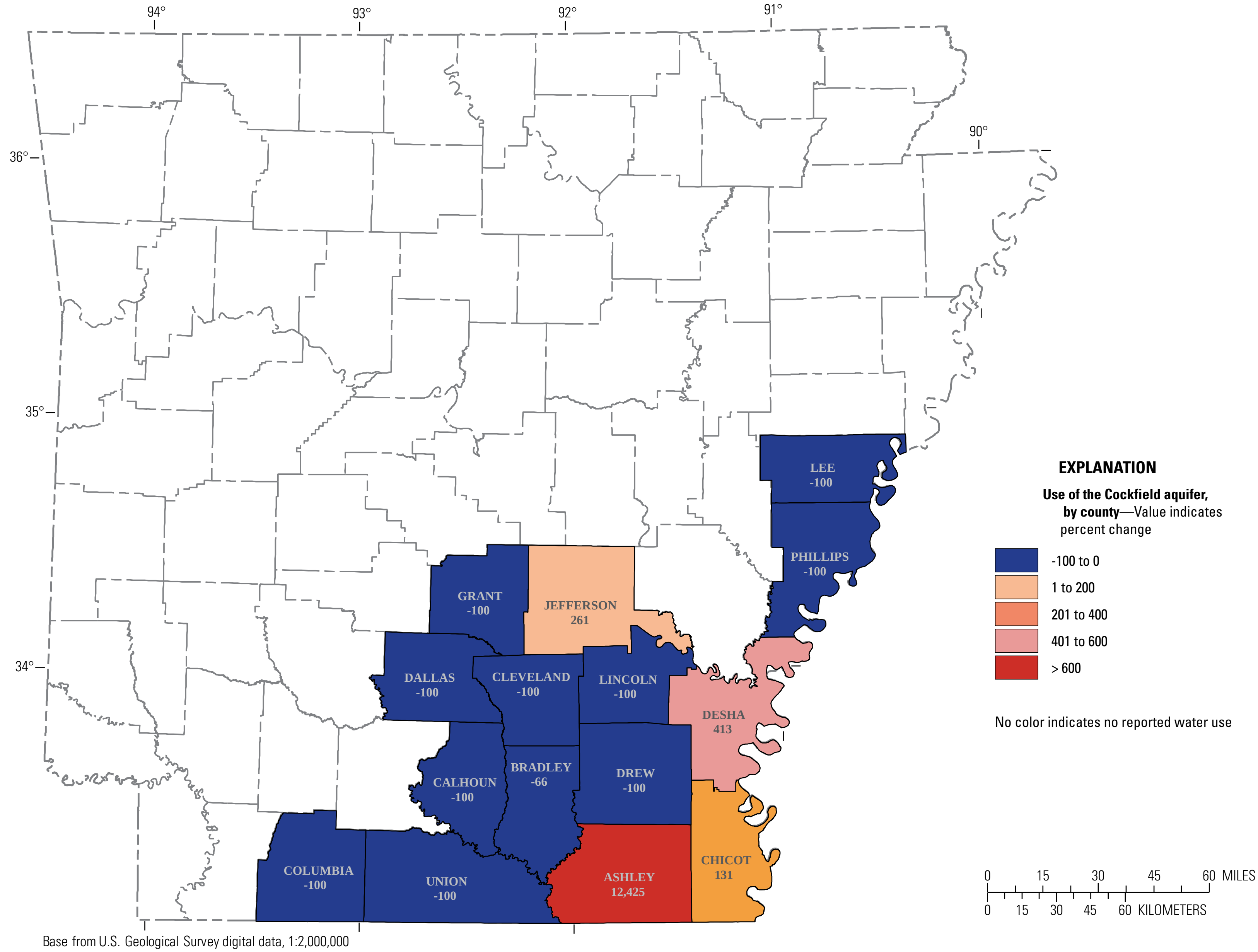



**Figure 37.** Change in percentage of water use from the Cockfield aquifer in southeastern Arkansas from 1965 to 2010.

**Table 22.** Water use from the Cockfield aquifer in southeastern Arkansas, 1965–2010.

[Counties shown are only those with published data. Data from Halberg and Stephens (1966); Halberg (1972, 1977); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1965 | 1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|
| Arkansas | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.57 | 0.48 | 0.38 |
| Ashley | 0.08 | 0.39 | 0.50 | 1.01 | 1.18 | 2.44 | 2.81 | 3.40 | 8.17 | 10.02 |
| Bradley | 0.29 | 0.42 | 0.27 | 0.38 | 0.17 | 0.11 | 0.10 | 0.00 | 0.08 | 0.10 |
| Calhoun | 0.18 | 0.24 | 0.26 | 0.39 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Chicot | 0.85 | 0.96 | 1.16 | 1.41 | 2.12 | 5.00 | 6.23 | 1.26 | 1.93 | 1.96 |
| Cleveland | 0.10 | 0.40 | 0.44 | 0.65 | 0.05 | 0.05 | 0.02 | 0.00 | 0.00 | 0.00 |
| Columbia | 0.14 | 0.27 | 0.34 | 0.38 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Crittenden | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.57 | 0.00 | 0.00 |
| Dallas | 0.02 | 0.07 | 0.07 | 0.08 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Desha | 0.40 | 0.46 | 0.34 | 0.44 | 0.18 | 0.38 | 0.48 | 0.24 | 1.58 | 2.05 |
| Drew | 0.12 | 0.23 | 0.21 | 0.48 | 0.13 | 0.11 | 0.12 | 0.00 | 0.00 | 0.00 |
| Grant | 0.08 | 0.23 | 0.19 | 0.21 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Jefferson | 0.31 | 0.30 | 0.17 | 0.23 | 0.00 | 0.00 | 0.00 | 3.42 | 1.97 | 1.12 |
| Lafayette | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| Lee | 0.02 | 0.02 | 0.02 | 0.06 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lincoln | 0.08 | 0.10 | 0.07 | 0.07 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lonoke | 0.00 | 0.37 | 0.30 | 0.45 | 0.00 | 0.00 | 0.00 | 0.08 | 0.90 | 0.00 |
| Monroe | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.94 | 0.95 |
| Phillips | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.38 | 0.00 | 0.00 |
| Poinsett | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.97 |
| Prairie | 0.00 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| St. Francis | 0.00 | 0.20 | 0.17 | 0.23 | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 | 0.67 |
| Union | 0.55 | 0.61 | 0.67 | 0.67 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Total** | **3.25** | **5.27** | **5.19** | **7.15** | **3.83** | **8.09** | **9.76** | **9.92** | **16.11** | **19.23** |

Total water use reported from the Cockfield aquifer has increased by almost 500 percent from 3.25 to 19.23 Mgal/d from 1965 to 2010, with much of this resulting from increased industrial use in Ashley County and for irrigation (figs. 35 and 36; table 22). Total water use increased 2.02 Mgal/d from 1965 to 1970 (table 22) when Lonoke and St. Francis Counties began reporting use, and several other counties (Ashley, Cleveland, Dallas, and Drew) had large increases. Water use during the 1970s was stable. A 38-percent increase in use was noted between 1975 and 1980 because of increased withdrawals during the drought of 1980. Pumping rates as well as the number of counties pumping from the Cockfield aquifer decreased from 1980 to 1985, decreasing from 17 counties reporting a total of 7.15 Mgal/d use in 1980 to 6 counties reporting a total of 3.83 Mgal/d use in 1985 (fig. 35; table 22). This decrease was likely because of the changes in reporting to ARWUDBS.

Water use from the Cockfield aquifer has increased steadily since 1985, with users relying more heavily on the aquifer as population grows and as other groundwater sources experience depletion. Traditionally, the Cockfield aquifer has been used less for irrigation, although irrigation has increased in many areas. As early as the 1950s, 20–30 wells in the Grand Prairie tapped the Cockfield aquifer for irrigation (Baker, 1955). Farmers in eastern Arkansas are increasingly turning to the Cockfield aquifer to support irrigation as water levels decline in the Mississippi River Valley alluvial aquifer. Since 2000, use of the aquifer has begun in several counties for the first time and most of this new use is for irrigation (fig. 35). By 2005, water use reported for the Cockfield aquifer in Monroe and St. Francis Counties was solely for irrigation. From 2000 to 2010, all water use reported for the Cockfield aquifer in Desha County was for irrigation, whereas in 1957 all irrigation water came from the Mississippi River Valley alluvial aquifer (Bedinger and Reed, 1961). A small amount from the Cockfield aquifer also has been used to flood fields for duck hunting in Arkansas County (Terrance W. Holland, USGS, written commun., 2012).

Chicot County was the largest user of the Cockfield aquifer prior to 2000. Water use in Chicot County increased through the middle 1990s and decreased dramatically in 2000. The upward trend resulted from growth in aquaculture, and the downward trend resulted from declines in aquaculture related to low-cost imports of fish from Vietnam and other countries (Kaliba and Engle, 2006). Water use increased in Jefferson County in 2000 because of withdrawals by an electric company and has decreased in subsequent reporting periods (Terrance W. Holland, U.S. Geological Survey, written commun., 2013).

## Water Levels

Several reports have examined the water levels of the Cockfield aquifer (Ackerman, 1987a; Westerfield, 1994; Joseph, 1998b; Schrader and Joseph, 2000; Yeatts, 2004; Schrader, 2007a; Pugh, 2010). The potentiometric surface generally declines from higher altitudes at the western outcrop of the aquifer to lower altitudes in the deeper subcrop area to the east (fig. 38). However, pumping centers have disturbed predevelopment water levels and flow paths causing depressions in the potentiometric surface in several areas including western Drew County, southeastern Lincoln County, Ashley County near Crossett, southwestern Calhoun County, and Chicot County west of the city of Greenville, Miss. (Ackerman, 1987a; Joseph, 1998b; Schrader and Joseph, 2000; Yeatts, 2004; Schrader, 2007a; Pugh, 2010).

The first study documenting the potentiometric surface of the Cockfield aquifer, based on measurements in 1980, did not recognize the extensive occurrence of long-term declines. However, three wells in Chicot, Drew, and Lincoln Counties exhibited considerable long-term declines (Ackerman, 1987a). Onellion (1956) speculated that water levels had declined in Drew County based on decreases in water pressure, although water levels were not measured. The declines in Chicot, Drew, and more recently Desha Counties have been attributed to withdrawals by the city of Greenville, Miss. (Ackerman, 1987a; Joseph, 1998b; Pugh, 2010). Water levels declined 21.62 ft at Eudora (Chicot County) from 1971 to 1991 (well A; figs. 38 and 39) (Westerfield, 1994). Later reports showed relatively stable water levels from 1998 to 2009 (Joseph, 1998b; Schrader and Joseph, 2000; Yeatts, 2004; Schrader, 2007a; Pugh, 2010).

The lowest water levels in the Cockfield aquifer are generally in southeastern Lincoln County. Declines in water levels in Lincoln County were recognized as early as the 1960s. Water levels in one domestic well (well B; figs. 38 and 39) dropped by about 40 ft from 1966 to 1987 (Ackerman, 1987a). Rebounds in the water levels for this well (fig. 39) from 2000 through 2003 are attributed to intermittent use of the well during this period (T.P. Schrader, U.S. Geological Survey, oral commun., 2013). Domestic use of the Cockfield aquifer is common in Lincoln County.

A cone of depression in the Cockfield aquifer has been developing near Crossett in Ashley County since 2003 (Yeatts, 2004). Water levels previously were reported to have declined nearly 9 ft in central Ashley County from 1971 to 1991 (Westerfield, 1994). Schrader and Joseph (2000) noted that a cone of depression might be forming in that area. The depression at Crossett is centered on a single well (well C; figs. 38 and 39). Between 2003 and 2009, the depression at Crossett grew to the northwest and southeast because of groundwater withdrawals (Pugh, 2010).

Between 2003 and 2006, a new depression formed in the potentiometric surface of Cockfield aquifer in southwestern Calhoun County (Yeatts, 2004; Schrader, 2007a; Hart and others, 2008). This depression further extended to the southeast between 2006 and 2009 (Pugh, 2010). A hydrograph of well D near the center of that cone of depression is shown in figure 39. Water levels declined 1 ft from 2003 to 2009.

No regionally extensive declines have yet been observed in the Cockfield aquifer; however, with continued development, these individual cones may coalesce to encompass broader areas of the extent of the aquifer. Published summary statistics for water levels in the Cockfield aquifer are available in Schrader (2007a) and Pugh (2010). Declines were noted in all counties except Cleveland County in the 1986–2006 period (Schrader, 2007a) along with Calhoun and Columbia Counties in the 1990–2009 period (Pugh, 2010). The largest mean annual decline of 1.46 ft/yr was seen in Chicot County from 1990 to 2009. Desha County had annual mean declines more than 1 ft/yr in the 1986–2006 and 1990–2009 periods.

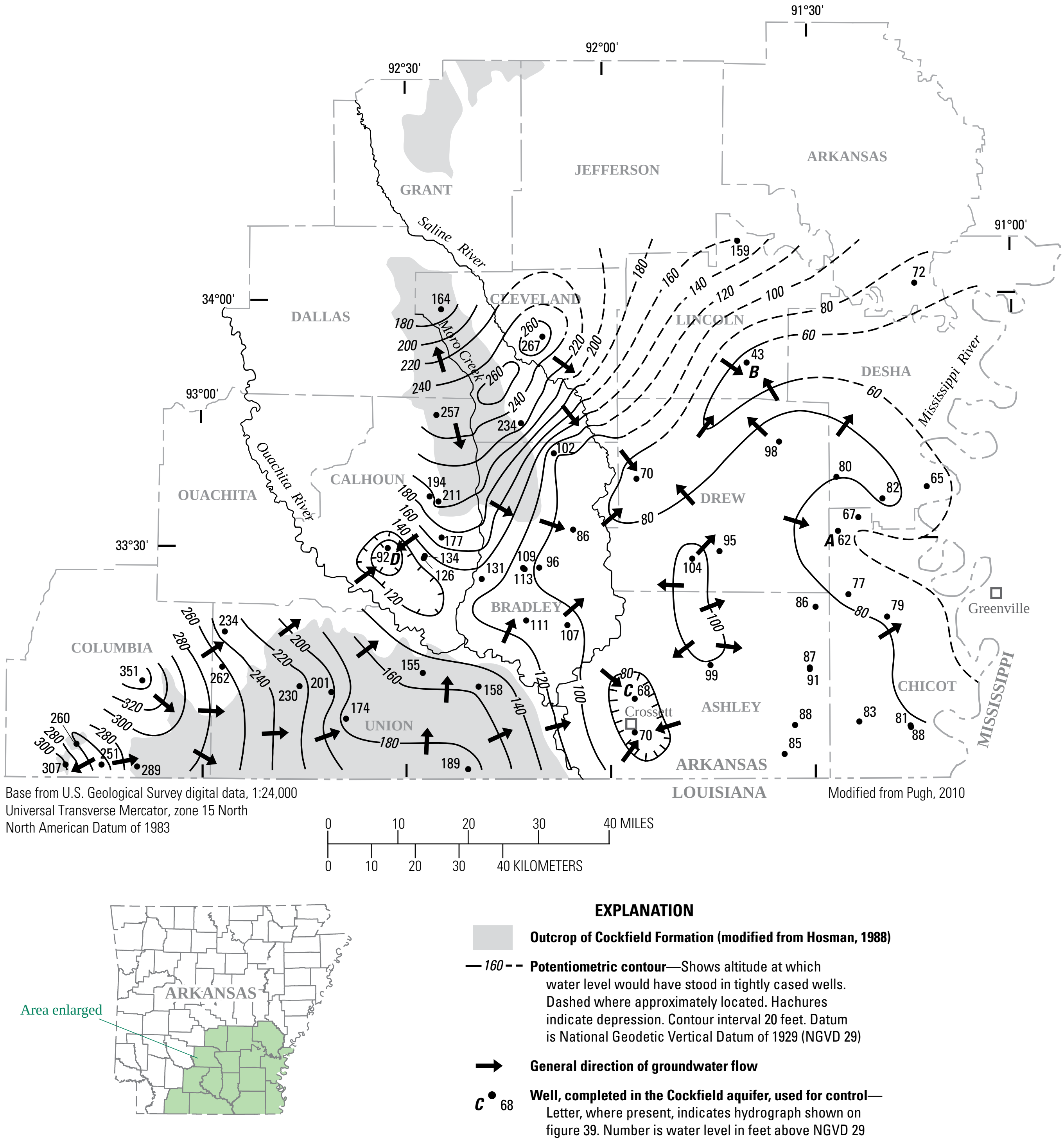



**Figure 38.** Potentiometric surface of the Cockfield aquifer in Arkansas, 2009.

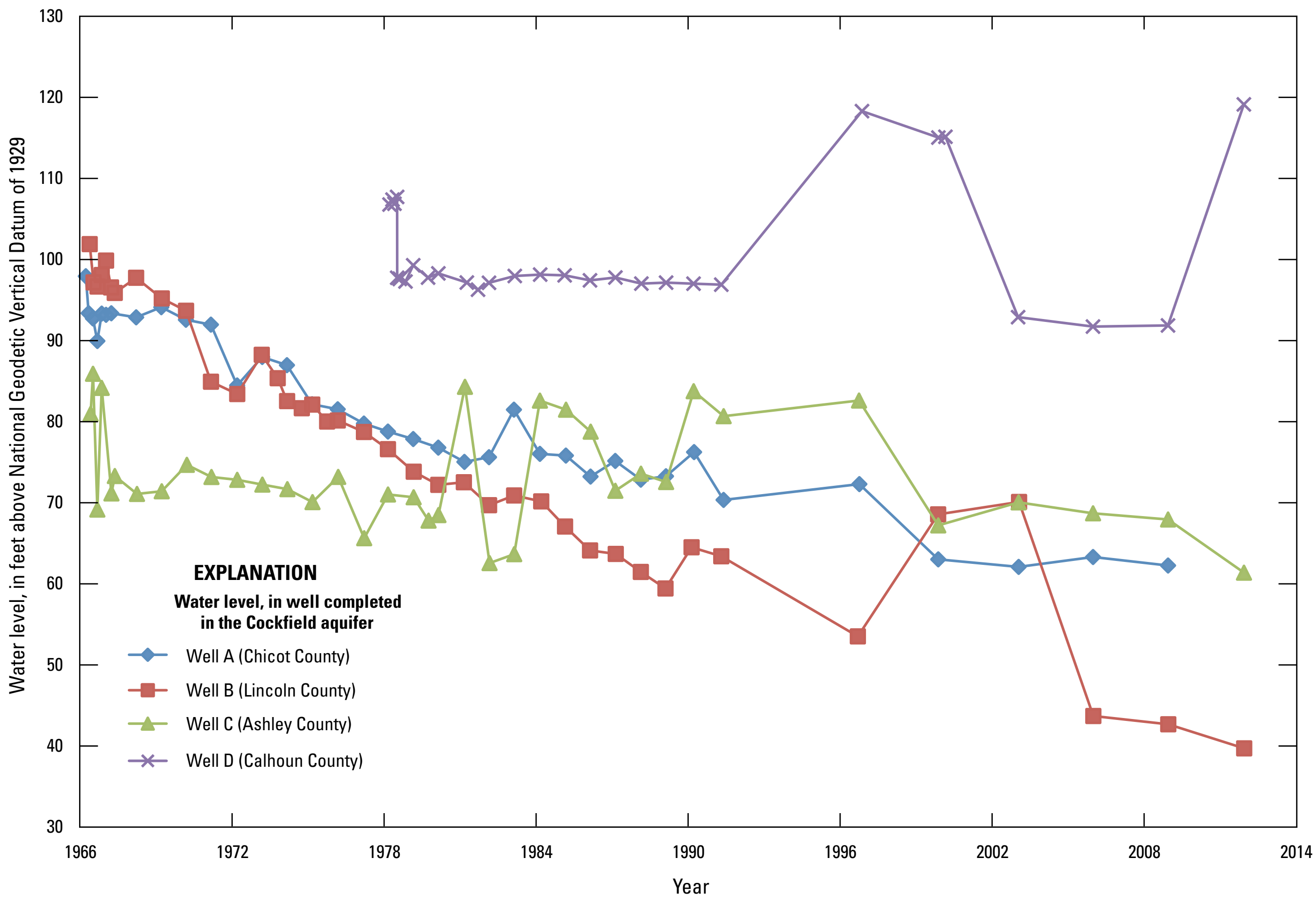



**Figure 39.** Hydrographs of water levels in wells completed in the Cockfield aquifer in southeastern Arkansas.

## Water Quality

Water quality in the Cockfield aquifer is generally very good throughout its extent, except for an area of high salinity in Chicot County and isolated areas of elevated sulfate in parts of Grant, Jefferson, Drew, and Bradley Counties. Hewitt and others (1949) stated that the quality of groundwater from the aquifer was fairly good and quite uniform for all of Ashley County. Tait and others (1953) described groundwater from the aquifer as being exceptionally soft and containing only a moderate amount of dissolved solids for all of Columbia County. Plebuch and Hines (1969) described the water quality as good throughout Cleveland and Dallas Counties. Halberg and others (1968) described groundwater from the Cockfield aquifer as varying from a soft, sodium-bicarbonate to a hard, calcium-bicarbonate water type and having greater dissolved-solids content than water from other formations in Grant County. They additionally noted that the sulfate content can be high, indicating possible migration of groundwater from the overlying Jackson Group (see section “Jackson Group”). Halberg and others (1969) also stated that much of the groundwater had a high iron content and that the water was corrosive locally (indicating low pH). Broom and others (1984) cited the aquifer in Union County as having a low mineral content with dissolved-solids concentrations ranging from less than 100 mg/L to approximately 200 mg/L.

### General Geochemistry and Water Type

Data compiled for this report revealed 247 sites with water-quality data for the Cockfield aquifer (table 23). A review of these data revealed very good water quality throughout most of the aquifer with isolated areas of poor-quality groundwater. A spatial analysis of the water-quality sites showed distinct patterns for many of the constituents of interest. Several of the chemical constituents revealed spatial trends related to geochemical processes along regional flow paths or leakage of poor-quality groundwater from overlying or underlying formations.

Values for pH in the Cockfield aquifer ranged from 5.1 to 8.8 with a median value of 7.9 (table 23). In general, pH values were lowest in the area of aquifer outcrop and subcrop (pH ranging from 5.1 to 7.0 in 34 samples). Values of pH generally increased (upward to 8.8) in the southeast trending

**Table 23.** Descriptive statistics for selected chemical constituents in groundwater from the Cockfield aquifer in southeastern Arkansas.

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

| Constituent or characteristic | Minimum | Median | Maximum | Standard deviation | Number of wells |
|---|---|---|---|---|---|
| Calcium (mg/L) | 0.2 | 5.0 | 124 | 21.8 | 193 |
| Magnesium (mg/L) | 0.10 | 1.3 | 38 | 6.08 | 185 |
| Sodium (mg/L) | 1.2 | 77 | 747 | 102.76 | 189 |
| Potassium (mg/L) | 0.2 | 3.0 | 13 | 2.16 | 169 |
| Bicarbonate (mg/L) | 1.0 | 207 | 504 | 110 | 217 |
| Chloride (mg/L) | 1.0 | 13 | 1,800 | 207.5 | 238 |
| Sulfate (mg/L) | 0.02 | 2.4 | 470 | 64.7 | 214 |
| Silica (mg/L) | 0.9 | 15 | 82 | 14.55 | 106 |
| Nitrate (mg/L as nitrogen) | 0.01 | 0.18 | 89 | 6.70 | 223 |
| Dissolved solids (mg/L) | 20 | 241 | 2,366 | 306 | 188 |
| Iron (µg/L) | 0.05 | 70 | 30,600 | 2,578 | 181 |
| Manganese (µg/L) | 0.13 | 25 | 3,640 | 474 | 59 |
| Arsenic (µg/L) | 0.03 | 0.50 | 7.3 | 1.59 | 47 |
| Hardness (mg/L as calcium carbonate) | 1.0 | 16 | 600 | 89 | 183 |
| Specific conductance (µS/cm) | 25 | 406 | 5,050 | 758 | 232 |
| pH (standard units) | 5.1 | 7.9 | 8.8 | 0.8 | 217 |

direction of flow within short distances of outcrop and subcrop areas (fig. 40*A*). Increases in pH in the downgradient direction are attributed to increased dissolution of carbonate minerals with resulting increased buffering of low-pH water and increased bicarbonate concentrations. Bicarbonate was the dominant anion (greater than 50 percent of anions in 78 percent of samples) throughout the aquifer, except for an area of high salinity in Chicot County. Bicarbonate also followed a similar trend to that of pH and with increasing concentrations to the southeast in the downgradient direction of flow (fig. 40*C*).

Percent sodium in the Cockfield aquifer followed a similar trend of increasing values in the downgradient direction of flow (fig. 40*B*) similar to that of pH and bicarbonate. Groundwater throughout most of the aquifer is of a strongly sodium-bicarbonate water type. More than 80 percent of sites had sodium values that were more than 50 percent of the total cations (in milliequivalents per liter); 60 percent of these sites had values exceeding 70 percent sodium and ranging upward to 98 percent sodium. Increased sodium is attributed to cation exchange of calcium for sodium at solid-phase exchanges sites, thus increasing sodium in solution at the expense of calcium along the flow path. Sodium percentages less than 50 percent (generally a calcium-bicarbonate water type) occurred in the outcrop and subcrop areas generally in Bradley, Calhoun, Dallas, Grant, and Union Counties.

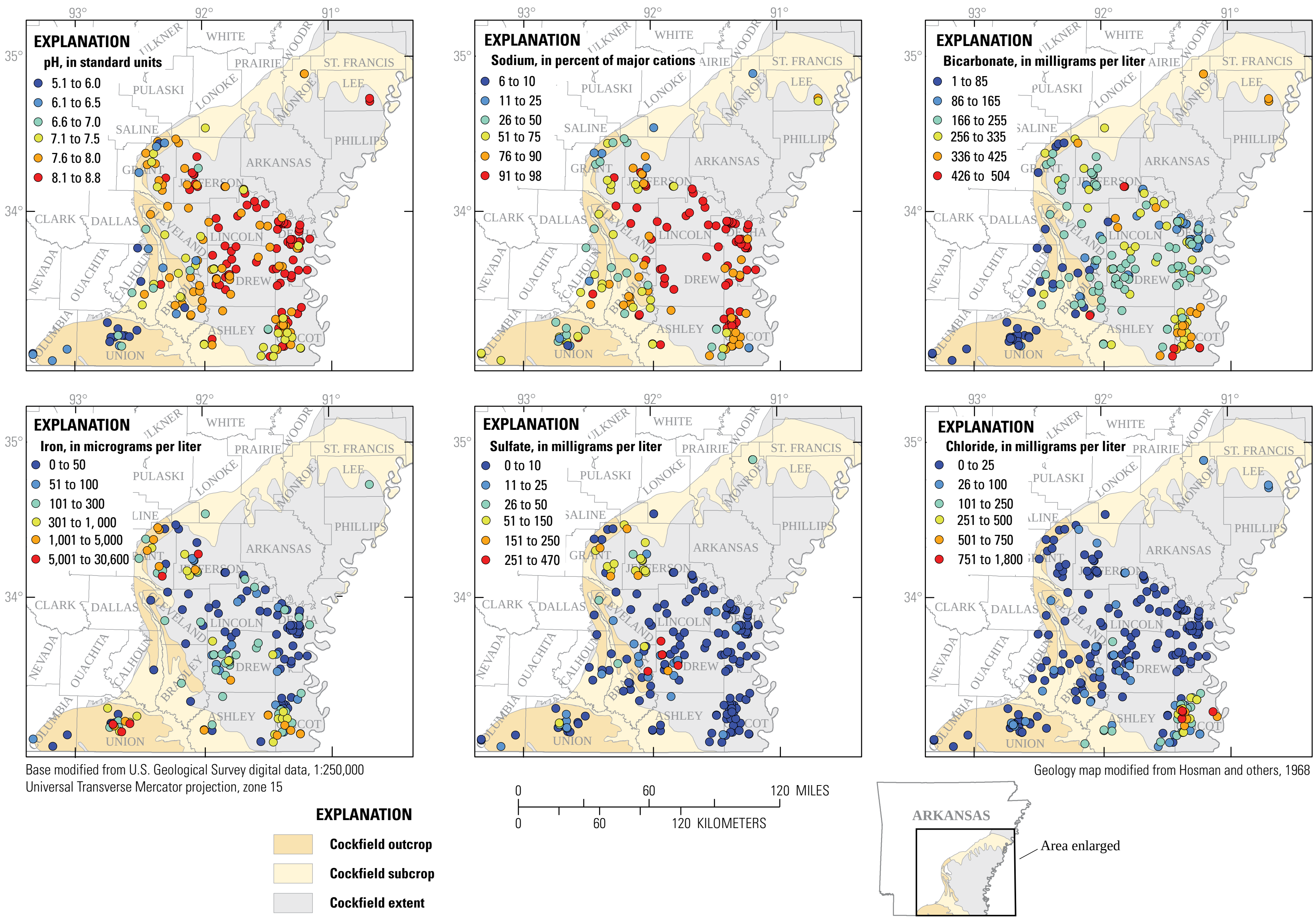



**Figure 40.** Spatial distribution of selected chemical constituents for groundwater from the Cockfield aquifer in southeastern Arkansas.

## Iron

Iron concentrations in the Cockfield aquifer ranged from 0.05 to 30,600 µg/L with a median of 70 µg/L. The median concentration is below the 300 µg/L secondary drinking-water regulation and illustrates the generally low iron concentrations throughout the aquifer (fig. 41; table 23). Iron concentrations generally are greatest (upward to 30,600 µg/L) in the outcrop and subcrop areas of the westernmost extent of the aquifer and consistently lower, dominantly less than 200 µg/L, throughout the rest of the aquifer (fig. 40*D*). Two exceptions are an area in Chicot County and an area in eastern Grant and Jefferson Counties. Upwelling of brines from the Jurassic-age Smackover Formation in Chicot County has been identified as the cause of elevated salinity identified in the Sparta, Cockfield, and alluvial aquifers. Elevated iron concentrations ranging from greater than 500 µg/L to 3,730 µg/L in this area probably are related to intrusion of poor-quality groundwater from underlying formations (see section on "Chloride" below). In the area of eastern Grant and Jefferson Counties, elevated iron concentrations are possibly the result of infiltration of high-iron content in the groundwater from overlying formations.

## Nitrate

Nitrate concentrations were relatively low throughout the aquifer and ranged from 0.01 to 89 mg/L with a median concentration of 0.18 mg/L (table 23). Two sites contained extremely high nitrate concentrations of 46 and 89 mg/L. No information was available to explain these high nitrate concentrations, and no other site had nitrate concentrations exceeding the Federal MCL of 10 mg/L. Of the 223 sites with nitrate data, 213 (96 percent) had nitrate concentrations less than 1.0 mg/L. No strong spatial trend was noted in the distribution of nitrate concentrations. Additionally, there was no strong relation of nitrate concentration to well depth; however, all but two sites with nitrate concentrations greater than 1.0 mg/L occurred in wells less than 200 ft deep. The maximum well depth was 690 ft.

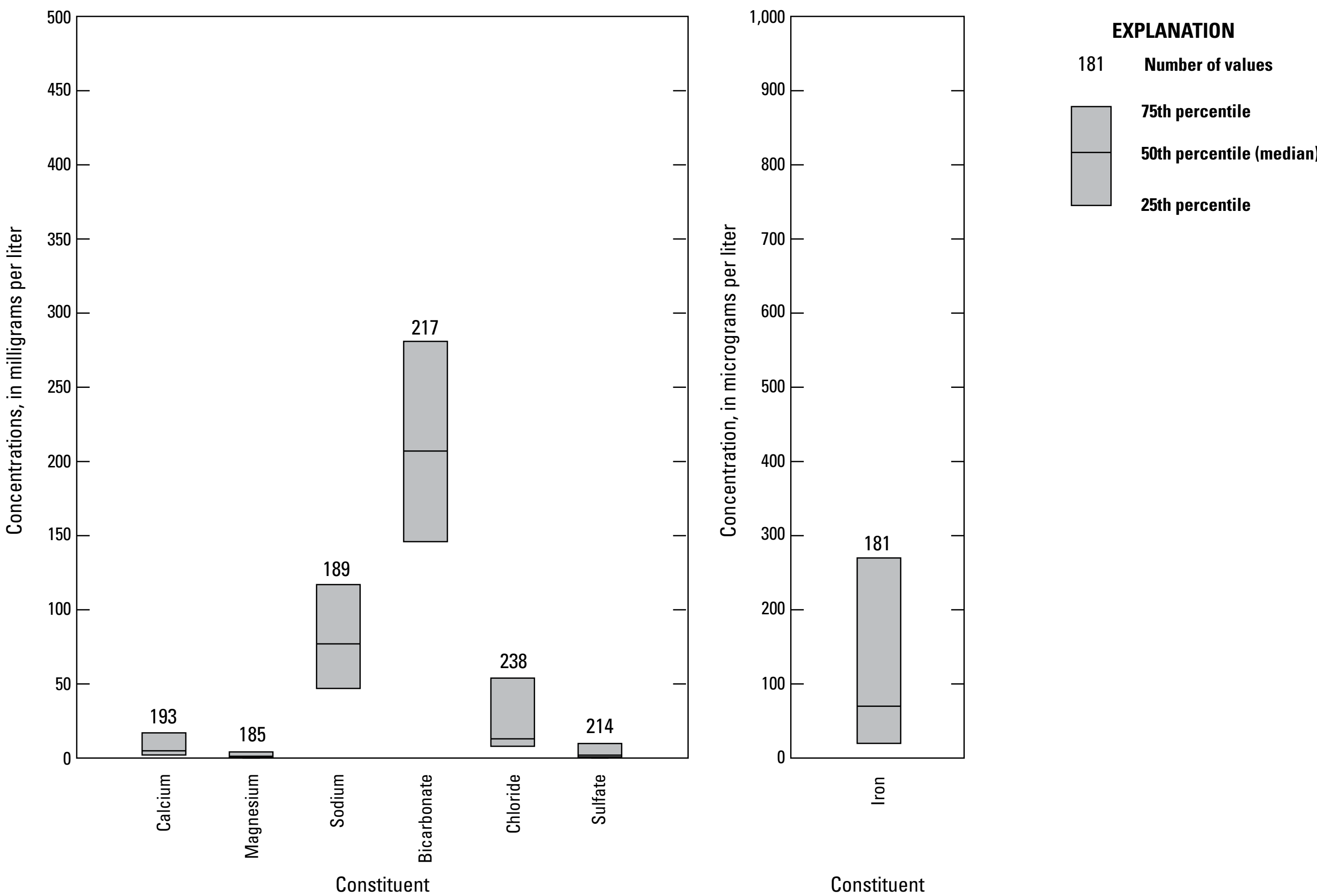



**Figure 41.** Box plots showing interquartile range of selected chemical constituents in groundwater from the Cockfield aquifer in southeastern Arkansas.

### Sulfate

Although water quality generally is good throughout the Cockfield aquifer, poor water quality occurs in two areas: (1) an area in the central part of the aquifer in southeastern Arkansas with elevated sulfate concentrations, and (2) a large area of high salinity (elevated chloride concentrations) in Chicot County. The high-salinity area in Chicot County that affects several aquifers is discussed in greater detail (sources and solubility control) in the section "Mississippi River Valley Alluvial Aquifer." Sulfate concentrations ranged from 0.02 to 470 mg/L with a median of 2.4 mg/L (table 23). A high density of sites with elevated (greater than 50 mg/L) sulfate concentrations occurs in Grant, Jefferson, Drew, and eastern Bradley Counties (fig. 40*E*). Only 4 of 214 samples (2 percent) exceeded the Federal secondary drinking-water regulation of 250 mg/L sulfate, and 184 of 214 sites (86 percent) had concentrations that were less than 20 mg/L. In Grant and Jefferson Counties, however, a large area of elevated sulfate concentrations occurs in which 4 of 24 sites exceeded 150 mg/L with a maximum of 220 mg/L. Isolated wells with elevated sulfate occur in eastern Bradley and western Drew Counties, where four sites with the highest sulfate concentrations (greater than 250 mg/L) were located. All of these counties are areas where the Cockfield aquifer is overlain by deposits of the Jackson Group, which contains numerous groundwater sites with sulfate concentrations exceeding 250 mg/L and ranging upward to 3,080 mg/L. Halberg and others (1968) hypothesized groundwater from the Jackson Group was the source for elevated sulfate concentrations in groundwater from the Cockfield aquifer in Grant County. The larger dataset, and resulting greater spatial distribution afforded by this study, supports the theory of infiltration of high sulfate groundwater from the overlying Jackson Group.

### Chloride

A review of chloride concentrations for the Cockfield aquifer shows overall low values throughout the aquifer with the exception of an area in Chicot County (fig. 40*F*). Bicarbonate dominates the anion chemistry and increases with increases in dissolved solids for dissolved-solids concentrations up to approximately 500 mg/L (fig. 42*A*). Chloride dominates the anion chemistry for dissolved-solids concentrations greater than 500 mg/L as evidenced by the strong linear relation between dissolved-solids and chloride concentrations at this transition point (fig. 42*B*). Mixing of poor-quality, high-salinity groundwater from underlying formations generally accounts for dissolved solids greater than approximately 500 mg/L. This concentration represents a transition zone from dissolution of carbonate minerals to a geochemistry reflecting influx and mixing of high-salinity groundwater from other sources. Chloride ranged from 1.0 to 1,800 mg/L with a median concentration of 13 mg/L (fig. 41; table 23); 159 of 238 samples (67 percent) were less than 20 mg/L, and only 21 of 238 samples (9 percent) had concentrations greater than the Federal secondary drinking-water regulation of 250 mg/L. All sites having chloride concentrations greater than 100 mg/L occurred in Chicot County, with the exception of one site in Drew County and three sites in Ashley County. Kresse and Clark (2008) used chloride concentration data from five monitoring wells (Kresse and others, 2000) and 21 domestic wells completed in the Cockfield aquifer to construct a chloride concentration map. The resulting map showed that the distribution of elevated chloride concentrations in the Cockfield aquifer was similar to that of the overlying Mississippi River Valley alluvial aquifer with the zone of elevated chloride manifested as an elongated north-south oriented band. Kresse and Clark (2008) suggested that the most likely source was upwelling of brine water from the Smackover Formation along the intersection of two mapped wrench faults (Zimmerman, 1992). Mixing curves were developed using bromide/chloride ratios from the alluvial aquifer, Tertiary aquifers, and brine water from the Smackover Formation, in addition to the use of chloride isoconcentration maps and data from early oil and gas wells. Additional information and maps of chloride concentrations for the Mississippi River Valley alluvial, Cockfield, and Sparta aquifers are found in Kresse and Clark (2008).

In summary, groundwater quality throughout the Cockfield aquifer is good except for isolated areas with elevated sulfate and chloride concentrations that are a result of influx of poor-quality groundwater from overlying or underlying formations. The groundwater typically is of a calcium-bicarbonate type in the outcrop area but transitions to a sodium-bicarbonate type downdip to the east and southeast as a result of cation-exchange processes. Groundwater is of a sodium-chloride type in areas of mixing of poor-quality, high-salinity groundwater from underlying formations. Nitrate concentrations generally were low throughout the aquifer.

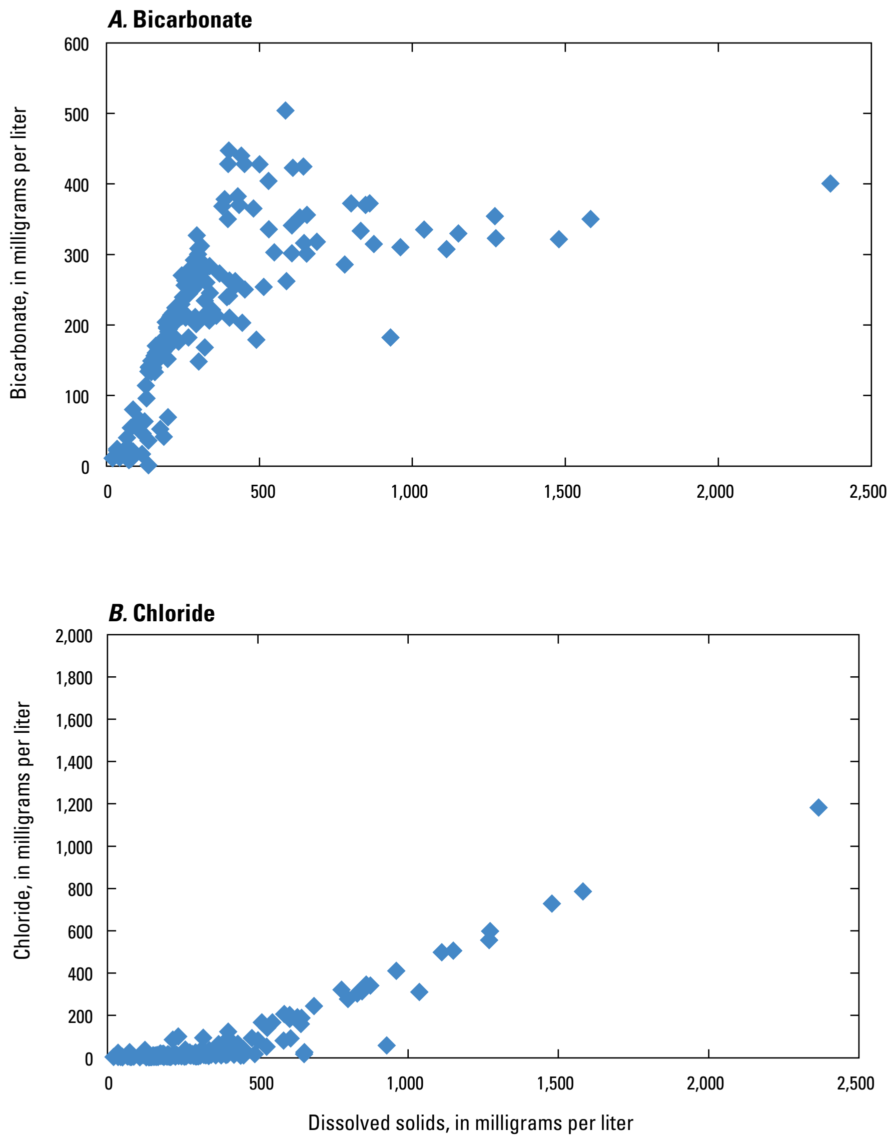



**Figure 42.** Graphs showing relation of concentrations of dissolved solids to *A*, bicarbonate and *B*, chloride in groundwater from the Cockfield aquifer in southeastern Arkansas.

## Sparta Aquifer

The Tertiary-age Sparta Sand is the thickest sand in the Mississippi embayment and its importance as an aquifer is recognized by the fact that it is second in use only to the Mississippi River Valley alluvial aquifer. Veatch (1906) included the Sparta Sand as part of the undifferentiated Eocene deposits in southern Arkansas. Stephenson and Crider (1916) included the strata between the Wilcox Formation and the Jackson Formation, including the Sparta Sand, as the Claiborne Group. In Arkansas, the Claiborne Group is differentiated into the Carrizo Sand, Cane River Formation, Sparta Sand, Cook Mountain Formation, Cockfield Formation, and the Memphis Sand (Hosman and others, 1968; Payne, 1968, 1970, 1972, 1975).

In northeastern Arkansas, the underlying Cane River Formation and Carrizo Sand undergo a facies change northward of latitude 35 degrees, and the formations become sand. The northern sand facies of these two formations are generally indistinguishable and undifferentiated from the Sparta Sand, and all three formations are grouped together as the Memphis Sand in northeastern Arkansas (Counts, 1957; Hosman and others, 1968; Payne, 1972; Petersen and others, 1985). Therefore, in northeastern Arkansas, the Sparta aquifer locally is referred to as the Memphis aquifer. In various USGS water-use and water-level reports referenced herein that address the aquifer as one aquifer throughout the State, the most recent being Schrader (2013) and Holland (2007), the aquifer is referred to as the “Sparta-Memphis aquifer.” To avoid confusion between local terminology and differences across States, regional hydrogeologic framework models designated the Sparta aquifer and Memphis aquifer as part of the regional Middle Claiborne aquifer (Arthur and Taylor, 1990; Hosman and Weiss, 1991; Renken, 1998; Hart and Clark, 2008; Clark and Hart, 2009).

Additional confusion is noted for local usage in southern Arkansas. In the area of Union County, the Sparta Sand is divisible into three distinct hydrogeologic units: the Greensand (upper Sparta aquifer), the middle confining unit, and the El Dorado sand (lower Sparta aquifer). The terms "Greensand" and "El Dorado sand" are informal terms applied to the upper and lower major sand units within the Sparta aquifer in southern Arkansas. For the sake of clarity, it should be noted that the term "Sparta aquifer" is applied to a sequence of hydraulically connected sands that are often separated by silts and clays and is not an absolutely equivalent term with "Sparta Sand," the formal name for the geologic formation. This distinction is important because by Arkansas law, critical groundwater area designation criteria for the Sparta aquifer are based on the top of the geologic formation rather than the top of the aquifer (Arkansas Natural Resources Commission, 1996). In areas where clays and silts in the Sparta Sand (the geologic formation) occur above productive sands, the top of the Sparta aquifer does not coincide with the top of the Sparta Sand. In this report, the term "Sparta Sand" always will refer to the geologic formation (comprising sands, silts, and clays), and the term "Sparta aquifer" will refer to the sequence of productive, hydraulically connected sands that constitute a part of the geologic formation. Use of the term Sparta aquifer in the following sections is noted to include the groundwater in the saturated part of the Sparta Sand (and Memphis Sand) throughout Arkansas. Use of other terms will only be used to make distinctions in depositional and stratigraphic environments when appropriate.

## Geologic Setting

The Sparta Sand overlies the Cane River Formation and is overlain by either the Cook Mountain Formation or the Mississippi River Valley alluvium where the formation subcrops. The Sparta Sand consists of varying amounts of well-sorted, rounded to subrounded, fine- to medium-grained quartz sand interspersed with silt, clay, shale, and lignite. Layers of coarse sand and fine gravel occur in some areas. Glauconite occurs in various areas, particularly in the upper part of the formation. Shales within the Sparta Sand are gray to dark brown or black (Payne, 1968). The lithology of the Sparta Sand is variable vertically and laterally. The lower part of the unit generally contains more sand, and the upper part generally contains more clay and shale (Hosman and others, 1968; Petersen and others, 1985). In southern Arkansas, well-developed lineations of high sand content occur at a generally north/south orientation that is presumed to be normal to the shoreline at the time of deposition. This pattern was likely created by a system of shifting stream channels, lakes, marshes, and swamps that were present in a deltaic-fluvial plain (Payne, 1968). Onellion and Criner (1955) describe the Sparta Sand in Chicot County as white to gray, fine- to medium-grained sand with beds and lenses of sandy or silty clay and some thin beds of lignite. The occurrence, thickness, and continuity of the sand beds are quite variable, but in general, the sands appear to be hydraulically connected. Albin (1964) described the Sparta Sand in Bradley and Calhoun Counties as gray, very fine- to medium-grained sand and brown to gray sandy clay. Ludwig (1973) described the Sparta Sand in Nevada, Lafayette, and Miller Counties as gray, fine- to medium-grained sand, brown and gray sandy clay, with lenses of lignite in the formation as much as 2 ft thick. Ludwig (1973) noted that local drillers identify the Sparta Sand in well cuttings by its "salt and pepper" appearance as a result of the lignite.

The Sparta Sand in northeastern Arkansas is mainly composed of thick-bedded, very fine to gravely, well-sorted sand, with some argillaceous, micaceous, and lignitic materials. Clay layers are minor, but layers as thick as 20 ft may locally occur and separate the sand hydraulically (Hosman and others, 1968). Counts (1957) described the Claiborne Group that includes the Sparta Sand in Lonoke, Prairie, and White Counties as generally white to light-gray, fine- to medium-grained sand with interbedded gray or tan clay and sandy clay, lignitic clay, and lignite. The Sparta Sand thickens southward and toward the axis of the Mississippi embayment downdip from its depositional extent to a maximum thickness of approximately 900 ft (Hosman and others, 1968; Petersen and others, 1985; Brahana and Broshears, 1989).

In and near Union County, the Sparta Sand is divisible into three distinct units. The lower 300 ft consists of thick-bedded sands with grains ranging from fine to coarse and referred to locally as the El Dorado sand. The El Dorado sand overlies the Cane River Formation and regionally dips southeastward. The El Dorado sand is faulted against the Cane River Formation in some areas. The fault zones are described in more detail by Leidy and Taylor (1992). The middle 50–155 ft of the Sparta Sand are composed of clay and silt and is referred to as the middle confining unit, and the upper 200 ft are composed of thin-bedded, very fine- to fine-grained sands and clays. In places, the upper unit is distinctively green because of the presence of glauconite and therefore is referred to as the Greensand. In some areas of Union County, the middle confining unit contains sand that makes the unit difficult to distinguish from the Greensand and El Dorado sand. However, differences in potentiometric surfaces above and below this unit confirm that it effectively isolates the upper and lower units of the Sparta aquifer in this area. The Greensand is overlain by the Cook Mountain Formation and regionally dips southeastward. The Greensand is partially in contact with the middle confining unit and the El Dorado sand along faults. Differences in static water levels measured in sand beds within the Greensand aquifer indicate that some clay beds in the Greensand locally act as confining beds.
In general, the El Dorado sand is more productive than the

Greensand, and the local flow pattern within the El Dorado sand are heavily influenced by groundwater withdrawals (Hosman and others, 1968; Broom and others, 1984; Leidy and Taylor, 1992; Clark and Hart, 2009).

The Sparta Sand crops out in southern Arkansas, and the aquifer is unconfined at its western extent within the Mississippi embayment. It becomes confined east of the outcrop area as it dips toward the axis of the embayment and southward toward the Gulf of Mexico. It is confined by the Cook Mountain Formation above and by the Cane River Formation below (McKee and Clark, 2003). In and near the outcrop area, the Sparta Sand ranges in thickness from 0 to 200 ft (Petersen and others, 1985). In south-central and southwestern Arkansas, the dip is to the east and southeast at about 25–50 feet per mile (ft/mi) into the Mississippi embayment and the Desha Basin (fig. 8), and the thickness ranges from approximately 600–800 ft with percentage of sand varying from 60 to 100 percent (Klein and others, 1950; Terry and others, 1979; Kresse and Huetter, 1999). In southeastern Arkansas, the dip is to the south at about 25–50 ft/mi (Payne, 1968). The Sparta Sand exceeds 800 ft in thickness near the axes of the Mississippi embayment and the Desha Basin in southeastern Arkansas (Payne, 1968); Pugh (2008a) reported a maximum thickness of 900 ft. The Sparta Sand does not crop out in northern Arkansas except for some exposed erosional remnants along Crowleys Ridge. In the Sparta Sand subcrop area, the Sparta aquifer and overlying Mississippi River Valley alluvial aquifer are hydraulically connected. This area serves as an important recharge area to the Sparta aquifer (Hosman and others, 1968; Broom and Lyford, 1981). Groundwater in the Sparta Sand generally flows toward the axis of the Mississippi embayment and then southward (Hosman and others, 1968; Edds and Fitzpatrick, 1984b; Stanton, 1997; Schrader, 2004, 2006b, 2009, 2013; Schrader and Jones, 2007).

## Hydrologic Characteristics

Hydraulic properties vary widely in the Sparta aquifer, and the highest transmissivity is tied to the thickest sand intervals, not necessarily the highest sand percentage (Payne, 1968). Hosman and others (1968) reported transmissivity of the Sparta aquifer ranging from 1,800 to 17,400 $ft^2/d$, storage coefficients ranging from 0.0002 to 0.0024, hydraulic conductivity ranging from about 11 to 110 ft/d, and specific capacities ranging from 7 to 14 (gal/min)/ft. Plebuch and Hines (1969) reported well yields as high as 700 gal/min and transmissivities from 3,200 to 15,400 $ft^2/d$.

Pugh (2008a) summarized aquifer-test data from the Sparta aquifer as follows: based on data from 16 sites, the average specific capacity was 61.7 (gal/min)/ft with a minimum of 0.13 (gal/min)/ft and a maximum of 439 (gal/min)/ft; based on data from 33 sites, the average transmissivity was 7,990 $ft^2/d$ with a minimum of 23 $ft^2/d$ and a maximum of 31,000 $ft^2/d$; based on data from 3 sites, the average hydraulic conductivity was 13.1 ft/d with a minimum of 1.7 ft/d and a maximum of 29 ft/d; and based on data from 17 sites, the average storage coefficient was 0.00209 with a minimum of 0.000017 and a maximum of 0.03. Pugh (2008a) also reported that the Sparta aquifer commonly yields 1,000 gal/min to wells, and that yields may exceed 1,900 gal/min. A transmissivity of nearly 7,400 $ft^2/d$ and a storage coefficient of 0.0009 were reported from the Sparta aquifer in St. Francis County (Hosman and others, 1968). Data from 23 aquifer tests in northern Arkansas (listed under Memphis Sand) throughout the northern Mississippi embayment show transmissivity ranging from 2,700 to 54,000 $ft^2/d$, and storage coefficients ranging from 0.0001 to 0.2 (Brahana and Broshears, 1989).

The Sparta aquifer outcrop area is recharged by direct infiltration, from rivers, and by leakage from overlying alluvium and other aquifers with higher hydraulic heads. Natural discharge occurs by leakage through the overlying and underlying confining units, lateral movement into adjacent units with lower hydraulic heads, and discharge to rivers within the outcrop area. Groundwater flow is generally downdip toward the axis of the embayment and southward toward the Gulf of Mexico. The rate of groundwater flow within the aquifer varies with local lithology and may be affected by local faulting (Payne, 1968; McKee and Clark, 2003). The above generalized groundwater-flow pattern was present in the aquifer prior to aquifer development (Reed, 1972). Continued, large withdrawals have resulted in water-level declines affecting changes in flow direction (discussed further under the section “Water Levels”).

## Water Use

The Sparta aquifer is an extremely important source of groundwater in eastern Arkansas. The aquifer generally provides water of excellent quality, and wells often yield hundreds to thousands of gallons per minute. The Sparta aquifer provided 196.64 Mgal/d in 2010, which was 2.5 percent of all groundwater used in Arkansas, with over 700 wells withdrawing water from the aquifer (fig. 43). Historically, the Sparta aquifer has been used for public and industrial supply, but irrigation use has increased as water levels in the Mississippi River Valley alluvial aquifer have decreased, particularly in the Grand Prairie region. In the past, drilling costs for completing wells in the deeper Sparta aquifer had been cost prohibitive; however, as the Mississippi River Valley alluvial aquifer became depleted in some areas, the lack of other water sources has necessitated drilling in the Sparta aquifer to support agriculture (Czarnecki and Schrader, 2013). As of 2010, more water was used from the Sparta aquifer for irrigation than for any other purpose.

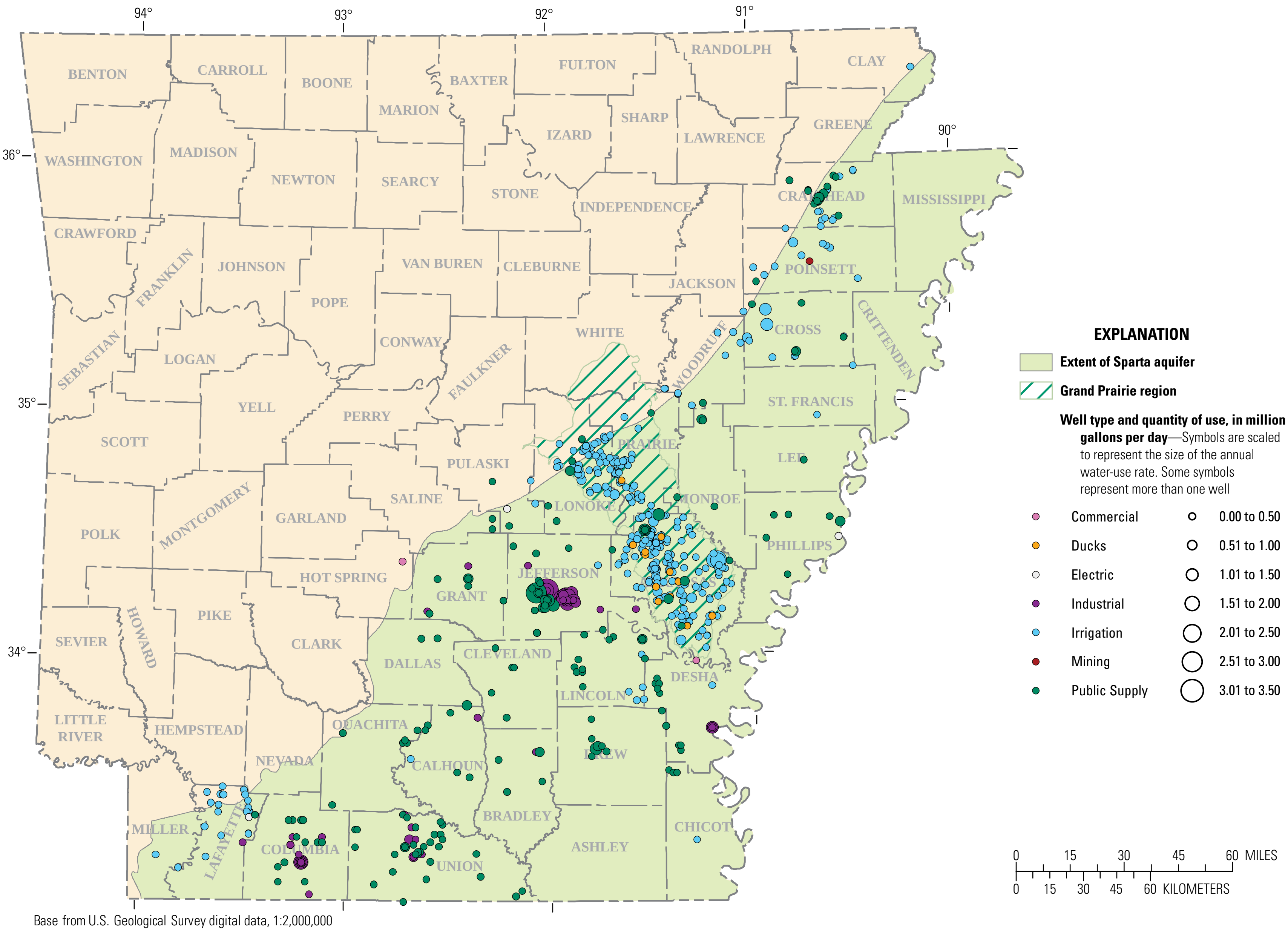



**Figure 43.** Wells with reported water use from the Sparta aquifer in Arkansas, 2010.

The majority of Sparta aquifer water use in Arkansas currently is centered in the Grand Prairie region (figs. 43 and 44). Use of the aquifer almost doubled between 1965 and 1995 (table 24). From 1965 to 1985, the largest amount of use occurred in Jefferson County; whereas Arkansas County had the most use in 1990, 1995, and 2010 (fig. 44; table 24). Although use has decreased in both of these counties, Arkansas and Jefferson Counties continue to be the greatest users of the aquifer.

Statewide water use from the Sparta aquifer decreased 32 percent from the 2000 peak of 287.44 Mgal/d to 196.64 Mgal/d in 2010 (table 24), primarily because of changes in reporting criteria that occurred in Jefferson County in 2000. Anecdotal reports from drillers indicated many wells drilled around 2000 were dual completed in the Mississippi River Valley alluvial and Sparta aquifers. For the 2000 report, 10 percent of the water use from dual-completed wells was reported as use from the Sparta aquifer (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). This resulted in the greatest one-time reported use from Jefferson County of 90.63 Mgal/d, a use that was approximately 35–40 Mgal/d more than what was reported in 1995 and 2005.

Jefferson County, especially in the Pine Bluff area, has been the largest user of the Sparta aquifer in the State. Domestic and industrial wells, including those for railroads and ice manufacturing (Veatch, 1906), were present before 1890 (Klein and others, 1950), and the aquifer was not used for public supply until the late 1890s (Veatch, 1906). Water use and the number of wells completed in the aquifer in Jefferson County steadily increased over time from 5 wells in 1900 (Klein and others, 1950), to 27 wells in 1950 (Klein and others, 1950), and 60 wells in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

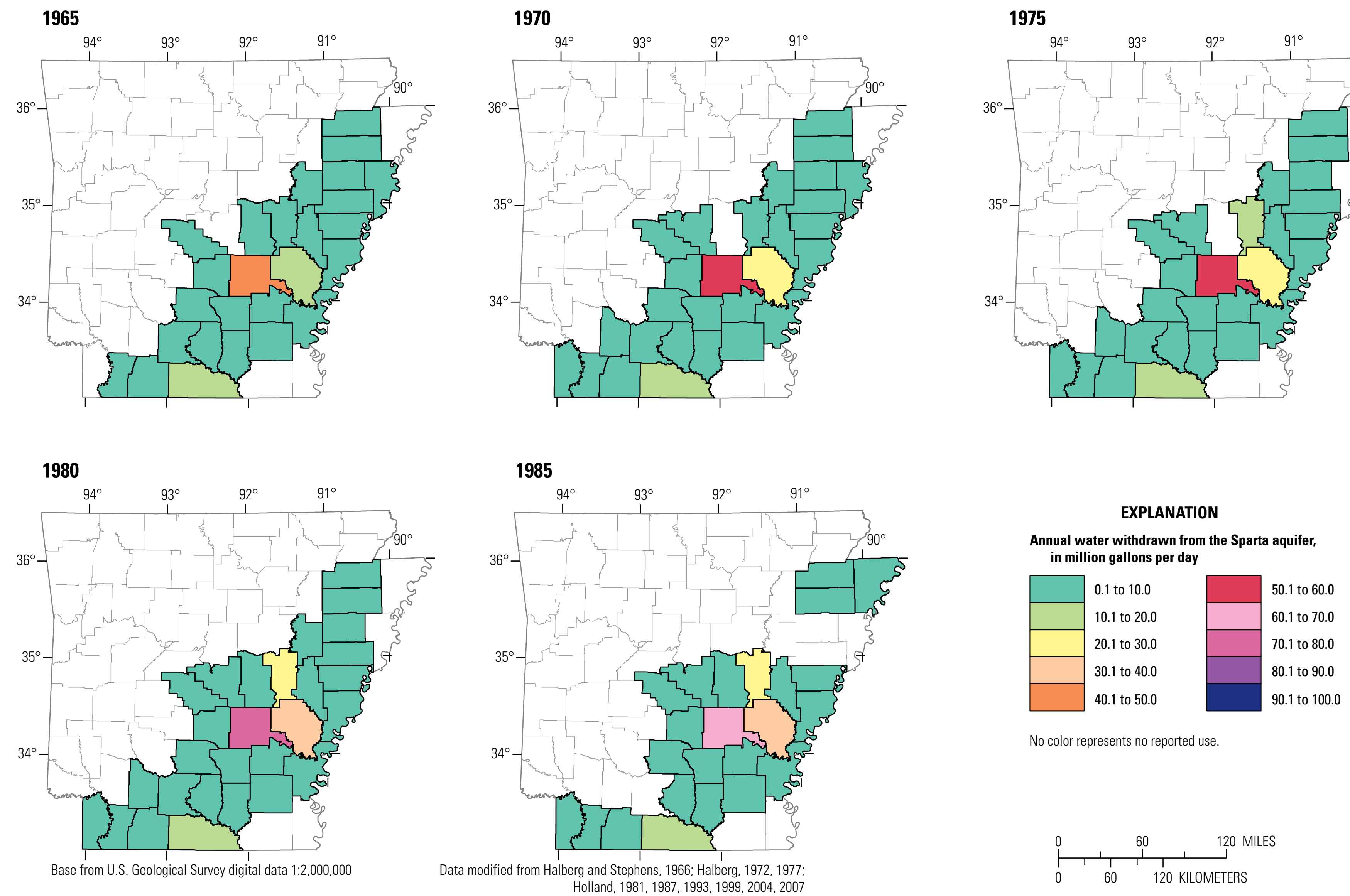



**Figure 44.** Water-use rates for the Sparta aquifer in Arkansas from 1965 to 2010.

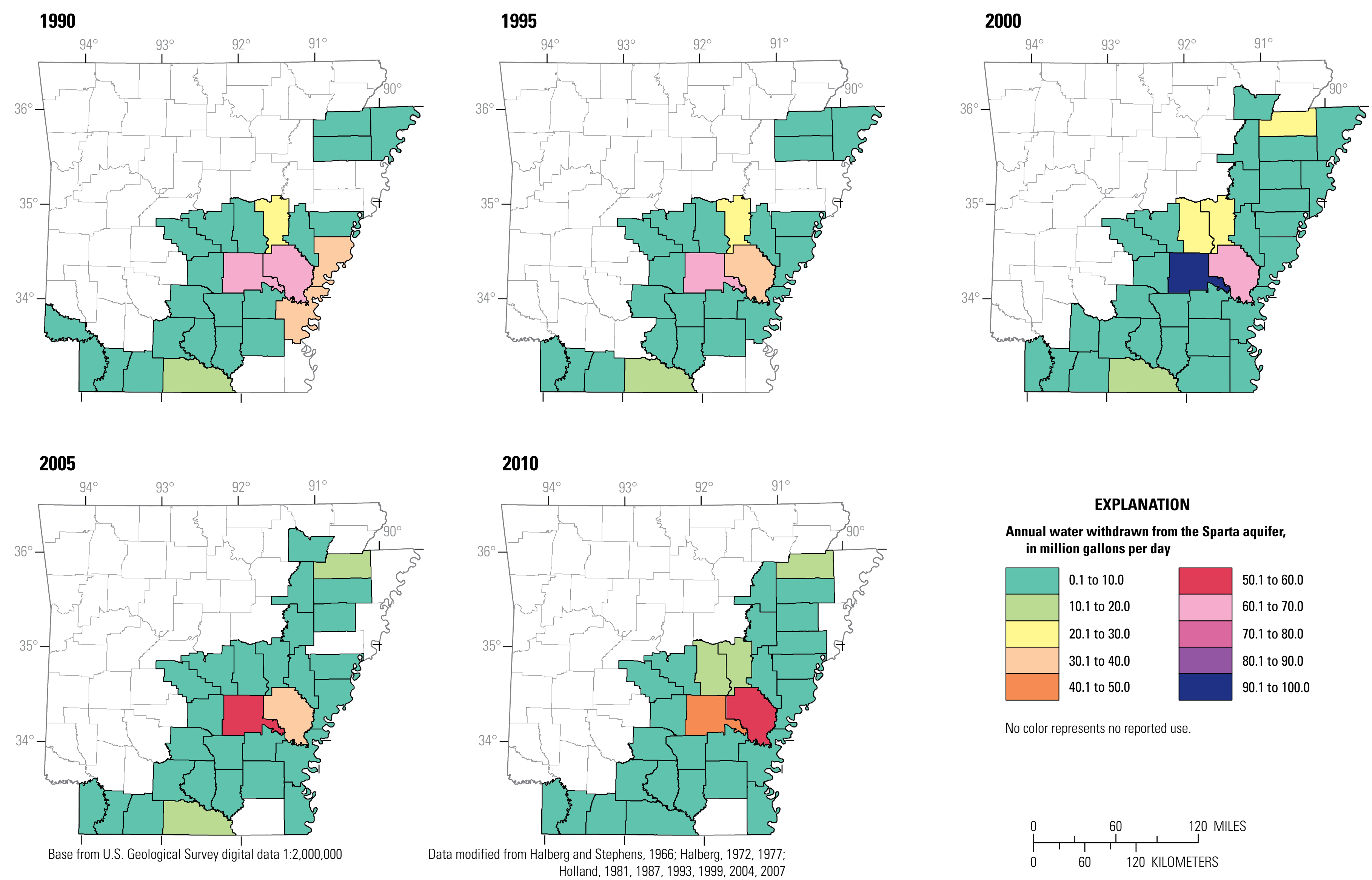



**Figure 44.** Water-use rates for the Sparta aquifer in Arkansas from 1965 to 2010.—Continued

**Table 24.** Water use from the Sparta aquifer in Arkansas, 1965–2010.

[Counties shown are only those with published data. Data from Halberg and Stephens (1966); Halberg (1972, 1977); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1965 | 1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|
| Arkansas | 17.39 | 20.26 | 24.25 | 36.97 | 36.50 | 67.99 | 76.69 | 63.40 | 36.03 | 58.29 |
| Ashley | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.18 | 0.00 | 0.00 |
| Bradley | 1.14 | 1.39 | 1.34 | 1.83 | 1.44 | 0.91 | 0.91 | 1.76 | 1.70 | 1.88 |
| Calhoun | 0.17 | 0.19 | 0.47 | 0.69 | 0.53 | 0.70 | 0.98 | 0.61 | 0.53 | 0.63 |
| Chicot | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.16 | 0.52 | 0.48 |
| Clay | 0.20 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.12 |
| Cleveland | 0.26 | 0.16 | 0.16 | 0.24 | 0.85 | 0.98 | 0.89 | 1.44 | 0.73 | 1.16 |
| Columbia | 3.03 | 5.84 | 6.02 | 7.22 | 7.10 | 6.50 | 5.24 | 2.90 | 3.61 | 9.41 |
| Craighead | 3.26 | 0.21 | 0.19 | 0.29 | 0.40 | 0.68 | 0.76 | 22.74 | 14.14 | 13.38 |
| Crittenden | 0.07 | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.50 | 0.00 | 0.00 |
| Cross | 0.71 | 0.40 | 0.40 | 0.53 | 0.00 | 0.00 | 0.00 | 4.17 | 7.02 | 5.21 |
| Dallas | 0.67 | 1.04 | 1.19 | 1.42 | 1.19 | 1.07 | 0.93 | 1.15 | 1.47 | 0.78 |
| Desha | 0.83 | 0.76 | 1.35 | 1.73 | 6.45 | 6.23 | 6.65 | 3.85 | 5.42 | 4.36 |
| Drew | 1.12 | 2.45 | 2.97 | 3.88 | 3.06 | 2.60 | 3.11 | 0.88 | 2.82 | 2.56 |
| Grant | 0.50 | 1.41 | 1.41 | 1.53 | 1.39 | 1.41 | 1.84 | 1.92 | 2.60 | 1.73 |
| Greene | 0.22 | 0.34 | 0.31 | 0.63 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Hot Spring | 0.06 | 0.15 | 0.15 | 0.17 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.24 |
| Jackson | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.18 | 0.42 | 0.33 |
| Jefferson | 44.36 | 59.30 | 53.82 | 71.13 | 65.00 | 63.80 | 53.87 | 90.63 | 50.38 | 45.50 |
| Lafayette | 2.63 | 0.49 | 0.24 | 0.46 | 0.14 | 0.04 | 0.30 | 0.24 | 0.42 | 0.75 |
| Lawrence | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 5.99 | 0.13 | 0.00 |
| Lee | 0.09 | 0.57 | 0.98 | 2.84 | 1.72 | 3.32 | 3.29 | 1.18 | 0.93 | 0.94 |
| Lincoln | 0.34 | 1.02 | 1.20 | 1.28 | 1.03 | 1.12 | 1.33 | 2.01 | 1.20 | 3.23 |
| Little River | 0.00 | 0.00 | 0.00 | 0.00 | 0.47 | 0.40 | 0.24 | 0.00 | 0.00 | 0.00 |
| Lonoke | 0.24 | 0.00 | 0.00 | 0.09 | 3.43 | 3.08 | 3.98 | 23.19 | 9.35 | 16.50 |
| Madison | 0.00 | 0.03 | 0.06 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Miller | 0.00 | 0.25 | 0.35 | 0.80 | 0.09 | 0.03 | 0.04 | 0.01 | 0.04 | 0.01 |
| Mississippi | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.15 | 0.57 | 0.00 | 0.00 |
| Monroe | 0.24 | 0.76 | 0.83 | 1.67 | 0.51 | 0.73 | 1.80 | 0.17 | 0.77 | 1.33 |
| Nevada | 0.00 | 0.10 | 0.13 | 0.16 | 0.00 | 0.00 | 0.00 | 0.01 | 0.19 | 0.00 |
| Ouachita | 2.27 | 7.39 | 4.28 | 3.89 | 0.00 | 1.23 | 1.52 | 2.60 | 1.03 | 1.11 |
| Phillips | 4.57 | 9.19 | 7.56 | 5.84 | 6.00 | 9.27 | 9.70 | 1.07 | 4.14 | 3.75 |
| Poinsett | 0.08 | 0.46 | 0.78 | 1.36 | 0.02 | 0.03 | 0.04 | 1.28 | 1.29 | 2.40 |
| Prairie | 6.75 | 7.72 | 15.80 | 20.92 | 20.70 | 22.58 | 24.72 | 27.65 | 5.79 | 10.32 |
| Pulaski | 0.00 | 0.16 | 0.20 | 0.30 | 0.85 | 0.82 | 0.52 | 0.43 | 0.12 | 0.93 |
| Saline | 0.57 | 0.20 | 0.18 | 0.28 | 3.43 | 3.43 | 3.72 | 3.35 | 0.38 | 0.49 |
| Sevier | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| St. Francis | 0.76 | 0.29 | 0.36 | 0.49 | 0.00 | 0.00 | 0.00 | 0.77 | 0.00 | 0.09 |
| Union | 19.07 | 18.85 | 17.40 | 16.07 | 13.85 | 14.83 | 15.23 | 17.97 | 15.55 | 7.59 |
| Woodruff | 0.13 | 0.10 | 0.10 | 0.75 | 0.00 | 0.00 | 0.00 | 1.48 | 1.21 | 1.14 |
| **Total** | 111.73 | 141.53 | 144.48 | 185.46 | 176.16 | 213.80 | 218.45 | 287.44 | 169.94 | 196.64 |

Use of the Sparta aquifer in southern Arkansas is less than use in the Grand Prairie or Jefferson County; however, the aquifer remains vitally important in southern Arkansas as it is the best source for industrial and public supply. In southern Arkansas, Union County is the biggest user of the Sparta aquifer (fig. 44; table 24). The maximum historic withdrawals in Union County most likely occurred during the oil boom of the 1920s before consistent water-use record keeping began in 1965. From reported water-use data, a maximum use of 19.07 Mgal/d occurred in Union County in 1965, and usage since has decreased (table 24). Water levels in the Sparta aquifer have continued to fall until the early to mid-2000s. At that time, the Union County Water Alliance, a local stakeholder group with local governmental, utilities, industrial, commercial, and public representation, led El Dorado and other users in Union County in implementing large-scale, coordinated conservation and alternative-source development efforts. This resulted in considerable decreases in withdrawals from the Sparta aquifer (discussed further in the “Water Levels” section below). From 2005 to 2010, water use in Union County decreased more than 50 percent because of conservation efforts and use in 2010 was 60 percent less than in 1965 (fig. 45; table 24). Sparta aquifer water use in Columbia County decreased by almost 20 percent from 6.50 Mgal/d in 1990 to 5.24 Mgal/d in 1995 with the 1993 completion of Lake Columbia and associated water treatment and transfer infrastructure.

Water use from the Sparta aquifer increased in northeastern Arkansas beginning about 2000 (fig. 44; table 24). Use in Craighead County increased 310 percent from 1965 to 2010 (fig. 45), primarily as a result of increasing public-supply demand. Irrigation use also has increased in Cross and Poinsett Counties since 2000.

### Domestic and Public Supply

The Sparta aquifer accounts for the greatest volume of groundwater used for public supply in Arkansas. More than 115 towns across Arkansas use the Sparta aquifer as their water source (fig. 43), withdrawing a combined 57.44 Mgal/d in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). The greatest number of towns using groundwater from the Sparta aquifer are in Arkansas and Union Counties. Municipalities generally turned to this aquifer because of water-quality issues in shallower aquifers or after shallower water sources were depleted. Multiple counties withdraw exclusively from the Sparta aquifer for their public supply, including those in the Grand Prairie, southern, and southeastern Arkansas. Craighead County had the most public-supply use, followed by Arkansas, Jefferson, Union, and Phillips Counties.

Municipalities in the Grand Prairie transitioned to the Sparta aquifer as water levels declined in the Mississippi River Valley alluvial aquifer. Stuttgart (Arkansas County), the largest city in the Grand Prairie, originally used the Mississippi River Valley alluvial aquifer for its public supply but because of declining water levels in this aquifer, the city completed its first well into the Sparta aquifer in 1947 (Stephenson and Crider, 1916; Engler and others, 1945, 1963; Hale and others, 1947). Stuttgart is the largest public user of the Sparta aquifer in the Grand Prairie and withdrew 3.13 Mgal/d in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

The cities of Brinkley (Monroe County), Des Arc (Prairie County), Carlisle, and Lonoke (both Lonoke County) originally used the Mississippi River Valley alluvial aquifer for public supply but have added new wells or completely switched to the Sparta aquifer (Stephenson and Crider, 1916; Engler and others, 1945, 1963; Halberg and Reed, 1964). The cities of DeWitt and Gillett (Arkansas County) tapped the Sparta aquifer in the 1950s (Lyle Godfrey, Arkansas Health Department, written commun., 2012). As of 2010, Des Arc pumped from Mississippi River Valley alluvial wells but installed an additional well tapping the Sparta aquifer in 2004. Brinkley and Lonoke now (2013) exclusively use the Sparta aquifer.

Use of the Sparta aquifer for public supply began at the turn of the 20th century in Pine Bluff (Jefferson County). Searching for better quality drinking water, two wells were drilled to the aquifer in the late 1890s; one of these wells was reported as pumping as much as 1 Mgal/d (Veatch, 1906). Pine Bluff completed additional public-supply wells in the Sparta aquifer in 1924; pumping was estimated at 2 Mgal/d in 1945 (Klein and others, 1950). With expanding population, public-supply pumpage increased to 2.7 Mgal/d in 1948, 3.6 Mgal/d in 1958, approximately 8 Mgal/d in 1977, and 11 Mgal/d in 1999 (Klein and others, 1950; U.S. Army Corps of Engineers, 1977; Kresse and Huetter, 1999). Use of the Sparta aquifer peaked in 2000 and has dropped as the population of Pine Bluff has declined (fig. 44; table 24).

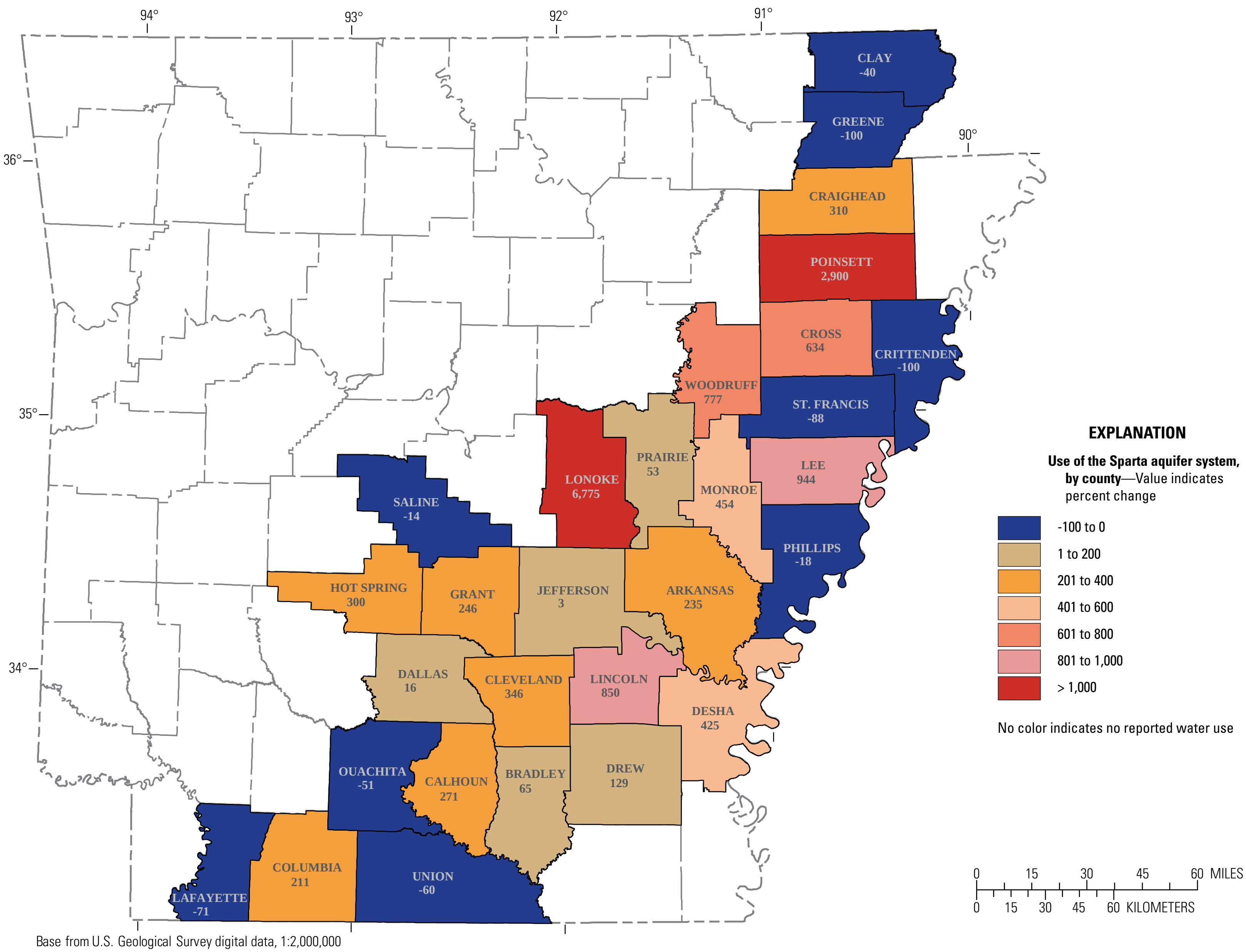



**Figure 45.** Change in percentage of water use from the Sparta aquifer in Arkansas from 1965 to 2010.

Most of the historical groundwater used in Union County was drawn by the city of El Dorado (fig. 46). El Dorado began public-water supply service in 1909, primarily drawing from the Cockfield aquifer (Hale, 1926; Hale and others, 1947; Baker and others, 1948; Broom and others, 1984). Oil was discovered near El Dorado in 1921 (Parker, 2001) and the population of El Dorado expanded within weeks of the discovery from 4,000 to 15,000 (Buckalew and Buckalew, 1974), which put a heavy demand on water resources in the region. Prior to the oil boom, public supply from the Sparta aquifer at El Dorado was estimated to be 0.1 Mgal/d in 1921 (Baker and others, 1948). In 1922, after the oil discovery, El Dorado completed additional public-supply wells into the Sparta aquifer to supply the rapidly increasing population (Baker and others, 1948). The population of El Dorado continued to increase, reaching 25,000 in 1924, while public-supply use correspondingly increased to 1.5 Mgal/d, with 0.4 Mgal/d coming from the Sparta aquifer (Hale, 1926; Baker and others, 1948). Total El Dorado public-supply water use was 1.32 Mgal/d in 1944, of which 1.2 Mgal/d was from the Sparta aquifer (Hale and others, 1947; Bakers and others, 1948). Many rural domestic wells in Union County also were completed in the Sparta aquifer during the 1930s and 1940s, whereas most domestic wells previously had tapped the Cockfield aquifer (Baker and others, 1948; Broom and others, 1984). The Sparta aquifer has been the sole public-supply source for El Dorado since the late 1940s (Bakers and others, 1948).

Magnolia (Columbia County) tapped the Sparta aquifer as early as 1928 (Hale and others, 1947). An oil discovery near Magnolia in 1938 caused population growth and increased groundwater withdrawals for public supply (Fancher and Mackay, 1946; Tait and others, 1953). Prior to the oil boom, Columbia County used 0.25 Mgal/d from the aquifer for all uses; in 1950, public-supply use had increased to about 1.2 Mgal/d (Tait and others, 1953). A larger percentage of surface water has been consumed by Magnolia since Lake Columbia was constructed and connected to the town's water supply in 1993; correspondingly, water use from the Sparta aquifer in Columbia County (table 24) decreased by almost

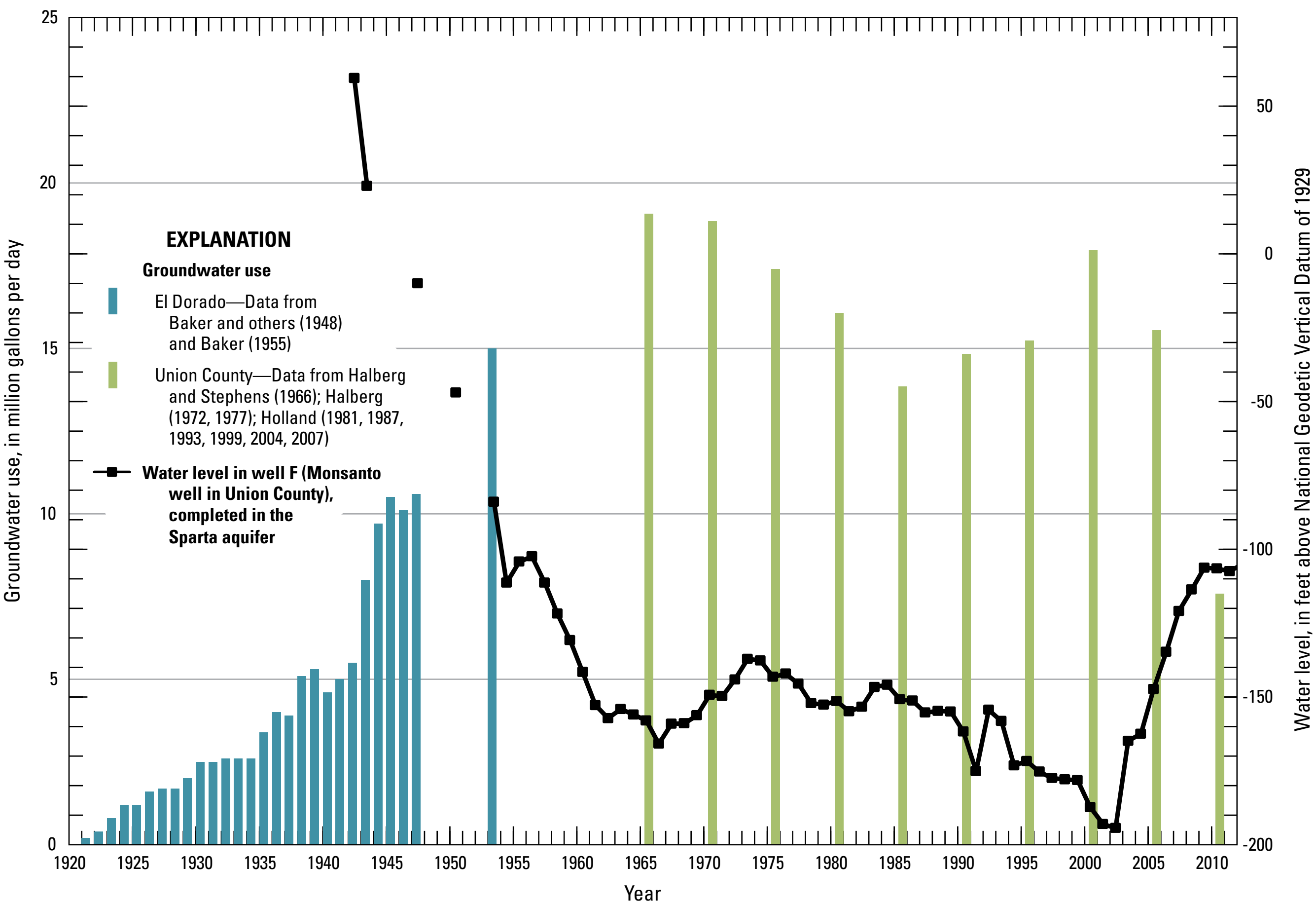



**Figure 46.** Hydrograph showing water use in the Sparta aquifer from the city of El Dorado and Union County and water levels in the Monsanto well (location shown as well F on fig. 49) in the Sparta aquifer near El Dorado, Union County, Arkansas.

20 percent from 1990 (6.50 Mgal/d) to 1995 (5.24 Mgal/d) and further decreased to 2.90 Mgal/d by 2000 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Total use of the aquifer has since risen to 9.41 Mgal/d in 2010, which corresponds with an increase in industrial use. Public-supply withdrawals have remained between 0.5 Mgal/d and 1.3 Mgal/d since 2000 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

The Sparta aquifer has many municipalities in other areas in southern Arkansas. Carthage, Fordyce (both Dallas County), and Rison (Cleveland County) were documented as using the aquifer in 1965 and continue, as of 2010, to draw from the aquifer (Plebuch and Hines, 1969). Albin (1964) reported that the Sparta aquifer at Camden (Ouachita County) was nearing maximum sustainable yield in the mid-1960s, but Camden now gets their water from the Ouachita River (Arkansas Department of Health, 2013).

Public-supply use of the Sparta aquifer in eastern Arkansas is not as intensive as in central and southern Arkansas. In southeastern Arkansas, the Mississippi River Valley alluvial and Cockfield aquifers are the primary groundwater sources. Only Dermott in the most northwestern part of Chicot County pumps from the Sparta aquifer (fig. 43). Many smaller municipalities in Drew County completed wells in the Sparta aquifer in the 1930s and 1940s (Hale and others, 1947). Monticello, the largest user in Drew County, first tapped the Sparta aquifer in 1910 (Hale and others, 1947) and withdrew 2.28 Mgal/d from the aquifer in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Winchester (Drew County) originally drew from the Cockfield aquifer but switched to the Sparta aquifer (Onellion, 1956). In northeastern Arkansas, there is less use of the Sparta aquifer as the Mississippi River Valley alluvial or Wilcox aquifers are viable water sources (Counts, 1957; Ryling 1960; Plebuch, 1961; Halberg and Reed, 1964). In northeastern Arkansas, Jonesboro (Craighead County) is the largest city using the Sparta aquifer and withdrew 11.20 Mgal/d in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Other cities using the Sparta aquifer in eastern Arkansas include Brinkley (Monroe County), Marianna (Lee County), Wynne (Cross County), and Helena (Phillips County).

### Irrigation

Rice farming began in the Grand Prairie region of Arkansas around 1905 (Engler and others, 1945; Sniegocki, 1964; Gates, 2005). Rice yields were greatly improved by irrigation, and fields were initially irrigated with groundwater from the Mississippi River Valley alluvial aquifer. By 1915, the Mississippi River Valley alluvial aquifer was being depleted faster than it was being recharged, and large water-level declines in the Mississippi River Valley alluvial aquifer were noticed in 1927 (Engler, 1963; see the section “Mississippi River Valley Alluvial Aquifer”). Development of the Sparta aquifer for irrigation supply consequently increased in areas where the Mississippi River Valley alluvial aquifer had been effectively dewatered. It is unknown when the Sparta aquifer first began to be used for irrigation supply, but Thompson (1936) noted about 10 irrigation wells, Engler and others (1945) documented 11 wells, and Sniegocki (1964) recorded 40 wells in the Sparta aquifer in the Grand Prairie region. As of 2010, 173 irrigation wells were reported as completed in the Sparta aquifer in Arkansas County and 64 in Lonoke County (fig. 43). Drought in the early 1980s dramatically increased water use for irrigation (Mahon and Poynter, 1993). Use of the Sparta aquifer has increased over 6,500 percent in Lonoke County and about 235 percent in Arkansas County from 1965 to 2010 (fig. 45; table 24). There is little irrigation use outside the Grand Prairie (fig. 43), although irrigation use has been increasing in Poinsett and Cross Counties.

Many rice farmers inundate their fields in winter to provide habitat for migratory waterfowl. “Duck tours,” guided duck hunting trips, are a lucrative business in the Grand Prairie, and this practice can bring more income to farmers than their rice crops. Arkansas and Prairie Counties used water from the Sparta aquifer to flood agricultural fields for duck hunting in 2010 (fig. 43). Arkansas County withdrew 1.02 Mgal/d in 2010, a decrease from 2.03 and 1.89 Mgal/d in 2000 and 2005, respectively (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

### Industrial Use

Industrial use of the Sparta aquifer is primarily for oil and gas processing or development, chemical industry, and the lumber and paper industries. Sawmills scattered across southern Arkansas primarily tap this aquifer. Chemical and oil and gas companies are located in Columbia, Jefferson, Lafayette, and Union Counties. Most industrial use occurs in Jefferson and Union Counties; however, Broom and Lyford (1981) reported 11.6 Mgal/d of use in 1973 in northeastern Arkansas for combined public and industrial supply. Several oil fields were discovered in the 1920s and 1930s in southern Arkansas (Ragsdale, 2003). Water was intensively used in the development of the oil fields, and untold amounts of water were consumed for this use. The Cockfield aquifer was the primary source of water used near El Dorado for this purpose (Baker and others, 1948), while near Smackover (Union County), water was primarily from the Sparta aquifer (Baker and others, 1948). For refining and other processes, companies tapped the Sparta aquifer (Baker and others, 1948). One refinery pumped between 0.2 and 1.5 Mgal/d from the Cockfield aquifer from 1921 to 1935, when it began to draw from the Sparta aquifer (Baker and others, 1948). Refiners in Union County started withdrawing 0.4 Mgal/d in 1923 and steadily increased to 0.7 Mgal/d in 1924, 1.1 Mgal/d in 1926, 4.0 Mgal/d in 1938, and 5.0 Mgal/d in 1947 (Baker and others, 1948). The peak of the oil boom occurred in 1925 and declined thereafter because of poor oil conservation and drilling practices (Ragsdale, 2003); consequently, water use in the oil fields waned after this time (Baker and others, 1948).

A majority of water use from the Sparta aquifer in Union County was centered in El Dorado (fig. 46). As of 1953, water use from the Sparta aquifer had reached its safe yield of 15 Mgal/d near El Dorado (Baker and others 1948; Baker, 1955). Use in Union County reached a high of 19.07 Mgal/d in 1965, declined through 1985, increased from 1985 to 2000, and decreased thereafter to 7.59 Mgal/d in 2010 (fig. 46; table 24). Industrial use in Union County was 3.98 Mgal/d in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Decreases in use are attributed to the implementation of conservation measures and development of alternative water sources. To remove the critical groundwater area designation for the Sparta aquifer by the ANRC, further reduction in use is required to reach the sustainable yield goal of 5.9 Mgal/d (Hays, 1999) that will allow water levels of the Sparta aquifer to rise to the top of the formation.

Just east of Magnolia (Columbia County), oil was discovered in 1938 (Fancher and Mackay, 1946), and many wells were drilled in the 1940s and 1950s to support oil production and refining (Tait and others, 1953). Unlike oil fields to the east in Union County that tapped the Cockfield aquifer, oil fields in Columbia County used water exclusively from the Sparta aquifer. Water use in Columbia County was estimated to have increased from 0.25 Mgal/d in 1928 to about 0.60 Mgal/d in 1941 from the Sparta aquifer prior to intensive water use for oil development (Tait and others, 1953; Baker, 1955). In 1950, after the oil boom had slowed and much infrastructure was in place for oil development, Magnolia used an estimated 2.7 Mgal/d (Tait and others, 1953). Tait and others (1953) suggested that 3 Mgal/d is the optimum withdrawal rate of the Sparta aquifer at Magnolia. Sparta water use in Columbia County increased from 0.33 Mgal/d in 1950 to 3.03 Mgal/d in 1965 (fig. 47) and to 7.22 Mgal/d in 1980 (table 24).

Use of the Sparta aquifer in Columbia County decreased from 1985 through 2000 (fig. 47; table 24) resulting from completion of Lake Columbia as an alternative water source. There was a long-term overall increase of 211 percent from 1965 to 2010 (fig. 45) as a result of increased industrial withdrawals in 2010. Industrial use of the Sparta aquifer in Columbia County increased 160 percent from 2005 to 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Major industries in Columbia County currently include lumber, chemical, and steel companies.

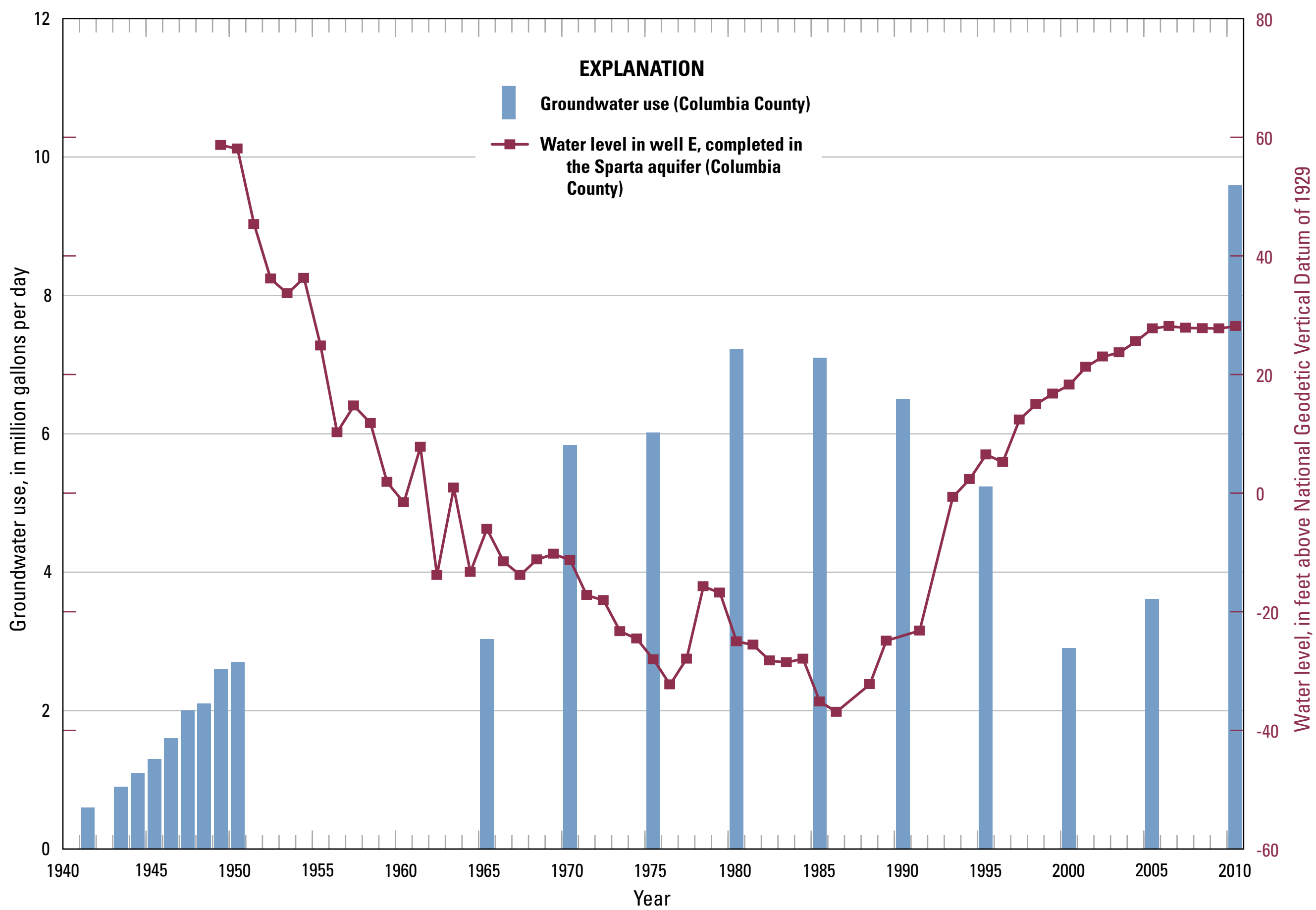



**Figure 47.** Hydrograph showing water use and water levels in well E (location shown on fig. 49) in the Sparta aquifer in Columbia County, Arkansas.

Large water users in Jefferson County included paper mills, railroads, and food companies. Two paper mills constructed in the late 1950s in Pine Bluff began using the Sparta aquifer, which dramatically increased total water use with a combined use of 31.8 Mgal/d in 1958 (Bedinger and others, 1960) and 40 Mgal/d in the mid-1970s (U.S. Army Corps of Engineers, 1977). Since construction of these paper mills, industrial water use has grown at a more moderate pace (Kresse and Huetter, 1999). Industrial water use from the aquifer in Jefferson County has fluctuated between 25 and 35 Mgal/d from 2000 to 2010 and was 31.79 Mgal/d in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

## Water Levels

Water-level declines in the Sparta aquifer are a major concern for users in Arkansas. Multiple studies have documented water-level trends in the Sparta aquifer (Bedinger and others, 1960; Albin and others, 1967b; Reed, 1972; Ryals, 1980; Edds and Fitzpatrick, 1984b, 1985, 1986, 1989; Ackerman, 1987b; Westerfield, 1995; Stanton, 1997; Joseph, 1998a, 2000; Schrader, 2004, 2006b, 2008b, 2009, 2013; Schrader and Jones, 2007). Severe water-level declines were noted in southern and east-central Arkansas after development of the Sparta aquifer for primarily public and industrial uses in these areas, and overall declines since predevelopment are shown in figure 48. Selected potentiometric maps from predevelopment to 2009 are shown in figure 49, which provides a general overview of changing water levels over time. The 2009 potentiometric surface (fig. 49*J*) documented eight cones of depression in the Sparta aquifer (Schrader, 2013). Major cones of depression occurred in (1) Pine Bluff (Jefferson County); (2) El Dorado (Union County); and (3) Magnolia (Columbia County) with minor cones in (4) Poinsett and Cross Counties, west of Crowleys Ridge; (5) northern Cleveland County; (6) northeastern Bradley County; (7) eastern Calhoun County; and (8) northern Ashley County. Declines also have been noted at Camden (Ouachita County) and West Memphis (Crittenden County) (Ackerman, 1987b).

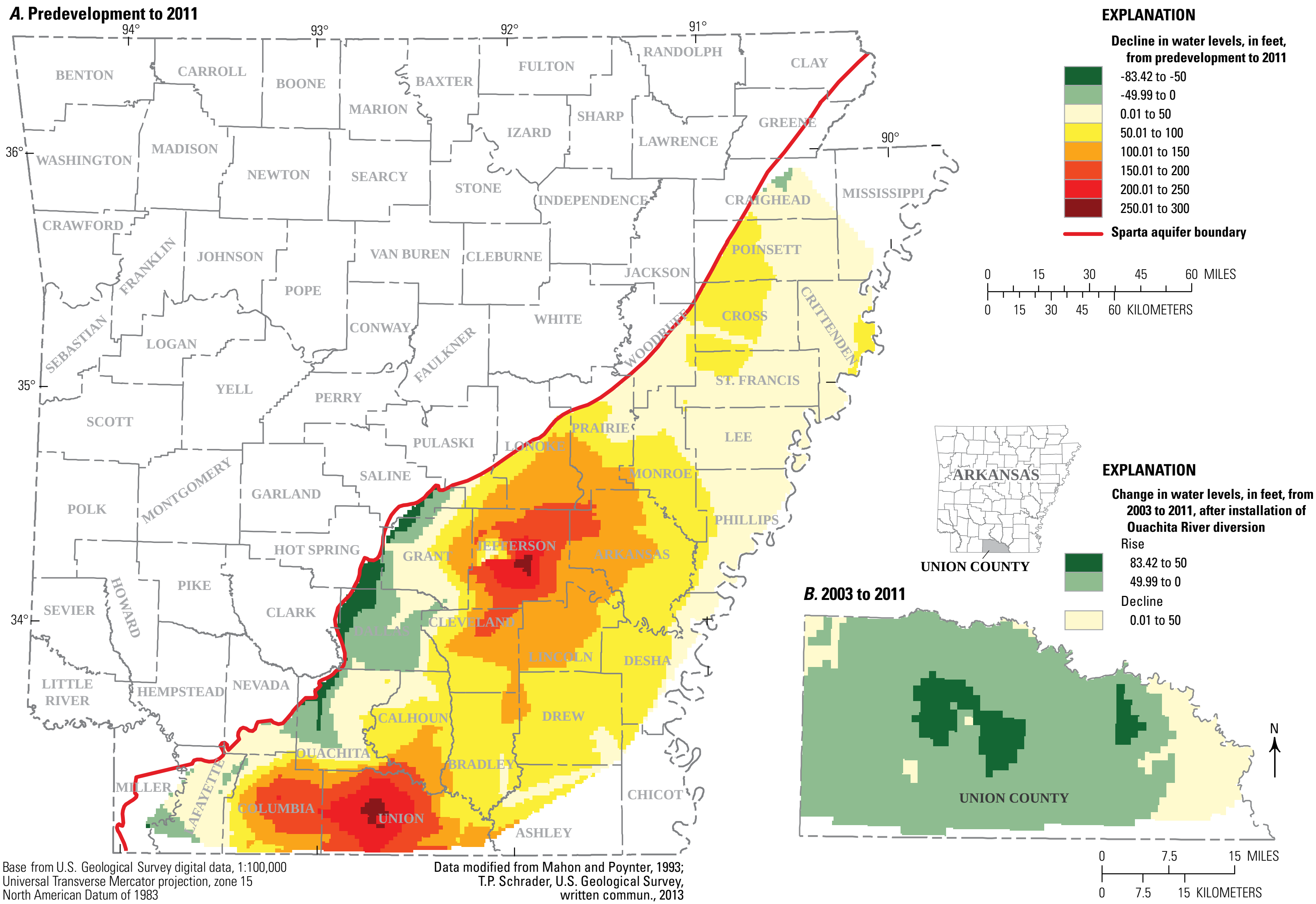



**Figure 48.** *A*, change in water levels for the Sparta aquifer in Arkansas from predevelopment to 2011; *B*, change in water levels for the Sparta aquifer in Union County from 2003 to 2011.

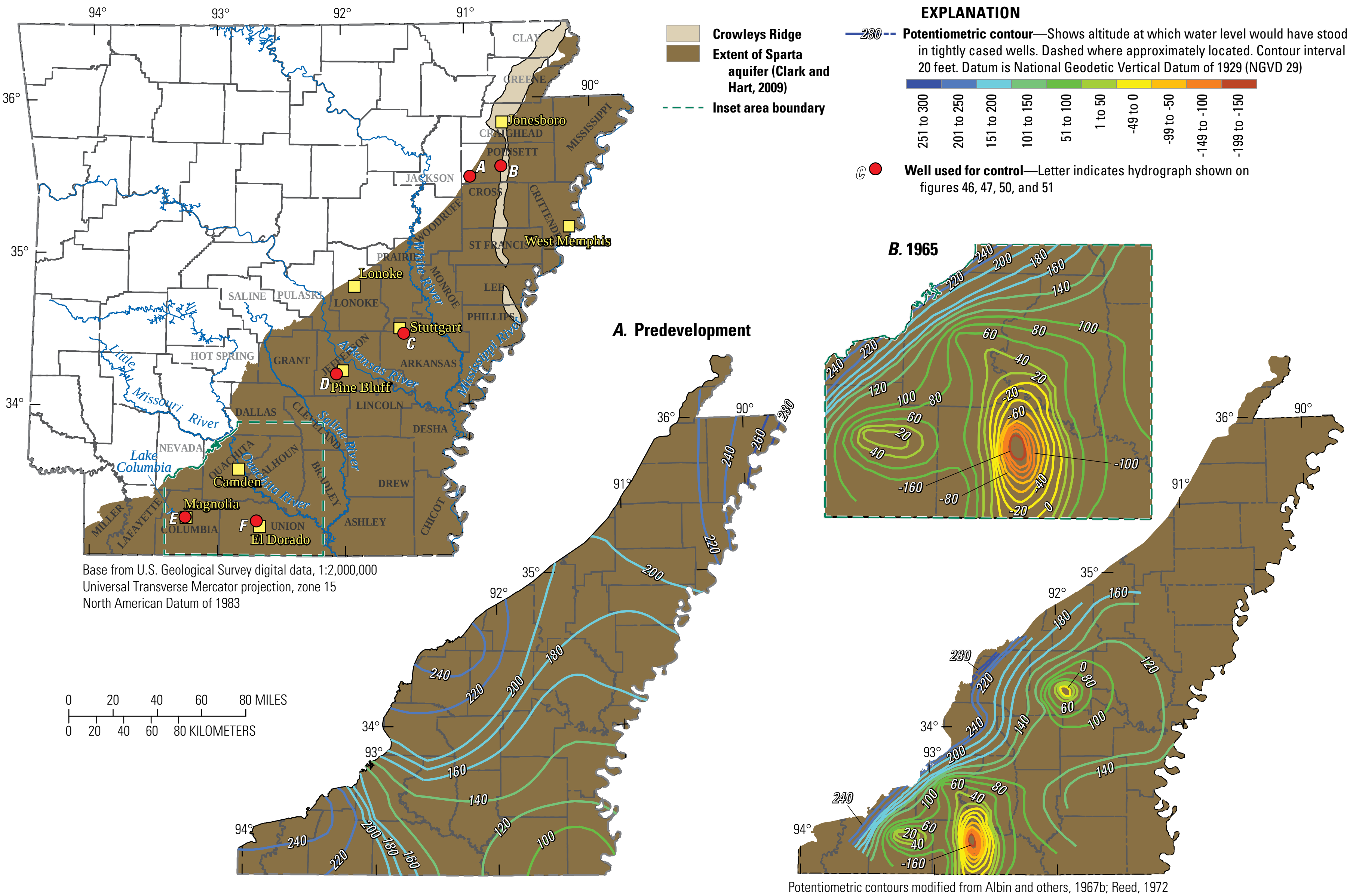



**Figure 49.** Selected potentiometric contours of water levels in the Sparta aquifer in Arkansas.

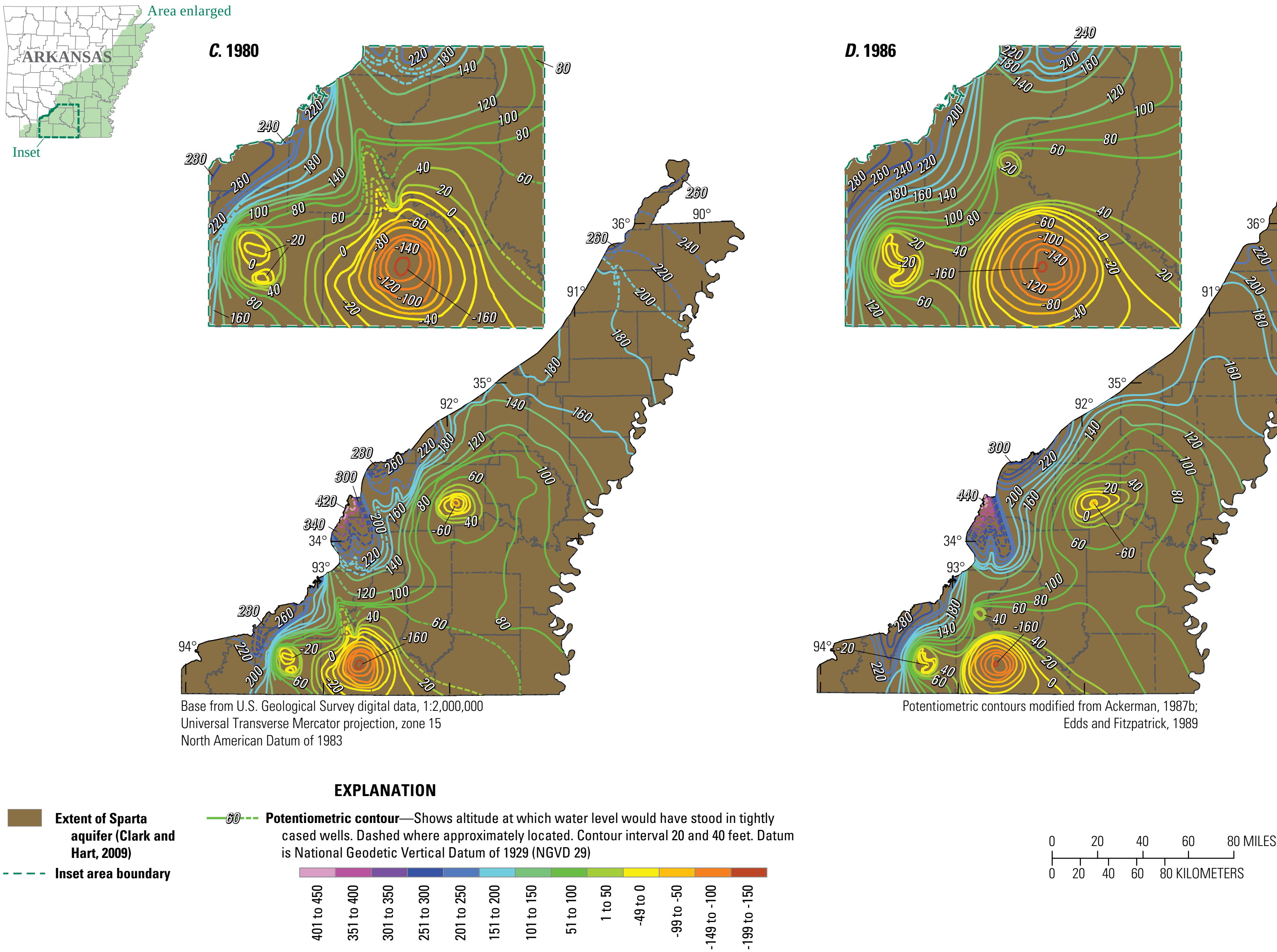



**Figure 49.** Selected potentiometric contours of water levels in the Sparta aquifer in Arkansas.—Continued

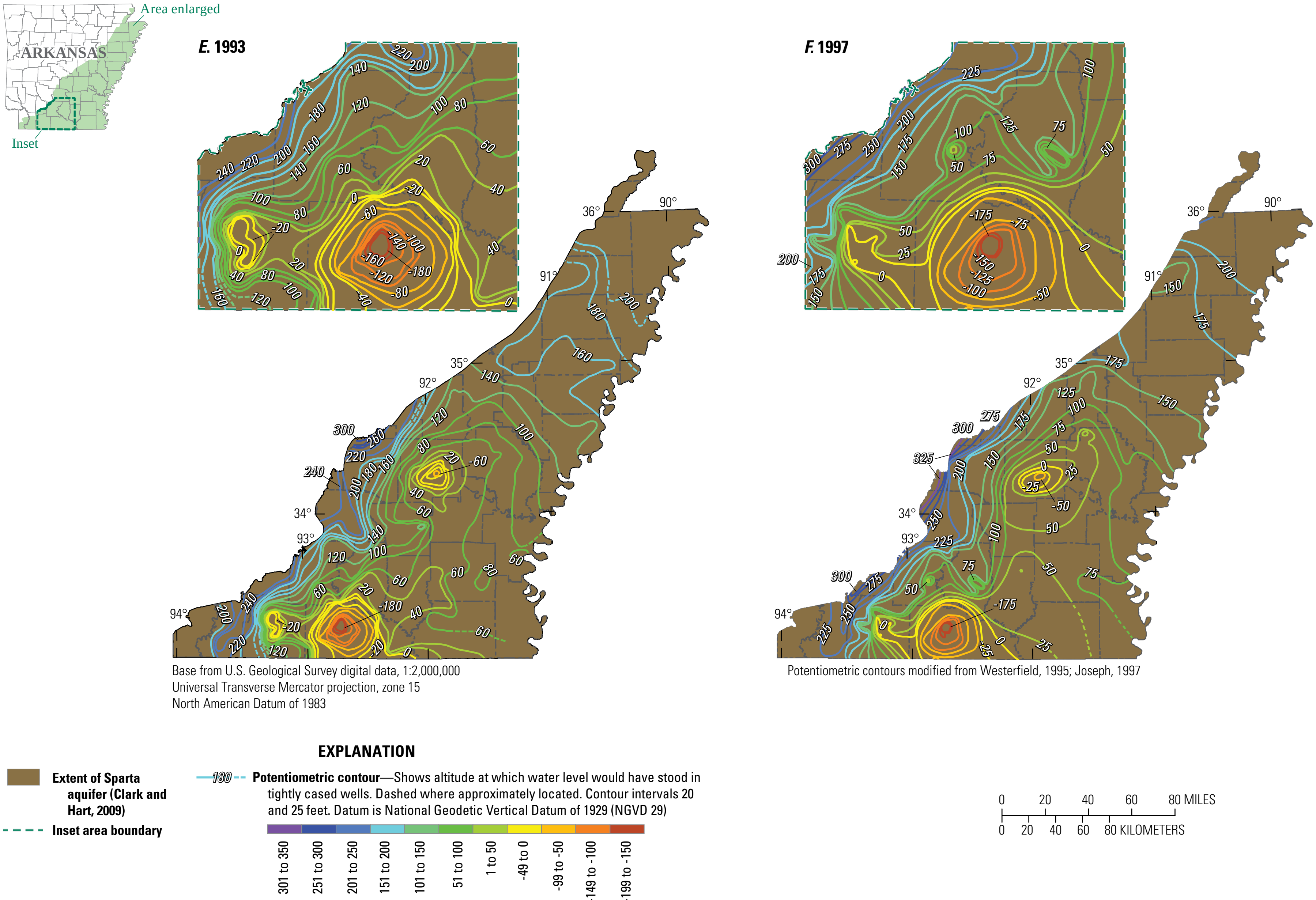



**Figure 49.** Selected potentiometric contours of water levels in the Sparta aquifer in Arkansas.—Continued

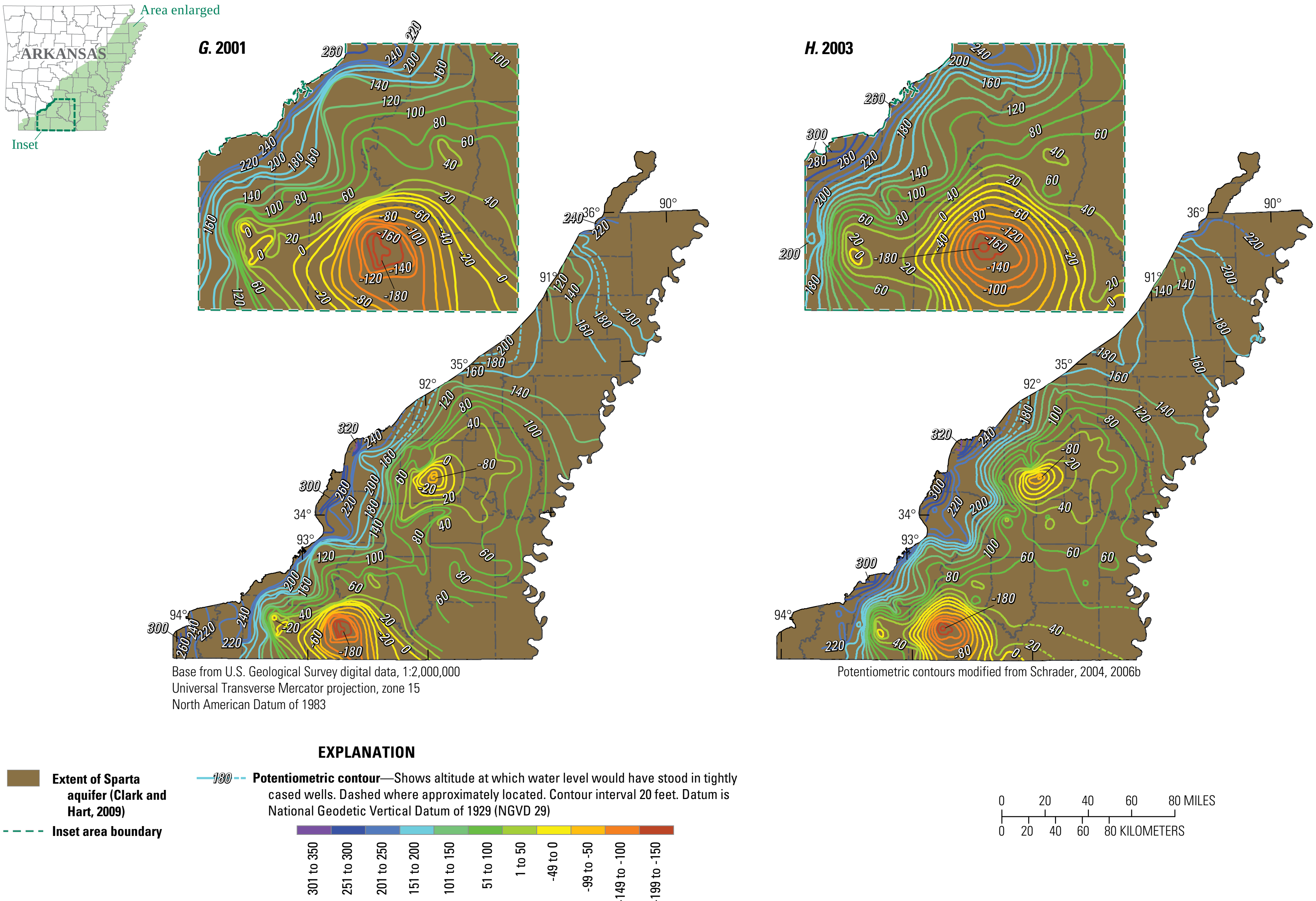



**Figure 49.** Selected potentiometric contours of water levels in the Sparta aquifer in Arkansas.—Continued

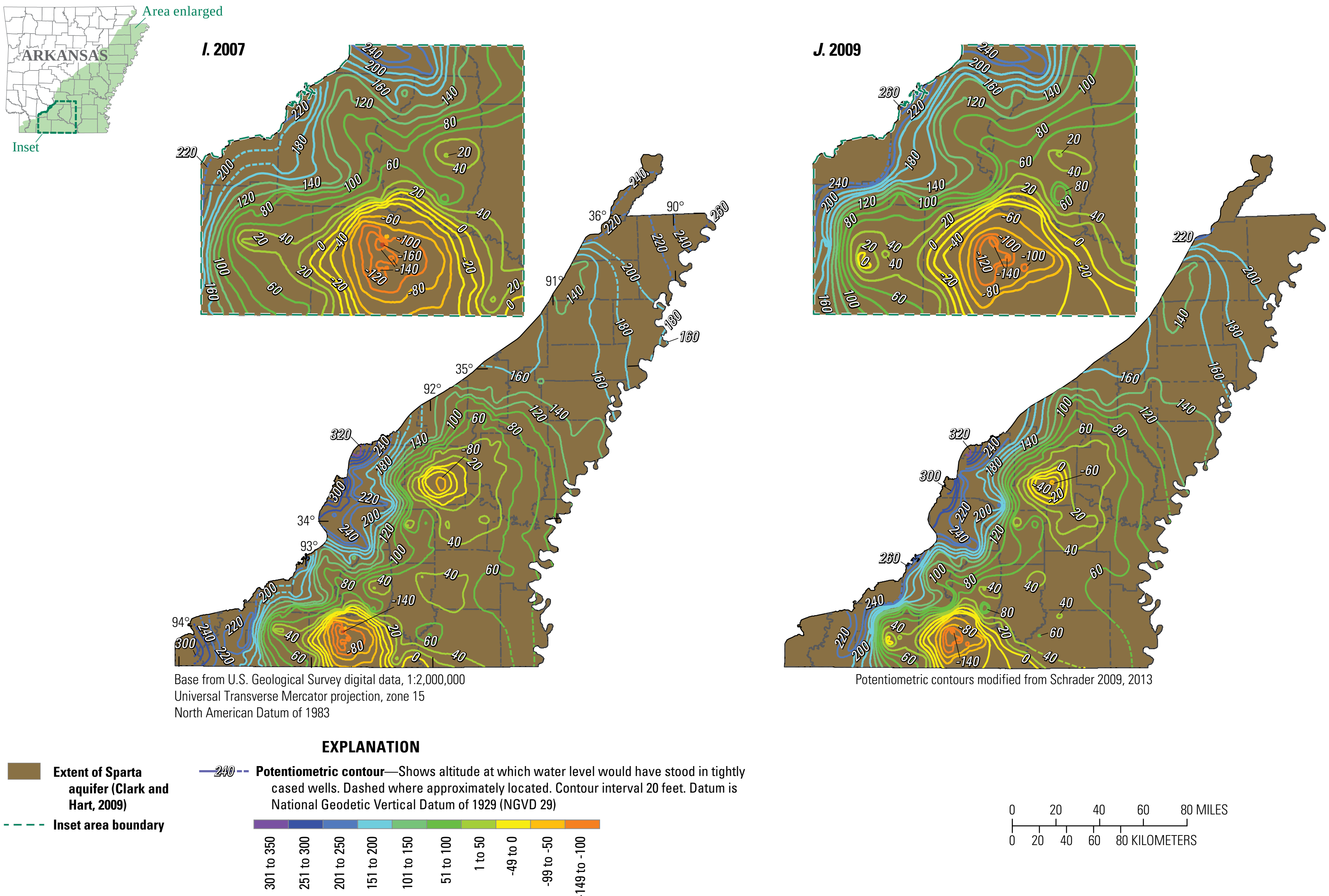



**Figure 49.** Selected potentiometric contours of water levels in the Sparta aquifer in Arkansas.—Continued

## Northeastern Arkansas

The first cone of depression in the potentiometric surface of the Sparta aquifer in the southwestern corner of Poinsett County in northeastern Arkansas was first depicted in the 1995 surface with the contour at 150 ft above NGVD 29 (not shown on fig. 49; Stanton, 1997). The 1996–97 potentiometric surface of the Sparta aquifer illustrated that the 150-ft contour had enlarged from the southwestern corner of Poinsett County to central Poinsett County (fig. 49*F*; Joseph, 1998a). In the 2001 surface, the cone of depression at the 140-ft contour had elongated south into Cross County (fig. 49*G*; Schrader, 2004). However the surfaces for 2003 (fig. 49*H*), 2005 (not shown on fig. 49; Schrader and Jones, 2007), and 2007 (fig. 49*I*) depict the cone of depression at the 140-ft NGVD contour primarily in western Poinsett County and only extending into Cross County beginning in 2005 (Schrader, 2006b, 2009; Schrader and Jones, 2007). In 2009, the 140-ft contour covered a large part of western Cross County (fig. 49*J*). While irrigation pumping from the Sparta aquifer increased in these counties throughout this time period (table 24), increased use may not be the sole cause of an enlarged cone of depression (Schrader, 2008b, 2013). Hydrologic connection and transfer of water from the Sparta aquifer to the highly stressed Mississippi River Valley alluvial aquifer also may have exacerbated water-level declines in Cross and Poinsett Counties west of Crowleys Ridge. Support for this hypothesis is that water levels in two wells in the Sparta aquifer mirror those in a nearby well in the Mississippi River Valley alluvial aquifer (fig. 50).

Another depression in the Sparta potentiometric surface has been noted in Crittenden County, near the Memphis, Tenn., metropolitan area (Schrader, 2008b). The depression from Memphis extends into the eastern part of Crittenden

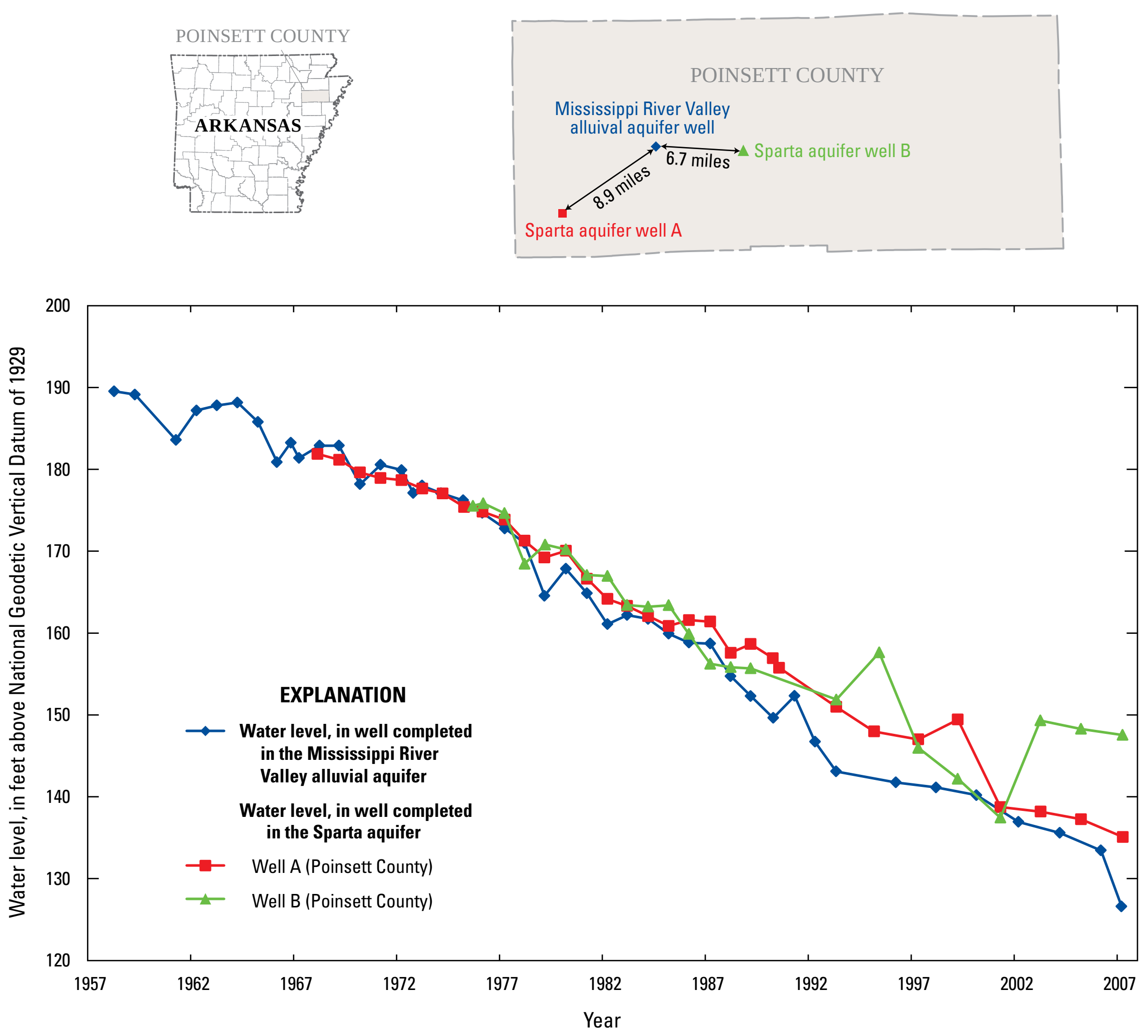



**Figure 50.** Hydrographs showing water levels in wells A and B in the Sparta aquifer (locations of wells shown on fig. 49) and water levels in a well in the Mississippi River Valley alluvial aquifer in Poinsett County, Arkansas.

County, and includes West Memphis, Ark. Intensive pumping at Memphis has resulted in considerable water-level declines in Arkansas of approximately 50 ft from predevelopment to 2011 (fig. 48; Schrader, 2009). The depression extended from Memphis to just east of West Memphis in the 2003, 2005, and 2007 surfaces (Schrader, 2006b, 2008b, 2009; Schrader and Jones, 2007). Plebuch (1961) also recorded water-level declines of 28 ft from 1934 to 1958 at West Memphis.

### Grand Prairie and Jefferson County

Water-level declines in the Sparta aquifer were first observed at Pine Bluff (Jefferson County) around the turn of the 20th century (Veatch, 1906; figs. 48 and 49). Veatch (1906) described a Pine Bluff well in which the water level dropped 15 ft from 1899 to 1900. The water level in another well at Pine Bluff dropped 35 ft from 1899 to 1949 (Klein and others, 1950). Other water levels in wells at Pine Bluff fell 16 ft in 7 years during a period of increased use in the 1940s (Klein and others, 1950). In 1958, after a year of substantial increase in use (approximately 37 Mgal/d) at two paper mills, a decline of 115 ft was observed in a well near the center of the pumping from April 1958 to May 1959 (Bedinger and others, 1960). Water-level declines at well D near Pine Bluff (fig. 51; location of well shown in fig. 49) were directly related to increases in water use in Jefferson County. A similar decline was observed in well D; water levels fell approximately 170 ft from the early 1950s to 1975 (fig. 51). Although there was a large increase in water use from 1995 to 2000, this was because of changes in reporting; water levels were stable from 1999 to 2001. Corresponding to decreased water use from 2000 to 2010, water-level rises of approximately 5 ft were recorded in Jefferson County between 2005 and 2007 (fig. 51; Schrader, 2009).

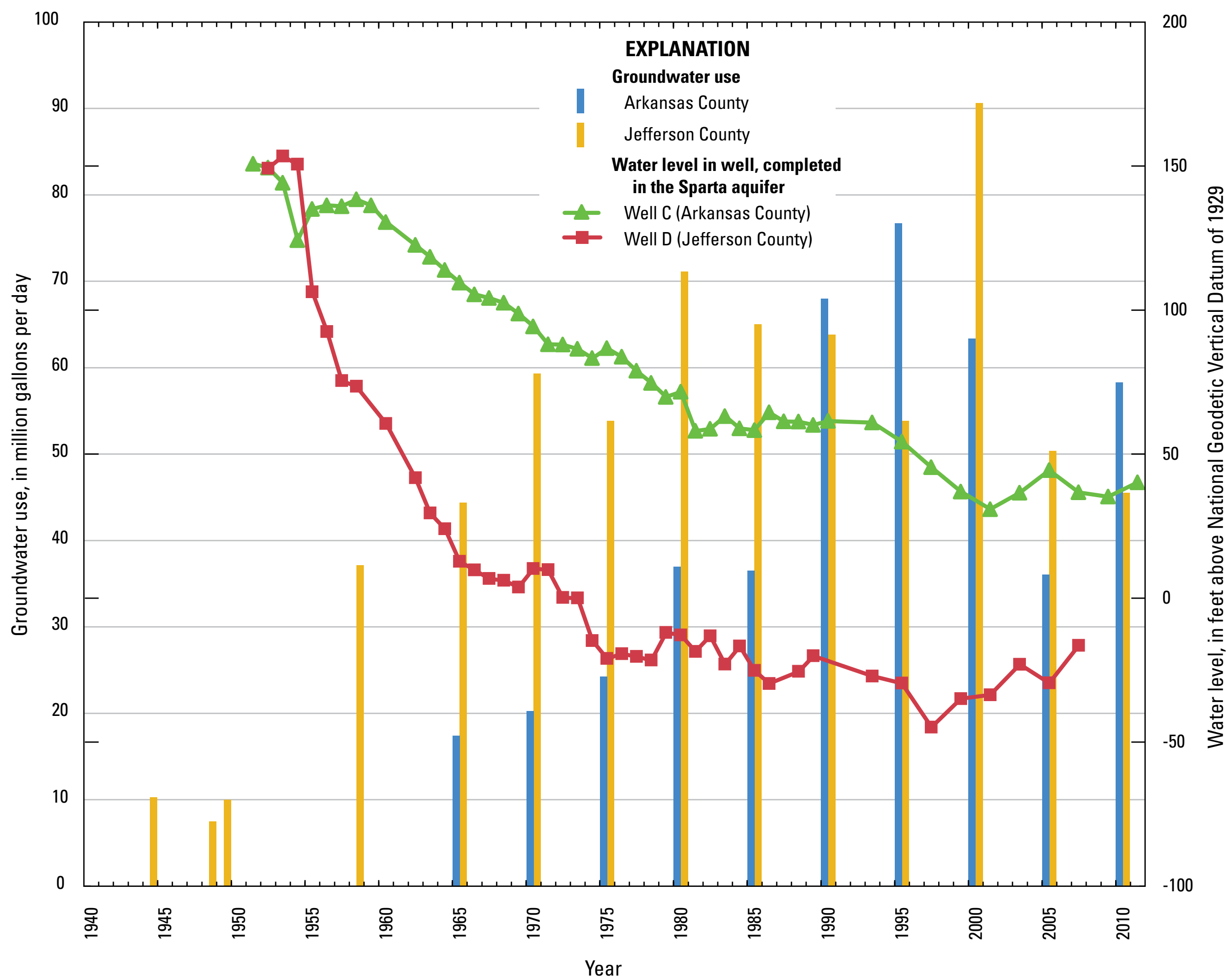



**Figure 51.** Hydrographs showing water use and water levels in wells C and D (locations of wells shown on fig. 49) in the Sparta aquifer in Arkansas and Jefferson Counties, Arkansas.

In the mid-20th century, large industrial withdrawals and seasonal irrigation use began in Jefferson County, which put further demand on the aquifer. The 1959 potentiometric contours of the Sparta aquifer showed a cone of depression at the 40-ft contour around Pine Bluff (Bedinger and others, 1960). By the 1980s, the center of the cone of depression had shifted to the east of Pine Bluff, where many industrial users were located (Edds and Fitzpatrick, 1984b, 1985, 1986; Ackerman, 1987b). The 1993 surface (fig. 49*E*) revealed the center of the cone of depression had dropped to the -60-ft contour (Westerfield, 1995); the 2001, 2003, and 2005 surfaces showed the center of the cone of depression at the -80-ft contour (Schrader, 2004, 2006b; Schrader and Jones, 2007). Rises in the potentiometric surface were seen in the 2007 and 2009 surfaces (Schrader, 2009, 2013).

The cone of depression centered near Pine Bluff encroached into Arkansas County as irrigation wells were drilled to the Sparta aquifer. In Arkansas County, water levels in the Sparta aquifer have fallen over 150 ft since the late 1930s (T.P. Schrader, U.S. Geological Survey, written commun., 2012). Water levels in well C fell 110 ft from 1951 to 2001 but rebounded from 2001 to 2005 in conjunction with decreased pumping in 2000 and 2005 (fig. 51; location of well shown in fig. 49).

The 1980 potentiometric surface of the Sparta aquifer revealed expansion of the cone of depression at the 60-ft contour from Jefferson County into Arkansas County (fig. 49*C*) (Ackerman, 1987b). By 2001, the closed 60-ft contour encompassed all or parts of Jefferson, Lonoke, Prairie, Arkansas, Lincoln, and Drew Counties (Schrader, 2004) (fig. 49*G*). The 2007 potentiometric surface (fig. 49*I*) showed western Arkansas County circumscribed by the depression with closure at the 40-ft contour (Schrader, 2009). Lincoln County had two smaller cones of depression with closure at the 40-ft contour (fig. 49*I*). Also, as early as the mid-1950s, Onellion (1956) hypothesized that water levels had declined in Drew County because of changes in water pressure, but water levels were not recorded at that time.

Water levels of the Sparta aquifer have declined in central Arkansas. Artificial-recharge approaches have been evaluated for alleviation of water-level declines in the Mississippi River Valley alluvial and the Sparta aquifers (Crider, 1906; Sniegocki, 1953, 1963a, b; Steinbrugge and others, 1954; Engler and others, 1963; Sniegocki and Reed, 1963; Sniegocki and others, 1963, 1965; Signor and others, 1970; Fitzpatrick, 1990; Hays, 2001) but generally have not been initiated because economic considerations have not supported artificial recharge. Surface-water diversions are planned for the White and Arkansas Rivers to provide irrigation water and thus decrease dependence on the Mississippi River Valley alluvial and Sparta aquifers (see section “Mississippi River Valley Alluvial Aquifer”; U.S. Army Corps of Engineers, 2007, 2013b).

### Southern Arkansas

Smaller cones of depression in the Sparta aquifer have developed in northern Ashley County, northeastern Bradley County, eastern and southern Calhoun County, northcentral Cleveland County, and eastern Ouachita County (fig. 49; Schrader, 2013). A depression in eastern Cleveland County appeared only in the 1993 surface (fig. 49*E*). The depression in north-central Cleveland County was first noted in 2003 (fig. 49*H*; Schrader, 2006b) and has since deepened (figs. 49*I* and 49*J*; Schrader, 2013). The depression in Calhoun County was first identified in the 1996–97 surface (fig. 49*F*; Joseph, 1998a) and had expanded and deepened in the following surfaces from 1999 through 2009 (figs. 49*G–J*; 1999 surface not shown in fig. 49; Joseph, 2000). A second cone of depression in Calhoun County developed to the south of the original cone in 2003 (fig. 49*H*), and was seen in subsequent surfaces (figs. 49*I* and 49*J*). In 1997 (fig. 49*F*) and 1999 (not shown on fig. 49), a cone of depression was noted in northeastern Bradley County at the 25-ft contour. It was not seen in either the 2001 or 2003 surfaces, but the 2007 surface (figs. 49*I*) showed the cone expanded at the 40-ft contour to also include Drew and northwestern Ashley Counties. By 2009 (fig. 49*J*), the cone had contracted back into mostly Bradley County and had reduced again in size in the 2011 surface (not shown on fig. 49; Schrader, 2014). Lower water levels in the Sparta aquifer in eastern Ouachita County have centered around the city of Camden. While the impact of pumping was seen in all surfaces around Camden since 1965 (figs. 49*B–J*), a cone of depression was seen in 1986 (fig. 49*D*) and again in 1997 (fig. 49*F*).

Heavy pumping for industrial and public supply lowered water levels at Magnolia (Columbia County). Early industrial development for paper and lumber increased water use tenfold from 1928 to 1950, and water levels declined 75 ft over that time (Tait and others, 1953; Baker, 1955). Water levels at Magnolia declined from when measurements began in the 1940s through the 1990s (fig. 47). Water levels in Columbia County declined an average of 3.0 ft/yr from 1969 to 1995 (Joseph, 2000). A cone of depression in the Sparta aquifer had formed beneath Magnolia and expanded to coalesce with the cone of depression in Union County when the first potentiometric surface was created for 1965 (fig. 49*B*). Depths in well E (fig. 47; location of well shown in fig. 49) declined from the 1940s through the 1980s, reaching a minimum altitude of -36.8 ft in 1986. Construction of Lake Columbia and installation of a surface-water supply system in 1993 resulted in decreased withdrawals from the Sparta aquifer, resulting in a much smaller size of the cone of depression centered beneath Magnolia (Hays and others, 1998). With diminishment of the cone between 1993 and 2007 (figs. 49*E–I*), water levels in well E rose 64.8 to 28.3 ft by 2010 (fig. 47; location of well in fig. 49). However, recent increased industrial usage of the Sparta aquifer in Columbia County threatens further water-level recovery. From 2007 to 2009, water levels in the aquifer declined in the county and the center of the cone of depression deepened from the 20-ft to 0-ft contour (figs. 49*I* and *J*).

In the El Dorado (Union County) area, water levels for the Sparta aquifer dropped 240 ft from 1922 to 1953, while water use over that same period increased from less than 1 Mgal/d to 15 Mgal/d (Baker, 1955). Industrialization began in earnest following World War II, and dramatic water-level declines were noted throughout the Sparta aquifer in this area (fig. 46; Johnson, 2004). Water levels for the Sparta aquifer dropped steadily as water use increased. As of 1964, water levels near El Dorado were declining about 12.5 ft/yr (Albin, 1964). Decline of the Sparta aquifer at El Dorado was first noticed in the 1965 potentiometric surface (Albin and others, 1967b); the cone of depression in Union County deepened and expanded through 2003 (figs. 49*B–H*). Maximum drawdown in the El Dorado area exceeded 360 ft in 1993 relative to water levels in about 1920, when development first began in the area. Water levels in Union County in the mid-1990s had been declining at rates more than 1 ft/yr for over a decade (Hays and others, 1998), and saltwater intrusion caused by intensive pumping increased near the cone of depression (Broom and others, 1984). Simulated results (Hays and others, 1998) indicated that if pumping rates from the 1990s continued to 2027, water levels would approach or fall below the top of the Sparta aquifer at the major pumping centers in Arkansas and Louisiana.

In 1996, the Sparta aquifer was declared a critical groundwater area by ANRC in Bradley, Calhoun, Columbia, Ouachita, and Union Counties. In the late 1990s, Federal, State, and local agencies, industries, and citizens implemented conservation measures and alternative source development efforts aimed at raising the Sparta aquifer water levels. The Union County Water Conservation Board (UCWCB) was formed and approved by ANRC in 1999. In an effort to conserve water levels in the aquifer, UCWCB instituted several water conservation measures, including (1) public education about water conservation practices, (2) industrial water reuse and sharing, and (3) reuse of reclaimed treated wastewater at local golf courses (Johnson, 2004).

In addition, a temporary 1-cent sales tax was adopted in 2002 by the citizens of Union County to help pay for a pumping facility on the Ouachita River as an alternative water source to local industry. This funding, in combination with a grant from the EPA, was used to construct a pumping station and pipeline from the Ouachita River to major industrial groundwater users in the El Dorado area. The river intake, pumping facility, and 5 miles of a 48-inch pipeline were completed in 2004. The facility is capable of producing 10 Mgal/d and could expand to produce another 19 Mgal/d (Johnson, 2004). Lion Oil began using the water from the Ouachita River in December 2004, El Dorado Chemical converted in February 2005, and Chemtura (Formerly Great Lakes Chemical) in October 2005; Pilgrim's Pride ceased operations in 2009. The funding also allowed for the installation of eight real-time water-level monitors (Scheiderer and Freiwald, 2006). These monitors were installed in 2003 in six existing and two new wells (fig. 52). More information on data collected from these monitors can be found on the UCWCB Website (http://www.ucwcb.org/). As a result, wells in Union County were the first to show a rise in water levels in Arkansas since 2003 (Schrader, 2009).

Based on model simulations of sustainable yield for the Sparta aquifer in Union County, withdrawals would need to be reduced to 28 percent of the 1997 use levels from around 20 Mgal/d to approximately 6 Mgal/d in order to bring water levels up to the top of the Sparta Sand (Hays, 2000). After the conversion of three main industrial users to the Ouachita River, industrial users used 4.8 Mgal/d of Ouachita River water in 2005 (Freiwald and Johnson, 2007). Industrial and public supply water use decreased 80 and 50 percent, respectively, from 2000 to 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Overall groundwater withdrawals in Union County were reduced by an estimated 7.5 Mgal/d (Freiwald and Johnson, 2007). These voluntary conservation measures were estimated to have decreased overall groundwater use 15 to 20 percent in Union County (Union County Water Conservation Board, 2007).

The cone of depression in the Sparta aquifer in Union County was projected to coalesce with other cones of depression in Columbia County and northern Louisiana Parishes; however, the efforts undertaken to reduce groundwater use led to rising water levels (figs. 46–48, and 53) and a smaller cone of depression from 2004 to present (2013) (figs. 49*I* and *J*; Schrader, 2014). In the 2009 surface, the center of the cone of depression was enclosed at the -40-ft contour (fig. 49*J*), which represents a rise from the deepest -200-ft contour in the 1999 surface (Joseph, 2000). The area which the cone of depression at the -60-ft contour encompassed also was reduced 41 percent in size from 1993 to 2011 (Schrader, 2014). Increases in water levels in individual wells ranged from 0.5 to 60.2 ft across Union County (Schrader, 2013), although some seasonal fluctuations were observed (fig. 53). Water levels in the Monsanto, Airport El Dorado, and Welcome Center wells had risen after the implementation of the conservation measures outlined above (fig. 53). Directly after the Lion Oil (2004) and El Dorado Chemical (2005) conversions to surface water, water-level rises of about 30 ft were noted in the Monsanto well by late 2005 (fig. 53). After the Chemtura (2006) conversion, rises were seen in multiple wells. Additional rises were noted after Pilgrim's Pride ceased operation in 2009 (fig. 53).

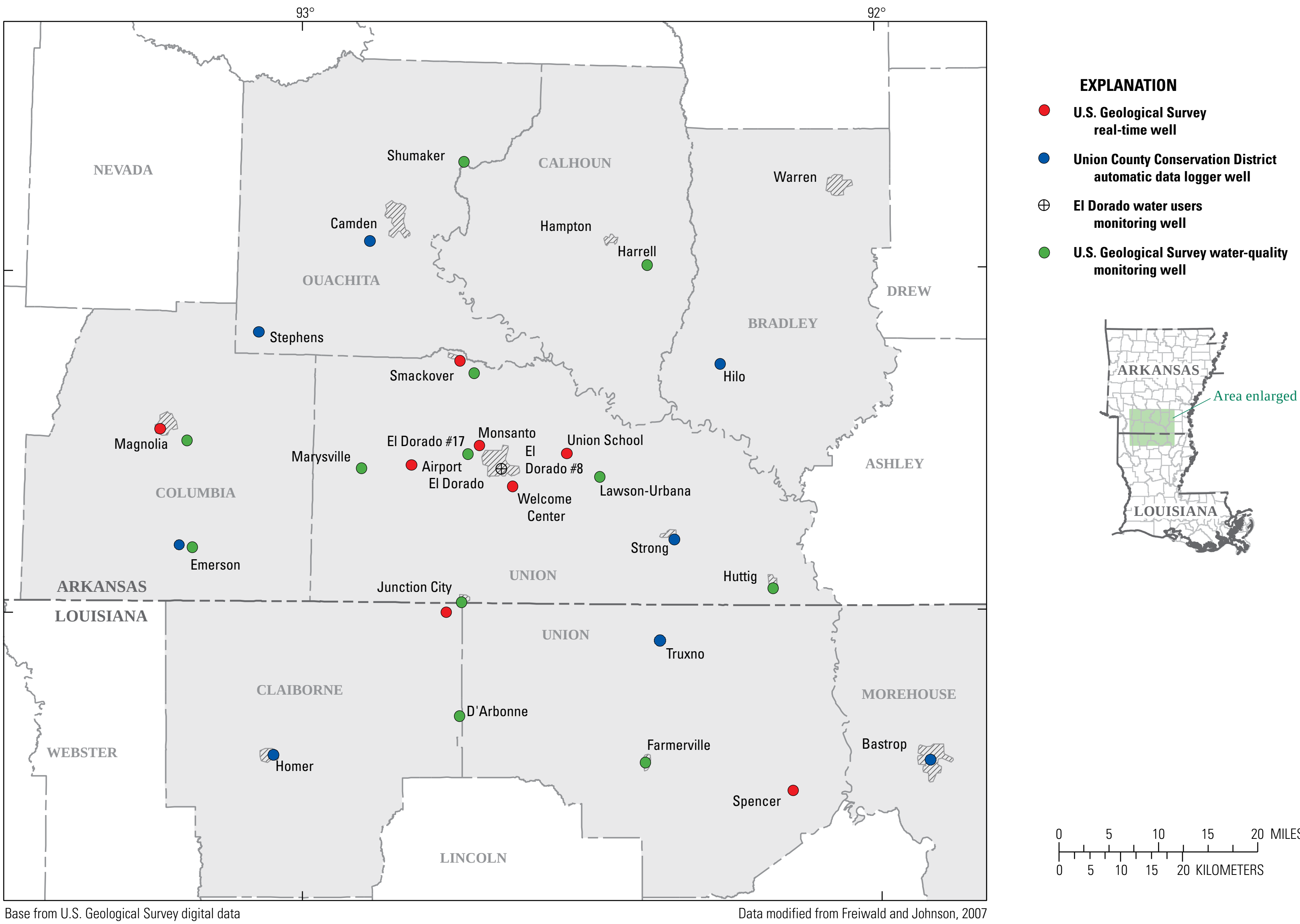



**Figure 52.** Location of water-level and water-quality monitoring wells in the Sparta aquifer of southern Arkansas and northern Louisiana.

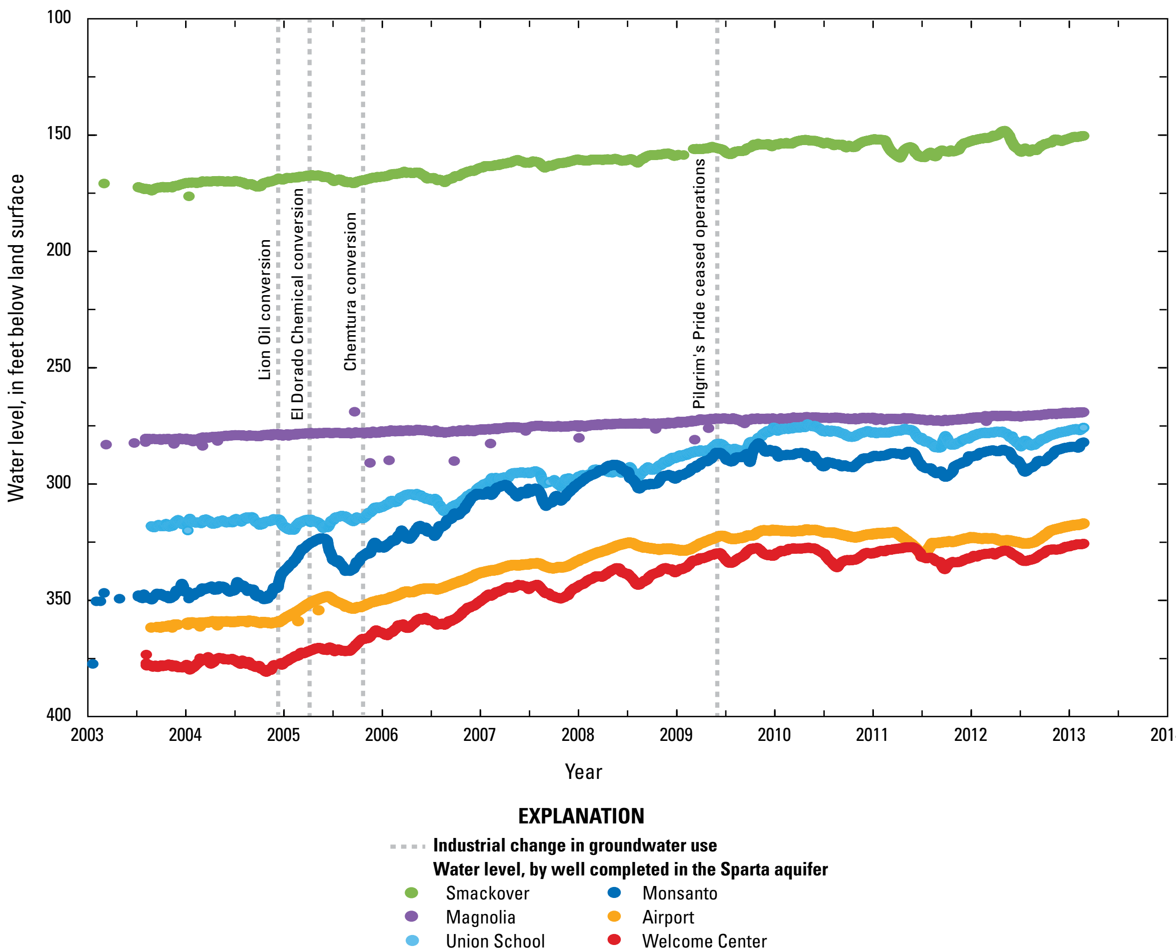



**Figure 53.** Hydrographs showing effects of change in industrial groundwater use on water levels in wells (location of wells shown in fig. 52) completed in the Sparta aquifer in southern Arkansas.

## Deductive Analyses, Projections of Aquifer Conditions, and Sustainable Use

Groundwater often is overlooked by water managers, in part, because groundwater cannot be directly observed. Another consequence of the hidden nature of groundwater is that the collection of information and development of a competent understanding of groundwater behavior is challenging. This is partly the result of the expansive scale of groundwater flow and the fact that groundwater moves very slowly in most systems. Consequently, understanding groundwater flow necessitates the development and use of approaches that are somewhat different than those applied to surface water. Important questions that groundwater managers and groundwater scientists may pose include: How much water is stored in a given aquifer? At what rate can water be produced? Where does groundwater flow, what are the sources and outlets? What is a sustainable long-term yield? How long will the aquifer produce water if pumping rate is exceeded? How will aquifer yields and groundwater flow paths be affected by naturally or human-induced changes? These and other more specific questions can be effectively addressed by digital simulations of aquifers using groundwater-flow models.

Groundwater-flow models simulate the physical aquifer system and hydrologic processes affecting groundwater flow using a set of governing equations. Construction of a groundwater-flow model is time-consuming, labor-intensive, data-intensive, and expensive; however, the utility of groundwater-flow models in understanding and simulating groundwater behavior has made them a tool of great value. Thus, the tremendous investments that have been made in developing and maintaining groundwater models in Arkansas are warranted for purposes of effective water management.

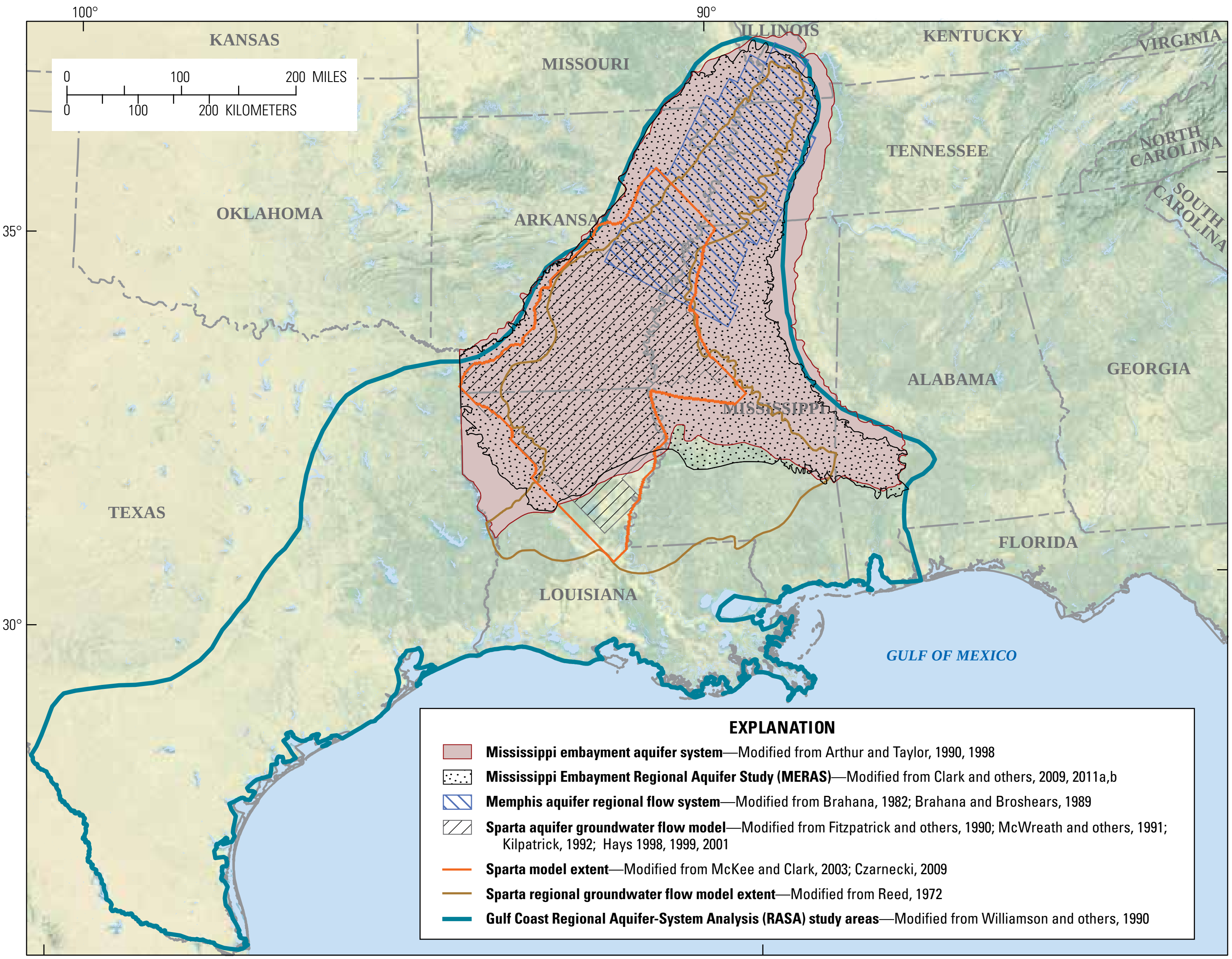
Long-term water-level declines and imminent problems associated with the extensive development of groundwater as a resource led to development of a regional analog groundwater-flow model of the Sparta aquifer in the late 1960s (Reed, 1972). The model was used to simulate the effects of potential increases in groundwater withdrawals. Reed (1972) simulated the period from 1966 to 1990, incorporating a simulated average increase in pumpage of 80 percent; a value based on then-current estimates of water-use increase rates (fig. 54). The model results indicated that by 1990 approximately 10 percent of the projected pumpage would be supplied from storage with the remainder from recharge or stream capture. The model projected water-level declines of approximately 170 ft at El Dorado, 130 ft at Pine Bluff, and 40 ft at West Memphis over the simulation period from 1966 to 1990. These model results indicated that projected withdrawal rates in several areas would not be sustainable for the long term. Another notable projection from this early model was that water levels would decline below the top of the aquifer in some areas, including the area of El Dorado.

The City of Memphis, Tenn., depends upon the Sparta aquifer as a source of public-supply water, and withdrawals increased from 200 to more than 250 Mgal/d from 1985 to 2005 (Robinson and Brooks, 2010). The Memphis pumping center is in hydraulic connection with the Sparta aquifer across the border in Arkansas. ANRC and other water planners and managers in Arkansas have tracked declines caused by pumping at Memphis (Edds and Kilpatrick, 1985; Joseph, 1998a; Schrader, 2009) and have considered implications for Arkansas groundwater users. The USGS conducted a series of studies in the 1980s to better understand the groundwater flow in the Memphis and West Memphis area. These studies included development of groundwater-flow models for simulation of the Sparta aquifer (termed Memphis aquifer in reports) and other major aquifers in the Memphis area (Brahana, 1982; Brahana and Broshears, 1989). Brahana (1982) developed a two-dimensional digital-flow model of the Sparta aquifer and used it to estimate aquifer response to hypothetical pumpage projections. An improved three-layer, digital-flow model was then constructed to simulate the regional flow system in the Memphis area (fig 54; Brahana and Broshears, 1989). Model results determined that pumping during the time of their study accounted for almost all discharge from the Memphis aquifer. Model simulations indicated that lateral inflow, including flow from Arkansas to the west, replaced 42 percent of pumped water. Simulations indicated that continued pumping at the Memphis pumping center would result in expanding water-level declines in Arkansas.

Understanding of conditions in the Sparta aquifer in Arkansas was advanced by modeling conducted as part of the USGS Gulf Coast RASA model investigation (Williamson and others, 1990), which covered 290,000 $mi^2$ across Alabama, Arkansas, Florida, Illinois, Kentucky, Mississippi, Missouri, Tennessee, Texas, and all of Louisiana (fig. 54). An important subproject of the larger national effort was the Mississippi embayment aquifer system study (Arthur and Taylor, 1990, 1998; fig. 54), which was described as comprising five major aquifers and two confining units in the Tertiary System Wilcox and Claiborne Groups: (1) upper Claiborne aquifer, (2) middle Claiborne confining unit, (3) middle Claiborne aquifer that comprises the Sparta Sand in most of Arkansas and includes the upper part of the Memphis Sand in east-central Arkansas, (4) lower Claiborne confining unit, (5) lower Claiborne-upper Wilcox aquifer, (6) middle Wilcox aquifer and, (7) lower Wilcox aquifer.

A digital groundwater-flow model was developed to represent the aquifer system using five layers representing the five major aquifers (Arthur and Taylor, 1990, 1998). Model results showed that flow in the Mississippi embayment aquifer system generally moves downdip from the outcrop areas and then upward through the confining units as flow paths approach the Mississippi embayment axis. Shorter flow paths occur near outcrop areas where the shallow water table intersects land surface. Model results generally indicated that groundwater leakage through confining layers between adjacent aquifers was less than 0.1 in/yr. A notable exception is the heavily pumped Memphis area where as much as 4.0 in/yr moves from the upper Claiborne aquifer down to the middle Claiborne/Sparta aquifer. Arthur and Taylor (1990, 1998) noted that simulated water-level declines were greater in the middle Claiborne/Sparta aquifer than in any of the other aquifers in the Mississippi embayment aquifer system because of pumping stress. Consequently, flow from adjacent units in the subcrop areas generally was into the middle Claiborne aquifer. Comparison of the predevelopment and 1987 groundwater-flow model budgets indicated that 1985 pumpage from the five major aquifers was predominantly from: (1) increased recharge in the outcrop areas of the upper Claiborne and Sparta aquifers and (2) reduction of discharge from those two aquifers to the Mississippi River Valley alluvial aquifer (Arthur and Taylor, 1990, 1998). The total contribution from aquifer storage was relatively small. Arthur and Taylor (1998) determined that the five aquifers had potential for additional groundwater development. The middle Claiborne aquifer exhibited the greatest potential for additional development, but simulation results showed that a 20-percent increase in pumping relative to 1985 rates would produce substantial water-level declines by 2000. This is about 30 ft below 1987 levels in the Sparta aquifer at El Dorado and about 20 ft after 13 years at Pine Bluff. These results indicated that the simulated withdrawal rates were, in some areas, not sustainable for the long term. Several of the embayment models referenced herein were derived from or benefitted in some fashion from this RASA model.

Extensive use of the Sparta aquifer in southern Arkansas, particularly in Union and Columbia Counties, resulted in withdrawals that substantially exceeded recharge. Water levels were documented as declining at rates more than 1 ft/yr through the 1980s and 1990s (Joseph, 2000). Regional cones of depression centered on El Dorado and Monroe, La., coalesced by 1990 (Joseph, 1998a, 2000). As water levels began to drop below the top of the formation, water users and managers began to question the ability of the aquifer to supply water for the long term and began to evaluate management approaches to protect the aquifer. Groundwater-flow models were and are an important part of the aquifer evaluation and management for the Sparta aquifer in southern Arkansas.




Base from U.S. National Park Service
Natural Earth physical map at 500 meters per pixel
Albers Equal Area Conic projection

**Figure 54.** Extent of area for historical groundwater flow-simulation models constructed for regional analysis of the Sparta aquifer in the Mississippi embayment of the southern United States.

In 1985, the USGS, in cooperation with the Arkansas Soil and Water Conservation Commission (now called the Arkansas Natural Resources Commission), the Louisiana Department of Transportation and Development, the El Dorado Water Utility, the Union County Water Alliance, UCWCB, and Louisiana Sparta Groundwater Conservation District Commission began a series of projects to study the hydrogeologic characteristics of the Sparta aquifer. These studies also evaluated regional water-availability, water-level, and water-quality effects of long-term pumping trends. A primary tool for the projects was a groundwater-flow model of the Sparta aquifer (Fitzpatrick and others, 1990; McWreath and others, 1991) encompassing an area of approximately 12,000 $mi^2$ in southern Arkansas and northern Louisiana (fig. 54). Three model scenarios by Fitzpatrick and others (1990) tested differing pumping rates for the 1985–2005 simulation period. The first scenario carried the 1985 pumping rate as a constant through to 2005 and resulted in water levels with little change over the simulation period. For the second scenario, pumping rates in the area of the Grand Prairie (fig. 5) were doubled that resulted in water-level declines of 30–70 ft over the 20-yr simulation period; effects on water levels in southern Arkansas were minimal. For the third scenario, pumping rates were doubled across the entire model area that resulted in simulated water-level declines of 40–130 ft in the Grand Prairie, 80–200 ft in the Pine Bluff area, and 20–40 ft near El Dorado. Model results showed that whereas 1985 pumping rates appeared to be only slightly more than steady-state condition, projected increases in pumping would be unsustainable for the long term.

In 1990, the ANRC and the city of El Dorado water managers and planners became increasingly concerned about saltwater intrusion and declining Sparta groundwater levels. El Dorado stakeholders were considering options for protecting the aquifer and needed to know the degree of influence of potential local management approaches and the local effects of pumping activities further removed from the city. This problem particularly arose as a result of extensive use from the Sparta aquifer near Magnolia, Ark., and Monroe, La. Kilpatrick (1992) updated the Sparta model with the then-current, 1990 water-use data and ran scenarios to address the following specific questions posed by ANRC and the city of El Dorado (fig. 54):

4. The city of Magnolia was completing a reservoir in 1991 that would enable a switch from Sparta groundwater to surface water for public supply, leading to the question: What effect will the anticipated reduction of pumpage in the Magnolia area have on water levels in the El Dorado area?

5. What effect will future increases in pumping rates in the Monroe, La., area have on water levels in the El Dorado area?

6. What effect would changing the locations of El Dorado supply wells have on water levels in the El Dorado cone of depression?

Scenario 1a of Kilpatrick (1992) addressed the completion in 1991 by the city of Magnolia of a surface-water reservoir capable of providing 5 Mgal/d to replace use of the Sparta aquifer. Model simulations into 2020 showed dramatic results in the Magnolia area of water levels rebounding to the point that the cone of depression beneath Magnolia disappeared; however, effects on water levels in the El Dorado area were minor. Scenario 1b in which pumping in El Dorado increased by 25 percent from 1990 to 2019, with the decrease in pumping at Magnolia from the switch from groundwater to surface water, resulted in water-level declines to a level at or near the top of the El Dorado sand by 2020, well below the top of the Sparta Sand.

Scenario 2 explored the effect that a 25-percent increase in pumping would have in the Monroe area on water levels in the El Dorado area. Results showed that the simulated changes in pumping in the Monroe area had very little effect on water levels in the El Dorado area. Scenario 3 tested the effect of redistributing the location of the El Dorado public-supply wells on water levels in the cone of depression. Model results showed that the modest 25-percent increase in pumpage over the 30-year simulation period resulted in substantial, additional water-level declines. Thus, redistribution of city wells would have minimal influence. Kilpatrick (1992) noted that any additional declines in water levels would further induce the flow of saltwater toward the cone of depression in the potentiometric surface of the Sparta aquifer in the El Dorado area. These model results were integral to understanding that the causes of the water-level declines for the Sparta aquifer in the El Dorado area were local and consequently would require local remedial action.

The issue of declining Sparta groundwater levels resulted in the designation by the ANRC of the Sparta aquifer in southern Arkansas as a critical groundwater area in 1996. This designation was designed to focus needed attention and resources, to encourage conservation and management, and to achieve sustainable use of the aquifer. To evaluate potential direct management approaches for the Sparta aquifer in the Union County area, the USGS, working with ANRC and the Union County Water Alliance, updated the previously completed Sparta groundwater flow model with 1997 water-use data (Hays and others, 1998; fig. 54). The effort was unique in that all major aquifer users in Bradley, Calhoun, Columbia, Ouachita, and Union Counties in Arkansas were queried to assess accuracy of then-current water use and develop a realistic database of minimum, median, and maximum predicted water use for a 30-year forecast period. Five potential pumping scenarios were tested to evaluate the effects of static, increased, decreased, and redistributed water withdrawals from the Sparta aquifer for the period 1998–2027. Model results for Scenario 1 showed that maintaining pumpage at then-current rates would result in relatively minor additional declines in water levels, affecting an area less than 10 ft away from the center of the El Dorado cone of depression. Scenario 2 applied increasing pumping rates from the then-current rates, resulting in declines of more than 130 ft near El Dorado and 220 ft near Pine Bluff. Scenario 3 applied minimum-forecast pumping rates provided by major water users for facilities in Bradley, Calhoun, Columbia, Ouachita, and Union Counties. This resulted in simulated water levels that were substantially higher near the major pumping centers of Monroe and El Dorado (more than 70 ft and 180 ft of rebound, respectively). Maximum-forecast pumping rates input for Scenario 4 resulted in drastic water-level declines of more than 110 ft near El Dorado. Scenario 5 explored potential future effects of increased irrigation use from the aquifer because of overuse and water-level declines noted in the Mississippi River Valley alluvial aquifer. In the scenario, total pumpage in Lonoke and central Prairie Counties was increased by twice the then-current rate of increase, resulting in extensive water-level declines with maximum declines of more than 100 ft.

The differences in simulated water-level distributions under the various water-use scenarios explored by Hays and others (1998) were substantial and effectively demonstrated the importance and potential efficacy of water-management planning. Hays and Fugitt (1999) demonstrated that the aquifer could not meet growing water-use demands and also noted that water levels in Union County would drop below the top of the primary producing sand unit (locally termed the El Dorado sand) by 2008 under then-current water-use trends. The result of water levels dropping below the top of the El Dorado sand, including loss of yield, decreased water quality, and compaction and loss of storage, motivated further cooperation between stakeholders and further action towards greater protection of the aquifer.

Arkansas' water-resources policy and programs have moved forward with the goal of conjunctive use of the State's groundwater and surface-water resources at optimized levels that are sustainable. This sustained yield-conjunctive use strategy has been supported using groundwater models developed largely through the USGS and the ANRC cooperative program. The ANRC and other State water planners have advocated sustainable yield groundwater protection as a means of achieving specific goals. These goals include preventing groundwater-level declines, assuring long-term viability of aquifers to provide certain yields, preventing litigation, providing groundwater supplies for drought, preventing groundwater-quality degradation, protecting riparian rights, and providing courts with an objective means for determining and prioritizing uses. Arkansas' water policy has tended to follow a deferred perennial yield strategy, which accepts that current groundwater levels or levels defined by the critical groundwater area designation are reasonable or acceptable.

The Sparta critical groundwater area designation, coupled with the work of Hays and others (1998), focused regional attention on the declining water levels for the Sparta aquifer in southern Arkansas and particularly in the area of El Dorado and Union County. Stakeholders in Union County reviewed the historical Sparta water-use and water-level data and posed the following questions: How much water can the Sparta provide for the long term? By what amount must Sparta groundwater use be decreased to be sustainable? These questions had to be answered before serious, focused, and cost-effective management and protection approaches could be designed. Only then could the amount of water needed from alternative water-supply sources be quantified.

Hays (1999; fig. 54) conducted a modeling study to determine sustainable yield from the Sparta aquifer in Union County to address these questions. Sustainable yield is a critical element in identifying and designing viable water-supply alternatives (Alley and others, 1999). With sustainable yield defined and total water demand identified in a given area, any unmet demand that must be supplied from alternative water sources can be determined by calculating the difference. The Sparta aquifer groundwater-flow model provided a tool capable of determining sustainable yield using an iterative approach. The sustainable yield of the aquifer was calculated by establishing the top of the Sparta Sand as the minimum acceptable water level in Union County and varying pumpage to achieve this target water level. A stabilization yield also was determined that reflected the amount of water the aquifer could provide while maintaining target water levels. Sustainable and stabilization yields were estimated for two pumping conditions: (1) simulation of future pumpage outside of Union County by accelerating at the rate of increase observed from 1985 to 1997, and (2) simulation of future pumpage outside of Union County by accelerating at twice the rate of increase observed from 1985 to 1997. Results of the study provided three primary conclusions: (1) Sparta water-use outside of Union County was not a major control on water levels within the county, (2) withdrawals would have to be reduced to about 88–91 percent of 1997 rates to stabilize water levels above the top of the Sparta Sand, and (3) the yield from the aquifer was determined not to be great enough to support a doubling of the rate of increase in pumpage in Union County over the long term. Irrespective of how withdrawals from the Sparta aquifer were changed outside of Union County, withdrawals within Union County had to be reduced to about 25–28 percent of 1997 rates—a 72–75-percent reduction in use—to cause water levels to rise permanently back to the top of the Sparta Sand and thereby achieving a sustainable yield and addressing State critical groundwater area designation criteria.

The projected local and regional negative consequences of continued unabated expansion of Sparta withdrawals detailed in Hays and others (1998), Hays (1999), Hays and Fugitt (1999), and Hays and McKee (2003) provided important impetus for passage of Arkansas legislative Act 1050 of 1999. This act allowed counties within designated Arkansas critical groundwater areas to establish local Conservation Boards with management, regulatory, and taxing authority to plan, guide, and implement management approaches targeting achievement of modeled sustainable yields. Model results ultimately were used to guide a large-scale, coordinated conservation, and alternative-source development effort that resulted in rebound of Sparta aquifer water levels in Union County for the first time in more than 100 years of pumping. Model results indicated that rebound of water levels would occur with implementation of conservation and use of alternative sources. Results also highlighted the need for monitoring of aquifer conditions. Beginning in 2002, the UCWCB, in cooperation with the USGS and the EPA, began intensive monitoring of Sparta aquifer recovery with eight continuously monitored wells (Scheiderer and Freiwald, 2006). By 2006, groundwater levels had risen more than 60 ft in the immediate area of El Dorado and more than 10 ft as far away as 56 mi southeast of the city. The potential irreparable damage to the aquifer and water quality that might have occurred with continued unsustainable withdrawals was avoided by implementation of the intensive, science-based management approach. The Sparta aquifer recovery in Union County is a nationally recognized success, and the USGS, ANRC, and UCWCB were awarded the Department of Interior National Conservation Award for the effort in 2008.

Results of previous studies provided impetus to consider augmented recharge of the Sparta aquifer. Consequently, in 2000, the Arkansas State Senate requested that ANRC and USGS evaluate the hydrogeologic feasibility of augmented recharge approaches. Using the Sparta groundwater-flow model of Hays and others (1998), Hays (2001) simulated the effects of constructing a series of lakes and canals along the Sparta outcrop area. The basic concept of augmented recharge is to increase the amount of water being introduced into the aquifer at the outcrop belt so that more water will be available for pumping and for use downgradient from the recharge zone. Model results showed that recharge from the simulated lakes and canals provided notable benefit to aquifer conditions. Simulated total flow through the Sparta aquifer was greater with the presence of canals; 80 $Mft^3/d$ with the canals compared to about 62 $Mft^3/d$ without the canals. Water levels in the aquifer also showed considerable improvement. The zone of positive influence on water levels extended from the recharge area eastward to the Mississippi River with the canal simulations. Aquifer water levels increased 5 ft or more with the canal simulation across a broad area comprising all or a substantial part of 15 counties. Increases of 20 ft or more were noted in El Dorado, Pine Bluff, and Stuttgart. Although water levels in the aquifer increased substantially with augmented recharge, water levels continued to decline through the 30-year simulations, with or without additional recharge. This indicates that water was still being removed at a greater rate than the aquifer could supply for the long term.

In 2001, the Louisiana Sparta Groundwater Conservation District Commission funded a study to determine limitations of the Sparta aquifer for meeting groundwater needs. A secondary purpose was to test hypothetical conservation approaches on hydraulic heads in Sparta wells in Louisiana from 2000 to 2025 using the USGS-developed Sparta model (Hays and others, 1998; Meyer, Meyer, LeCroix, Hixson, Inc., and others, 2002). A sustained maximum pumpage rate of 52 Mgal/d simulated a recovery in water levels and indicated a need to reduce withdrawals by 18 Mgal/d from the then-current pumpage rate of approximately 70 Mgal/d.

The intense use of the Sparta groundwater flow model in the 1980s through the 1990s and the ongoing need for management input warranted improvement of the model. McKee and Clark (2003) worked to modify, recalibrate, and convert the Sparta model (fig. 54), addressing potential improvements identified by Hays and others (1998) in a cooperative study involving USGS, USACE, and ASWCC. Modifications to the previous Sparta model included rediscretizing the model grid, extending the model area northward, updating the surfaces representing the top and bottom of the Sparta Sand, and changing the model platform from MODFLOWARC used by Hays and others (1998) to MODFLOW–2000. The updated model was used to simulate the effects of four pumping scenarios on hydraulic heads over the period 1998–2027. The most intense pumping continued to occur in the El Dorado and Pine Bluff areas, which had extensive cones of depression. Results of McKee and Clark (2003) reported simulated drawdowns with respect to the center of the cones of depression in each area. In scenario 1a of McKee and Clark (2003), withdrawals were held constant for 30 years at 1990–97 rates, resulting in projected water-level declines of 10 ft and 17 ft in the center of the cones in El Dorado and Pine Bluff, respectively. With these withdrawals extended indefinitely under steady-state conditions (scenario 1b), water levels declined an additional 7 ft and 27 ft in the center of the cones in El Dorado and Pine Bluff, respectively. Scenario 2 tested the effect of decreasing withdrawals in El Dorado and Pine Bluff for industries that were considering alternative water sources. Simulated water levels under scenario 2 recovered more than 165 ft and 120 ft in the center of the cones in El Dorado and Pine Bluff, respectively. The area of Union County where simulated water levels were below the top of the Sparta Sand decreased from 52 percent in 1997 to 7 percent by 2027. For scenario 3, most withdrawals had a simulated increase of 25 percent over 30 years with selected industrial wells in Pine Bluff and El Dorado having reduced withdrawals. The model results showed recoveries of 124 ft and 100 ft in the center of the cones in El Dorado and Pine Bluff, respectively. Results for the targeted industrial reductions in scenarios 2 and 3 showed the potential effectiveness of the specific water-source alternatives and management approaches to achieve sustainable yields that were being considered at the time.

Czarnecki (2009) used the Sparta model by McKee and Clark (2003) to explore potential groundwater withdrawal scenarios at the Pine Bluff public-supply well field. The Pine Bluff well field was within a critical groundwater area, and local water managers and ANRC wanted to evaluate potential effects of various potential withdrawal rates. The model simulated a 50-year period from 1998 to 2048 for each scenario. Model results showed a water-level decline of about 20 ft for the baseline scenario, which applied the 1990–97 reported water use of 25.4 Mgal/d. Scenarios 1 and 2 at the Pine Bluff well field simulated water-use reductions of 7.2 Mgal/d and 12 Mgal/d, respectively, as compared to the then-current rates. Simulated results indicated that water levels were approximately 90 ft and 65 ft higher, respectively, compared to the baseline scenario. Scenarios 3 and 4 applied water-use rates that were within 10 percent of then-current water-use levels; simulated results were very similar (within 10 ft at the well field) to the baseline scenario results. An important observation of the study was that an overall downward trend of water levels occurred in the area, even for the scenarios that applied decreased withdrawals at the Pine Bluff well field. This indicates that pumping from the Sparta aquifer outside the well field had a considerable effect and exceeded levels that would be sustainable.

The USGS initiated a National Water Census (http://water.usgs.gov/watercensus/) from 2004 to 2012 involving Federal, State, local governments, and the private sector to assess regional groundwater-flow systems and groundwater availability across the conterminous United States (Reilly and others, 2008). The Mississippi embayment was a focus region and included the Mississippi Embayment Regional Aquifer Study (MERAS; fig. 54; Clark and Hart, 2009; Clark and others, 2011b). A numerical groundwater-flow model was developed to simulate the effects of human activities and climate variability on aquifer systems and surface-water bodies. The MERAS model resulted in 13 layers covering 78,000 $mi^2$ and representing multiple aquifers, including the Sparta aquifer. MERAS simulations showed that the confined middle Claiborne aquifer, which includes the Sparta Sand, exhibited dramatic water-level declines of more than 100 ft occurring across 7,529 $mi^2$ (13.3 percent of the model area) by 2007. The largest declines of more than 300 ft in the middle Claiborne aquifer (Sparta aquifer) occurred in southern Arkansas.

The importance of the MERAS model lies primarily in the future utility of the model as a management tool that can be updated to address new and continuing questions arising from changing human activities and natural conditions that challenge water managers and stakeholders. The tools and databases integral to the MERAS model include a database of over 2,600 geophysical logs used in the construction of the hydrogeologic framework (Hart and Clark, 2008). The MERAS model represents the current state-of-the-science modeling tool for the Sparta and other aquifers of eastern Arkansas. It is an integrated tool capable of being updated to address diverse issues and questions for years to come. Since initial development of the MERAS model, two updates have been implemented as of 2013 (Clark and others, 2013) in the effort to continually improve upon the ability to accurately simulate groundwater flow.

Clark and others (2011a) used the MERAS model (Clark and others, 2011b) in an ANRC-USGS cooperative study to simulate groundwater flow and water-level altitudes for the period 2007–37. The study focused on the Bayou Meto and Grand Prairie agricultural area, which was designated as the Grand Prairie critical groundwater area by ANRC in 1998 (Arkansas Natural Resources Conservation Commission, 2009). The ANRC was concerned about potential water-level declines from an increasing number of wells and an increasing demand on the Sparta aquifer in the Bayou Meto and Grand Prairie area, resulting from increased reliance on the aquifer for agricultural use. In scenario 1, the study compared simulated water levels resulting from continuance of 2005 pumping rates. In scenario 2, the study simulated the addition of new Sparta wells in the Bayou Meto and Grand Prairie area at a rate of 13 wells per year. Simulated water-level declines in scenario 1 ranged from 20 to 40 ft. The additional pumping wells in scenario 2 resulted in considerably greater water-level declines and caused cones of depression by 2037 in Lonoke and Arkansas Counties. Water-level declines ranged from 40 to 50 ft across most of the Bayou Meto and Grand Prairie area in scenario 2. A maximum water-level decline of approximately 102 ft occurred in Lonoke County. Model results emphasized the substantial effects that additional agricultural pumping from the Sparta aquifer would have in the Bayou Meto and Grand Prairie areas if the Mississippi River Valley alluvial aquifer continues to be unable to meet demands. These results also showed that increased agricultural usage would cause increased water-level declines in public-supply wells that depend on the Sparta for public supply, ultimately decreasing long-term water availability for public-supply use.

The prevalence of long-term water-level declines and regional cones of depression in large areas of the Sparta aquifer highlight the need for greater knowledge and better definition of sustainable yield for this aquifer. The work of Hays (1999) and Clark and others (2011a, b) provides a preliminary estimate of sustainable yield for the aquifer in the El Dorado and Pine Bluff areas. The importance of the Sparta aquifer in other areas of Arkansas, however, requires a more detailed and broader-scale assessment of sustainable use and deferred perennial yield for the aquifer throughout the State.

## Water Quality

The Sparta aquifer is sand dominated and generally yields freshwater of very high quality throughout its extent in Arkansas. The groundwater is cited as a sodium-bicarbonate water type throughout most of its extent (Tait and others, 1953; Onellion, 1956; Payne, 1968; Ludwig, 1973; Broom and others, 1984; Terry and others, 1986). Calcium and magnesium are cited as occurring in appreciable amounts only in very small areas (Payne, 1968). In the northeastern part of the State, groundwater from the Sparta is reported as a calcium-bicarbonate water type with dissolved-solids concentrations ranging from 200 to 500 mg/L (Ryling, 1960; Plebuch; 1961; Halberg and Reed, 1964; Hosman and others, 1968; Broom and Lyford, 1981). Only a few areas of the State experience problems with use of groundwater from the Sparta aquifer, and these dominantly are related to problems of elevated salinity.

## General Geochemistry and Water Type

The percent sodium calculated from data gathered for this study was plotted using a geographical information system (fig. 55). This spatial analysis revealed an overall pattern of low sodium occurring dominantly in the area of outcrop, with an overall increasing trend in sodium percentage in the downgradient direction of flow (fig. 55). Low sodium is herein defined as any water type where sodium is less than 50 percent of the total cations (calcium, sodium, magnesium, and potassium) in milliequivalents per liter. The above finding suggests that cation exchange along a given flow path accounts for the transitioning of an initial calcium-bicarbonate to a sodium-bicarbonate water type with increased residence time in the aquifer. In the northeastern part of the State, from St. Francis to Craighead Counties, the groundwater is a strongly calcium-bicarbonate water type. Percent sodium in this area generally is less than 25 percent, and no sodium-bicarbonate water type is encountered in this area. Hosman and others (1968) similarly classified groundwater from the Sparta in northeastern Arkansas dominantly as a calcium-magnesium-bicarbonate water type, with other areas of the State containing a sodium-bicarbonate water type. Geophysical log analysis by Clark and Hart (2009) indicated sand content in the Sparta from 80 to 100 percent in much of the northeastern part of the State and from 0 to 60 percent over much of the southern part of the State. This implies an increase in clay content for the Sparta in the southern part of the State. Higher cation-exchange capacity on clay surfaces results in greater opportunity for cation exchange in the southern part of the State as compared to the northeastern part of the State.

Values of pH are invaluable indicators for tracking groundwater flow paths from recharge to discharge areas and for preliminary identification of rock type. Values of pH ranged from 4.0 to 9.0 with a median of 7.5 (table 25). Values generally increased in the downgradient (southeasterly) direction of flow. Values of pH were lowest (4.0 to 6.5) in the outcrop area in the southwestern part of the State but increased to greater than 8.0 within a short distance of the outcrop area (fig. 55). In Sparta subcrop areas in the northeastern part of the aquifer, pH values were generally greater than 6.5. The absence of pH values less than 6.5 in the northeastern part of the State may be ascribed to the fact that the Sparta does not crop out throughout most of this area; thus, recharge has moved through overlying units that likely buffer the infiltrating, low-pH water prior to its moving into the Sparta aquifer. Values of pH generally increased in the downgradient direction, but this trend is most pronounced in the southern part of the State.

The increase of pH along a given flow path possibly results from the increased dissolution of carbonates, consistent with similar increases in bicarbonate concentrations in the downgradient direction of flow (not shown on fig. 55). The lowest bicarbonate concentrations (less than 50 mg/L) were found in the outcrop area in southern Arkansas, with sharp increases occurring in the downgradient direction. Conversely, in the northeastern part of the State, most bicarbonate concentrations are greater than 100 mg/L and generally increase to greater than 400 mg/L in the downgradient direction. Dissolved-solids concentrations similarly reflect the trend of increasing carbonate concentrations, as bicarbonate is the dominant anion in groundwater from the Sparta aquifer. Hosman and others (1968) similarly noted that dissolved-solids concentrations are lower in outcrop areas and increase as the water moves downgradient, mainly as a result of increases in sodium, bicarbonate, and chloride.

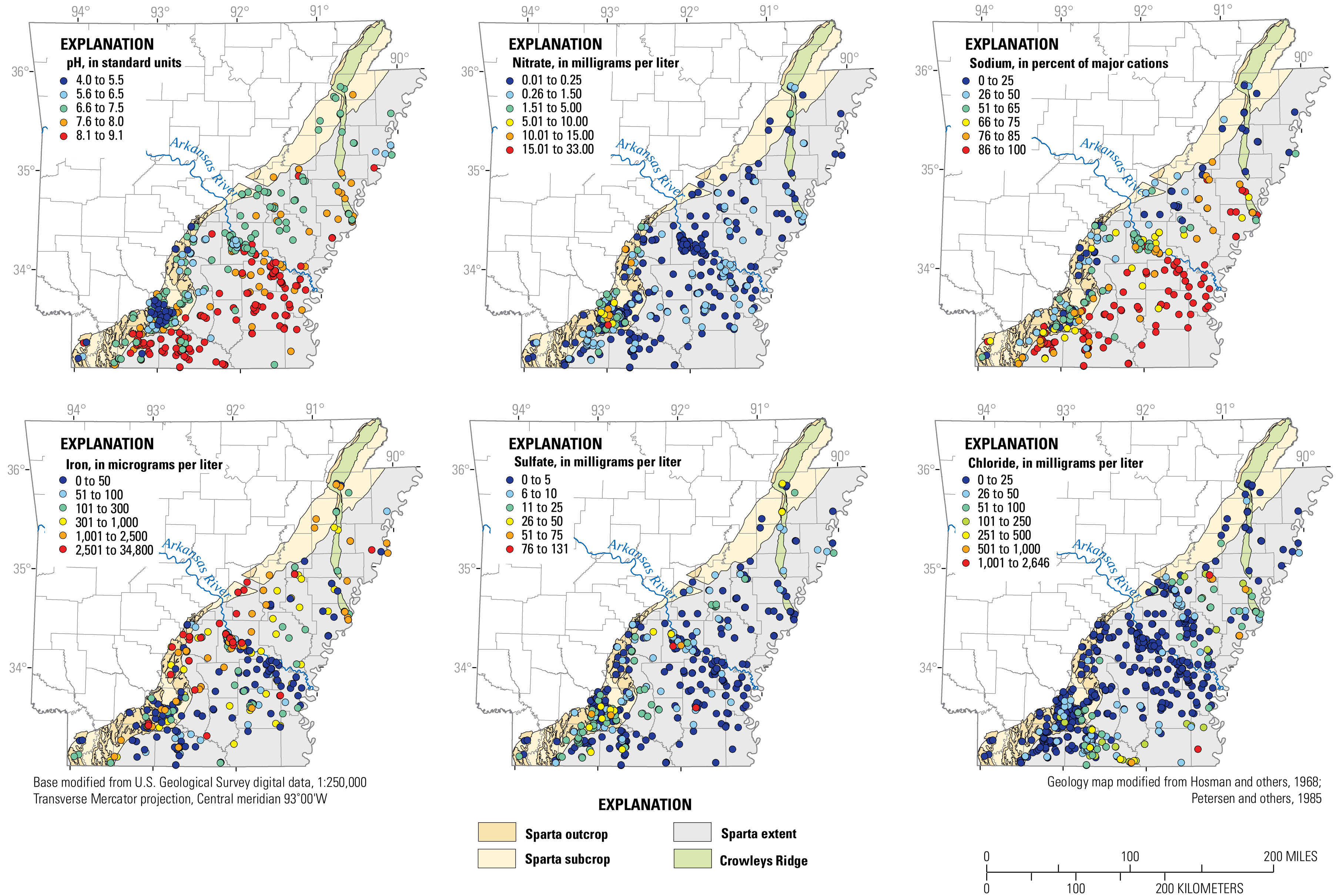



**Figure 55.** Spatial distribution of selected chemical constituents for groundwater from the Sparta aquifer in Arkansas.

**Table 25.** Descriptive statistics for selected chemical constituents in groundwater from the Sparta aquifer in Arkansas.

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

| Constituent or characteristic | Minimum | Median | Maximum | Standard deviation | Number of wells |
|---|---|---|---|---|---|
| Calcium (mg/L) | 0.1 | 7 | 130 | 18 | 415 |
| Magnesium (mg/L) | 0.01 | 1.7 | 84 | 7.62 | 415 |
| Sodium (mg/L) | 0.04 | 44 | 700 | 87.1 | 412 |
| Potassium (mg/L) | 0.4 | 3.04 | 56 | 4.27 | 366 |
| Bicarbonate (mg/L) | 2.0 | 146 | 1,280 | 134 | 412 |
| Chloride (mg/L) | 0.3 | 8.1 | 2,650 | 136 | 673 |
| Sulfate (mg/L) | 0.02 | 3.8 | 131 | 11 | 448 |
| Silica (mg/L) | 1.0 | 14 | 74.6 | 8.87 | 338 |
| Nitrate (mg/L as nitrogen) | 0.01 | 0.09 | 33 | 2.23 | 427 |
| Dissolved solids (mg/L) | 12 | 186 | 2,210 | 228 | 440 |
| Iron (µg/L) | 0.05 | 111 | 34,800 | 2,560 | 333 |
| Manganese (µg/L) | 0.13 | 28.7 | 1,090 | 144 | 192 |
| Arsenic (µg/L) | 0.03 | 0.07 | 5.67 | 0.65 | 135 |
| Hardness (mg/L as calcium carbonate) | 1.0 | 25 | 477 | 70 | 374 |
| Specific conductance (µS/cm) | 22 | 321 | 8,870 | 482 | 692 |
| pH (standard units) | 4.0 | 7.5 | 9.0 | 0.9 | 446 |

## Nitrate

Nitrate concentrations were low throughout most of the Sparta aquifer, with a median concentration of 0.09 mg/L (as nitrogen) and 85 percent of all nitrate concentrations were less than 1.0 mg/L. Nitrate concentrations ranged from 0.01 to 33 mg/L (table 25). The MCL of 10 mg/L (U.S. Environmental Protection Agency, 2009) was exceeded in only 1.5 percent of samples. The highest nitrate concentrations occurred in the outcrop area, where the formation is exposed and wells are shallow, thus increasing the vulnerability to surface sources of nitrogen (fig. 55). A strong inverse relation was noted for nitrate and well depth (fig. 56*A*). Most wells with nitrate concentrations greater than 2 mg/L occurred in wells less than 50 ft deep. Except for isolated areas of elevated nitrate concentrations in the outcrop area, concentrations dominantly were less than 0.25 mg/L downgradient from and northeast of the outcrop area. In these areas, overlying formations protect the groundwater from surface sources of contamination. Dilution, denitrification processes, and low groundwater-flow velocities also may serve to prevent appreciable transport of nitrate to areas downgradient from the outcrop area.

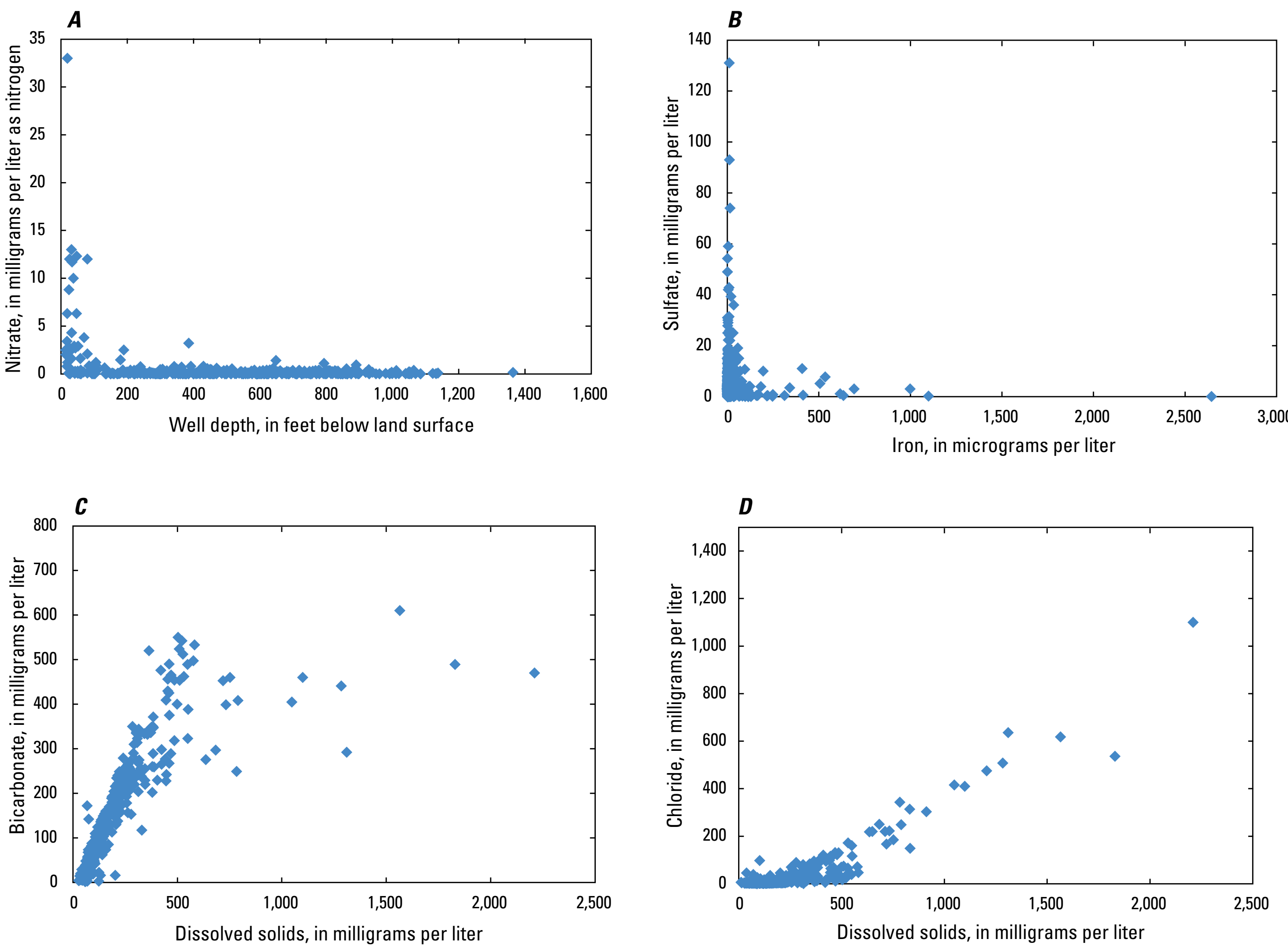



**Figure 56.** Relation between *A*, well depth and nitrate; *B*, iron and sulfate; *C*, dissolved solids and bicarbonate; and *D*, dissolved solids and chloride for groundwater from the Sparta aquifer in Arkansas.

## Iron

Iron concentrations in 333 samples ranged from 0.05 to 34,800 µg/L with a median of 111 µg/L (fig. 57; table 25). Similar to nitrate, iron concentrations are greater in the outcrop area and generally below 1,000 µg/L for areas downgradient from and north of the outcrop area. An area of high concentrations also occurs along the Arkansas River (fig. 55). Hosman and others (1968) also noted that higher concentrations of iron occurred generally in groundwater along the outcrop of the Sparta Sand throughout the Mississippi embayment. Iron concentrations more than 1,000 µg/L occur in isolated areas in the northeastern part of the State. The Sparta subcrops beneath alluvial deposits bearing iron-rich groundwater that potentially is the source for the elevated iron. The lower iron concentrations downgradient from the outcrop area are attributed to changes in redox conditions that result in iron mineralization along the flow path.

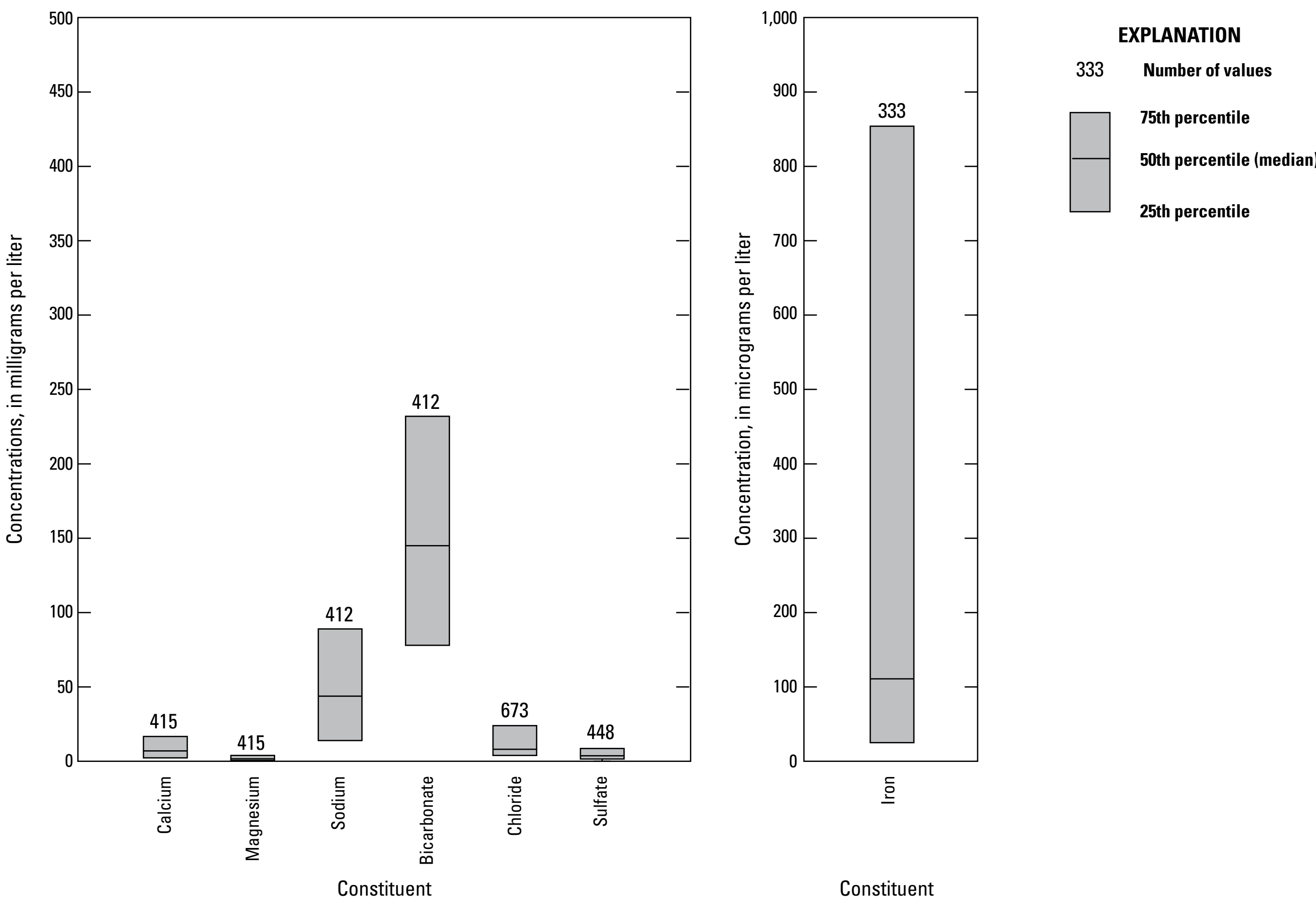



**Figure 57.** Interquartile range of selected chemical constituents for groundwater from the Sparta aquifer in Arkansas.

## Sulfate

Sulfate concentrations generally are low throughout the Sparta aquifer, with a median concentration of 3.8 mg/L for 448 samples (fig. 57; table 25). Of the 448 samples, 300 had sulfate concentrations less than 5 mg/L and 88 were less than 1.0 mg/L. Sulfate concentrations were very low compared to other aquifers. The low sulfate concentrations were at least half the concentration capable of being derived naturally from evaporation of recharging precipitation (Kresse and Fazio, 2002). Sites with sulfate concentrations between 10 and 51 mg/L generally occurred in or near the outcrop area of the Sparta Sand. Concentrations decreased within short distances in the downgradient direction of flow to concentrations typically less than 5 mg/L (fig. 55). This result lends additional support to the hypothesis that changes in redox conditions control iron and sulfate concentrations. Iron- and sulfate-reducing conditions along the groundwater-flow path may result in the formation of iron-sulfide minerals thus reducing the concentration of each constituent. Support for this theory is found in the inverse correlation of iron and sulfate concentrations; iron concentrations are less than 50 µg/L for sulfate concentrations between 20 and 140 mg/L. Sulfate concentrations generally are less than 10 mg/L for iron concentrations greater than approximately 50 µg/L (fig. 56*B*).

The reduction of sulfate to hydrogen sulfide is directly related to the abundance of available sulfate. Similar to the relation between iron and sulfate, dissolved iron ($Fe^{2+}$) and hydrogen sulfide ($H_2S$) tend to be inversely related according to a hyperbolic function, such that when $Fe^{2+}$ concentrations are high, $H_2S$ concentrations tend to be low and vice versa. This reflects the rapid reaction kinetics of $Fe^{2+}$ with $H_2S$ to produce relatively insoluble ferrous sulfides (Chapelle and others, 2009). Where abundant sulfate is available, the resulting sulfide binds with ferrous iron in solution to form iron sulfide minerals and controls soluble iron and sulfate concentration.

Elevated sulfate concentrations south of the Arkansas River are exceptions to the generally low concentrations beyond the area of outcrop. The greatest sulfate concentrations (as much as 131 mg/L) were from wells located in this area. Elevated concentrations also were noted from wells completed in the Cockfield aquifer in this area. The source of sulfate is interpreted as leakage of water from the overlying Jackson Group (Halberg and others, 1968), which outcrops in southern Arkansas and exhibits some of the highest sulfate concentrations of any aquifer in the State (see “Jackson Group” section). The fact that the Jackson Group, the Cockfield aquifer, and the Sparta aquifer all contain elevated sulfate concentrations in this area suggests a high level of connectivity and interchange of water between these hydrogeologic units. Maximum and median sulfate concentrations in all three hydrologic systems, respectively, were 3,080 and 110 mg/L for the Jackson Group, 470 and 2.4 mg/L for the Cockfield aquifer, and 131 and 3.8 mg/L for the Sparta aquifer. The trend of lower maximum concentrations with depth is consistent with the uppermost Jackson Group as the possible source of sulfate. It should be noted, however, that the top of the Sparta aquifer is approximately 600 ft below land surface with a clay confining unit between the Cockfield and Sparta aquifers. A high level of communication between these aquifers could only result from thinning of the confining unit, increased sand content of the confining unit, vertical fractures in the confining unit, or possible flow along unmapped faults in Jefferson and Drew Counties. Sand thickness maps do not reveal anomalous sand percentages for these areas (Clark and Hart, 2009). More information is needed to validate the above potential transport mechanisms.

The possibility also exists for the elevated sulfate concentrations being the result of incorrectly identified completion depths, leakage across formations through a poorly cased annulus section (or no casing), or wells that are screened through one or more producing formations. However, the likelihood of this occurring only in Jefferson and Drew Counties is low. Only three wells in Jefferson County and one well in Drew County had concentrations greater than 25 mg/L, ranging up to 131 mg/L. No elevated sulfate concentrations were noted in earlier publications. Klein and others (1950) list 20 wells in Jefferson County with concentrations from 0.6 to 10 mg/L, and Onellion (1956) listed 17 wells in Drew County with concentrations from 0.9 to 7.0 mg/L.

## Chloride

Chloride concentrations in 673 samples ranged from 0.3 mg/L to 2,650 mg/L (table 25). Except for isolated areas of the State, chloride concentrations in the Sparta generally are low, as indicated by a median concentration of 8.1 mg/L (fig. 57; table 25). Chloride concentrations are defined as elevated when exceeding 100 mg/L, which follows the definition first established in Kresse and Clark (2008). The secondary drinking-water regulation for public-supply systems is 250 mg/L, which is based on aesthetic characteristics that include taste. For dissolved-solids concentrations less than approximately 500 mg/L, bicarbonate dominates the anion chemistry. For dissolved-solids concentrations greater than 500 mg/L, a positive, strongly linear relation is noted between dissolved-solids and chloride concentrations, and chloride generally dominates the anion chemistry (fig. 56*D*). Three main areas of elevated chloride concentrations are (1) an elongated band of elevated chloride concentrations trending in a northwest to southeast direction within Ouachita and Union Counties, (2) an area in Chicot County, and (3) an area extending eastward from Prairie County through Monroe and Lee Counties. Elsewhere, chloride concentrations are low. Approximately 70 percent of 1,223 samples were below 20 mg/L, reflecting chloride derived from rainwater concentrated by evapotranspiration processes (Kresse and Fazio, 2002; Kresse and Clark, 2008).

An elongated band of slightly elevated chloride concentrations (maximum of 475 mg/L) extends from southeastern Ouachita County to southeastern Union County in the southern part of the aquifer (fig. 55). Broom and others (1984) reported on an isolated area of high salinity in central Union County and attributed the source of elevated chlorides to high-salinity water in a faulted graben in Union County. Although no water wells were completed inside of the graben, estimates based on electric logs in Sparta wells in the graben indicated that chloride concentrations might be as high as 2,500 mg/L. Alignment of the graben and the spatial distribution of chloride concentrations nearby indicated that increased pumping from a nearby public supply led to movement of high-salinity water within the graben into previously unaffected parts of the aquifer west of the graben (Broom and others, 1984).

With the exception of Broom and others (1984) discussed above, few studies have performed a detailed assessment of groundwater quality in Ouachita and Union Counties. Terry and others (1986) reported on water resources, including the Sparta aquifer in Ouachita and Union Counties, but did not address salinity issues and listed specific conductance ranging from 20 µS/cm in a sample from Lafayette County to 4,610 µS/cm in a sample from Ouachita County. Chloride concentrations ranged from 612 to 1,120 mg/L in three wells listed as Sparta wells (Terry and others, 1986), but these wells later were discovered to actually be completed in the Wilcox and Cane River Formations (T.P. Schrader, U.S. Geological Survey, oral commun., 2012). Albin (1964) reported on groundwater resources in Bradley, Calhoun, and Ouachita Counties and listed chemical analyses for 34 well-water samples from the Sparta aquifer with a maximum chloride concentration of 84 mg/L. No areas of high salinity were noted for the Sparta aquifer in Ouachita County. Currently (2013), no defined sources for the band of elevated chloride concentrations have been identified in this area.

The occurrence of saline water in the Sparta aquifer in Chicot County was first noted by Onellion and Criner (1955). They described a well drilled to a depth of 1,064 ft in south-central Chicot County that reportedly encountered brackish water and subsequently was backfilled and completed at a depth of 150 ft. Data from electric logs of oil test wells in the county also indicated that water from the Sparta was saline, but that freshwater might possibly exist in the northern part of the county (Onellion and Criner, 1955). Payne (1968) described a saline-water tongue for a downdip area of the Sparta in eastern Louisiana and southeastern Arkansas, which corresponded to the area described by Onellion and Criner (1955). Payne noted that the area of saline water generally represents an area of discharge where the dominant component of flow is upward and lies beyond the limits of extensive flushing by freshwater.

A well was drilled into the Sparta aquifer in Chicot County near the center of a zone of elevated chloride concentrations in the Mississippi River Valley alluvial aquifer (Kresse and others, 2000) (see “Mississippi River Valley Alluvial Aquifer” section). A sample from the well had a chloride concentration of 2,646 mg/L compared to a chloride concentration of only 36 mg/L from a well in southeastern Ashley County and a concentration of 171 mg/L from a well in northeastern Chicot County (Kresse and others, 2000). Kresse and Clark (2008) attributed the occurrence of saline water in the Sparta aquifer and overlying formations to brine water from the Smackover Formation moving up along the intersection of two mapped wrench faults (Zimmerman, 1992). The lack of data prevents an assessment of the spatial extent of the saline water in the Sparta aquifer for Chicot County. Fresh groundwater may be present in eastern Chicot County if similar trends for an elongated north-south band noted for the occurrence of saline water in the alluvial and Cockfield aquifers exist in the Sparta aquifer.

A third area of elevated chloride concentrations is found northeast of the White River and primarily confined to Prairie, Monroe, and Lee Counties. Chloride concentrations in wells south of the White River and north of Monroe and Lee Counties are low and mostly less than 25 mg/L (fig. 55). Chloride concentrations for wells northeast of the White River range up to 1,100 mg/L in Monroe County, and several wells have chloride concentrations between 500 and 1,000 mg/L. Many older publications did not differentiate the Cockfield, Cane River, or Sparta Sand Formations of the Claiborne Group; however, any indication of salinity in the Claiborne Group and the underlying Wilcox aquifer provides important information on salinity issues related to the Sparta aquifer. Stephenson and Criner (1916) provided some of the first evidence for the occurrence of high-salinity groundwater from the Sparta in northeastern Arkansas. The public supply for Brinkley (Monroe County) during the time of their report contained water that was cited as being “slightly brackish.” Application of the well depth to the recently developed geologic framework by Hart and others (2008) indicates that the well was completed in the lower part of the Sparta aquifer.

Counts (1957) stated that no wells were completed in the Sparta aquifer in Lonoke, Prairie, and White Counties. Interpretation of electric logs, however, indicated that freshwater could be drawn from the upper sands of the Claiborne Group to a maximum depth of approximately 500 ft. An increase of salinity in the lower beds corresponding to the Sparta aquifer was inferred for groundwater in the downdip direction (to the southeast) and below a depth of 500 ft.

Halberg and Reed (1964) reported that in parts of Prairie, Monroe, and Lee Counties, some sands of the Claiborne Group yielded brackish water. Two wells in Monroe County were noted as yielding moderately mineralized water “that contains much sodium and chloride.” An electric log for one well in Lee County indicated saline water in the Claiborne Group below 700 ft, generally corresponding to the depth of high salinity water inferred by Counts (1957). Hosman and others (1968) reported elevated chloride concentrations in Monroe and Lee Counties that were attributed to upward movement of mineralized water from lower aquifers and noted that the occurrence of mineralized, high-salinity groundwater coincided within a zone of transition. This transition zone is where the marine clays of the Cane River undergo a facies change to sand to the north, with a corresponding apparent increase in vertical permeability. Because the Carrizo Sand contained saline water and had a hydrostatic head 10 ft higher than the Sparta (Hosman and others, 1968), upward movement of high-salinity water from underlying formations was indicated as the source of saline water in the Sparta aquifer.

Morris and Bush (1986) investigated the occurrence of high-salinity water in the alluvial aquifer near Brinkley in Monroe County. An oil and gas test well open to the Nacatoch

Sand, which was flowing artesian, was sealed off because of saline water contamination at the surface. Mixing curves for bromide/chloride, iodide/chloride, and boron/chloride showed Sparta and alluvial aquifer wells plotted on the same line as the Nacatoch wells, indicating an upwelling of groundwater from the Nacatoch aquifer as the source. Morris and Bush (1986) hypothesized two possible sources: (1) leakage of saltwater from the Nacatoch aquifer into the Sparta aquifer along a fault and (2) saltwater intrusion from the Nacatoch aquifer into the Sparta aquifer through abandoned oil and gas test wells. The potentiometric surface of the Nacatoch aquifer was cited as high enough in the area to force water into the Sparta or alluvial aquifer through a breached well casing (Morris and Bush, 1986). Earlier documentation of high salinity in the Sparta aquifer by Stephenson and Criner (1916), however, tends to rule out contamination by oil and gas test wells. Clark and Hart (2009) developed a sand percentage map for the upper and lower Claiborne aquifer within the Mississippi embayment and showed a well-defined zone of increased sand for the Claiborne Group in the general vicinity of the elevated chloride concentrations in the Sparta aquifer in northeastern Arkansas. This sand zone lends some support to the theory proposed by Hosman and others (1968), and described in the preceding paragraph, for upwelling of saltwater from formations underlying the Sparta.

In summary, the quality of groundwater from the Sparta aquifer is very good. The groundwater generally is a sodium-bicarbonate type; however, a calcium-bicarbonate water type is found in northeastern Arkansas and in the outcrop area in southern Arkansas. Elevated iron and nitrate concentrations occur dominantly in the outcrop area with lower concentrations in the downgradient direction of flow. Generally, pH, bicarbonate, and dissolved-solids concentrations increase with increased residence time along the flow path moving downgradient from the outcrop, as well as the shallow subcrop in the northeastern part of the State. These effects are attributed to the increased dissolution of carbonate minerals. Areas of high salinity are noted in isolated areas of the Sparta, predominantly as a result of inferred upwelling from high-salinity groundwater in underlying formations.

## Cane River Aquifer

The Cane River Formation (hereinafter referred to as the “Cane River aquifer” when referring to the saturated part of the formation) comprises an aquifer of mixed clastic lithology with resultant variable water quality and water yield. Areas where good quality water can be extracted from the Cane River aquifer are generally in or very near the outcrop in southwestern Arkansas. Hosman and others (1968) listed the Cane River as a distinct aquifer in southern Arkansas; where locally extensive, water-producing sands were clearly identified in and near the outcrop area. Because the sand units are thin and regionally discontinuous, the clay-dominated lithology of the Cane River Formation in southern Arkansas was listed as part of the regional lower Claiborne confining unit (Arthur and Taylor, 1990; Hosman and Weiss, 1991; Hart and others, 2008; Clark and Hart, 2009). In northeastern Arkansas, the formation changes from a clay-dominated to sand-dominated facies that cannot be differentiated from the Sparta Sand or the Carrizo Sand. These three formations collectively are referred to as the Memphis Sand aquifer or in regional geologic framework analysis as the middle Claiborne aquifer (Hosman and Weiss, 1991; Hart and others, 2008; Clark and Hart, 2009).

### Geologic Setting

The Cane River Formation (Spooner, 1935) is a sequence of marine clays and shales that includes minor amounts of marls, silts, and marine sand. The Cane River was incorporated as a part of the undifferentiated Eocene (Veatch, 1906; Stephenson and Crider, 1916). The Cane River Formation represents the most extensive marine transgression during Claiborne time. At the margins of the embayment, the formation becomes extremely variable in lithology. The sand content exceeds 40 percent in parts of Desha and Lincoln Counties. The orientation of the high-sand content area is normal to the presumed sea shoreline during Cane River deposition. Other sand bodies, such as those located in Columbia County, have an orientation parallel to the presumed shoreline. The occurrence of massive sand bodies and the pattern of sand distribution are believed to represent a combination of channel sands near the seaward extremities of the ancestral Mississippi River and other large rivers. These rivers fed sediment that developed offshore and nearshore sand bars near the mouths of river-delta distributaries (Payne, 1972).

The Cane River overlies the Carrizo Sand and is overlain by the Sparta Sand. Well-developed sand bodies normally are found only around the margins of the Mississippi embayment (Hosman and others, 1968; Payne, 1972). Regionally, the sand percentage decreases south and southwest of the embayment; in southeastern Arkansas, the Cane River virtually contains no sand. The sand accumulation extending from northern Louisiana, through parts of southwestern Arkansas, and into northern Mississippi probably represents a marginal edge of a delta of the ancestral Mississippi River (Payne, 1972). In the subsurface of southern Arkansas, the Cane River becomes a marine clay and serves as a confining unit (Onellion and Criner, 1955; Hosman and others, 1968; Petersen and others, 1985). In northern Arkansas, the Cane River undergoes a facies change and north of latitude 35 degrees, the marine clay becomes sand. This northern sand facies of the Cane River is included as the middle part of the Memphis Sand and is generally indistinguishable from the Sparta aquifer. Although the Cane River is undifferentiated, a massive sand (Winona Sand of Mississippi) and overlying clay (Zilpha Clay of Mississippi) are easily observed in electric logs in Lee and Phillips Counties (Hosman and others, 1968; Payne, 1972).

Tait and others (1953) report that in Columbia County, the Cane River Formation consists mainly of shale and silty shale with thin beds of sand in the south and becomes sandier in the northern part of the county. Some sand beds attain a thickness of 40–50 ft. Plebuch and Hines (1969) described the Cane River in Clark, Cleveland, and Dallas Counties as consisting of sand, clay, and sandy clay with some ferrous cement. Ludwig (1973) describes the Cane River Formation in Hempstead, Miller, and Nevada Counties as being composed of sand, silt, clay, and lignite. Zachry and others (1986) reported that in Columbia and Union Counties, the Cane River dominantly is composed of claystone with thin scattered sandstone units near its outcrop in Columbia County.

The strike of the Cane River Formation is inferred to be approximately northeast to southwest and parallel to the general structure of the Mississippi embayment (Stephenson and Crider, 1916). In south-central and southwestern Arkansas, the regional dip of the Cane River is to the east and southeast at 25–50 ft/mi toward the Mississippi embayment and the Desha Basin. Major regional structural elements experienced considerable growth during the deposition of the Cane River, as noted by the thickening of the formation within these structures. In Arkansas, these structural features include the Gulf Coast geosynclines, the Mississippi embayment, and the Desha Basin. Normal faulting is common in the Cane River (Payne, 1972). In Hempstead, Miller, and Nevada Counties, the Cane River is cut by several northeast-southwest trending faults with displacement of as much as 280 ft (Ludwig, 1972). In a faulted graben in Union County, the lower half of the Cane River (about 150 ft) is in contact against the Wilcox Group (Broom and others, 1984).

The reported thickness of the Cane River Formation varies greatly, likely because of the fact that for some time the Claiborne Group was undifferentiated. Payne (1972) reported that the thickness ranged from 200 to 750 ft thick, which is in agreement with most historical reports. Generally the formation thickens from west to east. A minimum thickness of 200 ft is noted in western Arkansas in the area of Hempstead, Miller, and Nevada Counties (Ludwig, 1973). The formation reaches a maximum thickness of 600–750 ft (Payne, 1972).

## Hydrologic Characteristics

The Cane River is considered an important aquifer along the margin of the Mississippi embayment in southern Arkansas. In this area, the Cane River comprises an aquifer system composed of poorly connected sand bodies of which each are 25 ft or more in thickness. The hydraulic conductivity of the aquifer is estimated to be 5.3 to 6.7 ft/d for sand units that are 25–50 ft thick and conservatively estimated to be 13.4 ft/d for sand units that are 100–125 ft thick (Payne, 1972).

Near the outcrop and subcrop areas, the aquifer is under water-table conditions. Downdip from these areas, the aquifer becomes confined by overlying and underlying beds and is under artesian conditions (Petersen and others, 1985). In Chicot County, the Cane River is not considered an aquifer because it is composed of fine-grained materials (Onellion and Criner, 1955). The Cane River gradually changes downslope to a relatively uniform confining clay bed (Hosman and others, 1968; Payne, 1972; Petersen and others, 1985). In Union County, the Cane River Formation is considered to be a confining unit with little capacity for transmission of fluids, with the exception of possible fluid transfer along fault zones (Broom and others, 1984).

Yields of the Cane River are variable but are sufficient for public supply in the smaller towns in southwestern Arkansas. Public-supply wells for three cities in Lafayette County produced 120, 300, and 920 gal/min (Ludwig, 1972), and two public-supply wells in Dallas County each produced 50 gal/min (Plebuch and Hines, 1969). Wells in Columbia County may yield as much as 300 gal/min (Tait and others, 1953). Shallow wells in the outcrop area generally yield between 5 and 10 gal/min (Hosman and others, 1968).

The principal source of recharge to the aquifer is infiltration of precipitation through exposures in the outcrop area in the western part of the Mississippi embayment (Hosman and others, 1968). Recharge may occur through younger sedimentary materials, when the Cane River outcrop is covered. A minor amount of recharge takes place by upward movement of water from the underlying Carrizo aquifer and the overlying Wilcox aquifer. Water is lost from the aquifer from pumping wells and from natural discharge of upward leakage through confining units. A very minor component of natural discharge may occur as base flow into streams incised into the Cane River (Hosman and others, 1968; Payne, 1972).

Regional flow of water is generally south and southeast toward the Gulf Coast geosyncline and the Mississippi Alluvial Valley. Upward flow from the aquifer occurs through overlying leaky confining units. This occurs when the hydraulic head of the Cane River is more than the hydraulic head of the overlying Sparta aquifer (Payne, 1972; Petersen and others, 1985). A potentiometric-surface map was created for the Cane River by Ludwig (1973) and Terry and others (1986). The direction of flow was to the south and east. Ludwig (1973) noted that water levels were not affected by pumping. Although historical water-level measurements have been made in the Cane River aquifer, recent water levels in the aquifer have not been measured.

## Water Use

Although present in many areas of southern Arkansas, water-quality concerns have restricted use of the Cane River aquifer. In many areas in southeastern Arkansas, the aquifer is too salty for most uses (Hewitt and others, 1949; Onellion and Criner, 1955; Onellion, 1956; Bedinger and Reed, 1961; Albin, 1964). Historically in southwestern Arkansas, the greatest use has been for domestic supply. The aquifer also was a source of public-supply water in Lafayette County (Ludwig, 1973) and Dallas County (Plebuch and Hines, 1969). Lower yields inadequate for public-supply use were noted in wells in northern and western Columbia County and in Union County, north of El Dorado (Baker and others, 1948; Tait and others, 1953). Twenty-three wells reported use from the aquifer in 2010 (fig. 58). Also, water use for irrigation was reported from the aquifer for the first time in 2007 in Lafayette County (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

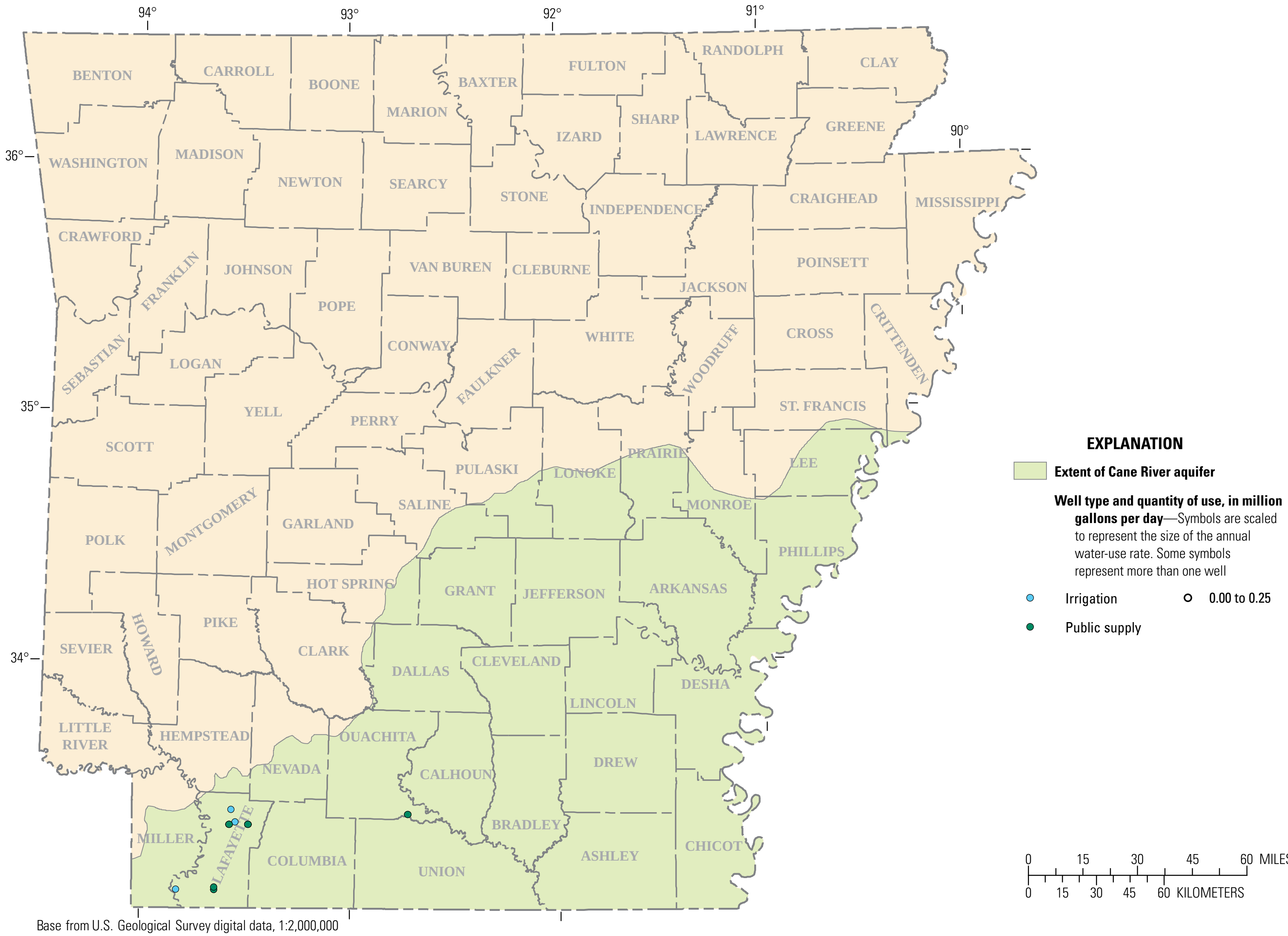



**Figure 58.** Wells with reported water use from the Cane River aquifer in Arkansas, 2010.

Reported water use for the Cane River aquifer is shown in table 26. It appears that the amount of use reported for 1965 by Halberg and Stephens (1966) might have been underestimated, as Ludwig (1973) assessed 3.04 Mgal/d were withdrawn in 1965. In 1965, a steam generation plant withdrew 1.8 Mgal/d in the town of Stamps in Lafayette County (Ludwig, 1973). It is unknown how long this plant was operated.

Lafayette County has consistently been the largest user of the Cane River aquifer, primarily for public supply (fig. 59). Municipalities using the aquifer included Bradley, Lewisville, and Stamps (all Lafayette County) and Sparkman (Dallas County), whose wells were drilled in the early 1930s (Hale and others, 1947). Lewisville used 0.1 Mgal/d in 1960 and 1965, while Stamps used 0.18 and 0.19 Mgal/d (Ludwig, 1973). Cities in Lafayette County have continued use of the aquifer (2013) as their public-supply source, while in the mid-2000s, Sparkman switched from the Cane River aquifer to the Ouachita River.

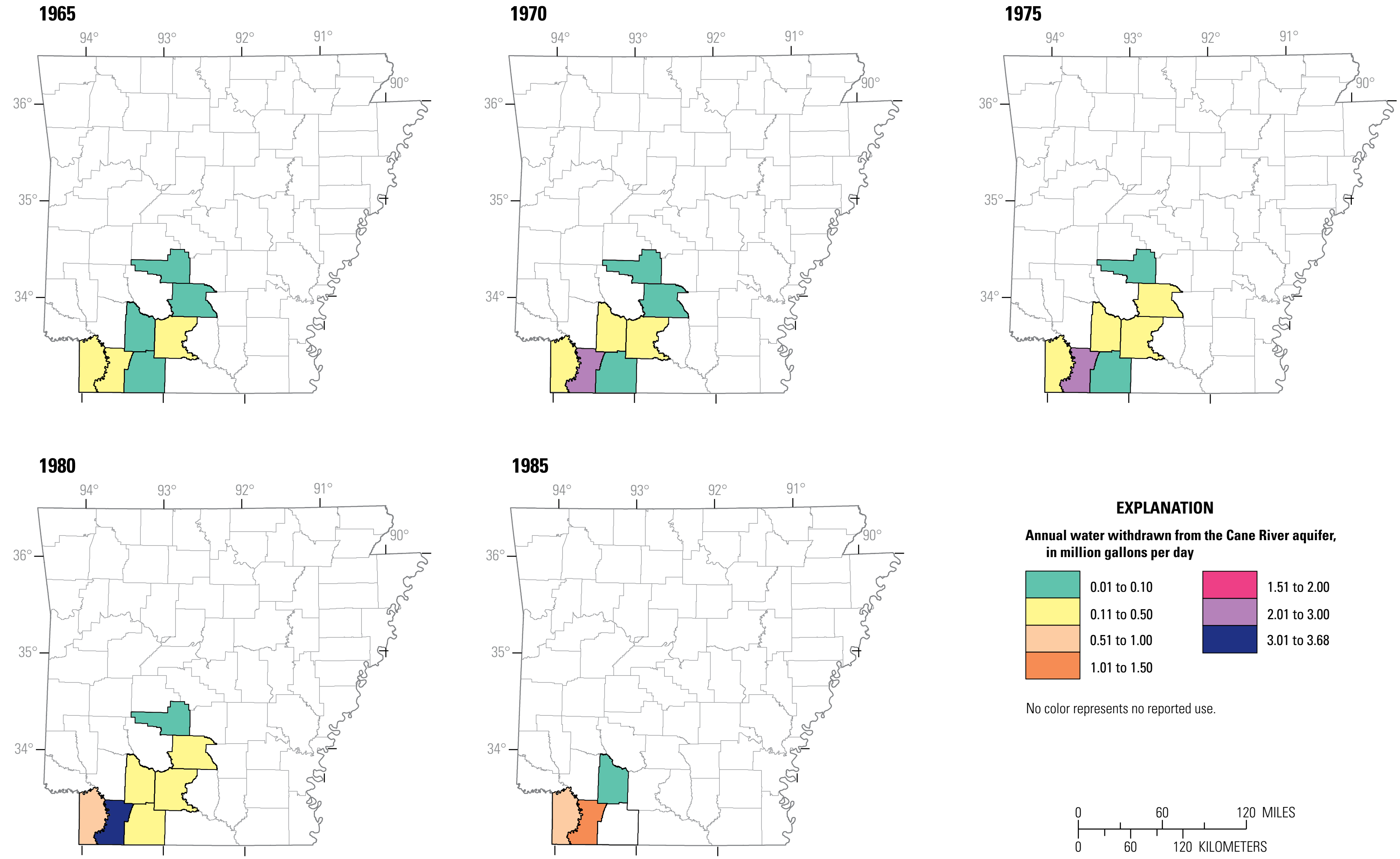
**Table 26.** Water use from the Cane River aquifer in Arkansas, 1965–2010.

[Counties shown are only those with published data. Data from Halberg and Stephens (1966); Halberg (1972, 1977); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1965 | 1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|
| Columbia | 0.06 | 0.09 | 0.10 | 0.16 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Dallas | 0.06 | 0.04 | 0.13 | 0.15 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Hot Spring | 0.02 | 0.07 | 0.08 | 0.08 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lafayette | 0.32 | 2.08 | 2.47 | 3.68 | 1.30 | 0.19 | 1.43 | 0.13 | 0.67 | 0.65 |
| Miller | 0.14 | 0.50 | 0.42 | 0.92 | 0.59 | 0.23 | 0.27 | 0.00 | 0.00 | 0.00 |
| Nevada | 0.05 | 0.39 | 0.13 | 0.16 | 0.05 | 0.02 | 0.02 | 0.00 | 0.00 | 0.00 |
| Ouachita | 0.17 | 0.18 | 0.15 | 0.12 | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 | 0.08 |
| **Total** | **[1]0.82** | **3.35** | **3.48** | **5.27** | **[2]1.91** | **[2]0.44** | **[2]1.72** | **0.13** | **0.71** | **0.73** |

[1]Ludwig (1973) reported that total water use from the Cane River aquifer in 1965 was 3.04 million gallons per day.

[2]In the 1985–95 reports, withdrawals in Greene County were reported to the Cane River aquifer; these were later removed. The published totals are slightly different from Holland (1987, 1993, 1999).




Base from U.S. Geological Survey digital data 1:2,000,000

Data modified from Halberg and Stephens, 1966; Halberg, 1972, 1977; Holland, 1981, 1987, 1993, 1999, 2004, 2007

**Figure 59.** Water-use rates for the Cane River aquifer in Arkansas from 1965 to 2010.

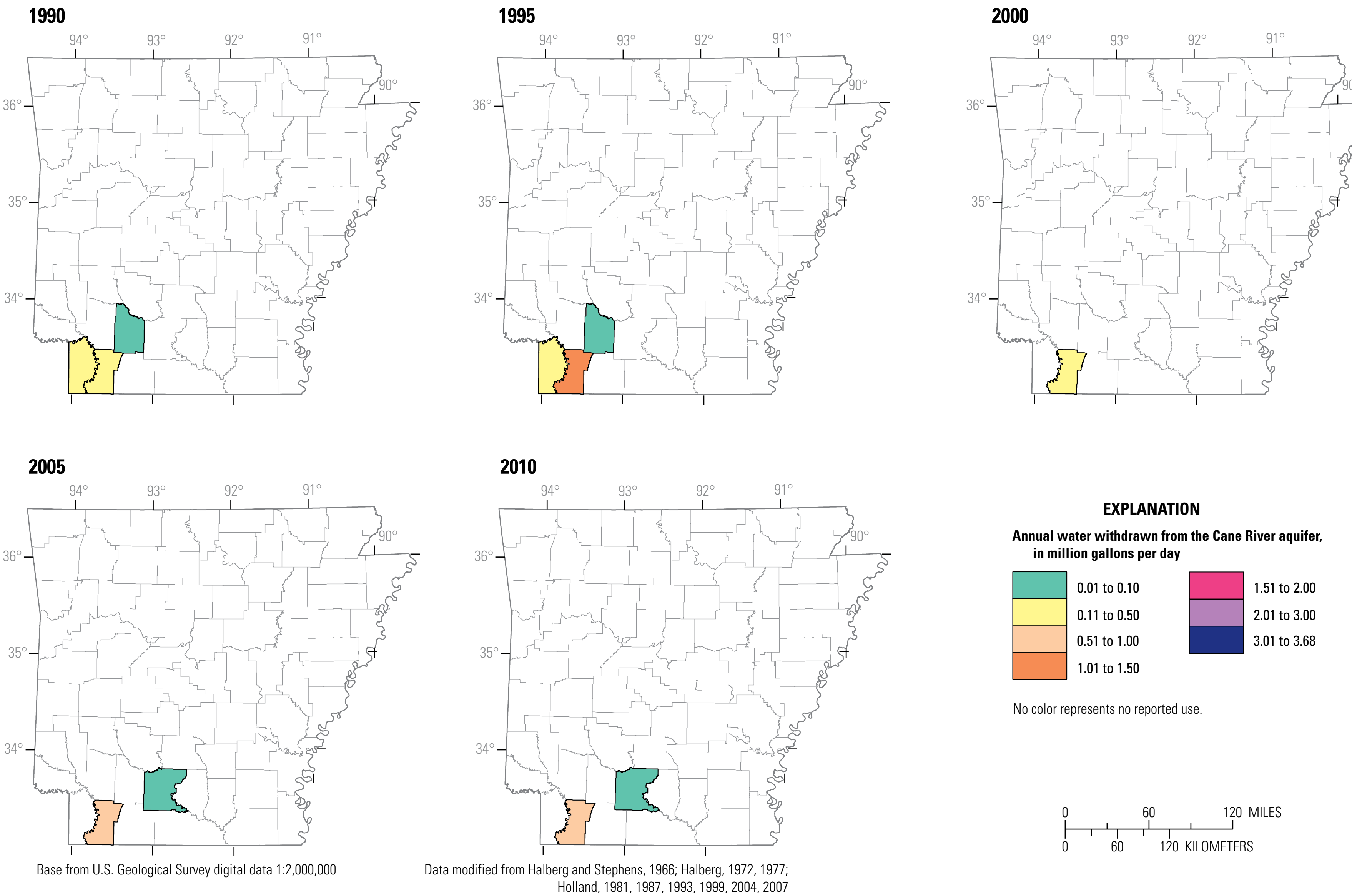



**Figure 59.** Water-use rates for the Cane River aquifer in Arkansas from 1965 to 2010.—Continued

## Water Quality

Areas where good quality water can be extracted from the Cane River aquifer are generally in or very near the outcrop. The outcrop extends in a narrow band from the very southwestern corner of the State up through central Arkansas. Changes in lithology and sand thickness throughout the extent of the Cane River affect water quality as the aquifer dips to greater depths below land surface. In the southern and southeastern part of the State, data from electric logs indicate that the water is too saline for most uses (Hewitt and others, 1949; Onellion and Criner, 1955; Broom and others, 1984). In northeastern Arkansas, the Cane River changes from a clay-dominated to sand-dominated facies and cannot be differentiated from the Sparta Sand or the Carrizo Sand.

Plebuch and Hines (1969) described groundwater from the Cane River aquifer in Clark, Cleveland, and Dallas Counties as soft with generally low iron concentrations. In other areas, however, iron concentrations were high enough to require treatment for certain uses. Ludwig (1973) reported that freshwater possibly could be obtained from most of the area comprising Hempstead, Lafayette, Miller, and Nevada Counties, although groundwater was increasingly mineralized in the downgradient direction of flow. These results were based on electric logs and chemical analysis of groundwater from wells serving as sources of public supply. Dissolved-solids and chloride concentrations ranged upward to 679 and 142 mg/L, respectively, and iron concentrations were generally less than 0.3 mg/L (Ludwig, 1972). South of this area, groundwater was described as a soft, sodium-bicarbonate water type with a moderately high mineral content that increased with depth (Tait and others, 1953). Further north in Hot Spring County, groundwater from the aquifer was described as very soft with low dissolved-solids concentrations, high iron concentrations, and low pH that could cause corrosion (Halberg and others, 1968). Hosman and others (1968) noted that the chemical characteristics of the groundwater varied with dissolved-solids concentrations; at lower dissolved-solids concentrations, a calcium-bicarbonate water type was predominant. As dissolved-solids increased, the groundwater transitioned first to a sodium-bicarbonate, then to a sodium-bicarbonate chloride type, and finally to a sodium-chloride type at the highest dissolved-solids concentrations. Dissolved-solids concentrations generally increased with depth, and the highest dissolved-solids concentrations in the aquifer were associated with fault zones. Outside of fault zones, dissolved-solids concentrations typically were less than 1,000 mg/L (Hosman and others, 1968).

### General Geochemistry and Water Type

Available data for the Cane River aquifer from the USGS NWIS and ADEQ databases yielded 45 groundwater sites with associated water-quality data. In general, the water quality is very good compared to Federal drinking-water standards (U.S. Environmental Protection Agency, 2009). A review of the USGS NWIS and ADEQ data supports earlier assessments of the groundwater from the aquifer being a soft, sodium-bicarbonate water type. Median concentrations for calcium (5.8 mg/L), magnesium (1.5 mg/L), and sodium (53 mg/L) indicate that sodium is the most prominent cation, giving the groundwater its overall soft-water identification (fig. 60; table 27). A review of cation (calcium, magnesium, sodium, and potassium) data supports the geochemical transitioning of groundwater from a calcium- to a sodium-dominated water type (Hosman and others, 1968). Spatial analysis reveals that calcium-dominated groundwater occurs only in the outcrop area. Abundant clay in the aquifer provides a high cation-exchange capacity. The result is that sodium replaces calcium at solid-phase exchange sites along the flow path. This results in a transitioning to sodium-dominated groundwater (sodium more than 50 percent of total cations) downgradient from the outcrop area (fig. 61). Isolated areas of elevated chloride (sodium-chloride water type) were observed in the aquifer and are discussed below.

Values of pH in the Cane River aquifer range from 4.5 to 8.6 with a median of 7.7 standard units (table 27). The lowest pH values are associated with sites in the outcrop area with large increases in pH occurring over short distances from the outcrop area (fig. 61). The average pH value for precipitation in southern Arkansas is approximately 4.7 standard units (Kresse and Fazio, 2002), which explains the lower pH values of groundwater in the outcrop area (recharge zone) for the Cane River aquifer. The infiltrating water is rapidly buffered along the flow path by dissolution of carbonate minerals, which is reflected by the very low bicarbonate concentrations (less than 20 mg/L) for groundwater in the outcrop area compared to the high concentrations (more than 100 mg/L) at short distances from the outcrop area (fig. 61).

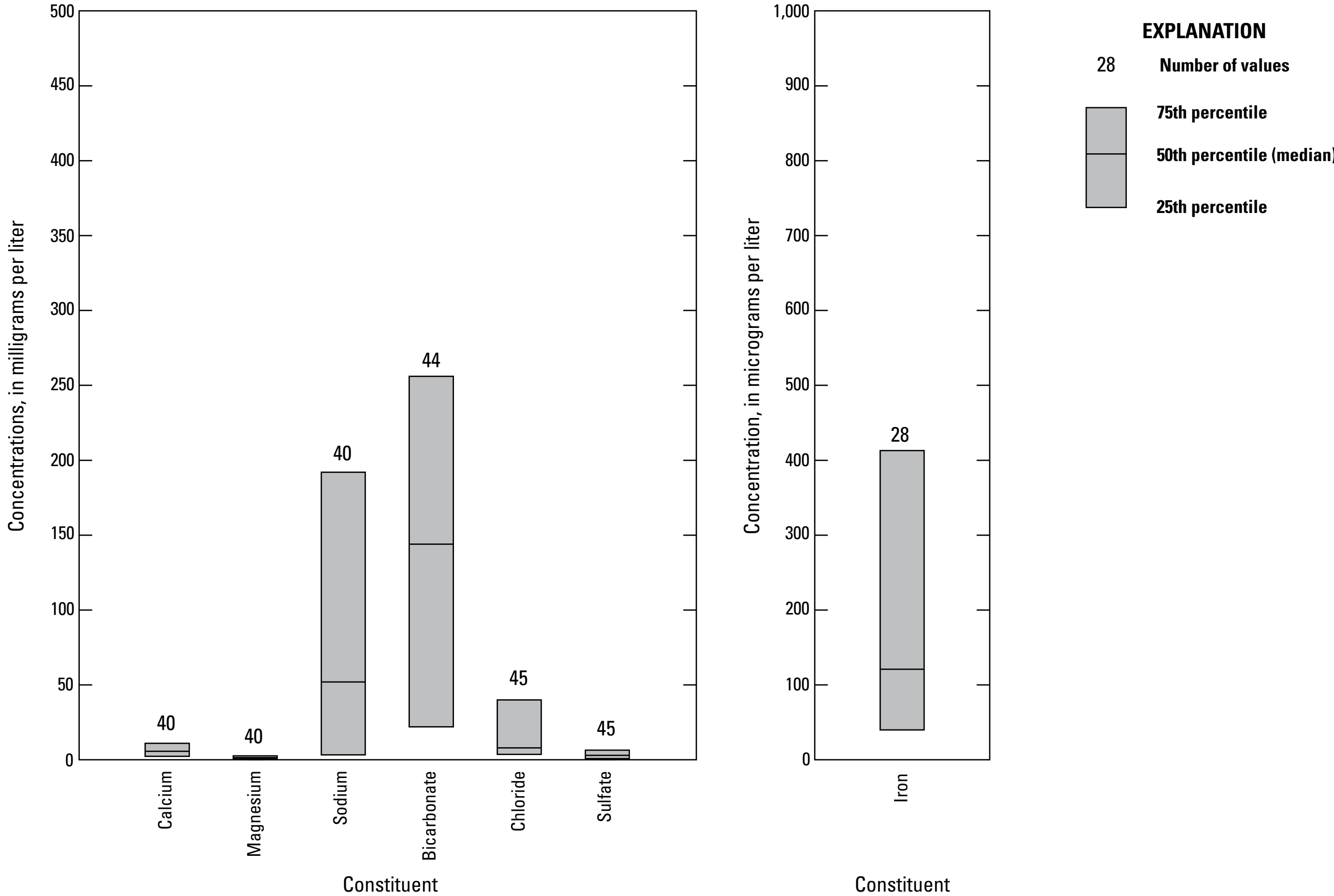



**Figure 60.** Interquartile range of selected chemical constituents for groundwater from the Cane River aquifer in Arkansas.

**Table 27.** Descriptive statistics for selected chemical constituents in groundwater from the Cane River aquifer in Arkansas.

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

| Constituent or characteristic | Minimum | Median | Maximum | Standard deviation | Number of wells |
|---|---|---|---|---|---|
| Calcium (mg/L) | 1.0 | 5.8 | 65 | 13.4 | 40 |
| Magnesium (mg/L) | 0.07 | 1.5 | 18 | 3.45 | 40 |
| Sodium (mg/L) | 0.8 | 53 | 964 | 223 | 40 |
| Potassium (mg/L) | 0.4 | 2.3 | 17 | 3.99 | 40 |
| Bicarbonate (mg/L) | 1.0 | 145 | 460 | 127 | 44 |
| Chloride (mg/L) | 0.7 | 8.0 | 1,410 | 314 | 45 |
| Sulfate (mg/L) | 0.02 | 3.0 | 37 | 7.65 | 45 |
| Silica (mg/L) | 7.4 | 11 | 28 | 5.45 | 31 |
| Nitrate (mg/L as nitrogen) | 0.01 | 0.18 | 6.1 | 0.98 | 43 |
| Dissolved solids (mg/L) | 30 | 158 | 2,660 | 622 | 40 |
| Iron (µg/L) | 0.05 | 120 | 52,000 | 9,580 | 28 |
| Manganese (µg/L) | 0.13 | 20 | 293 | 77.6 | 18 |
| Arsenic (µg/L) | 0.03 | 0.03 | 0.03 | 0.03 | 4 |
| Hardness (mg/L as calcium carbonate) | 4 | 22 | 240 | 46 | 42 |
| Specific conductance (µS/cm) | 22 | 245 | 4,610 | 1,020 | 45 |
| pH (standard units) | 4.5 | 7.7 | 8.6 | 1.1 | 44 |

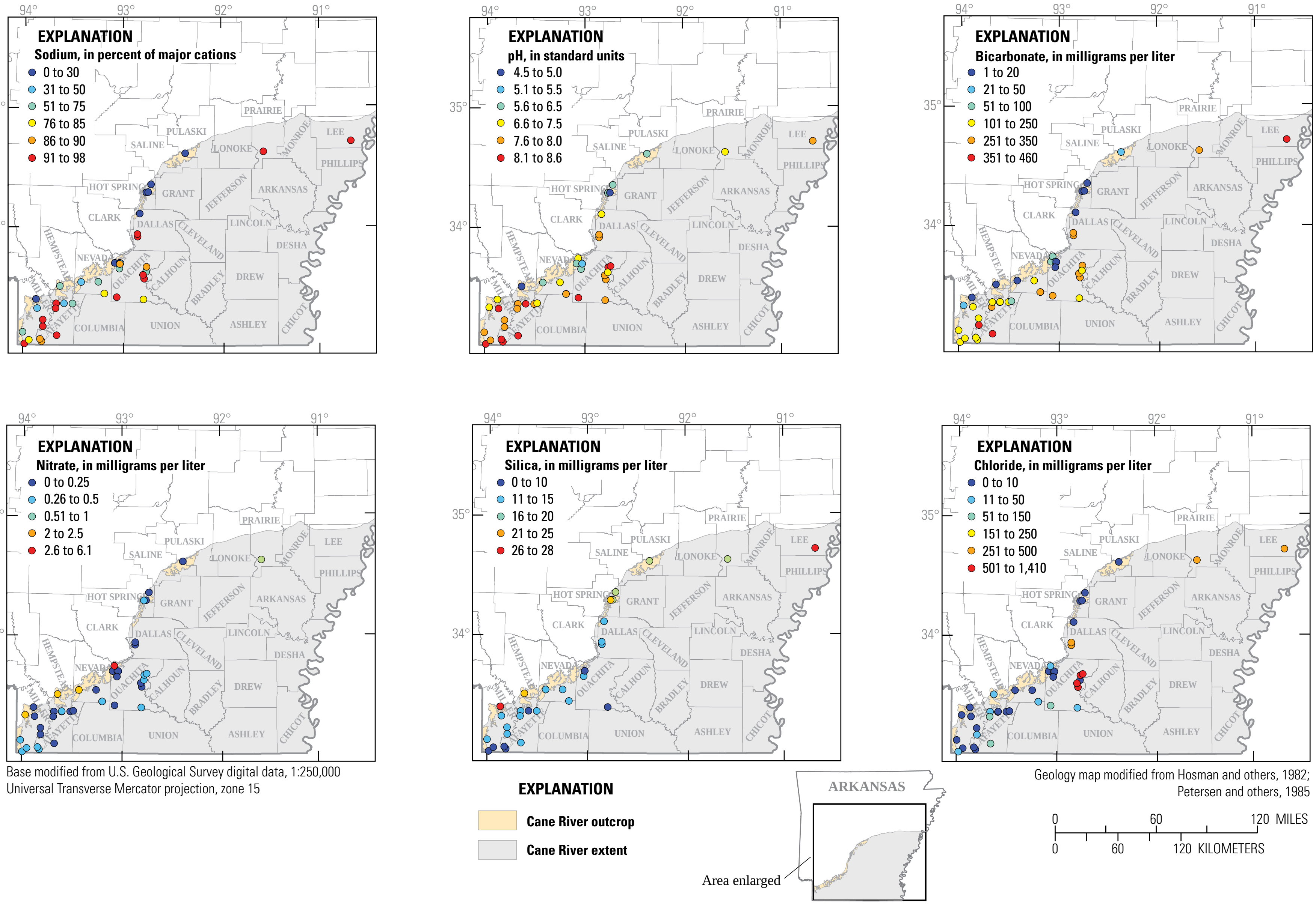



**Figure 61.** Spatial distribution of selected chemical constituents for groundwater from the Cane River aquifer in Arkansas.

### Nitrate

Nitrate concentrations generally were low in the Cane River aquifer, ranging from 0.01 to 6.1 mg/L with a median of 0.18 mg/L as nitrogen (table 27). No site had a concentration that exceeded the MCL of 10 mg/L, and only 5 of 43 sites had concentrations exceeding 0.5 mg/L. Nitrate concentrations greater than 1.0 mg/L occurred only in the outcrop area, demonstrating the vulnerability of shallow groundwater. Concentrations were less than 0.5 mg/L for all sites downgradient from the outcrop area, indicating one or more of the following conditions: (1) less connection with the surface because of greater depth and the presence of confining units, (2) dilution, (3) slow groundwater velocities, or (4) denitrification under reducing conditions hypothesized for groundwater downgradient from the outcrop area.

### Iron

Similar to other Tertiary aquifers reviewed in this report, iron concentrations in the Cane River aquifer generally were greatest in the outcrop area (ranging up to 52,000 µg/L) and lowest (mostly less than 300 µg/L) downgradient from the outcrop area. Lower iron concentrations downgradient from the outcrop area are hypothesized to be the result of changes in redox zonation along the flow path, leading to possible mineralization of iron sulfides and other minerals formed under reducing conditions. A more detailed discussion for this theory of reducing conditions leading to formation of iron sulfides is found in the “Water Quality” section for the Sparta aquifer.

### Silica

Silica concentrations in the Cane River aquifer ranged from 7.4 to 28 mg/L with a median of 11 mg/L (table 27). Similar to iron and some other constituents, the highest silica concentrations (more than 15 mg/L) occurred solely in the outcrop area, decreasing to less than 15 mg/L downgradient from the outcrop area. Likely mechanisms accounting for this spatial distribution include greater relative abundance of amorphous forms of quartz in the outcrop area, which results from weathering and diagenesis that contributes higher solubility forms of silica, and competition of silica, phosphorus, and other ions in solution for exchange sites on minerals along the flow path away from the outcrop area. Soil development and shallow groundwater processes can provide a source of mobile silica involving opal and microcrystalline forms of quartz cements (Basile-Doelsch and others, 2005; Macaulay, 2005). Organic compounds formed by cellulose-consuming fermentative bacteria can raise silica solubility to concentrations more than 110 mg/L and enhance silica dissolution. These organic compounds are unstable in many subsurface environments and can break down resulting in later precipitation of amorphous silica at relatively low temperatures (as low as 20° C) (Turner and others, 2002). It should be noted that higher concentrations of silica in the outcrop area of the Cane River also were noted for other Cretaceous and Tertiary aquifers including the Sparta and Cockfield aquifers. Silica behavior and early diagenesis has been implicated in control of aquifer hydraulic properties in the shallow Tertiary aquifers (Androes, 2006). Future studies are needed to elucidate this spatial geochemical phenomenon that has yet to be addressed in current and past publications.

### Sulfate

Sulfate concentrations in the Cane River aquifer ranged from 0.02 mg/L to 37 mg/L with a median of 3.0 mg/L (fig. 60; table 27). These represent some of the lowest median and maximum sulfate concentrations of any of the aquifers in the Coastal Plain. No spatial relation was noted for the distribution of sulfate concentrations in the Cane River aquifer.

### Chloride

Chloride concentrations ranged from 0.7 to 1,410 mg/L with a median of 8.0 mg/L (fig. 60; table 27). This median demonstrates the overall low chloride concentrations in groundwater from the Cane River aquifer, dominantly derived from rainwater concentrated by evapotranspiration processes (Kresse and Fazio, 2002; Kresse and Clark, 2008). Of the 45 wells with chloride data, 26 (58 percent) had concentrations less than 10 mg/L. Only eight wells had concentrations exceeding the Federal secondary drinking-water regulation of 250 mg/L. A spatial distribution of chloride revealed concentrations greater than 250 mg/L generally occurring in Dallas and eastern Ouachita Counties. The four wells with chloride concentrations greater than 500 mg/L occurred in eastern Ouachita County (fig. 61).

In summary, water quality from the Cane River aquifer is good with respect to Federal drinking-water standards. Groundwater generally is a calcium-bicarbonate water type in the outcrop area but transitions to a sodium-bicarbonate water type as a result of cation-exchange processes. Nitrate concentrations were less than the MCL of 10 mg/L for all samples. Salinity increases downdip from the outcrop area, and chloride concentrations can exceed the Federal secondary drinking-water regulation of 250 mg/L in some areas.

## Carrizo Aquifer

The Carrizo Sand (hereinafter referred to as the “Carrizo aquifer” where referring to the saturated part of the formation) comprises an aquifer of limited use only in and near the outcrop area in southwestern Arkansas. Although the hydrologic characteristics associated with the Carrizo aquifer were deemed favorable for future development in south-central Arkansas (Hosman and others, 1968), abundant groundwater from overlying formations supplies water needs in that area of the State. In the northeastern part of the State, sand units within the Carrizo cannot be differentiated from those of the overlying Cane River Formation and Sparta Sand. In previous regional geohydrologic framework analyses, the Carrizo aquifer was included in the lower Claiborne-upper Wilcox aquifer (Arthur and Taylor, 1990; Hosman and Weiss, 1991) or the lower Claiborne aquifer (Hart and others, 2008; Clark and Hart, 2009).

## Geologic Setting

The Tertiary-age Carrizo Sand unconformably overlies the Wilcox Group and is overlain by the Cane River Formation. The Carrizo consists predominately of fine to coarse, micaceous, massive-bedded quartz sands with minor amounts of interbedded clays and silts and occasional lenses of lignite. The lithology is composed of more than 80 percent sand in the majority of Arkansas. The Carrizo was deposited as valley and channel fills and as beach sands over an irregular erosion surface (Payne, 1975). In Clark, Cleveland, and Dallas Counties, the Carrizo consists mainly of very fine to medium sand with minor clay and lignite (Plebuch and Hines, 1969).

Formation and sand-thickness maps (Payne, 1975) indicate a thickening along relatively narrow sinuous bands elongated in a northerly direction, likely normal to the shoreline of the early Claiborne sea. These deposits likely represent an ancient delta or fluvial plain. The pattern of deposition of the Carrizo is believed to have resulted from deposition in shore and nearshore environments during initial advance of the Claiborne sea over an erosional surface that was developed on sediments of the Wilcox Group by an ancestral Mississippi River system. The elongated areas of thickened Carrizo is interpreted to be the result of infilling of preexisting channels and valleys during Carrizo time. The lack of seaward gradation of the sand to clay ratio is indicative of a lack of appreciable deposition on the steep seaward side of the delta.

The Carrizo Sand and overlying Cane River Formation undergo facies changes north of latitude 35 degrees, and both formations become sand. This northern sand facies of the Cane River Formation and the underlying Carrizo Sand are generally indistinguishable from the Sparta Sand and are grouped together as the Memphis Sand (Counts, 1957; Hosman and others, 1968; Payne, 1972; Petersen and others, 1985). The Claiborne Group in Cross, Lee, Lonoke, Monroe, Prairie, St. Francis, and Woodruff Counties was noted to be undifferentiated (Halberg and Reed, 1964). In parts of southern Lonoke and Prairie Counties, however, the Carrizo and the Sparta Sand can be recognized in the subsurface. Wells completed in the Carrizo aquifer were as far north as Prairie and Lee Counties.

The regional dip of the Carrizo Sand is into the Desha Basin, the Mississippi embayment, and the Gulf Coast geosynclines. Some movement of major structural features took place during Carrizo time. Normal faulting is extensive in southern Arkansas (Payne, 1975). The Carrizo dips toward the east-southeast in southern Arkansas, to the southeast in central and eastern Arkansas, and to the northeast into the Desha Basin in extreme southeastern Arkansas at a rate of 20–50 ft/mi. The Carrizo is discontinuous and highly variable in thickness, notably in parts of Columbia, Ouachita, and Union Counties, where thicknesses of 30 ft or less occur. The thickness in the subsurface ranges from zero ft in areas of nondeposition to nearly 400 ft in southeastern Arkansas in the Desha Basin (Hosman and others, 1968; Payne, 1975; Petersen and others, 1985). The Desha Basin in southeastern Arkansas is a major negative structural element seen on the top of the Carrizo. Normal faulting is extensive in southern Arkansas as shown on structural maps (Plebuch and Hines, 1969; Payne, 1975; Hosman, 1982; Petersen and others, 1985). Thickness of the Carrizo in Clark, Cleveland, and Dallas Counties varies considerably over short distances, ranging from about 60 to 200 ft (Plebuch and Hines, 1969). The Carrizo crops out in a narrow band, 2–5 miles wide, through southern Hempstead, central Miller, and central Nevada Counties.

## Hydrologic Characteristics

Recharge to the Carrizo aquifer comes from rainfall on the outcrop, seepage from the overlying Mississippi River Valley alluvial aquifer, and lateral flow from the Sparta aquifer downdip into the Carrizo south of latitude 35 degrees. Discharge from the Carrizo occurs by withdrawals from wells and natural discharge by leakage through the overlying confining beds. Regional flow of water is generally downdip toward the axes of the Mississippi embayment and the Desha Basin (Hosman and others, 1968; Payne, 1975).

The Carrizo aquifer is not considered a major aquifer in Arkansas because of its erratic distribution, and therefore available hydrologic data are limited. There is an increase in permeability with increasing sand thickness. Results of 45 aquifer tests provided the following hydraulic conductivity values: 29 ft/d for sands from 25 to 100 ft thick, 40 ft/d for sands from 100 to 200 ft thick, and 53 to 60 ft/d for sands from 200 to more than 300 ft thick (Payne, 1975). A single aquifer test in Hot Spring County yielded a transmissivity of about 550 $ft^2$/d, a hydraulic conductivity of about 13 ft/d, and a specific capacity of 2 (gal/min)/ft (Hosman and others, 1968). A well in Miller County yielded 100 gal/min and had a specific capacity of 3 (gal/min)/ft (Ludwig, 1973). Except in the outcrop area, the aquifer is under artesian conditions, and the regional flow is downdip to the east and southeast into the Desha Basin and the Mississippi embayment (Payne, 1975). In southern Arkansas, groundwater flow in the Carrizo aquifer is confined by the Wilcox Group below and the Cane River Formation above (Hosman and others, 1968).

## Water Use

The Carrizo is only a minor aquifer in Arkansas and mainly used for domestic supply in southwestern Arkansas. Hosman and others (1968) noted that in south-central Arkansas the aquifer was untapped, where the hydrology of the Carrizo was most favorable for future development. Older reports state that the aquifer was not commonly utilized, perhaps because of high iron concentrations or limited available information on the aquifer’s extent and water availability (Halberg and others, 1968; Plebuch and Hines, 1969). Most withdrawals from the Carrizo were domestic users within 5–10 mi of its outcrop (Albin, 1964; Terry and others, 1986). The Carrizo was evaluated for industrial use at Pine Bluff; however, the poor water quality rendered its use unsuitable (Hosman, 1964).

Published water-use data for the Carrizo aquifer are only available from 1965 to 1980 (table 28). Ludwig (1973) reported that 0.23 Mgal/d was withdrawn from Miller County wells in 1965, slightly higher than what was reported in Halberg and Stephens (1966). Prairie County users withdrew the most water from 1970 to 1980, but Ludwig (1973) attributed most use of the Carrizo to domestic use in Miller County (table 28). The city of Fouke (Miller County) obtained its water supply from a well screened in the Carrizo aquifer (Ludwig, 1973); however, later inventories reported the water source for Fouke was the Wilcox aquifer (Baker and others, 1991). No wells currently are recorded in the ARWUDBS for this aquifer. A few commercial enterprises that do not meet the reporting requirements for ARWUDBS use the aquifer in Miller and Nevada Counties (Lyle Godfrey, Arkansas Department of Health, written commun., 2012).

**Table 28.** Water use from the Carrizo aquifer in Arkansas, 1965–80.

[Counties shown are only those with published data. Data from Halberg and Stephens (1966); Halberg (1972, 1977); Holland (1981). Units are million gallons per day]

| County | 1965 | 1970 | 1975 | 1980 |
|---|---|---|---|---|
| Hempstead | 0.00 | 0.06 | 0.09 | 0.10 |
| Hot Spring | 0.02 | 0.06 | 0.06 | 0.07 |
| Miller | 0.09 | 0.06 | 0.08 | 0.18 |
| Nevada | 0.00 | 0.03 | 0.04 | 0.06 |
| Ouachita | 0.05 | 0.07 | 0.06 | 0.08 |
| Prairie | 0.00 | 0.18 | 0.19 | 0.25 |
| **Total** | **0.16** | **0.46** | **0.52** | **0.74** |

## Water Quality

Databases accessed for this study contained water-quality results for only 12 wells completed in the Carrizo aquifer. Although groundwater quality of the aquifer generally is good in and near the outcrop area, it degrades downgradient and becomes unusable for most purposes because of increased chloride concentrations (Hosman and others, 1968; Terry and others, 1986). Most wells completed in the Carrizo are located in a southwest to northeast trending line, which trends from western Miller County into southern Saline County. Few data were available for the Carrizo aquifer in Clark, Cleveland, and Dallas Counties, but in south-central Dallas and southern Cleveland Counties the aquifer probably contained more than 1,000 mg/L dissolved solids, making it unsuitable for most uses (Plebuch and Hines, 1969). The Carrizo aquifer contains freshwater throughout much of Hempstead, Lafayette, Little River, Miller, and Nevada Counties except in south-central Lafayette County (Ludwig, 1973). One well completed in the Carrizo produced groundwater of a soft, sodium-bicarbonate type, but another well in eastern Grant County had 280 mg/L chloride (Halberg and others, 1968). Most reports listed groundwater from the Carrizo as a soft, sodium-bicarbonate water type with a low to moderate mineral concentration (Hosman and others, 1968; Ludwig, 1972; Terry and others, 1986). Hosman and others (1968) stated that water type varies with dissolved-solids concentration and noted that the water is either a calcium/magnesium-bicarbonate or a sodium-bicarbonate type for groundwater with low dissolved-solids concentrations and evolves to a sodium-bicarbonate-chloride water type for dissolved-solids concentrations greater than 400 mg/L.

### General Geochemistry and Water Type

Median concentrations for most constituents in the Carrizo aquifer reveal an overall good quality, sodium-bicarbonate groundwater with low iron concentrations. All samples had percent sodium (as a percentage of the total cations) values indicative of a sodium-bicarbonate water type. Six samples had sodium greater than 95 percent, and 11 of 12 samples exceeded 80 percent (fig. 62). Values of pH ranged from 7.2 to 8.4 with a median of 7.9 (table 29), and no strong spatial trend was evident, likely a result of the paucity of data. Bicarbonate concentrations were less than 250 mg/L in 8 of 12 samples. Two samples had concentrations of 449 and 518 mg/L and were in southeastern Ouachita and southeastern Lee Counties, respectively (fig. 62).

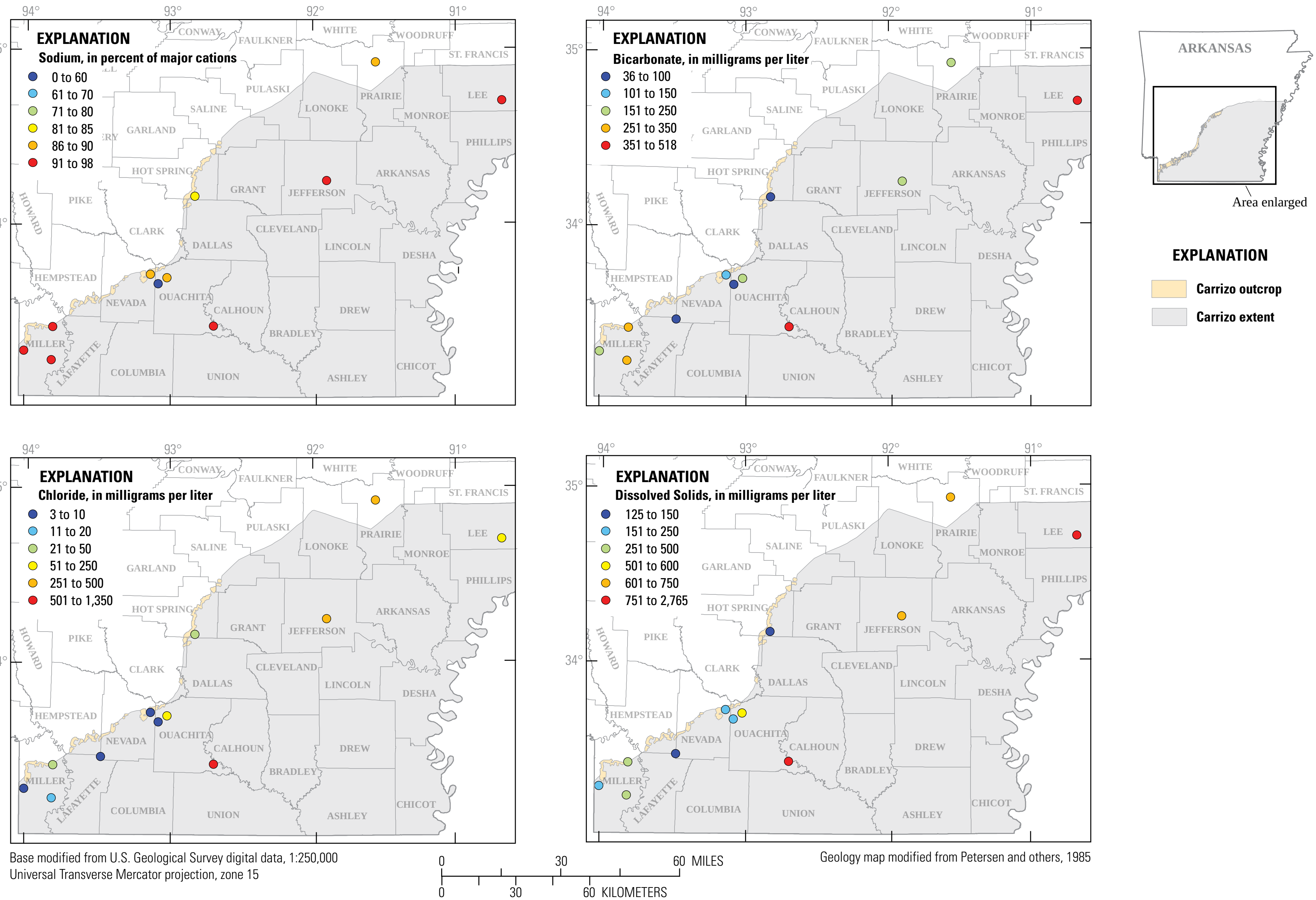



**Figure 62.** Spatial distribution of selected chemical constituents for groundwater from the Carrizo aquifer in Arkansas.

**Table 29.** Descriptive statistics for selected chemical constituents in groundwater from the Carrizo aquifer in Arkansas.

[mg/L, milligrams per liter; µg/L, micrograms per liter; NA, not analyzed; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

| Constituent or characteristic | Minimum | Median | Maximum | Standard deviation | Number of wells |
|---|---|---|---|---|---|
| Calcium (mg/L) | 0.5 | 3.9 | 20 | 7.2 | 12 |
| Magnesium (mg/L) | 0.35 | 1.0 | 7 | 2.09 | 11 |
| Sodium (mg/L) | 6.2 | 130 | 1,050 | 271 | 12 |
| Potassium (mg/L) | 0.6 | 2.67 | 11 | 2.81 | 12 |
| Bicarbonate (mg/L) | 36 | 197 | 518 | 144 | 12 |
| Chloride (mg/L) | 3.0 | 34 | 1,350 | 363 | 12 |
| Sulfate (mg/L) | 0.02 | 3.0 | 90 | 24.3 | 12 |
| Silica (mg/L) | 9.25 | 12 | 30 | 5.82 | 9 |
| Nitrate (mg/L as nitrogen) | 0.01 | 0.09 | 1.1 | 0.3 | 11 |
| Dissolved solids (mg/L) | 125 | 329 | 2,770 | 701 | 12 |
| Iron (µg/L) | 0.05 | 130 | 1,000 | 372 | 9 |
| Manganese (µg/L) | 0.13 | 0.13 | 120 | 41.6 | 7 |
| Arsenic (µg/L) | NA | NA | NA | NA | NA |
| Hardness (mg/L as calcium carbonate) | 4.0 | 15 | 79 | 27 | 12 |
| Specific conductance (µS/cm) | 127 | 572 | 4,680 | 1,200 | 12 |
| pH (standard units) | 7.2 | 7.9 | 8.4 | 0.4 | 12 |

## Nitrate

Nitrate concentrations in the Carrizo aquifer ranged from 0.01 to 1.1 mg/L with a median of 0.09 mg/L as nitrogen (table 29). All but one of the nitrate samples had concentrations below 1.0 mg/L, which is well below the Federal MCL of 10 mg/L as nitrogen. All well depths were more than 195 ft, ranging from as much as 400 ft in the outcrop area up to 2,050 ft for a well in Jefferson County. In most aquifers of the Coastal Plain, nitrate concentrations showed an inverse relation with depth and were dominantly more than 1.0 mg/L for well depths less than 50–100 ft. The paucity of data prevented a rigorous statistical analysis of well depth and nitrate concentrations in the Carrizo aquifer. The somewhat greater depths for wells completed in the Carrizo aquifer compared to other Tertiary aquifers may render the groundwater producing zone less vulnerable to surface sources of nitrogen and other contaminants. Other Tertiary aquifers in Arkansas (Jackson Group, Cockfield, Sparta, Cane River, and Wilcox aquifers) generally had nitrate concentrations more than 5 mg/L in groundwater from wells with depths less than approximately 150 ft.

## Iron

Iron concentrations for nine wells in the Carrizo aquifer ranged from 0.05 to 1,000 µg/L with a median of 130 µg/L (fig. 63; table 29). Only three of the nine wells had iron concentrations that exceeded the Federal secondary drinking-water regulation of 300 µg/L. All iron concentrations were relatively low compared to other aquifers in the State. Samples were too few to evaluate the spatial distribution of iron concentrations throughout the Carrizo aquifer.

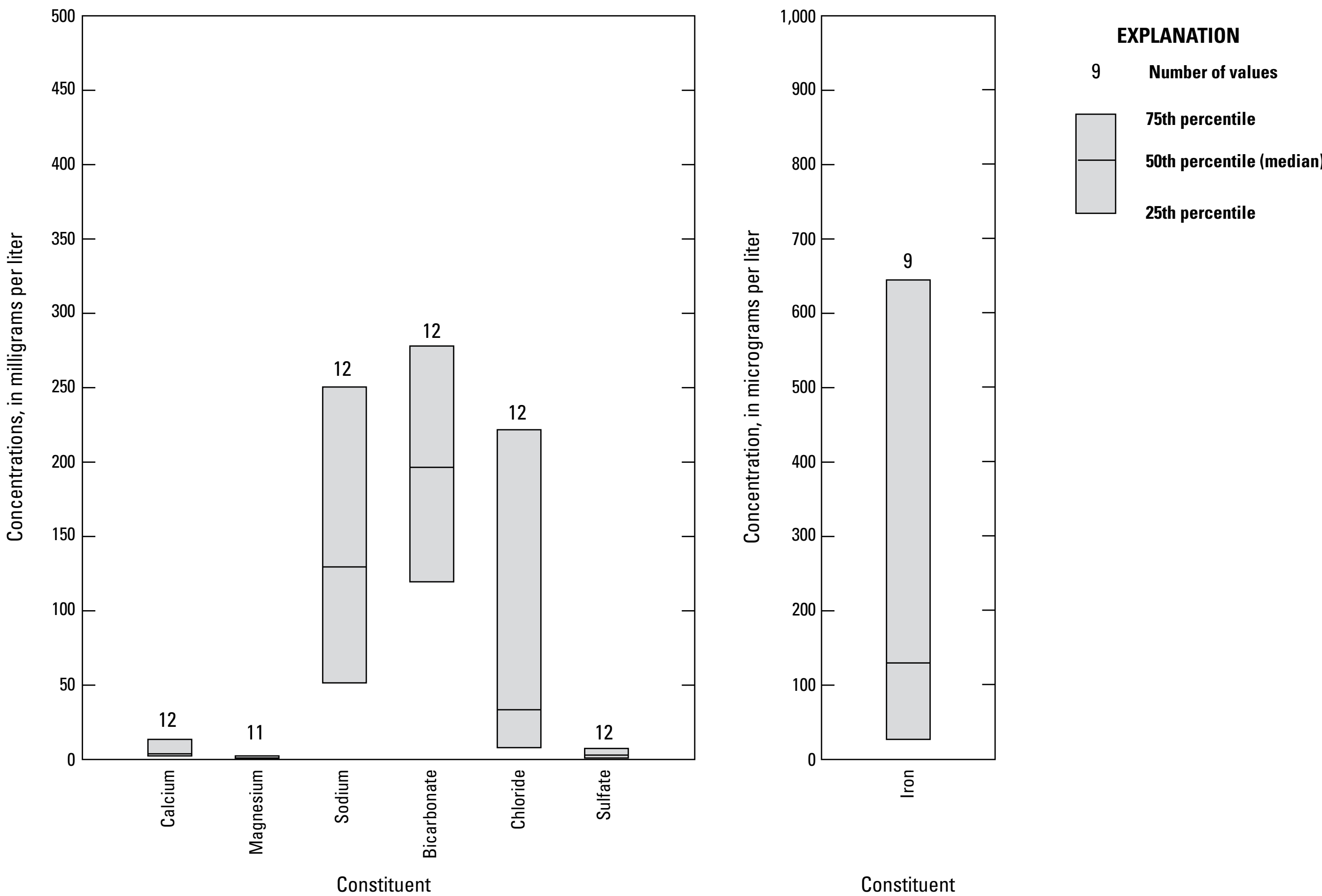



**Figure 63.** Interquartile range of selected chemical constituents for groundwater from the Carrizo aquifer in Arkansas.

## Sulfate

Sulfate concentrations in 12 samples from the Carrizo aquifer were low compared to that in many other aquifers and ranged from 0.02 to 90 mg/L with a median of 3.0 mg/L (fig. 63; table 29). The second highest sulfate concentration was 22 mg/L, which demonstrates the overall low sulfate concentration of groundwater from the Carrizo. The maximum concentration of 90 mg/L was in a sample from a well in northwestern Ouachita County. No pattern of increasing sulfate concentrations was noted downdip from the outcrop area, and too few well sites were available for a meaningful interpretation of the spatial distribution of sulfate.

## Chloride and Dissolved Solids

Chloride concentrations in 12 samples from the Carrizo aquifer ranged from 3.0 to 1,350 mg/L with a median of 34 mg/L (fig. 63; table 29). The maximum concentration was for a well in southeastern Ouachita County that was approximately 30 mi from the outcrop area. Hosman and others (1968) and Terry and others (1986) noted that groundwater downdip from the outcrop area becomes unusable as a result of increasing chloride concentrations. Only two other wells were higher than the Federal secondary drinking-water regulation of 250 mg/L for chloride, and these wells were in Jefferson (277 mg/L) and Prairie (310 mg/L) Counties northeast of the outcrop area (fig. 62). The distribution of dissolved-solids concentrations was similar to the distribution of chloride concentrations, which is typical. The highest concentrations were in areas outside of the outcrop area (fig. 62). Four of the five wells with dissolved solids exceeding the Federal secondary drinking-water regulation of 500 mg/L were far removed from the outcrop area.

In summary, samples from the Carrizo aquifer reveal an overall good quality, sodium-bicarbonate groundwater with low iron concentrations as compared to many other aquifers of the Coastal Plain. Nitrate concentrations from data compiled for this report were extremely low throughout the aquifer. Sulfate and chloride concentrations generally are low for areas near the outcrop but appreciably increase with distance from the outcrop area.

## Wilcox Aquifer

The Wilcox Group contains a major lower aquifer, termed the lower Wilcox aquifer, and minor aquifers associated with sands of the upper Wilcox Group (Hosman and others, 1968). In later regional framework and embayment models, three units were used to represent the Wilcox Group: the lower Claiborne-upper Wilcox aquifer, the middle Wilcox aquifer, and the lower Wilcox aquifer (Arthur and Taylor, 1986; Brahana and Mesko, 1988; Renken, 1998; Hart and others, 2008; Clark and Hart, 2009). The lower Claiborne-upper Wilcox aquifer included all sand beds below the clay beds of the lower Claiborne Group and included sand beds present in the upper Wilcox Group. In Arkansas, this model unit included the Carrizo Sand of the Claiborne Group and sand units in the upper Wilcox Group that are hydraulically connected to the lower Claiborne Group. The middle Wilcox aquifer included the irregular and discontinuous sand beds that are interbedded with layers of clay, silt, and lignite within the upper unit of the Wilcox Group. The lower Wilcox aquifer included thin, interbedded layers of lignitic sands and clays of the lower Wilcox unit. Water-use (Holland, 2007) and water-level reports (Pugh, 2010) refer to the combined sands simply as the Wilcox aquifer. For purpose of this report, the saturated part of the Wilcox Group most often will be referred to as the “Wilcox aquifer,” unless summarizing historical reports that reference the aquifer according to divisions cited above.

### Geology

The Wilcox Group is a predominantly unconsolidated sequence comprising two distinct lithologic units: a lower unit of mostly sand and an upper predominately shale or clay unit (Cushing and others, 1964). The Wilcox is of Eocene age and extends throughout most of eastern and southern Arkansas. Most of the beds of the Wilcox of eastern Arkansas are considered to be nonmarine in origin (Renfroe, 1949). The Wilcox (Crider and Johnson, 1906) generally is undifferentiated, except in central Arkansas where the Berger and Saline Formations and the Detonti Sand may be identified (Gordon and others, 1958). Although undifferentiated, the upper and lower units of the Wilcox are recognizable in the State.

The upper unit of the Wilcox Group predominates in the southern part of Arkansas and consists of complexly interbedded layers of clay, sandy clay, thin and discontinuous sand, and lignite (Joseph, 1998b). The thin sands of this unit serve as aquifers primarily in the southern extent of the Wilcox (Hosman and others, 1968). In southern Arkansas, the Wilcox overlies the Midway Group, and crops out in a discontinuous band 1–3 mi wide (Joseph, 1998b) and commonly is overlain by terrace deposits and alluvium of Quaternary age. The Wilcox becomes progressively thicker downdip from the outcrop, ranging in thickness from only a few feet at the outcrop to about 1,100 ft in Bradley County in southern Arkansas (Albin, 1964; Petersen and others, 1985). The Wilcox dips toward the axis of the Mississippi embayment at about 50 ft/mi in southern Arkansas (Hosman and others, 1968).

In northeastern Arkansas, the upper and lower Wilcox Group units are present. The upper Wilcox Group unit is composed of thin, interbedded layers of lignitic sands and clays. The lower predominately sand unit may contain as many as three major sand units, although they are collectively referred to as the lower Wilcox aquifer (Hosman and others, 1968). Where differentiated in northeastern Arkansas, the Wilcox contains the Flour Island Formation, the Fort Pillow Sand, and the Old Breastworks Formation (Renken, 1998). Of note, the lower sand contains the “1,400-foot” sand as first used by Klaer (1940), which is a common term for this aquifer in northeastern Arkansas. The Wilcox contains sand beds more than 200 ft thick east of Crowleys Ridge in northeastern Arkansas (Petersen and others, 1985). The maximum thickness of the lower Wilcox aquifer where it contains freshwater is 300 ft. In most of the northern half of the embayment, the lower Wilcox aquifer is more than 80 percent sand (Hosman and others, 1968). The lower Wilcox unit is confined by an overlying clay bed of the Wilcox Group and an underlying clay bed of the Midway Group. The Wilcox crops out in the area of Crowleys Ridge (fig. 64) in Clay, Craighead, and Green Counties (Broom and Lyford, 1981). The Wilcox dips toward the axis of the Mississippi embayment at about 20 ft/mi in the north (Hosman and others, 1968). Locally, the upper part of the Wilcox is unconformably overlain by the Carrizo Sand. Where sand is present in the upper Wilcox Group, it is difficult to differentiate from the Carrizo Sand (Hosman and others, 1968).

The Wilcox crops out in northern Nevada and Hempstead Counties and underlies the Cane River Formation throughout Columbia and Union Counties (Zachry and others, 1986). In this area, the Wilcox is dominantly composed of clay with thin discontinuous sand units and thin lignite beds in some areas. Near Columbia and Union Counties, the Wilcox Group ranges from 350 to 550 ft in thickness but does not make a good aquifer because of the lithology and water quality. In fact, the Wilcox has been examined as a potential reservoir for hydrocarbons in some parts of eastern Arkansas. A few sandstones show staining that were possibly hydrocarbons, but the Wilcox was not considered to have good potential as an oil reservoir (Renfroe, 1949).

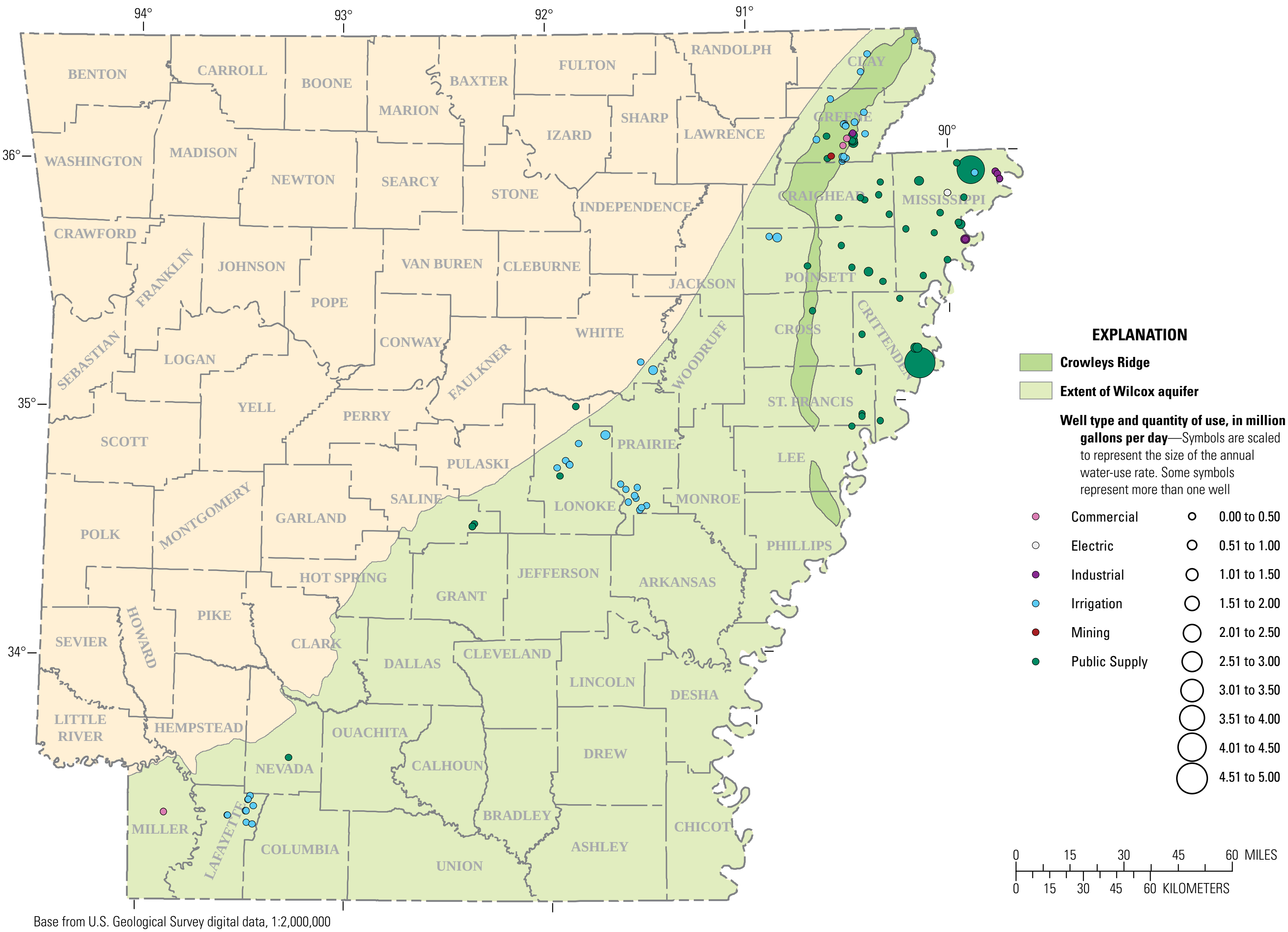



**Figure 64.** Wells with reported water use from the Wilcox aquifer in Arkansas, 2010.

## Hydrologic Characteristics

Wells completed in the Wilcox aquifer typically yield from 500 to more than 2,000 gal/min (Hosman and others, 1968). An aquifer test in Mississippi County resulted in a transmissivity value of 21,390 $ft^2/d$, a storage coefficient of 0.0002, and a hydraulic conductivity of 174 ft/d. An aquifer test in Hot Spring County resulted in a transmissivity value of 2,406 $ft^2/d$, a storage coefficient of 0.00002, and a hydraulic conductivity of 60 ft/d (Hosman and others, 1968). Pugh (2008a) noted that specific capacity for the aquifer ranged from 0.25 to 641 (gal/min)/ft with a mean of 142 (gal/min)/ft (12 tests). Transmissivity ranged from 39 to 32,000 $ft^2/d$ with a mean of 10,700 $ft^2/d$ (14 tests). The estimated hydraulic conductivity for the aquifer was 9.73 ft/d based on the mean transmissivity value (Pugh, 2008a). Wells near Blytheville had yields from 200 to 1,800 gal/min (Halberg and Reed, 1964). Discharge from the aquifer is mainly to wells (Westerfield, 1994). Pumping from the aquifer has caused substantial declines in local water levels.

In most of Arkansas, the potentiometric surface of the Wilcox aquifer is below land surface (Hosman and others, 1968). However, where the lower Wilcox unit is confined in northeastern Arkansas, the potentiometric surface may rise above land surface (Joseph, 1998b). Regional groundwater flow is toward the axis of the Mississippi embayment (Westerfield, 1994; Joseph, 1998b; Schrader and Joseph, 2000; Yeatts, 2004; Schrader, 2007a; Pugh, 2010). Cones of depression associated with pumping centers locally affect the groundwater movement (Hosman and others, 1968).

The main source of recharge to the Wilcox aquifer in the southern part of the State is infiltration of precipitation in the outcrop areas. In the northern part of the State where the aquifer subcrops, recharge is by leakage from the overlying Carrizo Sand and other overlying formations (Hosman and others, 1968). Pumping from the Wilcox aquifer in southern Arkansas has caused substantial declines in water levels in some areas.

## Water Use

The Wilcox aquifer generally yields water of excellent quality, and users often refer to the water as having the best water quality in the State (Scott and others, 1998). Approximately 150 wells were reported to use water from the aquifer as of 2010 (fig. 64). Good water quality and yields have led to its use for public, domestic, and industrial supplies. Several municipalities in eastern Arkansas historically have used the aquifer for public supply (Baker, 1955) with 65 percent of water from the aquifer being used for this purpose (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Water use from the aquifer has been greatest in Crittenden, Greene, and Mississippi Counties. East of the outcrop area in Chicot, Desha, Jefferson, and Union Counties, salinity limits usage of the deeper parts of the aquifer (Klein and others 1950; Onellion and Criner, 1955; Bedinger and Reed, 1961; Terry and others, 1986).

Total water use from the Wilcox aquifer peaked in 1995 and has since declined to amounts comparable to those of 1980. The aquifer is nevertheless an important, high-quality water source in Arkansas. Water-use rates for the Wilcox increased from 1965 through 1980 but declined in 1985 (table 30). Decreases in use are likely attributed to reduced irrigation following heavy use of the aquifer during the drought in the 1980s. In addition, changes were made associated with reporting procedures with the switch to the ARWUDBS system that affected reported usage. Use of the aquifer again increased in 1990 and peaked at 40.98 Mgal/d in 1995. Water use dropped 10.59 Mgal/d from 1995 to 2000 following a large decrease in use by Mississippi County. It subsequently increased to 36.52 Mgal/d in 2010. Mississippi County historically had the greatest water use from the aquifer when several municipalities depend on the aquifer for public supply (figs. 64 and 65). Industrial use is also important in Mississippi County with industries using approximately 1.66 Mgal/d in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

Most early use of the Wilcox aquifer around the 1900s occurred east of Crowleys Ridge (figs. 64 and 65) and primarily was for domestic supply. However, industrial use for lumber, ice, and railroad companies in Cross and Greene Counties was locally important (Stephenson and Crider, 1916). The Wilcox aquifer was also tapped by users on Crowleys Ridge, whereas users to the east and west of the ridge that could access Quaternary deposits used the Mississippi River Valley alluvial aquifer during the early part of the last century (Stephenson and Crider, 1916). Beginning in the 1920s, public-water suppliers east of Crowleys Ridge depended heavily on the aquifer (Hale and others, 1947; Counts and other, 1955; Ludwig, 1973). Towns in Crittenden, Mississippi, and St. Francis Counties reported average water usage ranging from 0.05 to 5.4 Mgal/d during the 1940s through the 1960s (Hale and others, 1947; Counts and others, 1955; Ryling, 1960; Plebuch, 1961; Halberg and Reed, 1964; Ludwig, 1973).

The greatest public-supply use of the Wilcox aquifer was in Crittenden and Mississippi Counties with Crittenden County using 2.5 Mgal/d in 1959 (Plebuch, 1961) and Mississippi County using 5.4 Mgal/d in 1957 (Ryling, 1960). Use in these counties has continued to increase. West Memphis (Crittenden County) was the largest user of the Wilcox aquifer in 2010 (5.04 Mgal/d) and Blytheville (Mississippi County) used 4.35 Mgal/d (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Other municipalities using the Wilcox aquifer are Marion (Crittenden County), Osceola (Mississippi County), and Paragould (Greene County). Total public-supply use of the Wilcox aquifer in Arkansas was 23.8 Mgal/d in 2010, which is about 65 percent of total use of this aquifer in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

**Table 30.** Water use from the Wilcox aquifer in Arkansas, 1965–2010.

[Units are million gallons per day; Data from Halberg and Stephens (1966); Halberg (1972, 1977); Holland (1981, 1987, 1993, 1999, 2004, 2007). Only counties with published data for consumption of groundwater from the Wilcox aquifer are shown]

| County | 1965 | 1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|
| Clark | 0.07 | 0.13 | 0.19 | 0.52 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Clay | 0.26 | 0.17 | 0.18 | 0.50 | 0.00 | 0.00 | 0.00 | 2.97 | 0.33 | 0.80 |
| Craighead | 0.38 | 0.44 | 0.62 | 0.95 | 0.47 | 1.83 | 2.42 | 0.79 | 0.81 | 0.77 |
| Crittenden | 2.25 | 3.56 | 4.77 | 9.76 | 6.8 | 5.05 | 7.85 | 5.75 | 8.09 | 7.12 |
| Cross | 0.05 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | [1]0.32 | 0.00 | 0.35 |
| Greene | 1.20 | 2.18 | 2.19 | 4.48 | 1.21 | 1.59 | 2.07 | 7.12 | 5.55 | 5.78 |
| Hempstead | 0.00 | 0.06 | 0.08 | 0.10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Hot Spring | 0.43 | 2.20 | 0.29 | 0.30 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Lafayette | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.02 |
| Lee | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 |
| Lonoke | 0.17 | 0.32 | 0.55 | 0.76 | 1.35 | 1.72 | 2.14 | 0.76 | 0.51 | 1.92 |
| Miller | 0.14 | 0.09 | 0.14 | 0.31 | 0.66 | 0.43 | 0.49 | 0.03 | 0.10 | 0.02 |
| Mississippi | 6.83 | 10.41 | 10.9 | 10.00 | 8.12 | 16.85 | 22.31 | [1]7.49 | 6.57 | 9.92 |
| Nevada | 0.08 | 0.04 | 0.07 | 0.09 | 0.00 | 0.00 | 0.00 | 0.76 | 0.18 | 0.22 |
| Poinsett | 1.37 | 1.53 | 3.04 | 5.28 | 2.14 | 3.38 | 3.70 | 0.59 | 2.85 | 3.32 |
| Prairie | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.22 | 2.17 |
| Pulaski | 0.05 | 0.59 | 0.47 | 0.30 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Saline | 0.63 | 0.14 | 0.18 | 0.28 | 0.00 | 0.00 | 0.00 | [1]1.31 | 0.93 | 2.74 |
| St. Francis | 0.15 | 0.20 | 0.16 | 0.21 | 0.00 | 0.00 | 0.00 | 0.00 | 0.33 | 0.56 |
| White | 0.12 | 0.46 | 0.50 | 2.10 | 0.00 | 0.00 | 0.00 | 1.43 | 0.54 | 0.76 |
| **Total** | **14.18** | **22.52** | **24.33** | **35.94** | **20.75** | **30.85** | **40.98** | **30.39** | **27.01** | **36.52** |

[1]Unpublished data from Terrance W. Holland, U.S. Geological Survey, written commun., 2013.

Notable changes in water use occurred as new communities began to tap the Wilcox aquifer. Water use increased in Greene County from 1965 to 1970 after the installation of two wells in Paragould (table 30). Increased use in Poinsett County from 1970 to 1980 was because of the drilling of multiple new public-supply wells. An increase of use from the aquifer of approximately 10 Mgal/d from 1990 to 1995 is attributed to use as cooling water for power generation (table 30; Pugh, 2010).

Counts (1957) suggested that the Wilcox aquifer could be developed in the future as a supplemental water source for the Mississippi River Valley alluvial aquifer in Prairie County. The Mississippi River Valley alluvial aquifer has been depleted in some areas of Prairie and Lonoke Counties over the past 70 years (Engler and others, 1945, 1963; Counts and Engler, 1954; Plebuch, 1962; Albin and others, 1967b; Ackerman, 1989a, b; Mahon and Poynter, 1993; Westerfield and Poynter, 1994; Joseph, 1999; Schrader, 2006a, 2008a, 2010). While it is difficult to determine when the Wilcox aquifer originally was tapped for irrigation, wells in the Grand Prairie have increased in the last 20 years. In Lonoke County, use of the Wilcox increased more than 1,000 percent from 1965 to 2010 (fig. 66). In 2010, 2.13 Mgal/d was withdrawn from the aquifer in Prairie County for irrigation purposes (Terrance W. Holland, written commun., 2012). Irrigation use was also prevalent in Lafayette, Lonoke, Mississippi, and Poinsett Counties. All of the irrigation wells in Poinsett County were located west of Crowleys Ridge.

Total water use from the Wilcox aquifer in southern and southwestern Arkansas is less than in northeastern Arkansas; however, the Wilcox aquifer is very important in those areas for domestic supply near its outcrop area. Many residences have wells completed in the Wilcox and depend on it for drinking water. Schools and small businesses also are reported to use water from the Wilcox aquifer in those areas (Counts and others, 1955; Onellion and Criner, 1955; Albin, 1964; Halberg and others, 1967; Plebuch and Hines, 1969; Ludwig, 1973; Terry and others, 1986). Domestic use has declined in recent years as more residents convert to public-supply use. However, small amounts are assumed to be withdrawn for domestic supply in Lafayette, Miller, and Nevada Counties. Rosston (Nevada County) is the only town in southern Arkansas using the Wilcox aquifer for public supply. The town installed a well in 1928 that pumped 0.03 Mgal/d from 1945 to 1965 and 0.06 Mgal/d in 2010 (Hale and others, 1947; Counts and other, 1955; Ludwig, 1973; Terrance W. Holland, U.S. Geological Survey, written commun., 2013).

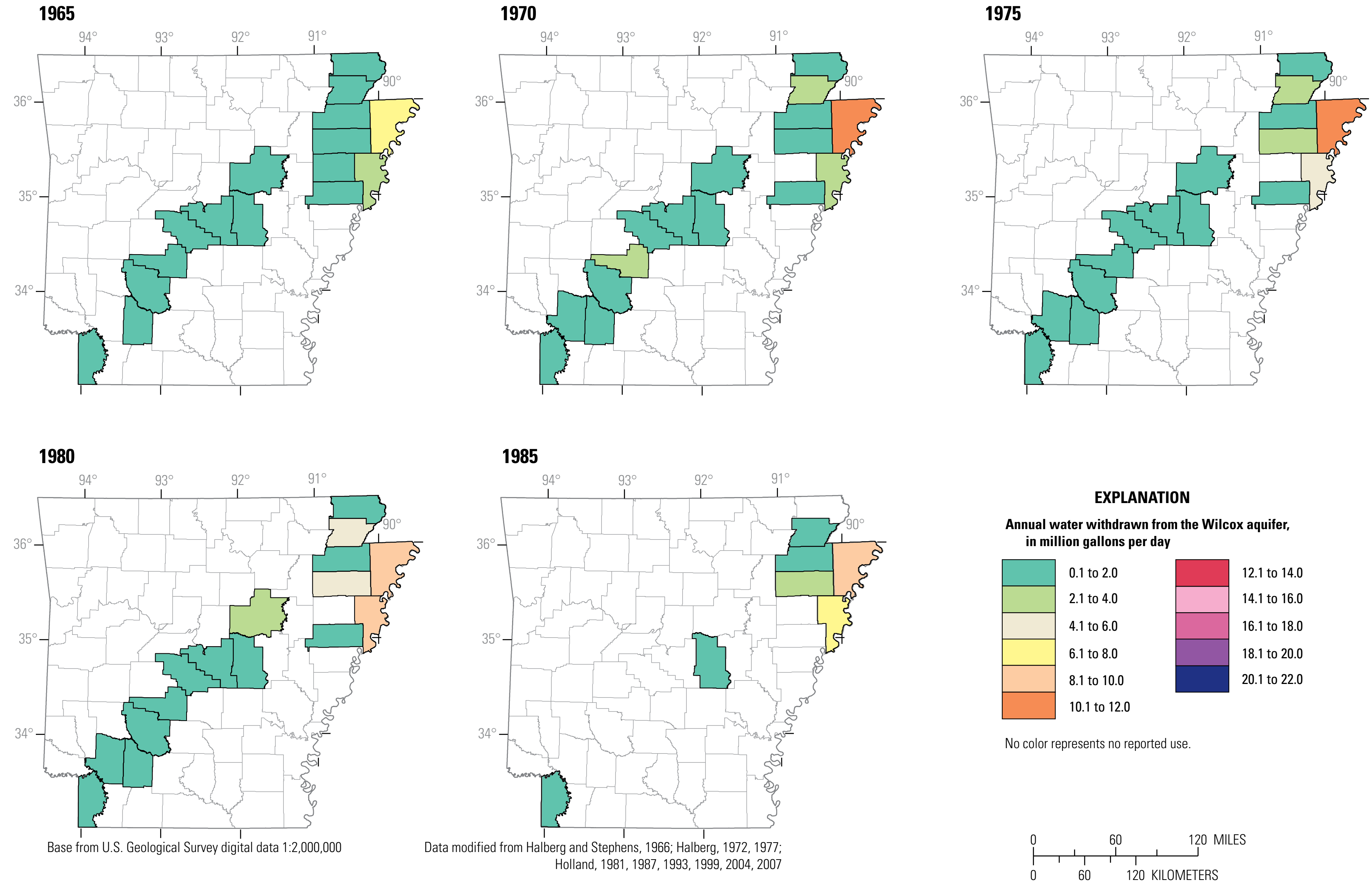



**Figure 65.** Water-use rates for the Wilcox aquifer in Arkansas from 1965 to 2010.

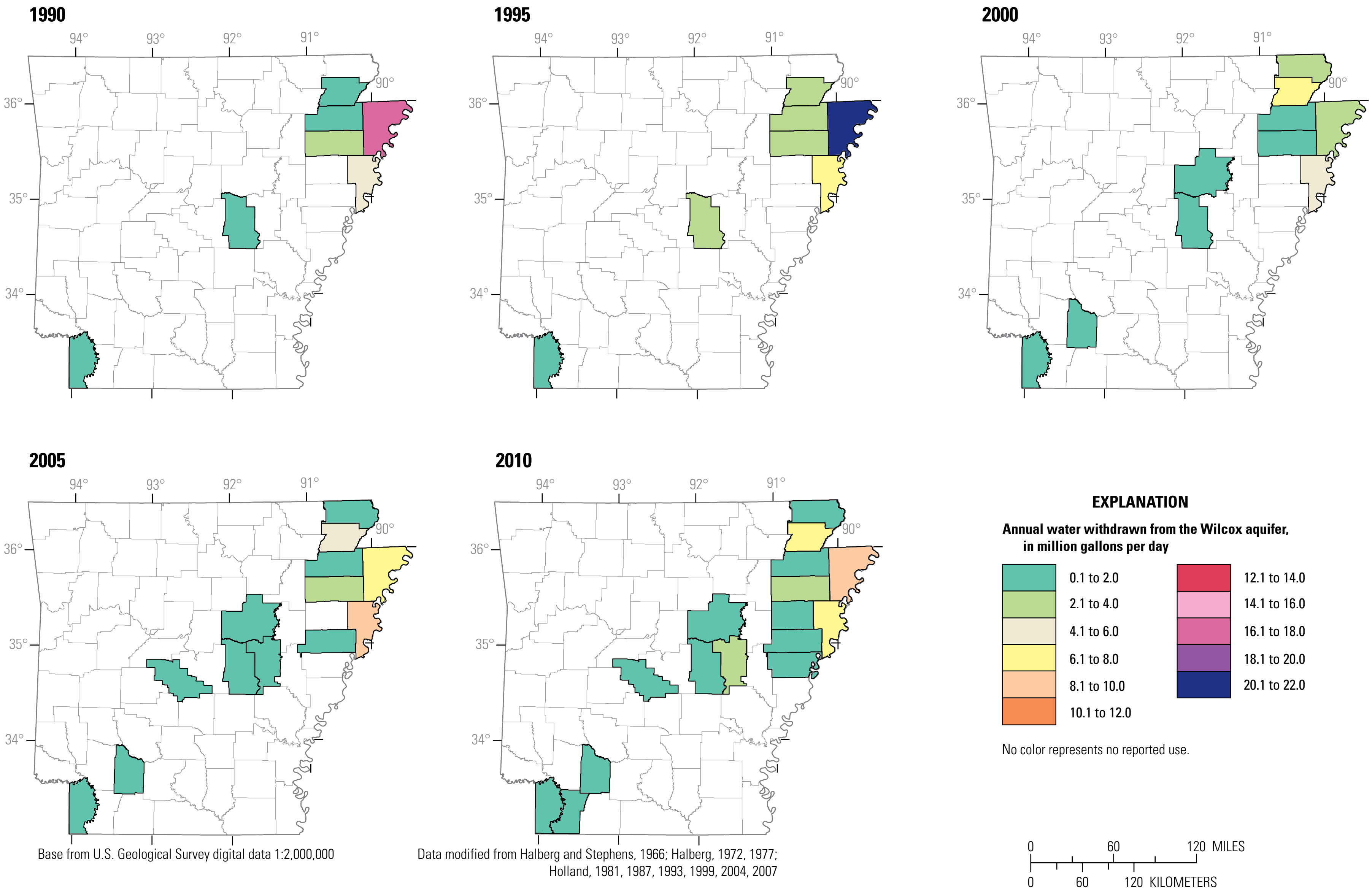



**Figure 65.** Water-use rates for the Wilcox aquifer in Arkansas from 1965 to 2010.—Continued

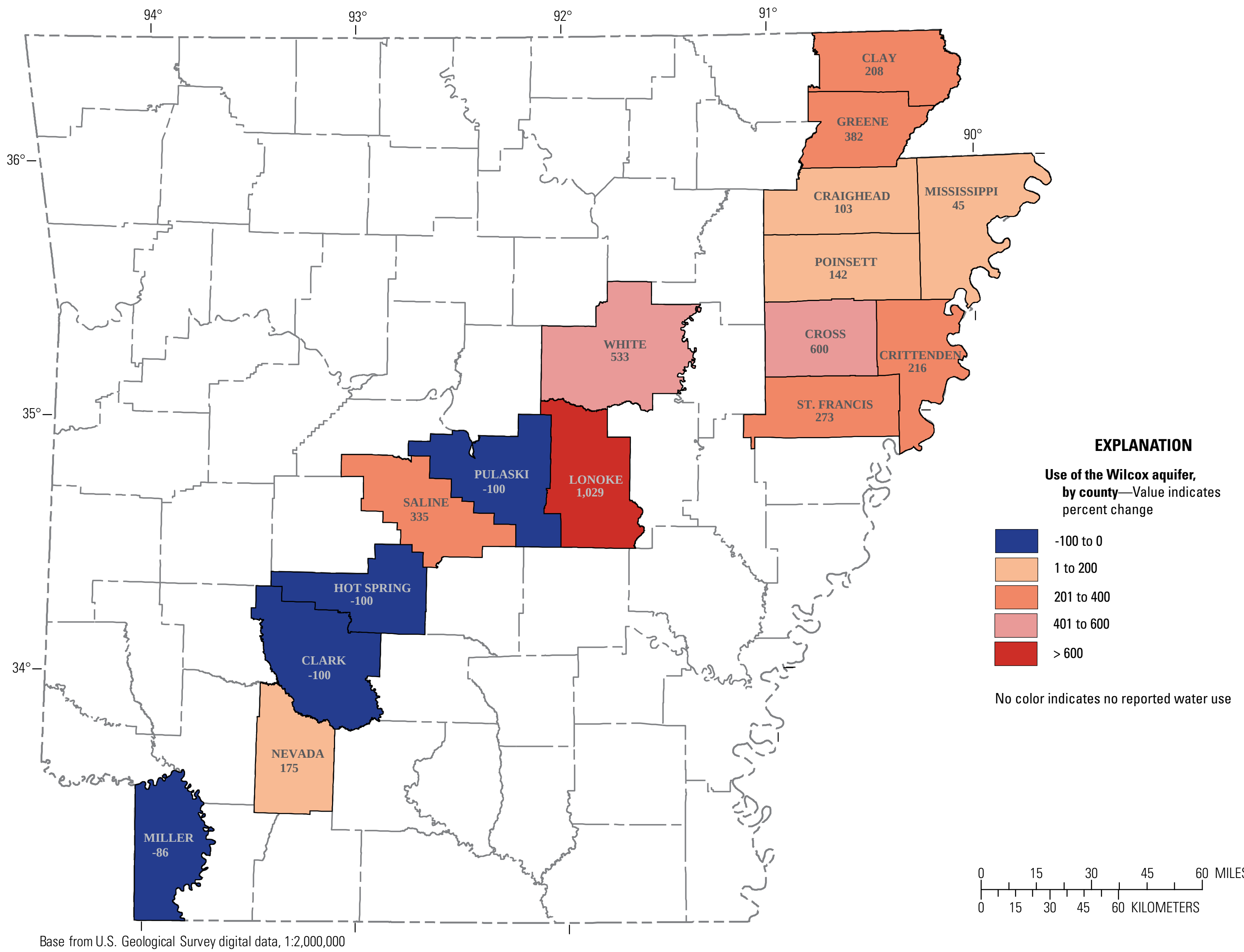



**Figure 66.** Change in percentage of water use from the Wilcox aquifer in Arkansas from 1965 to 2010.

The limited extent and poor quality of groundwater from the aquifer in some areas has prevented its use. It was too mineralized for most uses in Desha and Lincoln Counties (Bedinger and Reed, 1961). A report by Klein and others (1950) hypothesized that wells drilled to the Wilcox in Jefferson County would not yield water or was too salty. Domestic use was present in Chicot County, but its high mineral and iron concentration precluded its use for other purposes (Onellion and Criner, 1955). Wells in parts of Cross, Poinsett, Prairie, and Woodruff Counties were reported to contain high dissolved solids (Broom and Lyford, 1981). A small part of the Wilcox underlies eastern Jackson County but is not very thick in that area (less than 25 ft) and has not been considered a water source, although it may have good quality water (Albin and others, 1967a).

## Water Levels

Water-level declines in the Wilcox aquifer have been associated with the development and growth of large pumping centers (Westerfield, 1994; Joseph, 1998b; Schrader and Joseph, 2000; Yeatts, 2004; Schrader, 2007a; Pugh, 2010). In northeastern Arkansas (fig. 67), water-level declines and coalescing cones of depression were recorded at major pumping centers near Paragould (Greene County) and West Memphis (Crittenden County) (Joseph, 1998b; Schrader and Joseph, 2000; Yeatts, 2004). Flowing-artesian wells in Crittenden County were common around the late 1920s and early 1930s. By the late 1950s, these wells ceased to flow, and water levels had fallen to a maximum of 22 ft below the land surface (Plebuch, 1961). Water levels in West Memphis declined 30 ft from 1929 to 1951 (Plebuch, 1961). Near West Memphis, well A (fig. 68) had a water-level decline of approximately 25 ft from 1983 to 2012 (location of wells shown in fig. 67). Declines at Paragould were approximately 26 ft from 1967 to 2012 (well B, figs. 67 and 68).

The 1991 and 1996–97 potentiometric surfaces of the Wilcox aquifer showed minimum levels at the 180–200 ft altitude near Paragould and at the 150–170 ft altitude near West Memphis (Westerfield, 1994; Joseph, 1998b). In 2000, minimum levels in the depression near Paragould had shifted slightly to the southwest along Crowleys Ridge, and the minimum levels at West Memphis had dropped some 30 ft to an altitude of 130 ft (Schrader and Joseph, 2000). A 2006 study showed the contours under West Memphis had declined another 10 ft to an altitude of 120 ft (Schrader, 2007a). A 2009 study showed contours south of Paragould declined some 20 ft to an altitude of 170 ft (fig. 67). Pumping near Blytheville (Mississippi County) does not appear to have made as large an impact on the potentiometric surfaces; however, large water-level declines previously have been documented elsewhere in Mississippi County. Stephenson and Crider (1916) measured three wells in Mississippi County in 1912. These wells were revisited in 1958 by Ryling (1960) with reported declines of 25–30 ft over the period of measurement. Water levels in the Mississippi County well (well C, fig. 68) dropped 21 ft from 1968 to 2010.

Cones of depression were noted in the 2006 potentiometric surface in Nevada County near Rosston and in southeastern Clark County (Schrader, 2007a). The cone in Nevada County is centered near a single well. From 2003 to 2009, water levels in this well dropped 17.7 ft, which was the largest decline documented in the southern extent of the aquifer (Pugh, 2010). Previous work in the 1970s had reported the lowest water levels in the southern part of the State near the Rosston public supply well (Ludwig, 1973). The lowest water levels of the aquifer were recorded in 2009 at the depression in southeastern Clark County (fig. 67; Pugh, 2010).

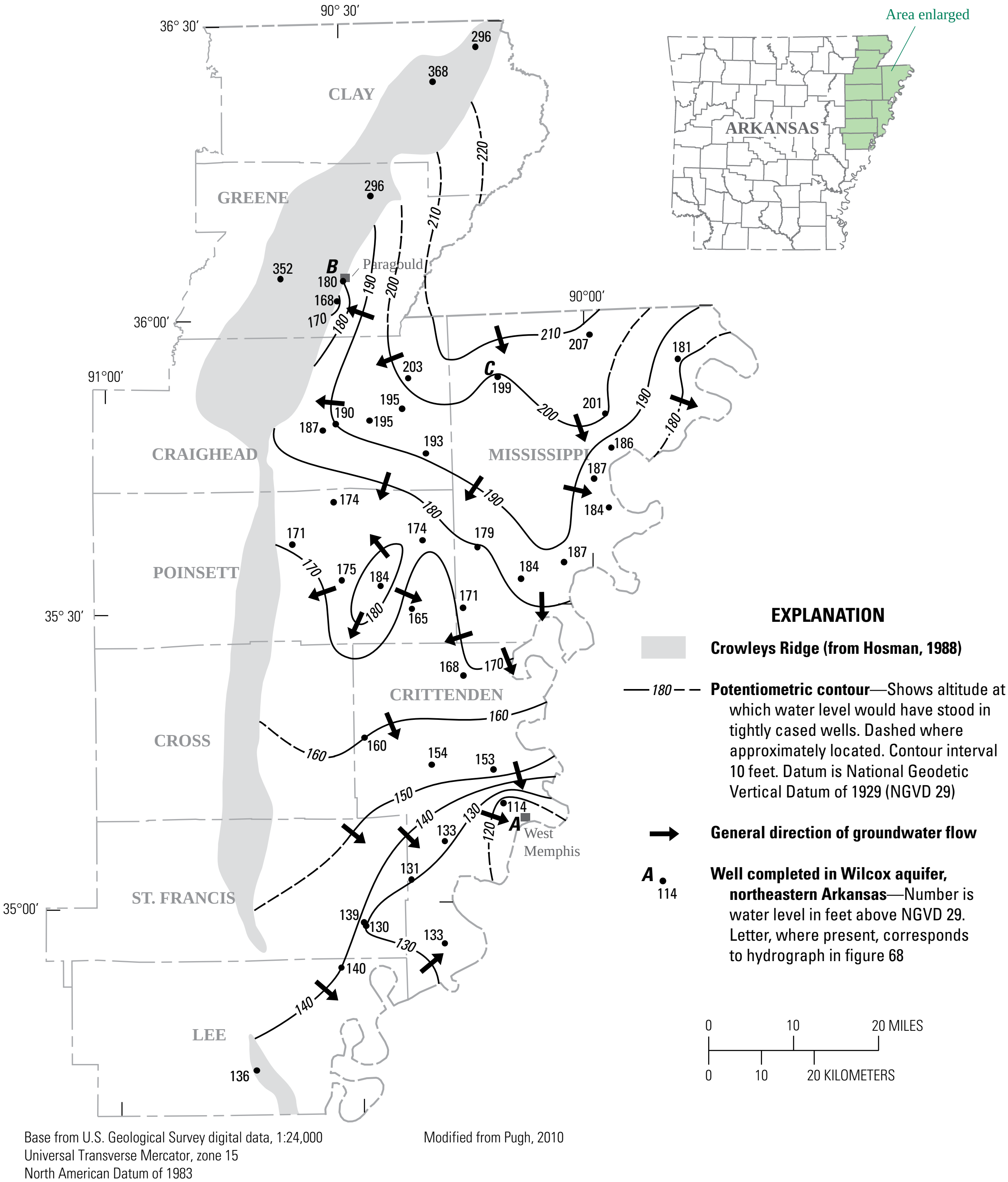



**Figure 67.** Potentiometric surface of the Wilcox aquifer in Arkansas, 2009.

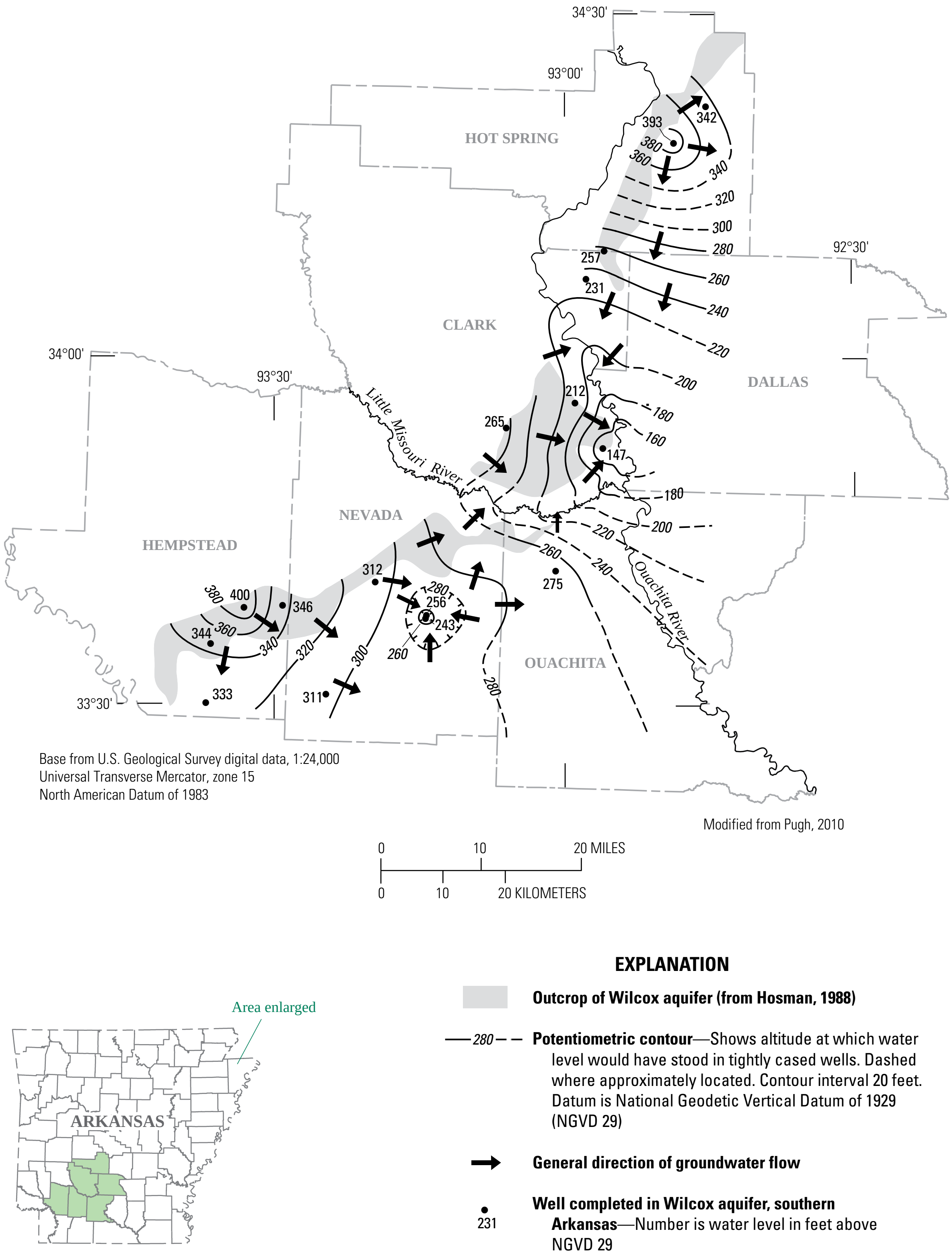



**Figure 67.** Potentiometric surface of the Wilcox aquifer in Arkansas, 2009.—Continued

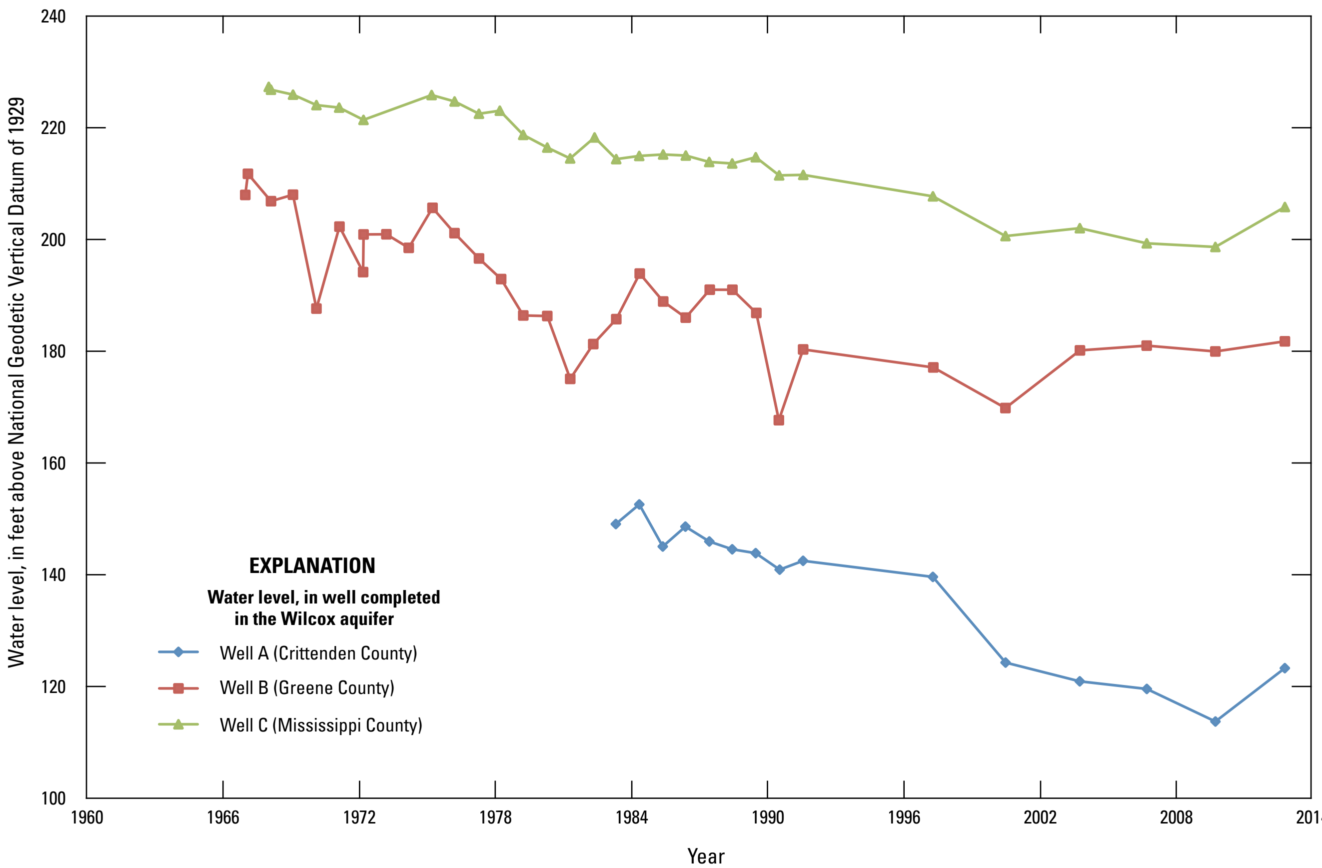



**Figure 68.** Hydrographs of water levels in wells completed in the Wilcox aquifer in Arkansas.

## Water Quality

The distinctive lithologic characteristics of the sand-rich lower Wilcox unit and the clay-rich upper Wilcox unit, coupled with the relative thickness of the two units across Arkansas, exercise a strong control on yields and water quality. Because of these stratigraphic differences, a distinct trend exists in the water quality from the northeast to the west. Producing wells in Miller County in southwestern Arkansas to approximately Lonoke County in central Arkansas are completed almost solely in the outcrop area; however, in the extreme northeastern part of the State and east of Crowleys Ridge, numerous wells have been completed in a broad area downgradient from the outcrop and subcrop areas. Water-quality differences are related to the facies change for the Wilcox Group, which are discussed in further detail below.

For most of the western extent of the aquifer, the Wilcox aquifer is a viable groundwater supply only in the outcrop area. The water becomes brackish or saline within a short distance downdip from the outcrop and is unfit for most purposes (Plebuch and Hines, 1969; Ludwig, 1973; Terry and others, 1986). Plebuch and Hines (1969) describe groundwater from the Wilcox in Clark, Cleveland, and Dallas Counties as a sodium-bicarbonate type, with water increasing in dissolved-solids concentrations and becoming a sodium-chloride type downdip. Broom and others (1984) noted that the Wilcox and Carrizo aquifers are indistinguishable in Union County, are hydraulically connected, and used solely for injection of brine. Hewitt and others (1949) noted abundant saltwater at depths of 1,000 ft in Ashley County. Onellion and Criner (1955) additionally noted that groundwater was too salty for any use based on electric logs from wells in Chicot County. Ludwig (1972) described groundwater from the Wilcox as a soft to moderately hard, sodium-bicarbonate type for most of Hempstead, Lafayette, Miller, and Nevada Counties. The southern extent of freshwater coincided with a fault system extending through central Lafayette, Miller, and Nevada Counties. Groundwater south of the fault zone contained more than 1,000 mg/L dissolved solids based on electric logs (Ludwig, 1973). Halberg and others (1968) reported that groundwater from the Wilcox in Hot Spring and Grant Counties was a soft, sodium-bicarbonate type. They also stated that iron concentrations could be high and that groundwater from shallow wells was slightly acidic. Hosman and others (1968) noted that water type varied with dissolved-solids concentrations as follows: (1) when dissolved-solids concentrations were low, water was a calcium-magnesium-bicarbonate or a sodium-bicarbonate type; (2) increases in dissolved solids up to 400 mg/L were attributed to predominantly sodium and bicarbonate; and (3) increases in dissolved solids greater 400 mg/L were attributed to increases in sodium, bicarbonate, and chloride.

In the northeastern part of the State, east of Crowleys Ridge, the Wilcox is a much more regionally important aquifer and was cited as the second most important aquifer in Mississippi County (Ryling, 1960). Counts (1957) stated that the Wilcox was "… the most important mineral resource in parts of Lonoke, Prairie, and White Counties." Groundwater in the Wilcox was reported as a very soft, sodium-bicarbonate type with generally low mineralization (Ryling, 1960; Plebuch, 1961; Halberg and Reed, 1964; Broom and Lyford, 1981). Broom and Lyford (1981) reported dissolved-solids concentrations from 100 to 150 mg/L in the area east of Crowleys Ridge. To the west of the ridge in parts of Cross, Poinsett, Prairie, and Woodruff Counties, the report listed dissolved solids in excess of 1,000 mg/L. Ryling (1960) cited much of the groundwater from the Wilcox in Mississippi County as being under flowing artesian conditions at rates of 300 gal/min. Broom and Lyford (1981) reported yields exceeding 2,000 gal/min. The high yields and good water quality associated with the Wilcox reveal the importance of this water resource for eastern Arkansas.

### General Geochemistry and Water Type

Much of the following discussion is focused on differences in groundwater geochemistry between the two areas described above: (1) the main outcrop area for the Wilcox Group, generally extending from Miller County in extreme southwestern Arkansas through Lonoke County in central Arkansas, hereinafter referred to as the "western extent" and (2) an area east of Crowleys Ridge in northeastern Arkansas, hereinafter referred to as the "eastern extent." Increases of pH along a given flow path often reflect the degree of carbonate dissolution by infiltrating low-pH and poorly buffered precipitation. Thus, pH can be used to assist in tracking flow paths for carbonate-dominated groundwater that is typical of most aquifers of the Coastal Plain in Arkansas (see sections on Sparta and Cockfield aquifers). Because of the absence of wells downgradient from the Wilcox outcrop area, no well-defined pH trends are evident in the western extent (fig. 69). Values of pH less than 6.0 dominantly occurred in the outcrop area in central Arkansas, with the higher values, greater than 8.0, occurring in and near the subcrop areas. Only 37 of 137 sites had pH values less than 7.0, and most of these were in the western extent of the aquifer. In the eastern extent of the aquifer, no samples exhibited pH values less than 6.0 with the majority having pH values greater than 7.5. Because the aquifer is confined at all of the sites in the eastern extent, sufficient buffering has occurred for recharging water within the overlying units prior to entering the aquifer.

The exchange of calcium for sodium occurs on solid-phase exchange sites as groundwater travels through the unsaturated and saturated zones. This results in an overall increase in sodium at the expense of calcium in solution. When sodium is greater than 50 percent of the major cations (calcium, magnesium, potassium, and sodium), the resultant groundwater is deemed sodium-dominated with respect to cations. For most aquifers, calcium is derived from dissolution of carbonates and is the dominant major cation in the early stages of geochemical evolution; therefore, calcium-bicarbonate is the dominant water type in this less geochemically evolved groundwater. Groundwater generally transitions to a sodium-bicarbonate water type further along the flow path, as calcium exchanges for sodium on clay exchange sites. Groundwater from the Wilcox generally does not show a well-defined trend in its western extent, although most of the calcium-dominated groundwater occurs in the outcrop areas from Nevada to White Counties. In the eastern extent of the aquifer, practically all of the sites exhibit a strongly sodium-bicarbonate water type. Nearly half of the sites have sodium constituting greater than 90 percent of the total cations, which reflects a more geochemically evolved groundwater at greater distances from the subcrop area (fig. 69).

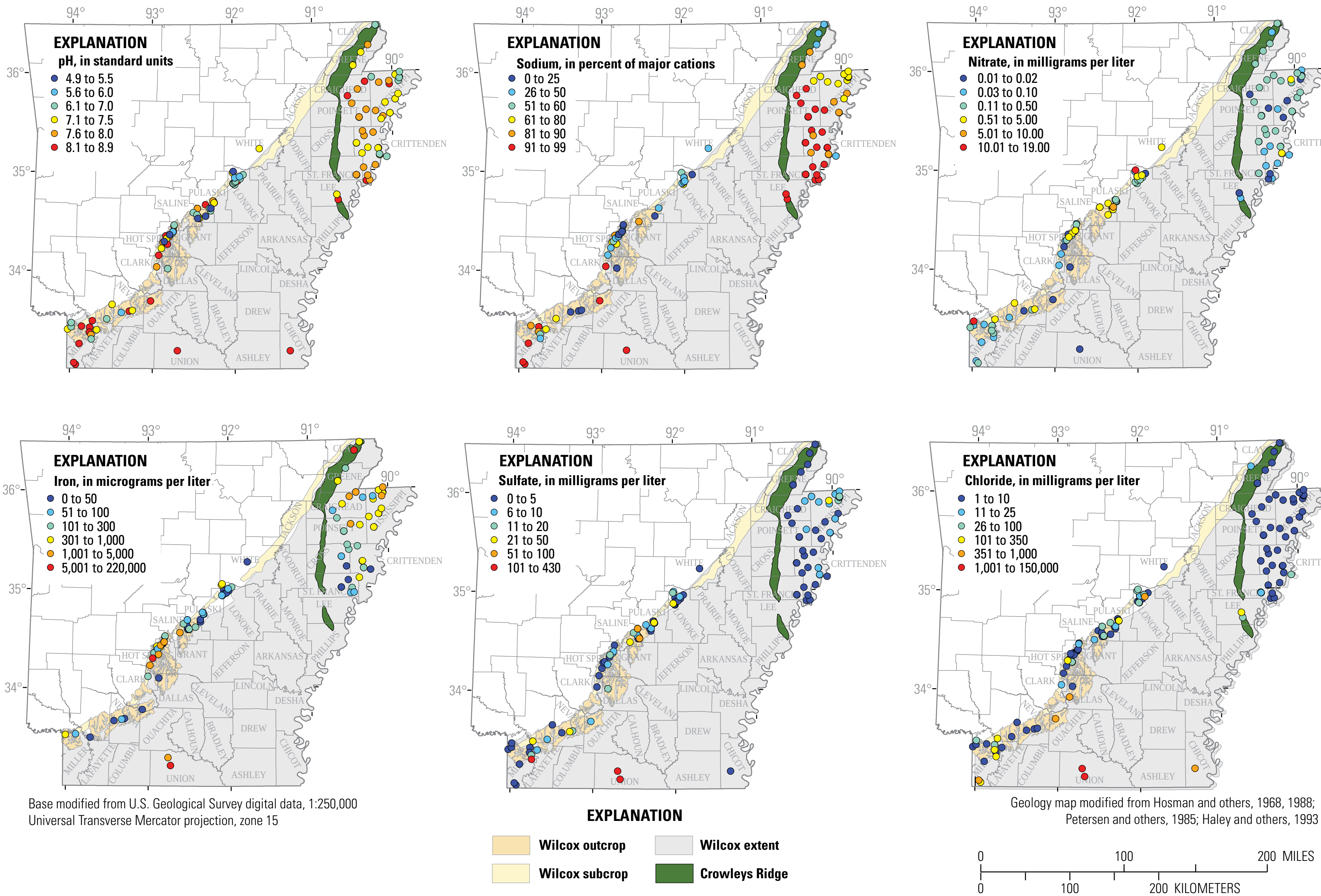



**Figure 69.** Spatial distribution of selected chemical constituents in groundwater from the Wilcox aquifer in Arkansas.

## Nitrate

Similar to most of the Tertiary aquifers of eastern Arkansas, higher nitrate concentrations generally occurred only in the outcrop and subcrop areas for the Wilcox aquifer. The median nitrate concentration was 0.11 mg/L (table 31), and only two wells had nitrate concentrations greater than the Federal MCL of 10 mg/L. All but two wells in the eastern extent of the aquifer had nitrate concentrations less than 0.5 mg/L; most had concentrations less than 0.1 mg/L (fig. 69). The most vulnerable areas to contamination are those where the aquifer is exposed in the outcrop or shallow subcrop areas. A comparison of well depth to nitrate concentrations revealed that all nitrate concentrations greater than 2.0 mg/L occurred in wells less than approximately 120 ft deep (fig. 70). Simple dilution or denitrification processes possibly serve as the primary controls on the occurrence of appreciable nitrate downgradient from outcrop and subcrop areas. In addition, low velocities add a temporal element to the transport of nitrate.

**Table 31.** Descriptive statistics for selected chemical constituents in groundwater from the Wilcox aquifer in Arkansas.

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

| Constituent or characteristic | Minimum | Median | Maximum | Standard deviation | Number of wells |
|---|---|---|---|---|---|
| Calcium (mg/L) | 0.3 | 4.4 | 24,000 | 2,260 | 112 |
| Magnesium (mg/L) | 0.01 | 1.2 | 2,600 | 244 | 112 |
| Sodium (mg/L) | 0.5 | 37.8 | 73,000 | 6,930 | 110 |
| Potassium (mg/L) | 0.1 | 2.1 | 840 | 81.8 | 104 |
| Bicarbonate (mg/L) | 2.0 | 110 | 512 | 101 | 134 |
| Chloride (mg/L) | 0.8 | 4.8 | 150,000 | 12,600 | 140 |
| Sulfate (mg/L) | 0.02 | 3.4 | 430 | 52.7 | 136 |
| Silica (mg/L) | 4.6 | 11 | 66 | 11 | 90 |
| Nitrate (mg/L as nitrogen) | 0.01 | 0.11 | 19 | 2.33 | 122 |
| Dissolved solids (mg/L) | 14 | 128 | 253,000 | 23,700 | 113 |
| Iron (µg/L) | 0.05 | 130 | 220,000 | 20,800 | 111 |
| Manganese (µg/L) | 0.13 | 10 | 1,800 | 287 | 38 |
| Arsenic (µg/L) | 0.03 | 0.52 | 1.0 | 0.48 | 6 |
| Hardness (mg/L as calcium carbonate) | 1.0 | 21 | 71,000 | 6,060 | 136 |
| Specific conductance (µS/cm) | 16 | 205 | 13,500 | 1,200 | 146 |
| pH (standard units) | 4.9 | 7.5 | 8.9 | 0.8 | 137 |

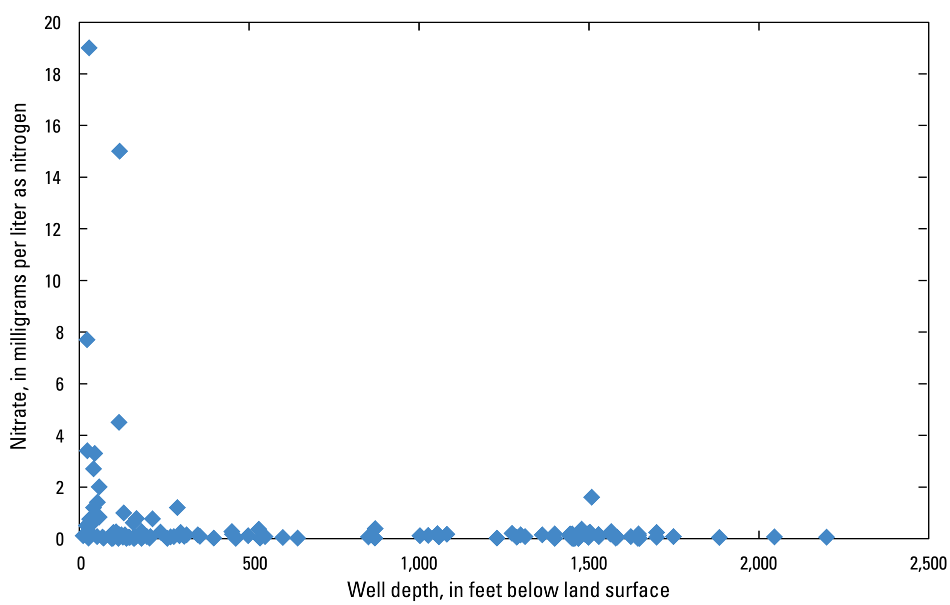



**Figure 70.** Relation of well depth and nitrate in groundwater from the Wilcox aquifer in Arkansas.

## Iron

No well-defined patterns or spatial trends were revealed for iron concentrations in the Wilcox aquifer. Iron concentrations ranged from 0.05 to 220,000 µg/L with a median of 130 µg/L (fig. 71; table 31), which is below the Federal secondary drinking-water regulation of 300 µg/L. A trend of lower iron concentrations along flow paths was noted for other Tertiary-age aquifers in eastern Arkansas. This trend was particularly noticeable for the Sparta and Cockfield aquifers, which had elevated concentrations of iron almost solely in or near the outcrop areas with lower concentrations downdip from outcrop areas. This trend was attributed to iron-reducing conditions in the outcrop areas and subsequent precipitation of iron minerals with changing redox conditions in the downgradient direction of flow. The Wilcox is an exception to this general trend, as noted by the relatively high concentrations of iron throughout the eastern extent of the aquifer downgradient from the subcrop area. The highest iron concentration occurred in a site in southern Arkansas that also exhibited the highest chloride, sulfate, and other constituent concentrations (fig. 69). This study did not focus on dissolved oxygen (or other gases), dissolved organic matter, ammonia, or other redox-sensitive constituents besides sulfate and iron. Thus, no definitive statements can be made with respect to the distribution of iron concentrations in the Wilcox in regard to redox zonation. Iron concentrations exceeding the Federal secondary drinking-water regulation (300 µg/L) are found predominantly in eastern Clay, Craighead, and Poinsett Counties, and throughout most of Mississippi County. In the western extent, elevated concentrations are found dominantly in Hot Spring, Saline, and Lonoke Counties.

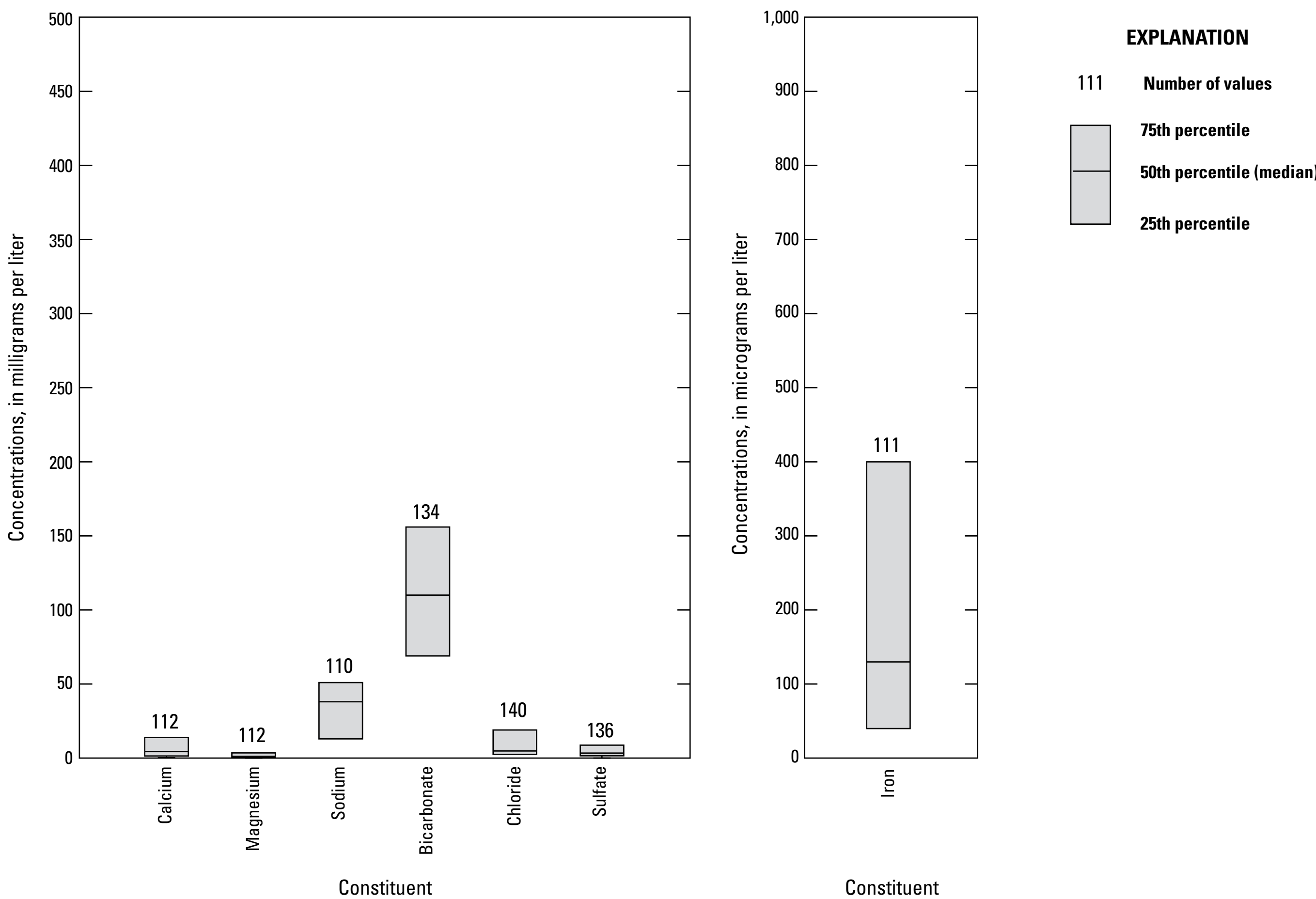



**Figure 71.** Interquartile range of selected chemical constituents in groundwater from the Wilcox aquifer in Arkansas.

### Sulfate

Sulfate concentrations generally are low throughout the Wilcox aquifer, except for downgradient from the outcrop areas in the western extent (fig. 69). Sulfate concentrations ranged from 0.02 to 430 mg/L with a median of 3.4 mg/L (fig. 71; table 31). Only three wells had sulfate concentrations exceeding 100 mg/L; two were in Union County at a great distance downgradient from the outcrop area, and one was in eastern Miller County. In the eastern extent of the aquifer, nearly all of the wells had concentrations less than 5 mg/L. The only exception was for the northeastern part of Mississippi County, where concentrations exceeded 10 mg/L (upward to 25 mg/L).

### Chloride and Dissolved Solids

Chloride concentrations for the Wilcox aquifer generally are extremely low, except for areas downgradient from the outcrop and subcrop areas in the western extent. Groundwater in these areas becomes saline and is unfit for most uses (Plebuch and Hines, 1969; Ludwig, 1972; Terry and others, 1986). The low chloride concentrations are reflected in the median concentration of 4.8 mg/L (fig. 71; table 31), the lowest median for chloride of any aquifer reviewed in this study. Chloride concentrations in the eastern extent of the aquifer generally were below 5.0 mg/L. The highest concentrations (upward to 150,000 mg/L) occurred at great distances from the outcrop and subcrop areas in the western extent of the aquifer in Union County (fig. 69). These water samples were taken from oil exploration wells and were not meant to be used as freshwater sources. In the eastern extent of the aquifer, only one well exhibited a slightly elevated chloride concentration of 170 mg/L. This well was located in Lee County in an area that was identified in earlier reports as an elongated zone of high salinity for several aquifers extending from Lee, Monroe, and Prairie Counties (Counts, 1957; Halberg and Reed, 1964; Hosman and others, 1968; Morris and Bush, 1986). For more information on this high-salinity zone see the sections on the Sparta and Mississippi River Valley alluvial aquifers.

Spatial patterns for dissolved solids in the Wilcox aquifer tend to follow that of chloride concentrations, as high-salinity groundwater had chloride as the dominant anion. The median concentration for dissolved solids was 128 mg/L, and only nine sites had concentrations greater than the secondary drinking-water regulation of 500 mg/L (U.S. Environmental Protection Agency, 2009). These data demonstrate the overall good quality of groundwater from the Wilcox. Hosman and others (1968) noted that groundwater transitions from a sodium-bicarbonate to a sodium-chloride type water for dissolved-solids concentrations greater than 400 mg/L throughout the Mississippi embayment. Data compiled for Arkansas in this report showed a slightly different evolution of water types in the Wilcox. Calcium-bicarbonate was the dominant water type for dissolved-solids concentrations up to approximately 100 mg/L, and calcium was the dominant cation in all but one sample within this range. For dissolved-solids concentrations greater than approximately 100 mg/L, 67 of 80 samples (84 percent) had sodium exceeding 50 percent of the total cations. Groundwater dominantly was represented by sodium-bicarbonate, with calcium-bicarbonate as the secondary water type. Sodium-chloride water type generally occurred only for dissolved-solids concentrations more than approximately 800 mg/L. Six of seven samples with dissolved-solids concentrations greater than approximately 800 mg/L (upward to 253,000 mg/L) had chloride concentrations greater than 50 percent of the total anions (up to 98 percent).

In summary, groundwater from the Wilcox aquifer is of very good quality, with the exception of high salinity and elevated dissolved solids downgradient from the outcrop and subcrop areas for most of the western extent of the aquifer. Numerous groundwater samples had iron concentrations that exceeded the secondary drinking-water regulation of 300 μg/L. Generally, the overall best water quality is located in the eastern extent of the aquifer in northeastern Arkansas. Groundwater generally evolves from a calcium-bicarbonate to a sodium-bicarbonate water type at dissolved-solids concentrations greater than 100 mg/L. For dissolved-solids concentrations greater than 800 mg/L, groundwater is represented by a sodium-chloride water type.

## Nacatoch Aquifer

Cretaceous formations in Arkansas (Nacatoch Sand, Ozan Formation, Tokio Formation, and the Trinity Group) and the aquifers comprised by these formations are not included in any of the regional hydrogeologic framework models of the Mississippi embayment (Arthur and Taylor, 1990; Hart and others, 2008; Clark and Hart, 2009). The Midway Group, a thick clay sequence serving as a lower confining layer for the Wilcox aquifer, is the oldest hydrogeologic unit included in the aquifers of the Mississippi embayment aquifer system. The Nacatoch aquifer was included as the McNairy-Nacatoch aquifer in the Gulf Coast RASA study by Hosman and Weiss (1991) and the Groundwater Atlas of the United States for segment 5 (Arkansas, Louisiana, and Mississippi) of Renken (1998). Because the McNairy Sand does not occur in Arkansas, the saturated part of the Nacatoch Sand often is referred to, and listed in various USGS reports, as simply the Nacatoch aquifer (Holland, 2007; Schrader and Blackstock, 2010). This will be the nomenclature used within this report.

### Geology

The Nacatoch Sand of southwestern Arkansas is a Cretaceous-age formation of interbedded lithologies, predominated by generally unconsolidated sands with local lenses and beds of fossiliferous sandy limestone (Counts and others, 1955; Plebuch and Hines, 1969). The Nacatoch Sand is named after its type exposure at Nacatoch Bluff on the east bank of the Little Missouri River in Clark County, Ark., where about 50 ft of the upper Nacatoch Formation are exposed. Veatch (1906) defined the Nacatoch as the beds lying between the Marlbrook Marl and the Arkadelphia Marl, including the Saratoga Chalk. Stephenson (1927) and Dane (1929) separated the Saratoga Chalk from the Nacatoch and established the essentials of the definition of the formation that are used today.

Considerable sea transgressions and regressions occurred after the lower Cretaceous. While the lower Cretaceous deposition in Arkansas occurred mainly in nearshore environments, transgression resulted in finer-grained, carboniferous marls and chalks being deposited during the upper Cretaceous (Veatch, 1906). The contact of the Nacatoch Sand with the underlying Saratoga Chalk is sharp and slightly irregular, indicating an unconformity. The sediments of both formations suggest that they were deposited in a shallow nearshore environment. Dane (1929) noted that the lithologic variability and sedimentary structure within the Nacatoch represent changing conditions characteristic of a nearshore, shallow-water environment. The variation in sand content represents input switching among multiple sediment sources.

The Nacatoch Sand includes three distinct lithologic units: a lower unit comprising interbedded clays, marls, and sands; a middle unit comprising fossiliferous, glauconitic sand; and an upper principal water-bearing unit. The upper unit consists of unconsolidated, crossbedded, gray, fine-grained quartz sand. In southwestern Arkansas, the Nacatoch unconformably overlies the Saratoga Chalk, Marlbrook Marl, or Ozan Formation. The Nacatoch Sand is overlain unconformably by the Arkadelphia Marl where the Nacatoch Sand serves as an aquifer in southwestern Arkansas. Formation thickness ranges from 150 to nearly 600 ft (Boswell and others, 1965; Zachry and others 1986). The Nacatoch generally has a higher sand percentage to the west and north, with the exception of an anomalously high sand content along the eastern border of Union County (Dollof and others, 1967).

The Nacatoch Sand crops out in southwestern Arkansas along a belt 3–8 mi wide that extends southwest from central Clark County to the west of Hempstead County. In Little River County, the Nacatoch is covered by Quaternary alluvial and terrace deposits (Counts and others, 1955). In southwestern Arkansas, the Nacatoch dips south and southeast at a rate of about 30 ft/mi (Veatch, 1906; Boswell and others, 1965; Ludwig, 1972). Spooner (1935) noted structural control on Nacatoch lithology with sand being abundant over structurally high areas and grading rapidly to finer sediment on the flanks. The Nacatoch is faulted downdip in Bradley, Calhoun, Hempstead, Little River, Lafayette, Miller, Nevada, and Ouachita Counties (Petersen and others, 1985). The lower sand unit in the Nacatoch Sand is a petroleum producing formation in the Smackover Field of southern Arkansas (Weeks, 1938).

The Nacatoch Sand is present in the subsurface across most of northeastern Arkansas; formation thickness ranges up to 380 ft (Caplan, 1954). In northeastern Arkansas, the formation is composed of glauconitic sands interbedded with gray laminated clays. Localized calcareous and fossiliferous layers occur in the formation. In much of northeastern Arkansas, the formation rests unconformably on Paleozoic rocks and is overlain by Quaternary alluvium. In Lonoke, Pulaski, and White Counties, the Nacatoch rests unconformably on Paleozoic rocks and is overlain by Eocene strata, primarily of the Midway Group. The Nacatoch strikes to the northeast roughly parallel to the trend of the Paleozoic rocks and the Fall Line and dips to the southeast (Stephenson and Crider, 1916; Petersen and others, 1985). Near southwestern Lawrence County, the Nacatoch dips at about 40 ft/mi to the southeast. In this area, sand content increases downdip and makes up 40–60 percent of the formation in extreme southeastern Randolph and eastern Lawrence Counties (Lamonds and others, 1969).

## Hydrologic Characteristics

Hydraulic test data for the Nacatoch aquifer are sparse. Aquifer tests in Clark and Hempstead Counties yielded transmissivities of 161 $ft^2/d$ and about 480 $ft^2/d$, respectively. Aquifer tests on wells at Hope, in Hempstead County, and Prescott, in Nevada County, resulted in transmissivities of about 480 $ft^2/d$ (Ludwig, 1973).

Most wells completed in the Nacatoch aquifer are relatively low yielding. Throughout southwestern Arkansas, well yields were reported from 1 to more than 300 gal/min (Counts and others, 1955). Flowing artesian wells in the lower stream valleys of Nevada County yield less than 5 gal/min, whereas many wells in southwestern Arkansas reported yields as high as 300 gal/min (Boswell and others, 1965). Wells in Hempstead and Nevada Counties can be expected to yield from 150 to 300 gal/min (Counts and others, 1955; Ludwig, 1973). Wells yielding 200 to 500 gal/min can be expected in Jackson County; however, electric logs indicate that the water is saline (Albin and others, 1967a). Flowing artesian wells indicate the Nacatoch is under confined conditions away from the outcrop area. Renfroe (1949) defined the Nacatoch aquifer as an artesian aquifer in areas of northeastern Arkansas. In parts of eastern Arkansas, the Nacatoch Sand, downdip from the Fall Line, is porous but does not contain water; however, gas is found in these areas.

In southwestern Arkansas, the Nacatoch aquifer receives direct recharge from precipitation in its outcrop area, and in northeastern Arkansas, the aquifer receives recharge through the alluvium and terrace deposits where it subcrops. (Stephenson and Crider, 1916; Boswell and others, 1965; Petersen and others, 1985). In southwestern Arkansas, the regional direction of groundwater flow is to the southeast (Schrader and Blackstock, 2010; Schrader and Rodgers, 2013). Flow directions may be locally controlled by clay content and faulting (Boswell and others, 1964). Groundwater flow rates and direction have been altered by pumping at Hope (Hempstead County), where water levels in the aquifer declined 40 ft from 1942 to 1969 (Ludwig, 1973), and a cone of depression developed in the potentiometric surface. In northeastern Arkansas, groundwater moved southeast in the direction of the aquifer dip (Stephenson and Crider, 1916; Petersen and others, 1985; Schrader and Blackstock, 2010; Schrader and Rodgers, 2013).

## Water Use

Use of the Nacatoch aquifer has been restricted to areas near its outcrop and subcrop areas in southwestern and northeastern Arkansas, respectively. The water is considered too saline for use in other areas, such as Craighead, Jackson, Monroe, and Poinsett Counties (Albin and others, 1967a; Hines and others, 1972; Broom and Lyford, 1981). Few early wells were completed in the Nacatoch in east-central Arkansas (Stephenson and Crider, 1916). Water-use reports since 1965 show use only in Clay, Greene, and Lawrence Counties in northeastern Arkansas (fig. 72). Primary use of the aquifer has been for public and industrial supply. Domestic wells also tap the aquifer in eastern Lawrence and southeastern Randolph Counties (Lamonds, 1969). Countywide domestic use is attributed to the primary aquifer present in the county, therefore domestic use for Randolph County would not be attributed the Nacatoch aquifer and is not presented in table 32. Poor water-quality downdip from the outcrop area has restricted the aquifer's use in parts of southwestern Arkansas (Terry and others, 1986).

Veatch (1906) reported that the Nacatoch aquifer had been extensively developed in southwestern Arkansas and stated "over a thousand wells" had been developed between Arkadelphia (Clark County) and Texarkana (Miller County), which was most likely an overestimation because later work recorded just over 400 wells completed in the aquifer (Boswell and others, 1965). Many wells that were flowing artesian wells had been abandoned and allowed to flow because of the lack of concern for conserving this resource (Veatch, 1906). Other flowing artesian wells were present in the Nacatoch in southern Clark County (Boswell and others, 1965; Plebuch and Hines, 1969), but yields and water levels in the aquifer were declining as a consequence of unrestricted artesian flows.

Water use from the Nacatoch aquifer has varied over the years. Boswell and others (1965) reported 1.2 Mgal/d were produced prior to 1965, primarily by municipalities and industries in southwestern Arkansas. Use of groundwater from the aquifer increased 174 percent from 1965 to 1980 (table 32), the peak year for use of water from the Nacatoch aquifer. Use decreased from 1980 to 1995, jumped to a second high in 2000, and again decreased after 2000. Water use from the aquifer in 2010 was approximately 66 percent public supply, 4 percent for industrial supply, 10 percent for electric supply, and the remainder for mining, domestic, and livestock uses (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). As of 2010, 33 wells completed in the Nacatoch were registered in ARWUDBS.

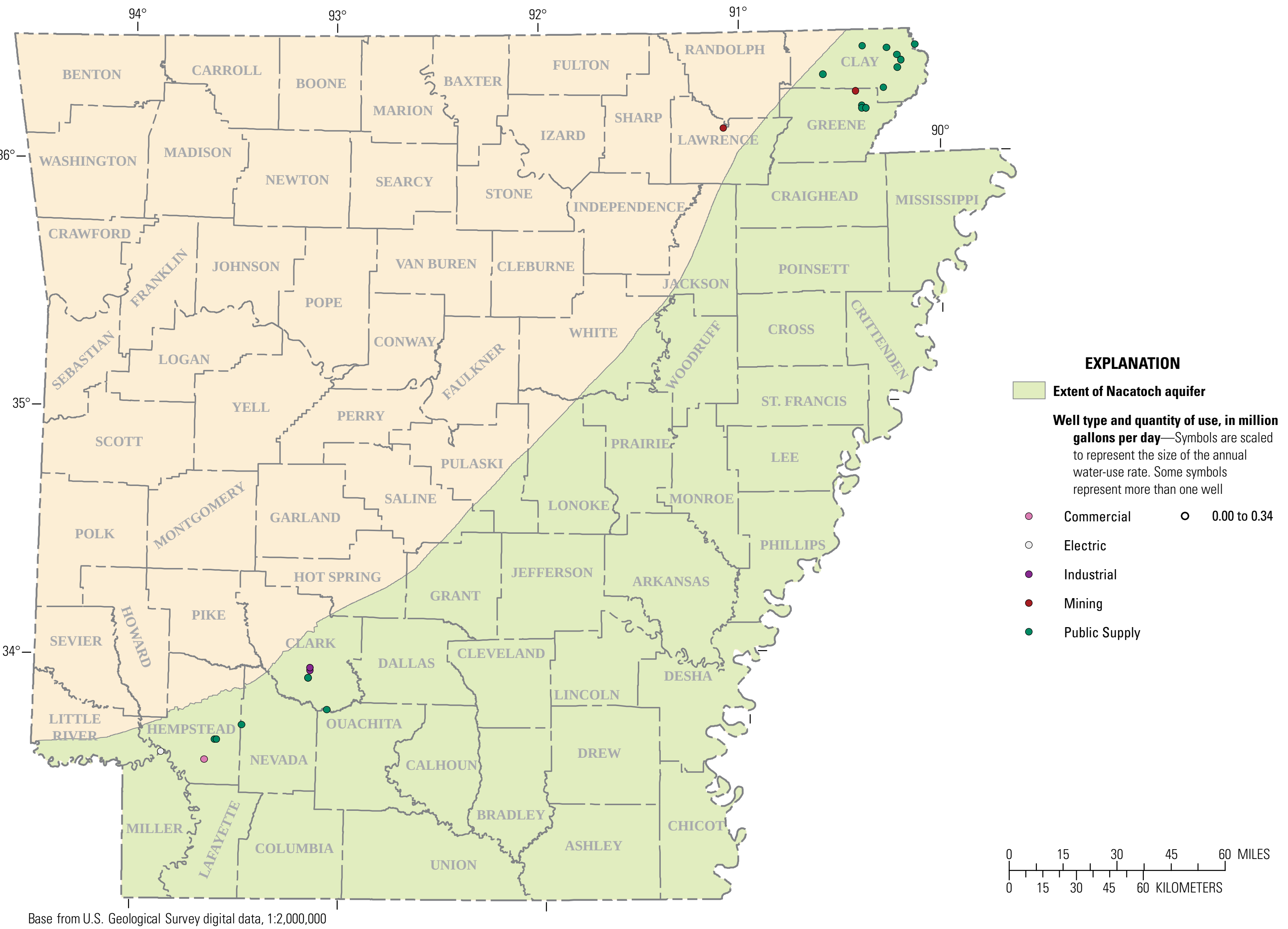



**Figure 72.** Wells with reported water use from the Nacatoch aquifer in Arkansas, 2010.

**Table 32.** Water use from the Nacatoch aquifer in Arkansas, 1965–2010.

[Counties shown are only those with published data. Data from Halberg and Stephens (1966); Halberg (1972, 1977); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1965 | 1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|
| Clay | 0.25 | 0.51 | 0.63 | 1.55 | 1.13 | 1.98 | 1.72 | [1]1.28 | 0.97 | 1.22 |
| Greene | 0.00 | 0.06 | 0.08 | 0.16 | 0.09 | 0.23 | 0.00 | [1]0.40 | 0.48 | 0.46 |
| Lawrence | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 |
| **Northeast total** | **0.25** | **0.57** | **0.71** | **1.71** | **1.22** | **2.21** | **1.72** | **[1]1.68** | **1.46** | **1.69** |
| Clark | 0.44 | 0.55 | 0.64 | 1.73 | 0.91 | 0.29 | 0.34 | 0.54 | 0.43 | 0.15 |
| Hempstead | 1.12 | 1.72 | 1.44 | 1.98 | 0.15 | 0.20 | 0.32 | 1.83 | 1.92 | 1.29 |
| Hot Spring | 0.00 | 0.00 | 0.00 | 0.24 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Howard | 0.00 | 0.14 | 0.22 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Little River | 0.20 | 0.04 | 0.04 | 0.06 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Miller | 0.14 | 0.03 | 0.04 | 0.06 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Nevada | 0.21 | 0.45 | 0.55 | 0.68 | 1.11 | 0.44 | 0.36 | [1]0.08 | 0.18 | 0.21 |
| Ouachita | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 |
| **Southwest total** | **2.11** | **2.93** | **2.93** | **4.75** | **2.17** | **0.93** | **1.02** | **[1]2.45** | **2.54** | **1.66** |
| **Total** | **2.36** | **3.50** | **3.64** | **6.46** | **3.39** | **3.14** | **2.74** | **[1]4.13** | **4.00** | **3.35** |

[1]Unpublished data from Terrance W. Holland, U.S. Geological Survey, written commun., 2013.

Northeastern and southwestern Arkansas generally exhibited the same patterns of water use from the Nacatoch aquifer. Hempstead County generally had the most use in southwestern Arkansas and Clay County in northeastern Arkansas (fig. 73). Southwestern Arkansas had the greatest use in 1980, and northeastern Arkansas had the greatest use in 1990. Groundwater use in southwestern Arkansas usually was more than in northeastern Arkansas except for reporting years 1990, 1995, and 2010. From 1965 to 2010, use decreased in southwestern Arkansas, while use increased in northeastern Arkansas (fig. 74; table 32).

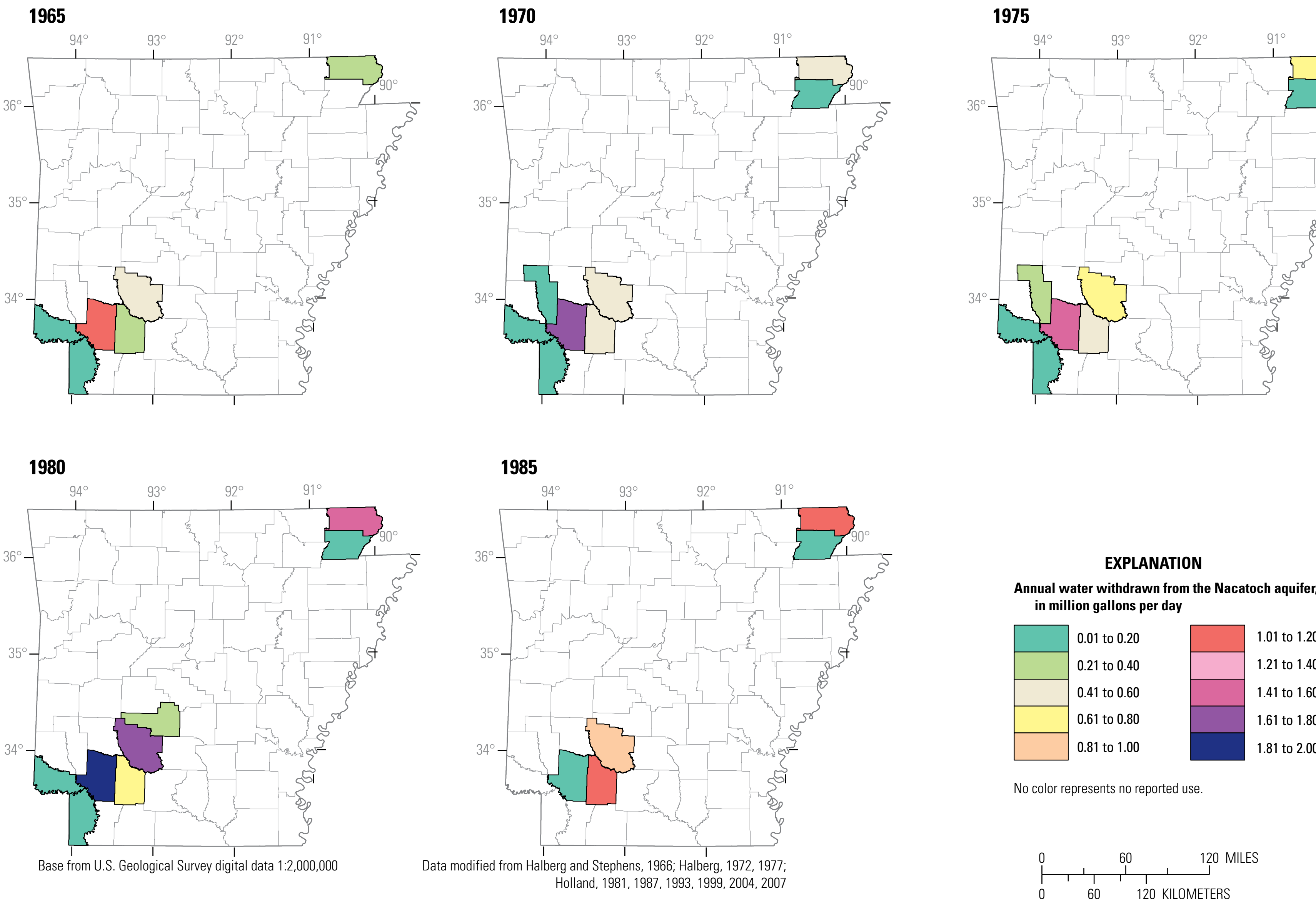



**Figure 73.** Water-use rates for the Nacatoch aquifer in Arkansas from 1965 to 2010.

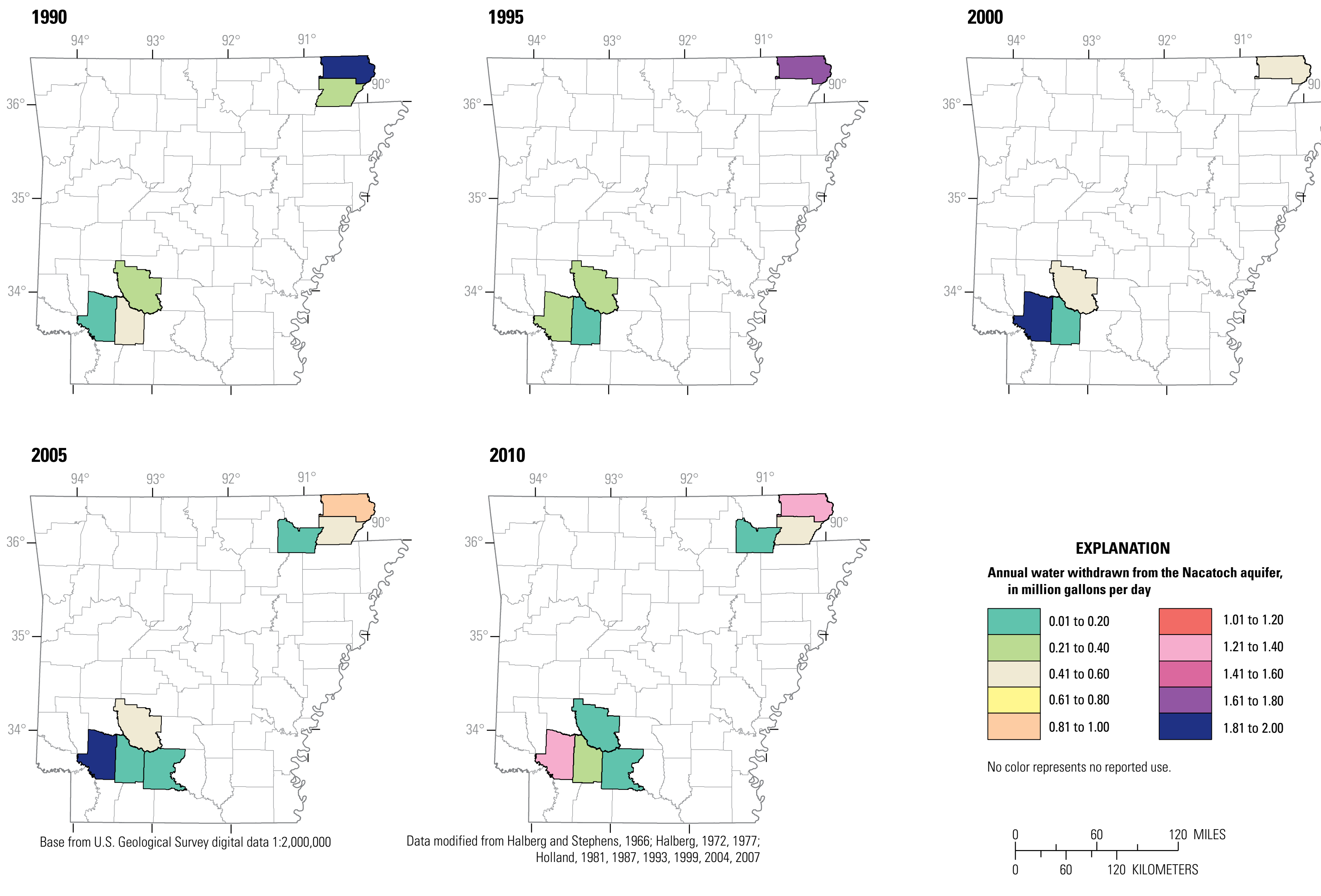



**Figure 73.** Water-use rates for the Nacatoch aquifer in Arkansas from 1965 to 2010.—Continued

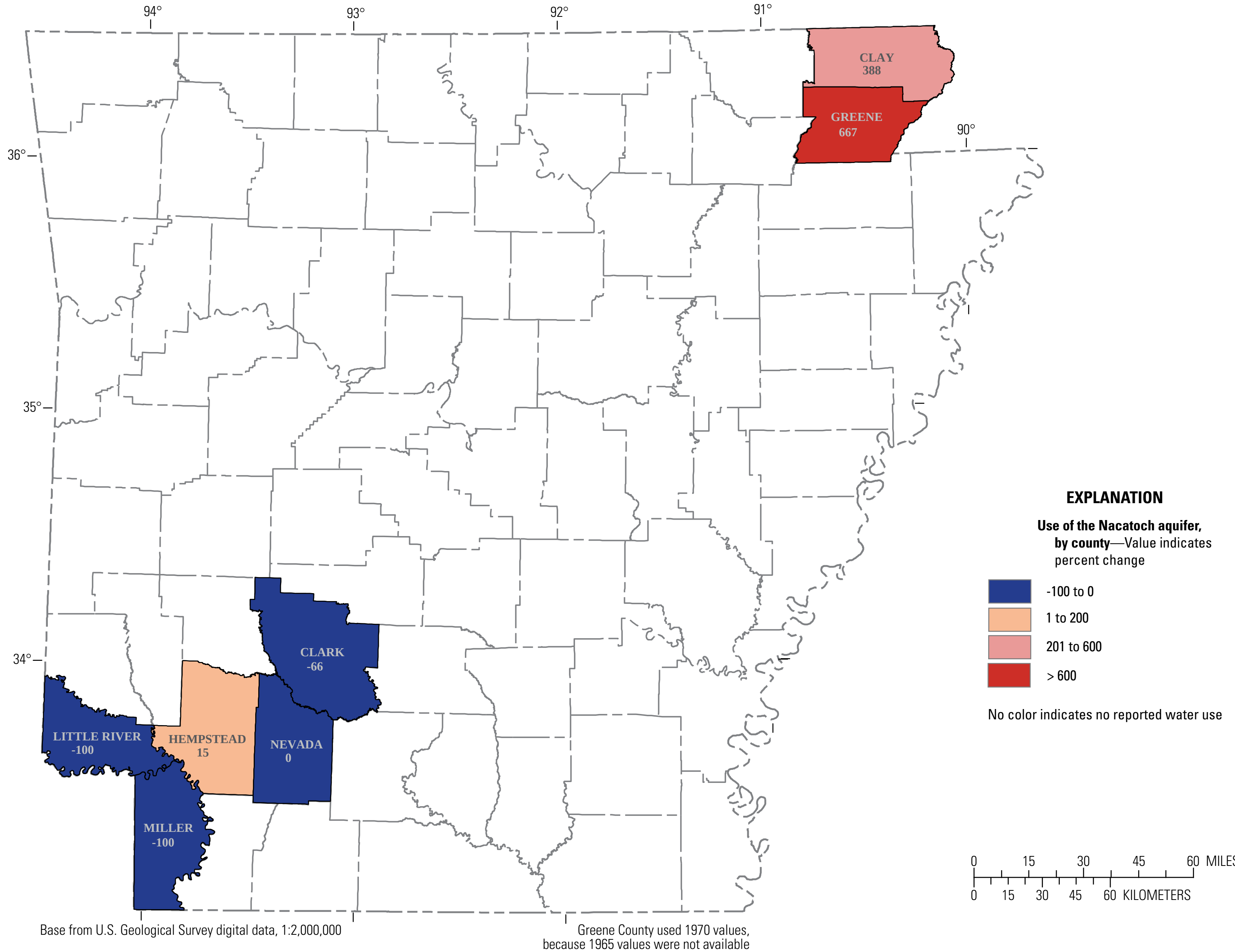



**Figure 74.** Change in percentage of water use from the Nacatoch aquifer in Arkansas from 1965 to 2010.

### Public Supply

Water use from the Nacatoch aquifer for public supply currently (2013) is greater in northeastern Arkansas than in southwestern Arkansas. Clay County Regional Water District is the largest user of the Nacatoch for public supply with a total of 0.64 Mgal/d, which accounted for approximately 19 percent of total Nacatoch water use in 2010. Piggott (0.35 Mgal/d) and Rector (0.17 Mgal/d) in Clay County were other large users in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). The well in Piggott was drilled in 1923 and, at one point, was a flowing artesian well (Hale and others, 1947).

Hope (Hempstead County) is the largest user for public supply in southwestern Arkansas, using 15 percent of the total water withdrawn from the aquifer. Hope completed two wells in the Nacatoch in 1933, after completing one well in the Tokio aquifer in 1918 (Hale and others, 1947; Counts and others, 1955). Hope has drilled additional wells into both aquifers over the years but now supplements its groundwater with surface water.

Prescott (Nevada County) drilled two wells in the Nacatoch aquifer in 1925 and 1948 (Hale and others, 1947; Counts and others, 1955) but currently (2013) withdraws water only from the Little Missouri River. Water use for Nevada County decreased (fig. 73) after Prescott switched water sources between 1985 and 1990. Smaller communities in the area, including Gurdon (Clark County) and Emmet (Nevada County), tap the aquifer for public supply. Also, a school district in Hempstead County continues to use a well drilled in 1948 (Counts and others, 1955; Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

### Industry

Industrial use from the Nacatoch aquifer in Clark County was dominated by lumber and paper companies in the mid-1900s. Counts and others (1955) recorded five different lumber companies with wells withdrawing from the aquifer. Lumber-processing facilities currently (2013) depend on the aquifer in Clark County. Ice and gas companies also were recorded users of the aquifer. In 2010, the largest single use of the aquifer was for cooling water at a powerplant in Hempstead County. In northeastern Arkansas, mining interests are active users of the aquifer in Greene and Lawrence Counties.

## Water Levels

Southwestern Arkansas has experienced water-level declines in the Nacatoch aquifer since its early and intense development. During early development, many flowing artesian wells were unrestricted and allowed to flow freely, causing a decline in water levels of approximately 7 ft over 17 years near Prescott (Nevada County) (Veatch, 1906). Veatch (1906) created a potentiometric-surface map from water levels measured in 1902. Water levels were highest north of Hope at the northern limit of the aquifer outcrop and decreased to the south.

The ANRC and USGS monitor water levels in the Nacatoch aquifer as part of a long-term, statewide program (Schrader, 1998, 1999, 2007b; Schrader and Scheiderer, 2004; Schrader and Blackstock, 2010; Schrader and Rogers, 2013). In southwestern Arkansas, recent potentiometric-surface maps have shown the same pattern as in Veatch (1906), where groundwater-surface altitudes gradually decrease from the outcrop of the aquifer to the south (Schrader and Blackstock, 2010). Water levels in some wells declined by approximately 40 ft at Hope from 1942 to 1969 as a result of large groundwater withdrawals, mostly for public supply and industry. A cone of depression has been documented in this area since 1967 (Ludwig, 1973; Schrader, 1999; Schrader and Scheiderer, 2004; Schrader and Blackstock, 2010). Water levels rose in well A near the cone of depression at Hope in 2010 (figs. 75 and 76), corresponding to decreasing water use in Hempstead County. The 2011 potentiometric surface depicts a cone of depression near Hope (fig. 76).

Two other cones of depression in the Nacatoch aquifer potentiometric surface were noted in southern Clark and north-central Hempstead Counties (fig. 76). The Clark County depression was first identified in 2002 (Schrader and Scheiderer, 2004), whereas the Hempstead County depression was first identified in 2008 (Schrader and Blackstock, 2010). Groundwater altitudes in each of these depressions have dropped a foot since construction of the 2005 potentiometric-surface map (Schrader, 2007b).

In well B, near Prescott (Nevada County), water levels declined more than 30 ft from the mid-1950s to the mid-1970s (figs. 75 and 76). Dramatic water-level rises of approximately 70 ft were later identified in well B from 1985 to 1990, when the drinking-water supply of Prescott switched from groundwater to the Little Missouri River (Schrader and Blackstock, 2010). Water levels have stabilized since the early 1990s.

Water-level declines in wells completed in the Nacatoch aquifer in northeastern Arkansas were recorded in Clay (well C) and Greene (well D) Counties from the 1960s and 1970s until the late 1990s (figs. 75 and 76). Water levels have stabilized since 1990 with the decrease in use of the Nacatoch aquifer (table 32). Interestingly, a localized potentiometric high that had not been noted previously appeared in the 2011 surface in southeastern Clay County (fig. 76).

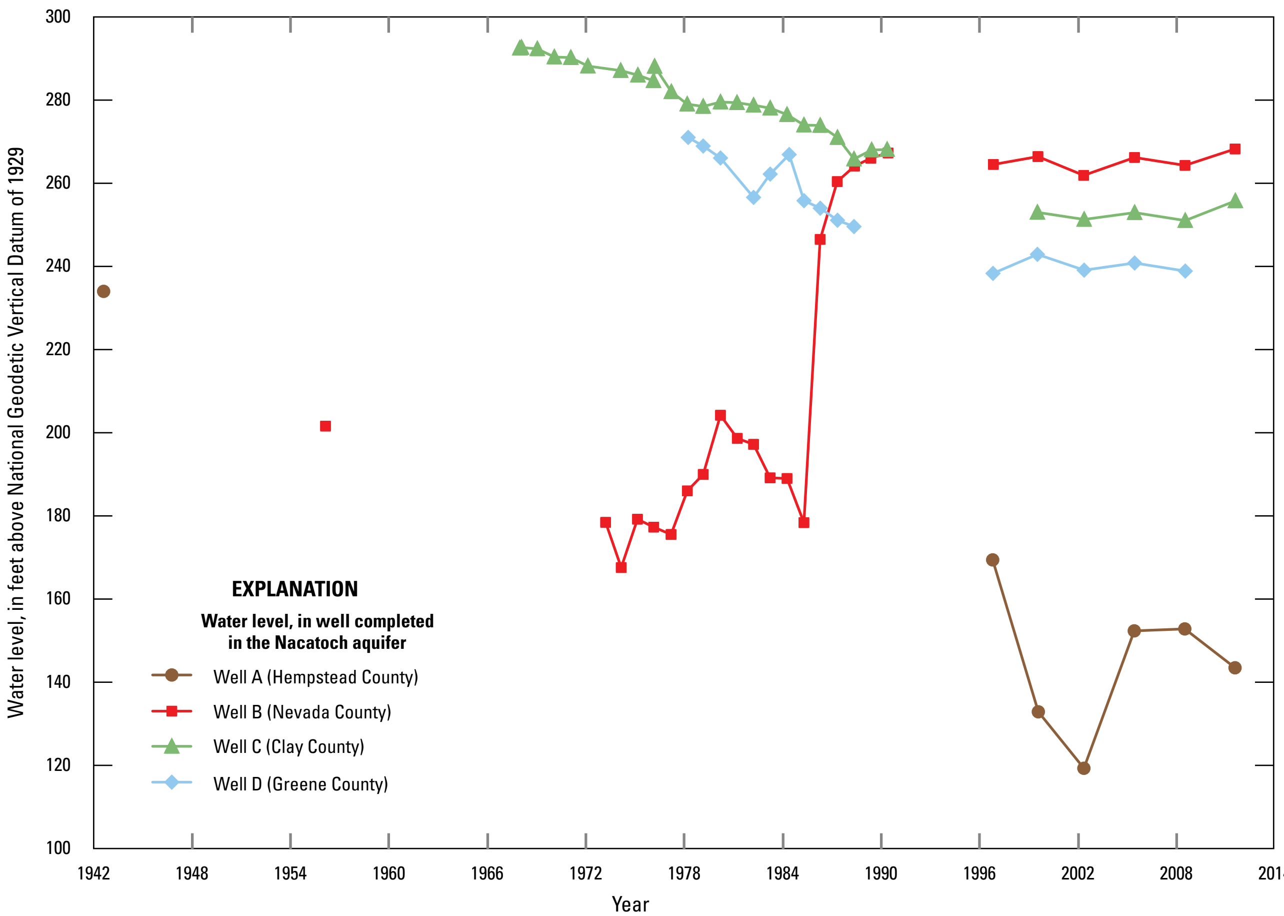



**Figure 75.** Hydrographs of water levels in wells completed in the Nacatoch aquifer in Arkansas.

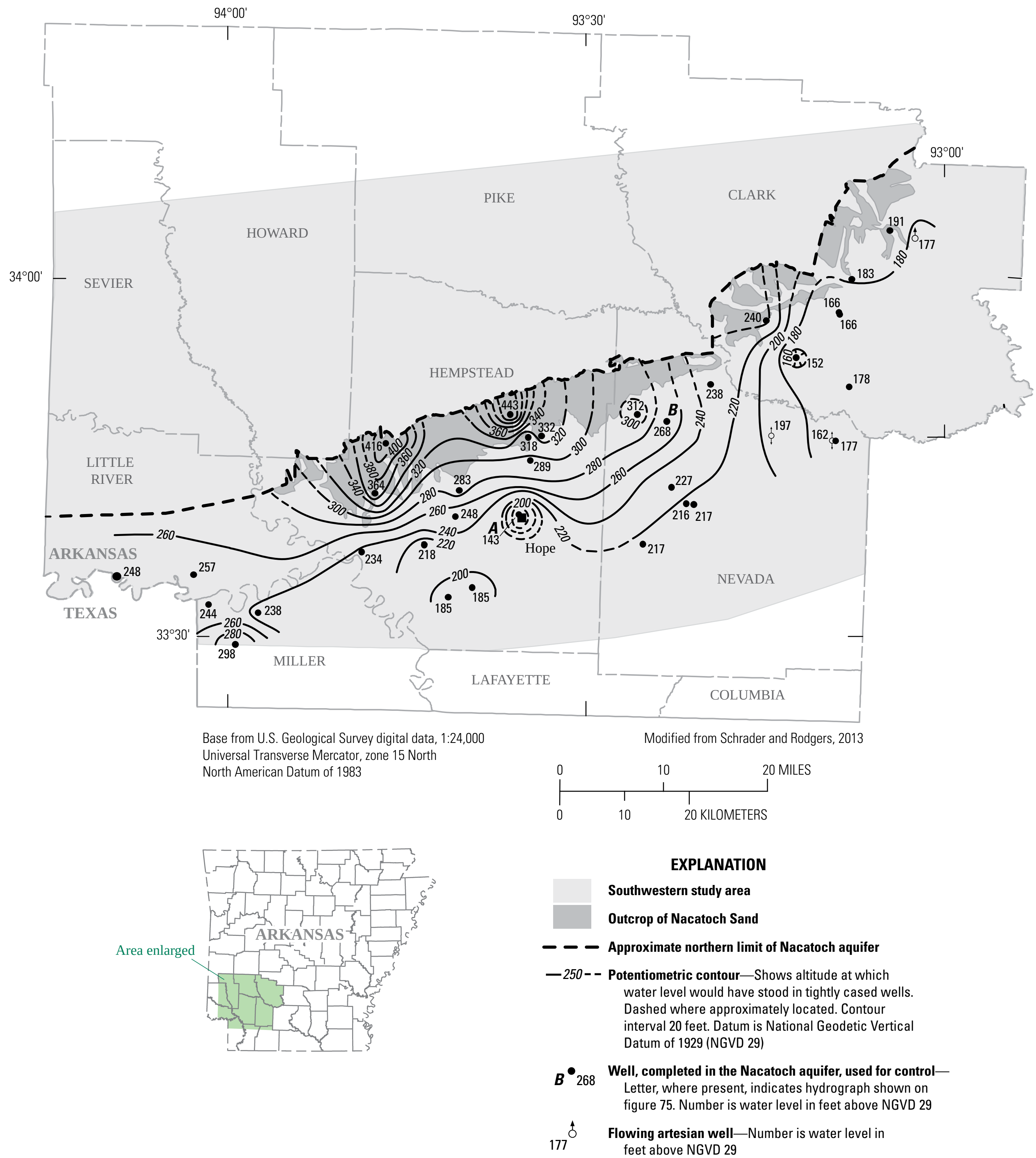



**Figure 76.** Potentiometric surface of the Nacatoch aquifer in Arkansas, February–March 2011.

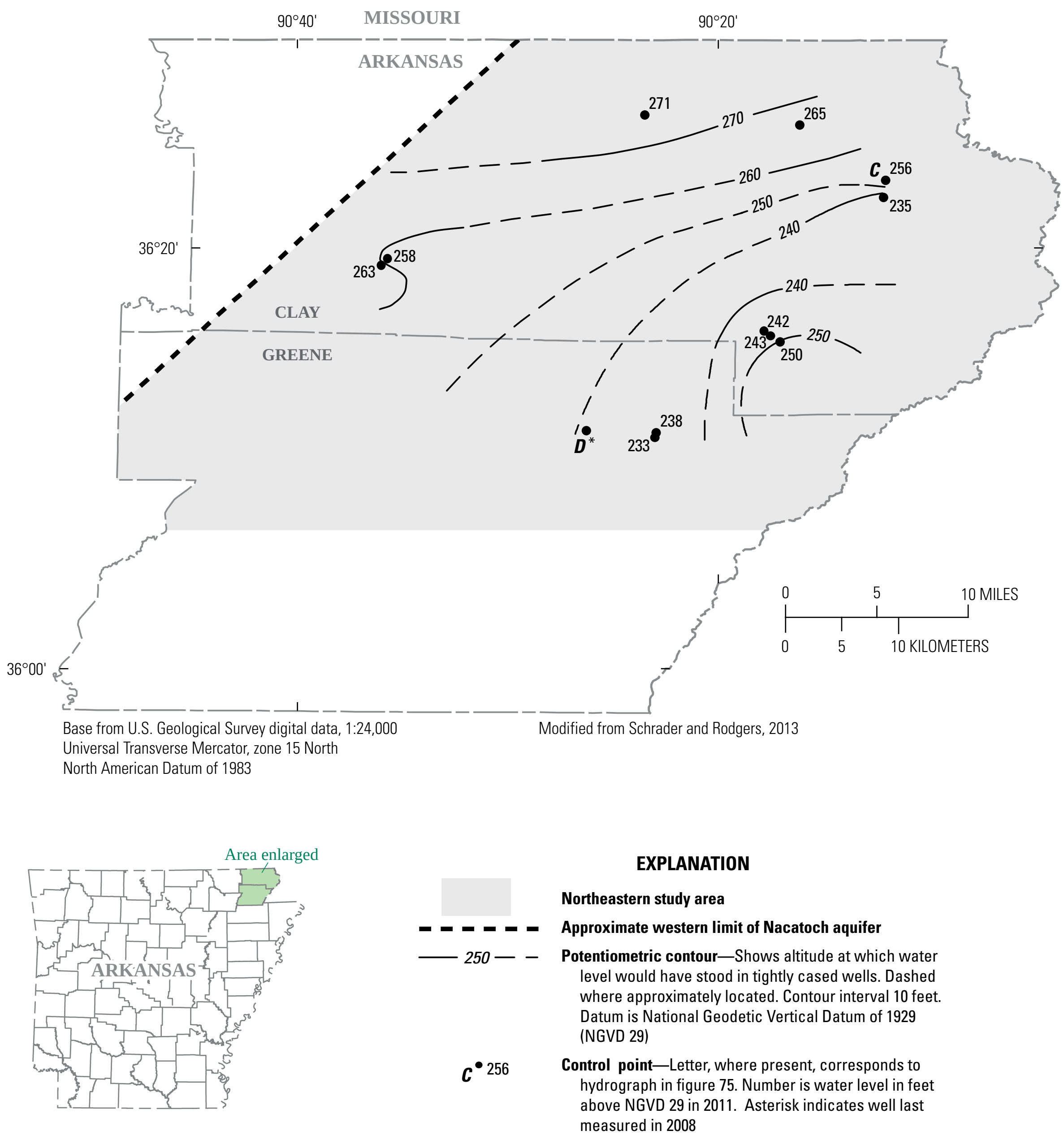



**Figure 76.** Potentiometric surface of the Nacatoch aquifer in Arkansas, February–March 2011.—Continued

## Water Quality

The Nacatoch aquifer is an important source of groundwater in the southwestern part of the State. It is also a good-quality source of water in the extreme northeastern part of the State. Geological controls on lithology and structure explain its occurrence and viability as an aquifer in these areas. The Nacatoch crops out in a narrow band in the southwestern part of the State, extending from western Hempstead County to northeastern Clark County (fig. 77).

Freshwater occurs almost solely in an isolated area in and near this area of outcrop (Terry and others, 1986). The upper part of the Nacatoch is composed of sand and is the principal water-bearing part of the formation in this area (Counts and others, 1955; Ludwig, 1973). Counts and others (1955) noted that water quality in the Nacatoch varied considerably in southwestern Arkansas. Within 2–20 mi from the outcrop area, the groundwater was too salty for most uses. The change in water quality along flow paths downgradient from the recharge area is gradual in some areas, degrading to unusable over 20 mi, or abrupt, changing from less than 100 mg/L to greater than 1,000 mg/L in less than 4 mi. Similarly, Plebuch and Hines (1969) stated that chloride concentrations in Clark County were low but increased rapidly downgradient to concentrations unsuitable for most uses within 2–17 mi from the outcrop. Within a distance of 3 mi along the northeastern edge of the outcrop area in Clark County, chloride concentrations were noted to increase from 7.0 to 7,560 mg/L and dissolved solids from 92 to 12,300 mg/L. Near the outcrop area in Hempstead, Little River, and Nevada Counties, groundwater was soft or moderately hard with low chloride concentrations (Ludwig, 1972). Downgradient from the outcrop area, however, sodium and chloride concentrations increased with a concomitant increase in dissolved solids. Counts (1955) hypothesized that because the Nacatoch was a marine deposit, the original salt content had never been flushed completely from the formation, accounting for the higher salinity in the downgradient and deeper parts of the aquifer. Groundwater from the Nacatoch generally had very low iron concentrations (Counts and others, 1955; Ludwig, 1973) as well as low sulfate and nitrate concentrations (Counts and others, 1955).

The Nacatoch aquifer provides a productive source of groundwater in the southwestern part of the State near the outcrop (hereinafter referred to as the “southwestern extent” of the aquifer). This is because of the higher sand content in the upper unit compared to the lower unit of the Nacatoch that consists of a mixture of interbedded clays, marls, and sands (Counts and others, 1955; Plebuch and Hines, 1969). The lithology in central Arkansas consists of bluish-gray, calcareous, fossiliferous sandstones and clays (Stephenson and Crider, 1916). Elevated dissolved-solids concentrations in groundwater from this area render the water unusable (Boswell and others, 1965; Petersen and others, 1985). In northeastern Arkansas (hereinafter referred to as the “northeastern extent” of the aquifer), the sand content of the Nacatoch increases to 40–60 percent, and the aquifer once again becomes a viable aquifer (Renfroe, 1949; Caplan, 1954; Lamonds and others, 1969). The Nacatoch is a silty and fine-grained sand in Jackson County but transitions to a clean, medium- to coarse-grained sand in Clay, Greene, and Lawrence Counties. The aquifer thickens in these counties to approximately 200 ft and yields are as much as 500 gal/min in parts of Clay and Greene Counties. In Craighead County, the aquifer yielded slightly saline to brine water, and one sample in Monroe County contained chloride concentrations of 21,500 mg/L (Broom and Lyford, 1981). Because the northeastern extent contained only 8 of 132 wells in the combined water-quality database used for this report, most of the following detailed discussion, especially with respect to spatial trends for the various constituents, is confined to the southwestern extent of the aquifer.

### General Geochemistry and Water Type

The Nacatoch aquifer is similar to other Cretaceous and Tertiary aquifers and tends to have increasing pH values along the flow path resulting from increased dissolution of carbonate minerals. The Nacatoch is somewhat unique, however, in that only 1 of 129 samples, including samples from wells in the outcrop area, had a pH value less than 7.0 (value of 4.7). Because the average pH of precipitation for southern Arkansas is approximately 4.7 standard units (Kresse and Fazio, 2002), pH values for Cretaceous and Tertiary aquifers often are much lower than 7.0 for many shallow wells in the recharge (outcrop) area. Downgradient from the outcrop area, pH values tend to increase along a given flow path as a result of buffering by carbonate minerals. Values of pH for groundwater from the Nacatoch ranged upward to 9.0 with a median of 8.4 (table 33). Only 25 of 129 samples had pH values less than 8.0. Lower groundwater velocities coupled with an abundance of carbonate minerals throughout the formation may result in dissolution of carbonates and associated buffering of acidic recharge within a relatively short distance along the flow path. Additionally, many of the wells completed in the Nacatoch produce from sands at relatively great depths. Out of 129 wells with well-depth information, only 13 were less than 100 ft deep, and 39 wells were more than 500 ft deep with a maximum of 2,231 ft in depth. The increased vertical distance and traveltime of infiltrating recharge water allows greater time for rock/water interaction, including dissolution of carbonate minerals.

The lowest pH values (4.7–7.5) in the Nacatoch aquifer occurred in or near the outcrop area and trended progressively upward to values exceeding 8.0 in the downgradient (southeasterly) direction of flow (fig. 77). Because pH generally increases with increasing dissolution of carbonates along the flow path, bicarbonate concentrations generally followed the trend of increasing pH. The lowest concentrations (less than 200 mg/L) occurred in and near the outcrop and progressively increased in the downgradient direction of flow. The highest bicarbonate concentrations were in wells located in the eastern and western sections of the outcrop area in the southwestern extent of the aquifer (fig. 77).

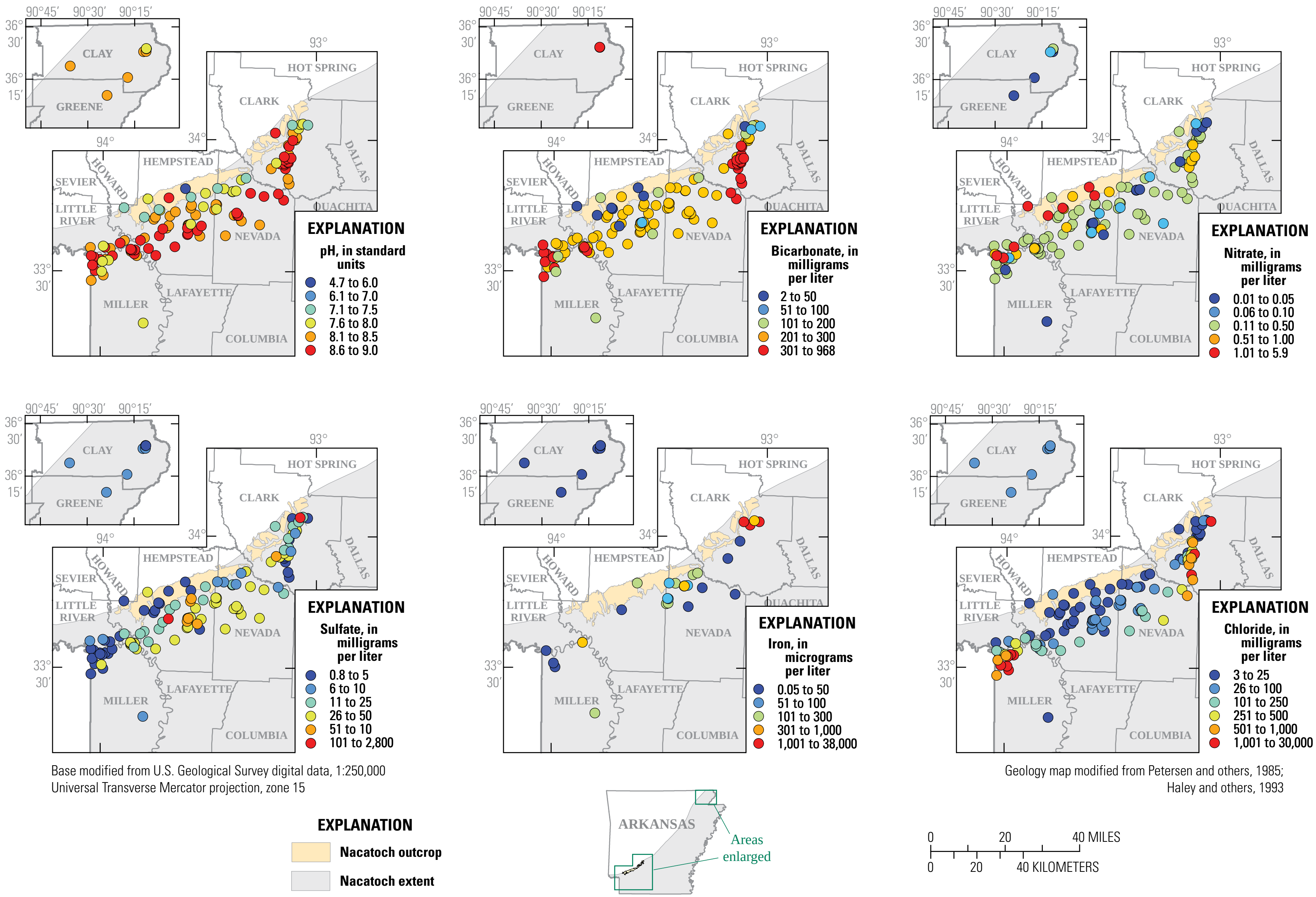



**Figure 77.** Spatial distribution of selected chemical constituents for groundwater from the Nacatoch aquifer in Arkansas.

**Table 33.** Descriptive statistics for selected chemical constituents in groundwater from the Nacatoch aquifer in Arkansas.

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

| Constituent or characteristic | Minimum | Median | Maximum | Standard deviation | Number of wells |
|---|---|---|---|---|---|
| Calcium (mg/L) | 1.0 | 17 | 2,100 | 438 | 40 |
| Magnesium (mg/L) | 0.1 | 3.1 | 570 | 97 | 40 |
| Sodium (mg/L) | 6.5 | 168 | 20,000 | 3,740 | 40 |
| Potassium (mg/L) | 0.8 | 3.0 | 119 | 27.5 | 40 |
| Bicarbonate (mg/L) | 2.0 | 260 | 968 | 118 | 123 |
| Chloride (mg/L) | 3.0 | 45 | 30,000 | 4,240 | 132 |
| Sulfate (mg/L) | 0.8 | 21 | 2,800 | 251 | 131 |
| Silica (mg/L) | 7.4 | 13 | 63 | 13.6 | 41 |
| Nitrate (mg/L as nitrogen) | 0.01 | 0.25 | 5.9 | 0.78 | 127 |
| Dissolved solids (mg/L) | 94 | 444 | 55,400 | 10,900 | 40 |
| Iron (µg/L) | 0.05 | 80 | 38,000 | 6,200 | 38 |
| Manganese (µg/L) | 0.13 | 10 | 1,800 | 382 | 21 |
| Arsenic (µg/L) | 0.03 | 0.52 | 1.0 | 0.48 | 6 |
| Hardness (mg/L as calcium carbonate) | 4.0 | 33 | 6,700 | 807 | 131 |
| Specific conductance (µS/cm) | 38 | 706 | 53,000 | 6,080 | 130 |
| pH (standard units) | 4.7 | 8.4 | 9.0 | 0.6 | 129 |

Rock/water interactions in the aquifer can change the major chemical composition and resulting water type along the groundwater-flow path. The exchange of calcium for sodium on solid exchange sites certainly is one of the most important processes affecting inorganic chemistry in aquifers of the Coastal Plain (Kresse and Fazio, 2002; Kresse and Clark, 2008; Kresse and others, 2012) Only 32 sites had sufficient data for calculating percent sodium of total cations in the Nacatoch aquifer. These data, however, were sufficient to note general trends in water type. Generally, sites with sodium less than 50 percent of the total cations, indicating a calcium-bicarbonate water type, were located in or less than about 1 mi from the outcrop area. Sites further downgradient had sodium percentages more than 50 percent and ranging upward to 99 percent (not shown on fig. 77).

## Nitrate

Nitrate concentrations were extremely low in most samples from the Nacatoch aquifer. Nitrate concentrations ranged from 0.01 to 5.9 mg/L as nitrogen with a median of 0.25 mg/L (table 33). No concentrations exceeded the Federal MCL of 10.0 mg/L as nitrogen (U.S. Environmental Protection Agency, 2009). Out of 127 sites, 118 had nitrate concentrations less than 1.0 mg/L, of which 106 were less than 0.5 mg/L. The highest nitrate concentrations were in and near the outcrop area in the southwestern extent, with the lowest (less than 0.5 mg/L as nitrogen) occurring downgradient from the outcrop area (fig. 77). In the vicinity of the outcrop, well depths are shallower, and all nitrate concentrations greater than 2.0 mg/L occurred in wells with depths of 60 ft or less (fig. 78). All groundwater samples from the northeastern extent had nitrate concentrations less than 0.5 mg/L. Similar to other aquifers in the Coastal Plain, the highest nitrate concentrations tend to occur in and near the outcrop area. Well depths are shallow in these areas, and the aquifer is more vulnerable to surface (fertilizers, applied animal waste) and shallow subsurface (septic tanks) sources of nitrate.

## Iron

Iron is ubiquitous in groundwater for aquifers throughout the State and can present problems for most uses. Groundwater from the Nacatoch aquifer, however, contained some of the lowest iron concentrations for any aquifer in the State. Iron concentrations ranged from 0.05 to 38,000 µg/L with a median of 80 µg/L (fig. 79; table 33). Only 8 of 38 samples had iron concentrations exceeding the secondary drinking-water regulation of 300 µg/L (U.S. Environmental Protection Agency, 2009). All samples from the northeastern extent (Clay and Greene Counties) had iron concentrations less than 50 µg/L. Most of the highest iron concentrations (ranging up to 7,400 µg/L) were in the extreme northeastern part of the outcrop area in Clark County (fig. 77), with the highest concentration of 38,000 µg/L from an unused oil-exploration well in Union County (not shown on map). Downgradient from the outcrop area, iron concentrations were generally less than 100 µg/L. Higher iron concentrations in and near the outcrop area were noted for other Cretaceous and Tertiary aquifers. Lower concentrations downgradient from outcrop areas were attributed to iron-sulfide mineralization as a dominant control on iron solubility (see sections on Sparta and Cockfield aquifers for detailed discussion).

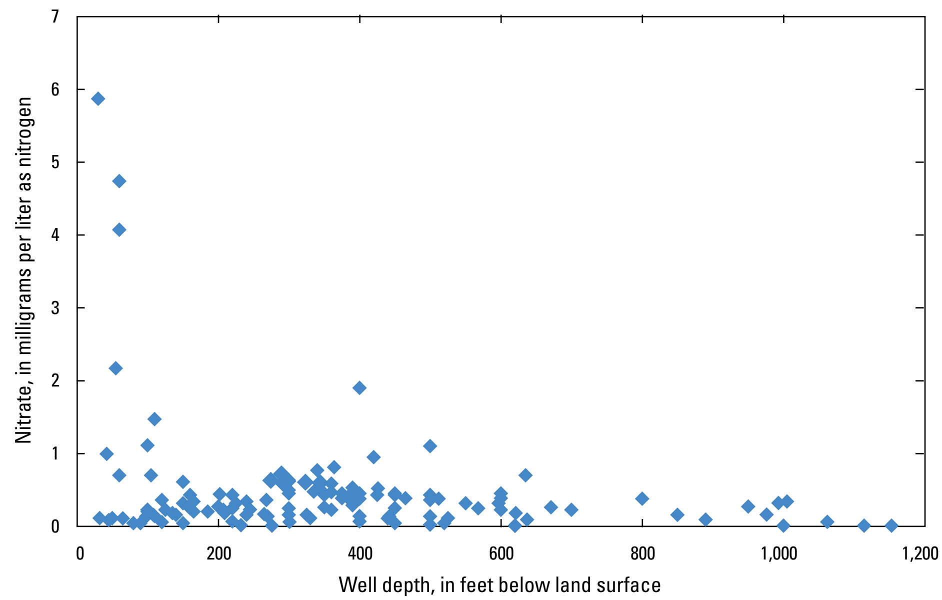



**Figure 78.** Relation of well depth and nitrate concentrations in groundwater from the Nacatoch aquifer in Arkansas.

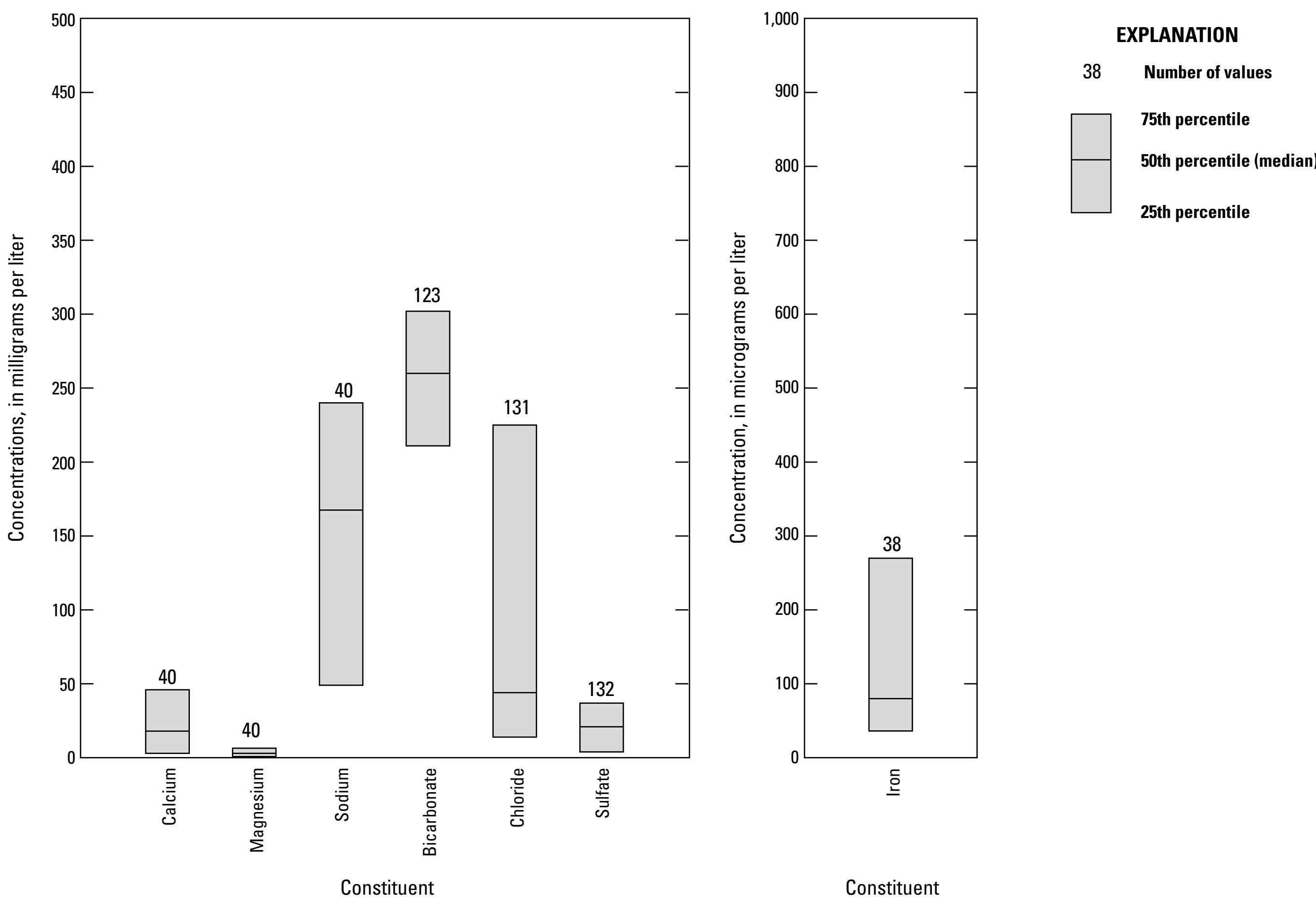



**Figure 79.** Interquartile range of selected chemical constituents in groundwater from the Nacatoch aquifer in Arkansas.

### Sulfate

Earlier reports (Counts and others, 1955; Ludwig, 1972) noted the low concentrations of nitrate, iron, and sulfate concentrations in groundwater from the Nacatoch aquifer. Inspection of data compiled for this report confirmed these observations. Sulfate concentrations ranged from 0.8 to 2,800 mg/L with a median of 21 mg/L (fig. 79; table 33). Of 131 samples with sulfate concentration data, 118 (90 percent) were less than 50 mg/L, 55 (42 percent) were less than 10 mg/L, and 35 (27 percent) were less than 5 mg/L. Only three samples had sulfate concentrations greater than the secondary drinking-water regulation of 250 mg/L (U.S. Environmental Protection Agency, 2009). These three samples were (1) from unused oil-exploration wells in Union County (not shown on figures), (2) were not used as water-supply sources, and (3) were far removed from the outcrop area where high-salinity, high-dissolved-solids groundwater is known to occur. In and near the outcrop area, sulfate concentrations generally were less than 50 mg/L (fig. 77). The lowest concentrations (less than 5 mg/L) were from wells in the outcrop area and along the extreme eastern (Clark County) and western (Little River and Miller Counties) parts of the southwestern extent of the aquifer (regardless of proximity to outcrop area). This distribution was the inverse of that observed for bicarbonate concentrations, which were highest in the extreme eastern and western part of the outcrop area (fig. 77). In the central part of the outcrop area (Hempstead and Nevada Counties), sulfate concentrations generally were lowest and increased downgradient. Higher clay content and gypsum mineralization in the central part of the aquifer may account for the higher sulfate concentrations downgradient from the outcrop area. However, data on mineralogy, redox zonation, or other aquifer characteristics were not available to make definitive statements in regard to specific rock/water interaction that would explain occurrence and spatial distribution for sulfate or other constituents. All samples from wells in the northeastern extent had sulfate concentrations less than 10 mg/L.

### Chloride

Increasing salinity downgradient from the outcrop area in the southwestern extent of the Nacatoch aquifer is documented in numerous earlier reports (Counts and others, 1955; Plebuch and Hines, 1969; Ludwig, 1973; Terry and others, 1986). Data collected for this report corroborate these earlier studies and reveal a strong spatial component to the occurrence and distribution of elevated chlorides. Although chloride concentrations generally increased downgradient from the outcrop area in Hempstead and Nevada Counties, the gradient is not as sharp as noted for sites in the southwestern and northeastern parts of the outcrop area (fig. 77). Groundwater in Hempstead and Nevada Counties has chloride concentrations that are below the secondary drinking-water regulation of 250 mg/L as far as 13 mi from the outcrop area. Thus, good-quality, low-salinity groundwater can be extracted in a much broader area in these counties. However, much sharper concentration gradients and higher concentrations are noted for groundwater from sites located in the western and eastern parts of the outcrop area. Chloride concentrations sharply increased in a southeasterly direction in Miller County from 355 mg/L, to 565 mg/L, and finally to 1,670 mg/L, all within a distance of 0.7 mi. In the eastern part of the outcrop area (Clark County), one well containing a chloride concentration of 7,560 mg/L was less than 0.8 mi from the outcrop area and less than 1.5 mi from a well containing a chloride concentration of only 10 mg/L.

Four exploratory wells in Union County contained chloride concentrations ranging from 3,500 to 30,000 mg/L. These wells were at a distance of approximately 60 mi from the outcrop area, where high salinity would be expected in the Nacatoch aquifer (not shown on fig. 77). Samples from all wells in the northeastern extent (Clay and Greene Counties) contained chloride concentrations less than 100 mg/L. One well located in Monroe County (not shown on fig. 77) was located in an area of high salinity that occupies a narrow band extending from Prairie County, through Monroe County, and into Lee County. This area was noted in past publications as containing high salinity that affected all Quaternary- and Tertiary-age aquifers (Stephenson and Criner, 1916; Counts, 1957; Halberg and Reed, 1964; Morris and Bush, 1986). See the section on Mississippi River Valley alluvial and Sparta aquifers for detailed information on this area of high salinity groundwater.

In summary, the Nacatoch aquifer is a viable and important source of water for parts of the southwestern and extreme northeastern parts of the State. In the southwestern extent, freshwater mainly is obtained from areas in or near to the outcrop area. This is especially true for the eastern and western parts of the outcrop area. Salinity increases in a downgradient direction from the outcrop area to a point where the groundwater is not suitable for most uses. Gradients of increasing chloride concentrations are sharpest in the western and eastern parts of the outcrop, with a larger area of freshwater downgradient from the outcrop area in the central part of the outcrop area. Concentrations of sulfate, iron, and nitrate generally are very low throughout the Nacatoch aquifer. Values for pH, bicarbonate, and sodium tend to increase downgradient from the outcrop area as a result of mineral dissolution coupled to cation exchange.

## Ozan Aquifer

The Cretaceous-age Ozan Formation comprises an aquifer that is used in isolated parts of southwestern Arkansas. This aquifer is not listed in any regional reports, is one of the least-used aquifers, and contains some of the poorest-quality groundwater of any aquifer in the State. For purposes of this report, the saturated part of the Ozan Formation will be referred to hereinafter as the “Ozan aquifer.”

## Hydrogeologic Setting

The Ozan Formation is a mixed limey, clayey, and primarily sand unit that ranges in thickness from 0 to about 200 ft thick. The Ozan unconformably overlies the Brownstone Marl and grades conformably into the Annona Chalk above (Dane, 1929; Boswell and others, 1965). The formation is difficult to differentiate from the underlying Brownstone Marl but in some areas can be distinguished by a glauconitic sand bed (known as the Buckrange sand lentil) at the base of the formation or by a common occurrence of smooth, convex oyster shells (Dane, 1929; Counts and others, 1955; Plebuch and Hines, 1969). The upper part of the Ozan consists of gray sandy marl with a few beds of sand and sandy limestone. The formation changes facies from a sandy clay and marl to a chalk and marl in Little River County (Counts and others, 1955).

A considerable change in sea depth occurred in Arkansas following the Lower Cretaceous. While Lower Cretaceous units in Arkansas dominantly were nearshore deposits, deepening water resulted in more clayey and carboniferous sediments being deposited during the Upper Cretaceous (Veatch, 1906), resulting in the formation of mainly marls and chalks. The base of the Ozan shows evidence of nearly continuous, very slow deposition, indicating a period of nondeposition as an explanation of the unconformity at the base. The upper part of the Ozan indicates increased sediment supply, as evidenced by the increased sand content and micaceous nature of the sediment.

The Ozan Formation outcrop extends from northeastern Clark County towards the southwest into Oklahoma. The outcrop is from 1 to 4 mi wide and is covered by terrace and alluvial deposits through large areas (Boswell and others, 1965). From central Union County eastward, the sand content and thickness increase rapidly, indicating an approach to the sea strand line and the presence of a sedimentary trough (Dollof and others, 1967). While the extent is limited, an equivalent of the formation does appear at depth in northeastern Arkansas. In this area, the formation ranges up to 150 ft thick and consists of a dark-gray, silty to sandy, micaceous, calcareous marl with shale layers.

## Hydrologic Characteristics

Hydrologic data for the Ozan aquifer are limited because of its lack of importance as a regional water supply. Most wells completed in the Ozan are used for domestic water supply (Boswell and others, 1965). Aquifer yields are limited, and the water is highly mineralized. Most producing wells are located in Clark County (Counts and others, 1955), and some of these were listed as flowing artesian wells (Plebuch and Hines, 1969); however, most of these wells are no longer flowing, possibly because of decades of unrestricted flow. A few wells are completed in Hempstead and Sevier Counties, but the water in these counties is not suitable for drinking. A flowing artesian well yielding approximately 1 gal/min was noted in Sevier County (Counts and others, 1955). The Ozan dominantly receives recharge in the outcrop area.

Zachry and others (1986) investigated the potential of injecting wastewaters from petroleum exploration into Cretaceous aquifers in southern Arkansas, demonstrating the poor water quality in this area. They concluded that the variability of sand thickness and sand distribution prevented confident prediction of lateral movement of water within the Nacatoch, Ozan, and Tokio Formations. Vertical movement towards Tertiary aquifers was projected to be slow or nonexistent. Fractures were hypothesized to provide for enhancement of potential lateral movement of water within the formation but would have little influence on vertical movement into Tertiary aquifers as a result of the characteristics of the confining units.

## Water Use

Eleven domestic wells were recorded in Clark County, and 2 other wells were recorded in Hempstead and Sevier County, but their use was restricted because of high chloride concentrations (Counts and others, 1955; Boswell, 1965). Plebuch and Hines (1969) estimated that 0.13 Mgal/d was withdrawn from the Ozan aquifer in Clark County in 1965. Water-use data for the Ozan are only available from 1965 to 1980 (table 34), and no use has been reported for this aquifer thereafter.

## Water Quality

Wells completed in the Ozan aquifer occur dominantly in the outcrop area, which extends along an extremely narrow band extending from western Little River County (near the State border) through northeastern Clark County. The Ozan contains some of the poorest quality water of any of the aquifers in the Coastal Plain. Limited use of groundwater from the Ozan has been cited in several reports. Plebuch and Hines (1969) noted that the aquifer generally contained groundwater with dissolved-solids concentrations of more than 1,000 mg/L in Clark County and was used only because no other water source was available. Counts and others (1955) noted that the aquifer yielded only small amounts of highly mineralized water for domestic purposes, although

**Table 34.** Water use from the Ozan aquifer in southwestern Arkansas, 1965–80.

[Data from Halberg and Stephens (1966); Halberg (1972, 1977); Holland (1981). Only counties with published data for consumption of groundwater from the Ozan aquifer are shown]

| County | 1965 | 1970 | 1975 | 1980 |
|---|---|---|---|---|
| Clark | 0.13 | 0.15 | 0.19 | 0.52 |

noting that some of the water was not suitable for even that purpose. Boswell and others (1965) reported that even groundwater from the Ozan outcrop area contained dissolved-solids concentrations of more than 1,000 mg/L and that it was an important aquifer only in Clark County because no other water source was present.

As a consequence of limited use, the Ozan aquifer has received limited attention in terms of aquifer characterization and documentation of water quality. Older reports contain sparse water-quality information, and most of this information is related to salinity problems. Counts and others (1955) reported chloride concentrations ranging from 32 to 2,100 mg/L in the Ozan aquifer. One well in Sevier County was reported as containing a chloride concentration of 1,100 mg/L and was not used at the time of sampling. Only wells in Hempstead County yielded less mineralized water, containing dissolved-solids concentrations from 400 to 500 mg/L (Counts and others, 1955). Boswell and others (1965) calculated dissolved-solids concentrations from specific conductance values and cited a range from 600 to greater than 4,000 mg/L.

### General Geochemistry and Water Type

Only 14 sites had water-quality data from the Ozan aquifer. These data dominantly included major anions (bicarbonate, chloride, sulfate), nitrate, and field parameters including pH and specific conductance; only 2 wells contained information related to major cations (calcium, magnesium, sodium, potassium). Thus, no meaningful analysis can be made with regard to water type. However, certain assumptions can be made in regard to the evolution of geochemistry with existing data, and these are discussed further in “Conceptual Model of Groundwater Geochemical Evolution” at the end of this section.

Values of pH ranged from 6.8 to 8.6 with a median of 8.3 (table 35). All pH values except one were greater than 7.5. No trends were noted in the spatial distribution of pH, except that the highest values tend to occur in the eastern part of the aquifer in Clark County (fig. 80). Generally, areas of higher pH correlated to areas of higher bicarbonate concentrations, indicating dissolution of carbonate minerals as a primary catalyst for buffering the low pH of rainwater and increasing pH. However, the distribution and concentrations of other anions indicate additional rock/water reactions and possible mixing with other water sources to explain the evolution of groundwater geochemistry. For instance, several sites with low bicarbonate concentrations were in the extreme eastern extent of the aquifer in Clark County, but samples from these wells exhibit some of the highest pH values and highest sulfate concentrations (fig. 80). Further discussion on the occurrence and distribution of the major anions is found below.

### Nitrate

Nitrate concentrations ranged from 0.02 to 1.9 mg/L as nitrogen with a median of 0.43 mg/L (table 35). All concentrations were below the MCL of 10 mg/L. Insufficient data were available to assess any relations of nitrate with depth. However, wells with nitrate concentrations exceeding 0.5 mg/L were less than 200 ft below the land surface. Well depths ranged up to 380 ft.

**Table 35.** Descriptive statistics for selected chemical constituents in groundwater from the Ozan aquifer in southwestern Arkansas.

[mg/L, milligrams per liter; μg/L, micrograms per liter; μS/cm, microsiemens per centimeter at 25 degrees Celsius]

| Constituent or characteristic | Minimum | Median | Maximum | Standard deviation | Number of wells |
|---|---|---|---|---|---|
| Calcium (mg/L) | 0.8 | 3.4 | 6.0 | 2.6 | 2 |
| Magnesium (mg/L) | 0.35 | 1.32 | 2.3 | 0.97 | 2 |
| Sodium (mg/L) | 33.6 | 477 | 920 | 443 | 2 |
| Potassium (mg/L) | 1.62 | 2.21 | 2.8 | 0.59 | 2 |
| Bicarbonate (mg/L) | 96 | 261 | 560 | 154 | 14 |
| Chloride (mg/L) | 5.3 | 479 | 2,100 | 771 | 14 |
| Sulfate (mg/L) | 4.9 | 230 | 517 | 151 | 14 |
| Silica (mg/L) | 11.1 | 12.1 | 13 | 0.95 | 2 |
| Nitrate (mg/L as nitrogen) | 0.02 | 0.43 | 1.9 | 0.54 | 12 |
| Dissolved solids (mg/L) | 136 | 1,230 | 2,330 | 1,090 | 2 |
| Iron (μg/L) | 20 | 600 | 1,180 | 580 | 2 |
| Manganese (μg/L) | 19.8 | 19.8 | 19.8 | 0.13 | 1 |
| Arsenic (μg/L) | 0.03 | 0.03 | 0.03 | 0.03 | 1 |
| Hardness (mg/L as calcium carbonate) | 6.0 | 98 | 400 | 128 | 13 |
| Specific conductance (μS/cm) | 213 | 2,550 | 7,200 | 2,370 | 14 |
| pH (standard units) | 6.8 | 8.3 | 8.6 | 0.4 | 14 |

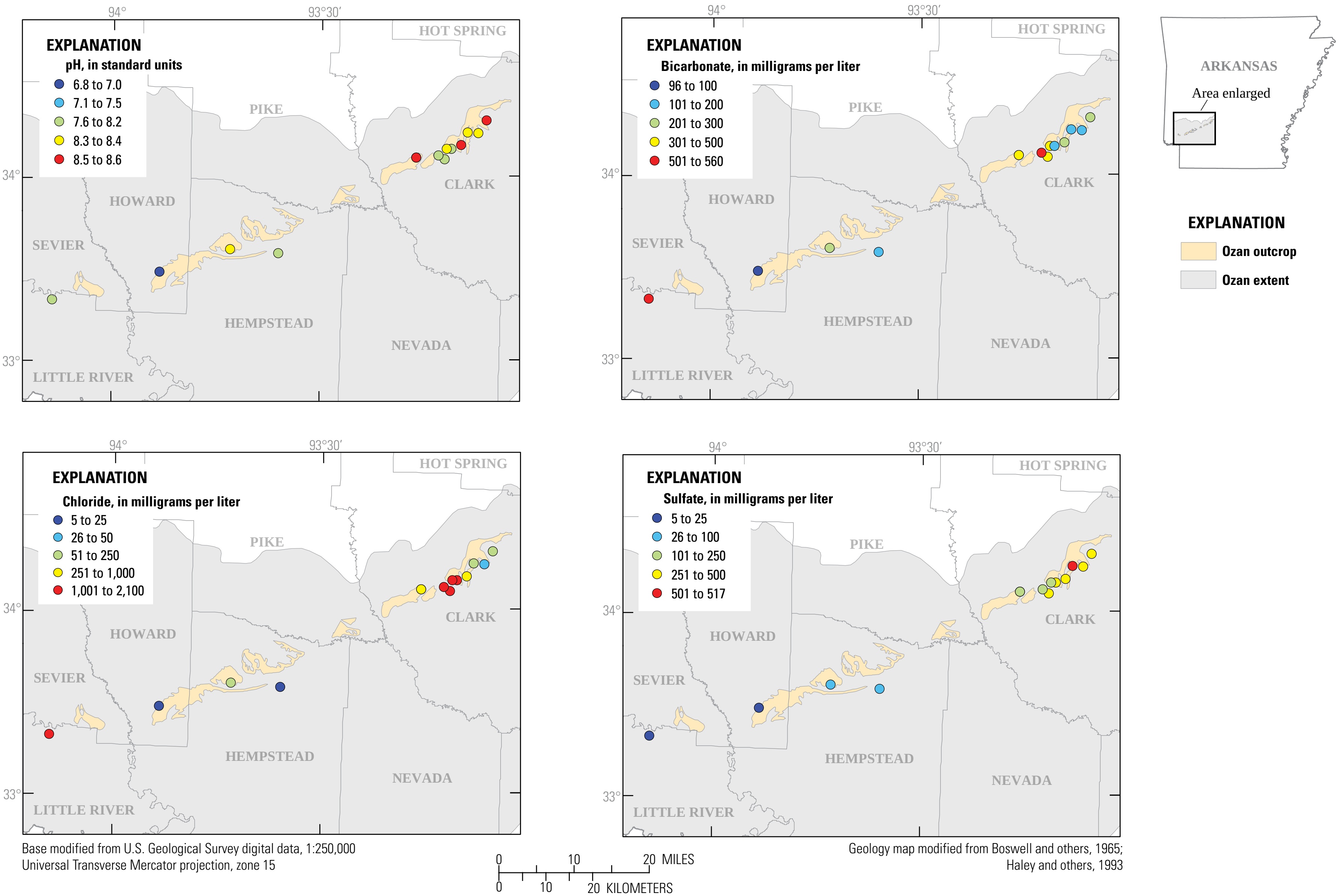



**Figure 80.** Spatial distribution of selected chemical constituents in groundwater from the Ozan aquifer in southwestern Arkansas.

## Iron

Only two wells had iron analyses, with concentrations of 20 and 1,180 µg/L. These two samples reveal that iron concentrations vary widely, similar to other Cretaceous and Tertiary aquifers of the Coastal Plain. Typically, iron concentrations in Coastal Plain aquifers tend to be higher in the outcrop area and decrease downgradient. This is attributed to increasing reducing conditions and formation of iron-sulfide minerals along the flow path. However, data were inadequate to make any assessment of the spatial distribution of iron for the Ozan aquifer.

## Sulfate

Sulfate concentrations ranged from 4.9 to 517 mg/L with a median of 230 mg/L, which is the highest median sulfate concentration of any aquifer in the State (fig. 81; table 35). However, groundwater from the Jackson Group (table 21) contained the overall highest sulfate concentrations of any aquifer. A general relation was observed between sulfate and bicarbonate concentrations. Four wells had sulfate concentrations greater than 300 mg/L (ranging upward to 517 mg/L) with associated bicarbonate concentrations that were less than 300 mg/L. Conversely, five wells had sulfate concentrations less than 300 mg/L and associated bicarbonate concentrations that were greater than 400 mg/L (upward to 542 mg/L) (fig. 82*A*).

## Chloride

Chloride concentrations ranged from 5.3 to 2,100 mg/L with a median of 479 mg/L (fig. 81; table 35). Chloride exceeded the Federal secondary drinking-water regulation of 250 mg/L (U.S. Environmental Protection Agency, 2009) dominantly at sites located in central Clark County with the exception of one site located in northeastern Little River County that had a chloride concentration of 1,100 mg/L (fig. 80). Six wells with chloride concentrations

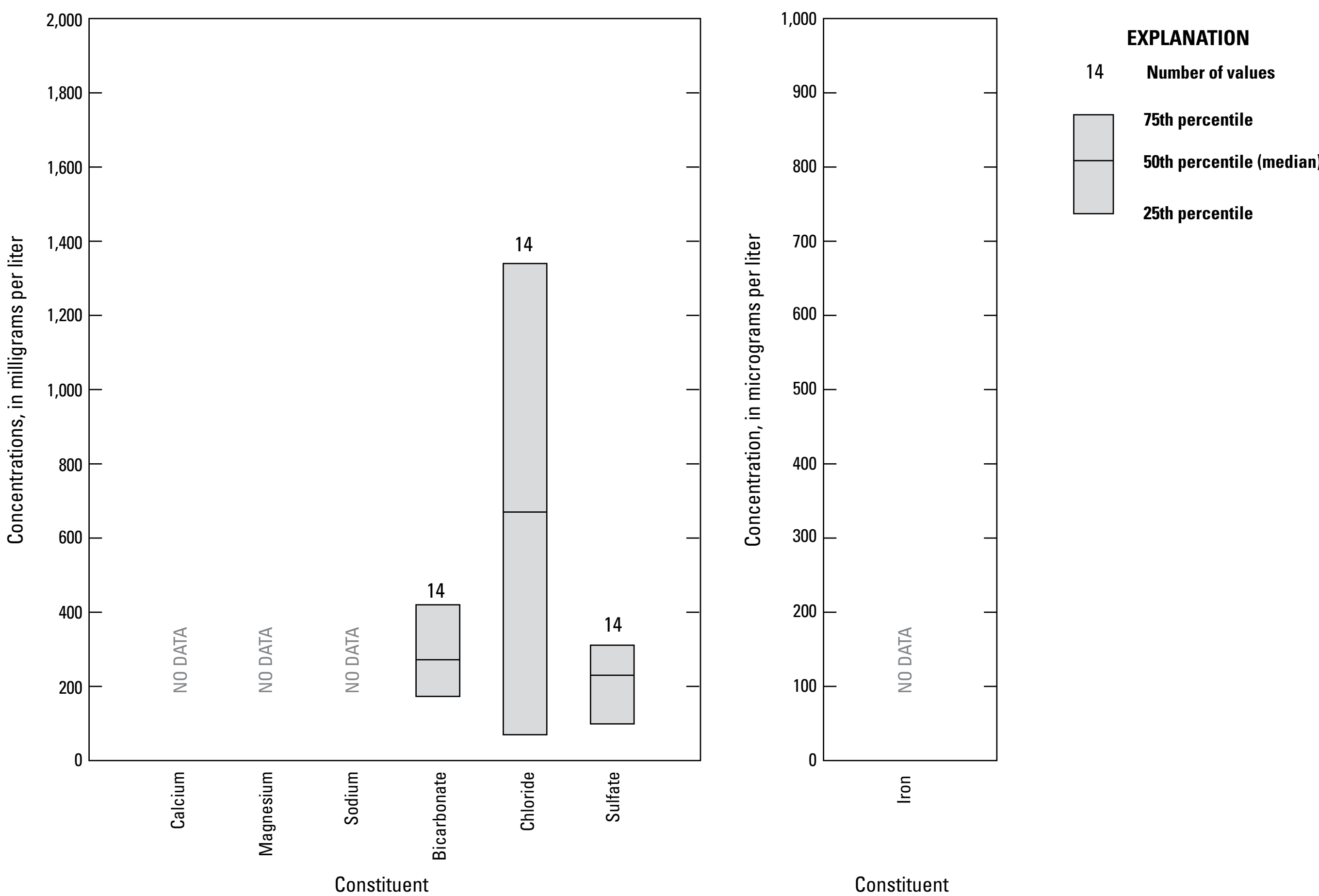



**Figure 81.** Interquartile range of selected chemical constituents in groundwater from the Ozan aquifer in southwestern Arkansas.

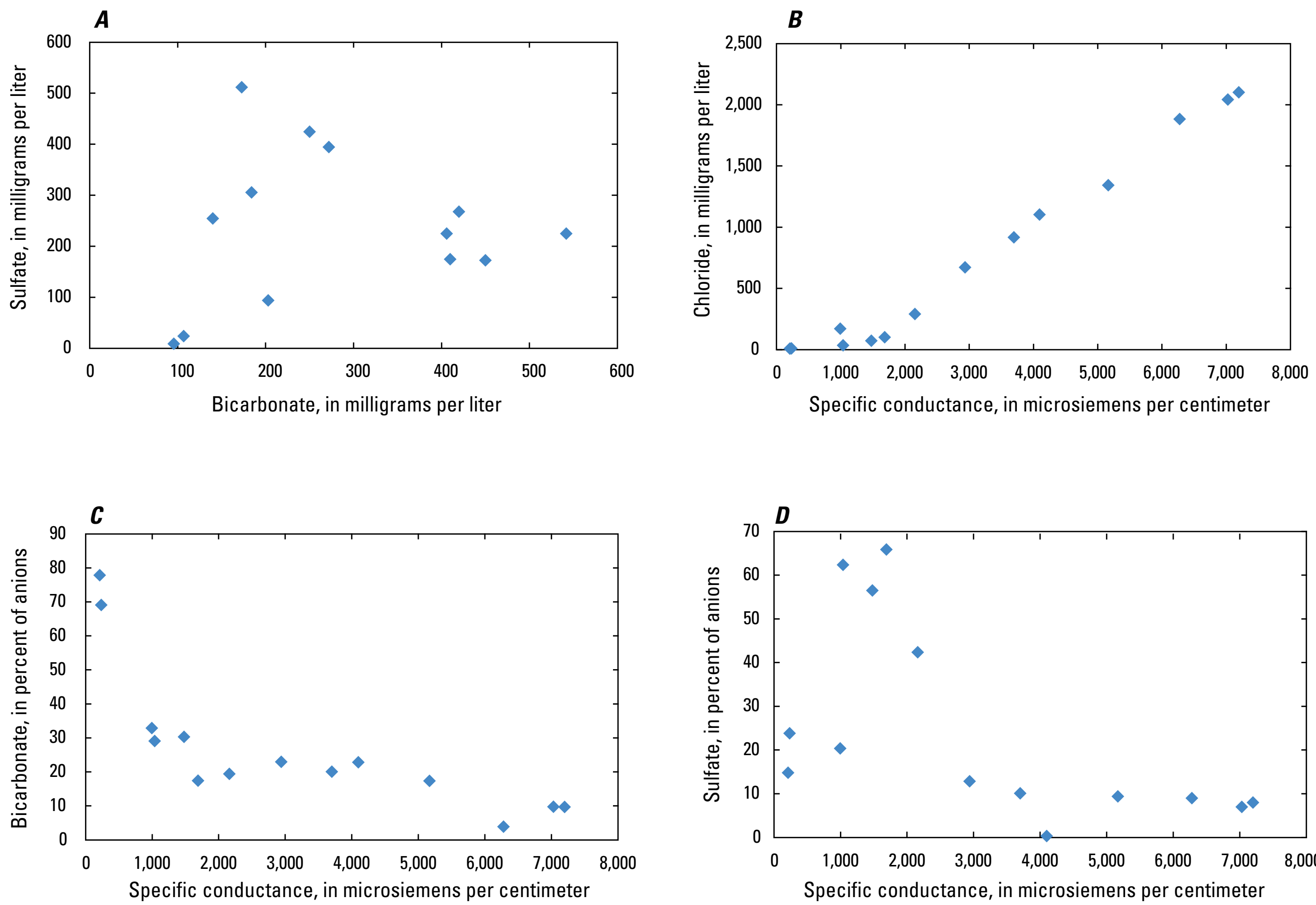



**Figure 82.** Relation of *A*, bicarbonate and sulfate; relation of specific conductance and *B*, chloride; *C*, percent bicarbonate; and *D*, percent sulfate in groundwater from the Ozan aquifer in southwestern Arkansas.

exceeding 250 mg/L in Clark County ranged in depth from 150 to 360 ft. These were located in the outcrop area, and the depths are relatively shallow compared to other high-chloride occurrences in Cretaceous and Tertiary aquifers in southwestern Arkansas. Because the outcrop generally represents the area of recharge and shallow well depths, flushing of residual salinity would normally occur resulting in lower chloride concentrations. Other Cretaceous formations generally contained freshwater in and near the outcrop with higher salinity occurring downgradient. No mechanisms for the cause of high chloride were provided in older reports. The authors also cannot provide mechanisms confidently because of the lack of information for this unusual occurrence. Counts and others (1955) noted the low well yields from a dominant sandy-clay facies of the Ozan in the area of outcrop, and one plausible explanation for elevated chloride concentrations may be that residual connate water in the high percentage clayey deposits of the Ozan Formation have not been sufficiently flushed over time. Another possible explanation is that elevated chloride concentrations result from the upwelling of high-salinity groundwater from underlying formations.

## Conceptual Model of Groundwater Geochemical Evolution

Although only two samples had analysis of dissolved solids, all samples had field specific conductance, which is a reasonable proxy for assessing changes in constituent concentrations with increased residence time in the aquifer. Specific conductance and chloride show a positive linear relation when specific conductance values exceed 2,000 µS/cm (fig. 82*B*). Analysis of the geochemical data shows that bicarbonate or sulfate is the dominant anion (by weight) for specific conductance values less than approximately 2,000 µS/cm. Therefore, certain assumptions can be made in regard to geochemical evolution of groundwater in the Ozan aquifer based on extensive review of other aquifers in the Coastal Plain.

Groundwater from the Ozan aquifer appears to be dominated by bicarbonate in the early stages along the groundwater flow path with short residence time within the aquifer. This is reflected in two samples with bicarbonate greater than 50 percent of anions and values of specific conductance less than 1,000 µS/cm (fig. 82*C*). A sharply decreasing trend is noted for percent bicarbonate when specific conductance is greater than 1,000 µS/cm. Therefore, this fits the model of early-stage carbonate-mineral dissolution observed for many aquifers of the State. This model typically results in a calcium-bicarbonate to sodium-bicarbonate water type with increased carbonate dissolution and cation exchange. For samples with specific conductance values between approximately 1,000 and 2,200 µS/cm, sulfate is the dominant anion (fig. 82*D*). Groundwater with higher sulfate than bicarbonate concentrations is theorized to be derived from dedolomitization processes in the aquifer, in which gypsum dissolution leads to calcite precipitation (see sections on Tokio and Trinity aquifers). Groundwater with specific conductance values exceeding approximately 2,200 µS/cm has chloride as the dominant anion (ranging from 64 to 87 percent of total anions). Chloride additionally exhibits a positive linear relation with specific conductance for specific conductance values greater than 2,200 µS/cm (fig. 82*B*). The increasing chloride concentration may result from dissolution of residual salts (or saline water) that have not been flushed from the original marine deposits or from leakage of high-salinity water from underlying formations. Thus, one model of geochemical evolution of groundwater in the Ozan aquifer is carbonate dissolution in the early phases resulting in a bicarbonate water type, transitioning to a sulfate-dominated water type with dissolution of gypsum, and eventually to a chloride water type by mixing with high-salinity water. Groundwater with elevated chloride concentrations would be expected to contain elevated sodium (sodium-chloride type water), which is a concern for consumptive use (U.S. Environmental Protection Agency, 2009). One groundwater sample contained chloride and sodium concentrations of 1,100 mg/L and 920 mg/L, respectively, which may be a problem for individuals with a restricted sodium diet.

In summary, groundwater from the Ozan aquifer is some of the least used and poorest quality water in the State. Several reports mentioned that use of the aquifer as a domestic source was predicated on the fact that no other water source was available. High chloride concentrations occur in groundwater within the outcrop area of the Ozan aquifer, which is atypical of most Cretaceous and Tertiary aquifers of the Coastal Plain. Elevated sulfate concentrations and pH from wells located in the northeastern extent are attributed to possible gypsum dissolution coupled to calcite precipitation.

## Tokio Aquifer

Cretaceous formations in Arkansas (Nacatoch Sand, Ozan Formation, Tokio Formation, and the Trinity Group) and the aquifers comprised by these formations are not included in any of the regional hydrogeologic framework models of the Mississippi embayment (Arthur and Taylor, 1990; Hosman and Weiss, 1991; Hart and others, 2008; Clark and Hart, 2009); however, the Tokio was included in the hydrologic investigations atlas for Segment 5 (Arkansas, Louisiana, and Mississippi) of Renken (1998) as the Tokio-Woodbine aquifer. The aquifer is referred to as the Tokio aquifer in various USGS water-use and water-level reports referenced herein; the most recent being Holland (2007) and Schrader and Rodgers (2013). This report will follow this terminology and for purpose of this report, the saturated part of the Tokio Formation yielding groundwater to wells in Arkansas will be referred to hereinafter as the "Tokio aquifer."

### Geology

The Tokio Formation is a Cretaceous-age, clastic formation primarily comprising sand and gravel units with interbedded clay and marl, ranging in thickness from 50 to more than 300 ft (Boswell and others, 1965). The Tokio Formation initially was included with strata named as the Bingen Sand by Hill (1888). Stephenson (1927) divided the Bingen Sand into the Tokio Formation and the Woodbine Formation, discarding the term Bingen Sand. During the Cretaceous age, a considerable change of sea depth occurred in Arkansas after deposition of the Lower Cretaceous formations. While deepening water resulted in more clayey and carboniferous rocks being deposited during the Upper Cretaceous, Lower Cretaceous units in Arkansas, including the Tokio Formation, mainly were nearshore deposits (Veatch, 1906).

The Tokio Formation unconformably overlies consolidated rocks of Mississippian and Pennsylvanian age in Clark and northeastern Nevada Counties (Plebuch and Hines, 1969); overlies the Trinity Group in Pike, Nevada, Miller, and most of Hempstead Counties (Petersen and others, 1985); and overlies the Woodbine Formation in Little River, Sevier, Howard, and northwestern Hempstead Counties (Boswell and others, 1965). The Tokio is overlain by the Brownstown Marl, although in an area of Union County, the Brownstone Marl is absent and the Tokio is overlain by the Ozan Formation (Boswell and others, 1965; Zachry and others, 1986). The formation outcrops from Clark County southwestward to Sevier County and attains a maximum width of about 10 mi in Howard County (Schrader and Blackstock, 2010). The Tokio consists of discontinuous, interbedded gray clay and poorly sorted crossbedded sands, lignite, and scattered carbonaceous materials. In some areas, there is a prominent basal gravel (Counts and others, 1955; Boswell and others, 1965; Dollof and others, 1967; Plebuch and Hines, 1969; Petersen and others, 1985).

The Tokio Formation dips at about 60 ft/mi to the southeast away from the outcrop and ranges in thickness from 50 to more than 300 ft (Boswell and others, 1965), obtaining its maximum thickness in Miller County (Dollof and others, 1967). A fault zone through the Tokio occurs across Miller, Little River, Lafayette, Hempstead, Nevada, Ouachita, Calhoun, and Bradley Counties (Petersen and others, 1985, pl. 8). Dane (1929) identified the Tokio as a nearshore marine deposit. The presence of lignite and terrestrial plant fossils indicates nearshore deposition. The basal gravel is interpreted as a beach deposit formed by a transgressing sea with the gravel mainly being reworked from older Cretaceous formations (Dane, 1929).

In southern Sevier County and parts of Howard and Hempstead Counties, the Tokio comprises three distinct aquifers, including a basal sand that grades to gravel to the east and two upper sands (Boswell and others, 1965). Toward the east, the clay layers separating the sands thin, and the sands merge into a single massive sand aquifer, which is prevalent over most of Hempstead, southern Pike, and northern Nevada Counties.

## Hydrologic Characteristics

The Tokio aquifer receives direct recharge at its outcrop and from the overlying alluvial deposits where it subcrops (Boswell and others, 1965). At its outcrop, the Tokio weathers into a sandy soil, facilitating percolation of surface and rainwater into the sand (Counts and other, 1955). Well depths and yields vary throughout the aquifer. Ludwig (1972) listed well depths ranging from less than 30 ft to 1,200 ft below land surface for parts of Hempstead, Lafayette, and Little River Counties. Most wells in the Tokio have low yields, but some produce 150–300 gal/min. Many are flowing artesian wells that typically produce less than 20 gal/min. The Tokio is the most important source of water from flowing artesian wells in southwestern Arkansas. Wells in central Hempstead County yield as much as 300 gal/min. Wells flowing at rates as much as 90 gal/min occur adjacent to streams (Counts and others, 1955). Wells in northwestern Little River County penetrated a 15- to 20-ft thick, water-bearing sand that produced yields of less than 10 gal/min (Ludwig, 1973). The prevalence of artesian wells in the Tokio indicates that the aquifer is confined away from the outcrop and the potentiometric surface is above land surface. An aquifer test in southern Howard County resulted in a transmissivity of about 170 $ft^2/d$ and a storage coefficient of 0.000044. A test using a public-supply well in Hempstead County resulted in a transmissivity of about 600 $ft^2/d$ (Boswell and others, 1965).

## Water Use

The Tokio aquifer dominantly has been used as a source of domestic water supply. Counts and others (1955) recorded 143 domestic wells in the Tokio aquifer in Clark, Hempstead, Howard, Nevada, Pike, and Sevier Counties in southwestern Arkansas. Many of these wells originally were flowing. An estimated 66 percent of water was lost from the total 3 Mgal/d that was withdrawn in southwestern Arkansas as a result of uncontrolled flowing artesian wells (Boswell and others, 1965). Domestic-supply and livestock use continued into the late 1960s and early 1970s in Clark County and northwestern Little River County near Winthrop (Plebuch and Hines, 1969; Ludwig, 1973). For 2010, there were 18 wells registered in ARWUDBS from the Tokio (fig. 83). Current (2013) use is for domestic purposes in Hempstead County and for livestock purposes in Howard County.

Several towns in southwestern Arkansas have used the Tokio aquifer for public supply. Hope (Hempstead County) tapped the aquifer in 1918 (Hale and others, 1947). Hope drilled additional wells into the Nacatoch aquifer in 1933 (Hale and others, 1947). The city continues to use groundwater from this and the Nacatoch aquifers but supplements with surface water. Hope withdrew 1.83 Mgal/d, which was 64 percent of its total public-supply use from this aquifer in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Other small communities in the area including Okolona (Clark County), Mineral Springs (Howard County), Blevins (Hempstead County), and Ben Lomond (Sevier County) tap the Tokio for public supply. Prescott (Nevada County) formerly had one well in the Tokio, which was completed in 1912, and two wells in the Nacatoch (Counts and others, 1955) but now solely withdraws water from the Little Missouri River. Also, wells historically were used at several schools in the area (Counts and others, 1955).

A small amount of industrial use, including gas production near Prescott, a cement company in Howard County, and a handful of lumber operations occurred in the past (Counts and others, 1955). Current industrial use of the aquifer only occurs in Miller County (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

Historical use of the Tokio aquifer by county is listed in table 36. Use of groundwater from the aquifer increased about 200 percent from 1965 to 1980 (fig. 84), the peak year for use of water from the aquifer. Use decreased from 1980 to 1995 and then jumped to a second high in 2000. Since 2000, water use from the Tokio has declined. Approximately 73 percent of water used from the Tokio aquifer is for public supply, 7 percent for industrial use, and the remainder for domestic and livestock uses (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

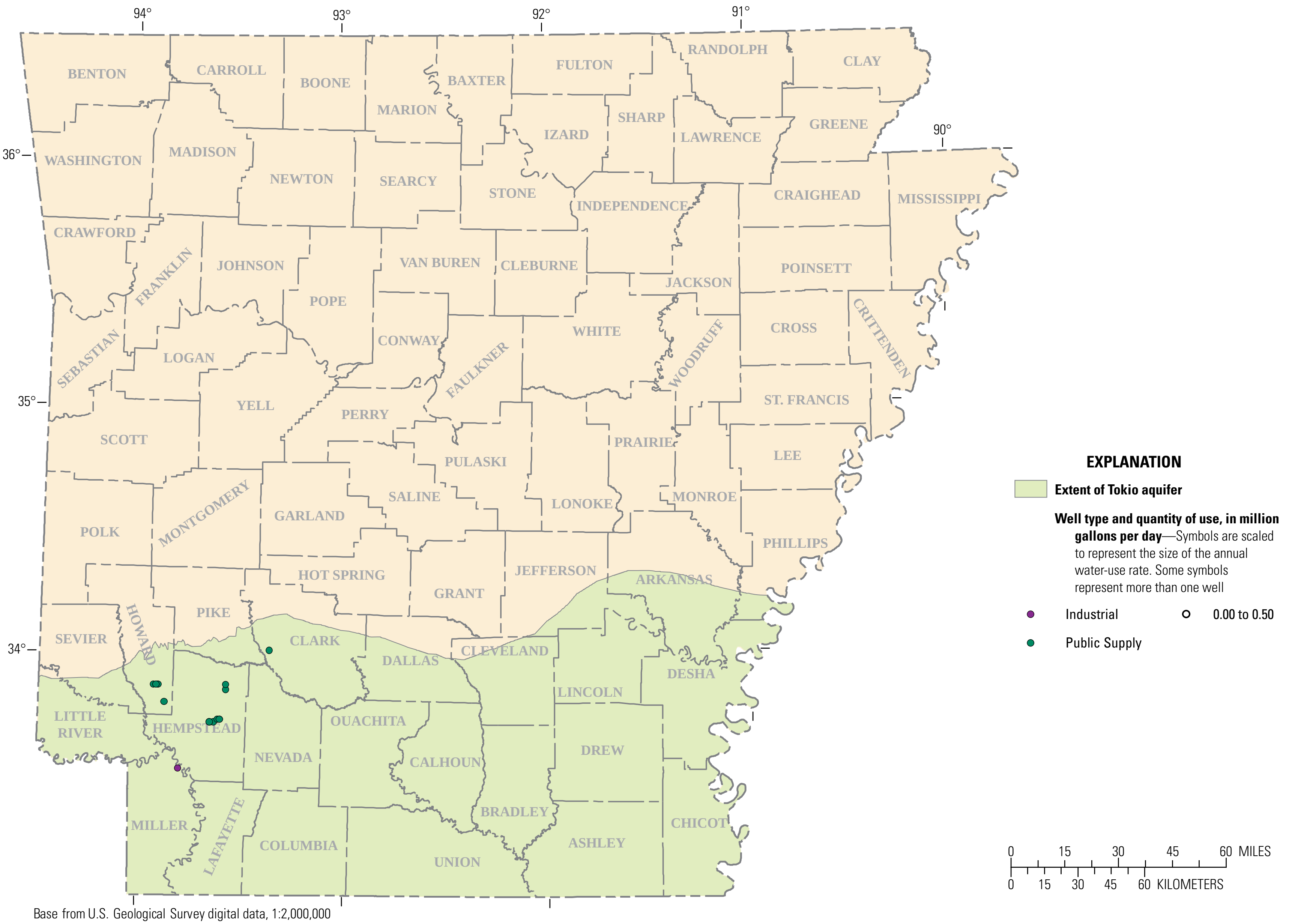



**Figure 83.** Wells with reported water use for the Tokio aquifer in Arkansas, 2010.

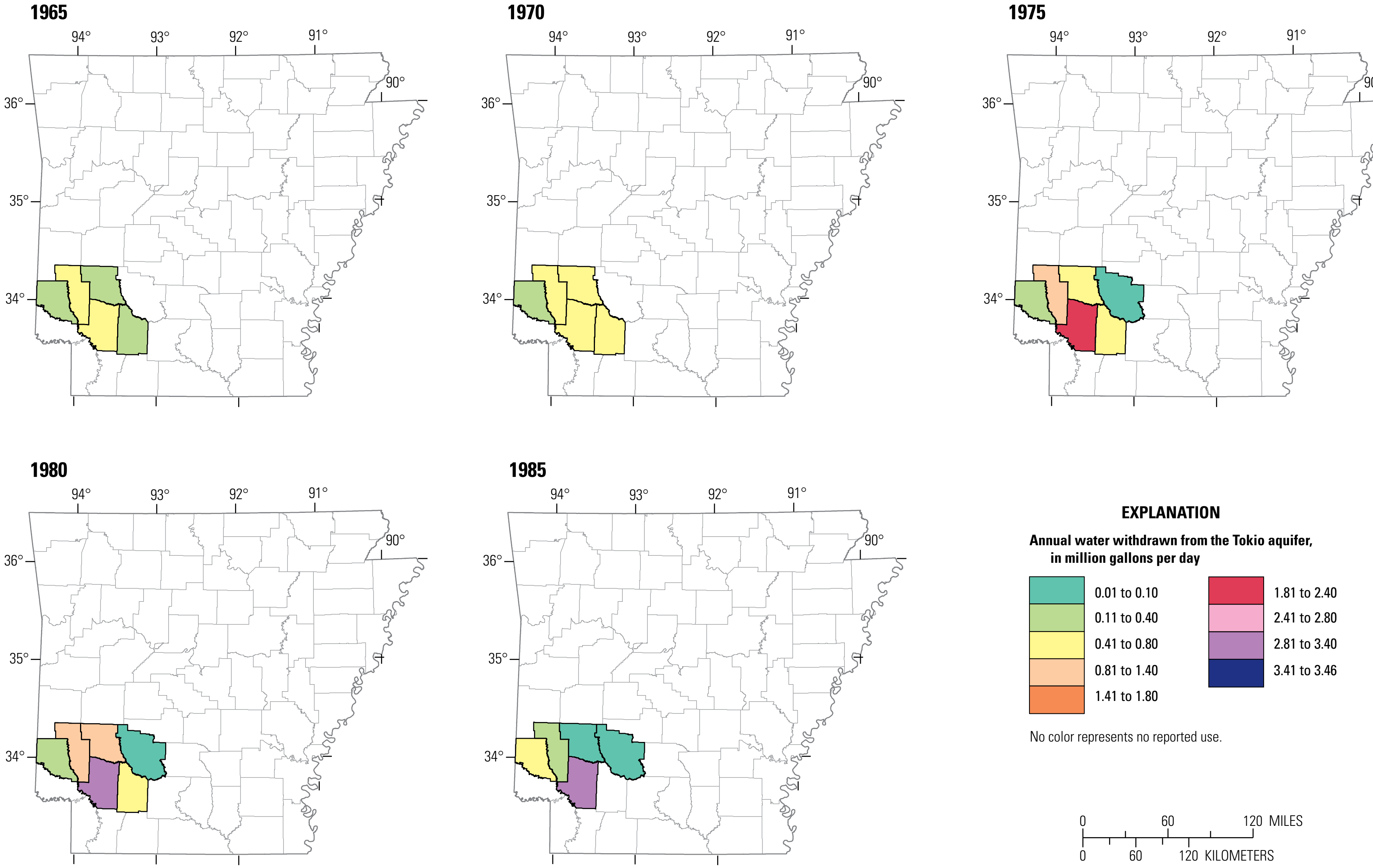
**Table 36.** Water use from the Tokio aquifer in Arkansas, 1965–2010.

[Counties shown are only those with published data. Data from Halberg and Stephens (1966); Halberg (1972, 1977); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

| County | 1965 | 1970 | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|
| Clark | 0.00 | 0.00 | 0.02 | 0.06 | 0.04 | 0.01 | 0.01 | [1]0.06 | 0.07 | 0.06 |
| Hempstead | 0.67 | 0.68 | 2.15 | 3.00 | 2.86 | 1.10 | 1.66 | 3.46 | 2.10 | 2.12 |
| Howard | 0.69 | 0.62 | 0.97 | 1.11 | 0.14 | 0.00 | 0.00 | [1]0.06 | 0.50 | 0.54 |
| Miller | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.15 |
| Nevada | 0.37 | 0.47 | 0.55 | 0.68 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Pike | 0.12 | 0.41 | 0.43 | 0.82 | 0.06 | 0.03 | 0.02 | 0.00 | 0.00 | 0.00 |
| Sevier | 0.15 | 0.17 | 0.25 | 0.35 | 0.79 | 1.15 | 0.54 | 2.36 | 1.73 | 0.00 |
| **Total** | **2.00** | **2.35** | **4.37** | **6.02** | **3.89** | **2.29** | **2.23** | [1]**5.94** | [2]**4.40** | **2.87** |

[1]Unpublished data from Terrance W. Holland, U.S. Geological Survey, written commun., 2013.

[2]In the 2005 report, 0.08 million gallons per day in Sharp County was inadvertently reported as being withdrawn from the Tokio aquifer when it should have been applied to the Everton Formation. Therefore, the published total is slightly different from Holland (2007).




Base from U.S. Geological Survey digital data 1:2,000,000

Data modified from Halberg and Stephens, 1966; Halberg, 1972, 1977; Holland, 1981, 1987, 1993, 1999, 2004, 2007

**Figure 84.** Water-use rates for the Tokio aquifer in Arkansas from 1965 to 2010.

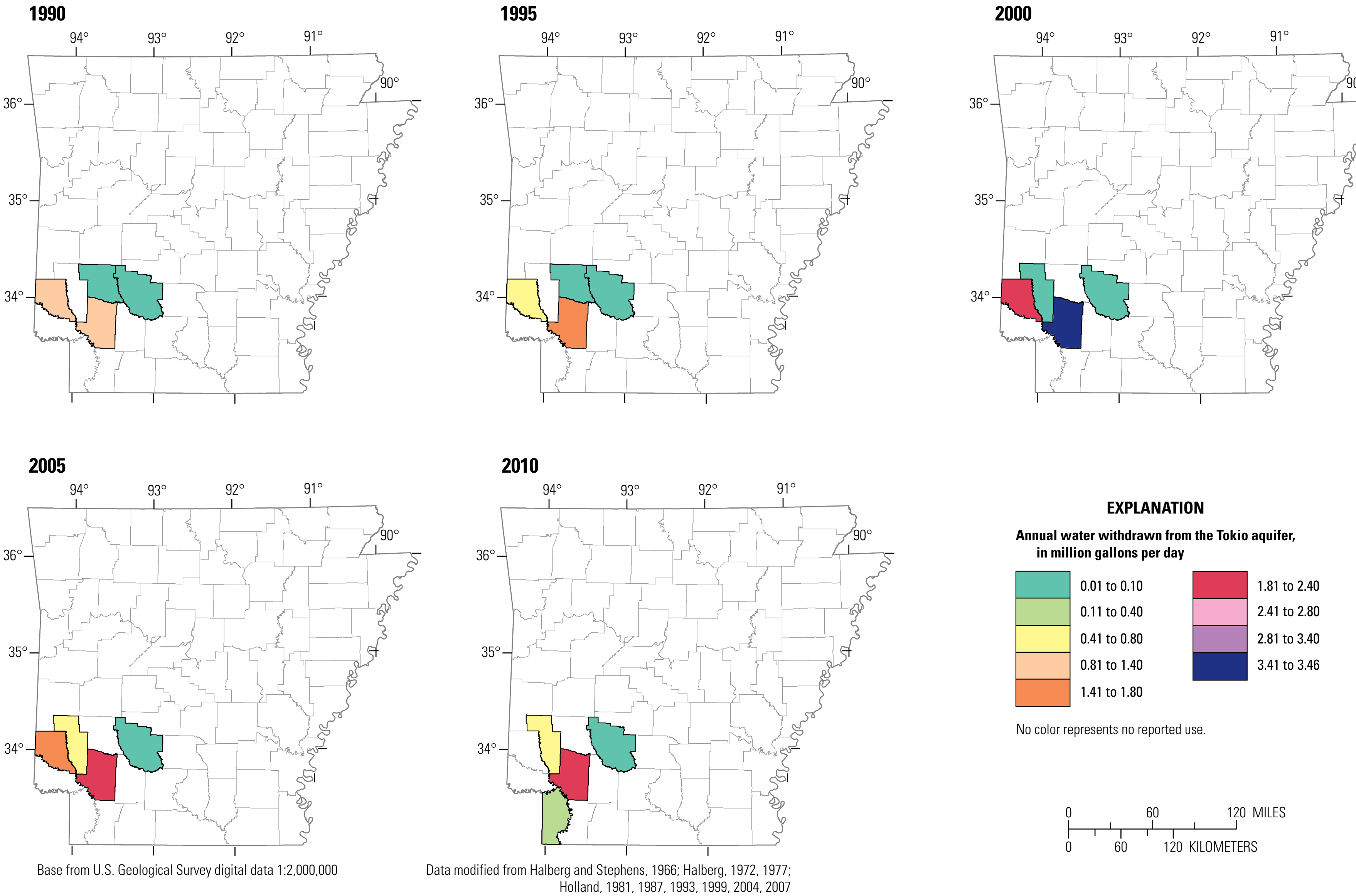



**Figure 84.** Water-use rates for the Tokio aquifer in Arkansas from 1965 to 2010.—Continued

## Water Levels

Long-term ANRC and USGS cooperative monitoring has documented water-level changes in the Tokio aquifer (Schrader, 1998, 1999, 2007b; Schrader and Scheiderer, 2004; Schrader and Blackstock, 2010; Schrader and Rogers, 2013). The potentiometric surface for the Tokio aquifer is highest within the outcrop area in northeastern Howard County (fig. 85), with groundwater flowing to the south and primarily southeast (Counts and others, 1955; Boswell and others, 1965; Plebuch and Hines, 1969; Petersen and others; 1985; Schrader and Blackstock, 2010; Schrader and Rodgers, 2013). No appreciable changes in water levels were noted between the 1996, 1999, and 2001 investigations (Schrader and Scheiderer, 2004), but the addition of a single well changed the position of the 300-ft contour in Howard County for the 2008 potentiometric-surface map (Schrader and Blackstock, 2010). A cone of depression in southern Howard County appeared in the 2011 potentiometric surface (fig. 85). Many reports cite the possibility of a cone of depression forming 5 mi northwest of Hope; however, data are insufficient in the southern part of the study area to confirm this situation (Schrader, 2007; Schrader and Blackstock, 2010; Schrader and Rodgers, 2013). Ludwig (1973) previously reported that large withdrawals from Prescott and Hope did not appear to affect the potentiometric surface between 1950 and 1968.

Water levels in well A (figs. 85 and 86) near the possible cone of depression northwest of Hope have declined with increasing use. A large decline was documented between 1990 and 2000, when water use increased from 1.10 Mgal/d to 3.46 Mgal/d in Hempstead County, a 215-percent increase. Water levels additionally appear to have slowly declined at Prescott; water-level changes in well B previously have been associated with changes in water use in Nevada County. Water levels near the outcrop and artesian-flow areas have remained relatively constant since the 1950s (well C in northeastern Hempstead County and well D in southwestern Howard County; figs. 85 and 86).

## Water Quality

Similar to other Tertiary-age aquifers in southwestern Arkansas, water quality varies with flow direction as controlled by formation dips to the southeast. The Tokio aquifer crops out in a narrow band from southeastern Sevier through western Clark Counties with a small, isolated outcrop located in extreme western Little River County. Most producing wells are located within the larger outcrop belt. Chloride concentrations increased to the southeast in the downgradient (downdip) direction of groundwater flow (Counts and others, 1955; Plebuch and Hines, 1969; Ludwig, 1972). Counts and others (1955) stated that bicarbonate and sulfate were high, indicating a moderately high sodium-bicarbonate to sodium-sulfate water type. Plebuch and Hines (1969) and Ludwig (1973) listed groundwater from the Tokio as a soft to moderately hard, sodium-bicarbonate water type throughout most of its extent, except for areas of increased chloride concentration downgradient from the outcrop area. Iron concentrations were cited as being high in some areas, ranging up to 54 mg/L (Counts and others, 1955; Ludwig, 1972).

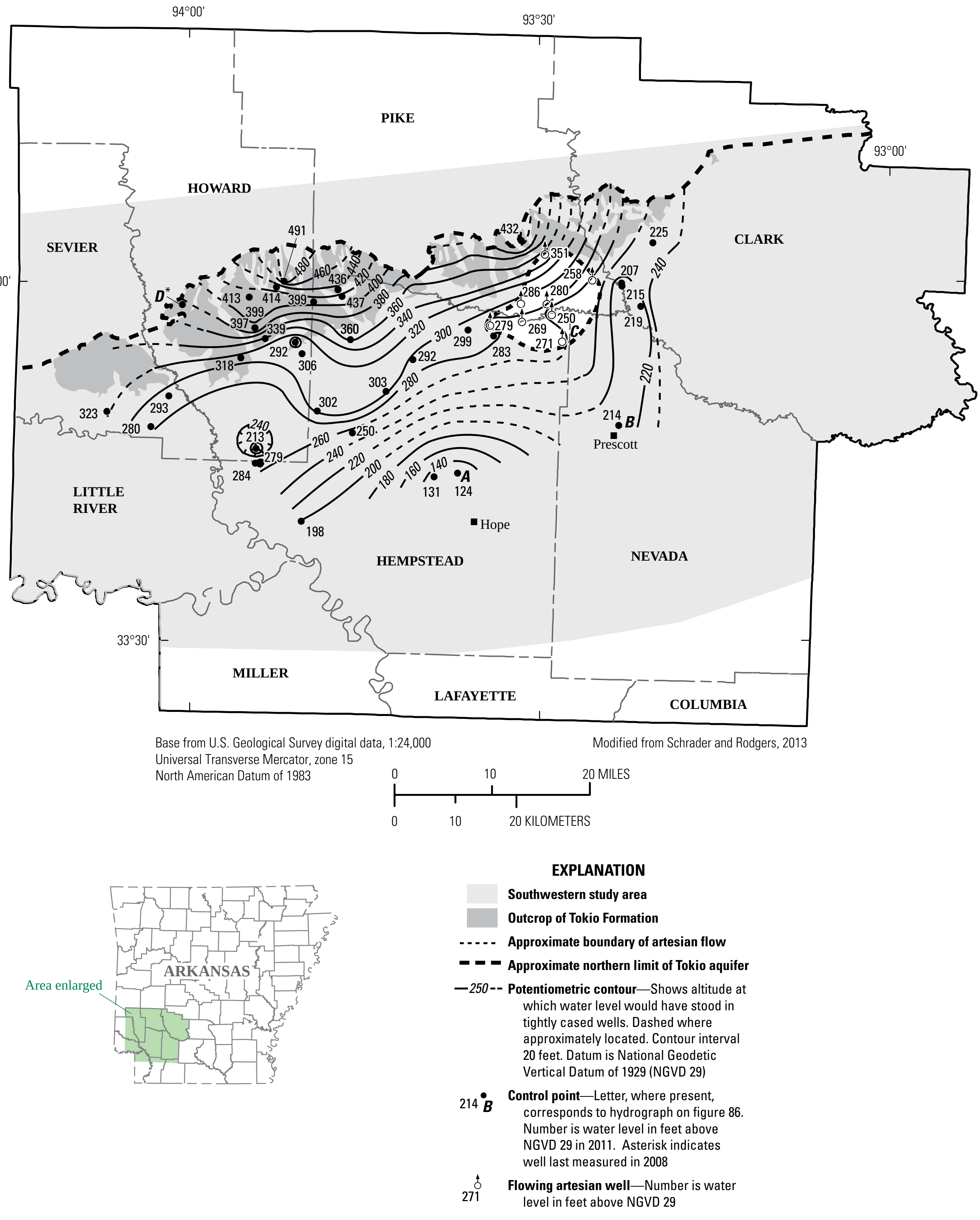



**Figure 85.** Potentiometric surface of the Tokio aquifer in Arkansas, spring 2011.

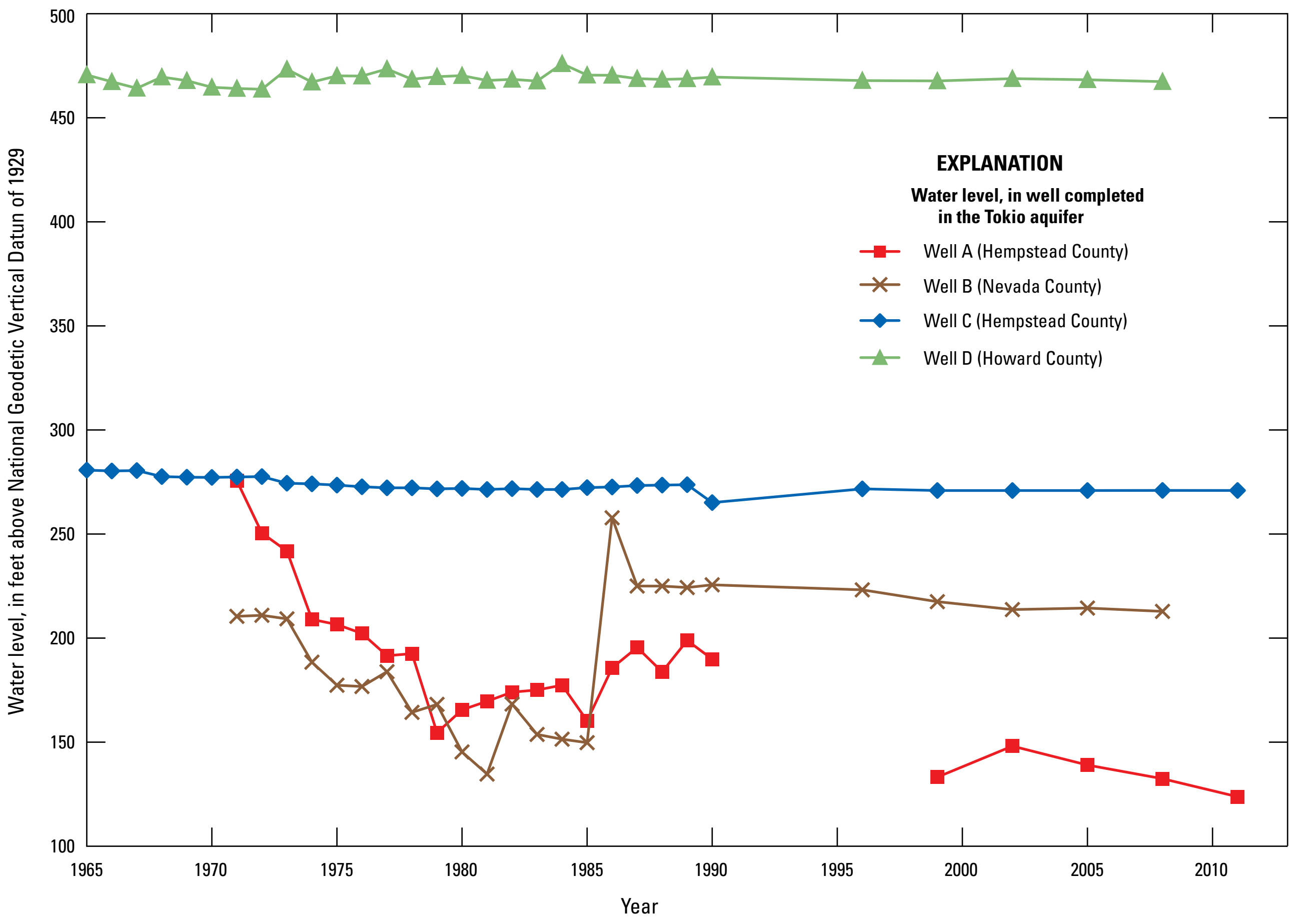



**Figure 86.** Hydrographs of water levels in wells completed in the Tokio aquifer in Arkansas.

## General Geochemistry and Water Type

Similar to other Cretaceous- and Tertiary-age aquifers reviewed in this report, pH values generally were lowest in the outcrop area, reflecting rainwater recharge values. Values of pH increased abruptly within short distances in the downgradient direction of flow as buffered by dissolution of aquifer carbonate minerals (fig. 87). Values of pH ranged from 5.4 to 9.1 standard units with a median of 8.3 (table 37). The median value demonstrates the high-pH characteristic of Tokio groundwater. Only 20 of 158 samples were less than 7.0, and 102 of the 158 samples were greater than 8.0. Values of pH were highest, greater than 8.5, in the southwestern and northeastern outcrop areas. In the southwestern part of the outcrop area, bicarbonate concentrations were very low, which is at odds with application of the carbonate buffering explanation of high pH mentioned earlier. In this area, sulfate was the dominant anion. Detailed discussion of sulfate geochemistry and explanation of high pH values in the southwestern area are found in the “Sulfate” section below.

Most Cretaceous and Tertiary aquifers have sodium as the dominant cation downgradient from their respective outcrop areas, and the Tokio aquifer follows this pattern. Only 29 samples had sufficient major cation data for calculating percent sodium of total cations (in milliequivalents per liter). Samples having percent sodium less than 50 percent of the total cations were from wells in the outcrop area at the origin of the groundwater flow path where groundwater is less geochemically evolved (fig. 87). At the beginning of the flow path, calcium is often the dominant cation, and cation-exchange processes have not appreciably affected groundwater chemistry. The exchange of calcium for sodium on solid-phase exchange sites increases sodium in solution at the expense of calcium, and groundwater transitions ultimately from a calcium- to a sodium-bicarbonate water type along a given flow path. Fifteen samples had greater than 90 percent sodium. All of these wells were located within 2–5 mi of the outcrop area except for one site located on the southern edge of the outcrop area in Howard County.

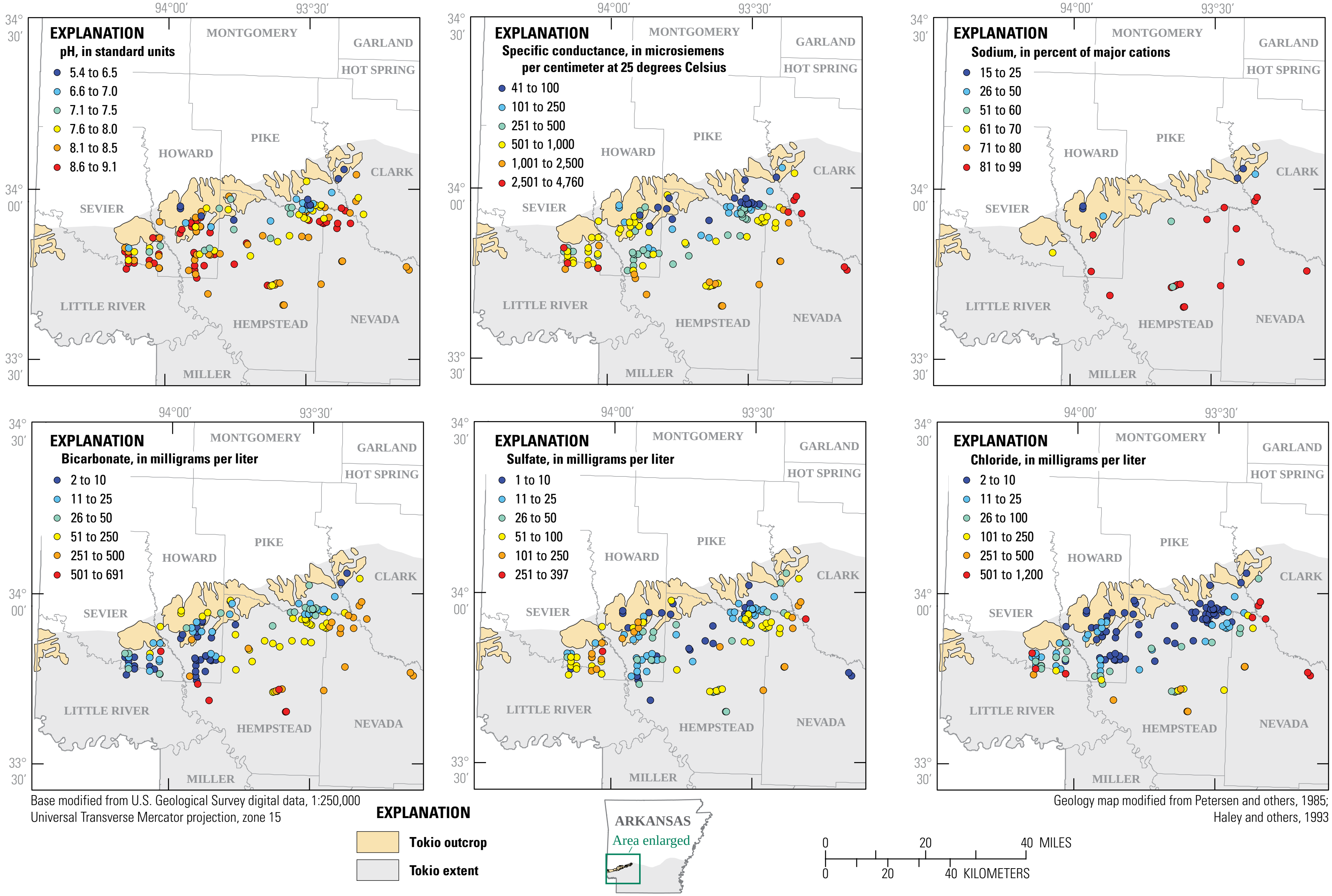



**Figure 87.** Spatial distribution of selected chemical constituents in groundwater from the Tokio aquifer in Arkansas.

**Table 37.** Descriptive statistics for selected chemical constituents in groundwater from the Tokio aquifer in Arkansas.

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

| Constituent or characteristic | Minimum | Median | Maximum | Standard deviation | Number of wells |
|---|---|---|---|---|---|
| Calcium (mg/L) | 0.7 | 5.3 | 66 | 14.8 | 29 |
| Magnesium (mg/L) | 0.07 | 1.2 | 9.2 | 1.95 | 29 |
| Sodium (mg/L) | 1.99 | 196 | 694 | 204 | 29 |
| Potassium (mg/L) | 0.7 | 2.62 | 29 | 5.3 | 28 |
| Bicarbonate (mg/L) | 2.0 | 27 | 691 | 152 | 156 |
| Chloride (mg/L) | 2.3 | 11 | 1,200 | 205 | 159 |
| Sulfate (mg/L) | 1.0 | 31 | 397 | 59.4 | 158 |
| Silica (mg/L) | 4.8 | 13.2 | 28.5 | 6.1 | 26 |
| Nitrate (mg/L as nitrogen) | 0.01 | 0.18 | 4.1 | 0.41 | 154 |
| Dissolved solids (mg/L) | 52 | 498 | 1,820 | 502 | 29 |
| Iron (µg/L) | 0.05 | 80 | 4,000 | 736 | 117 |
| Manganese (µg/L) | 0.13 | 4.09 | 2,100 | 446 | 21 |
| Arsenic (µg/L) | 0.03 | 0.03 | 0.03 | 0.03 | 6 |
| Hardness (mg/L as calcium carbonate) | 2.0 | 48 | 700 | 135 | 155 |
| Specific conductance (µS/cm) | 41 | 435 | 4,760 | 808 | 159 |
| pH (standard units) | 5.4 | 8.3 | 9.1 | 0.8 | 158 |

## Nitrate

Nitrate concentrations in 154 samples generally were low in samples from the Tokio aquifer, ranging from 0.01 to 4.1 mg/L as nitrogen with a median of 0.18 mg/L (table 37). All samples were below the Federal MCL of 10 mg/L as nitrogen (U.S. Environmental Protection Agency, 2009). Typical of other aquifers in the Coastal Plain, higher nitrate concentrations generally were in or near outcrop areas, with low concentrations downgradient. Three of the four samples with nitrate concentrations greater than 1.0 mg/L were in the outcrop area. There was a relatively greater density of nitrate concentrations more than 0.5 mg/L in the southwestern part of the aquifer. Overall low nitrate concentrations precluded an effective relation between nitrate and well depth. However, the two highest nitrate concentrations of 2.0 and 4.1 mg/L were in wells with depths of 25 and 16 ft. Well depths ranged upward to 1,500 ft.

## Iron

The Tokio aquifer generally had the lowest median and maximum iron concentrations of any of the Cretaceous- and Tertiary-age aquifers in Arkansas. Iron concentrations ranged from 0.05 to 4,000 µg/L with a median of 80 µg/L (fig. 88; table 37). The median concentration is below the Federal secondary drinking-water regulation of 300 µg/L (U.S. Environmental Protection Agency, 2009). Iron concentrations generally were lower in and near the outcrop area, although no strong spatial trend was evident for iron concentrations. Several wells that had concentrations exceeding 1,000 µg/L were located 6 mi or more downdip from the outcrop area. Ludwig (1973) stated that elevated iron concentrations were not necessarily indicative of iron originating in the Tokio aquifer; instead, he hypothesized it resulted from a mixing of water in uncased wells from shale formations overlying the Tokio. This could explain the lack of spatial trends noted for other Cretaceous and Tertiary aquifers, such as higher iron concentrations in outcrop areas.

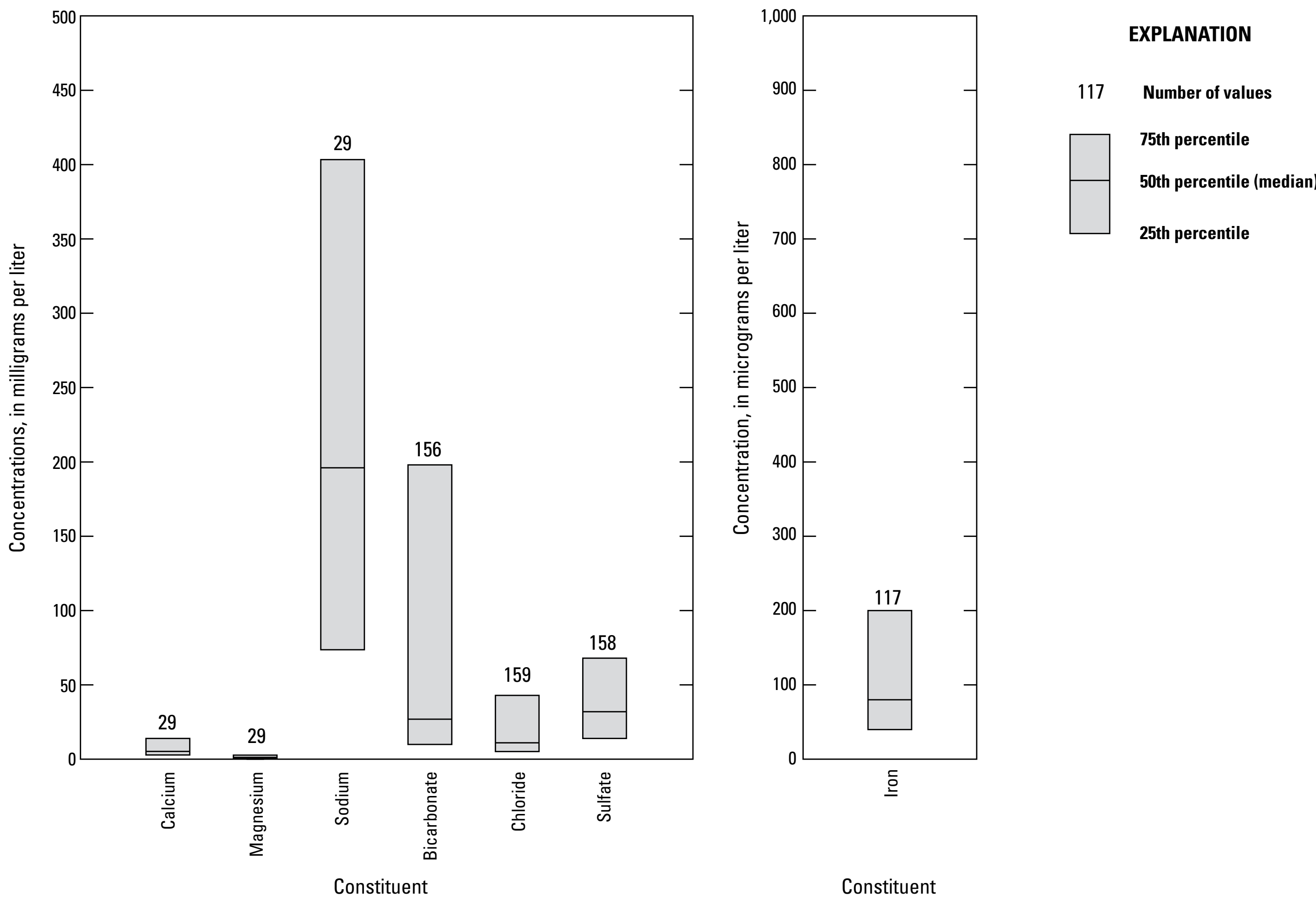



**Figure 88.** Box plots showing interquartile range for selected chemical constituents in groundwater from the Tokio aquifer in Arkansas.

## Sulfate

Sulfate concentrations for the Tokio aquifer ranged from 1.0 to 397 mg/L with a median of 31 mg/L (fig. 88; table 37). This median concentration was an order of magnitude higher than in the Sparta, Cockfield, Carrizo, Cane River, and Wilcox aquifers. Only the Ozan and Jackson Group aquifers had higher sulfate concentrations, with medians of 230 and 110 mg/L, respectively. Therefore, the Tokio exhibits a wider range and higher concentrations of sulfate compared to other Cretaceous and Tertiary aquifers. Counts (1955) stated that bicarbonate and sulfate concentrations frequently were high in the Tokio, indicating a moderately high sodium-bicarbonate to sodium-sulfate water type. However, Ludwig (1972) had little mention of elevated sulfate in the aquifer. The spatial distribution of sulfate suggests very different geochemical processes controlling groundwater-evolution trends in various parts of the Tokio.

Prior to this discussion, a review of general salinity trends is useful. Conceptually, salinity is represented by the quantity of dissolved salts in water, which is directly related to the dissolved-solids concentration. Only 29 of 160 wells with water-quality data had analyses for dissolved solids. However, 159 of the wells had specific conductance values. Specific conductance exhibited a strong linear relation with dissolved solids with a coefficient of determination ($R^2$) value of 0.99 (fig. 89*A*) from a regression analysis (Helsel and Hirsch, 2002), making specific conductance an excellent proxy for dissolved solids by the equation:

$$\underline{DS} = (0.556 \times \underline{SC}) + 35.7 \qquad (1)$$

where

$\underline{DS}$ is the concentration of dissolved solids in milligrams per liter, and

$\underline{SC}$ is the specific conductance in microsiemens per centimeter.

An inspection of the spatial distribution of specific conductance values revealed steep gradients for increases in groundwater salinity downgradient from the outcrop area (fig. 87). Specific conductance values exceeding

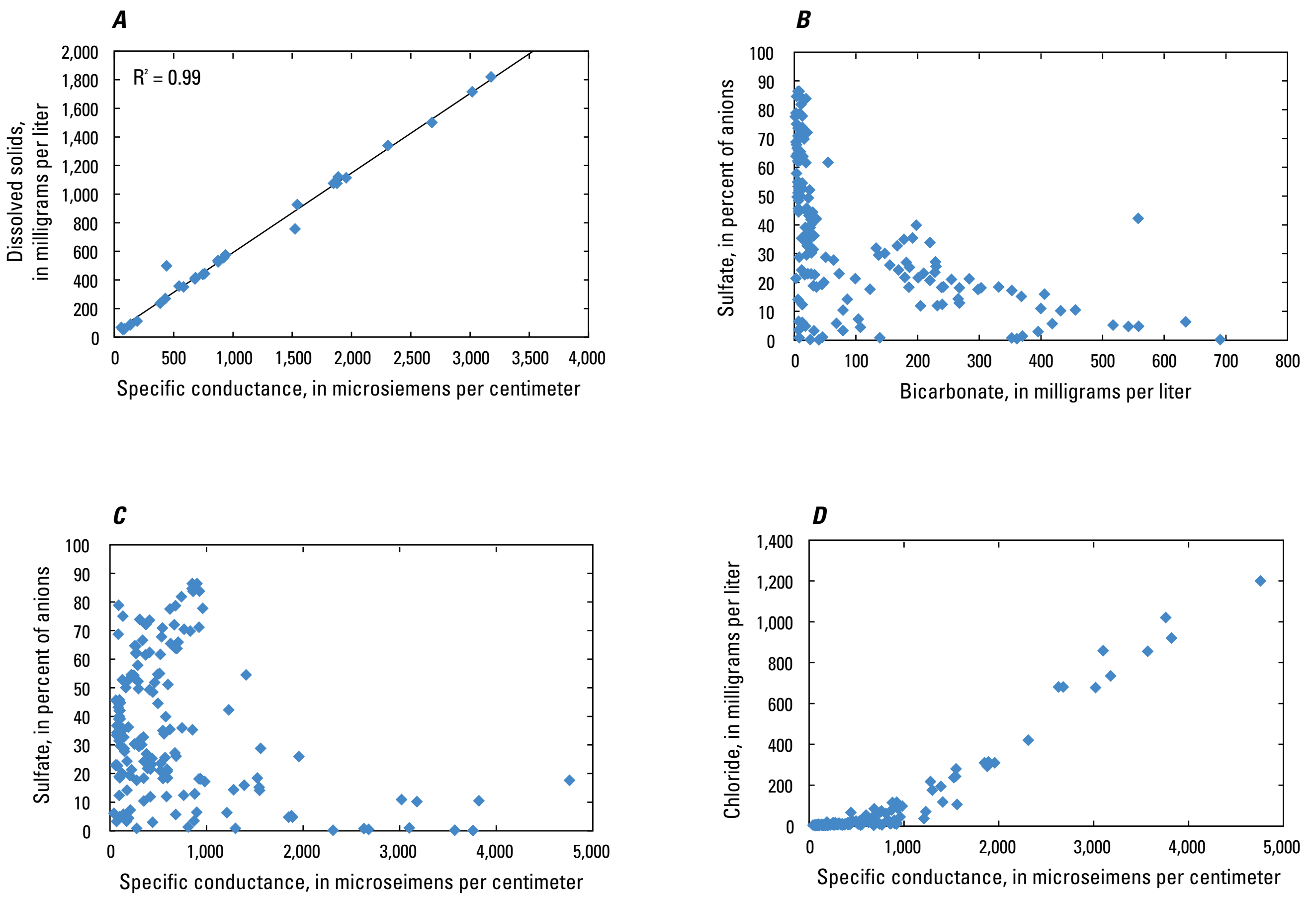



**Figure 89.** Relation of *A*, specific conductance and dissolved solids; *B*, sulfate and bicarbonate; *C*, specific conductance and sulfate; and *D*, specific conductance and chloride in groundwater from the Tokio aquifer in Arkansas.

2,500 µS/cm are located within 1–5 mi of the outcrop areas in the southwestern and northeastern parts of the aquifer. Conversely, no values exceeding 2,500 µS/cm are noted in the central part. Even as far as 15–20 mi from the outcrop area, specific conductance values are less than 2,500 µS/cm in the central part of the aquifer. This situation is similar to the Nacatoch aquifer, which exhibited sharper salinity gradients in the southwestern and northeastern parts of the aquifer compared to the central part.

These abrupt increases in salinity, indicated by increases in specific conductance, appear to be the result of different processes in the southwestern and northeastern areas of the aquifer. In the northeastern part of the aquifer, the higher-conductance groundwater is dominated by chloride and bicarbonate as the major anions. Six samples have chloride concentrations exceeding 500 mg/L, and 14 samples have bicarbonate concentrations exceeding 250 mg/L and ranging upward to 432 mg/L (fig. 87). The increase in salinity in the northeastern area is similar to other Cretaceous aquifers, where salinity tends to increase within short distances in the downgradient direction of flow. There usually is a clear transition from a calcium- or sodium-bicarbonate water in and near the outcrop area to a sodium-chloride water type downgradient. In the extreme southwestern part of the aquifer, sulfate is the dominant anion, rather than bicarbonate or chloride. Only 4 of 27 wells in the southwestern part of the aquifer had chloride concentrations exceeding 250 mg/L, and all but 2 wells had bicarbonate concentrations less than 50 mg/L (many less than 10 mg/L) (fig. 87). When sulfate was the dominant anion (sulfate greater than 50 percent of anions in milliequivalents per liter), bicarbonate concentrations generally were less than approximately 25 mg/L. An inverse relation was noted between percent sulfate and bicarbonate concentrations (fig. 89*B*). Additionally, sulfate-dominated groundwater generally occurred in less mineralized water. When sulfate was the dominant anion, conductance values generally were less than approximately 800 µS/cm (fig. 89*C*), which correlates to a dissolved-solids concentration of about 480 mg/L. Thus, sulfate concentrations did not increase with increasing dissolved solids along the flow path, typical of other Cretaceous aquifers, but rather constitutes the major anion chemistry in this area.

For Arkansas aquifers, bicarbonate concentrations generally exceed sulfate concentrations. One mechanism that results in high (greater than 20 mg/L) sulfate concentrations is diffusion from fine-grained sediments. Fine-grained sediments often contain several hundred milligrams per liter of sulfate, whereas concentrations in coarse-grained sediments are less than 50 mg/L (Chapelle, 2001). Although abundant clays are noted for most of the Cretaceous formations in southwestern Arkansas, this mechanism does not account for the increases in sulfate with concomitant decreases in bicarbonate concentrations. This mechanism also does not explain the high pH values (greater than 8.5 standard units) in this area.

A second viable mechanism that results in elevated sulfate concentrations is dedolomitization. Sacks (1996) noted that high-sulfate groundwater in Florida was controlled by gypsum and dolomite dissolution linked with calcite precipitation. This process, referred to as dedolomitization, accounts for increased sulfate concentrations with concomitant decreases in bicarbonate for several areas of the country (Appelo and Postma, 1999). Gypsum (a mineral composed of calcium and sulfate) is cited as a source of sulfate in other Cretaceous and Tertiary aquifers in southwestern Arkansas. Thus, dedolomitization provides a plausible explanation for elevated sulfate that is consistent with the geochemistry of groundwater, particularly bicarbonate and chloride, in the southwestern part of the aquifer. Only a limited number of samples had major cation chemistry (table 37) including calcium, magnesium, sodium (29 samples), and potassium (28 samples), whereas most samples had major anion chemistry including bicarbonate (156), chloride (159) and sulfate (158). This precludes detailed analysis of mineral equilibrium constraints on resulting groundwater geochemistry. Availability of more detailed geochemical data sets would enable such an analysis and provide a more confident determination of dissolved-species sources.

### Chloride

Similar to other Cretaceous aquifers in southwestern Arkansas, salinity was noted to increase to the southeast in the downdip direction of groundwater flow (Counts and others, 1955; Plebuch and Hines, 1969; Ludwig, 1973). Chloride exhibited a positive, linear relation with specific conductance values greater than 1,000 µS/cm, indicating dominance of chloride in the higher salinity groundwater (fig. 89*D*). The elevated salinity in southern Arkansas led Zachry and others (1986) to investigate the potential of injecting wastewaters from petroleum exploration into Cretaceous aquifers in southern Arkansas as the groundwater was too saline for other uses.

Chloride concentrations from the Tokio aquifer ranged from 2.3 to 1,200 mg/L with a median of 11 mg/L (fig. 88; table 37). This median concentration is capable of being derived naturally from evapotranspiration of infiltrating precipitation (Kresse and Fazio, 2002). Similar to the Nacatoch aquifer, gradients of increasing salinity are sharper along the northeastern and southwestern parts of the aquifer. Chloride concentrations exceeding 500 mg/L occurs within 1–5 mi of the outcrop area in the western and eastern parts of the aquifer. In the central part of the aquifer, chloride concentrations are less than approximately 300 mg/L as much as 20 mi from the outcrop area (fig. 87). Thus, the central part of the aquifer affords a much larger area of low-salinity groundwater for various uses. There was no variation in formation structure or dominant stratigraphy to explain the observed chloride distribution. Further investigations into the spatial variation in geochemistry for the Tokio aquifer ultimately will require a more indepth analysis of stratigraphy, sediment mineralogy, and redox zonation.

In summary, good-quality water is obtained from the Tokio aquifer throughout much of its extent. Sharp increases in salinity are noted in the extreme southwestern and northeastern parts of the aquifer, limiting use at distances more than approximately 5 mi downdip from the outcrop area. In the central part of the aquifer, salinity increases are more gradual, affording a larger area of low-salinity, high-quality water for multiple uses. In the southwestern part of the aquifer, sulfate is the dominant anion. Dedolomitization is a likely process that may account for the high-sulfate, low-bicarbonate groundwater in this area of the aquifer; however, this theory requires further analysis to achieve greater confidence.

# Trinity Aquifer

Cretaceous formations in Arkansas (Nacatoch Sand, Ozan Formation, Tokio Formation, and the Trinity Group) and the aquifers comprised by these formations are not included in any of the regional hydrogeologic framework models of the Mississippi embayment (Arthur and Taylor, 1990; Hart and others, 2008; Clark and Hart, 2009). Although the Nacatoch was included in the Gulf Coast RASA by Hosman and Weiss (1991), no older Cretaceous formations were included in their model. Renken (1998) included the Trinity as a minor aquifer in the Ground Water Atlas of the United States for Segment 5 (Arkansas, Louisiana, and Mississippi). USGS water-use reports referenced herein record use from the “Trinity aquifer,” although it accounts for the lowest use of any aquifer in Arkansas. For purpose of this report, the saturated part of the Trinity Group yielding water to wells will be referred to hereinafter as the “Trinity aquifer.” The following sections describe the geology, hydrologic characteristics, use, water levels, and water quality of the Trinity aquifer in Arkansas.

## Geologic Setting

The Trinity Group is a sequence of clastic rocks ranging from less than 100 ft thick in outcrop areas to more than 1,000 ft thick at downdip locations. The Trinity is a locally important aquifer in southwestern Arkansas and comprises six distinct units (Counts and others, 1955). The basal unit is the Pike Gravel, overlain by the Delight Sand, overlain by the

Dierks Limestone, overlain by the Holly Creek Formation, overlain by the De Queen Limestone, and finally overlain by the Paluxy Sand. The three important water-bearing sands of the Trinity are the Pike Gravel, the Ultima Thule Gravel Member of the Holly Creek Formation, and the Paluxy Sand Formation (Boswell and others, 1965).

The Trinity Group is named for type exposures on the Trinity River in Texas. The Lower Cretaceous Series Trinity Group unconformably overlies rocks of Paleozoic age and is unconformably overlain by the Upper Cretaceous Woodbine and Tokio Formations (Miser and Purdue, 1919; Boswell and others, 1965). The Trinity crops out in a belt 5–10 mi wide that extends from Pike County westward into southeastern Oklahoma. The outcrop is irregular and may cap outlying hills (Veatch, 1906; Counts and others, 1955; Boswell and others, 1965). The strike of the beds is generally westward, and the dip is generally to the south at about 50 ft/mi. The dip increases to the south and may exceed 100 ft/mi (Miser and Purdue, 1919). The Trinity attains a maximum thickness of more than 2,500 ft (Boswell and others, 1965).

The Pike Gravel is the thickest and most persistent gravel unit of the Trinity Group. It consists of rounded pebbles and cobbles intermixed and interbedded with sand and clay (Counts and others, 1955). The Pike Gravel is a resistant unit and forms an even, though dissected, southward-dipping upland. The gravel is composed mainly of dense white, gray, brown, black, or red novaculite and lesser amounts of quartz, quartzite, and sandstone gravel. The Pike Gravel ranges in thickness from 20 to 50 ft thick near the outcrop to a maximum known thickness of about 100 ft downdip (Miser and Purdue, 1919; Counts and others, 1955).

The Ultima Thule Gravel is similar in lithology to the Pike Gravel but is comprised of finer materials (Boswell and others, 1965). The sand and clay separating the Ultima Thule and Pike gravels thin to the west and the Ultima Thule rests directly on the Pike Gravel or Paleozoic rocks into Oklahoma (Miser and Purdue, 1919). The Ultima Thule Gravel thickens to the west, reaching a maximum thickness of approximately 40 ft near the State line (Counts and others, 1955). The Paluxy Sand generally consists of well-sorted, fine white sand interbedded with clay and limestone and local gravel lenses (Boswell and others, 1965). The Paluxy Sand has a maximum thickness of about 900 ft. The Paluxy Sand is present in southern Howard and Sevier Counties (Boswell and others, 1965).

The lowest beds of the Trinity Group represent nearshore deposits of the advancing Cretaceous sea that were followed by overlying limestone and marls indicating deeper waters. The upper sand represents shallow-water conditions, which mark the beginning of the Upper Cretaceous (Veatch, 1906).

## Hydrologic Characteristics

The upper Paluxy Sand is the principal water-bearing sand in the group. Well yields range from 0 to 200 gal/min, and flowing artesian wells were common at lower altitudes. A flowing artesian well in the Saline River bottoms in Sevier County yielded about 100 gal/min (Counts and others, 1955). Counts and others (1955) provided a table that listed 16 of 35 wells as "flowing." Public-supply wells in western Sevier County generally are completed in the upper and lower gravels at depths of 145–450 ft and have reported yields as high as 200 gal/min. Flowing artesian wells that yield from 1 to 50 gal/min were reported in Howard County (Counts and others, 1965). Wells screened in the Pike Gravel in southern Pike County initially were under flowing artesian conditions but ceased to flow as potentiometric surfaces declined with large withdrawals and overpumping. One aquifer test showed a transmissivity of about 1,300 $ft^2/d$ and a storage coefficient of about 0.00004 (Boswell and others, 1965). In Pike County, the Trinity is a calcareous clay with little potential to yield water. The Trinity aquifer receives recharge in the outcrop area, and the direction of groundwater flow is southward (Boswell and others, 1965).

## Water Use

The Trinity aquifer is present in several counties in southwestern Arkansas, but the clayey sediments common throughout the extent impede its use from a water-quality and yield standpoint. Five wells are recorded in the ARWUDBS for this aquifer in 2010 (fig. 90). Multiple wells in the outcrop area were also in use for domestic and livestock supply but do not meet registration requirements.

Veatch (1906) reported a scattering of well completion attempts into the Trinity aquifer in southwestern Arkansas, but only one well was completed in central Howard County. Counts and others (1955) reported 37 wells completed in the Trinity aquifer, including public-supply wells at Murfreesboro (Pike County), DeQueen, Horatio, Lockesburg (Sevier County), and Mineral Springs (Howard County). The public-supply well for the town of Horatio was drilled in 1921. Public-supply wells were drilled for Murfreesboro and Mineral Springs in the mid-1930s (Hale and others, 1947). Horatio and Lockesburg continue (2013) to use the Trinity aquifer (fig. 90), Murfreesboro uses the Little Missouri River, and Mineral Springs uses groundwater from the Tokio aquifer. Albin (1960) estimated that Murfreesboro used 0.07 Mgal/d in 1960, which quickly increased to 0.215 Mgal/d in the later 1960s because of increased industrial demands.

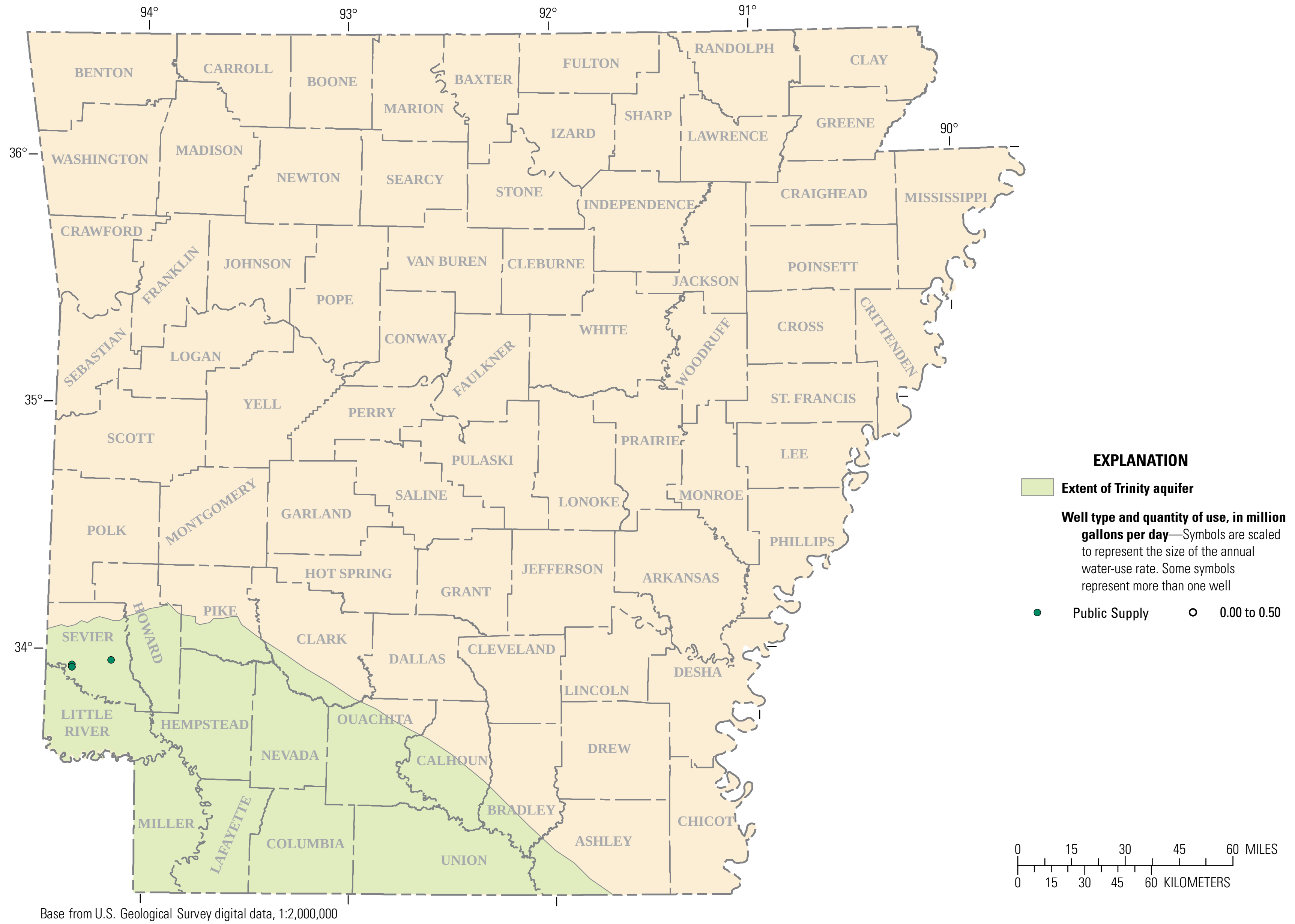



**Figure 90.** Wells with reported groundwater use for the Trinity aquifer in Arkansas, 2010.

Use of the Trinity aquifer has been restricted to a few counties in southwestern Arkansas (figs. 90–91). Estimated use from the aquifer in 2010 was available only for Columbia and Sevier Counties with a combined total of 0.86 Mgal/d (table 38). Sevier County generally had the most use. Although no data were published for Sevier County from 1985 through 1995, Horatio and Lockesburg were assumed to have used the aquifer for public supply. Approximately 20 percent of water used from the Trinity in Sevier County is for public supply (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Domestic use of the Trinity is still (2013) widespread and common; however, water use is assumed to be underestimated because domestic wells are not required to be registered. In addition, livestock wells generally do not meet the minimum-use requirement for registration. In 1990–2000, water use attributed to those two purposes was reported for Howard County (fig. 90).

## Water Levels

The Trinity aquifer is recharged by infiltration of precipitation in the outcrop area. The direction of flow is southward with regional dip of the formation (Boswell and others, 1965). Water levels have not been monitored following measurements taken by Boswell and others (1965) in the mid-1960s. High rates of withdrawal from the Trinity probably contributed to potentiometric-head declines in formerly flowing artesian wells with water-level declines of more than 40 ft below the land surface in the mid-1960s (Boswell and others, 1965).

## Water Quality

The Trinity aquifer crops out in an east-west trending band from western Sevier County to near the southeastern extent of Pike County. Only 32 wells with limited water-quality data were available, and these data were from wells located only in Sevier and Howard Counties. Generally, water quality from the Trinity is good, although chloride and sulfate can be somewhat elevated locally (Counts and others, 1955; Boswell and others, 1965). Counts and others (1955) noted that although sulfate concentrations generally were less than 30 mg/L, a few samples had sulfate concentrations exceeding 100 mg/L. Chloride concentrations generally were below 10 mg/L, except for one sample that exceeded 100 mg/L. Boswell and others (1965) reported that groundwater varied from a calcium-magnesium bicarbonate to a sodium-bicarbonate water type and that dissolved-solids concentrations usually were less than 300 mg/L, indicating overall good quality water.

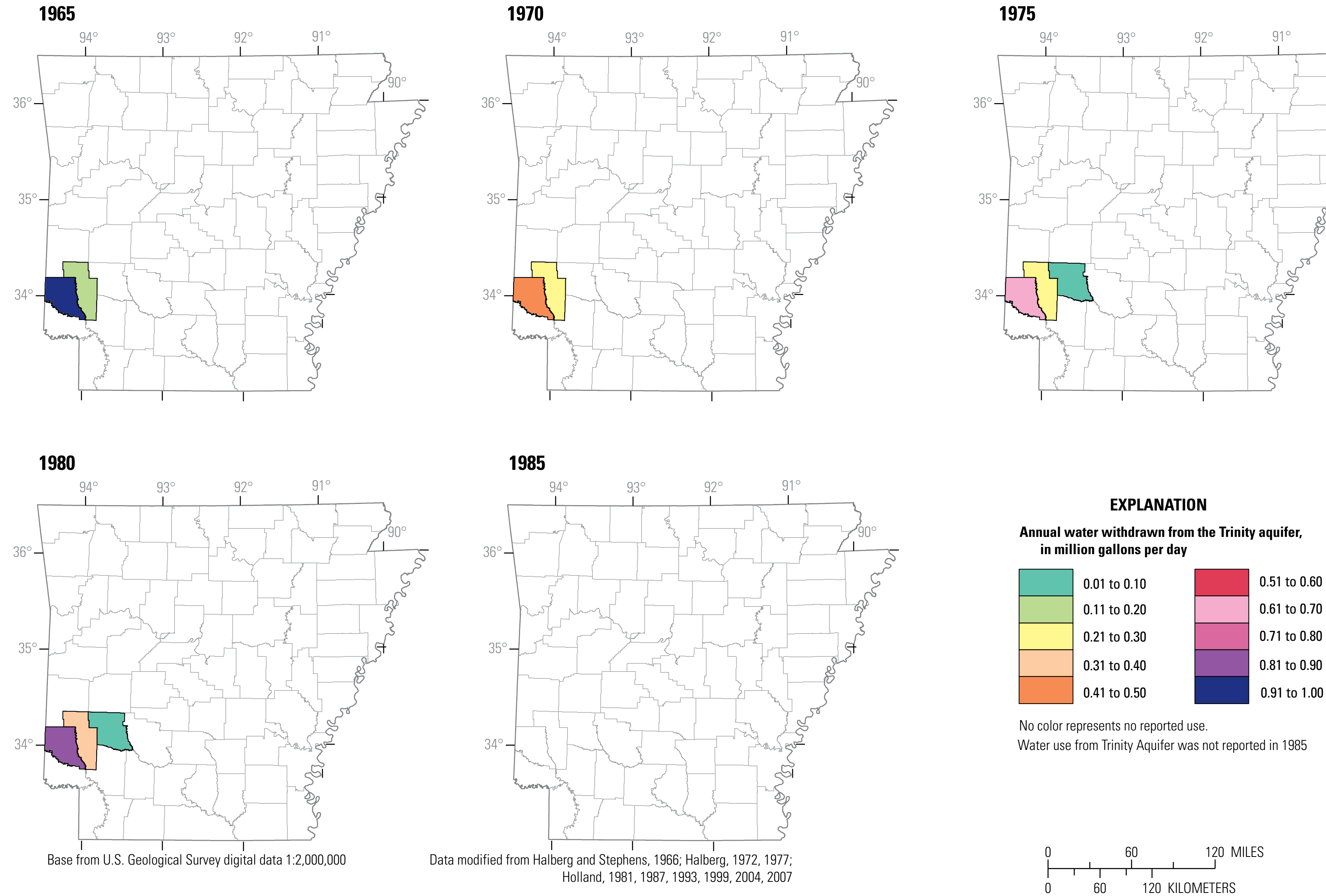



**Figure 91.** Water-use rates for the Trinity aquifer in Arkansas from 1965 to 2010.

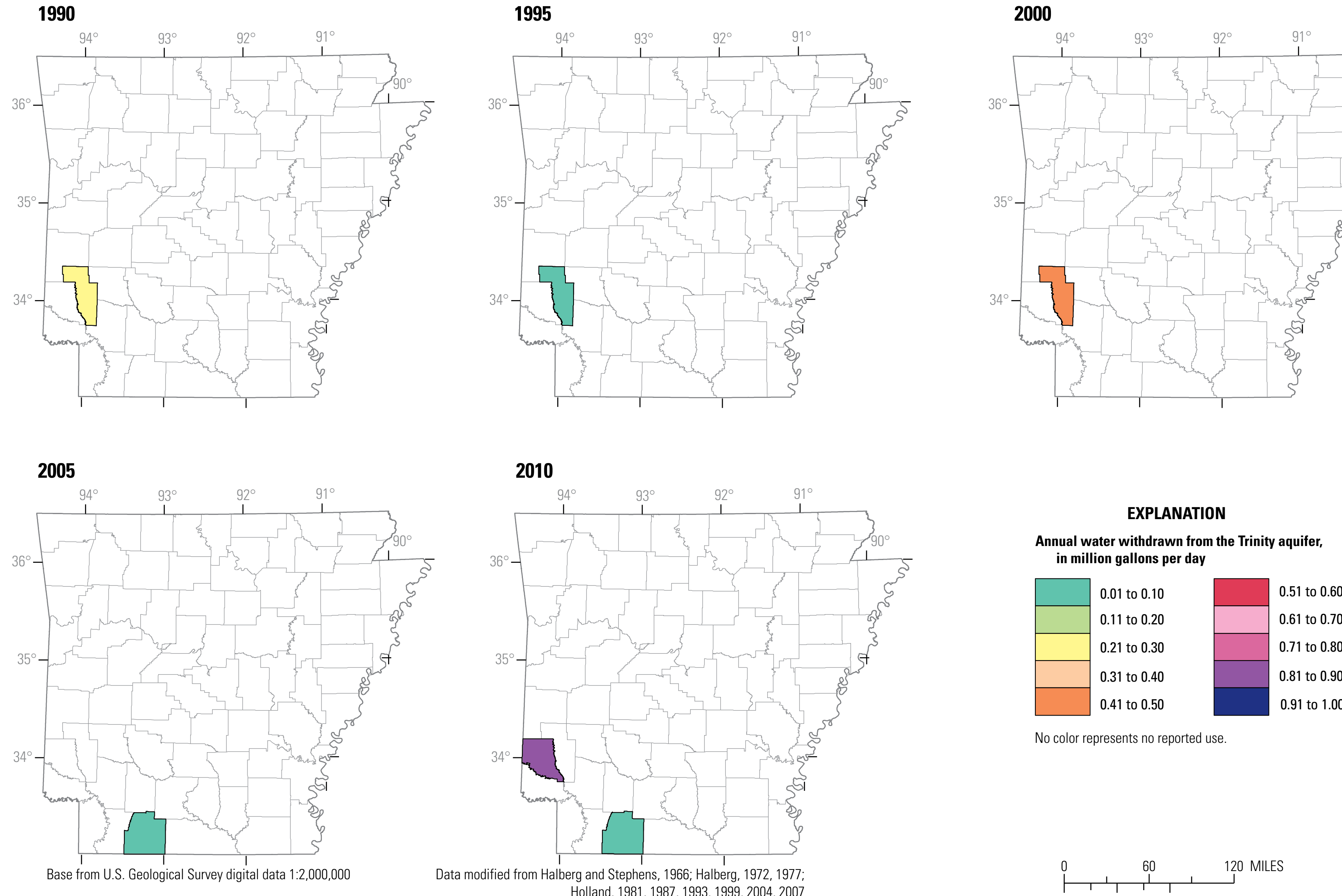



**Figure 91.** Water-use rates for the Trinity aquifer in Arkansas from 1965 to 2010.—Continued

**Table 38.** Water use from the Trinity aquifer in Arkansas, 1965–2010.

[Counties shown are only those with published data. Data from Halberg and Stephens (1966); Halberg (1972, 1977); Holland (1981, 1987, 1993, 1999, 2004, 2007)]

| County | 1965 | 1970 | 1975 | 1980 | [1]1985 | 1990 | 1995 | 2000 | 2005 | 2010 |
|---|---|---|---|---|---|---|---|---|---|---|
| Columbia | 0.00 | 0.00 | 0.00 | 0.00 | -- | 0.00 | 0.00 | 0.00 | 0.03 | 0.02 |
| Howard | 0.13 | 0.22 | 0.30 | 0.35 | -- | 0.23 | 0.08 | 0.42 | 0.00 | 0.00 |
| Pike | 0.00 | 0.00 | 0.01 | 0.02 | -- | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sevier | 0.99 | 0.49 | 0.65 | 0.89 | -- | 0.00 | 0.00 | [2]0.94 | [2]0.16 | 0.84 |
| **Total** | **1.12** | **0.71** | **0.96** | **1.26** | **--** | **0.23** | **0.08** | **1.36** | **0.19** | 0.86 |

[1]Water use from the Trinity aquifer was not reported in 1985.

[2]Unpublished data from Terrance W. Holland, U.S. Geological Survey, written commun., 2013.

## General Geochemistry and Water Type

Generally, groundwater from the Trinity aquifer is of a calcium-magnesium water type, transitioning to a sodium-bicarbonate water type downdip from the outcrop area, similar to other Cretaceous- and Tertiary-age aquifers in southern Arkansas. Sodium was less than 50 percent of the total cations for locations in the outcrop area. Groundwater from wells at a distance from 5 to 25 mi downdip from the outcrop area contained as much as 98 percent sodium (fig. 92). Values of pH ranging from 6.2 to 7.5 occur only in the outcrop area. Values of pH from about 5 to 20 mi downgradient from the outcrop area generally were greater than 8.5 and ranged upward to 9.2 (fig. 92).

For many aquifers in Arkansas, bicarbonate concentrations tend to increase with increasing pH and dissolved-solids concentrations, indicating dissolution of carbonate minerals. Therefore, groundwater tends to evolve toward a strongly bicarbonate water type with bicarbonate accounting for the highest percentage of total anions at higher dissolved-solids concentrations. The only exception to this situation is when groundwater is affected by saltwater intrusion or mixing with poor-quality groundwater. Several geochemical relations indicate that reactions other than simple dissolution of carbonate minerals affect groundwater geochemical evolution in the Trinity aquifer. This is discussed in greater detail later in this section.

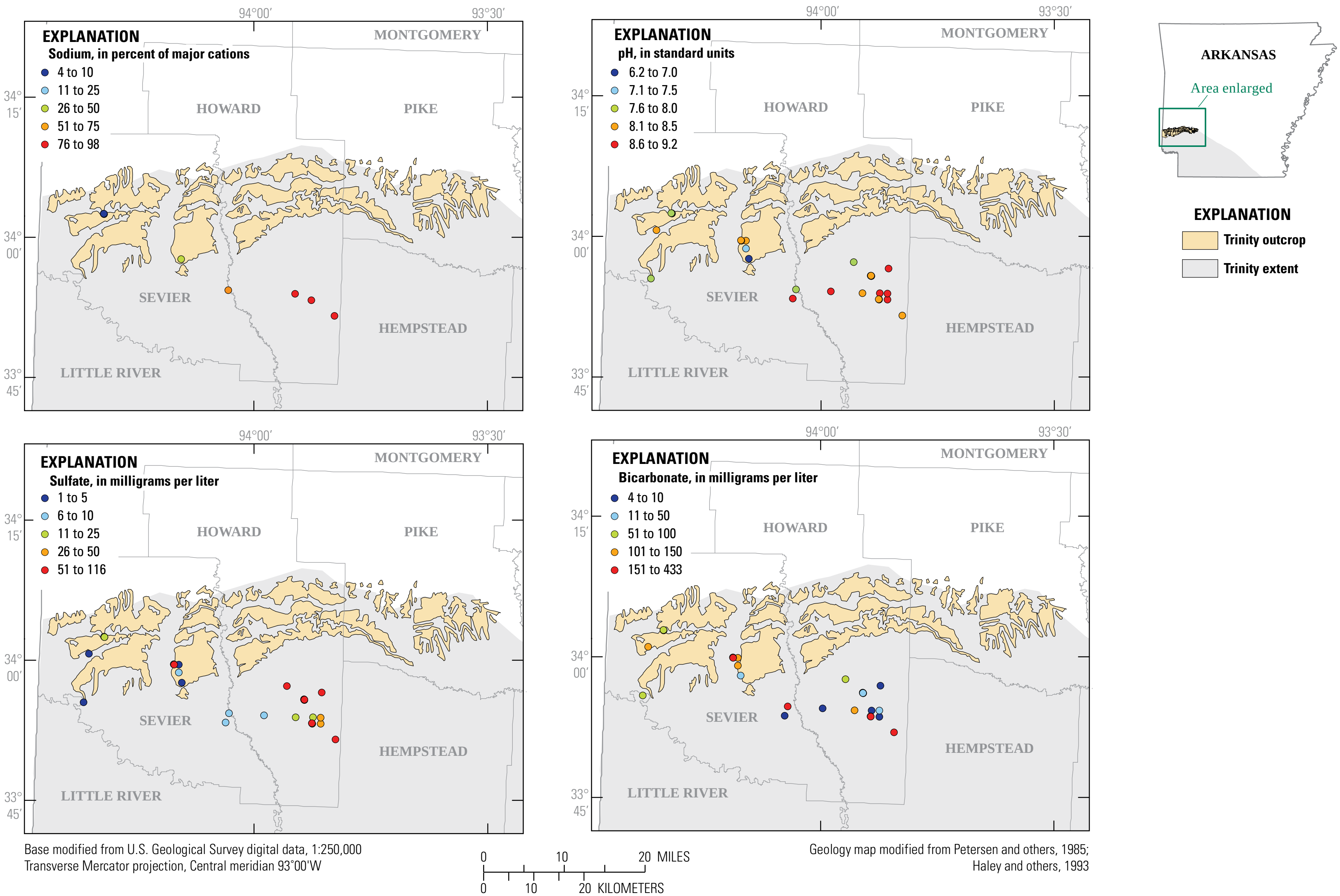



**Figure 92.** Spatial distribution of selected chemical constituents in groundwater from the Trinity aquifer in Arkansas.

## Nitrate

Nitrate concentrations generally are low in the Trinity aquifer. Nitrate concentrations ranged from 0.04 to 29 mg/L in 26 samples with a median of 0.26 mg/L as nitrogen (table 39). One well, only 25 ft deep, exceeded a nitrate concentration of 1.0 mg/L with a nitrate concentration of 29 mg/L. Two wells, 130 ft and 260 ft northwest of the 25-ft deep well, had nitrate concentrations less than 0.5 mg/L, indicating the elevated nitrate for the 25-ft well was from an extremely localized source of nitrogen.

## Iron

Iron concentrations are extremely low in the Trinity aquifer with a median of 60 µg/L for 29 samples (fig. 93; table 39). Only one groundwater sample exceeded the Federal secondary drinking-water regulation of 300 µg/L (U.S. Environmental Protection Agency, 2009). This sample was taken from a well located in the outcrop area. Iron concentrations for several Cretaceous and Tertiary aquifers were noted to have higher iron concentrations in their outcrop areas compared to increasing concentrations downgradient, resulting from possible changes in redox conditions along the flow path.

## Sulfate

Sulfate concentrations ranged from 1.0 to 116 mg/L with a median of 16 mg/L (fig. 93; table 39). Concentrations exceeded 25 mg/L in seven wells located approximately 5–17 mi from the outcrop area in the southeastern part of the aquifer in southern Howard County (fig. 92), with five of these wells exceeding 50 mg/L. In this same area, all chloride concentrations were less than 15 mg/L, and bicarbonate concentrations generally were lower than sulfate concentrations (fig. 92). For other Cretaceous aquifers, salinity increased downdip from the outcrop area with chloride as the dominant anion. Increasing chloride concentrations generally result from ineffective flushing of residual marine-derived salinity or upwelling of high-salinity water from underlying formations. Six of seven wells exceeding 25 mg/L sulfate in this area had sulfate concentrations exceeding that of chloride and bicarbonate. Therefore, some process is thought to have accounted for the increased sulfate. This situation also was noted for the Tokio aquifer for an area in southeastern Sevier County, where increases in sulfate with concomitant decreases in bicarbonate were attributed to dedolomitization mechanisms (see section on “Tokio aquifer”). Although further research is required to validate such assumptions, dedolomitization appears to be the most likely process accounting for the chemistry of groundwater where sulfate is the anion of highest concentration in the Trinity aquifer.

**Table 39.** Descriptive statistics for selected chemical constituents in groundwater from the Trinity aquifer in Arkansas.

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

| Constituent or characteristic | Minimum | Median | Maximum | Standard deviation | Number of wells |
|---|---|---|---|---|---|
| Calcium (mg/L) | 0.4 | 13 | 54 | 20.7 | 9 |
| Magnesium (mg/L) | 0.2 | 2.2 | 11 | 4.38 | 9 |
| Sodium (mg/L) | 3.6 | 8.5 | 261 | 89.6 | 9 |
| Potassium (mg/L) | 1.24 | 2.8 | 9.3 | 2.32 | 9 |
| Bicarbonate (mg/L) | 4.0 | 67 | 433 | 109 | 30 |
| Chloride (mg/L) | 3.0 | 6.0 | 695 | 124 | 30 |
| Sulfate (mg/L) | 1.0 | 16 | 116 | 34.6 | 30 |
| Silica (mg/L) | 10 | 12 | 16 | 1.89 | 9 |
| Nitrate (mg/L as nitrogen) | 0.04 | 0.26 | 29 | 5.6 | 26 |
| Dissolved solids (mg/L) | 42 | 192 | 683 | 189 | 9 |
| Iron (µg/L) | 0.05 | 60 | 2,200 | 544 | 29 |
| Manganese (µg/L) | 4.29 | 4.29 | 4.29 | 0.13 | 1 |
| Arsenic (µg/L) | 0.03 | 0.03 | 0.03 | 0.03 | 1 |
| Hardness (mg/L as calcium carbonate) | 8.0 | 185 | 440 | 114 | 30 |
| Specific conductance (µS/cm) | 75 | 501 | 2,650 | 458 | 30 |
| pH (standard units) | 6.2 | 8.4 | 9.2 | 0.6 | 30 |

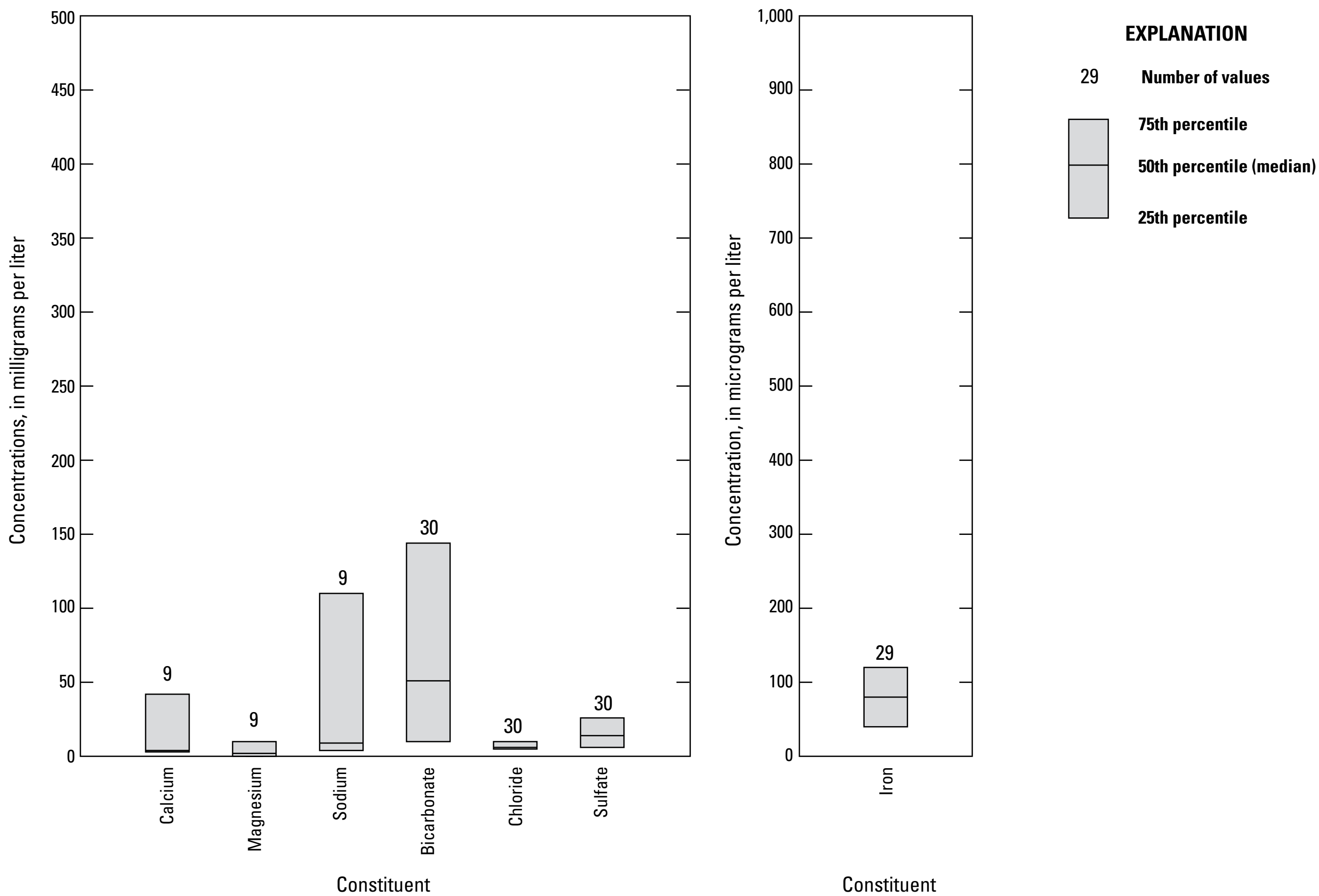



**Figure 93.** Interquartile range of selected chemical constituents in groundwater from the Trinity aquifer in Arkansas.

## Chloride

All but one chloride concentration was less than or equal to 15 mg/L, even as far as 13 mi from the outcrop area in southern Howard County. The one sample had an elevated chloride concentration of 695 mg/L and was from a shallow 25-ft well in Sevier County. Counts and others (1955) described this well as "almost dry." If the well was completed in a low-permeable, clayey section of the Trinity, it is possible that salinity originated during deposition in a marine environment that had not been adequately flushed. Because of the overall low chloride concentrations in higher yielding wells in the area, the geochemistry of groundwater from this well is simply an anomaly but assists in understanding localized water-quality problems in other aquifers of the Coastal Plain that have varying amounts of clay interbedded with sand lenses. In the absence of anthropogenic effects on water quality, poor-quality, higher-salinity groundwater often is explained by mixing with groundwater bound in low-permeable, clay-rich deposits that experience inadequate flushing of residual connate water at the time of deposition. The overall low salinity in samples from wells throughout the aquifer suggests that any saline water that originated in more permeable sands has been adequately flushed.

In summary, good-quality groundwater is found throughout the Trinity aquifer. Sulfate concentrations can be locally elevated, although all concentrations were less than the 250 mg/L secondary drinking-water regulation. Wells with elevated sulfate generally had low bicarbonate concentrations, which is hypothesized as resulting from dedolomitization processes. All chloride concentrations but one were less than or equal to 15 mg/L at distances as great as 15 mi from the outcrop area, demonstrating the low overall salinity in the aquifer.

# Aquifers of the Interior Highlands

The Interior Highlands of northern and western Arkansas have less reported groundwater use than other areas of the State. This reflects a combination of processes including: (1) prevalent and increasing use of surface water, (2) less intensive agricultural uses, (3) lower population and industry densities, (4) less potential yield of the resource, and (5) lack of detailed reporting. Reported use in 2010 for all aquifers of the Interior Highlands was approximately 115 Mgal/d, 1.5 percent of the total reported groundwater use in Arkansas of 7,873.75 Mgal/d. The various aquifers of the Interior Highlands generally occur in shallow, fractured, well-indurated, structurally modified bedrock of this mountainous region of the State. Rocks of the Interior Highlands are characterized by secondary, relatively low-porosity fractures and bedding planes. By comparison, the relatively flat-lying, unconsolidated sediments of the Coastal Plain have greater porosity, storage, and yields because they are composed of coarse-grained, uncemented sands and gravels. The laterally expansive and relatively continuous Coastal Plain aquifers contrast markedly with the more discontinuous aquifers and ancient bedrock in the highlands. The Interior Highlands have experienced multiple episodes of structural modification, uplift, and erosion causing truncation, dissection, and excision. Consequently, yields of aquifers in the Interior Highlands are lower, and domestic supply is the dominant use. Surface water is the greatest supplier when large volumes are required for population growth and industry.

Disparity in total water use for aquifers in the Coastal Plain and Interior Highlands arises from the major uses of groundwater in Arkansas. For example, irrigation use, which is almost solely from the Mississippi River Valley alluvial aquifer in eastern Arkansas, accounts for nearly 94 percent of the total groundwater used in the State. Thus, groundwater use from all other aquifers is insignificant compared to irrigation. Unfortunately, the magnitude of use for irrigation overshadows the important use of groundwater for thousands of households, numerous small-community supply systems (parks, stores, and small communities), and livestock supply, among other uses in the Interior Highlands.

Spatial trends in groundwater geochemistry in the Interior Highlands differ greatly from trends for aquifers in the Coastal Plain. In the Coastal Plain, the prevalence of long regional flow paths results in regionally predictable and mappable geochemical changes. In the Interior Highlands, groundwater flow paths are short and topographically controlled (from hilltops to valleys) within relatively small watersheds. Thus, dense data coverage from numerous wells would be required to effectively characterize these groundwater basins and define small-scale geochemical changes along any given flow path. Small-scale potentiometric-surface maps constructed in the Interior Highlands confirm the dominant control of topography on groundwater-flow directions (Leidy and Morris, 1990b; Kresse and Hays, 2009). Changes in geochemistry dominantly are related to rock type and residence time along individual flow paths.

The aquifers of the Interior Highlands are discussed from youngest to oldest in the following sections: the Arkansas River Valley alluvial aquifer, Ouachita Mountains aquifer, Western Interior Plains confining system, the Springfield Plateau aquifer, and the Ozark aquifer. The Western Interior Plains confining system, Springfield Plateau aquifer, and Ozark aquifer are regional hydrogeologic units, and regional nomenclature is adhered to in this report. The reader should refer to figure 5 for locations of cities and counties discussed in this section.

## Arkansas River Valley Alluvial Aquifer

The alluvial deposits of the Arkansas River are one of the most important sources of water in the Arkansas Valley section of the Ouachita Province. This water provides a valuable source of irrigation and public-supply use. Groundwater in alluvium of the Arkansas River Valley, hereinafter referred to as the Arkansas River Valley alluvial aquifer, is considered a distinct aquifer from approximately the State border at Fort Smith to Little Rock. In the Mississippi Alluvial Plain in eastern Arkansas, it is difficult to distinguish between groundwater from the alluvial deposits of the Arkansas River and those of the Mississippi Alluvial Plain. Consequently, all alluvial deposits east of Little Rock are considered part of the Mississippi River Valley alluvial aquifer.

The following sections provide information on the geohydrology and geochemistry of groundwater from the Arkansas River Valley alluvial aquifer. Much of this information was summarized from available historical and recent publications, which provide more detailed information.

### Geologic Setting

The Arkansas River Valley region is a synclinorium generally lying between dipping rocks of the Boston Mountains to the north and the highly folded rocks of the Ouachita Mountains to the south. Alluvial deposits overlie consolidated rocks along the Arkansas River and its major tributaries. They comprise terrace and flood-plain deposits that occur along the river in discontinuous segments 3–43 mi in length and 1–5 mi across the river valley (fig. 3). In some locations, the alluvium and terrace deposits are absent, and the river is bordered by consolidated rocks of the Interior Highlands (Bedinger and others, 1963; Cordova, 1963). Tops of older terraces lie 50 ft or more above the present flood plain and consist of interbedded gravel, clay, and sand. Younger terrace deposits lie 20–40 ft above the present flood plain and are composed of a coarsening downward sequence of clay, sand, and gravel. Flood-plain alluvial deposits consist of gravel, sand, silt, and clay. Younger terraces typically are hydraulically well connected with alluvium, whereas older terraces have bases far above the surface of the adjacent alluvium (Bedinger and others, 1963). The alluvial deposits typically are about 40 ft thick near Fort Smith and thicken downstream to about 80 ft near Little Rock (Cordova, 1963).

The alluvium represents several environments of deposition and characteristic deposits including point bar, swale, channel fill, natural levee, and backswamp. These can be distinguished on the basis of lithologic character and topographic expression. Infiltration of rainfall is an important source of groundwater recharge. Recharge is higher in areas that are underlain by the highly permeable point-bar and natural-levee deposits, and lower in backswamp and channel-fill deposits (Bedinger and others, 1963). Lithologic logs near Van Buren were used to determine why some wells did not have sufficient yield for use as irrigation water (Tim Kresse, U.S. Geological Survey, unpub. data, 2013). Percent sand thickness was calculated from each available log and overlain onto a photomosaic map to examine the areal distribution of sand thickness in relation to geomorphologic features (fig. 94). Several abandoned channels were identified from the map, and a consistent association was noted between higher sand percentages near the river on the point-bar (concave) side of abandoned channels and lower sand percentage on the convex side of the channel. Point-bar and channel deposits are located on the concave side and are characterized by coarser, higher-permeable deposits. Backswamp areas are located on the convex side of the channel and are characterized by finer, less permeable deposits. Modern-day point-bar deposits are easily recognizable on figure 94 as lighter colored sands and gravels on the concave side of the Arkansas River meander bend. The distribution of these deposits of varying permeability was in agreement with anecdotal information from farmers about the distribution of productive wells in the area and the proximity of low-permeable zones during irrigation well pumping (Tim Kresse, U.S. Geological Survey, unpub. data, 2013).

## Hydrologic Characteristics

Recharge to the Arkansas River Valley alluvial aquifer primarily is by downward percolation of precipitation in addition to leakage from the river (Bedinger and others, 1963; Kilpatrick and Ludwig, 1990a). Recharge in the vicinity of the Atkins well field (Pope County), which is underlain largely by backswamp deposits, was about 3 in/yr, whereas the average rate of recharge in nearby channel deposits was about 10 in/yr (Bedinger and others, 1963). Although absent locally beneath some channel-fill deposits, in most places 30–60 ft of saturated sand and gravel are present. The saturated thickness generally increases with distance downstream from Fort Smith. Wells completed in the sands and gravels in the lower part of the Arkansas River Valley alluvial aquifer are capable of yielding 300–700 gal/min of water and predominantly are used for sources of irrigation and public supply (Bedinger and others, 1963; Kilpatrick and Ludwig, 1990a). Water levels range from approximately 5 to 30 ft below the ground surface (Kilpatrick and Ludwig, 1990a). Transmissivity values range from 5,348 to 21,390 $ft^2/d$, and storage coefficient ranges from 0.0001 to 0.009 (Bedinger and others, 1963).

Groundwater in the Arkansas River Valley alluvial aquifer is largely unconfined. Historically, the water table sloped toward the river and larger tributary streams during normal and low river stages. During high river stages, the groundwater gradient is reversed with groundwater flowing away from the river. Local water-table highs are common beneath the more permeable surface materials where recharge rates are high. Locally, pumping can modify the shape of the water-table surface. Pumping for irrigation historically has had little pronounced effect because irrigation wells are widely spaced and pumpage is small. Withdrawals for public supply are nearly continuous and are concentrated in small areas. Bedinger and others (1963) noted that pumping for public supply near Atkins had a pronounced effect on the water table. The well fields near Ozark (Franklin County) and Dardanelle (Yell County), which are near the river, also had cones of depression extending from well fields to the river, which induced recharge from the river. Kline and others (2006), Kresse and others (2006), and Kresse and Clark (2008) also documented influx of river water into the Dardanelle well field. However, geochemical mixing curves indicated that a maximum of only 20 percent of the groundwater from the public-supply well was river water with greatly reduced mixing in other wells. They also noted that some wells near the river in adjacent well fields with similar production history showed very little, if any, influx of river water based on the same mixing approaches.

Bedinger and others (1963) contended that only when continuously pumping public-supply wells are in close proximity to the river will any appreciable influx of water occur from the Arkansas River. Similar findings were noted in southeastern Arkansas (Kresse and Clark, 2008). The lowest chloride concentrations occurred in wells next to the Arkansas River, in spite of intensive local and regional irrigation pumping, with the highest concentrations in backswamp deposits further from the river. Kresse and Clark (2008) hypothesized that recharge predominantly occurred through coarse natural levee and channel deposits near the river in this area, similar to that proposed for the Arkansas River Valley alluvial aquifer in the western part of the State.

## Groundwater-Flow Simulation Models

The groundwater-flow system of the Arkansas River Valley alluvial aquifer south of Dardanelle in Yell County was simulated by Kline (2003). A two-layer model was developed to characterize groundwater flow and to investigate the degree of groundwater connectivity with the Arkansas River. Results indicated that groundwater pumping induced flow from the river into the aquifer. Further work by Kline and others (2006) and Kresse and others (2006) used hydrographs and geochemical data to quantify the degree of interaction between groundwater and the Arkansas River and validate the results of the model.

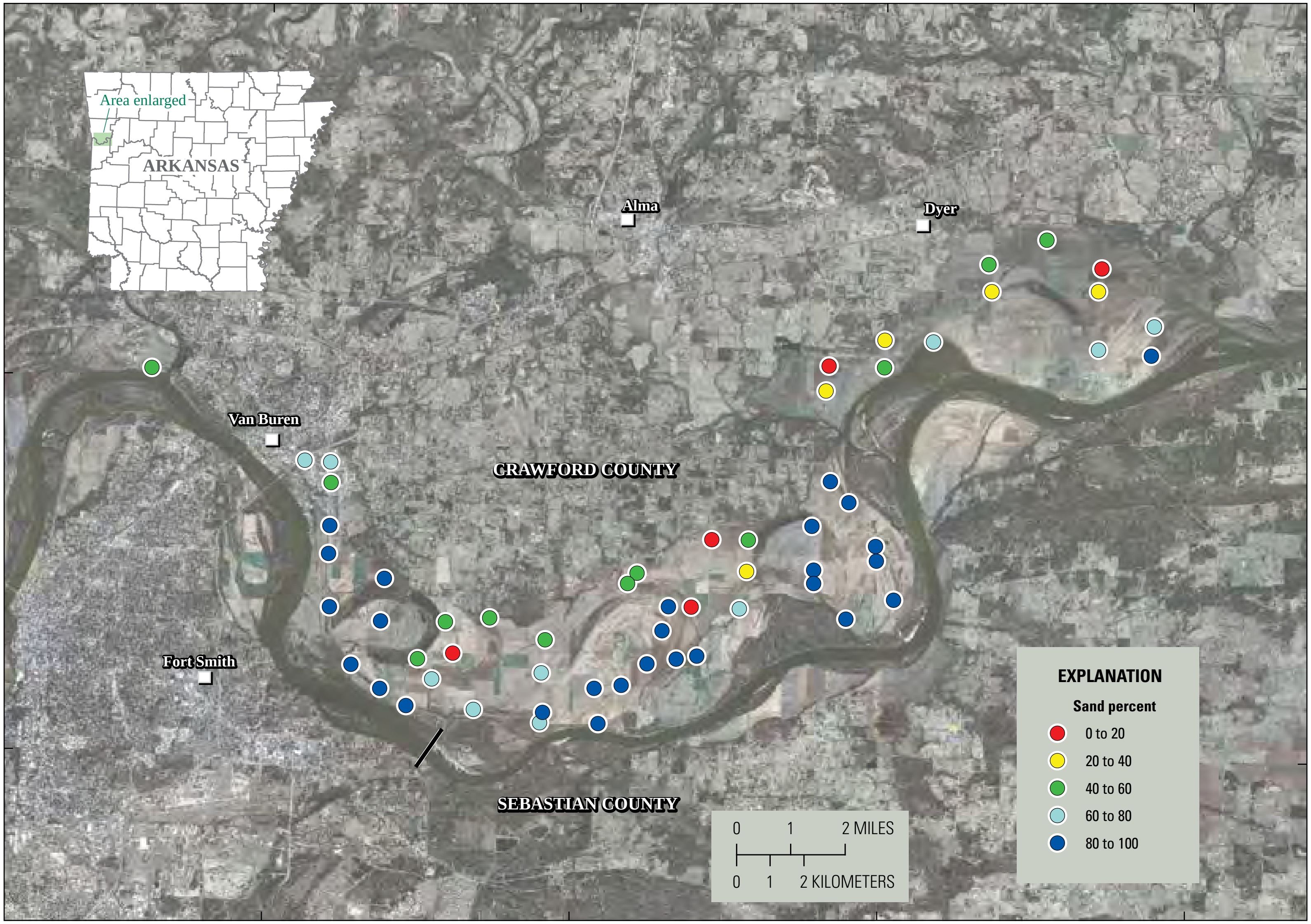



Image from Arkansas State Land Information Board, 2006 Natural Color County Mosaic
Universal Transverse Mercator, zone 15
North American Datum of 1983

**Figure 94.** Percent sand calculated from lithologic logs for the Arkansas River Valley alluvium in west-central Arkansas.

## Water Use

Groundwater from the Arkansas River Valley alluvial aquifer is, and historically has been, an important source of irrigation and public supply. Currently (2013), only the cities of Dardanelle and Maumelle are using the Arkansas River Valley alluvial aquifer as a source of public-supply water. In the past, the cities of Atkins, Dardanelle, Morrilton, and Ozark used the aquifer for public supply, but of these cities, only Dardanelle has continued and expanded the use of the aquifer as a sole public-supply water source. Bedinger and others (1963) described the use from these four systems and calculated the remaining development potential of the Arkansas River Valley alluvial aquifer based on aquifer thickness, extent, and average yields. During 1959, Atkins used three wells that yielded about 75–250 gal/min and pumped about 162,000 gal/d; Dardanelle used three wells that yielded about 300 gal/min and pumped about 225,000 gal/d; Morrilton used four wells that yielded about 200–500 gal/min and pumped about 681,000 gal/d; and Ozark used five wells to pump about 300,000 gal/d. Assuming natural recharge to the aquifer of 10 in/yr, Bedinger and others (1963) calculated that 130 Mgal/d could be pumped from the aquifer without overdraft of groundwater storage or inducting water from the river. In 1959, groundwater was pumped at an average rate of 3.2 Mgal/d from the aquifer, which is less than 3 percent of the amount regionally available from natural recharge (Bedinger and others, 1963).

Dardanelle continues to depend solely upon groundwater for public supply. Drilling efforts were part of the plan for continued long-term use of the aquifer. A review of data from 2003 through 2009 revealed total withdrawals increased from 1.1 to 2.2 Mgal/d with production from nine wells completed at depths of about 65 ft with each well pumping about 200 gal/min. Total reported use for Dardanelle in 2010 was 2.03 Mgal/d. In 2010, Dardanelle installed a horizontal interceptor well system 300 ft from the river that produced more than 2.5 Mgal/d. The interceptor well consists of a 13-ft by 16-ft caisson installed 45 ft below ground level with five 12-inch diameter lateral screens ranging from 150 to 250 ft in length. The collector well system replaced the nine production wells in January 2011 as the city’s primary water supply, but the nine wells are maintained as a backup water supply. A pumping rate of more than 3.0 Mgal/d from the interceptor well was reported in 2012 (Bill Smith, Dardanelle Water Works, oral commun., 2012). With improved directional-drilling techniques and innovative well design, Dardanelle has demonstrated that groundwater from the Arkansas River Valley alluvial aquifer may contain great potential as a valuable and productive water supply in other areas along the river.

In Maumelle, pumping from the Arkansas River Valley alluvial aquifer began in 1941 when wells were installed to provide water for the production of ammonium picrate (picric acid); water use continued until the plant was deactivated in March 1945. In 1972, the city of Maumelle converted those wells for public supply and installed two additional wells. Nine additional wells were installed to provide water for the growing municipality from 1995 through 2012 (Barry Heller, Maumelle Water Management, oral commun., 2013). Maumelle currently (2013) pumps from 13 wells completed in the Arkansas River Valley alluvial aquifer with a reported average use of 2.74 Mgal/d in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2013).

In addition to its important use as a source for public-supply water, the Arkansas River Valley alluvial aquifer continues to be a valuable source for irrigation along the Arkansas River. In 2010, the reported irrigation use was 2.6 Mgal/d, which was pumped from 34 wells for approximately 2,960 acres of cropland (Terrance W. Holland, U.S. Geological Survey, written commun., 2013).

## Water Quality

### General Geochemistry and Water Quality

Groundwater in the Arkansas River Valley alluvial aquifer is generally of good quality and appropriate for most uses, although elevated iron concentrations can require treatment for public supply and other uses. Values of pH ranged from 4.9 to 9.5 with a median of 8.0 (table 40). The relatively high median pH value results from the dissolution of carbonate minerals in the alluvial deposits. Groundwater from the aquifer principally has been identified as a calcium-bicarbonate type and is characterized by wide variations in dissolved-solids concentrations (Bedinger and others, 1963; Kresse and others, 2006). Data compiled for this report confirm this dominant calcium-bicarbonate water type and contain more analyses of total anions (bicarbonate, chloride, sulfate) than for total cations (calcium, magnesium, sodium, potassium). Bicarbonate was greater than 50 percent in 462 of 493 (94 percent) samples. Calcium was greater than 50 percent for 75 of 81 (93 percent) samples having sufficient cation data for calculation of the dominant cation.

**Table 40.** Descriptive statistics for selected chemical constituents in groundwater from the Arkansas River Valley alluvial aquifer in western Arkansas.

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

| Constituent or characteristic | Minimum | Median | Maximum | Standard deviation | Number of wells |
|---|---|---|---|---|---|
| Calcium (mg/L) | 0.5 | 58 | 433 | 60.4 | 143 |
| Magnesium (mg/L) | 1.69 | 16 | 70 | 10.4 | 139 |
| Sodium (mg/L) | 0.9 | 14 | 236 | 34.8 | 117 |
| Potassium (mg/L) | 0.08 | 1.6 | 48 | 5.12 | 102 |
| Bicarbonate (mg/L) | 8.0 | 231 | 1,050 | 150 | 503 |
| Chloride (mg/L) | 1.0 | 12 | 980 | 52.3 | 661 |
| Sulfate (mg/L) | 0.2 | 17 | 253 | 26.8 | 518 |
| Silica (mg/L) | 0.18 | 22 | 39.5 | 7.77 | 66 |
| Nitrate (mg/L as nitrogen) | 0.01 | 1.1 | 67 | 8.63 | 457 |
| Dissolved solids (mg/L) | 88 | 319 | 887 | 152 | 88 |
| Iron (µg/L) | 0.05 | 70 | 15,500 | 1,300 | 336 |
| Manganese (µg/L) | 0.13 | 338 | 1,360 | 403 | 17 |
| Arsenic (µg/L) | 0.03 | 0.76 | 6.8 | 1.78 | 15 |
| Hardness (mg/L as calcium carbonate) | 20 | 240 | 1,300 | 134 | 570 |
| Specific conductance (µS/cm) | 89 | 507 | 2,920 | 273 | 655 |
| pH (standard units) | 4.9 | 8.0 | 9.5 | 0.6 | 649 |

### Nitrate

Nitrate concentrations in the Arkansas River Valley alluvial aquifer ranged from 0.01 to 67 mg/L with a median of 1.1 mg/L in 457 samples (table 40). The median concentrations for all other aquifers in Arkansas, with the exception of the Springfield Plateau and Ozark aquifers, were less than 0.3 mg/L. The shallow depths and relatively high recharge to the aquifer are consistent with increased vulnerability to surface (for example, fertilizer and manure) and near-surface (for example, septic tanks) sources of nitrogen. Out of 457 samples with nitrate analyses, 58 (12.7 percent) had concentrations exceeding the Federal MCL of 10 mg/L. The greatest density of elevated nitrate concentrations was along the western (Crawford County) and the eastern (Conway, Faulkner, Pope, and Yell Counties) extents of the aquifer (fig. 95). The lower concentrations of nitrate in the central part of the aquifer (Franklin, Johnson, and Logan Counties) are hypothesized in this report to result from denitrification. Further evidence for denitrification as a control on nitrate concentrations in this part of the aquifer is provided in the discussions of iron, arsenic, and sulfate.

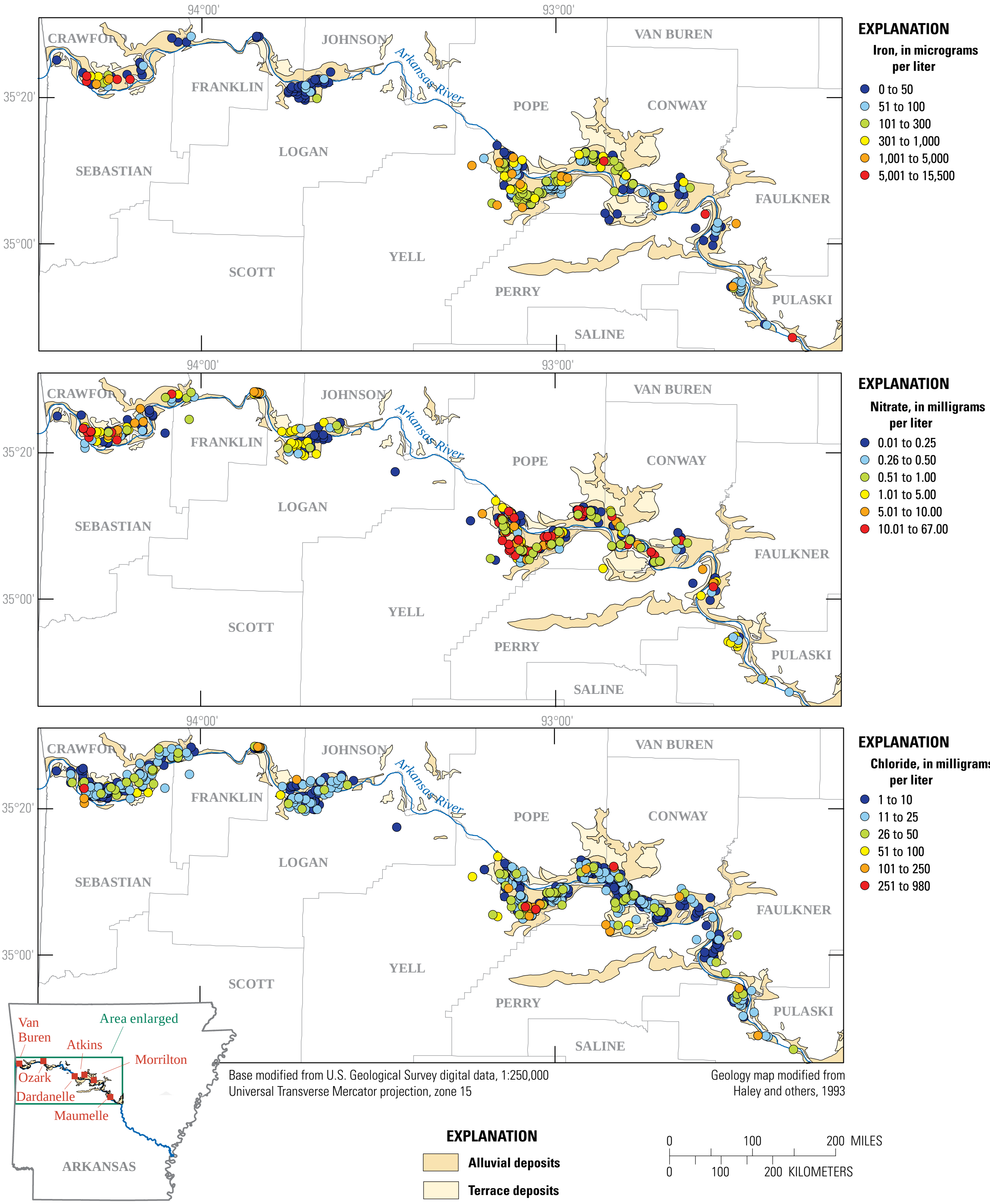



**Figure 95.** Spatial distribution of selected chemical constituents in groundwater from the Arkansas River Valley alluvial aquifer in western Arkansas.

## Iron and Arsenic

Iron concentrations in the Arkansas River Valley alluvial aquifer ranged from 0.05 to 15,500 µg/L with a median of 70 µg/L (fig. 96; table 40). For 336 samples with iron analyses, only 37 (11 percent) exceeded the Federal secondary drinking-water regulation of 300 µg/L. Iron concentrations ranged from 155 to 15,500 µg/L with a median of 2,955 µg/L near Van Buren. The large median iron concentration likely indicates iron-reducing conditions and dissolution of iron oxyhydroxides (Chappelle and others, 2009). In this area, arsenic concentrations ranged from 0.38 to 6.8 µg/L with a median of 1.3 µg/L; all concentrations were below the drinking-water standard of 10 µg/L (U.S. Environmental Protection Agency, 2009). Iron correlated positively to arsenic with an $R^2$ value of 0.76, indicating reduction of iron oxyhydroxides as a possible source of arsenic. Iron-reducing conditions were similarly noted in the aquifer near Dardanelle by Kresse and others (2006). A review of water-quality data from the Dardanelle area (Kresse and others, 2006) also revealed a positive correlation between iron and arsenic with an $R^2$ value of 0.77. Arsenic concentrations ranged as much as 19 µg/L in this area. Kresse and Fazio (2003) provided evidence for reductive dissolution of iron oxyhydroxides as the source of elevated iron and arsenic in the Mississippi River Valley alluvial aquifer along the Arkansas River in southeastern Arkansas. Detailed studies by Sharif and others (2008a, b) confirmed reductive dissolution of iron oxyhydroxides as the source of elevated iron and arsenic concentrations in this area. Holocene-age alluvial deposits contain abundant dissolved organic matter that provides a substrate for microbial respiration. This substrate results in utilization of electron acceptors such as oxygen, nitrate, iron oxyhydroxide, and sulfate thus increasing reducing conditions in the deeper sections of the aquifer. Reduction of iron oxyhydroxides likely is the source of elevated iron and arsenic concentrations in the Arkansas River Valley alluvial aquifer in the western part of the State.

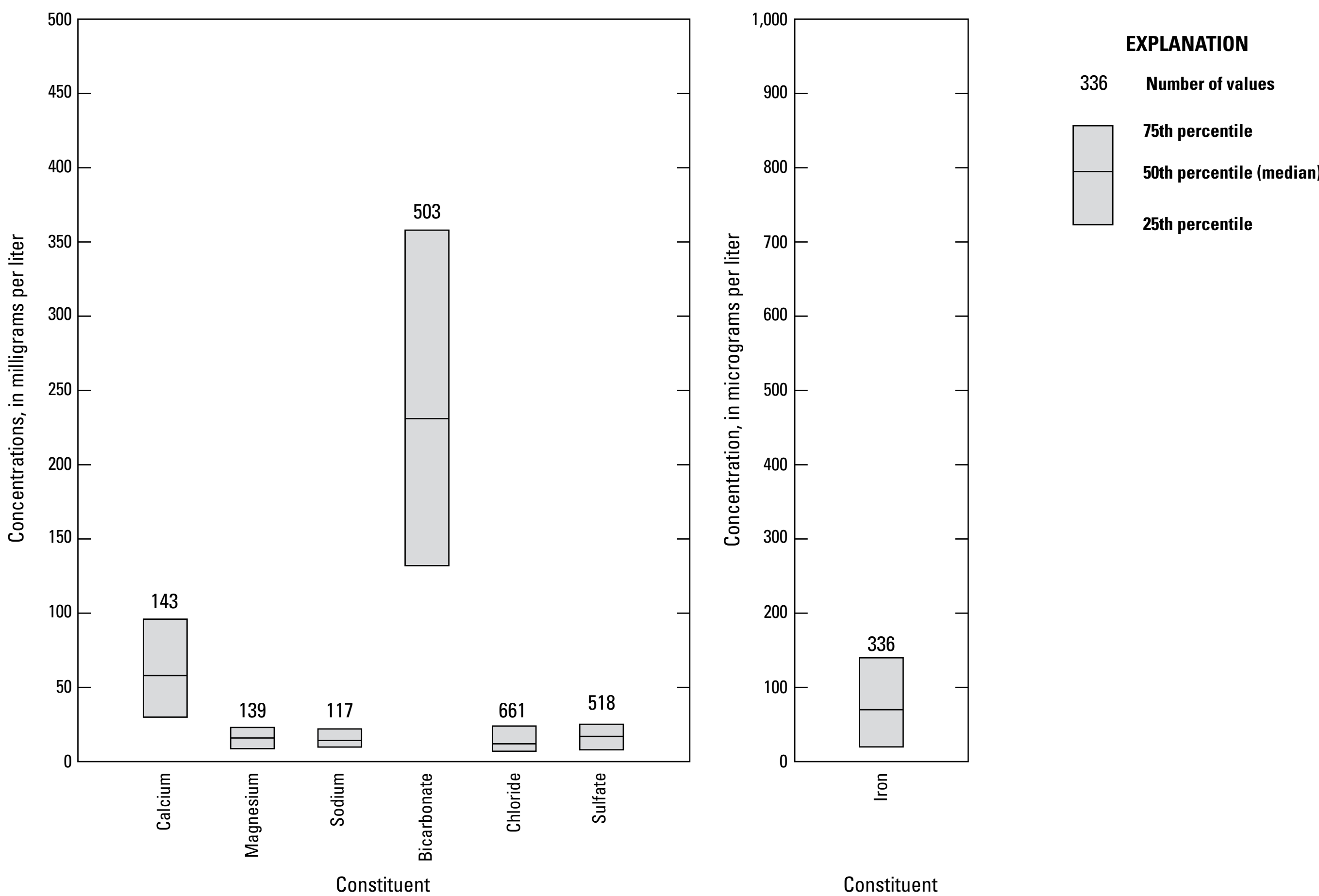



**Figure 96.** Interquartile range of selected chemical constituents in groundwater from the Arkansas River Valley alluvial aquifer in western Arkansas.

The spatial distribution of iron concentrations shows that the highest density of elevated iron concentrations, similar to that of nitrate, occurred in the western and eastern parts of the aquifer (fig. 95). All but one iron concentration in the central part of the aquifer were less than 100 µg/L. This suggests that the more energetically favorable terminal electron acceptors—oxygen, nitrate, and iron oxyhydroxides—have been exhausted, and geochemical conditions have evolved to favor sulfate-reducing conditions and the precipitation of iron-sulfide minerals. The inverse relation of iron and sulfate in the aquifer supports the theory of iron-sulfide mineralization as a control on iron in solution (fig. 97). Where iron-oxide supply has been exhausted in an aquifer and an appreciable sulfate and an organic substrate are available for sulfate-reducing bacteria, sulfate will be reduced to hydrogen sulfide, which quickly reacts with the soluble iron. Chapelle and others (2009) noted that sulfide was inversely related to dissolved iron, reflecting the rapid reaction kinetics of iron with hydrogen sulfide to produce relatively insoluble iron-sulfide minerals. Because sulfate concentrations are much greater than iron concentrations throughout most aquifers, any appreciable reduction of sulfate can remove a large fraction of the soluble iron.

## Sulfate

Sulfate concentrations generally were low throughout the Arkansas River Valley alluvial aquifer and ranged from 0.2 to 253 mg/L with a median of 17 mg/L (fig. 96; table 40). Of 518 samples with sulfate data, 470 (91 percent) had concentrations less than 50 mg/L, and 295 (57 percent) had concentrations less than 20 mg/L. Only one sample (253 mg/L) had a concentration greater than the secondary drinking-water regulation of 250 mg/L. In areas with sulfate concentrations exceeding approximately 30 mg/L, iron is virtually absent (less than 50 µg/L), suggesting sulfate reducing conditions in areas with higher sulfate concentrations (fig. 97). No discernible trends were noted in the spatial distribution of sulfate concentrations.

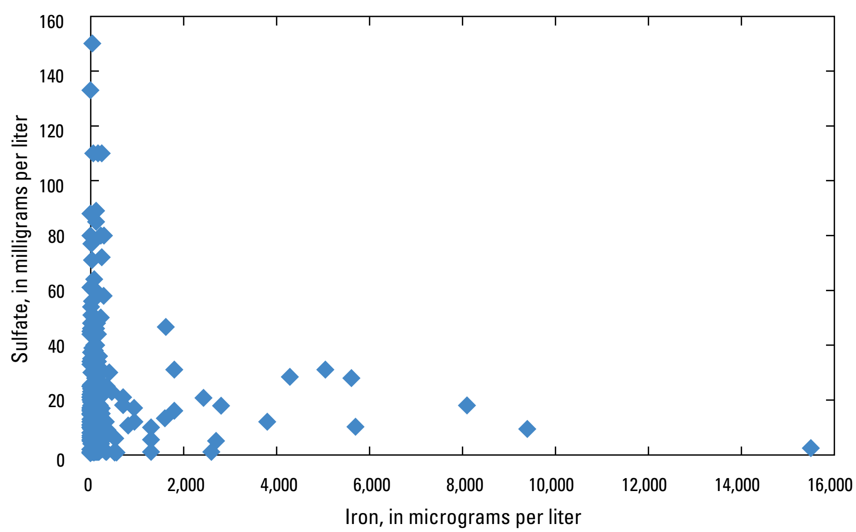



**Figure 97.** Relation of iron and sulfate concentrations in groundwater from the Arkansas River Valley alluvial aquifer in western Arkansas.

## Chloride

Chloride concentrations in the Arkansas River Valley alluvial aquifer ranged from 1.0 to 980 mg/L with a median of 12 mg/L (fig. 96; table 40). Only 4 of 661 samples with chloride analyses exceeded the Federal secondary drinking-water regulation of 250 mg/L; however, 32 samples exceeded 100 mg/L and are elevated as defined for this report. Bedinger and others (1963) hypothesized that natural variation in dissolved-solids content, salinity, and water type was related more to the movement of water from adjacent or underlying formations than from movement of groundwater within the alluvium. However, Kresse and others (2006) indicated that increases in salinity and dissolved-solids concentrations were the direct result of the type of deposits penetrated by wells in the aquifer in the Dardanelle area. They showed that groundwater in underlying formations was of better quality with lower salinity than water in the Arkansas River Valley alluvial aquifer. Higher chloride and dissolved-solids concentrations were noted for wells in two different areas of the aquifer: (1) areas with deposits having a higher percentage of clay and located further from the river, which correlates to areas of backswamp deposits, and (2) areas near to and directly affected by influx of higher salinity water from the Arkansas River. Trend lines for bromide and chloride concentrations in each area reflected differences in the source of salinity. Groundwater in backswamp areas contained higher bromide/chloride ratios and plotted along a trend line associated with evapotranspiration (fig. 98). Conversely, groundwater between the river and public-supply wells in the Dardanelle area had lower bromide/chloride ratios and plotted along a line with river water as an end member. Chloride concentrations in the river averaged approximately 200 mg/L during the study (Kresse and others, 2006), and the production well closest to the river had a maximum chloride concentration of 112 mg/L. Petersen (1988) provided a summary of water quality for four sites on the Arkansas River for 1975 through 1985 and showed maximum chloride concentrations ranging from 220 to 550 mg/L with means ranging from 90 to 150 mg/L for the four sites.

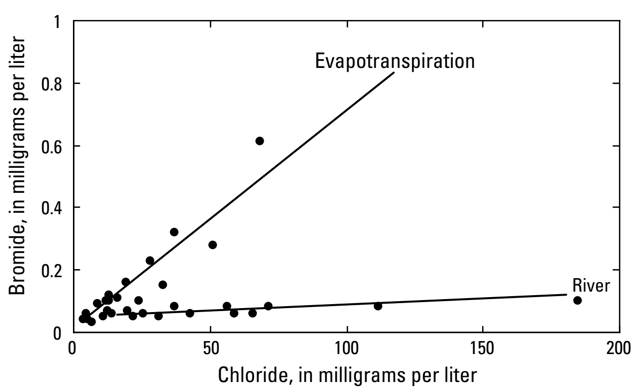



**Figure 98.** Relation of chloride and bromide concentrations in groundwater samples from the Arkansas River Valley alluvial aquifer near Dardanelle, Arkansas (from Kresse and Clark, 2008).

Kresse and Clark (2008) noted a relation between groundwater quality and the type of deposits that compose the Mississippi River Valley alluvial aquifer south of the Arkansas River in southeastern Arkansas. This was based on geochemical data for approximately 2,500 irrigation wells completed in the Mississippi River Valley alluvial aquifer south of the Arkansas River from Little Rock to the Mississippi River. This analysis showed that the lowest chloride concentrations were in wells completed in coarser-grained levee and channel deposits that tend to lie closest to the Arkansas River. The highest chloride concentrations were in wells completed in finer-grained backswamp deposits located away from the river (see Mississippi River Valley alluvial aquifer). Kresse and Clark (2008) hypothesized that a combination of rapid recharge and advective flushing in the relatively coarser channel and levee deposits near the river maintained low chloride concentrations in groundwater, which closely reflect that of evaporated rainwater. The fine-grained, clay-rich deposits associated with backswamp areas likely restrict recharge, induce increased ratios between evapotranspiration and recharge, and experience minimal flushing of salts concentrated during evapotranspiration. Although the spatial variability of various types of deposits is on a smaller scale for the Arkansas River Valley alluvium in the Interior Highlands, it is likely that restricted recharge through the lower permeable deposits results in groundwater of higher dissolved-solids concentration.

The highest chloride concentrations in the Arkansas River Valley alluvial aquifer generally occurred at further distances from the Arkansas River from Fort Smith to Little Rock. This situation is hypothesized to be the result of evapotranspiration in backswamp areas at greater distances from the river as proposed by Kresse and others (2006) and Kresse and Clark (2008). In the isolated areas where chloride concentrations were elevated next to the river, including an area in Franklin County, past pumping associated with public supply was likely the cause. In other words, past pumping for public supply resulted in the induced influx of water from the river into the alluvial aquifer. Bedinger and others (1963) also noted that pumping at the well fields in Dardanelle and Ozark had induced infiltration of river water into the aquifer.

In summary, groundwater in the Arkansas River Valley alluvial aquifer is of overall good quality, with the exception of elevated iron concentrations that often require treatment for use in public-supply systems. Chloride concentrations can be slightly elevated in backswamp areas or where influenced by an influx of water from the Arkansas River. Only 4 of 661 samples with chloride analyses exceeded the Federal secondary drinking-water regulation of 250 mg/L. Reducing conditions in various parts of the aquifer were hypothesized as controls on the distribution and concentration of nitrate, iron, and sulfate.

## Ouachita Mountains Aquifer

A thick sequence of Paleozoic rock formations in the Ouachita Mountains serves as an important source of groundwater supply for domestic users, in addition to a limited number of small commercial- and community-supply systems. The shallow saturated section of the combined formations in the Ouachita Mountains will hereinafter be referred to as the "Ouachita Mountains aquifer" (tables 2 and 4). Renken (1998) used a similar nomenclature in his listing of the "Ouachita Mountains aquifer" as a minor aquifer of Segment 5 (Arkansas, Louisiana, and Mississippi) of the Ground Water Atlas of the United States. Assignment of boundaries for various aquifers of Arkansas, and particularly those of the Ouachita Mountains, can be a daunting task. The Ouachita Province includes two sections: the Arkansas (River) Valley and the Ouachita Mountains (table 2). The Arkansas Valley lies between dipping rocks of the Boston Mountains to the north and the highly folded and deformed rocks of the Ouachita Mountains to the south and includes geologic formations that extend into both areas (fig. 3; Cordova, 1963; Kilpatrick and Ludwig, 1990a). Water-resources investigations in the Ouachita Mountains generally included an area south of the Arkansas Valley (Albin, 1965; Renken, 1998), which resulted in an arbitrary divide that omitted large, continuous exposures of formations that cross the divide to the north, particularly in Sebastian and Logan Counties. Some of these formations are included in Ouachita Mountains and Arkansas Valley sections and also extend into the Boston Mountains north of the river. For example, the Atoka Formation is exposed across a large part of the Boston Mountains physiographic region and is a major formation of the Western Interior Plains confining system. It extends as far south as Scott County in the heart of the Ouachita Mountains physiographic region (Haley and others, 1993).

Physiographic province and section boundaries often do not coincide with geologic or hydrologic boundaries. The Arkansas Valley section as identified on physiographic and regional hydrogeologic maps (Fenneman, 1938; Albin, 1965; Renken, 1998) includes formations that more appropriately belong to the Boston Mountains section of the Ozark Plateaus to the north or the Ouachita Mountains section of the Ouachita Province to the south. Including these formations as part of the Arkansas Valley for this report would result in (1) reproducing geologic, hydrologic, and water-quality discussions for either region in a separate section on the Arkansas Valley; (2) arbitrary boundaries of the Arkansas Valley cutting through continuously exposed formations (and possible groundwater flow paths) properly belonging to other sections; and (3) omitting important information, such as spatial water-quality trends or groundwater flow paths for aquifers in the Ouachita Mountains or Boston Mountains by arbitrary divides imposed by those defining the Arkansas Valley. For purposes of this report, the Arkansas River and associated alluvial deposits serve as a southern limit of the Western Interior Plains confining system (coinciding with the Boston Mountains section) and the northern limit of the Ouachita Mountains. Therefore, the Ouachita Mountains aquifer includes all formations extending north to the Arkansas River (and associated alluvial deposits), west to the State line, and south and east to the boundary with the Coastal Plain.

### Geology

Rocks forming the Ouachita Mountains aquifer are dominantly of sedimentary origin, ranging in age from Cambrian to Middle Pennsylvanian (table 4). These rocks were deposited by a regionally extensive sinking trough (geosyncline) that extended at minimum from central Oklahoma to central Arkansas. The geosyncline formed throughout most of the Paleozoic Era accounting for approximately 46,000 ft of accumulated sediment deposited in the trough. Lithification and compression of the sediments at a later time formed shales, sandstone, conglomerates, limestone, chert, and novaculite, ultimately resulting in deformation of a complexly folded and thrust-faulted arch (anticlinorium).

Orogenic activity into the Middle Pennsylvanian Epoch formed the rocks into a complexly folded and thrust-faulted anticlinorium in which many of the folds were broken by thrusts or high-angle reverse faults. The folds were overturned to the south, resulting in the dips off the fold axes to the north (Purdue, 1910; Albin, 1965; Stone and Bush, 1984). A long period of epeirogenic uplift and erosion subsequently occurred resulting in the present-day mountains (Albin, 1965; Stone and Bush, 1984). The present-day physiography is represented by long even-crested ridges and flat-intermontane basins. The higher ridges and crest-forming rocks typically consist of the more resistant quartz formations (Albin, 1965; Kresse and Hays, 2009). Major faults are essentially parallel to trends of the axes of folds, which generally lie along east-west trending lines throughout the Ouachita Mountains. Consequently, wells of similar water-yielding capacity typically lie on east-west trends relative to each other. The best places to drill wells in the Ouachita Mountains generally are on the flanks of anticlines (in synclinal valleys) and off the noses of plunging anticlines (Albin, 1965; Halberg and others, 1968).

### Hydrologic Characteristics

Formations in the Ouachita Mountains are dominated by thick sequences of shale, siltstones, and quartz (sandstone, chert, novaculite), with minor occurrences of carbonates and other rocks. Similar lithologies coupled with structural modification have created an extremely high degree of hydraulic connectively between the formations. The rock sequence serves effectively as a single aquifer from a regional perspective, and a detailed discussion of lithology and depositional environment for each formation is not provided. For additional information, the reader is directed to Purdue and Miser (1916), Albin (1965), Halberg and others (1968), Stone and Bush (1984), and McFarland (2004).

Primary porosity in rocks of the Ouachita Mountains was greatly decreased by compaction and lithification as sediments filled the synclinal trough and compression occurred during orogenic episodes. Secondary porosity and permeability are provided by faults, joints, fractures, bedding planes, and other structural features. These secondary permeability features generally result in low yields compared to unconsolidated sediments of Coastal Plain aquifers. Groundwater yields generally are sufficient for only domestic use. Groundwater geochemistry reflects the dominant aquifer rock types, with better quality water generally produced from quartz formations and poorer quality water from shale formations.

Groundwater availability afforded by secondary-porosity processes is strongly dependent on the degree of fracturing related to the tensile strength of the rock (Albin, 1965; Halberg and others, 1968; Stone and Bush, 1984; Cole and Morris, 1986; Kresse and Hays, 2009). Quartz formations such as the Bigfork Chert and Arkansas Novaculite are very brittle and prone to dense fracturing. Most researchers working in the Ouachita Mountains identified the Bigfork Chert as the most productive water-bearing formation in the region (Albin, 1965; Halberg and others, 1968; Stone and Bush, 1984; Cole and Morris, 1986; Kresse and Hays, 2009). Well yields have a fairly large range depending on individual formations and lithology but typically are low throughout the aquifer. Albin (1965) noted that most wells yielded less than 10 gal/min, and yields more than 50 gal/min were rare. The maximum recorded yield of 350 gal/min was for a well completed in the Bigfork Chert. Wells continuously yielding more than 10 gal/min for a week generally were considered "large-yield" wells. Wells in Hot Spring County generally yielded from 2 to 7 gal/min, with a few wells yielding 20 gal/min or more (Halberg and others, 1968). The average pumping rate measured in this area was 21 gal/min with a reported maximum of 40 gal/min. A well completed in the Bigfork Chert in Garland County was pumped at 30 gal/min over a 3-day period, resulting in drawdown of only 1–2 inches (Kresse and Hays, 2009). Specific capacities ranged from 0.1 to 9.0 (gal/min)/ft of drawdown (Albin, 1965; Halberg, 1968), and transmissivities ranged from 134 to 2,674 $ft^2/d$ (Albin, 1965). In spite of the few relatively high reported yields cited above, all publications cautioned that the aquifer should not be considered as a source of water supply unless the required quantity was small (Albin, 1965; Halberg and others, 1968; Stone and Bush, 1984).

Most wells in the Ouachita Mountains aquifer are less than 100 ft deep but can be as much as 700 ft deep. Static water levels generally are less than 20 ft below land surface, and flowing-artesian wells are common throughout the region (Albin, 1965; Kresse and Hays, 2009). Pumping water levels may be as much as 150 ft below land surface in the deepest wells. Of the 35 wells surveyed in Garland County, 83 percent were less than or equal to 200 ft deep, and all were less than 400 ft deep (Kresse and Hays, 2009). Of these wells, 25 were located in valleys and had a mean depth of 16 ft compared to a mean depth of 75 ft for wells located at higher elevations. Generally, wells in the valleys were completed in the Stanley Shale and those at higher elevations were completed in the Bigfork Chert.

Seasonal water-level fluctuations in the Ouachita Mountains aquifer generally were less than 10 ft. Larger fluctuations are common in abnormally wet or dry years because the groundwater reservoirs generally have small storage capacities and are recharged by rapid infiltration of local precipitation (Albin, 1965). Kresse and Hays (2009) collected water-level data for seven wells (two Stanley Shale, one Hot Springs Sandstone, three Bigfork Chert, and one Arkansas Novaculite) from October 2007 through April 2009. Substantial water-level rises occurred for the quartz formations compared to the shale formations from December through May (wet season), reflecting greater storage in the quartz formations. Smaller rises in water levels were noted for wells in the quartz formations compared to shale formations for individual rain events. However, water levels slowly increased to maximum overall rises of 8–15 ft during the wet season in the quartz formations. Conversely, there were only episodic increases and decreases relative to a similar base level for wells in shale formations throughout this same period. Kresse and Hays (2009) hypothesized that the brittle nature and intense fracturing of the quartz formations resulted in substantially greater fracture porosity compared to shale formations. This provided greater permeability and storage for the quartz formations, with the result of an overall large rise in water levels in the wet season and smaller rises during individual rain events. The lower permeability and secondary porosity in the shale formations resulted in rapid filling of the fractures and causing large, short-term water-level rises, followed by rapid water-level declines driven by steep hydraulic gradients. Aquifer tests for several wells in both types of formations confirmed that yields and storage properties were substantially lower in the shale formations than in the quartz formations.

Because of the similar rock types in the Boston and Ouachita Mountains regions, groundwater flow within both of these systems is likely explained by a similar conceptual model. Kresse and others (2012) proposed a general conceptual model explaining groundwater flow for a part of the Boston Mountains. They hypothesized that flow was controlled by secondary-porosity features (fractures, bedding planes), which provide limited groundwater storage and low yields generally sufficient only for domestic supply, and that flow paths were confined by small-scale topographic boundaries with short flow paths from elevated areas to valley floors in individual, small-scale watersheds. Topographic basins in the Ouachita Mountains generally are defined by the folded strata resulting in synclinal and anticlinal basins. Consequently, Halberg and others (1968) postulated that flow directions would reflect the structural geology, orientation, and hydraulic connection of the major east-west trending faults and likely have little interbasin flow of groundwater. Kresse and Hays (2009) tested this postulation using water levels from 53 shallow (less than 400 ft deep) wells and 24 springs in Garland County to construct a potentiometric-surface map. The map indicated a high degree of topographic control on shallow groundwater flow, with groundwater flow confined to individual synclinal and anticlinal basins. This observation adds support to the conceptual model of groundwater flow of topographically controlled, short flow paths within local watersheds in the Ouachita Mountains aquifer.

## Water Use

Determination of accurate values for the amount of water used from the Ouachita Mountains aquifer is difficult, and reported total use from the aquifer should be viewed with caution. The greatest use of groundwater from the Ouachita Mountains aquifer is for domestic supply. Domestic wells and wells producing less than 50,000 gal/d are exempt from reporting requirements; consequently, various methods that are used to estimate domestic water use commonly result in an underestimation of total groundwater use from the aquifer. Although Albin (1965) noted overall low yields and stated that wells in the aquifer that yield more than 10 gal/min are considered “large-yield wells,” some wells can yield between 10 and 50 gal/min, which are more than sufficient for many communities. Records from the ADH indicate that 72 wells are used by camps and other recreational areas, conference centers, rest areas, stores, and even sources of public supply. Five separate communities used wells completed in the Atoka, Bigfork Chert, Stanley Shale, and Arkansas Novaculite Formations for purpose of public supply. This demonstrates that many formations within the Ouachita Mountains aquifer are capable of supplying sufficient volumes of water for a small community.

## Water Quality

Past research indicated that groundwater in the Ouachita Mountains aquifer primarily is of a mixed calcium- and sodium-bicarbonate type and chemically is suitable for most domestic and farm uses. However, some groundwater exhibited high hardness and contained concentrations of iron, manganese, chloride, and nitrate in excess of concentrations recommended for various uses. The most common complaint from domestic users was that the groundwater can be hard and high in iron (Albin, 1965; Halberg and others, 1968; Cole and Morris, 1986; Kresse and Hays, 2009).

### General Geochemistry and Water Type

Bicarbonate was the dominant anion in 90 of 116 samples (78 percent) with complete anion (chloride, sulfate, bicarbonate) analyses and was greater than 50 percent of the total anions in 78 of the 116 samples (67 percent) for the Ouachita Mountains aquifer. The remaining samples had chloride or sulfate as the dominant anion or were of a mixed type. For samples with complete cation (calcium, magnesium, sodium, potassium) analyses, calcium was the dominant cation in 59 of 125 samples (47 percent) and greater than 50 percent in 37 of 125 samples (30 percent). Sodium was the dominant cation in 48 of 125 samples (38 percent) and greater than 50 percent in 23 of 125 samples (18 percent). The remaining samples generally had magnesium as the dominant cation. Therefore, groundwater is predominantly a calcium-bicarbonate type throughout the aquifer. Generally, samples with the highest percent sodium occur in the southern part of the aquifer in wells completed in the Stanley Shale and in the northern part in wells completed in the shale-rich Atoka and McAlester Formations (fig. 99). These areas represent the transition from a calicium-bicarbonate to a sodium-bicarbonate or a sodium-chloride water type.

Values of pH for the Ouachita Mountains aquifer ranged from 3.3 to 8.6 in 137 samples with a median of 7.0 (table 41). To better assess the extreme variability of pH, it is useful to understand the difference in geochemistry of the source rocks, which are dominantly shale and quartz. A study by Kresse and Hays (2009) in Garland County revealed substantial differences in groundwater geochemistry based on rock type. Low specific-conductance values were noted for groundwater from quartz formations (Bigfork Chert, Arkansas Novaculite, and Hot Springs Sandstone). All but one sample exhibited values less than 50 µS/cm with a median of 30 µS/cm. These low specific-conductance values reflect a low dissolved-solids concentration attributable to the low solubility of quartz and the lack of carbonate minerals. Specific-conductance values for the shale formations (Stanley Shale, Womble Shale, and the undifferentiated Missouri Mountain Shale and Polk Creek Shale) ranged from 97 to 490 µS/cm with a median of 293 µS/cm. These high specific-conductance values reflect high dissolved-solids concentrations attributable to the abundance of carbonate and other soluble minerals in the shale rocks. Values of pH in groundwater from shale rock ranged from 5.8 to 7.4 with a median of 6.6. Conversely, pH values in groundwater from quartz rocks ranged from 3.6 to 6.1 with a median of 4.4. Increased pH was attributed to dissolution of mineral species with buffering capacity, particularly carbonate minerals, resulting in a positive correlation of pH and conductance (Kresse and Hays, 2009).

Spatial patterns of pH and specific conductance generally followed formation outcrop patterns for the Ouachita Mountains aquifer. Generally, the lowest pH values (3.3–5.0) were from the eastern part of the aquifer, where the Bigfork Chert, Arkansas Novaculite, and Hot Springs Sandstone Formations have extensive outcrop. High pH values (8.1–8.6) occur in the south, dominantly represented by wells completed in the Stanley Shale, and also occur in the western and northern parts of the aquifer, where shale-dominated rocks of the Atoka Formation predominate in outcrop. A few of these wells also were completed in the shale-rich McAlester Formation (fig. 99).

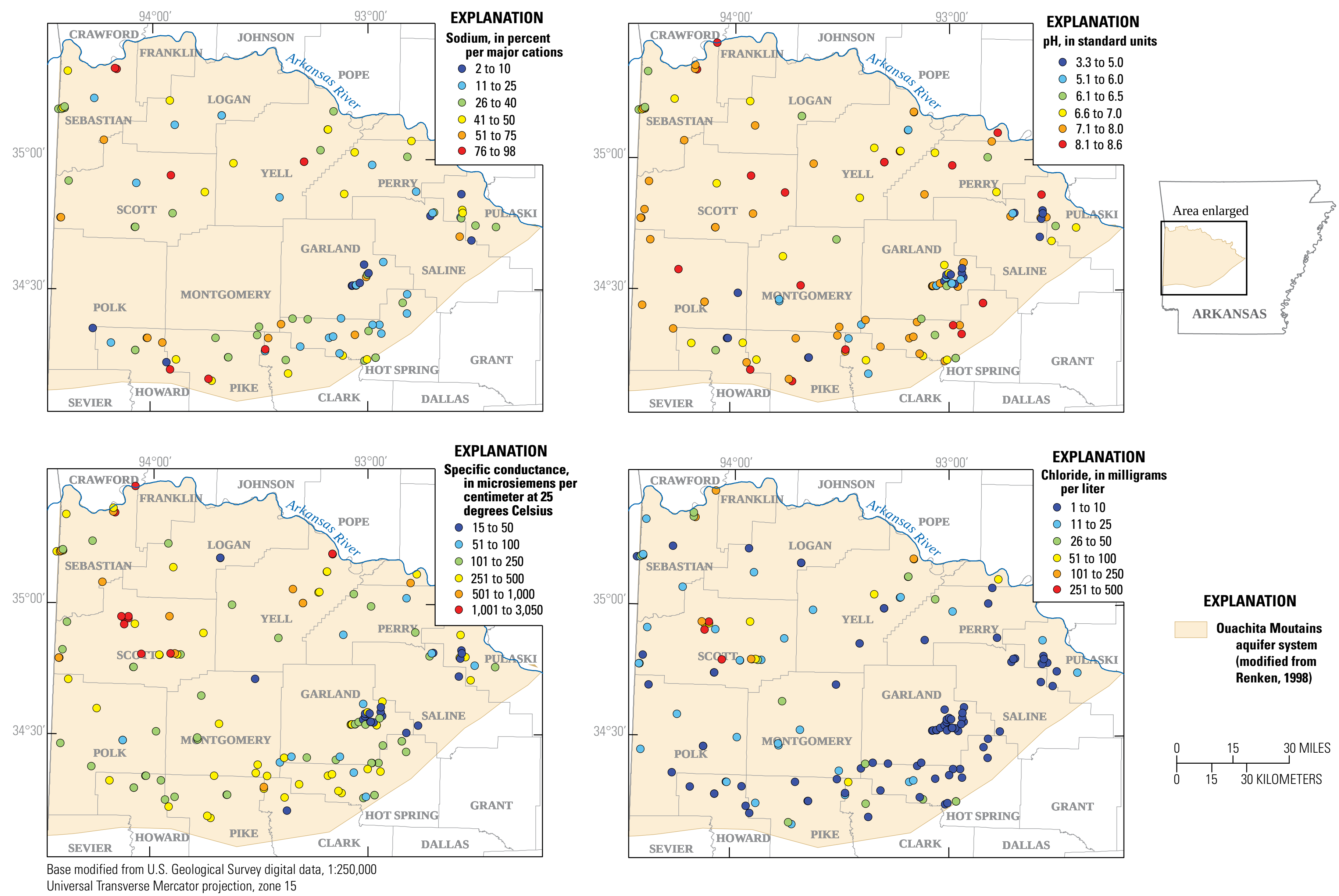



**Figure 99.** Spatial distribution of selected chemical constituents in groundwater from the Ouachita Mountains aquifer in western Arkansas.

**Table 41.** Descriptive statistics for selected chemical constituents in groundwater from the Ouachita Moutains aquifer in western Arkansas.

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

| Constituent or characteristic | Minimum | Median | Maximum | Standard deviation | Number of wells |
|---|---|---|---|---|---|
| Calcium (mg/L) | 0.04 | 13.9 | 303 | 30.7 | 136 |
| Magnesium (mg/L) | 0.01 | 4.25 | 307 | 27 | 136 |
| Sodium (mg/L) | 0.67 | 12 | 284 | 41.1 | 135 |
| Potassium (mg/L) | 0.08 | 1.2 | 24 | 3.88 | 124 |
| Bicarbonate (mg/L) | 1.0 | 89 | 511 | 107 | 118 |
| Chloride (mg/L) | 0.9 | 7.0 | 500 | 62.1 | 152 |
| Sulfate (mg/L) | 0.02 | 9.15 | 535 | 56.1 | 137 |
| Silica (mg/L) | 1.1 | 13.2 | 46.8 | 11.1 | 102 |
| Nitrate (mg/L as nitrogen) | 0.01 | 0.14 | 15 | 3.17 | 101 |
| Dissolved solids (mg/L) | 14 | 152 | 953 | 152 | 125 |
| Iron (µg/L) | 0.05 | 170 | 14,000 | 2,320 | 108 |
| Manganese (µg/L) | 0.13 | 71.8 | 2,600 | 403 | 86 |
| Arsenic (µg/L) | 0.03 | 0.03 | 7.2 | 1.76 | 41 |
| Hardness (mg/L as calcium carbonate) | 0 | 62 | 410 | 82 | 116 |
| Specific conductance (µS/cm) | 15 | 241 | 3,050 | 401 | 157 |
| pH (standard units) | 3.3 | 7.0 | 8.6 | 1.2 | 137 |

Specific conductance values follow the same general trend represented by pH values. The lowest conductance values (15–50 µS/cm) occur in the eastern part of the aquifer, represented by the quartz formations listed above. A generally increasing trend in conductance occurs in the southern part of the aquifer, represented by wells dominantly completed in the Stanley Shale with numerous samples having conductance values ranging from 250 to 500 µS/cm. Lower values (ranging from 15 to 100 µS/cm) in the southern part of the aquifer were from wells completed in the Jackfork Sandstone. The highest specific conductance values (ranging from 1,000 to 3,050 µS/cm) were from wells completed in the Atoka Formation in Scott County (fig. 99). The Atoka Formation is dominantly shale rock with some traceable sandstone units in the Ouachita Mountains. In general, the spatial distribution of pH and specific conductance values reflected source-rock types (Kresse and Hays, 2009).

Groundwater from quartz formations generally has lower conductance values than shale formations, reflecting lower dissolved-solids concentrations. This indicates that groundwater from quartz formations of the Ouachita Mountains aquifer is a highly desirable drinking-water source from the standpoint of hardness issues; however, the corresponding low pH values can present other problems related to leaching of metals in plumbing fixtures. Certain trace metals have solubility values that increase substantially at low pH values. These metals can be leached from pumps, pipes, fixtures, and other metallic parts of the water-distribution system, which leads to higher concentrations that affect taste, pitting and corrosion of pipes, and staining of plumbing fixtures (Hem, 1989). Dissolved aluminum and copper were higher in groundwater from the quartz formations than in groundwater from shale formations as a result of the low pH in groundwater from quartz formations. This interpretation was substantiated by an inverse correlation of these metals with pH from a regression analysis.

## Nitrate

Nitrate concentrations in the Ouachita Mountains aquifer ranged from 0.01 to 15 mg/L with a median of 0.14 (table 41), which reflects the generally low nitrate concentrations throughout the aquifer. Out of 101 samples with nitrate analyses, 40 had concentrations less than 0.10 mg/L and 72 were less than 1.0 mg/L. Only 4 of the 101 samples had concentrations exceeding the Federal MCL of 10 mg/L as nitrogen. No regional spatial trend was found in the distribution of nitrate. Although low concentrations can be found throughout the aquifer, a greater number of low (0.01 to 0.10) concentrations occur in the eastern part of the aquifer. Generally, decreasing nitrate concentrations were related to increasing well depth rather than to spatial variability, reflecting the differences in vulnerability based on regolith thickness, rock type, and other surface features. Nitrate concentrations greater than 2.0 mg/L occurred in wells less than 200 ft deep. Correlation of nitrate concentrations with nitrogen sources was outside the scope of this report and was not addressed in previous reports.

## Iron

Iron concentrations in the Ouachita Mountains aquifer ranged from 0.05 to 14,000 µg/L with a median of 170 µg/L (fig. 100; table 41). No spatial pattern was noted for iron; high and low concentrations occurred in shale and quartz formations. Iron is abundant in numerous minerals in alluvial sediments and sedimentary rocks throughout Arkansas. Controls on solubility generally are related to changes in redox zonation, which can result in dissolution or precipitation of various iron-rich minerals based on the presence or absence of oxygen and the availability of electron donors and acceptors. Although iron was cited as problematic for wells completed in the Ouachita Mountains aquifer (Albin, 1965; Halberg and others, 1968; Cole and Morris, 1986; Kresse and Hays, 2009), no studies currently (2013) have been completed to identify iron sources and transport pathways. Higher concentrations of some trace metals (barium, lithium, manganese, and strontium) are noted in shale formations, whereas other trace metals occur in higher concentrations from quartz formations related to the low pH values (Wagner and Steele, 1985; Kresse and Hays, 2009). Although no relations were noted for the spatial distribution or sources of iron, evidence shows some control on iron solubility by possible sulfate reduction as described in the next section.

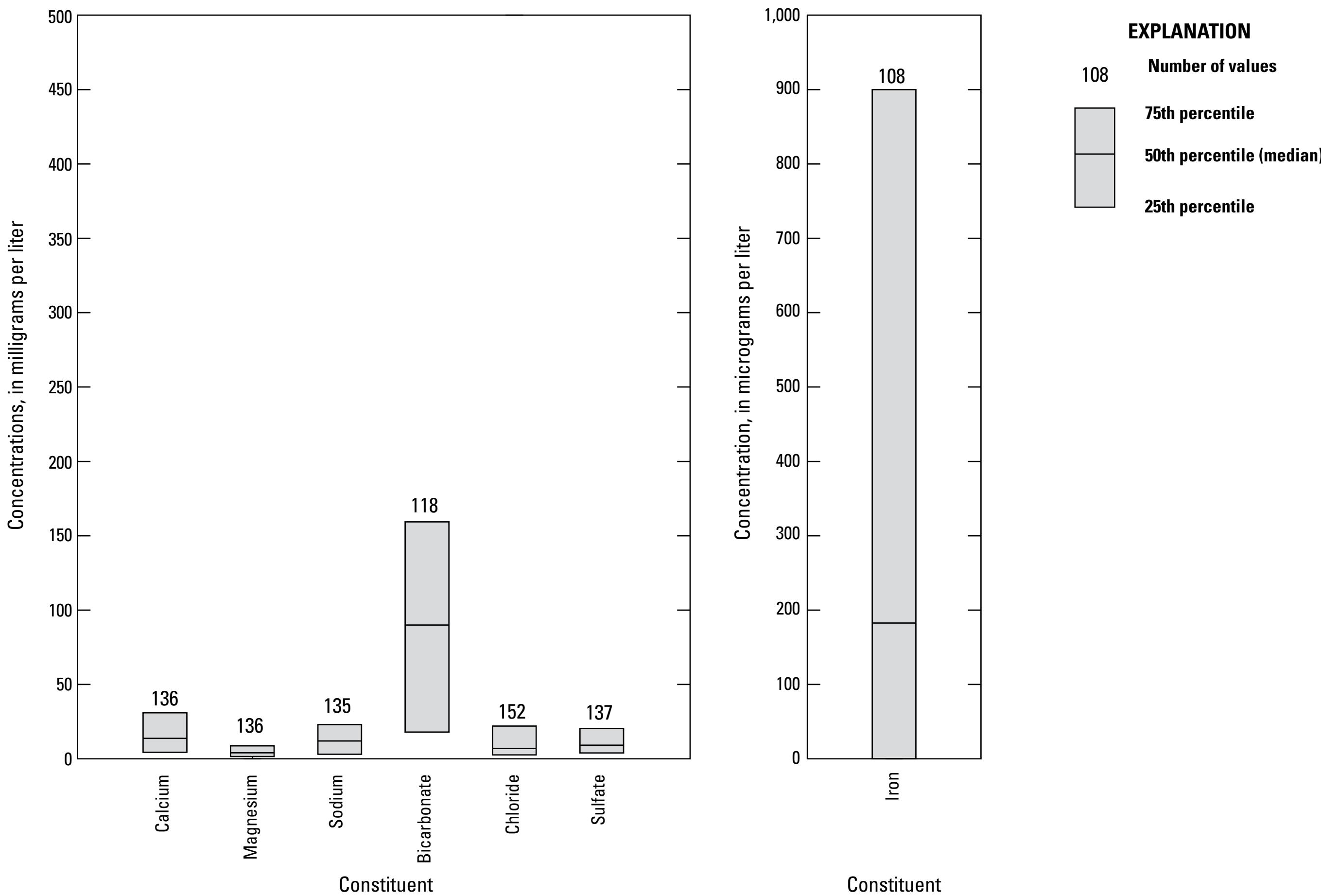



**Figure 100.** Interquartile range of selected chemical constituents in groundwater from the Ouachita Mountains aquifer in western Arkansas.

### Sulfate

Sulfate concentrations generally were low throughout the Ouachita Mountains aquifer. Of 137 samples, 72 wells (53 percent) had concentrations less than 10 mg/L, 124 wells (91 percent) had concentrations less than 50 mg/L, and only 1 well had a concentration greater than the Federal secondary drinking-water regulation of 250 mg/L. Sulfate was substantially greater in shale formations than in quartz formations in the Ouachita Mountains aquifer (Kresse and Hays, 2009). Grouping all data by aquifer codes confirmed that concentrations greater than 10 mg/L (up to 535 mg/L) generally occurred in groundwater from the Stanley Shale, McAlester Formations, and Atoka Formation (51 of 88 combined analyses greater than 10 mg/L). Nevertheless, low concentrations can be found throughout the aquifer in groundwater from all formations. This is demonstrated by the low concentrations throughout the southern part of the aquifer, an area with numerous wells completed in the Stanley Shale. The lowest concentrations (generally less than 5 mg/L) generally occurred in the Bigfork Chert, Arkansas Novaculite, Hot Springs Sandstone, and Jackfork Sandstone (only 6 of 44 combined analyses more than 10 mg/L).

Various constituent relations suggest that sulfate reduction in groundwater from shale formations may serve as a control on iron solubility. Iron and sulfate had inverse correlations with nitrate, indicating that denitrification occurred prior to iron and sulfate reduction. Nitrate concentrations greater than 0.5 mg/L occurred where iron concentrations generally were less than 1,200 µg/L. Iron concentrations greater than approximately 500 µg/L with corresponding nitrate concentrations more than 0.5 mg/L normally represent mixing of groundwater from different zones in the aquifer, which is typical of open-hole completions in bedrock aquifers (fig. 101*A*). Nitrate concentrations were greater than 0.5 mg/L for sulfate concentrations generally less than 30 mg/L (fig. 101*B*).

Sulfate concentrations in the Ouachita Mountains aquifer were inversely correlated with iron concentrations (fig. 101*C*). The reduction of sulfate to hydrogen sulfide is directly related to the abundance of available sulfate. Studies have shown that dissolved iron ($Fe^{2+}$) and hydrogen sulfide ($H_2S$) tend to be inversely related according to a hyperbolic function. When $Fe^{2+}$ concentrations are high, $H_2S$ concentrations tend to be low and vice versa, which reflects the rapid reaction kinetics of $Fe^{2+}$ with $H_2S$ to produce relatively insoluble ferrous sulfides (Chapelle and others, 2009). The transition from iron- to sulfate-reducing conditions occurs when higher sulfate concentrations are available for sulfate-reducing bacteria to produce sulfide, and the resulting precipitation of iron-sulfide minerals acts as a sink for soluble iron. Kresse and others (2012) provided evidence for the geochemical evolution of redox zonation in similar shale formations in the Boston Mountains area. A series of reduction steps from denitrification, through iron reduction, and ultimately to sulfate reduction occurred with increasing dissolved-solids concentrations, corresponding to increasing residence time in the aquifer.

Elevated (more than 2.0 mg/L) nitrate concentrations in the Ouachita Mountains aquifer dominantly occurred in association with dissolved-solids concentrations less than 200 mg/L (fig. 101*D*). Iron concentrations greater than 2,000 µg/L occurred in association with dissolved-solids concentrations less than 250 mg/L (fig. 101*E*). When dissolved-solids concentrations exceeded 250 mg/L, all but one of the iron concentrations were less than 200 µg/L. Although it appears that nitrate and iron concentrations overlap, the inverse correlation between iron and nitrate (fig. 101*A*) indicates that redox zonation varies for dissolved-solids concentrations less than 200 mg/L, depending on conditions along local flow paths in different parts of the aquifer. Sulfate concentrations increased with increasing dissolved solids, and sulfate concentrations exceeding 50 mg/L (up to 535 mg/L) occurred where dissolved-solids concentrations were greater than 250 mg/L (fig. 101*F*). All of these relations support a conceptual model of redox zonation that fits the theory by Kresse and others (2012) for shale formations in the Boston Mountains. Shale formations are rich in labile organic material, which drives the reduction of initially oxygenated water by aerobic and anaerobic bacteria. These redox processes proceed sequentially from the most to the least energetic microbially mediated reaction (Appelo and Postma, 1999). Oxygen is the first terminal electron acceptor, followed by nitrate, manganese oxide, iron oxyhydroxide, sulfate, and carbon dioxide. Data indicate that nitrate and iron reduction dominate the redox zonation for dissolved-solids concentrations less than 250 mg/L. Concentrations of nitrate and iron appear to overlap along the continuum of increasing dissolved-solids concentrations (representing increased residence time in the aquifer) between approximately 100 and 200 mg/L. Because nitrate reduction precedes iron reduction, this relation appears to violate redox zonation theory. However, the inverse correlation of iron and nitrate (fig. 101*A*) shows that elevated concentrations for these constituents are mutually exclusive. Either process can be dominant in this region based on the abundance and availability of the respective electron acceptors and dissolved organic matter. Dissolved-solids concentrations more than 250 mg/L are characterized by: (1) the virtual disappearance of iron and nitrate, (2) the dominance of higher sulfate concentrations, and (3) hypothesized sulfate-reducing conditions. This corresponds closely with groundwater-quality data from shale formations in the Boston Mountains (Kresse and others, 2012), which indicate that sulfate reduction dominates over iron reduction for dissolved-solids concentrations exceeding approximately 290 mg/L (see “Western Interior Plains Confining System” section). Therefore, geochemical evolution of groundwater in shale formations appears to be similar throughout the Ouachita Mountains and Interior Highlands. This model of redox zonation accounts for controls on iron solubility, which was not evident from a review of the spatial distribution of iron concentrations or relation to geologic formations.

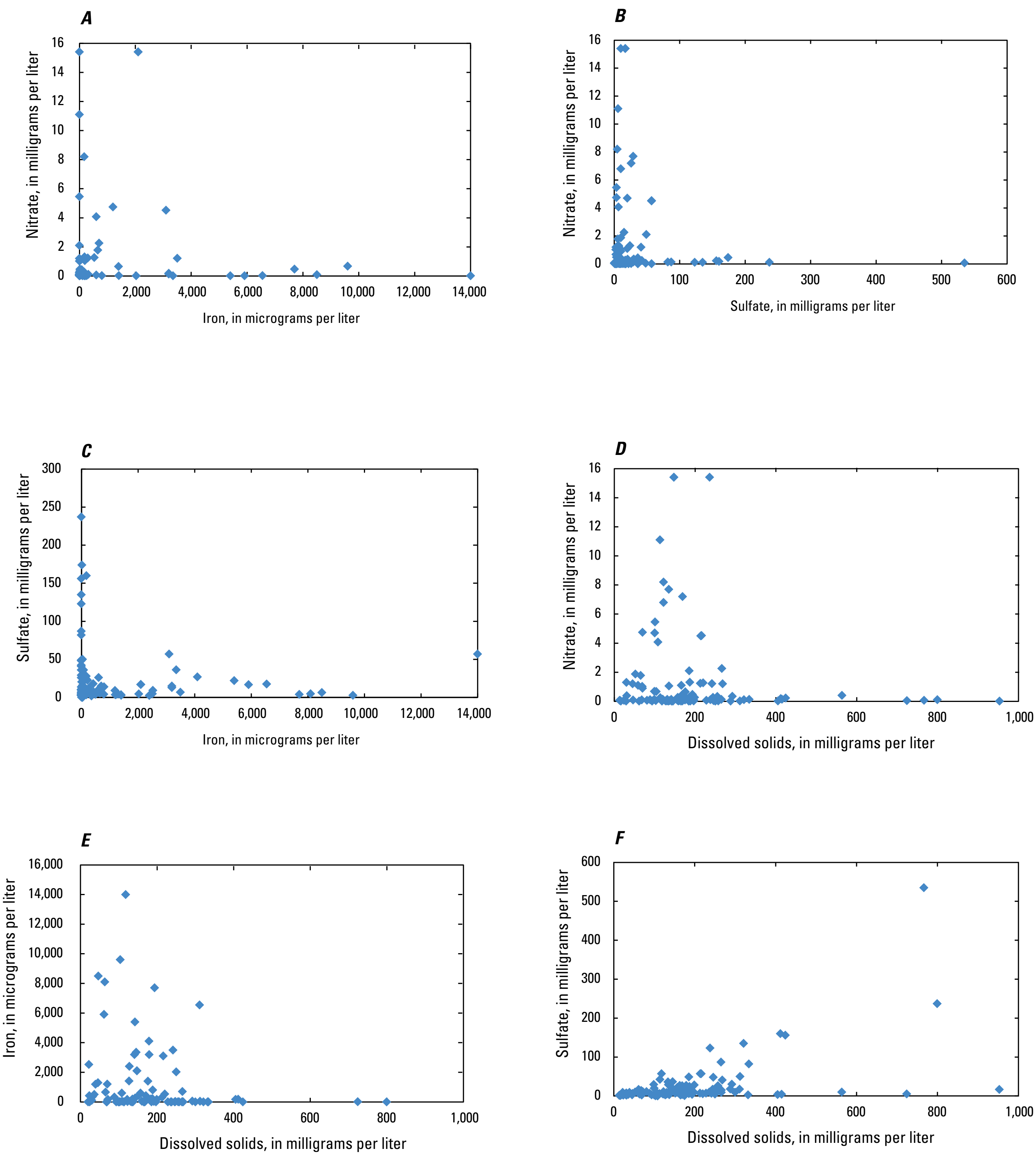



**Figure 101.** Relation of concentrations for *A*, nitrate and iron; *B*, nitrate and sulfate; *C*, sulfate and iron; *D*, nitrate and dissolved solids; *E*, iron and dissolved solids; and *F*, sulfate and dissolved solids in groundwater from the Ouachita Mountains aquifer in western Arkansas.

### Chloride

High salinity can be a problem in some aquifers, especially for some of the Tertiary and Cretaceous aquifers of the Coastal Plain, but chloride concentrations were low throughout the Ouachita Mountains aquifer. Shale formations formed from marine deposits often retain residual salts. Through the process of uplift and erosion, coupled to continuous flushing by meteoric water over time, much of the original salinity is often flushed from the aquifer. However, wells that penetrate low-porosity, hydraulically isolated zones that still retain high levels of chloride often result in production of slightly brackish water.

Chloride concentrations in the Ouachita Mountains aquifer ranged from 0.9 to 500 mg/L with a median of 7.0 mg/L (fig. 100; table 41). Out of 152 samples, 143 (94 percent) had concentrations that were less than 100 mg/L, 117 (77 percent) were less than 25 mg/L, and only 3 samples exceeded the Federal secondary drinking-water regulation of 250 mg/L. Chloride concentrations, similar to sulfate, generally increased with an increase in dissolved solids. All chloride concentrations more than 50 mg/L occurred at dissolved-solids concentrations greater than 200 mg/L. Extremely low chloride concentrations occur in the eastern part of the aquifer. The greatest density of elevated (greater than 100 mg/L) chloride concentrations occur in Scott County. Wells in this area are completed in the shale-dominated rocks of the Atoka Formation. For quartz formations, only 1 of 44 samples had a concentration that was greater than 10 mg/L (54 mg/L), and 38 of the 44 samples were less than 10 mg/L.

In summary, groundwater quality in the Ouachita Mountains aquifer is good with respect to Federal primary drinking-water standards. Problems in regard to taste, staining, and other aesthetic properties are related to elevated levels of iron, which is a common complaint among domestic users. Geochemical data indicate that an important control on iron solubility is sulfate reduction, which occurs dominantly in groundwater with dissolved-solids concentrations greater than 250 mg/L. Nitrate was somewhat elevated (greater than 1.0 mg/L) in numerous wells; however, only 4 of 101 samples exceeded the Federal MCL of 10 mg/L. Concentrations more than 1.0 mg/L generally occurred in wells less than 200 ft in depth. As is the case with most aquifers, shallow groundwater is more vulnerable to surface sources of contamination.

## Western Interior Plains Confining System

The Boston Mountains (fig. 3) are represented by a group of formations that comprise dominantly fractured shale and sandstone rocks, which are characterized by low secondary porosity and permeability with resulting low yields. Regional hydrogeologic framework studies (Imes and Emmett, 1994) characterize this system of formations as a regional confining unit, referred to as the Western Interior Plains confining system (table 5). Although regionally designated as a confining system, these formations are important locally as valuable sources of water supply. Unfortunately, there are no reports that view this collection of rocks as a regional aquifer system because of the dominance of shale formations and low well yields. However, historical reports discuss hydrologic characteristics and water quality for individual formations in this system of rocks. Historical and current USGS water-use reports use the term “rocks of Paleozoic age, undifferentiated” to refer to the total reported groundwater use from all shallow rock formations of the Interior Highlands, including those of the Ouachita Mountains, the Boston Mountains, and the Ozark and Springfield Plateaus regions. Although this report retains the accepted regional nomenclature of Western Interior Plains confining system for this system of formations, it is implied and often referred to in the following discussion as an important aquifer system in Arkansas.

### Geologic Setting

The Western Interior Plains confining system comprises 11 different predominantly clastic (sand, siltstone, shale) formations of Upper Mississippian and Pennsylvanian age (tables 2 and 5). These formations are relatively thin in the northern Boston Mountains and thicken considerably to the south at rates of approximately 180 ft/mi. Total thickness of the formations is more than 6,000 ft beneath the Arkansas River Valley (Imes and Emmett, 1994). The lithology and hydrogeological characteristics of these formations are very similar. Consequently, a detailed discussion of each formation is not integral to the understanding of this shallow aquifer system. For additional information on the stratigraphy of the individual formations composing the confining system, the reader is referred to McFarland (2004). A general knowledge of the basic rock types is sufficient to understanding the hydrologic characteristics and geochemistry of groundwater from the Western Interior Plains confining system.

### Hydrologic Characteristics

The Western Interior Plains confining system (fig. 3) consists of alternating sequences of low-permeable shale and siltstone, and low- to moderate-permeable sandstone, with minor occurrences of limestone and coal. Regionally, the confining system impedes the flow of water to and from the underlying Springfield Plateau aquifer (Imes and Emmett, 1994). The designation of these combined formations as a “confining system” is a consequence of the marked permeability contrast between the high porosity karst limestone of the Springfield Plateau aquifer compared to the low fracture porosity in the Western Interior Plains confining system. Porosity in the well-indurated clastic rocks of the Western Interior Plains confining system is dependent upon weathering and resultant fracture development. Chemical and physical weathering processes result in the development of secondary porosity through expansion and fracturing of the rocks. Fractures tend to exhibit denser distribution and larger apertures near the surface because of unloading expansion that is a mechanical response to decreased compressive stress as overlying rocks are eroded and removed. The hydraulic properties of the Western Interior Plains confining system exhibit low primary porosity, secondary porosity from fractures associated with compression, uplift and weathering, and low yields that rarely exceed 1–5 gal/min, similar to that of the shale- and sandstone-dominated Ouachita Mountains aquifer.

Imes and Emmett (1994) noted that local groundwater-flow systems in the Western Interior Plains confining system are dominantly present in the upper 300 ft of the weathered confining system. This is because fractures generally have a larger aperture near the surface and diminishing width with depth. Porosity and permeability generally decrease to a magnitude insufficient to support production from wells at depths more than approximately 300 ft (Cordova, 1963; Kilpatrick and Ludwig, 1990b; Imes and Emmett, 1994; Kresse and others, 2012). Kresse and others (2012) reported on 58 wells in the central part of the Western Interior Plains confining system with depths ranging from 25 to 385 ft with a median of 87 ft. Many wells in the Western Interior Plains confining system often go dry during pumping, particularly during drought periods (Cordova, 1963; Kresse and others, 2012). The quantity of groundwater available in the Western Interior Plains confining system is related directly to the density, size, openness, and degree of interconnection of fractures (Cordova, 1963).

Groundwater generally is recharged by precipitation that infiltrates in upland areas, percolates to the water table, flows downgradient toward lowland areas, and discharges into streams (Imes and Emmett, 1994). A conceptual model of groundwater flow for the Western Interior Plains confining system is controlled by expansion fractures with limited groundwater storage and has sufficient yields almost solely for use as domestic supply. Groundwater flow paths are constrained by small-scale topographic boundaries with flow from elevated areas to valley floors in small stream systems (Cordova, 1963; Imes and Emmett, 1994; Kresse and others, 2012). Regional hydraulic heads and flow gradients probably have changed little since predevelopment because of the poor hydraulic connection between lower and higher permeability zones. Water-level measurements in any one well represent averages of all the water-yielding layers in the Western Interior Plains confining system (Imes and Emmett, 1994).

Because of the low porosity of the Western Interior Plains confining system, well yields generally are sufficient only for household, small public-supply, and nonirrigation farm uses. Cordova (1963) noted that most wells yielded less than 60 gal/min, which is the maximum yield in the Western Interior Plains confining system. Thicker sandstone units in the Atoka Formation and the Batesville Sandstone in the eastern part of the confining system commonly yield 5–10 gal/min to wells less than 300 ft deep (Albin and others, 1967a). Kilpatrick and Ludwig (1990b) also noted that yields typically are less than 10 gal/min. Well yields for 16 shallow wells in southwestern Washington County ranged from 2 to 19 gal/min (Muse, 1982). Water levels in the Western Interior Plains confining system typically range from near land surface to approximately 50 ft below land surface. Seasonal fluctuations are approximately 10 ft with drawdowns from pumping as much as 45 ft (Cordova, 1963; Albin and others, 1967a).

## Water Use

Difficulties exist when attempting to gather information on use of groundwater in the Interior Highlands. Before development of surface-water resources, wells were common throughout the region for domestic and livestock supply and less common for public supply, commercial, and industrial purposes (Purdue and Miser, 1916; Cordova, 1963; Albin and others, 1967a; Lamonds, 1972). Because domestic and public-supply systems serving less than 50,000 gal/d are not required to report their groundwater use, there is no way to accurately quantify the number of domestic and livestock wells currently in use. Thirteen wells were reported as completed in the Atoka Formation of the Western Interior Plains confining system in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2013). These wells were mainly used for public supply or parks. Several schools, stores, parks, and some commercial businesses also withdraw water from the Western Interior Plains confining system (Lyle Godfrey, Arkansas Health Department, written commun., 2012).

## Water Quality

Little groundwater-quality monitoring has been done in the past related to the Western Interior Plains confining system. Most water-resource investigations in the Ozark Plateaus have concentrated on the Springfield Plateau and Ozark aquifers. Kilpatrick and Ludwig (1990a) reported that overall geochemistry in the area is closely related to the mineral concentration of the rock, although no detailed discussions were provided to explain this observation. The water was described as a calcium-magnesium-bicarbonate type, hard, and high in iron, with areas of slightly saline water and occasional high nitrate concentrations (Kilpatrick and Ludwig, 1990a).

Groundwater in formations of the Western Interior Plains confining system was noted to have bicarbonate as the principal anion with sodium, calcium, or magnesium dominating the cations dependent on the formation type (Cordova, 1963). Lamonds (1972) stated that groundwater ranged from a calcium- to a sodium-bicarbonate type with dissolved-solids concentrations ranging from 20 to 1,200 mg/L. Dissolved-solids concentrations for groundwater in sandstones of the Atoka Formation typically ranged up to 200 mg/L, whereas groundwater from shale formations typically had dissolved-solids concentrations greater than 200 mg/L. Cordova (1963) attributed sodium- and magnesium-chloride water types to proximity of hydrocarbon accumulations and attributed the sulfate water type to oxidation of pyrite. Cordova also noted that iron concentration varied widely, ranging from nondetectable to 19 mg/L. Odors of hydrogen sulfide and iron staining on plumbing fixtures were the major complaints of household residents (Cordova, 1963).

Albin and others (1967a) reported on water resources of Jackson and Independence Counties, which are located in the eastern extent of the Western Interior Plains confining system. Analyses for the Atoka Formation indicated that groundwater generally was of good quality with low concentrations for most chemical constituents; though, in a few areas, the water was hard with elevated iron concentrations. The poorest quality groundwater was noted in groundwater from the Fayetteville Shale, which contained elevated concentrations of iron, sodium, sulfate, chloride, and dissolved solids relative to other formations (Albin and others, 1967a). Lamonds (1972) also noted that groundwater from black shale can be high in sulfide and sulfate.

The primary scope of previously described earlier reports was a general assessment of the quantity and quality of surface and subsurface waters throughout the State. Detailed geochemical evaluations to assess rock/water interactions and microbially mediated processes affecting geochemical evolution of groundwater, in addition to anthropogenic sources affecting groundwater quality, were outside the scope of these earlier reports. Recent groundwater studies (Kresse and Hays, 2009; Kresse and others, 2012; Warner and others, 2013) collected a more extensive and comprehensive geochemical database. These recent studies also provided an analysis of isotopic compositions to better understand rock/water interactions and evolution of groundwater geochemistry with respect to rock type in the Interior Highlands. These recent studies confirmed the poor quality of groundwater quality from shale formations and showed marked differences in the geochemistry of groundwater from quartz formations (sandstone, chert, and novaculite) and shale formations in the Interior Highlands.

### General Geochemistry and Water Type

There is no definitive spatial trend for various chemical constituents in the Western Interior Plains confining system, which contrasts markedly with the strong trend noted for most of the aquifers of the Coastal Plain. One explanation for the lack of spatial trends is the predominance of relatively short, local flow paths, and small fracture size. These affect groundwater residence time and the amount of flushing in the Western Interior Plains confining system. The nature of the alternating geologic formations and differing associated mineralogies across the areal extent of the Western Interior Plains confining system are also a factor.

A detailed analysis of groundwater geochemistry in the central part of the Western Interior Plains confining system was performed by Kresse and others (2012) as part of an assessment of potential effects of gas-extraction activities in the Fayetteville Shale. This study used groundwater data from 127 wells completed dominantly in the Atoka and Bloyd Formations. Out of 282 groundwater samples compiled for this report, 260 (92 percent) samples were from the Atoka (191 samples) and Bloyd (69 samples) Formations, with the remaining 22 samples distributed among other formations. Because Kresse and others (2012) reported on groundwater quality and geochemistry using data dominantly from the Atoka and Bloyd Formations, their study can be used to explain the variation in geochemistry for most of the Western Interior Plains confining system, as these two formations constitute the greatest area of exposure throughout the confining system.

Much of the variation in groundwater geochemistry within the Western Interior Plains confining system can be explained by the dominant geology in the region, which mainly consists of alternating shale and sandstone units. In most areas, shale dominates the lithology with minor occurrences of thin sandstone units within any one vertical section. In some other areas, thicker sandstone units occur. Distinct geochemical differences were noted in groundwater extracted from shale compared to groundwater extracted from quartz formations in the Ouachita and Boston Mountains areas, which are dominated by these clastic lithologies (Kresse and Hays, 2009; Kresse and others, 2012). These differences in groundwater geochemistry were definable, reproducible, and consistent across both areas and were controlled by mineralogy. This is primarily related to the presence or absence of carbonate minerals, as well as redox zonation for a given section of aquifer penetrated by each well. Much of the following discussion on the evolution of geochemistry in the Western Interior Plains confining system is taken from Kresse and Hays (2009) and Kresse and others (2012).

Similar to most aquifers in Arkansas, groundwater in the Western Interior Plains confining system generally is a strong bicarbonate water type. Bicarbonate accounted for more than 50 percent of the total anions in 202 of 249 (81 percent) samples with complete anion (chloride, sulfate, bicarbonate) analyses. Eighty-three of these 202 samples had percent bicarbonate exceeding 90 percent. Bicarbonate concentrations ranged up to 980 mg/L with a median of 129 mg/L (fig. 102; table 42). For samples with bicarbonate as the dominant anion, groundwater ranged from calcium- and calcium-magnesium-bicarbonate to a sodium-bicarbonate water type. Bicarbonate concentrations increased with increasing dissolved-solids concentrations. This relation indicates that dissolution of carbonate minerals accounts for the increasing bicarbonate concentrations, which drives the concomitant increases in dissolved solids (fig. 103*A*). Shale formations in the Western Interior Plains confining system have abundant carbonate minerals because the source sediments accumulated in marine environments (McFarland, 2004). Similarly, increasing values of pH correlated to increasing concentrations of bicarbonate and dissolved solids (figs. 103*B*, *C*).

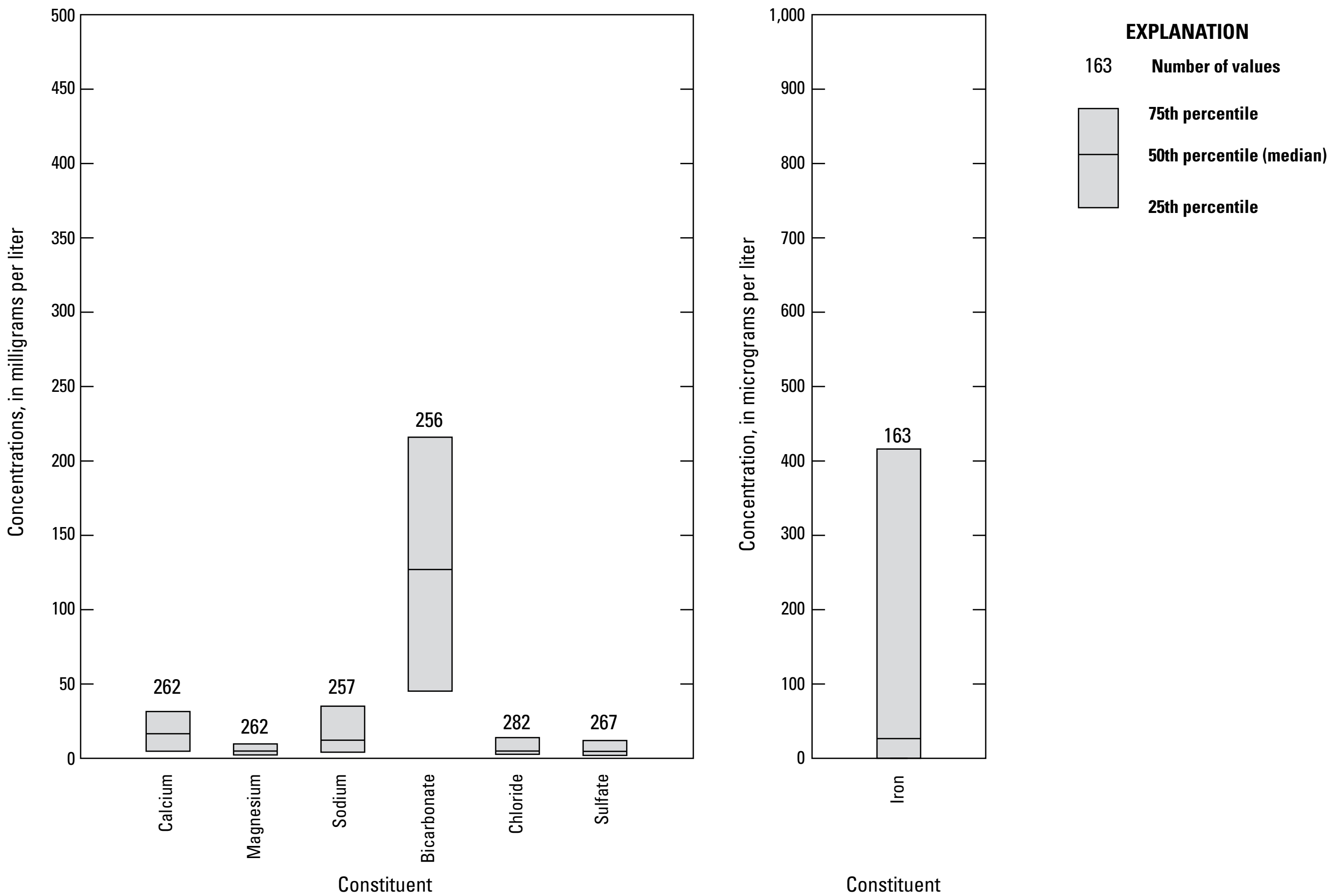



**Figure 102.** Interquartile range of selected chemical constituents in groundwater from the Western Interior Plains confining system in northern Arkansas.

**Table 42.** Descriptive statistics for selected chemical constituents in groundwater from the Western Interior Plains confining system in northern Arkansas.

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

| Constituent or characteristic | Minimum | Median | Maximum | Standard deviation | Number of wells |
|---|---|---|---|---|---|
| Calcium (mg/L) | 0.1 | 16.4 | 160 | 24.9 | 262 |
| Magnesium (mg/L) | 0.07 | 4.98 | 211 | 17.1 | 262 |
| Sodium (mg/L) | 0.9 | 12.3 | 844 | 74.7 | 257 |
| Potassium (mg/L) | 0.13 | 0.8 | 11 | 1.87 | 128 |
| Bicarbonate (mg/L) | 2.0 | 129 | 980 | 137 | 256 |
| Chloride (mg/L) | 0.9 | 5.0 | 1,100 | 78.2 | 282 |
| Sulfate (mg/L) | 0.02 | 4.7 | 1,030 | 80.6 | 267 |
| Silica (mg/L) | 0.18 | 11 | 47.7 | 8.2 | 252 |
| Nitrate (mg/L as nitrogen) | 0.01 | 0.09 | 18 | 1.95 | 214 |
| Dissolved solids (mg/L) | 7.0 | 176 | 2,460 | 346 | 129 |
| Iron (µg/L) | 0.05 | 27 | 13,800 | 2,410 | 163 |
| Manganese (µg/L) | 0.13 | 100 | 4,370 | 519 | 218 |
| Arsenic (µg/L) | 0.03 | 0.03 | 16.9 | 1.28 | 200 |
| Hardness (mg/L as calcium carbonate) | 4.0 | 73 | 1,100 | 131 | 195 |
| Specific conductance (µS/cm) | 13 | 267 | 3,500 | 388 | 280 |
| pH (standard units) | 3.5 | 6.6 | 8.8 | 1.1 | 266 |

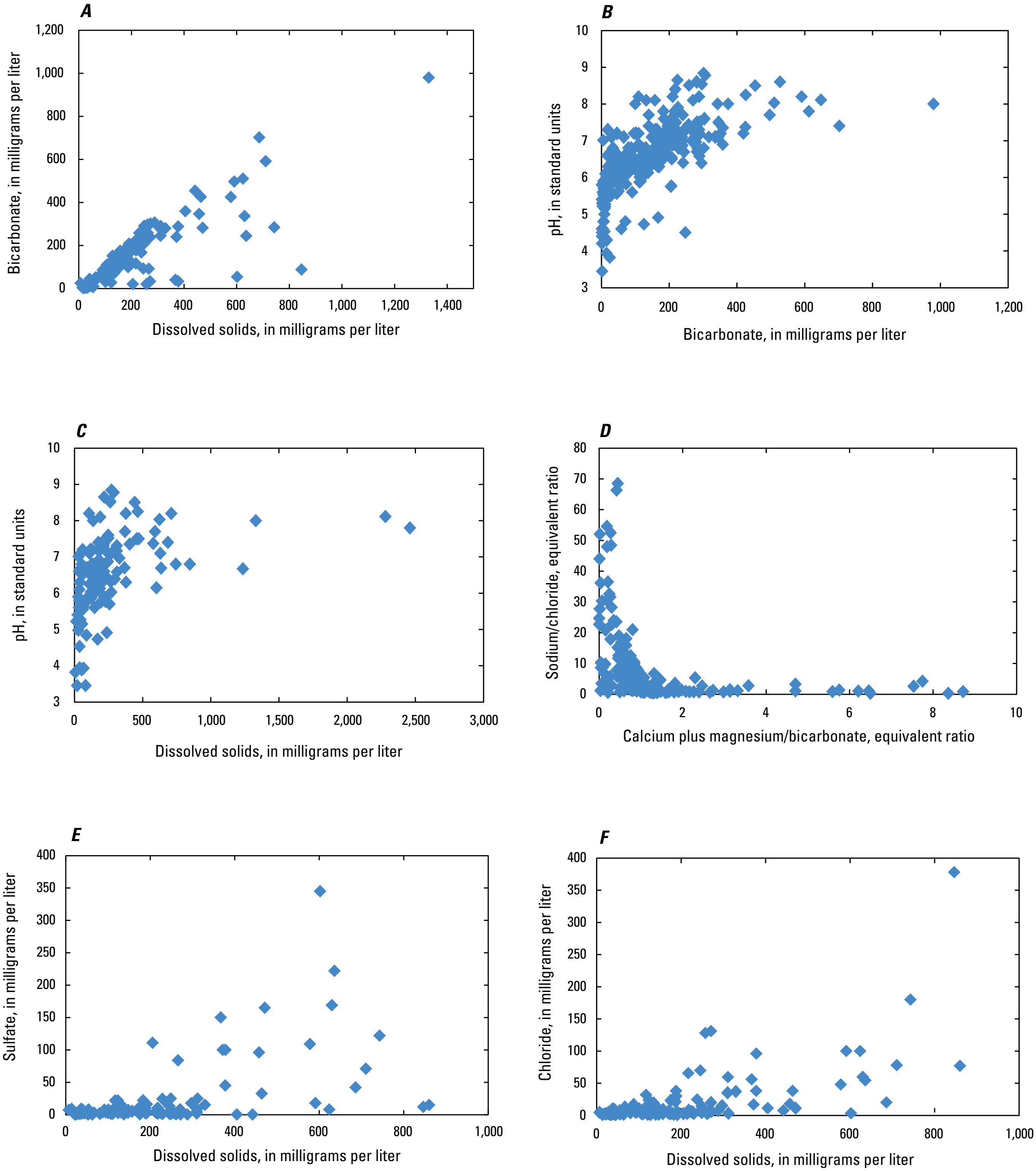



**Figure 103.** Relation of *A*, dissolved solids and bicarbonate; *B*, bicarbonate and pH; *C*, dissolved solids and pH; *D*, calcium plus magnesium/bicarbonate and sodium/chloride; *E*, dissolved solids and sulfate; and *F*, dissolved solids and chloride in groundwater from the Western Interior Plains confining system in northern Arkansas.

Similar to most aquifers in Arkansas, recharge of slightly acidic precipitation with a mean pH value of approximately 4.7 (Kresse and Fazio, 2002) is neutralized with the dissolution of carbonate minerals. This results in increasing pH values along a continuum of increased residence time with resultant increasing dissolved-solids concentrations in the Western Interior Plains confining system (Kresse and Fazio, 2002; Kresse and Hays, 2009; Kresse and others, 2012). Values of pH ranged from 3.5 to 8.8 (table 42), and 16 samples had pH values less than 4.7. Values of pH lower than the pH of rainwater are attributed to formation of carbonic acid by dissolution of carbon dioxide with recharging precipitation in the unsaturated zone of carbonate-free sandstone units (Kresse and Hays, 2009; Kresse and others, 2012). Bicarbonate concentrations and pH values show no clearly discernible spatial trends. However, some groupings of lower values for pH (for example, in extreme southern Van Buren County; fig. 104) suggest that wells may be producing from areal extensive sandstone units. Similarly, a grouping of higher pH values in northern Faulkner County may indicate wells completed in predominately shale rocks (fig. 104).

In addition to mineral dissolution, cation exchange is one of the more important rock/water interaction processes affecting groundwater geochemistry and resulting water type. Cation exchange occurs when groundwater is in contact with clays and weathered shale surfaces. Kresse and others (2012) showed that sodium/chloride equivalent ratios were inversely correlated to calcium plus magnesium/bicarbonate ratios. This suggests that cation exchange was actively occurring in the Western Interior Plains confining system, increasing sodium while decreasing calcium in solution. Data compiled for this report showed a similar relation between these two ratios for the Western Interior Plains confining system (fig. 103*D*). The lowest sodium/chloride ratios occur in groundwater with the lowest dissolved-solids concentrations and lowest pH values. Sodium/chloride ratios increase with increasing dissolved solids, indicating that cation exchange progresses with increasing residence time in the aquifer. Ultimately, this results in sodium/chloride equivalent ratios nearly 70 times the one-to-one ratio resulting from dissolution of sodium-chloride salts (Kresse and others, 2012).

## Nitrate

Nitrate concentrations in the Western Interior Plains confining system ranged from 0.01 to 18 mg/L as nitrogen with a median of 0.09 mg/L (table 42). Of 214 samples with nitrate data, 169 (79 percent) were less than 0.5 mg/L and 186 (87 percent) were less than 1.0 mg/L, reflecting the overall low nitrate concentrations in groundwater from the Western Interior Plains confining system. Only two samples had nitrate concentrations exceeding the Federal MCL of 10 mg/L as nitrogen. Generally, higher nitrate concentrations occurred near the southern boundary of Van Buren County in the same area as wells with low pH values (fig. 104) and, therefore, low dissolved-solids concentrations (fig. 103*C*). An inverse relation noted for nitrate and dissolved solids confirmed this observation in that most nitrate concentrations are more than 1.0 mg/L when dissolved-solids concentrations are less than 125 mg/L. Kresse and others (2012) similarly noted that nitrate concentrations were highest in groundwater samples with low pH and low dissolved-solids concentrations. Low pH and low dissolved-solids concentrations in groundwater were noted by Kresse and others (2012) as occurring in poorly buffered sandstone units. This suggests that sandy soils developed in these areas have increased permeability and concomitantly increased vulnerability to surface and shallow subsurface (for example, septic systems) sources of nutrients. By comparison, clayey soils developed in regions of weathered shale outcrops have less permeable soils that retard transport of nutrients to the water table. Kresse and others (2012) also showed inverse correlations of nitrate with iron and manganese concentrations. This suggests that nitrate is removed from the system by denitrification with increased residence time along the flow path. These relations suggest that the occurrence and distribution of nitrate is related to degree of vulnerability associated with soils of varying permeability, reduction of nitrate with increased residence time in the aquifer, or a combination of both processes. No relation was noted between well depth and nitrate in the Western Interior Plains confining system. For many of the aquifers in the Coastal Plain, nitrate generally was inversely correlated to well depth.

## Iron

Iron concentrations in the Western Interior Plains confining system ranged from 0.05 to 13,800 µg/L with a median of 27 µg/L (fig. 102; table 42). Iron concentrations were below the Federal secondary drinking-water regulation of 300 µg/L in 120 of 163 (74 percent) samples. Groupings of concentrations exceeding 500 µg/L generally occur in Faulkner County and into eastern Conway County and similarly throughout Cleburne and White Counties (fig. 104). However, wells with high iron concentrations occur next to wells with low concentrations, indicating the lack of a well-defined and consistent spatial distribution trend. The lack of any spatial trend suggests that the occurrence of iron is a function of mineralogical and reduction-oxidation processes occurring with increased residence time along localized and relatively short groundwater flow paths.

Kresse and others (2012) showed that dissolved iron was lowest (less than 500 µg/L) in groundwater with dissolved solids less than 60 mg/L, generally correlating to regions with high nitrate concentrations. Iron concentrations increased with increasing dissolved-solids concentrations up to approximately 290 mg/L and decreased for dissolved-solids concentrations greater than 290 mg/L. Arsenic concentrations had similar trends with increasing dissolved solids. Kresse and others (2012) hypothesized that sulfate reduction dominates redox zonation at dissolved solids more than 290 mg/L, removing iron from solution with the precipitation of iron sulfide minerals. For a more detailed discussion, see the later section “Conceptual Model of Groundwater Geochemical Evolution.”

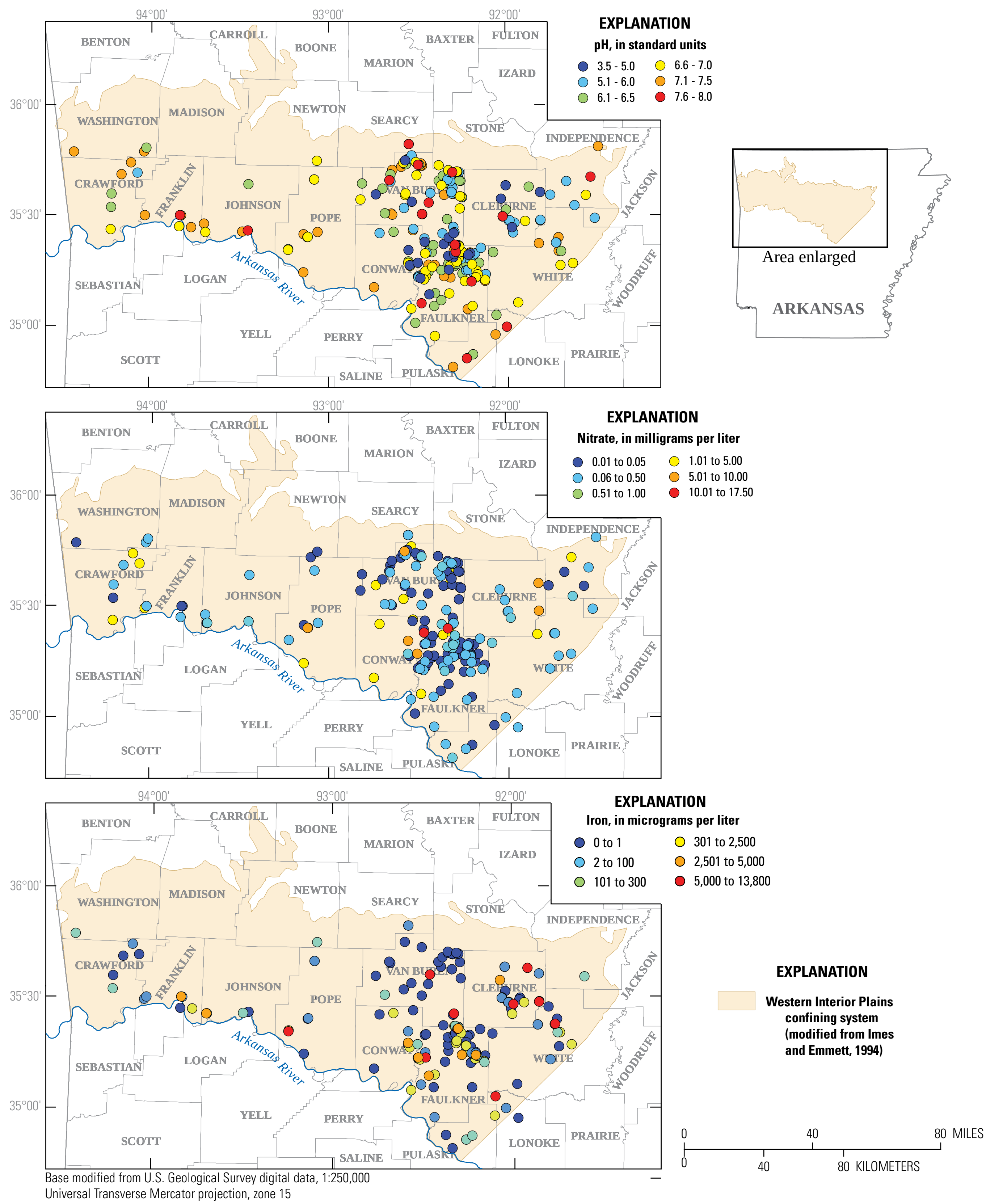



**Figure 104.** Spatial distribution of selected chemical constituents in groundwater from the Western Interior Plains confining system in northern Arkansas.

### Sulfate

Sulfate concentrations generally were low throughout the Western Interior Plains confining system. Only three samples were higher than the secondary drinking-water regulation of 250 mg/L. Sulfate concentrations ranged from 0.02 to 1,030 mg/L with a median of 4.7 mg/L (fig. 102; table 42). Out of 267 samples, 243 (91 percent) had concentrations less than 50 mg/L. Cordova (1963) attributed sulfate in groundwater to oxidation of pyrite; however, Kresse and others (2012) hypothesized that appreciable sulfate concentrations results from gypsum dissolution. Sulfate concentrations increased with increasing dissolved-solids concentrations (fig. 103*E*). For dissolved-solids concentrations less than 100 mg/L, sulfate was less than 10 mg/L. For dissolved-solids concentrations between 100 and 200 mg/L, sulfate was less than 25 mg/L. All sulfate concentrations greater than 50 mg/L occurred at dissolved-solids concentrations greater than 200 mg/L. This is a region that was shown by Kresse and others (2012) to be under iron- and possibly sulfate-reducing conditions in which pyrite would be stable. Additionally, increases in sulfate generally correlated to increases in calcium/bicarbonate equivalent ratios more than 1.0 and up to 8.0. This correlation suggested that excess calcium not accounted for by dissolution of carbonate minerals may be derived from dissolution of gypsum.

### Chloride

Chloride concentrations generally are low in groundwater throughout the Western Interior Plains confining system. Chloride concentrations ranged from 0.9 to 1,100 mg/L with a median concentration of 5.0 mg/L (fig. 102; table 42). Out of 282 samples, 195 (69 percent) were less than 10 mg/L, and only 5 samples exceeded the Federal secondary drinking-water regulation of 250 mg/L. Residual salinity from the marine environment in which shales of the Atoka and Bloyd Formations were deposited generally has been flushed over time by infiltrating precipitation. In low permeability zones or hydraulically isolated areas that have not been flushed over time, higher salinity water can be released into the well bore. This raises chloride concentrations above the generally low concentrations found across much of the Western Interior Plains confining system. Chloride concentrations increase with increasing dissolved solids (fig. 103*F*). This suggests that higher chloride concentrations in groundwater are more likely in regions of more evolved groundwater with a longer residence time along a given flow path, affording greater rock/water interaction over time.

### Conceptual Model of Groundwater Geochemical Evolution

A general analysis of abundant groundwater geochemical data enabled the development of a conceptual model for the evolution of groundwater geochemistry in the shallow Western Interior Plains confining system. Kresse and others (2012) used nonparametric statistical analysis to show that groundwater from the Atoka and Bloyd Formations have a similar geochemistry. This suggested that the geochemistry in both formations results from similarities in mineralogy of the interbedded sandstone and shale. Because 92 percent of the samples compiled for this report were from these formations, this general model may be applied to the system as a whole and is discussed in more detail in the following paragraphs.

Kresse and others (2012) evaluated data from 127 groundwater samples primarily from the Atoka and Bloyd Formations to construct a geochemical model for evolving water type. A plotting of water types along a continuum of increasing dissolved solids showed that major ion geochemistry is not random but follows a predictable pattern based on rock type and rock/water interaction. The continuum of increasing dissolved solids represents increased residence time in the aquifer system. The lowest pH values, ranging from 4.2 to 5.8, occurred in groundwater with dissolved-solids concentrations less than approximately 30 mg/L (fig. 105). Although chloride concentrations increased with increasing dissolved-solids concentrations, chloride was found to be the dominant anion almost solely for dissolved-solids concentrations less than 30 mg/L. The geochemistry of these samples resembled that of evaporated rainwater with minor addition of silica and trace metals (Kresse and Fazio, 2002). Much of this groundwater is theorized to be derived from carbonate-free sandstone units. Similar findings were noted in the Ouachita Mountains aquifer near Hot Springs (Garland County), where well-defined, thick sequences of quartz formations and shale formations allowed the association of unique groundwater chemistry for each rock type. Groundwater from the quartz formations was soft and acidic (7 of 11 samples had pH values less than 4.7 and 3 samples were less than 4.0), indicating a quartz source rock with little to no buffering capacity (Kresse and Hays, 2009).

In general, groundwater with dissolved-solids concentrations greater than 30 mg/L had bicarbonate as the dominant anion and shale as the dominant rock type. Groundwater with dissolved-solids concentrations between 31 and 95 mg/L exhibited a mixture of calcium-bicarbonate and mixed-bicarbonate water types. For groundwater with dissolved-solids concentrations between 96 and 249 mg/L, calcium-bicarbonate was the dominant water type in 24 of the 40 samples. A majority of the remaining samples had increasing sodium percentages and sodium as one of two major cations representing groundwater transitioning toward sodium as the dominant cation. For groundwater with dissolved-solids concentrations greater than 250 mg/L, 20 of 51 samples were a sodium-bicarbonate water type with sodium percentages ranging from 52 to 99 percent of the total cations. The remaining samples primarily were calcium-bicarbonate water types with a few transitional water types (fig. 105).

Kresse and others (2012) described the effects of reduction-oxidation (redox) processes in the Western Interior Plains confining system using redox-sensitive inorganic constituents and methane for 51 groundwater samples.

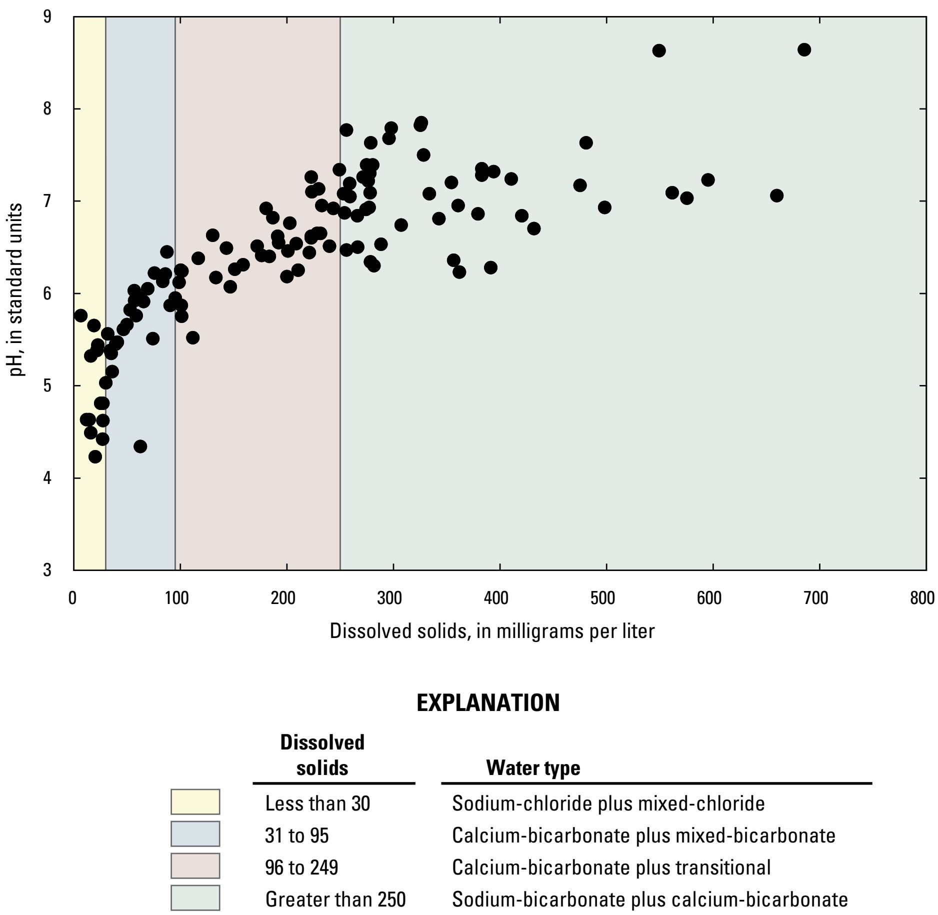



**Figure 105.** Relation between dissolved-solids concentrations and pH values with a depiction of the evolution of chemical water types for groundwater from the Western Interior Plains confining system in northern Arkansas (from Kresse and others, 2012).

Using the same continuum of increased residence time for groundwater to investigate evolution of redox zonation in the aquifer system is informative and enables refining of the geochemical model. Shale formations in the Western Interior Plains confining system are rich in labile organic material, which drives the reduction of oxygenated water by aerobic and fermentation bacteria. As recharging water enters an aquifer system having abundant organic matter, oxygen first will be used as a terminal electron acceptor; followed by nitrate, manganese oxide, iron oxyhydroxide compounds, and sulfate; and finally carbon dioxide with the generation of methane. Depending on the available supply of electron donors (carbon) and electron acceptors (oxidizers), redox zonation can stop at any point along this continuum or proceed through each sequence to methane production (Kresse and others, 2012).

Kresse and others (2012) noted that the highest nitrate concentrations occurred for groundwater with dissolved-solids concentrations less than approximately 100 mg/L. Conversely, the highest iron concentrations occurred in association with dissolved-solids concentrations greater than 90 mg/L. Data compiled for this report confirmed that nitrate concentrations generally were less than 0.5 mg/L for dissolved-solids concentrations greater than 100 mg/L. For dissolved-solids concentrations greater than approximately 90 to 100 mg/L, nitrate has been consumed, resulting in the prevalence of manganese- and iron-reducing conditions. Iron and manganese had well-defined inverse correlations with nitrate, thus confirming this assumption. As nitrate is depleted, iron and manganese oxides are reduced, releasing iron and manganese into solution. Iron concentrations generally increased to approximately 290 mg/L, at which point, iron concentrations steadily decreased to low and nondetectable concentrations for dissolved solids exceeding 500 mg/L (fig. 106*A*). Arsenic concentrations (fig. 106*B*) behaved in a similar fashion. Kresse and others (2012) hypothesized that beyond a dissolved-solids concentration of 290 mg/L, sulfate reduction dominates over iron reduction with free sulfide combining with iron (and arsenic) to precipitate as iron-sulfide minerals.

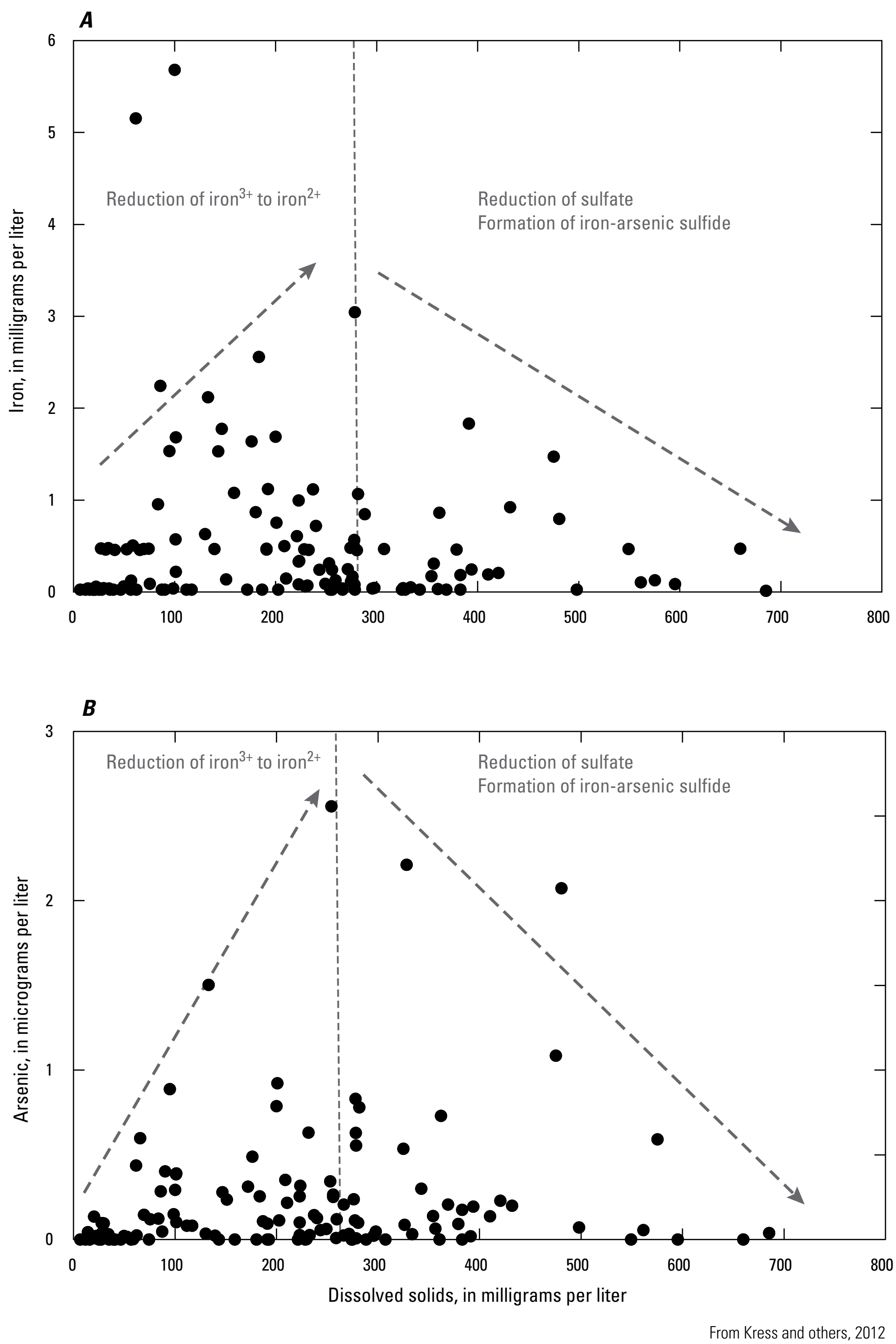



**Figure 106.** Relation between dissolved-solids concentrations and *A*, iron and *B*, arsenic concentrations in groundwater from the Western Interior Plains confining system in northern Arkansas.

Biogenic methane was detected in 32 of 51 samples with 7 of the samples having methane concentrations greater than 0.5 mg/L (maximum of 28.5 mg/L). Methane concentrations increased with increasing dissolved-solids concentrations. Concentrations greater than 1.0 mg/L generally occurred at dissolved-solids concentrations more than 475 mg/L. Therefore, the conceptual model for geochemical evolution in the Western Interior Plains confining system is one where increased groundwater residence time in the shallow aquifer system drives rock/water interaction, particularly cation exchange. This results in transitioning from a calcium- to a sodium-bicarbonate water type along the flow path. Microbial-mediated redox zonation similarly transitions with increasing residence time in the aquifer through oxygen consumption; reduction of nitrate, iron and manganese oxides, and sulfate; and eventually to the production of biogenic methane (Kresse and others, 2012).

In summary, water quality generally is good throughout the Western Interior Plains confining system. Groundwater with elevated iron, nitrate, sulfate, and chloride occurs in localized areas, depending on rock type and position along a flow path. Groundwater varies from a soft, slightly acidic type, typically encountered in wells completed in sandstone rocks, to a calcium-and sodium-bicarbonate water type dependent on the amount of cation exchange in the groundwater system. Reducing conditions are found throughout the Western Interior Plains confining system, predominantly for groundwater from shale rock, with a complete redox zonation from nitrate-reducing conditions to production of methane.

## Springfield Plateau Aquifer

The Springfield Plateau aquifer (fig. 3) lies within the Springfield-Salem Plateaus section of the Ozark Plateaus (fig. 3; tables 2 and 5) and comprises a sequence of limestone and cherty limestone of Mississippian age. The Ozark Plateaus (Ozarks) are a region of unique and complex hydrogeology and physiography. The Ozarks are characterized by a predominantly mantled karst terrain where aquifer anisotropy and heterogeneity, and variability in aquifer hydraulic characteristics are the norms. This variability is noted on a small spatial scale where (1) groundwater-flow velocities vary from $10^{-6}$ ft/s to several feet per second, (2) a well may produce 0.01 gal/min or 1,000 gal/min, (3) groundwater chemistry may not reflect interaction with the aquifer matrix compared in one location and nearby may be mineral saturated and actively precipitating authigenics, (4) surface-derived contaminants may be effectively ameliorated within a short distance or may travel great distances with little to no attenuation, and (5) a subsurface may be essentially lifeless or home to numerous cave-related species. Groundwater flow and quality within the Ozark Plateaus are controlled by (1) the lithologies of the rocks exposed at the surface that convey groundwater flow; (2) stratigraphic relations of these different lithologies; and (3) geologic structure, including the physical modifications to the rocks that have occurred over time.

### Geologic Setting

The Ozarks are referred to locally and regionally as the "Ozark Mountains." Geologic structure of the Ozarks, however, is characterized by a lack of any intense modification over an expanse of geologic time; therefore, the Ozarks generally are not considered a true mountain range. The great topographic relief in the area results from erosional dissection of the plateaus that has been controlled to a degree by presence of structural features such as faults and fracture zones as well as by lithology. The Ozarks were formed by a structural dome that has been uplifted during several periods since Precambrian time (Nunn and Lin, 2002; Tennyson and others, 2008; Cox, 2009). The core of the dome is in southeastern Missouri. Sedimentary units in Arkansas drape off of the southern and southwestern margins of the dome with gentle regional dips generally ranging from 10 to 100 ft/mi and steeper dips being common near faults (Frezon and Glick, 1959). Widespread extensional fracturing, jointing, and faulting of Ozarks' rocks occurred with uplift (Hudson and Cox, 2003), creating secondary porosity that has provided key nucleation points for initiation of dissolution of the carbonate rocks and karst development.

The karstic bedrock of the region is overlain by weathered regolith that greatly varies in thickness from near zero in many areas to more than 100 ft. Areas of low topographic relief, including plateau tops and valley floors, tend to have greater thicknesses of regolith. Steep areas tend to have lesser thicknesses of regolith, although thicknesses are variable within all areas. The regolith mantles the underlying karst topography, which typifies the Ozarks' karst and distinguishes the region from classic occurrences of karst elsewhere. The regolith is a clay-rich, typically low-permeable unit that contains variable amounts of chert. This material is derived from weathering of the original Mississippian and, in some areas, Pennsylvanian capping units and comprises refractory impurities and weathering products—predominantly chert and clay. The regolith generally is present as a silt-loam surface soil overlying a clay-loam subsoil, which can vary from being well-drained and exhibiting moderate permeability to very tight with low permeability. Chert constitutes up to 90 percent of the regolith in some areas. The chert is present from sand to boulder size and is present as remnant layers that remain in weathered soil profiles. These layers often create barriers to infiltration of recharge water. Where present in considerable thickness, the regolith is a strong impediment to infiltration of precipitation and leakage from surface water, protecting the underlying karst aquifer from rapid input of surface-derived contaminants. However, the variable thickness of the regolith and the variable clay content render the protective qualities of the regolith somewhat sporadic throughout the Ozarks.

The Boone Formation comprises the Springfield Plateau aquifer (Imes and Smith, 1990; Imes and Emmett, 1994) and is exposed across most of the Springfield Plateau. However, outlier remnants of confining clastics are observed in the southern area of the Springfield Plateau where the upper Mississippian section is represented by the Batesville Sandstone and the Fayetteville Shale (Adamski and others, 1995; table 5). These sandstone and shale units typically are well-cemented and exhibit low matrix porosity and permeability but exhibit moderate porosity and permeability where weathered or highly fractured. Owing to the predominance of low-permeable shale and sandstone, the Upper Mississippian and Pennsylvanian strata are included in the Western Interior Plains confining system hydrogeologic unit to the south in the Boston Mountains (Imes and Smith, 1990; Imes and Emmet, 1994; Adamski and others, 1995).

The Boone Formation has a thickness of about 200–500 ft (McFarland and others, 1979) but is variably eroded across the plateau. The basal St. Joe Limestone Member of the Boone Formation is a relatively pure limestone. Above the St. Joe, the Boone Formation contains abundant chert, which can exceed 70 percent of the interval. Matrix porosity and permeability of the Boone Formation are very low (Stanton, 1993), but where fracturing has occurred, carbonate dissolution has greatly enhanced porosity and permeability (Nunn and Lin, 2002). Solutioning of the fractures ultimately created the karst terrain that typifies the area.

Bedrock in the Ozarks shows evidence of multiple episodes of water movement and carbonate dissolution defining distinct karst development events through time (Stoffell and others, 2008). Exposure of Ordovician strata associated with the Ordovician-Mississippian unconformity resulted in dissolution and some paleokarst development. Widespread dissolution features associated with the lead and zinc ore-bearing fluids that moved from the Arkoma Basin (Leach and Rowan, 1986) are observed across the Ozarks region. Lead and zinc were mined commercially where faults conveyed mineral-saturated fluids up from depth. Hypogene indicators such as diagnostic calcite isotopic compositions (Brahana and others, 2009), collapse breccias (McKnight, 1935), and isotopic dating (Brannon and others, 1996) show that this episode of fluid movement and dissolution was a separate occurrence predating recent karst development. Exposure of Mississippian strata associated with the Mississippian-Pennsylvanian unconformity resulted in meteoric diagenesis followed by pedogenesis, regolith formation, and paleokarst development on the Pitkin Limestone (Webb, 1994). The Ozarks once again showed active karst development as uplift, denudation, and abundant precipitation; recharge initiated dissolution of soluble carbonate lithologies.

The recent period of dissolution and karst development has had a very visible impact on the modern karst land surface, controlling subsurface flow and ultimately the surface flow in the region. The hydrogeology of the region is typical of karst with focused flow paths that are well connected to the surface and deliver water from input to discharge points at streams and springs at velocities of tens to thousands of feet per day (Funkhouser and others, 1999; Mott and others, 2000; Hudson and others, 2005; Hudson and Turner, 2007). Abundant karst features are apparent—ponors, losing stream reaches, springs, caves, and sink holes. However, recent karst development often reactivated and followed previous dissolution-enhanced flow paths that originally developed during ancient exposure periods (such as at the Ordovician-Mississippian and the Mississippian-Pennsylvanian unconformities; Webb, 1994) or hypogene episodes (such as Mississippi Valley Type ore emplacement; Leach and Rowan, 1986; Brannon and others, 1996; Brahana and others, 2009). Another very important phenomenon caused by karst development is interbasin transfer of water. Dye tracing studies and observations of drainage-area and discharge relations show the abundant occurrence and transfer of groundwater across surface-water drainage-basin divides (Sullavan, 1974; Brahana and Davis, 1998; Mott and others, 2000). Consideration of interbasin movement of water is an important point for protection and management of groundwater because contributing zones are not apparent at the surface, and contaminants can be introduced into groundwater from unexpected locations. This interbasin transfer has been shown to be driven more by local hydraulic gradients than by interbasin structure and karst development (Mott and others, 2000).

## Hydrologic Characteristics

The Springfield Plateau aquifer generally is unconfined across the Springfield Plateau and confined in the Boston Mountains. The highly soluble nature of carbonate rocks of the Boone Formation has given rise to development of the distinctive karst terrain and pervasive occurrence of karst features, such as caves, springs, and sinkholes. There is hydraulic connection of surface water and groundwater as well as the variable aquifer characteristics that typify the area (fig. 107). Karst aquifers are typified by a bimodal distribution of porosity—primary matrix porosity and small fracture porosity. This results in low porosity values for individual small-scale samples that are pervasive through the aquifer matrix and constitute a large proportion of total porosity. Secondary fractures and dissolution-enhanced porosity are significant within focused areas but represent a smaller proportion of the total porosity. The control of these porosity types on permeability leads to two end-member flow types—diffuse and focused flow (Alley and others, 2002; Ghasemizadeh and others, 2012). The bimodal nature of karst porosity enables spring and stream base flow to be maintained. The slower diffuse flow allows for sustained groundwater input to streams and springs, even during dry periods. The faster focused flow provides extremely rapid response and short transit times for precipitation events. An observable and prominent feature associated with karst aquifers is caves,

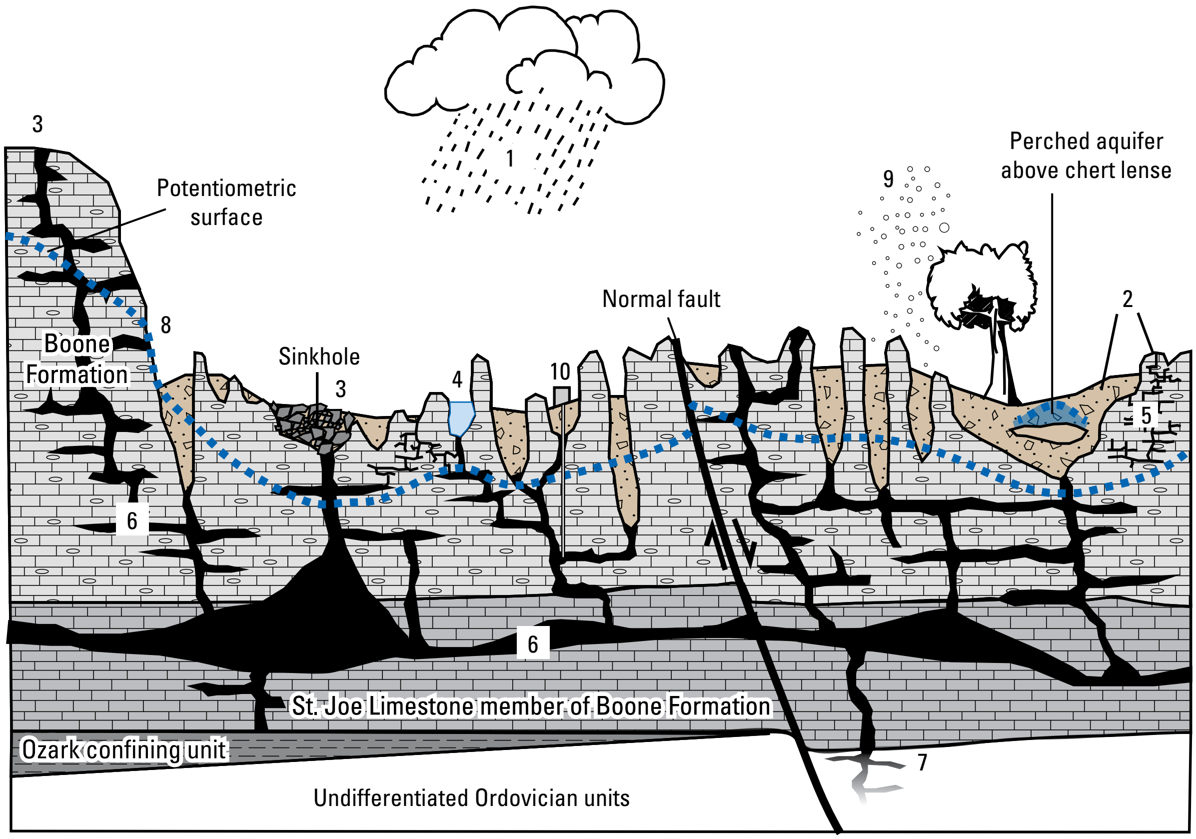



Figure not to scale

Modified from Kindinger and others, 2000

**EXPLANATION**

**Recharge**

1 Meteoric water
2 Diffuse infiltration
- small aperature fractures
- regolith
3 Focused: localized
- sinkholes
- large aperature fractures
4 Focused: indirect
- losing stream

**Groundwater flow**

5 Diffuse flow
6 Conduit flow

**Discharge**

7 Inter-aquifer flow
8 Spring
9 Evapotranspiration
10 Withdrawals

**Figure 107.** Conceptual model of karst hydrogeologic setting for the Springfield Plateau aquifer in northern Arkansas.

which serve as a window into the Springfield Plateau aquifer and allow the study of environments in the saturated and unsaturated zones. Large cavernous conduits and solution features allow for deep and rapid circulation of groundwater. Conduits and dissolution-enhanced fracturing help integrate flow to spring resurgences (Harvey, 1980). As a result, high-discharge springs are common throughout the exposed sections of the Springfield Plateau aquifer.

High hydraulic conductivities of as much as 1,000 ft/d (Stanton, 1993) associated with the Springfield Plateau aquifer result from the development of secondary porosity through diagenetic processes, which particularly results from dissolution of bedrock along joints, fractures, and bedding planes rather than from primary, matrix-type porosity. Enhancement or enlargements of fractures, bedding planes, and conduits by carbonate dissolution is an active, ongoing process (Adamski and others, 1995). Hydraulic conductivity of matrix porosity blocks is much lower, on the order of $10^{-7}$ ft/d or even less (Van den Heuvel, 1979; Peterson and others, 2002). Development of secondary porosity has produced anisotropic and heterogeneous hydraulic characteristics for the aquifer. The presence of smaller-scale matrix, small-aperture fracture, and small-conduit porosity combined with the dissolution-enhanced conduits results in a bimodal permeability distribution. Water movement may be described relative to the two flow end members of diffuse flow and focused (conduit) flow previously defined. Because of the low rock-matrix hydraulic conductivity, a large fraction of groundwater transfer is through the focused-flow component of the aquifer (Imes and Smith, 1990; Kilpatrick and Ludwig, 1990b). Rapid input of surface water, rapid-flow velocities, rapid mass transfer, and minimal attenuation of contaminants are associated with this component of flow. More time-averaged flow, maintenance of streamflows during dry periods, low-flow velocities, and effective attenuation of contaminants are behaviors associated with the diffuse component of flow.

Fracture and bedding-plane apertures typically decrease with depth as lithostatic pressure increases (Drogue, 1980). Correspondingly, groundwater storage, hydraulic conductivity, and well yields decrease with depth in the Springfield Plateau aquifer (Lamonds, 1972), and well depths rarely exceed 300 ft in the aquifer (Imes and Emmett, 1994). Most well depths associated with data compiled for this report were less than 200 ft. Average values of horizontal conductivity from groundwater simulations are 22 ft/d (Imes and Emmett, 1994) with vertical conductivities about an order of magnitude lower (Adamski and others, 1995). However, hydraulic conductivities as high as 886–2,100 ft/d occur locally (Vandike, 1997). Transmissivity values range from approximately 1,700 to 8,600 $ft^2/d$ (Imes and Emmett, 1994). Wells yields reflect the porosity types. Where wells intersect highly porous and permeable zones, yields of 10 gal/min to more than 100 gal/min are common. Where wells are completed in zones with little secondary development of porosity and permeability, well yields are typically less than 10 gal/min. Most wells yield less than 20 gal/min throughout the extent of the aquifer (Adamski and others, 1995; Peterson and others, 2002; McFarland and Prior, 2005; Gillip, 2007).

Most recharge to the Springfield Plateau aquifer is by infiltration of precipitation in the aquifer’s outcrop area. Where confined, recharge occurs by leakage through overlying units (Adamski and others, 1995). Recharge to the aquifer occurs as diffuse and focused recharge (Alley and others, 2002; Healy, 2010). Diffuse recharge occurs by infiltration of precipitation through the overlying regolith; however, most potential recharge water moving through the soil zone is lost to evapotranspiration, particularly during the growing season (Brahana, 2011b). Diffuse recharge likely amounts to a small percentage of the total recharge compared to focused recharge through karst features such as sinkholes, fractures and conduits, and losing stream reaches (Alley and others, 2002; Brahana and others, 2005). The distribution of recharge is not well understood for the Springfield Plateau aquifer. Karst features allow for rapid recharge, thus allowing the influx of surface-derived contaminants into the aquifer with little attenuation (Jagucki and others, 2009). Consequently, karst aquifers such as the Springfield Plateau aquifer have a high susceptibility to contamination.

Discharge from the Springfield Plateau aquifer is primarily through springs, withdrawals by wells, and interaquifer flow to the underlying Ozark aquifer system (Branner, 1937; Harvey, 1980; Brahana and Davis, 1998; Czarnecki and others, 2009; Hudson and others, 2011; Vardy, 2011). Seeps and springs are the predominant discharge points for the aquifer. Springs generally occur near the base of the Boone Formation coincident with structural lows and the underlying Ozark confining unit (Kilpatrick and Ludwig, 1990a; Adamski and others, 1995; Murray and Hudson, 2002; Bolyard, 2007; Hudson and others, 2011). Where the underlying Ozark confining unit is absent or incompetent, groundwater discharges from the Springfield Plateau aquifer to the underlying Ozark aquifer (Imes and Emmet, 1994). Groundwater withdrawals by pumping do not appear to have caused distinguishable differences in potentiometric surfaces over time in northern Arkansas (Gillip, 2007).

## Water Levels

Long-term groundwater-level measurements for the Springfield Plateau aquifer are limited. Only one record exists that has more than 15 years duration and was measured at an interval adequate to capture seasonal variability (fig. 108; see fig. 109 for location of the well). Direct correlation of seasonal water-level variations is weak ($R^2 = 0.063$). The potentiometric surface (Imes and Emmet, 1994) reflects relatively higher groundwater levels in high-altitude areas such as Benton, Carroll, Boone, Washington, Madison, and Newton Counties. A lower potentiometric surface occurs in lower altitude areas west towards Oklahoma, south towards the Arkansas River Valley, and east towards the Mississippi Alluvial Plain. An NWIS query revealed 543 wells with both land-surface altitude and water-level data. The potentiometric surface for the aquifer generally reflects topography and exhibits a strong correlation with land-surface altitude ($R^2 = 0.98$). However, a regional correlation between land-surface altitude and groundwater level below land surface cannot fully explain groundwater movement in the Springfield Plateau aquifer at more localized scales. Small-scale variation in flow is the result of fractures, faults, conduits, and other structures that facilitate or vertically and laterally impede flow (Leidy and Morris, 1990b; Brahana and Davis, 1998; Turner and Hudson, 2008; Hudson and others, 2011). Numerous dye-tracing studies have shown hydraulic connectivity across watershed divides (interbasin flow) (Adamski and others, 1995; Brahana and Davis, 1998; Adamski, 2000; Gillip, 2007; Brahana, 2011a, b). This connectivity can occur across considerable distances outside a given watershed (Mott and others, 1999; Murray and Hudson, 2002).

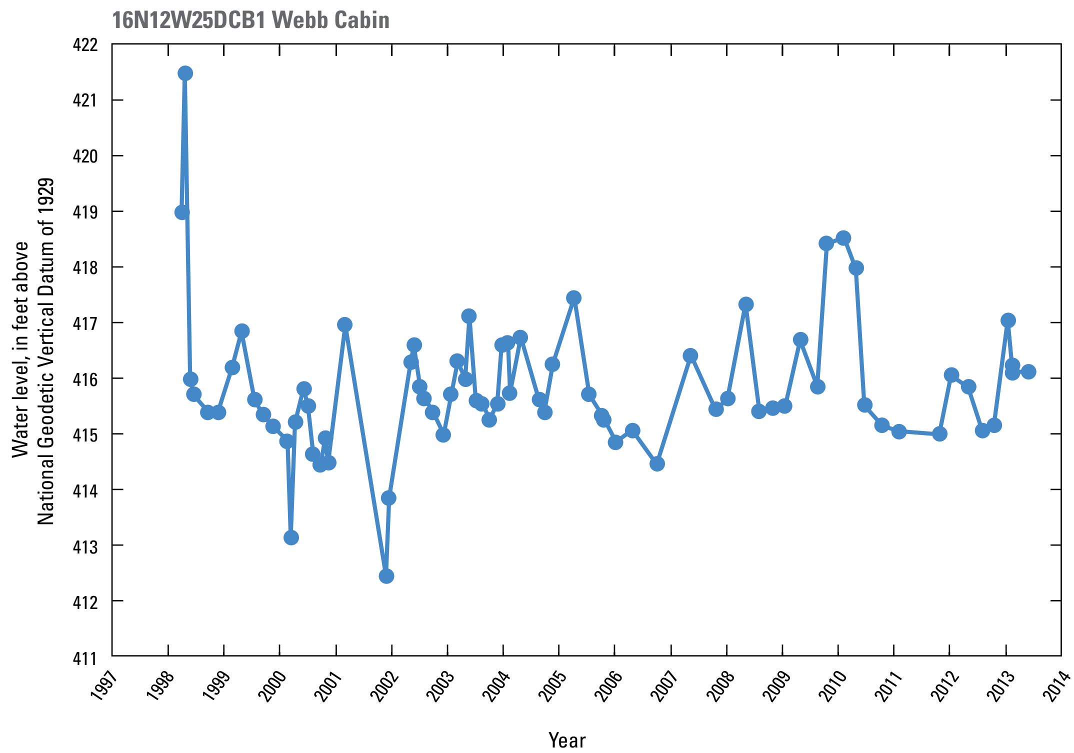



**Figure 108.** Water levels in a well completed in the Springfield Plateau aquifer in northern Arkansas.

## Water Use

The Springfield Plateau aquifer is widely used throughout northwestern Arkansas. Historically, the aquifer was used extensively for domestic, public-supply, commercial, and industrial purposes. Several towns were sited near areas of large springs, which were frequently used to power grain and lumber mills and to supply residents of the growing population. Several domestic and livestock wells were recorded in Carroll and Boone Counties (Brahana and others, 1991, 1993). At the time of this report (2013), numerous domestic and livestock wells were still in use. Because domestic and water-supply systems serving less than 50,000 gal/d are not required to report water use, total use of groundwater from the Springfield Plateau aquifer is unknown. The wider distribution of surface-water systems has largely supplanted use of the Springfield Plateau aquifer as a source of water supply. There were three public-supply wells in Carroll County reporting use from the Springfield Plateau in 2010. A limited number of small community-supply systems, as well as restaurants, resorts, recreational vehicle parks, and shops, are registered as using this aquifer with ADH (Lyle Godfrey, Arkansas Department of Health, written commun., 2012).

## Water Quality

Groundwater quality resulting from rock/water interaction in the Springfield Plateau aquifer generally is good. The water can be used without treatment as an important source of water supply throughout the Ozarks, although low yields limit its use primarily to domestic supply. Iron is the most frequent naturally derived constituent exceeding Federal drinking-water regulations (Lamonds, 1972; Steele, 1981). Hardness related to dissolved carbonate minerals can present problems related to scaling of pipes, water heaters, and other plumbing fixtures (Lamonds, 1972; Leidy and Morris, 1990b; Imes and Emmett, 1994; Adamski, 2000). Surface-derived, anthropogenic contaminants primarily related to livestock agricultural activities also affect water quality as a result of rapid influx of surface water with little attenuation in many areas. The aquifer constitutes a large part of the karst landscape of the Ozark Plateaus. This karst network creates a hydrologic system of great complexity with intimate groundwater/surface-water interaction, which makes the system highly vulnerable to surface-derived contamination. Anthropogenic contaminant sources can affect the natural groundwater geochemistry and water quality. Common contaminants include nutrients, fecal bacteria, and pesticides.

Agriculture in the form of beef and dairy cattle, swine, and poultry operations accounts for the greatest land-use activity in this region. Contamination of the aquifer often is derived from these activities (Peterson and others, 2000). Nationally, Arkansas ranks second in poultry production, and the three top counties for agricultural sales in Arkansas are located in the northwestern region of the State (U.S. Department of Agriculture, 2010). Another common source of contamination is septic systems, which are the primary means of domestic waste treatment in rural and in many suburban areas in the Ozarks. The thin, poorly developed soils in the Ozarks make installation of effective, functioning septic systems a challenge, resulting in frequent contamination of groundwater. A vulnerability map created for Arkansas (Arkansas Soil and Water Conservation Commission, 1991) generally listed the entire Ozarks of northern Arkansas at the highest vulnerability index. The spatial distribution of karst features, as well as the variable thickness and composition of soils in the overlying regolith, results in variable vertical permeability and resultant variable vulnerability.

## General Geochemistry and Water Quality

The predominant carbonate rock hosting the Springfield Plateau aquifer is limestone. Numerous reports have documented the dominant calcium-bicarbonate water type resulting from dissolution of the parent rock (Lamonds, 1972; Leidy and Morris, 1990b; Imes and Emmett, 1994; Adamski, 1997; Huetter and others, 1997). Groundwater derives acidity from carbonic, nitric, sulfuric, and other acids formed from natural and anthropogenic sources of carbon dioxide, sulfur dioxide and hydrogen sulfide, and nitrogen oxides. Gas sources include vehicle, industrial, and other anthropogenic emissions, in addition to carbon dioxide and organic acids derived from plant respiration and organic-matter decay in soil. This acidity drives dissolution of limestone and resultant increases in dissolved calcium and bicarbonate concentrations (Wagner and others, 1975). Because limestone is the dominant rock type of the Springfield Plateau aquifer and dolomite is more common in the Ozark aquifer, researchers frequently use calcium/magnesium ratios to differentiate groundwater in these two aquifers. Dolomite has equal parts of calcium and magnesium, and groundwater from predominant dolostone formations composing the Ozark aquifer generally reflects this one-to-one ratio. These ratios are considerably higher in groundwater from limestone of the Springfield Plateau aquifer. Calcium/magnesium equivalent ratios for 134 samples from the Springfield Plateau aquifer ranged from 1.2 to 359 with a median of 17. This median ratio reflects the higher calcium/magnesium ratio typical of groundwater from the Springfield Plateau aquifer. All ratios, except for the minimum of 1.2, were greater than 2.0, and all but 11 of the 134 samples were greater than 5.0. No strong spatial trend was evident in calcium/magnesium ratios, though a greater density of lower ratios occurs near the contact of the Springfield Plateau with Ordovician-age formations of the Ozark Plateaus in Boone and Independence Counties (fig. 109). Limestone often contains varying amounts of magnesium. Consequently, lower calcium/magnesium ratios in some areas result from a higher admixture of magnesium in the limestone or migration of Ozark aquifer groundwater across the Chattanooga confining layer in areas where it is absent or incompetent. Additionally, some wells labeled as completed in the Springfield Plateau aquifer may penetrate and receive water from upper units of the Ozark aquifer. The relation of calcium and bicarbonate shows the overall strong calcium-bicarbonate type water of the Springfield Plateau aquifer. Calcium was strongly correlated to bicarbonate with an $R^2$ of 0.78. The addition of magnesium to this analysis improved the correlation by only a small degree to an $R^2$ of 0.81 (fig. 110).

Low pH from precipitation recharging the aquifer is quickly buffered by carbonate minerals in the overlying regolith and bedrock of the Boone Formation. Values of pH subsequently increase to values exceeding 6.0 throughout the aquifer. Values of pH ranged from 6.0 to 9.1 with a median of 7.2 (table 43). Sixty-seven percent (110 of 163 samples) of the samples had pH values greater than 7.0. No correlation was established between dissolved-solids concentrations and pH values, and the entire range of pH values was found throughout the range of dissolved-solids concentrations (58 to 515 mg/L), which strongly suggests that buffering occurs in the weathered regolith and unsaturated bedrock prior to recharging the aquifer. Knierim and others (2011, 2013) and Pollock and others (2011) characterized basic geochemical changes, nutrient and carbon alterations, and isotopic behavior as groundwater moved through soils into diffuse and focused karst flow paths in the Ozarks. They noted modification of acidity and behavior of soil and regolith as a storage zone for organic carbon and other nutrients. For example, median calcium concentrations in the soil and regolith zones for sites from two different study locales were 5.0 and 5.9 mg/L, respectively, and median dissolved inorganic carbon (predominantly bicarbonate) concentrations were 13.1 and 1.7 mg/L, respectively. These results indicated considerable modification of recharge water in the soil and regolith zones prior to reaching the epikarst. Pollock and others (2011) used hydrograph separation mixing models to rigorously quantify source-water contributions to streams in caves and flow from springs during storm events and to measure evolution of groundwater geochemistry. A key finding was the importance of the soil and regolith zone on groundwater chemistry very early on for karst flow paths. Soil and regolith were found to be of particular importance in controlling chemistry during high-flow events. A metadata analysis for this study showed no spatial correlation for the distribution of pH values throughout the aquifer based on data compiled for this report.

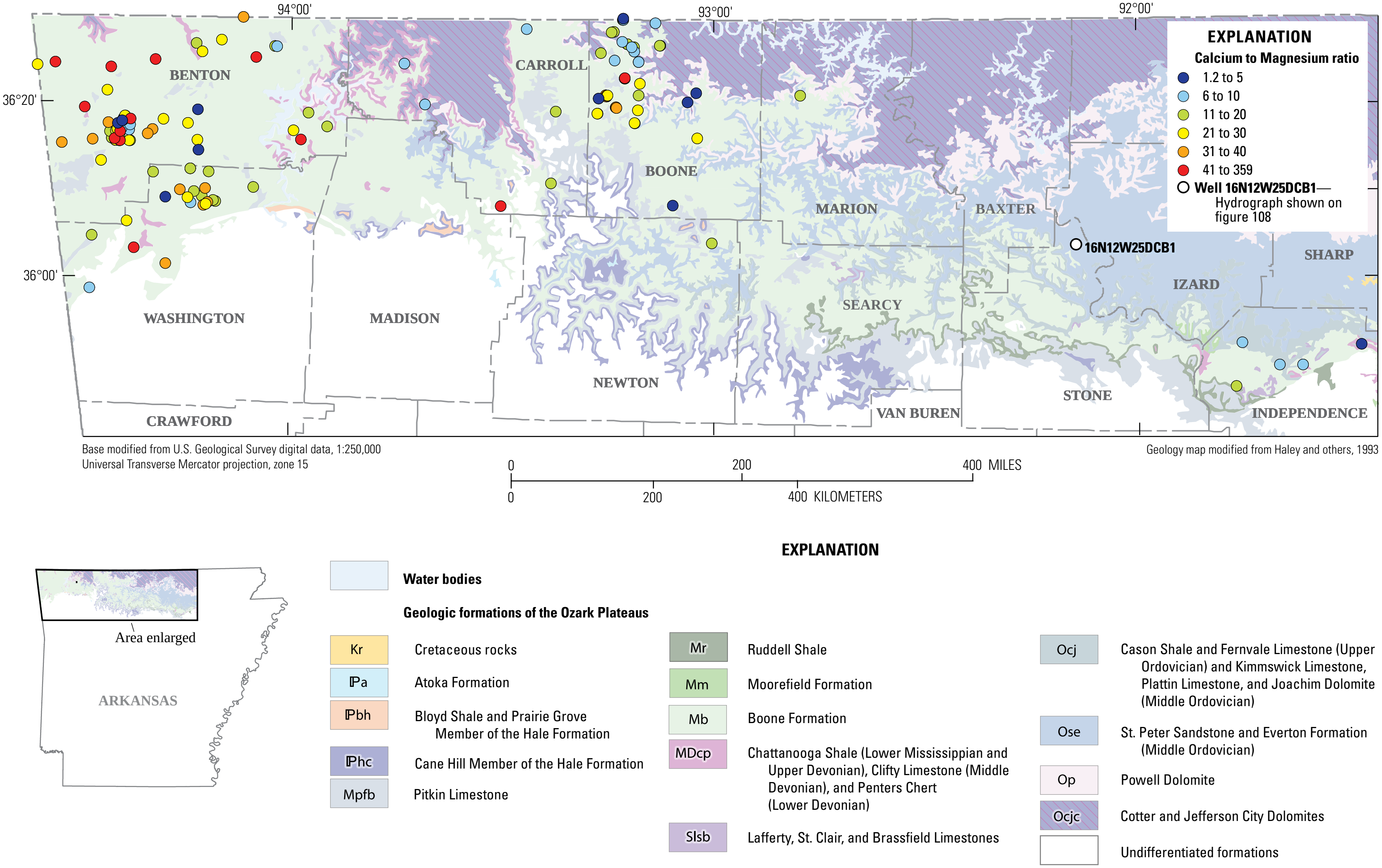



**Figure 109.** Spatial distribution of calcium/magnesium ratios (from milliequivalent concentrations) in groundwater from the Springfield Plateau aquifer in northern Arkansas.

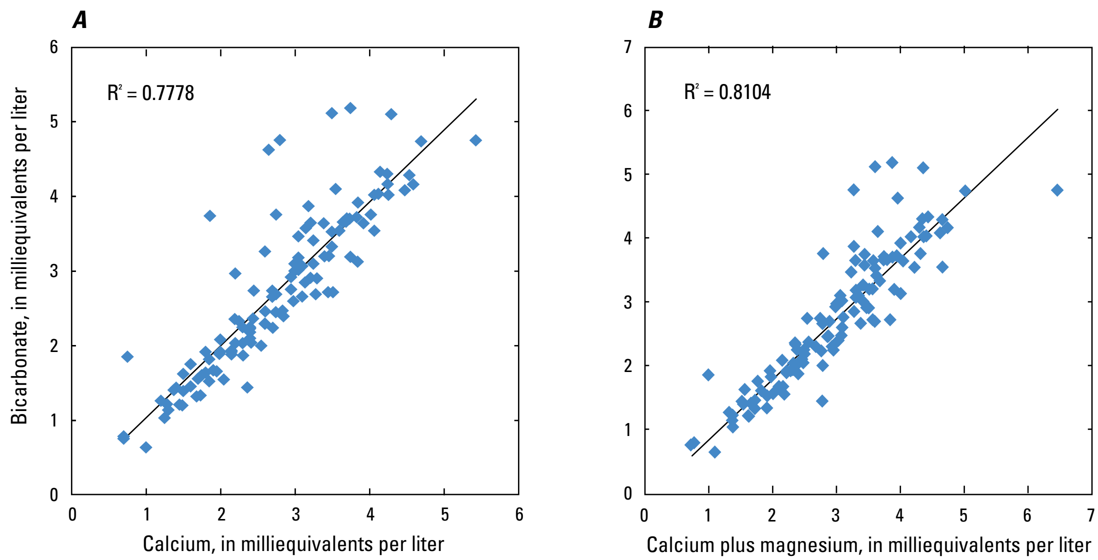



**Figure 110.** Relation of bicarbonate to *A*, calcium and *B*, calcium plus magnesium in groundwater from the Springfield Plateau aquifer in northern Arkansas.

**Table 43.** Descriptive statistics for selected chemical constituents in groundwater from the Springfield Plateau aquifer in northern Arkansas.

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

| Constituent or characteristic | Minimum | Median | Maximum | Standard deviation | Number of wells |
|---|---|---|---|---|---|
| Calcium (mg/L) | 0.04 | 55 | 109 | 20.4 | 134 |
| Magnesium (mg/L) | 0.01 | 1.7 | 21 | 3.31 | 134 |
| Sodium (mg/L) | 0.2 | 4.3 | 51 | 6.38 | 132 |
| Potassium (mg/L) | 0.1 | 1.2 | 15 | 1.58 | 132 |
| Bicarbonate (mg/L) | 39 | 164 | 316 | 65 | 119 |
| Chloride (mg/L) | 1.2 | 7.6 | 47 | 6.8 | 134 |
| Sulfate (mg/L) | 0.48 | 3.9 | 90 | 11.2 | 134 |
| Silica (mg/L) | 5.3 | 9.7 | 19 | 1.85 | 129 |
| Nitrate (mg/L as nitrogen) | 0.01 | 1.8 | 20 | 2.77 | 166 |
| Dissolved solids (mg/L) | 58 | 193 | 515 | 69 | 134 |
| Iron (µg/L) | 0.05 | 5.6 | 3,300 | 338 | 126 |
| Manganese (µg/L) | 0.13 | 0.13 | 1,410 | 198 | 129 |
| Arsenic (µg/L) | 0.03 | 0.03 | 2.52 | 0.39 | 90 |
| Hardness (mg/L as calcium carbonate) | 0.1 | 140 | 323 | 54 | 115 |
| Specific conductance (µS/cm) | 102 | 349 | 693 | 112 | 161 |
| pH (standard units) | 6.0 | 7.2 | 9.1 | 0.5 | 163 |

Adamski (2000) noted that groundwater from springs and wells was geochemically different. In general, median concentrations of dissolved solids, calcium, magnesium, and bicarbonate were greater in samples from wells than from springs. Additionally, groundwater from wells was more saturated with respect to calcite than from springs. Springs typically receive a large component of flow from focused-flow conduits in the flow system. Rapid flow through large conduits in spring basins results in minimal contact with carbonate rock. This is because the size of the conduits (solution channels) and shorter residence times result in a lesser degree of rock/water interaction for springs. In contrast, the low yield of many wells indicates that most boreholes receive a large component of flow from the more diffuse part of the flow system. This diffuse flow is through small conduits and fractures and is characterized by lower permeability, increased residence time, and increased rock/water interaction (Adamski, 2000; Pollock and others, 2011; Knierim and others, 2013).

Water-quality monitoring during storm events substantiates the shorter residence time and reduced rock/water interaction for groundwater moving through conduits that feed springs. Generally, concentrations of rock-derived dissolved constituents (for example, calcium, magnesium, and bicarbonate) have been observed to decrease substantially during storm events within hours of the storm. Conversely, concentrations of surface-derived constituents (for example, nitrate, chloride, phosphate, fecal bacteria) often increase over the rise and peak of storm events (Widmann, 1982; Steele and others, 1985; Adamski, 1987; Parr, 1987; Wickliff, 1988; Davis and others, 2000; Pollock and others, 2011; Knierim and others, 2013). Pollock and others (2011) described marked changes in groundwater chemistry for storm events compared to base-flow events. There was less rock/water interaction modifying recharging waters during the rapid input storm-event periods, but there was effective delivery of dissolved constituents such as nitrate from the surface and regolith zones. For example, median calcium and dissolved inorganic carbon concentrations were 38.4 mg/L and 24.8 mg/L, respectively, during base flow, and 20.3 mg/L and 11.8 mg/L, respectively, during times of stormflow. By comparison, the nitrate concentration did not change substantially but remained near 2.7 mg/L for base flow and stormflow. Nitrate remained essentially constant even as flows increased by orders of magnitude, indicating considerable transport of dissolved mass into and through the aquifer during storm events.

### Nitrate

The terms “elevated,” “background,” and “baseline” as applied to groundwater nitrate concentrations can, from a quantitative perspective, have different meanings in different comparative contexts and defining these terms as used for the discussion of nitrate in groundwater of the Ozarks is of great importance. The typical contexts are comparing watershed to watershed, within a watershed, between different land uses, land-use intensity, time steps, areas of differing scales, and between contaminant source inputs. One definition of “elevated” nitrate would be the Federal MCL of 10.0 mg/L as nitrogen, which was established based on potential health effects from consumption of high-nitrate water. This definition, however, does not address concentrations that are greater than background levels and can result in environmental effects, such as promotion of algal growth in streams.

Several studies of the Springfield Plateau aquifer have been conducted in areas that are dominantly forested and provide a better understanding of representative background nitrate concentrations in relatively pristine areas. Steele (1983) sampled 74 springs in three relatively pristine (forested) areas in northwestern Arkansas with mean and median nitrate concentrations of 0.32 mg/L and 0.15 mg/L as nitrogen, respectively. Steele and Adamski (1987) sampled 48 springs and noted that seasonal mean nitrate concentrations in dominant forested areas ranged from 0.16 to 0.40 mg/L for the same sites sampled in different seasons. None of these sites were completely forested because there were homes with septic systems located throughout the spring basin; therefore, a true background concentration is probably less than this range of concentrations. Kresse and others (2011) established what they considered a conservative estimate for a background nitrate concentration of 0.40 mg/L as nitrogen based on review of data in these previous studies. The term “elevated” nitrate as used in this report refers to nitrate concentrations exceeding the 0.40 mg/L background concentration estimated in the above studies.

Because soils are generally thin, rocky, and poorly suited for row-crop farming, poultry, cattle, and swine production is the predominant agricultural activity in the Ozarks. The karst terrain enables rapid infiltration of surface water into the subsurface, which renders groundwater highly vulnerable to surface-derived contamination. This results in widespread influx of nutrients and fecal bacteria from waste generated by agricultural activities and septic tanks. Nitrogen and phosphorus associated with these activities are the dominant nutrients posing environmental threats to surface and subsurface waters in the Ozarks. Because most of the phosphorus is strongly bound to clays and organic matter in soils, little phosphorus moves in the dissolved state. Conversely, nitrate is the most soluble form of nitrogen and is conservative in transport. Consequently, nitrate is more persistent than phosphorus in the subsurface and poses the largest threat to groundwater resources in the Ozarks.

Numerous studies in northwestern Arkansas have reported on the occurrence, sources, transport pathways, and fate of nitrate in the Springfield Plateau aquifer (Keener, 1972; Coughlin, 1975; MacDonald and others, 1976; Ogden, 1979; Cox and others, 1980; Leidy and Morris, 1990b; Davis and others, 2000). Most of these studies found a wide range of elevated nitrate concentrations with a small percentage that exceeds the Federal MCL of 10.0 mg/L. Most studies attributed nitrate contamination to an abundance of septic systems and chicken houses in northwestern Arkansas. Other studies have attributed elevated nitrate and other surface-derived contaminants to urban sources (Gillip, 2007; Kresse and others, 2011; Vardy, 2011). Concentrations of nitrate in 166 samples from the Springfield Plateau aquifer compiled for this report ranged from 0.01 to 20 mg/L with a median of 1.8 mg/L. Only three samples exceeded the Federal MCL of 10 mg/L. Contrary to most of the aquifers of the Coastal Plain, the occurrence of nitrate in the Springfield Plateau aquifer was not correlated with well depth. Concentrations of more than 5.0 mg/L as nitrate were found uniformly throughout the range of well depths from as shallow as 5 ft upwards to 250 ft.

Several variables can affect the transport of nitrate to the subsurface including nitrogen form and loading, soil type, regolith thickness, attenuation processes such as denitrification, plant uptake, as well as presence of karst features and other focused-flow pathways. A well-defined relation was noted for the Springfield Plateau aquifer between increases in agricultural land use and increases in nitrate. Adamski (1997) used regression analysis that revealed a positive correlation between nitrate concentrations and percent agricultural land use in 103 sampled sites across the Ozark Plateau in Arkansas, Kansas, Missouri, and Oklahoma. Kresse and others (2011) similarly applied regression analysis using groundwater samples from 823 sites (springs and wells) in northern Arkansas that showed a similar positive, though weak linear, correlation between the two variables. Although the sites included samples from groundwater throughout the Ozark Plateaus aquifer system, most were from the Springfield Plateau aquifer. Bar graphs also were employed to show a positive relation between increasing mean nitrate concentrations for 10 percent incremental increases in agricultural land use using the same dataset (fig. 111*A*). An overall mean nitrate concentration of 2.4 mg/L was exceeded by the mean nitrate concentration for agricultural land use that exceeded 40 percent. Most domestic wells that were sampled had a septic system nearby that could affect the groundwater sample from the well. Thus, inclusion of data from domestic wells can skew the analysis, regardless of surrounding land use. To overcome this problem, the regression of nitrate and land use was conducted for spring sites only, which generally would not be associated with nearby septic systems. The 254 spring sites in the database were extracted and similarly tested for relation to agricultural land use. For springs, a much more consistent stepwise increase in nitrate concentration was noted for increasing agricultural land use, indicating the well data were affected by septic systems. Hence, the water chemistry of springs better reflects the influence of increasing agricultural land use (fig. 111*B*). The mean nitrate concentration for all spring sites was 2.6 mg/L, which was exceeded for all agricultural land-use percentage categories more than 40 percent, similar to that of wells and springs. Higher mean nitrate concentrations occurred for each percent agricultural land-use category as compared to both wells and springs. The spring data showed that effects on nitrate concentrations in groundwater were discernible at any level of agricultural land use. Even at the lowest agricultural land-use category from 0 to 10 percent, the mean nitrate concentration for 46 samples was 0.9 mg/L, almost twice the background concentration of 0.4 mg/L. This finding demonstrates the effects of even small land-use changes on the concentration of nitrate in groundwater and indicates that agricultural land use of more than 40 percent has an effect on groundwater quality in the Springfield Plateau aquifer.

Elevated nitrate concentrations in previous groundwater studies of the Springfield Plateau aquifer were attributed to karst features that allow rapid movement of groundwater with minimal attenuation of surface-derived contaminants. None of these studies, however, produced data to quantitatively test the influence of karst. One problem in assessing other variables affecting the occurrence and concentration of nitrate was the overriding variable of land use (Adamski, 1997; Kresse and others, 2011). To separately test the influence of karst terrain features on nitrate transport in dominant agricultural land-use areas, Kresse and others (2011) used the density of mapped sinkholes as a surrogate representing the degree of karst development in north-central Arkansas (Newton and Searcy Counties). Only springs were sampled to reduce the local influence of septic systems. Sampling locations were limited to agricultural land-use areas to remove land use as the main control on nitrate occurrence. Following these constraints, 34 springs were sampled in an area of highly developed karst as indicated by a high density of mapped sinkholes (Group I), and 22 springs were sampled in an area of less developed karst as indicated by an area devoid of mapped sinkholes (Group II). A statistically significant difference ($p<0.01$) occurred between the two groups; nitrate concentrations were greater for Group I springs. A weak point in the analysis was that total acres of agricultural land use were greater in Group I than in Group II, indicating that land use likely remained a controlling variable between the two sites. Regression analysis of nitrate concentrations from all springs did show a positive correlation to agricultural land use. To account for this land-use inconsistency, an analysis of covariance was conducted to investigate the importance of karst development as an additional important variable in nitrate occurrence. The analysis revealed that nitrate concentrations for Group I springs were greater than Group II springs for increasing agricultural land use (fig. 112). The occurrence of karst features accounted for approximately 12 percent of the variation between the two groups. This indicates that while nitrate concentrations in springs generally increase with increasing agricultural land use, concentrations generally are greater in areas where karst development (represented by sinkholes) is greater. The occurrence of sinkholes and other karst features thus provided more direct and rapid transport of contaminants to groundwater (Kresse and others, 2011).

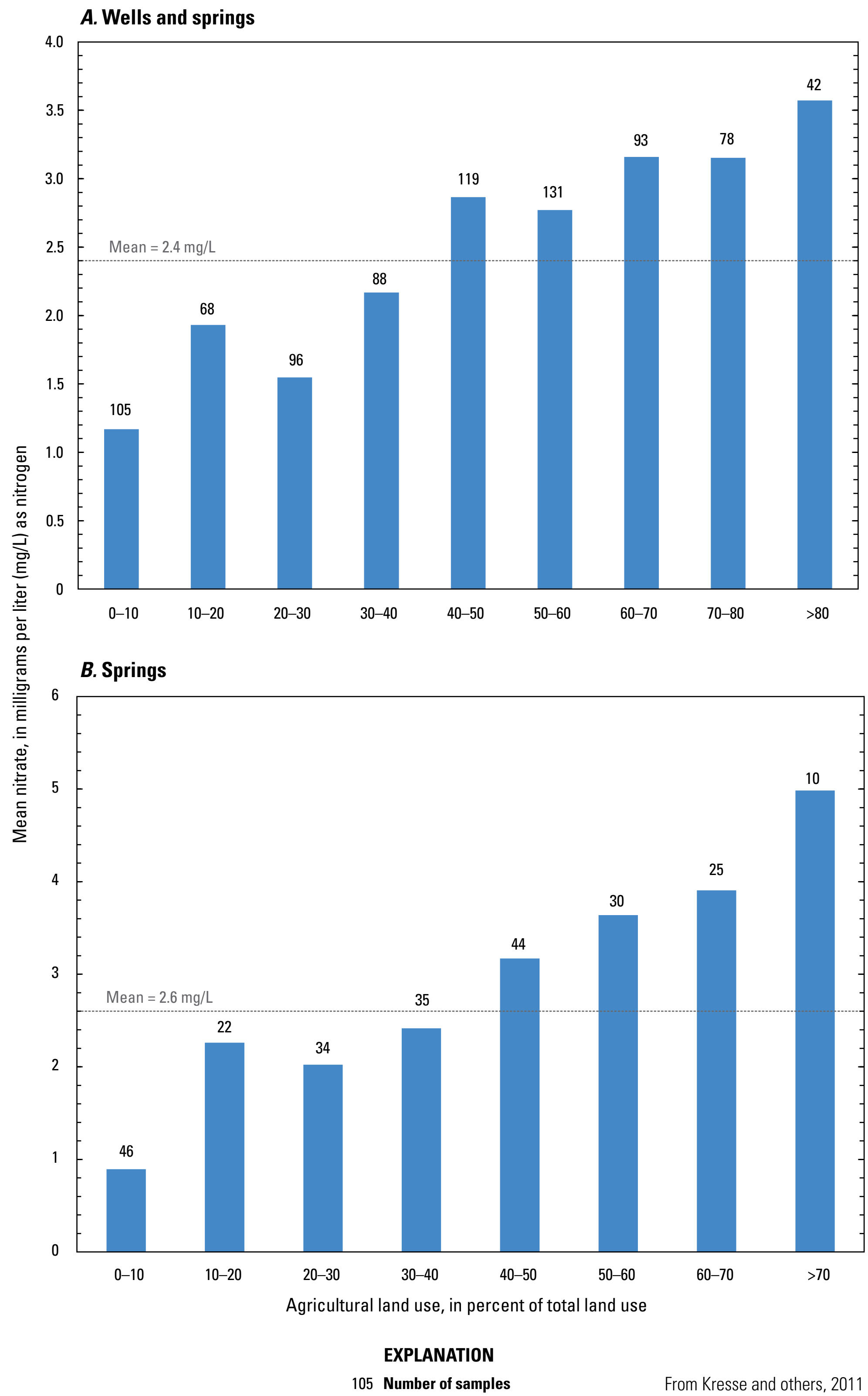



**Figure 111.** Relation of agricultural land use in percent of total land use to mean nitrate concentrations in groundwater from *A*, wells and springs and *B*, springs in the Ozark Plateaus aquifer system in northwest Arkansas.

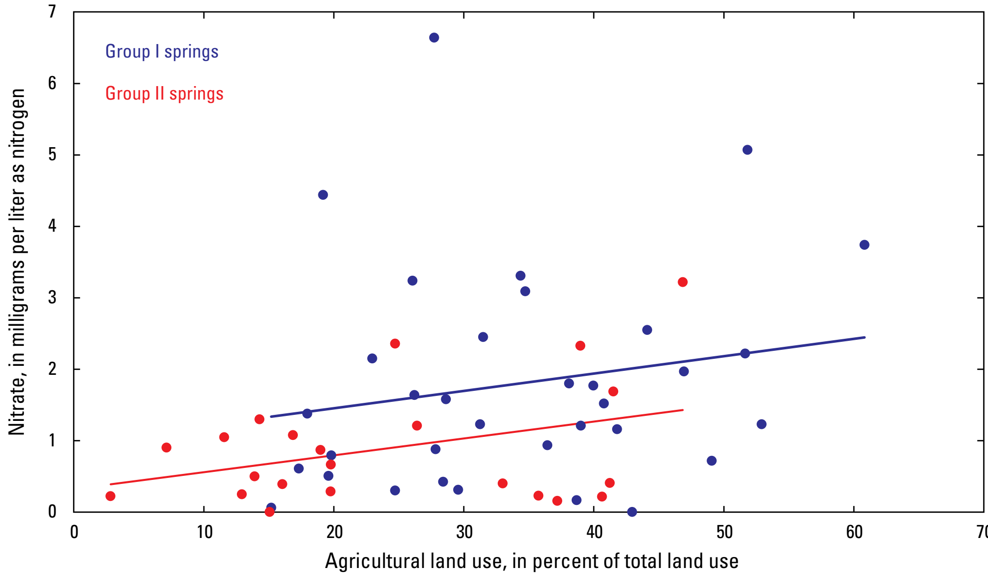



**Figure 112.** Analysis of covariance for nitrate concentrations and agricultural land use for Group I (highly developed karst) and Group II (less developed karst) springs.

Nitrate concentrations in the Springfield Plateau and Ozark aquifers have been compared in several studies, and higher mean and median concentrations have consistently been noted for the Springfield Plateau (Leidy and Morris, 1990b; Smith and Steele, 1990; Steele and McCalister, 1990, Adamski, 1997; Huetter and others, 1997; Kresse and others, 2011). For example, mean and median nitrate concentrations in 190 samples taken from the Springfield Plateau aquifer were 2.9 and 1.8 mg/L, respectively, compared to 0.47 and 0.10 mg/L, respectively, for 101 samples from the Ozark aquifer (Kresse and others, 2011). Most of the studies referenced above were in northwestern Arkansas, where the Ozark aquifer is confined and often overlain by exposures of the Boone Formation. Lower concentrations in the Ozark aquifer were attributed to protection from overlying formations. However, in areas of northeastern Arkansas and southeastern Missouri where the Ozark aquifer is exposed, mean and median nitrate concentrations remained low, similar to where the aquifer is confined (Kresse and others, 2011) (see section "Ozark Aquifer"). This finding suggests greater vulnerability to surface-derived contaminants for the Springfield Plateau aquifer compared to the Ozark aquifer. No definitive attributes have been identified to explain the higher vulnerability of the Springfield Plateau aquifer because the geology for both aquifers hosts abundant karst features (sinkholes, springs, and losing streams).

Recent research in northwestern Arkansas has been conducted at plot scale for assessing fate of nitrate in the Springfield Plateau aquifer (Peterson and others, 2002; Laincz, 2011). In these studies, nitrate transport was traced from its source through active microbial zones in soil, regolith, and epikarst, and ultimately into bedrock solution channels. The purpose was to determine controls on nitrate transport and the effectiveness of various zones in the aquifer system in removing nitrate. Results from one study indicated piston flow in the soil matrix with nitrate moving in pulses and the soil serving as a reservoir for nitrate (Peterson and others, 2002). Another study documented nitrate attenuation processes (denitrification) in the interflow zone between the soil and focused-flow (bedrock) zones, which can remove as much as 33 percent of infiltrating nitrate (Laincz, 2011).

## Bacteria

The increasing occurrence of pathogens in groundwater from the Springfield Plateau aquifer has been one of the primary water-quality factors limiting its use (Knierim and others, 2013).The potential occurrence of pathogens in groundwater usually is indicated by surrogate measurement of indicator bacteria, for example fecal coliform, fecal streptococcus, and *Escherichia coli* (*E. coli*). Fecal indicator bacteria commonly are detected in groundwater from the aquifer and are detected with great frequency in springs, where conduit flow and rapid transport prevent effective filtering. Bacteria in springs and wells in northwestern Arkansas have been documented at rates ranging from 42 to 80 percent of the sampling sites (Keener, 1972; Coughlin, 1975; MacDonald and others, 1976; Ogden, 1979; Cox and others, 1980; Leidy and Morris, 1990b; Davis and others, 2000). Bacteria sources are related to agricultural and urban land use, and bacteria survival and transport in the aquifer are controlled by degree of karst development, hydrologic flow condition, and sediment concentrations (Marshall and others, 1998). Davis and others (2005) found that fecal-coliform bacterial concentrations, including *E. coli*, were controlled by groundwater-flow conditions with bacteria concentrations varying by several orders of magnitude from base-flow to storm-flow conditions. Bacteria concentrations in spring water rapidly increased during the rising limb of storm-event hydrographs prior to breakthrough of nitrate and other conservative constituents, and the concentrations declined prior to the falling limb of the storm. Bacteria likely resided within sediment in the groundwater system, and the bacteria flux was associated with resuspension of sediment during the onset of turbulent flow. The survival period for bacteria in groundwater was at least 4 months (Davis and others, 2005).

### Sediment

Sediment, especially clay, is a contaminant that is virtually nonexistent in clastic aquifers in the State but is an important contaminant in karst settings, particularly from an ecosystem standpoint. Sediment commonly is associated with karst environments in urban land-use settings of the Ozarks. Sediment also is important in facilitating bacterial transport (Marshall and others, 1998; Davis and others, 2005). Gillip (2007) described large volumes of sediment that moved through karst and caves near urban areas in northwestern Arkansas as development denuded the landscape, exposing and enabling mobilization of the clayey regolith. Individual storm events were observed to deposit more than 3 ft of sediment in caves with considerable effects on the karst ecosystems. Gillip (2007) also showed the dynamic nature of sediment transport in karst as noted by deposition followed by removal of sediment during succeeding lower-precipitation events. Caving expeditions coupled with surface reconnaissance showed movement of sediment through fractures and conduits directly into caves during urban-development activities (Phillip D. Hays, U.S. Geological Survey, written commun., 2013). Ting (2005) used europium-labeled clays to demonstrate the effectiveness of suspended-phase transport in karst conduits and showed that the average transport velocity for a given mass of suspended material was more than the average transport velocity for dissolved material. Ting hypothesized that this discrepancy was the result of size exclusion and rapid preferential movement of suspended material through larger conduits.

### Pesticides

Because of the limited use of pesticides in the Ozarks relative to its pervasive use in row-crop areas of eastern Arkansas, very little sampling has been performed to document the occurrence of pesticides in groundwater from the Springfield Plateau aquifer. One regional study sampled for pesticides in groundwater from the Ozark Plateaus in Arkansas, Kansas, Missouri, and Oklahoma (Adamski, 1997). Pesticides were detected in 80 of 229 (35 percent) groundwater samples from 73 of 215 sites (9 sites in northern Arkansas). Twenty pesticides were detected, with a maximum of 5 detected in any one sample. The most commonly detected pesticides were tebuthiuron (31 samples), atrazine (30), prometon (25), desethylatrazine, a metabolite of atrazine (19), and simazine (18). These are herbicides that commonly are used on pastures and other noncrop areas. Pesticides were detected statistically ($p<0.01$) more often in groundwater from the Springfield Plateau aquifer than from the Ozark aquifer (Adamski, 1997). Pesticide detections additionally were related to nitrate concentrations in samples from agricultural sites. Median nitrate concentrations were statistically greater in samples with pesticide detections, further substantiating the increased vulnerability of the aquifer to surface contamination.

### Iron

Iron concentrations in 126 samples from the Springfield Plateau aquifer ranged from 0.05 to 3,300 µg/L with a median of 5.6 µg/L (fig. 113; table 43). Only five samples had iron concentrations exceeding the Federal secondary drinking-water regulation of 300 µg/L. Potential sources include: (1) iron mobilized from overlying regolith that contains abundant iron oxyhydroxide minerals that gives the unit its prevalent bright red coloration, (2) weathering of abundant pyrite that occurs in the Boone Formation limestone, and (3) iron sulfides associated with the Mississippi Valley Type ore mineralization that is common along fault zones in the Ozarks. The oxidation of iron-sulfide minerals as a source of iron is unlikely because of an observed inverse relation of iron and sulfate concentrations (graph not shown). Mobilization of iron from the regolith with onset of reducing conditions may explain elevated iron in isolated areas. This process is particularly common near landfills, waste lagoons, and other sources of abundant organic matter that provides a substrate for microbial activity using terminal electron acceptor processes (Hobza, 2005; Bolyard, 2007; Wagner, 2007). Regardless of the source, iron concentrations generally are low throughout the Springfield Plateau aquifer.

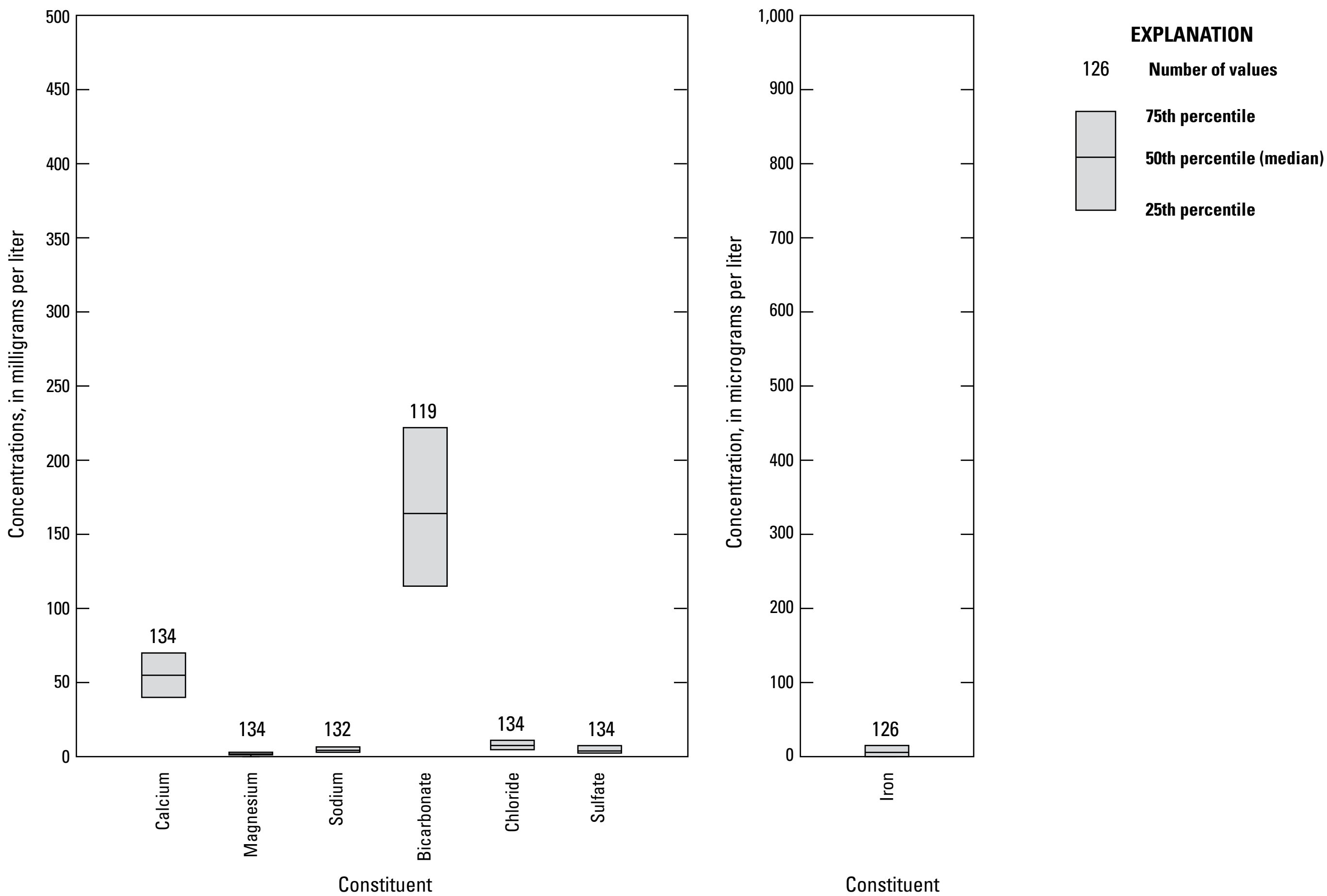



**Figure 113.** Interquartile range of selected chemical constituents in groundwater from the Springfield Plateau aquifer of northern Arkansas.

## Chloride

Chloride concentrations for 134 sites in the Springfield Plateau aquifer ranged from 1.2 to 47 mg/L with a median of 7.6 mg/L (fig. 113; table 43). Imes and Emmett (1994) reported concentrations generally are less than 10 mg/L in the aquifer throughout the Ozark Plateaus. Several studies noted the co-occurrence of nitrate and chloride in the aquifer, indicating that chloride may be derived from the same sources as nitrate (Ogden, 1979; Davis and others, 2000; Kresse and others, 2011; Vardy, 2011). Although a positive linear relation was noted between nitrate and chloride for this report, considerable variation occurred with an $R^2$ of only 0.12. This indicates that attenuation processes affecting the transport and resultant concentration of nitrate in groundwater are not affecting chloride, which is nonreactive (conservative) in transport within the hydrologic system. No spatial trend was noted for chloride concentrations.

## Sulfate

Sulfate concentrations for 134 sites in the Springfield Plateau aquifer ranged from 0.48 to 90 mg/L with a median of 3.9 mg/L (fig. 113; table 43). Imes and Emmett (1994) noted that sulfate concentrations generally are less than 10 mg/L. No spatial trend was noted for sulfate concentrations. As noted for iron, an inverse relation of iron and sulfate concentrations tends to rule out oxidation of iron-sulfide minerals as a source of sulfate. Because all but one sulfate concentration greater than 20 mg/L had ratios of calcium plus magnesium divided by bicarbonate that were more than 1.0, dissolution of gypsum may account for the increased sulfate concentrations.

In summary, groundwater from natural rock/water interaction processes in the Springfield Plateau aquifer is generally of good quality. Because of the steep topography and poor soils in the Ozarks, agriculture in the form of beef and dairy cattle, swine, and poultry operations accounts for the greatest land-use activity. Nutrients, bacteria, and pesticides from agricultural activities, home septic systems, and infiltration of urban runoff are the dominant threats to groundwater quality in the aquifer. Numerous studies have documented elevated nitrate and fecal bacteria in groundwater from springs and wells. A positive correlation between agricultural land use and nitrate concentrations validates concerns over agricultural wastes and the vulnerability of the aquifer to anthropogenic contaminants. Recent studies have shown a direct correlation between areas of greater karst development and increased vulnerability of the aquifer to these agricultural waste sources. Inorganic constituents, including chloride, sulfate, and iron, generally were low throughout the aquifer, revealing a relative high quality of groundwater for all water-supply uses.

## Ozark Aquifer

The Ozark aquifer (fig. 3) is exposed and generally unconfined within the Salem Plateaus section of the Ozark Plateaus (Ozarks) province (table 2). The aquifer underlies and is confined below the Springfield Plateau aquifer in the Springfield Plateau and Boston Mountains regions of the Ozarks (tables 2 and 5). The aquifer comprises a sequence of formations predominated by dolostones along with minor limestone, sandstone, and shale intervals of Ordovician age. These formations contribute to the unique and complex hydrogeology and physiography of the Ozarks. The karst of the carbonates in the upper Ozark aquifer presents a physiographic and hydrologic environment in the Salem Plateau similar in aspect and complexity to that seen for the Springfield Plateau.

The upper, carbonate-dominated part of the Ozark aquifer comprises the Clifty Limestone, Penters Chert, Lafferty Limestone, St. Clair Limestone, Brassfield Limestone, Cason Shale, Fernvale Limestone, Kimmswick Limestone, Plattin Limestone, Joachim Dolomite, St. Peter Sandstone, Everton Formation, Powell Dolomite, Cotter Dolomite, and Jefferson City Dolomite (table 5). The carbonate-dominated limestones and dolomites of Ordovician age are the predominant water-bearing units of the upper part of the aquifer. This differs from the lower part of the aquifer in predominant lithologies, groundwater levels, exposure and confinement, yields, and geochemistry, and hereinafter will be commonly referred to in this report as the "upper Ozark aquifer." The lower part of the aquifer includes the confined Roubidoux Formation, Gunter Member of the Gasconade Dolomite, Van Buren Formation, Eminence Dolomite, and Potosi Dolomite. The combined Roubidoux and Gunter Member of the Gasconade Dolomite are the primary water-bearing units of the lower part of the aquifer in Arkansas and are predominated by sandstone lithology with abundant dolomite and shaly intervals common in the Roubidoux Formation. The combined water-bearing units of the Roubidoux and Gunter Member of the Gasconade Dolomite are referred to hereinafter in this report as the "lower Ozark aquifer." Similar to the Springfield Plateau aquifer, groundwater movement and groundwater quality of the Ozark aquifer are controlled by regional and local geology. Geologic factors include the presence and composition of the regolith mantle, the lithologies of the rocks that convey groundwater flow, stratigraphic relations of these different lithologies, and geologic structure.

### Geologic Setting

The fundamental structural feature defining the Ozark Plateaus is a broad dome that has been uplifted during several periods since Precambrian time to bring the plateaus to their current altitude (Nunn and Lin, 2002; Tennyson and others, 2008; Cox, 2009). The core of the dome is in southeastern Missouri. Sedimentary units in Arkansas lie along the southern and southwestern margins of the dome with gentle regional dips generally ranging from 10 to 100 ft/mi and steeper dips being common proximal to faults (Frezon and Glick, 1959). Regional extensional fracturing, jointing, and faulting of rocks in the Ozark Plateaus occurred with uplift of the formations (Hudson and Cox, 2003) creating secondary porosity that has provided key nucleation points for initiation of dissolution of the carbonate rocks and karst development. Topographic relief resulted from erosional dissection of the Ozark Plateaus rather than from intense folding and faulting. This erosion has been controlled to a degree by structural features such as faults and fracture zones as well as by lithology.

Regolith mantles most areas of the underlying karstic bedrock where the formations of the Ozark aquifer are exposed on the Salem Plateau. In many areas of the regolith, thickness varies from near zero to more than 100 ft and typically comprises a silt-loam surface soil overlying a clay-loam subsoil. The regolith usually is clay-rich, low in permeability, and impedes recharging water. The regolith mantling the Salem Plateau generally contains less chert than the regolith over the Springfield Plateau. This compositional difference may make the Salem Plateau regolith a more competent barrier to surface-derived contamination. This has been theorized to explain observational differences in lower nitrate concentrations in the Ozark aquifer compared to the Springfield Plateau aquifer (see "Water Quality" section below).

The younger Ordovician-age rocks constituting the upper Ozark aquifer only require a brief description because yield and water quality are similar throughout. The Fernvale Limestone is generally observed as a massive, zero to more than 100 ft in thickness, coarsely crystalline, light-gray to pink limestone present in the Ozarks of northern Arkansas. The Fernvale is very similar to the underlying Kimmswick, which is generally less than 50 ft in thickness. The Plattin Limestone is a gray, thin-bedded limestone and is usually less than 100 ft in thickness. The Joachim Dolomite is generally described as a fine-grained dolostone or dolomitic limestone with thin beds of shale. Sand is abundant at the base of the formation with thin sandstones commonly occurring above the St. Peter Sandstone. The Joachim is absent in the western Ozarks and is as thick as 100 ft in the central and eastern Ozarks. The St. Peter Sandstone is usually observed as a massive-bedded, medium- to fine-grained, well-rounded, poorly cemented, white sandstone. The formation ranges from less than 1.0 ft to as much as 175 ft in thickness. The Everton Formation exhibits considerable spatial variation in lithologic character and comprises dolostone, sandstone, and limestone intervals in varying proportions. The Everton Formation includes members of thick, friable sandstone that are similar to the overlying St. Peter Sandstone. Thickness of the Everton Formation varies from about 300 ft to more than 650 ft. The Powell Dolomite usually is observed as a fine-grained, light to green-gray dolostone from less than 50 ft to more than 200 ft in thickness, with thin beds of shale, sandstone, and occasional chert. The Jefferson City and Cotter Dolomites constitute a thick interval of 1,000 ft or more of light- to dark-tan, fine- to medium-grained dolostone with common chert and some thin beds of sandstone and shale. These two formations are indistinguishable in Arkansas (McFarland, 1998).

The lower Ozark aquifer comprises the Roubidoux Formation and the Gasconade Dolomite for which the Gunter Sandstone Member is the primary water-yielding unit. These formations do not crop out in Arkansas. The Roubidoux consists of dolomite, sandstone, and chert. The dolomite is light gray to brown in color, finely granular to medium crystalline, and is sandy and cherty at some locations (Caplan, 1960; Howe and Konig, 1961; Imes and Emmet, 1994; Adamski and others, 1995). The sandstones consist of discontinuous beds of white to light-gray, fine to medium quartz (Snyder, 1976; McDonald and others, 1977) and are loosely to well cemented by silica or carbonate materials (Caplan, 1960). The Roubidoux Formation ranges from 100 ft to more than 450 ft in thickness in northern Arkansas.

The Gunter Sandstone Member at the base of the undifferentiated Gasconade Formation represents the oldest Ordovician rock present in northern Arkansas and rests unconformably on the Cambrian Eminence Dolomite. The Gasconade Formation comprises light brownish-gray, fine- to medium-crystalline dolomites that frequently contain chert (Caplan, 1960; Prior and others, 1999). The upper part of the Gasconade Formation contains relatively small amounts of chert; however, the formation may contain as much as 50 percent chert by volume above the Gunter Sandstone Member (Prior and others, 1999). The Gasconade Formation ranges from about 300 to over 700 ft in thickness (Caplan, 1960; Melton, 1976). The Gunter Sandstone is mainly composed of white to light-gray, fine- to coarse-grained quartz sandstone and sandy dolostone (McQueen, 1931; Knight, 1954; Caplan, 1960; Melton, 1976; Snyder, 1976; MacDonald and others, 1977; Adamski and others, 1995; Imes and Emmet, 1994; Prior and others, 1999a). The sand generally is loosely cemented by silica or carbonate material (Grohskopf and McCracken, 1949). The Gunter Sandstone Member typically averages about 30 ft in thickness (Caplan, 1960; Melton, 1976; Prior and others, 1999) but is locally reported to be approximately 100–120 ft in thickness (Caplan, 1960; Melton, 1976; Prior and others, 1999). The Gunter Sandstone Member may be locally absent (Caplan, 1960; Prior and others, 1999).

The tops and thicknesses of the Roubidoux Formation and the Gunter Sandstone encountered in wells in northern Arkansas were identified by Lamonds and Stephens (1969). Structural maps of the Roubidoux and the Gunter are presented by Caplan (1960), Lamonds (1972), Melton (1976), MacDonald and others (1977), and Prior and others (1999). A limited number of wells are drilled to the Roubidoux and the Gunter. As a result, data used to compile the structural maps are limited. Prior and others (1999) used 174 wells and provided the most comprehensive structural map available at this time (2013).

Karst-development processes and history are an important aspect of the geology controlling groundwater hydrology in the Ozarks. The exposed formations of the Ozark aquifer present an example of a dynamic and developing karst aquifer. Also evident are episodes of karst development through geologic time that results in overlap and interplay of recent and paleokarst features. Karst aquifers are typified by a combination of diffuse and focused flow. The slower flow occurs through diffuse flow paths and allows for sustained groundwater input to streams and springs, even during dry periods. Extremely rapid response and transit times occur during precipitation events and are provided through preferential flow paths and karst features. In karst systems, large cavernous conduits allow for deep and rapid circulation of recharge. Conduits and dissolution-enhanced fracturing help integrate flow to spring resurgences (Harvey, 1980). As a result, springs are common throughout the exposed sections of the Ozark aquifer.

Bedrock in the Ozarks shows evidence of multiple episodes of water movement and carbonate dissolution, which defines distinct karst-development events through time (Stoffell and others, 2008). Exposure of Ordovician strata associated with the Ordovician-Mississippian unconformity caused dissolution and initial paleokarst development. Widespread dissolution features associated with the lead and zinc ore-bearing fluids that moved from the Arkoma Basin (Leach and Rowan, 1986) are observed across the Ozarks region. Lead and zinc were commercially mined where faults conveyed mineral-saturated fluids up from depth. Hypogene indicators, such as diagnostic calcite isotopic compositions (Brahana and others, 2009), collapse breccias (McKnight, 1935), and isotopic dating (Brannon and others, 1996), show that this episode of fluid movement and dissolution was a separate occurrence predating recent karst development. The formations of the Ozark aquifer once again showed active karst development as uplift, denudation, and abundant precipitation, and recharge initiated further dissolution of the soluble carbonate lithologies.

The recent period of dissolution and karst development has had very visible impact on the modern karst land surface, on controlling subsurface flow, and ultimately on surface flow in the region. The hydrogeology of the region is typical of karst with focused flow paths that are well connected to the surface and delivers water from input to discharge points at streams and springs at velocities of tens to thousands of feet per day (Funkhouser and others, 1999; Mott and others, 2000; Turner and others, 2007; Hudson and others, 2011). Abundant karst features are apparent including ponors, losing stream reaches, springs, caves, and sink holes. However, recent karst development in the Ozark aquifer has often reactivated and followed previous dissolution-enhanced flow paths. These flow paths originally developed during ancient exposure periods (for example, at the Ordovician-Mississippian unconformity; Webb, 1994) or hypogene episodes (such as Mississippi Valley Type ore emplacement; Leach and Rowan, 1986; Brannon and others, 1996; Brahana and others, 2009).

## Hydrologic Characteristics

The upper Ozark aquifer is generally unconfined across the Salem Plateau and confined in the Springfield Plateau and Boston Mountains. The highly soluble nature of the carbonate rocks of the dolostones and limestones that comprise the upper Ozark aquifer has resulted in development of the hydrologically heterogeneous karst terrain. Karst features include caves, springs, and sinkholes, which result in the direct hydraulic connection of surface water and groundwater and create the highly variable aquifer characteristics that typify the area. In the upper Ozark aquifer, high hydraulic conductivity values typically result from secondary porosity created by dissolution of bedrock along joints, fractures, and bedding planes, rather than from primary, matrix-type porosity. Enhancement of fractures, bedding planes, and conduits by carbonate dissolution is an active, ongoing process (Adamski and others, 1995). Diagenetic processes have developed secondary porosity features and have produced anisotropic and heterogeneous hydraulic characteristics in the aquifer. At one end of the porosity-permeable continuum, smaller-scale matrix, small-aperture fracture, and small-conduit porosity give rise to diffuse groundwater flow in the aquifer. At the other end of the porosity-permeable continuum, dissolution-enhanced porosity creates the focused (conduit) groundwater flow. Because of the low rock-matrix permeability, a large fraction of groundwater transfer is through the focused-flow component of the aquifer (Imes and Smith, 1990). The rapid recharge of surface water, rapid flow velocities, rapid mass transfer, and minimal attenuation of contaminants are associated with this component of flow. The time-averaged groundwater flow, base flow of streams during dry periods, low groundwater-flow velocities, and effective attenuation of contaminants are behaviors associated with the diffuse component of flow.

In the unconfined upper Ozark aquifer, precipitation provides recharge to the aquifer where exposed. Recharge can be rapid and result in highly variable water levels, substantial seasonal changes, and groundwater-gradient reversals (Aley, 1988). In areas where the Ozark aquifer is overlain by the Springfield Plateau aquifer, most recharge occurs through downgradient flow originating in the outcrop area for the Ozark aquifer and leakage from the overlying Springfield Plateau aquifer. Leakage of water between the Springfield Plateau and Ozark aquifers is impeded by shales (primarily the Chattanooga Shale) and dense, low-permeable limestones and dolostones (Imes and Emmett, 1994; Adamski and others, 1995). In some areas, the Chattanooga Shale is absent and the potential is increased for hydraulic connection between the two aquifers.

Well yields are relatively low within the upper Ozark aquifer and are comparable to those of the exposed Springfield Plateau aquifer, reflective of the generally low permeability. Wells within the upper Ozark aquifer are generally less than 300 ft in depth (Lamonds, 1972) and have yields of approximately 5–10 gal/min (Lamonds, 1972; Leidy and Morris, 1990b). Data on the hydraulic properties of the upper Ozark aquifer are scarce. The hydraulic conductivity of the combined upper and lower Ozark aquifer is estimated to range from greater than 1,000 ft/d to less than $1.0\times10^{-2}$ ft/d (Imes and Emmet, 1994).

The Roubidoux Formation, Gasconade Dolomite, Eminence Dolomite, and Potosi Dolomite form aquifers of generally high yield (Harvey, 1980). Only the Roubidoux and Gunter Sandstone are commonly used in Arkansas and are grouped and discussed for the purposes of this report as the “lower Ozark aquifer.” Where these units are exposed in Missouri, multiple studies have been conducted using dye traces and other approaches (Gott, 1975; Aley and Aley, 1987; Imes and Kleeschult, 1996). Results indicate a complex karst hydrologic system having long, interwoven flow paths that change drastically in terms of basin boundary extents and dominant flow paths with changing hydrologic condition (Mesko and Imes, 1995; Imes and Fredrick, 2002). Secondary porosity is provided by fractures, joints, bedding planes, vugs, dissolution conduits, and other karst features. This contributes to the high permeability values and the ability of the aquifer to convey great amounts of water. Secondary-porosity features are observed to decrease with depth (Lamonds, 1972). High yields at depth in the lower Ozark aquifer are attributed dominantly to porous sandstone layers, as reported for the Roubidoux Formation and Gunter Sandstone Member, rather than high hydraulic conductivity provided by karst features. Emerging data indicate the potential for localized karst-flow systems at depth within the Ozark aquifer (Brahana, 2011a). Though observations of paleokarst and solutional development are difficult to identify at depth, evidence provided by Palmer (2011) has shown that deep-seated dissolution has occurred within the Ozarks. Orndorff and others (2006) also provided evidence of karst development at depth in confined aquifers.

The lower Ozark aquifer is under confined conditions (Prior and others, 1999) and receives recharge from rainfall and streamflow interception in its outcrop areas in southern Missouri (Lamonds, 1972; Melton, 1976; MacDonald and others, 1977; Harvey, 1980; Prior and others, 1999). Harvey (1980) further detailed important recharge components and listed sinkholes, infiltration through conduits, and losing streams as the primary mechanisms of recharge. Some recharge occurs as leakage from the upper Ozark aquifer (Imes and Emmett, 1994; Adamski and others, 1995); however, the majority of recharge is attributed to lateral flow from the outcrop areas (Imes and Emmett, 1994; Adamski and others, 1995). The direction of groundwater flow generally follows the regional dip toward the south. Wells in Missouri intercept some of the groundwater in the lower Ozark aquifer before it reaches Arkansas (Prior and others, 1999).

Wells in the lower Ozark aquifer are among the most productive in the region (Lamonds, 1972); yields from the Roubidoux Formation range from less than 10 gal/min to about 600 gal/min (Caplan, 1960; Lamonds, 1972; Melton, 1976; MacDonald and others, 1977; Kilpatrick and Ludwig, 1990b; Prior and others, 1999). Yields from the Gunter Sandstone Member range from less than 100 gal/min to about 600 gal/min (Lamonds, 1972; Melton, 1976; MacDonald, 1977; Kilpatrick and Ludwig, 1990b; Imes and Emmett, 1994; Adamski and others, 1995; Renken, 1998; Prior and others, 1999; Czarnecki and others, 2014). Prior and others (1999) noted that wells were drilled to the deeper Gunter Sandstone Member only when yields from the Roubidoux Formation were insufficient. The wells often were dually completed, making it difficult to determine yields for the individual formations. Caplan (1960) reported that combined yields from the lower Ozark aquifer can be as much as 300 gal/min, although yields commonly are 50 gal/min or less. Melton (1976) noted that the distribution of well yields is not uniform, indicating that local lithologic differences and distribution of secondary porosity may affect well yields.

Data on the hydraulic properties of the Roubidoux Formation and the Gunter Sandstone Member in Arkansas are scarce. The hydraulic conductivity of the Ozark aquifer as a whole is estimated to range from more than $1.0\times10^{-3}$ ft/s to less than $1.0\times10^{-8}$ ft/s (Imes and Emmet, 1994). Specific capacity values ranged from 0.1 to 3.8 (gal/min)/ft for the Roubidoux Formation, and several wells experienced no measurable drawdown while pumping. A single specific capacity of 0.1 (gal/min)/ft was reported from a well completed in the Gasconade Formation (Melton, 1976; MacDonald and others, 1977). Potentiometric surfaces of the lower Ozark aquifer are presented by Lamonds (1972), Melton (1976), MacDonald and others (1977), and Prior and others (1999) and generally show an overall southerly direction of flow following the regional deep of the formation constituting the aquifer.

## Water Levels

Water-level data for the Ozark aquifer are scarce. Where available, the data are very nonspecific in terms of the individual formation in which the well is completed, or if the well is completed in the lower Ozark aquifer compared to the upper Ozark aquifer. Most historical water levels were measured in open-hole wells, and the determination and assignment of the primary groundwater-yielding formation are difficult. This paucity of data results in (1) potentiometric maps that lack in detail, (2) a vertical distribution of head gradients that cannot be individually determined, and (3) an inability to understand groundwater flow in the aquifer, particularly at small, subregional scales.

The understanding of groundwater flow in the upper Ozark aquifer is derived from various reports and analysis of NWIS data performed for this report. Problems in understanding groundwater flow lies in the fact that the Ozark aquifer is not differentiated in most reports, although the dominantly unconfined upper Ozark aquifer has hydrologic characteristics vastly different from those of the deeper and confined lower Ozark aquifer. For the upper Ozark aquifer, precipitation provides direct recharge to the aquifer where exposed in Arkansas, and groundwater follows short (usually less than 10 mi), local flow paths that terminate near streams (Adamski and others, 1995). Therefore, recharge can be rapid and results in highly variable water levels with substantial seasonal changes. This also contributes to groundwater gradient reversals (Aley, 1988). The potentiometric surface of the combined (upper and lower Ozark aquifer undifferentiated) Ozark aquifer averages from about 700 to 1,000 ft of altitude (Adamski and others, 1995). The potentiometric surface generally is a subdued reflection of the topography where the upper Ozark aquifer crops out and is unconfined (Lamonds, 1972; Leidy and Morris, 1990b). Meta-analysis statistics conducted on data (altitude and water-level data from NWIS) compiled for this report from 1,081 wells showed that water levels closely correspond to land-surface altitudes with a correlation coefficient of 0.92. Groundwater-flow directions are lateral and outward from areas of high to low altitude. Small groundwater basins with short flow paths originating at higher altitudes and with discharge occurring at lower altitudes at streams and springs account for much of the overall groundwater-flow budget (Imes and Emmett, 1994; Adamski and others, 1995; Pugh, 1998, 2008b; Schrader, 2001a, 2005; Czarnecki and others, 2014).

Much of the understanding of groundwater flow in the lower Ozark aquifer is derived from extrapolation of data from Missouri. Water levels in the Roubidoux Formation of the lower Ozark aquifer vary spatially and temporally and may vary by as much as 200 ft/yr. Variations in the resulting potentiometric surface reflect topographic relief, changes in pumping, and regional formation dip (Kilpatrick and Ludwig, 1990b). Water levels from the Gunter Sandstone of the lower Ozark aquifer vary spatially and temporally and vary by approximately 100 ft in a period of a few years (Edds and Remsing, 1986; Freiwald and Plafcan, 1987). Representative hydrographs showing water levels from wells completed in the upper and lower Ozark aquifers are shown in figure 114. The upper Ozark aquifer generally shows greater and more rapid water-level change than the lower Ozark aquifer because it is shallower and more exposed to direct infiltration of locally recharging precipitation. Water-level changes in the lower Ozark are more subdued and slower in response to precipitation. This lag time for the lower Ozark as compared with the upper Ozark aquifer results from the greater distance of the wells in Arkansas from the recharge area located to

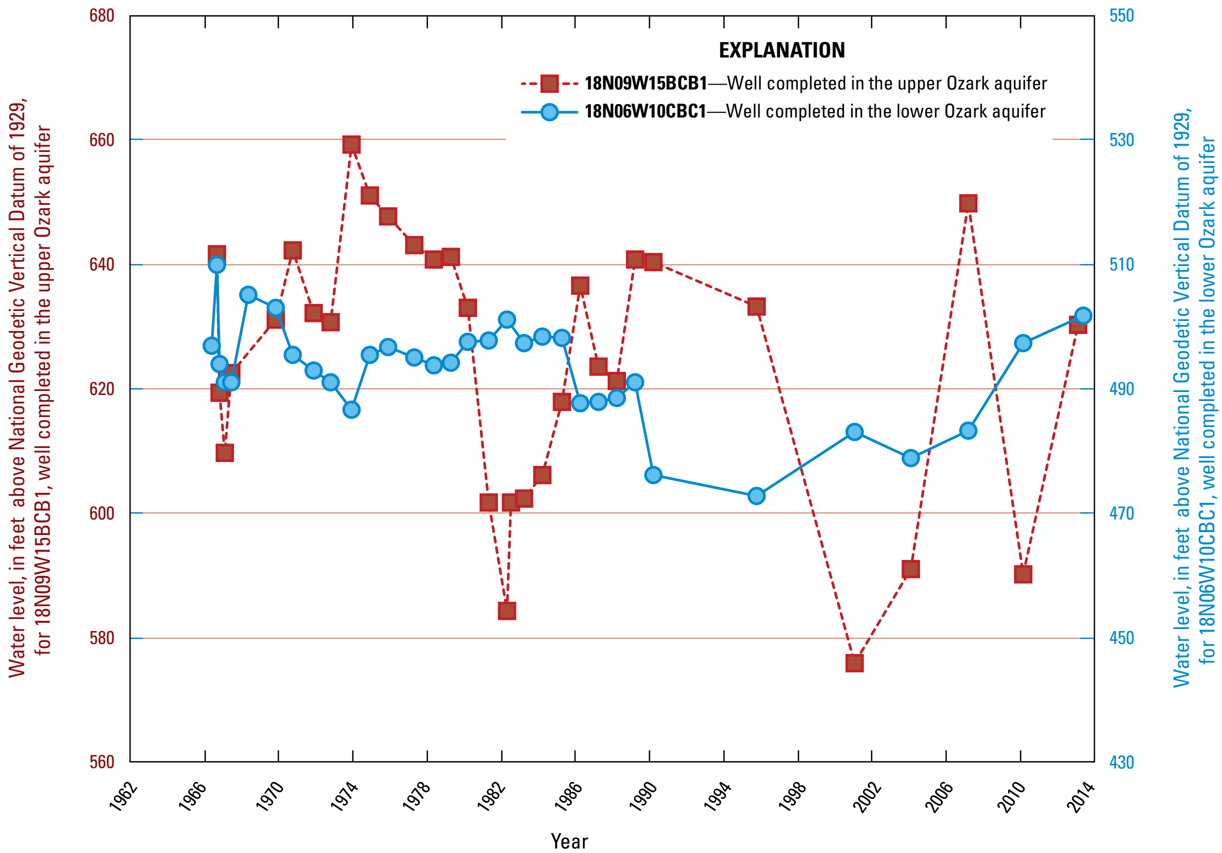
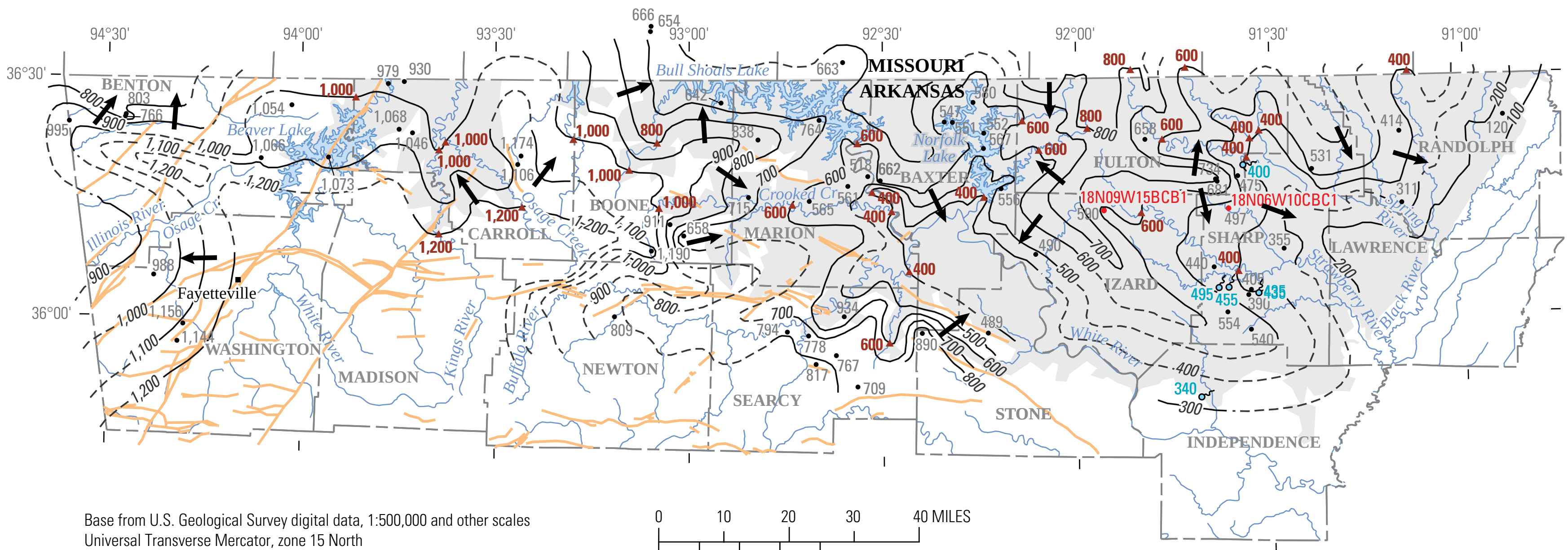



**Figure 114.** Water levels in wells completed in the upper and lower Ozark aquifer of northern Arkansas.

the north in Missouri. Water levels in the Ozark aquifer are measured on a 3-year rotational basis; measurements were last made in 2010 in 56 wells and 5 springs by the USGS in collaboration with ANRC (Czarnecki and others, 2014). No continuous water-level monitoring sites are active for the Ozark aquifer.

Water levels in the lower Ozark aquifer generally rise to altitudes of approximately 400–1,000 ft and typically are within about 200 ft below land surface (Lamonds, 1972). Water-level altitudes for the lower Ozark aquifer show a much less well-defined relation with land surface than the upper Ozark aquifer or the Springfield Plateau aquifer. Water-level and elevation data compiled from 1,085 wells for this report show that water levels correspond poorly to land-surface altitudes with a correlation coefficient of 0.70, as compared to correlation coefficients of 0.92 and 0.98 for the upper Ozark and Springfield Plateau aquifers, respectively. This lack of correlation between water-level and land-surface altitudes for the lower Ozark aquifer is a reflection of the lesser control of topography, the less frequent occurrence of short, small-basin flow paths, and the predominance of long, regional flow paths.

Regional flow within the lower Ozark aquifer is to the south and southeast following the dip of the units toward the Arkansas River and Mississippi Alluvial Plain (Lamonds, 1972, Czarnecki and others, 2014). Evidence of upward leakage from the lower Ozark aquifer into the embayment aquifers is seen in water-budget and geochemical data (Mesko and Imes, 1995; also see the “Mississippi River Valley Alluvial Aquifer” section in this report). The paucity of well control points for the lower Ozark aquifer in northern Arkansas greatly limits the confidence and detail of groundwater-flow interpretation and any delineation of topographic and other local controls on water levels. Additional data are needed to better understand the flow system in the lower Ozark aquifer (Lamonds, 1972; Imes and Emmett, 1994; Czarnecki and others, 2014). Potentiometric surfaces generated for the undifferentiated Ozark aquifer using the relatively scarce available water-level data (fig. 115) have changed little through time (Pugh, 1998; Schrader, 2001a, 2005; Pugh, 2008b; Czarnecki and others, 2014). Therefore, more recent potentiometric surfaces (Czarnecki and others, 2014) resemble predevelopment surfaces constructed by Imes and Emmett (1994). The St. Francois confining unit, the lower confining unit for the Ozark aquifer, limits the downward flow of groundwater and hydrologically separates the Ozark aquifer from the St. Francois aquifer (Adamski and others, 1995).




Base from U.S. Geological Survey digital data, 1:500,000 and other scales
Universal Transverse Mercator, zone 15 North
North American Datum of 1983

Modified from Czarnecki and others, 2013


**EXPLANATION**

**Outcrop of Ozark aquifer**

500 — **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour interval 100 feet. Datum is National Geodetic Vertical Datum of 1929 (NGVD 29)

**General direction of groundwater flow**

**Fault (Haley and others, 1993)**

778 **Observation well completed in the Ozark aquifer**—Measurement made in February and March 2010. Value is the water-level altitude above NGVD 29

497 18N06W10CBC1 **Observation well completed in the Ozark aquifer for which hydrograph is presented (fig. 114) and site name**—Measurement made in February and March 2010. Value is the water-level altitude above NGVD 29

455 **Spring in the Ozark aquifer**—Measurement made in February 2010. Value is the water-level altitude above NGVD 29

400 **Control point**—Intersection of land-surface contour and stream within area where the Ozark aquifer is unconfined. Altitude values determined from 1:500,000 topographic map

**Figure 115.** Potentiometric surface of the Ozark aquifer in northern Arkansas, 2010.

Several studies have investigated long-term water-level trends within the Ozark aquifer to identify areas at risk for groundwater decline and to quantify the effect of water users converting from groundwater to surface-water sources (Pugh, 2008b; Czarnecki and others, 2014). The sparse and limited number of water levels greatly limits effective assessment and prediction of sustainable water levels for the Ozark aquifer. Nevertheless, declines had been noted in northwestern Arkansas (Benton, Carroll, and Washington Counties), which is an area of development and population growth (Czarnecki and others, 2014). Czarnecki and others (2014) reported recent decreases in the rate of water-level decline in some wells and increases in water levels for others. This positive news was related to the expansion of rural water-supply districts that have predominately converted to surface-water sources.

## Deductive Analysis and Projections of Groundwater Movement

Groundwater often receives less focus in terms of monitoring and management efforts than does surface water because it is less visible, hydrologic and geochemical changes typically occur more slowly, and it responds less quickly to external processes or boundary conditions. Furthermore, collecting information and developing an effective understanding of groundwater behavior is more challenging than for surface water. Digital simulation of groundwater has been an important tool for evaluating basic aquifer characteristics such as recharge rates, storage, permeability, flow rates, and flow paths. Groundwater-flow models are also important as a tool to predict aquifer responses to future conditions such as changes in pumping, land-development effects, and climatic effects. Although numerous local-scale and regional investigations of groundwater have been conducted across the Ozarks, groundwater-flow models rarely have been used. Investigations that have developed groundwater-flow models specific to the Ozarks of Arkansas are Imes and Emmett (1994), Mesko and Imes (1995), and Czarnecki and others (2009).

A regional groundwater-flow model for the Ozarks was developed by Imes and Emmett (1994) as part of the USGS Central Midwest RASA to assess regional groundwater resources and to better understand hydraulic properties of the aquifer and groundwater flow. Simulation results indicated that the hydraulic conductivity of the Ozark aquifer is approximately 10 ft/d in the southern Ozarks of Arkansas and about 25 percent of precipitation occurring over the outcrop area of the Ozark aquifer infiltrated as recharge to the aquifer. Of that total, about 78 percent entered small-scale watersheds, flowing along short flow paths to quickly discharge into nearby streams and springs. The remainder (6 percent of precipitation) ended up in deeper, longer flow paths as regional groundwater flow. The pumping rates at that time (1990) were found to have little to no effect on the simulated regional water budget and potentiometric surfaces compared to simulated predevelopment conditions. These results illustrate the great differences in the predominantly karst aquifers of the Ozarks and the granular aquifers of the Mississippi embayment. Results also highlighted the prevalence of small-scale watersheds and associated short groundwater flow paths in the surficial aquifers in the overall groundwater-flow budget.

Regional groundwater-flow simulations were conducted by Mesko and Imes (1995) linking simulations of two regional-scale models: the Ozark Plateaus Aquifer System model (Imes and Emmett, 1994) and the Mississippi embayment Aquifer System Model (Brahana and Mesko, 1988). Historical hydrogeological data in the Mesko and Imes study indicated the potential for groundwater to move from the Ozarks aquifer system to beneath the Fall Line or escarpment into the northern Mississippi embayment, ultimately to discharge to overlying embayment aquifers or directly to streams. The quantity of water simulated by the linked Ozark model moving from the Ozark Plateaus aquifer system under the Fall Line into the Mississippi embayment was 650–800 $ft^3/s$ more than the quantity simulated by the MERAS model. The most likely explanation for this difference was groundwater discharge to streams. Therefore, the results were initially interpreted as indicating that a considerable volume of groundwater might be discharging to embayment streams. To determine if these differences in simulated groundwater flow could be explained by discharge to base flow in streams, low-flow seepage measurements were made on the Black and Current Rivers and their major tributaries in 1987. The seepage data indicated that groundwater contributed about 1,000 $ft^3/s$ to the streams. These results were in precise agreement with model results confirming the scale and great importance of groundwater contribution to streamflow (Mesko and Imes, 1995).

Availability of water has been a limiting factor for growth in the Ozarks; nevertheless, groundwater has historically been an important part of the resource base. Relatively minor attention and resources were focused on development of groundwater because of limited fiscal resources of the region and the regional groundwater system of the Ozarks is incredibly complex and challenging to characterize. As a result, an understanding of the Ozark Plateaus aquifer system is not at the same level as other important regional aquifers, and the available tools for assessing the system are insufficient to address evolving needs. Currently (2013), USGS is working on a regional assessment of groundwater availability of the Ozark Plateaus aquifer system as part of a USGS Groundwater Resources Program initiative (http://water.usgs.gov/ogw/gwrp/activities/regional.html), whose objectives are to assess (1) growing demand and the role of groundwater as a resource for agricultural, industrial, and public-supply uses (Emmett and others, 1978; Dintelmann and others, 2006; Richards and Mugel, 2008; Richards, 2010), (2) regional climate variability and pumping affecting groundwater levels and groundwater and surface-water flow paths (Macfarlane and Hathaway, 1987; Imes and Emmett, 1994), (3) effects of the gradual shifting to greater dependence upon surface water in some areas (Morgan, 2012) and, (4) potential effects on water use from shale-gas production (U.S. Environmental Protection Agency, 2010). Specific objectives related to the Ozark Plateaus aquifer system assessment include deductive analyses and projections of aquifer conditions using a newly developed groundwater flow model to (1) better understand groundwater movement in the Ozark Plateaus aquifer system, (2) quantify current water use and evaluate effectiveness of water-use monitoring approaches, (3) evaluate how groundwater and surface-water resources have changed over time, and (4) provide information to help project the systems response to future changes. The Ozark system model encompasses approximately 69,000 $mi^2$ extending north to the Missouri River, south to the Arkansas River, west into Oklahoma and Kansas, and east to the Mississippi embayment. Groundwater use, groundwater levels, surface-water levels, streamflow, precipitation, temperature, land use, geophysical, and drillers' logs have been compiled to define hydrogeology and hydraulic properties of the system. These data were used to develop a conceptual model and ultimately can be used to construct a numerical model of the system.

## Water Use

There were 108 wells reported in the Ozark aquifer in 2010. Of those, 79 wells withdrew groundwater from the lower Ozark aquifer (comprised of the Roubidoux Formation and Gunter Member of the Gasconade Formation), and the remaining wells withdrew from the upper Ozark aquifer (fig. 116; Terrance W. Holland, U.S. Geological Survey, written commun., 2013). Primary use of the Ozark aquifer is for public supply; 76.45 Mgal/d was withdrawn for public supply in 2010. The high costs associated with drilling prevent smaller community-supply systems from using the more productive lower Ozark aquifer; although, some gas stations, campgrounds, mobile home parks, and resorts withdraw a small amount of groundwater in rural areas, but most others rely on wells in the upper Ozark aquifer.

The Roubidoux and Gunter units together compose the lower Ozark aquifer and account for the greatest yields and overall use in the Ozarks. Total reported use from the Roubidoux and Gunter in 2010 was 50.73 Mgal/d and 26.58 Mgal/d, respectively. Primary use of both units is public supply; 99.8 percent of use from the Roubidoux and 80.9 percent of use from the Gunter in 2010 was for public supply. Cherokee Village in Sharp County withdrew the most water from the lower Ozark aquifer in 2010 at 9.72 Mgal/d; all withdrawals were from wells listed as completed in the Roubidoux (Terrance W. Holland, U.S. Geological Survey, written commun., 2013). Decatur (Benton County) withdrew the most water from the Gunter Member in 2010 at 5.08 Mgal/d (Terrance W. Holland, U.S. Geological Survey, written commun., 2013). Other large users include the public supplies of Holiday Island (Carroll County), Corning (Clay County), and Mammoth Spring (Fulton County).

The Rubidoux and Gunter units were suggested as potential future groundwater supply sources in Randolph and Lawrence Counties by Lamonds and others (1969). In Randolph County, one community tapped the Roubidoux in 1980 and the deeper Gunter in 2010; another community tapped the Roubidoux in 1978 (Lyle Godfrey, Arkansas Health Department, written commun., 2012). In Lawrence County, the Gunter was tapped in the late 1990s for public supply.

While groundwater use from the lower Ozark aquifer is substantial, and some wells have been drilled into the lower Ozark aquifer in recent years, use of the aquifer has decreased. Surface-water use has increased dramatically, and the vast majority of the population in northern Arkansas is served by surface water, especially in Benton and Washington Counties (see "Overview of Aquifers of Arkansas" section). Beaver Lake was developed in the 1960s by the U.S. Army Corps of Engineers primarily to provide water to the major cities in northwestern Arkansas: Fayetteville and Springdale (Washington County) and Rogers and Bentonville (Benton County) (Amy Wilson, Beaver Water District, written commun., 2012). Many other water districts have formed throughout northern Arkansas—Carroll-Boone Water District, Benton-Washington Regional Public Water Authority, and Madison County Regional Water District—to deliver surface water to smaller communities from Beaver Lake (Davis and Shephard, 2010). Bull Shoals, originally developed for hydroelectric generation and flood control, is currently (2013) providing water to many users in Marion County (U.S. Army Corps of Engineers, 2010). Thus, numerous wells in the lower Ozark aquifer have been abandoned.

Many communities have sought out surface water as a public-supply source because of quantity and quality issues with groundwater. Some municipalities have struggled to provide adequate supplies for growing demands with limited groundwater sources. Other areas tapping the lower Ozark aquifer have naturally occurring radon, radium, fluoride, and other undesirable constituents that have impaired use and increased treatment costs (Adamski, 1996). For some of these communities, like the Nail-Swain Water Association (Newton County), ADH issued Administrative Orders restricting groundwater use (U.S. Army Corps of Engineers, 2010). Development of an alternative water source for these areas is a top priority, and a project is underway to deliver water from Bull Shoals to multiple rural communities (U.S. Army Corps of Engineers, 2010; Ozark Mountain Regional Public Water Authority, 2013).

Irrigation use from the Ozark aquifers was estimated at approximately 20 Mgal/d in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). About 70 percent of irrigation water use is from the upper Ozark aquifer and occurs in counties in the aquifer's far eastern extent, where row crops like cotton, rice, and soybeans are commonly grown. Depth to water in most of these wells is approximately 100 ft. Agricultural use throughout the rest of the Ozark Plateaus is likely to be smaller in scale, mainly for growing fruit (Lamonds, 1972) that does not have the large water requirements of row crops. In addition, approximately 6 Mgal/d were withdrawn for two fish hatcheries in 2010 from the Gunter Member.

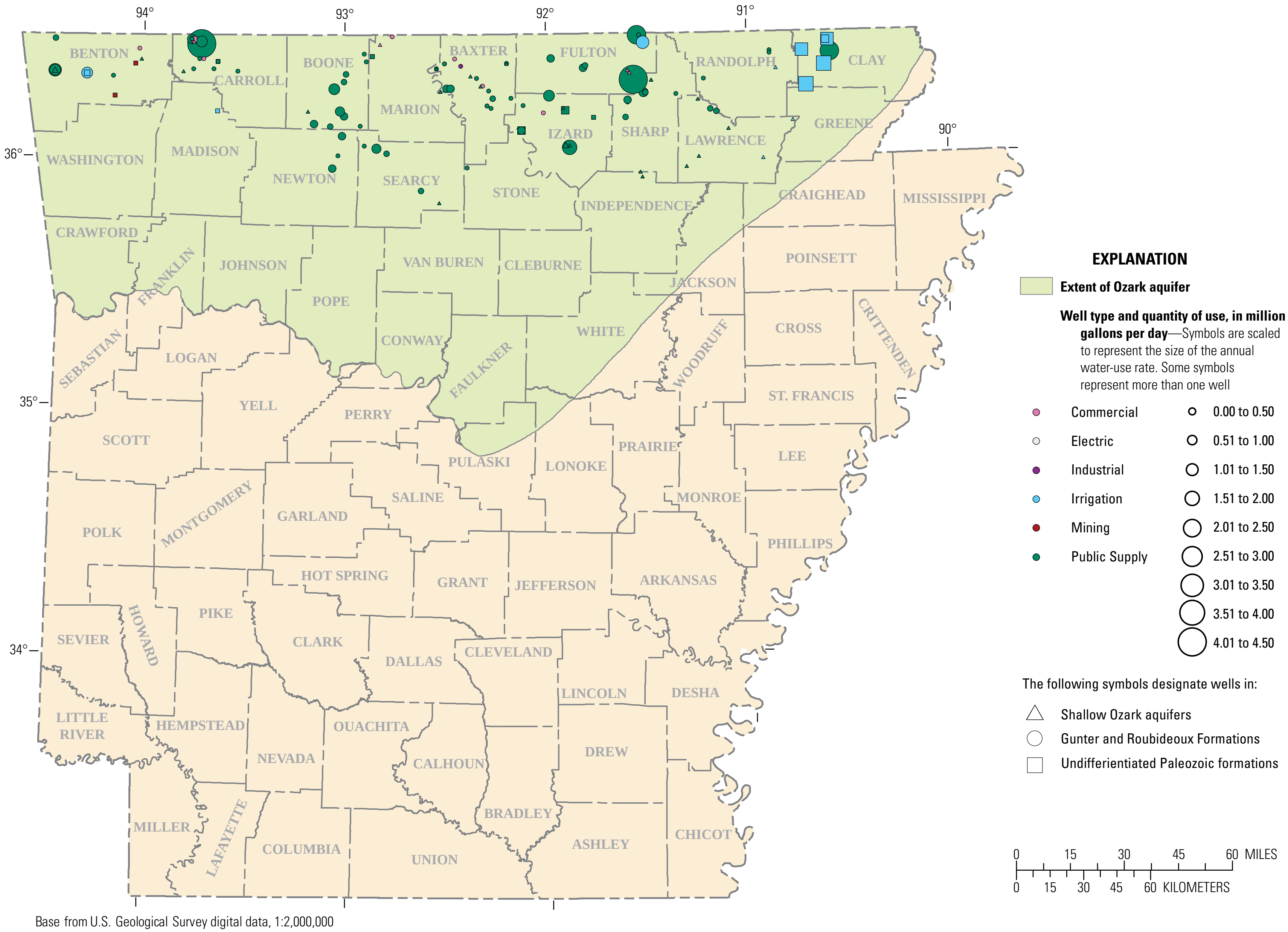



**Figure 116.** Wells with reported groundwater use from the Ozark aquifer in northern Arkansas, 2010.

Domestic and livestock use are known to be underestimated for the Ozark aquifer. Domestic wells have been widely used since the 1880s (Purdue and Miser, 1916). Use has been reported in the shallower upper Ozark aquifer (Albin and others, 1967a; Lamonds and Stephens, 1969; Lamonds 1972; Kilpatrick and Ludwig, 1990b) but has often been poorly estimated—records have been spotty and estimation methods were inaccurate. Also, many wells fail to meet the 50,000 gal/d reporting requirement or are coregistered as a domestic well and therefore exempt from the water-use reporting program. For example, a well producing from the Ozark aquifer for livestock purposes, such as a chicken house or other animal operation, and also has a waterline to an adjacent house or garden for domestic purposes, would not have to report use as a coregistered well.

Commercial groundwater use of the Ozark aquifer was estimated at 0.1 Mgal/d in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2013). Most use in the Ozarks is seasonal for recreational activities including resorts, parks, campgrounds, and golf courses. Commercial use is also suspected to be underreported because many wells may not meet the 50,000 gal/d reporting requirement. No industrial use was recorded for the Ozark aquifer in 2010, but previous industrial users have included concrete companies. In 1985, 1.53 Mgal/d was reported for commercial use (Kilpatrick and Ludwig, 1990a).

## Water Quality

The Ozark aquifer, together with the Springfield Plateau aquifer, is one of the major aquifers of the Ozark Plateaus. Similar to the Springfield Plateau aquifer, the Ozark is a karst aquifer within carbonate rocks described in previous sections. Additionally, agriculture in the form of beef and dairy cattle, swine, and poultry operations is the predominant land use in this region of steep topography and thin soils (Adamski, 1997). There is a high degree of connectivity between the surface and groundwater, expressed in the occurrence of sinkholes, solution fractures, caves, losing streams, large springs, and other karst features. This leads to nutrients, bacteria, and other surface-derived contaminants that are associated with the agricultural activities as posing the greatest threat to groundwater quality in the Ozark aquifer, particularly that of the upper Ozark aquifer (Peterson and others, 2000). The karst geology is well developed with the upland areas of the Salem Plateau estimated to have 1 to 10 sinkholes per 100 $mi^2$ (Harvey, 1980). Spring discharges that exceed 100 $ft^3/s$ are common (Imes and Smith, 1990). The surface extents of the Ozark aquifer and the Springfield Plateau aquifer in northern Arkansas are mapped at the highest groundwater vulnerability index in the State (Arkansas Soil and Water Conservation Commission, 1991).

There are 16 formations that constitute the upper Ozark aquifer (table 5), which dominantly are represented by dolostones composed of or containing a high percentage of dolomite. Water-quality data in USGS NWIS commonly are reported by the well-completion depth and formation penetrated by the driller. Water-quality data in USGS NWIS from the upper part of the Ozark aquifer are reported from 7 of the 16 upper Ozark formations: Fernvale Limestone, Everton Formation, Joachim Dolomite, St. Peter Sandstone, Cotter Dolomite, Jefferson City Dolomite, and Powell Dolomite. Well depths in the upper Ozark aquifer ranged from 19 to 1,210 ft, although 71 percent of the wells were less than 500 ft deep. By comparison, well depths for the lower Ozark aquifer in Arkansas ranged from 506 to 3,534 ft, with 45 of 62 wells (73 percent) being more than 1,000 ft. The following sections discuss water quality of the Ozark aquifer. Historical publications often do not separate the shallow upper Ozark aquifer from the lower Ozark aquifer, especially with respect to regional studies. The following discussion will focus on the upper and lower Ozark aquifers separately where the data are available and meaningful differences exist in geochemistry and water quality.

### General Geochemistry and Water Type

Groundwater from the carbonate rocks constituting the Ozark aquifer is of a hard to very hard, calcium-magnesium-bicarbonate type (Albin and others, 1967a; Lamonds and others, 1969; Lamonds, 1972; MacDonald and others, 1977; Harvey, 1980; Kilpatrick and Ludwig, 1990b; Leidy and Morris, 1990b; Imes and Emmett, 1994; Adamski and others, 1995; Prior and others, 1999; Kresse and Fazio, 2004). Pure dolomite minerals contain an equal number of calcium and magnesium ions. Dissolution of the dominant dolomite mineralogy in the Ozark aquifer produces a groundwater reflective of this rock chemistry and has approximately equal equivalent concentrations of calcium and magnesium. Some spatial variation is imparted by variable mineralogy and lithology and from formation to formation. Kresse and Fazio (2004) compared calcium/magnesium ratios in groundwater from individual formations of the upper Ozark aquifer and noted slightly higher median, mean, and maximum calcium/magnesium ratios in the combined St. Peter Sandstone and Everton Formation exposures compared to the Powell, Cotter, and Jefferson City Dolomites. Calcite cement in the lower part of the St. Peter Sandstone was noted as influencing the higher ratio. Calcium-magnesium ratios exceeding 1.0 for the upper Ozark aquifer, where exposed, probably are influenced by occurrence of limestone or calcite cement in various formations of the Ozark aquifer.

Data compiled for this report generally support the dominant calcium-magnesium water type for groundwater from the Ozark aquifer and reflect the dominant dolomitic geochemistry of rocks constituting the Ozark aquifer. The upper Ozark aquifer had calcium/magnesium equivalent ratios ranging from 0.5 to 32.5 with a median of 1.2. The lower Ozark aquifer had ratios ranging from 0.4 to 26.2 with a median of 1.1. All but the maximum ratio of 26.2 in the lower Ozark aquifer were less than 2.0 and demonstrate the narrow range of low ratios nearing the 1:1 ratio of pure dolomite. Conversely, 24 of 123 of the calcium/magnesium ratios for the upper Ozark aquifer exceeded 2.0. These 24 sites reflected ratios typical of that from the Springfield Plateau aquifer. Comparison of calcium/magnesium ratios from the upper Ozark aquifer to surface geology revealed that the higher ratios occurred in samples from wells located in outcrop areas of the Springfield Plateau aquifer (Boone Formation; fig. 117). By comparison, in areas where the Ozark aquifer is exposed (Fernvale Limestone through Jefferson County Dolomite; fig. 117), calcium/magnesium ratios are near 1.0 (fig. 117). Groundwater in the upper Ozark aquifer exhibiting higher calcium/magnesium ratios similar to those of the Springfield Plateau aquifer may be explained by (1) incorrect aquifer designation indicating that these wells are actually completed in the Springfield Plateau aquifer, (2) open-hole completions where wells penetrate rocks of the Ozark and Springfield Plateau aquifers, or (3) leakage from the Springfield Plateau aquifer down into the upper Ozark aquifer where the Chattanooga Shale confining layer is incompetent or absent. Harvey (1980) noted higher calcium/magnesium ratios for the Ozark aquifer on the Springfield Plateau and attributed slow leakage of water from overlying limestone formations to the increased ratios. Kresse (1991) compared calcium-magnesium ratios in groundwater from the Springfield Plateau and Ozark aquifers in Searcy County. Some wells that were cased and receiving groundwater only from the upper Ozark aquifer had ratios similar to that of the Springfield Plateau aquifer. Because the Chattanooga Shale was absent in Searcy County, Kresse (1991) attributed leakage from the overlying Springfield Plateau aquifer as the source of the higher ratios.

Values of pH ranged from 4.8 to 8.7 with a median of 7.3 in the upper Ozark aquifer (table 44). Values ranged from 6.7 to 8.4 with a median of 7.7 in the lower Ozark aquifer (table 45). For both aquifers, pH showed no trend with increasing well depth or dissolved solids. For the upper aquifer, $R^2$ values for relations of pH to well depth and dissolved-solids concentrations were 0.0003 and 0.0135 (fig. 118*A*, *B*), respectively, and were 0.0031 and 0.0687, respectively, in the lower aquifer (fig. 118*C*, *D*). Thus, median pH values and relations of pH to well depth and dissolved solids are similar in the less geochemically evolved groundwater for the upper Ozark aquifer compared to that in the more geochemically evolved groundwater for the lower Ozark aquifer. This suggests that infiltrating, low-pH rainwater (average of 4.7 standard units; Kresse and Fazio, 2002) is rapidly buffered by carbonate minerals in the overlying regolith and unsaturated bedrock prior to reaching the aquifer. This interpretation is supported by additional work conducted by Pollock and others (2011) who observed well-buffered regolith and cave drip water in the unsaturated zone above a cave in the upper Ozark aquifer.

No strong spatial trend was noted for the distribution of dissolved solids in the lower Ozark aquifer. However, a general trend of increasing dissolved solids was observed moving from the south toward the northeast, especially in the eastern extent. The greatest frequency of dissolved solids greater than 300 mg/L occurred in the exposed sections of the Powell, Cotter, and Jefferson City Dolomites as compared to the St. Peter and Everton Formations (not shown in fig. 117). Bicarbonate exhibited strong positive correlations with dissolved-solids concentrations for the upper (fig. 118*E*) and the lower (fig. 118*F*) Ozark aquifers, with $R^2$ values of 0.9235 and 0.7387, respectively. The spatial distribution of bicarbonate was similar to that of dissolved solids with higher concentrations observed to the northeast. Kresse and Fazio (2004) noted lower mean, median, and maximum bicarbonate and dissolved-solids concentrations in groundwater from the St. Peter and Everton Formations compared to other formations of the upper Ozark aquifer. There is insufficient evidence to discern if these differences are attributable to the solubility of carbonate minerals between the formations or if the higher concentrations are an artifact of longer residence time and greater rock/water interaction in the Powell, Cotter, and Jefferson City Dolomites along longer flow paths.

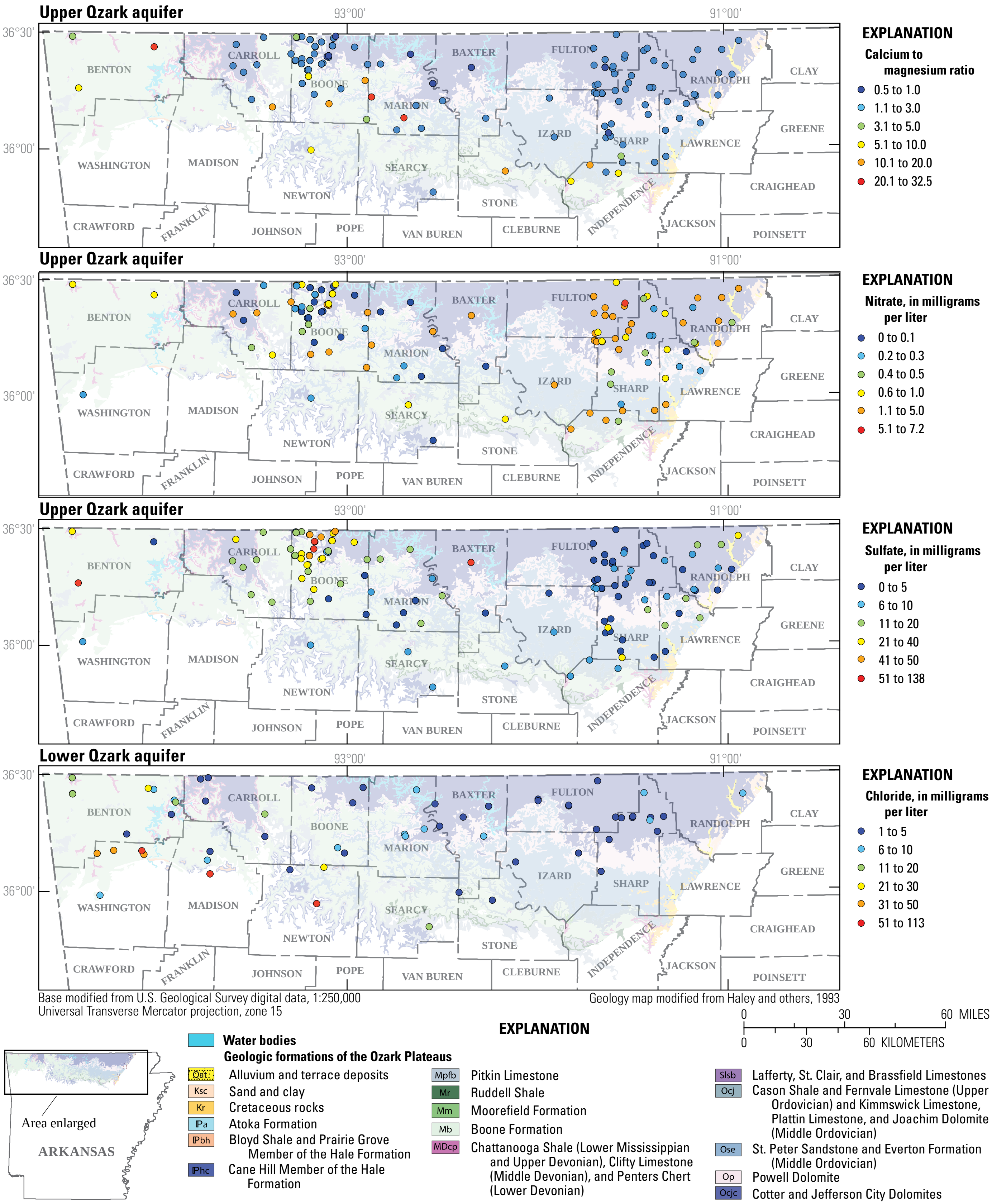



**Figure 117.** Spatial distribution of selected chemical constituents in groundwater from the Ozark aquifer in northern Arkansas.

**Table 44.** Descriptive statistics for selected chemical constituents in groundwater from the upper Ozark aquifer in northern Arkansas.

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

| Constituent | Minimum | Median | Maximum | Standard deviation | Number of wells |
|---|---|---|---|---|---|
| Calcium (mg/L) | 4.4 | 63 | 140 | 21.13 | 132 |
| Magnesium (mg/L) | 0.8 | 28 | 71 | 14.49 | 132 |
| Sodium (mg/L) | 0.7 | 2.4 | 696 | 61.95 | 129 |
| Potassium (mg/L) | 0.1 | 1.1 | 22 | 2.76 | 127 |
| Bicarbonate (mg/L) | 2.0 | 313 | 1,720 | 169.02 | 104 |
| Chloride (mg/L) | 0.3 | 4.1 | 105 | 12.27 | 133 |
| Sulfate (mg/L) | 0.4 | 8.8 | 138 | 20.40 | 133 |
| Silica (mg/L) | 0.13 | 9.9 | 20 | 2.56 | 117 |
| Nitrate (mg/L as nitrogen) | 0.01 | 0.62 | 7.2 | 1.26 | 124 |
| Dissolved solids (mg/L) | 52 | 285 | 1,735 | 154.64 | 132 |
| Iron (µg/L) | 0.05 | 5.2 | 1,600 | 252.26 | 112 |
| Manganese (µg/L) | 0.13 | 0.13 | 40 | 6.86 | 123 |
| Arsenic (µg/L) | 0.03 | 0.03 | 6.96 | 1.12 | 73 |
| Hardness (mg/L as calcium carbonate) | 20 | 243 | 520 | 101.88 | 84 |
| Specific conductance (µS/cm) | 89 | 518 | 2,840 | 250.98 | 130 |
| pH (standard units) | 4.8 | 7.3 | 8.7 | 0.45 | 133 |

**Table 45.** Descriptive statistics for selected chemical constituents in groundwater from the lower Ozark aquifer in northern Arkansas.

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

| Constituent or characteristic | Minimum | Median | Maximum | Standard deviation | Number of wells |
|---|---|---|---|---|---|
| Calcium (mg/L) | 11 | 45 | 91 | 16.95 | 55 |
| Magnesium (mg/L) | 0.07 | 23 | 83 | 13.95 | 55 |
| Sodium (mg/L) | 0.73 | 2.3 | 100 | 29.66 | 40 |
| Potassium (mg/L) | 0.4 | 1.7 | 6.1 | 1.45 | 27 |
| Bicarbonate (mg/L) | 22 | 270 | 548 | 102.16 | 31 |
| Chloride (mg/L) | 1.0 | 4.0 | 113 | 19.08 | 63 |
| Sulfate (mg/L) | 0.4 | 12 | 49 | 10.42 | 59 |
| Silica (mg/L) | 1.7 | 9.4 | 14.4 | 2.54 | 23 |
| Nitrate (mg/L as nitrogen) | 0.01 | 0.18 | 29 | 5.79 | 48 |
| Dissolved solids (mg/L) | 93 | 276 | 431 | 75.85 | 59 |
| Iron (µg/L) | 0.05 | 30 | 3,600 | 667.73 | 29 |
| Manganese (µg/L) | 0.13 | 10 | 7,000 | 1,181.78 | 35 |
| Arsenic (µg/L) | 0.03 | 0.03 | 4.5 | 1.43 | 12 |
| Hardness (mg/L as calcium carbonate) | 50.9 | 200 | 400 | 80.71 | 51 |
| Specific conductance (µS/cm) | 10 | 459 | 1,640 | 231.36 | 39 |
| pH (standard units) | 6.7 | 7.7 | 8.4 | 0.44 | 43 |

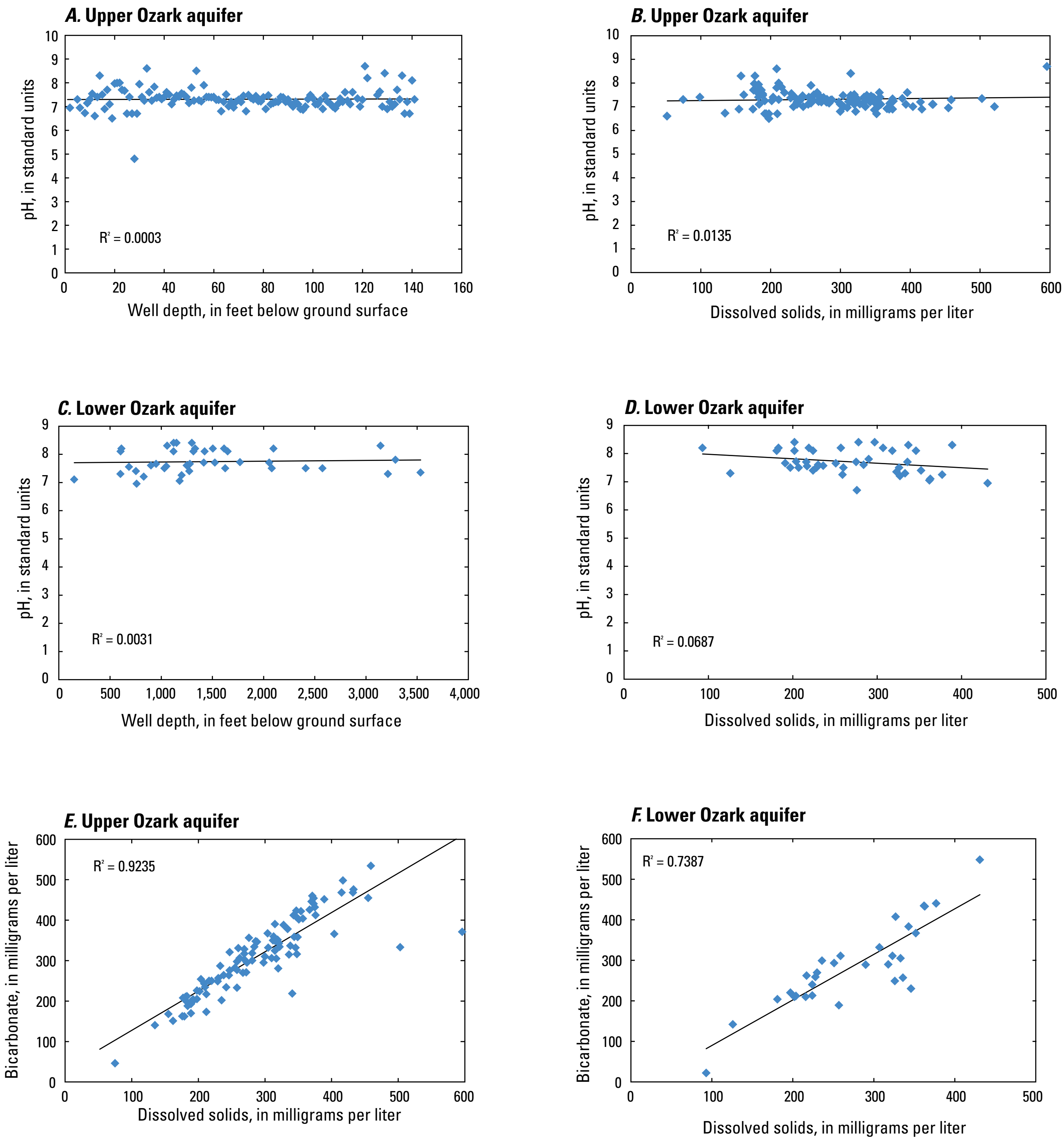



**Figure 118.** Relation of pH to *A*, well depth and *B*, dissolved solids in the upper Ozark aquifer and to *C*, well depth and *D*, dissolved solids in the lower Ozark aquifer; and relation of bicarbonate to dissolved solids in *E*, the upper Ozark aquifer and *F*, the lower Ozark aquifer.

## Nitrate

Nitrate concentrations in 124 samples from the upper Ozark aquifer ranged from 0.01 to 7.2 mg/L with a median of 0.62 mg/L (table 44). For purposes of this section, "elevated" concentrations of nitrate (expressed as nitrogen) refer to concentrations exceeding 0.4 mg/L, which is considered a background concentration for nitrate in relatively undisturbed areas of the Ozarks (see "Springfield Plateau Aquifer" section). For the lower Ozark aquifer, nitrate concentrations in 48 samples ranged from 0.01 to 29 mg/L with a median of 0.18 mg/L (table 45). Two wells in the lower Ozark aquifer had concentrations of 28 and 29 mg/L, which was far above the maximum concentration in the upper Ozark aquifer. However, the median of 0.18 mg/L reflects the overall lower nitrate concentrations in the lower Ozark aquifer compared to that of the upper Ozark aquifer (median of 0.62 mg/L).

The two very high nitrate concentrations in a deep, confined aquifer pose questions on the transport of nitrate to such depths. Prior and others (1999) noted that problems in the ability to retrieve samples representing groundwater only from the Roubidoux or Gunter geologic units (lower Ozark aquifer) were related directly to depth of the casing. Casing for domestic wells in the Ozark Plateaus typically is advanced only through 1–3 ft of bedrock (effectively casing off unconsolidated regolith material) with the remainder of the well being an open-hole completion. For deeper public-supply wells, the casing is advanced through parts of the upper, shallow formations to a depth determined by drillers and water suppliers, and the remainder is left as an open-hole completion. Although the ADH recommends casing entirely through overlying, shallow exposed formations, no legally binding regulation has been enacted that requires such casing. Because overlying formations are not fully cased, or perhaps the casing has become compromised during completion or deteriorated over time, there is increased opportunity for influx of surface-derived contaminants into the deeper confined formations of the lower aquifer. No relation was found between well depth and nitrate concentrations for the lower or upper Ozark aquifers. Several nitrate concentrations that exceeded 1.0 mg/L occurred throughout a range of 500–3,500 ft in the lower Ozark aquifer. One well with a depth of 3,420 ft had a concentration of 3.4 mg/L, although most concentrations were less than 1.0 mg/L. These elevated nitrate concentrations may be ascribed to the increased vulnerability of karst aquifers to surface-derived contaminants and to the lack of adequate well casing regardless of well depth.

Numerous studies have discussed the occurrence of elevated nitrate in groundwater from karst aquifers of the Ozark Plateaus, and several have noted lower overall concentrations in the Ozark aquifer compared to the Springfield Plateau aquifer (Leidy and Morris, 1990b; Smith and Steele, 1990; Steele and McCalister, 1990, Adamski, 1997; Huetter and others, 1997; Kresse and others, 2011). These studies were conducted in northwestern Arkansas, which is dominated by exposures of the Boone Formation that constitutes the Springfield Plateau aquifer. A common hypothesis within these studies was that the lower concentrations in the Ozark aquifer were because of the protection afforded by overlying formations of the Springfield Plateau aquifer and the Ozark aquifer confining unit (Chattanooga Shale). Median nitrate concentrations from the upper (table 44) and lower (table 45) Ozark aquifers were 0.62 and 0.18 mg/L, respectively, compared to 1.8 mg/L from the Springfield Plateau (table 43).

To investigate confinement as the dominant control on lower nitrate concentrations, Kresse and others (2011) compared nitrate data from two separate studies. One study (Adamski, 1997) was in northwestern Arkansas where the Ozark aquifer is confined by overlying Mississippian-age formations. The other study (Kresse and Fazio, 2004) was conducted in northeastern Arkansas where the aquifer is unconfined, exposed at the surface, and more vulnerable to contamination. Kresse and Fazio (2004) sampled groundwater from the upper Ozark aquifer in northeastern Arkansas and reported median nitrate concentrations in springs of 0.47 mg/L and median concentrations in wells of 0.63 mg/L. These data compared closely to median concentrations from springs (0.40 mg/L) and wells (0.60 mg/L) in the confined upper Ozark aquifer sampled in northwestern Arkansas (Adamski, 1997). Because median nitrate concentrations for the Ozark are similar in areas whether confined or exposed, Kresse and others (2011) hypothesized that other factors must influence the lower vulnerability of the Ozark aquifer to surface-derived contaminants.

A positive correlation between nitrate concentrations and agricultural land use in northwestern Arkansas for groundwater collected dominantly from the Springfield Plateau aquifer (see "Springfield Plateau Aquifer" section) was shown by Adamski (1997) and Kresse and others (2011). One plausible explanation for the lower nitrate concentrations in the Ozark aquifer is lower agricultural land use in the northeastern part of the Ozark Plateaus, where the Ozark aquifer is exposed at the surface. Kresse and others (2011) determined percent agricultural land use in the upper Ozark aquifer in northeastern Arkansas using data from Kresse and Fazio (2004) and plotted nitrate concentrations and 10 percent increments of increasing agricultural land use to investigate the effects of increasing agricultural land use on nitrate concentrations (fig. 119*A*). The results were compared to that of Kresse and others (2011) for well and spring nitrate concentrations in northwestern Arkansas (fig. 119*B*). Mean nitrate concentrations for the upper Ozark aquifer were much lower for all categories of percent agricultural land use compared to data taken from the Springfield Plateau aquifer in northwestern Arkansas. The overall mean nitrate concentration of 0.73 mg/L for data from the upper Ozark aquifer in northeastern Arkansas was exceeded for most agricultural land-use categories greater than 30–40 percent (fig. 119*A*), and all mean nitrate concentrations for agricultural land use below 30 percent were less than about 0.3 mg/L. Conversely, the mean nitrate concentrations for agricultural land use below

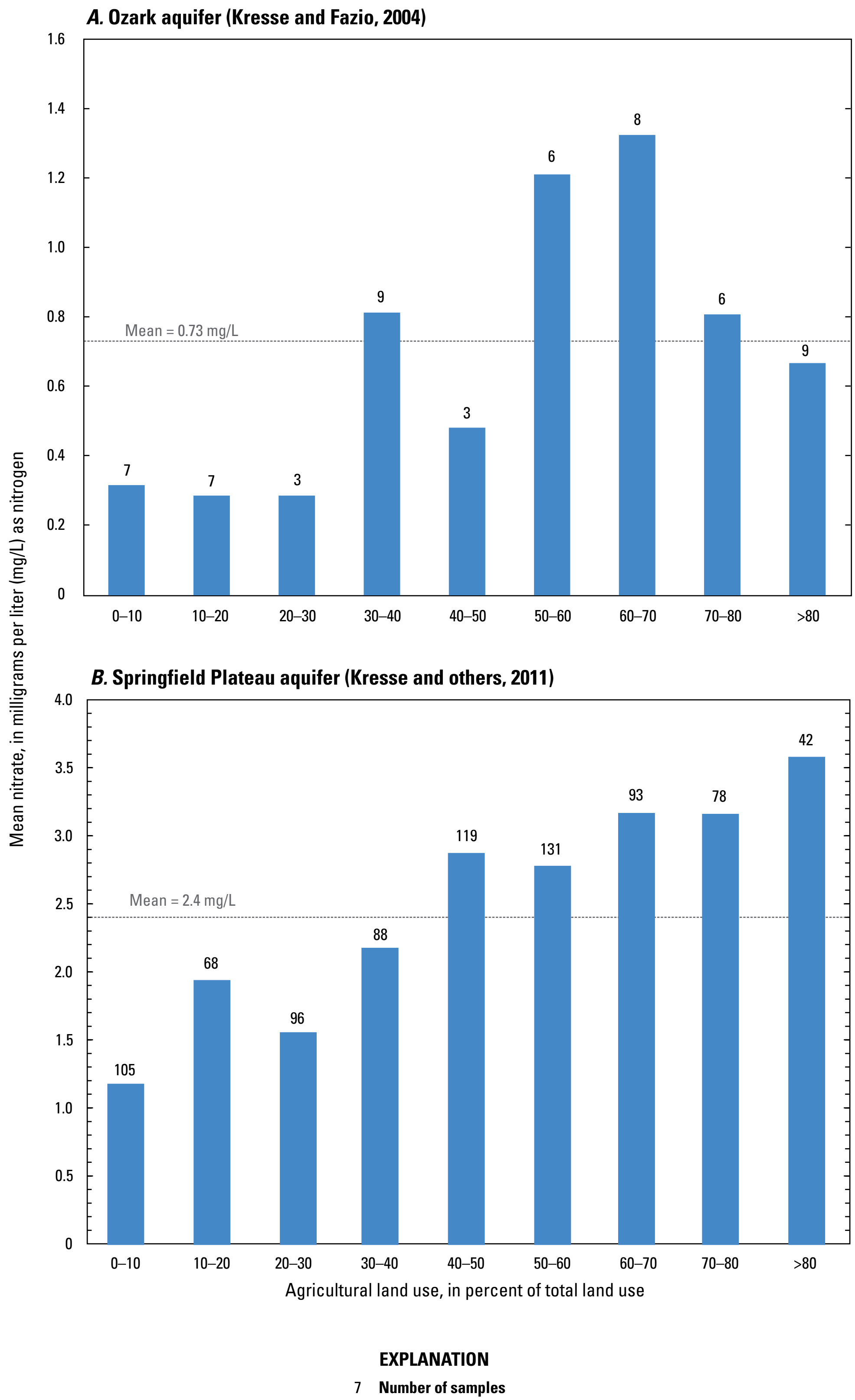



**Figure 119.** Nitrate concentrations and agricultural land use for groundwater from *A*, the Ozark aquifer in northeastern Arkansas and *B*, from the Springfield Plateau aquifer in northwestern Arkansas.

30 percent for the Springfield Plateau aquifer in northwestern Arkansas were all greater than 1.0 mg/L (upward to 1.9 mg/L) (fig. 119*B*). The highest mean nitrate concentrations for the upper Ozark aquifer (fig. 119*A*) occurred at percent agricultural land use between 50–60 percent (mean nitrate concentration of 1.2) and 60 to 70 percent (mean nitrate concentration of 1.3 mg/L). By comparison, the mean nitrate concentrations at these categories, 50–60 percent and 60–70 percent, for the Springfield Plateau aquifer data were 2.8 and 3.2 mg/L, respectively (fig. 119*B*). Therefore, nitrate concentrations are much lower in the upper Ozark aquifer than in the Springfield Plateau aquifer for similar increases in agricultural land use. This finding indicates that the upper Ozark aquifer, even where exposed at the surface, is less vulnerable to contamination than the Springfield Plateau aquifer, regardless of the percent agricultural land use. The soils overlying the upper Ozark aquifer, or the geologic units of the shallow part of the aquifer itself, may have physical characteristics (lower permeability soils, thicker regolith, less fracturing and dissolution of rocks, fewer bedding planes, and other factors) favoring a lower vulnerability to influx of surface-derived contaminants than the soils overlying the Springfield Plateau aquifer.

A general trend of a higher density of elevated nitrate concentrations was observed in the eastern part of the upper Ozark aquifer, where it is exposed, compared to areas where the upper Ozark aquifer is overlain by the Chattanooga Shale and the Springfield Plateau aquifer (fig. 117). Therefore, some protection is afforded where it is confined by overlying formations of the Springfield Plateau aquifer and the Ozark confining unit. An important protection and management conclusion based on these data is that sufficient casing for isolating groundwater from the more vulnerable Springfield Plateau aquifer should prevent influx of surface-derived contaminants into the upper Ozark aquifer in this area of the Ozark Plateaus. No spatial trend was noted for nitrate concentrations in the lower Ozark aquifer. The fact that elevated nitrate concentrations occur in the confined, lower Ozark aquifer at well depths exceeding 1,000 ft suggests inadequate casing in these wells. The casing of all overlying formations when drilling wells for public supply could prevent contamination of the lower Ozark aquifer.

### Pesticides

The occurrence of pesticides in groundwater from the Ozark Plateaus in Arkansas, Kansas, Missouri, and Oklahoma was investigated by Adamski (1997). Pesticides were detected in 14 of 63 (22 percent) of the samples from the Ozark aquifer (the upper and lower Ozark aquifer were not differentiated). Many of the sampling sites were located in northwestern Arkansas. Pesticides were detected at a lower rate in the Ozark aquifer compared to the Springfield Plateau aquifer, demonstrating the reduced vulnerability of the Ozark aquifer to surface-derived contaminants. The most commonly detected pesticides were tebuthiuron; atrazine; prometon; desethylatrazine, a metabolite of atrazine; and simazine. These compounds are herbicides that are commonly used on pastures and noncrop areas.

### Radium

Radium in groundwater was analyzed as part of the Ozarks National Water Quality Assessment study (Adamski and others, 1995). The combined radium-226 and radium-228 activity ranged from 5.1 to 13.9 picocuries per liter (pCi/L) in 18 water samples from public-supply wells in Missouri in 1983 and ranged from 4.9 to 12.8 pCi/L in samples from several public-supply wells in northern Arkansas in 1987–89. Depths of these wells ranged from 250 to more than 1,700 ft below land surface. Only one well in Arkansas had levels above the Federal MCL of 5 pCi/L.

Sampling of public-water systems by the ADH revealed a systemic radium problem in the lower Ozark aquifer. Three systems in Newton County, three in Searcy County, three in Boone County, and one each in Marion and Carroll Counties have had at least one well with historical violations for the combined radium MCL of 5 pCi/L. Contamination above the MCL of 5 pCi/L for these public-supply wells presently is attributed to an association with early Paleozoic shales within the lower Ozark aquifer. The contamination has resulted in abandonment of wells and selection of alternate sources of drinking water for most of these systems. The Ozark Mountain Regional Public Water Association is constructing a surface intake on Bull Shoals Lake in eastern Newton County to replace many of the public-water suppliers using groundwater from the Ozark aquifer (Darcia Routh, Arkansas Department of Health, written commun., 2013).

### Iron

Iron concentrations generally are low in groundwater from the Ozark aquifer throughout the Ozark Plateaus. Iron concentrations ranged from 0.05 to 1,600 µg/L with a median of 5.2 µg/L (fig. 120; table 44) in the upper Ozark aquifer and from 0.05 to 3,600 µg/L with a median of 30 µg/L in the lower Ozark aquifer (fig. 121; table 45). Only 4 of 112 samples from the upper Ozark aquifer exceeded the Federal secondary drinking-water regulation of 300 µg/L, and 4 of 29 samples from the lower Ozark aquifer exceeded this limit.

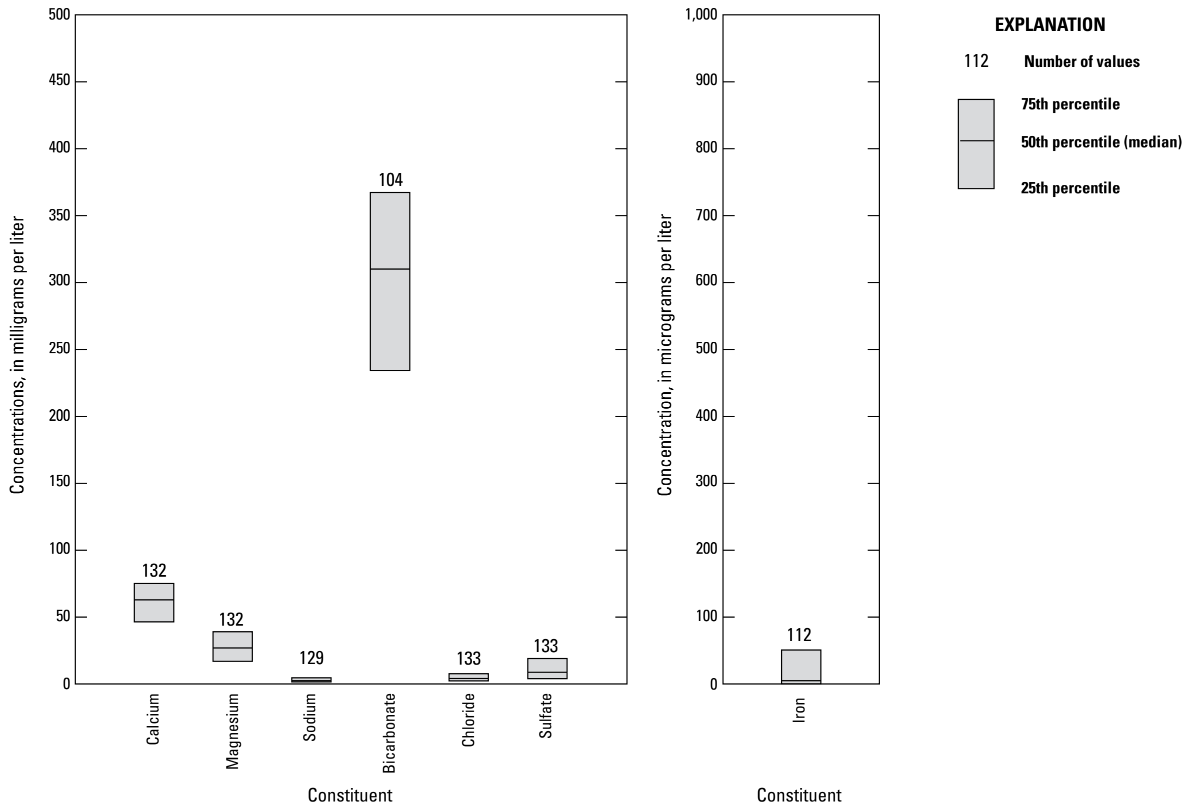



**Figure 120.** Interquartile range of selected chemical constituents in groundwater from the upper Ozark aquifer in northern Arkansas.

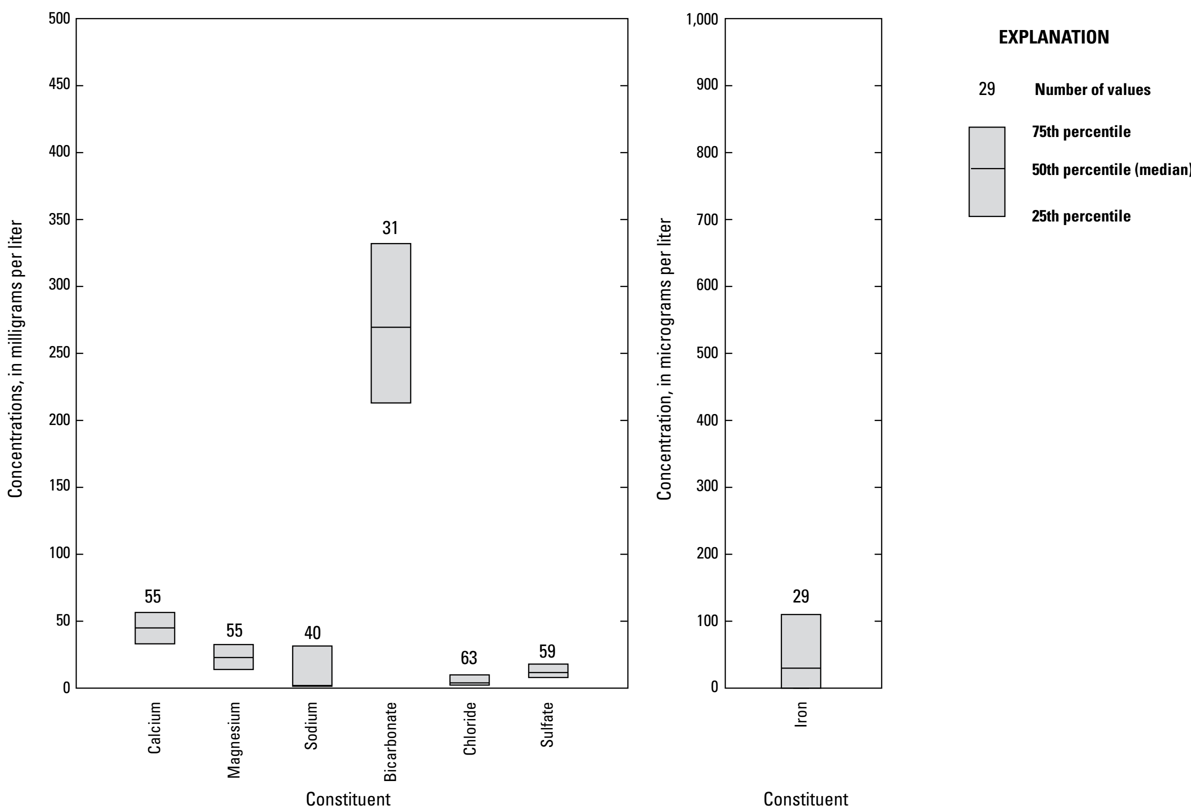



**Figure 121.** Interquartile range of selected chemical constituents in groundwater from the lower Ozark aquifer in northern Arkansas.

### Sulfate

Sulfate concentrations generally are low in the Ozark aquifer and were below the Federal secondary drinking-water regulation of 250 mg/L in all samples from the upper and lower Ozark aquifer. Whereas the maximum sulfate concentration in 59 samples from the lower Ozark aquifer was 49 mg/L, the upper Ozark aquifer had a maximum of 138 mg/L, and 6 of 133 samples were greater than 50 mg/L (table 44). Sulfate concentrations generally were below 10 mg/L in areas where formations composing the upper Ozark aquifer (Fernvale Limestone through Jefferson City Dolomite; fig. 117) are exposed and greater than 20 mg/L (upward to 138 mg/L) where the upper Ozark aquifer is overlain by younger formations (fig. 117). Shale formations typically have groundwater with elevated sulfate concentrations relative to overlying and underlying aquifers (Kresse and Hays, 2009). Leakage through the overlying Chattanooga Shale that serves as the Ozark aquifer confining unit may be contributing sulfate to the upper Ozark aquifer in this area.

### Chloride

Chloride concentrations generally are low throughout the Ozark aquifer. Concentrations ranged from 0.3 to 105 mg/L with a median of 4.1 mg/L in the upper Ozark aquifer (fig. 120; table 44) and ranged from 1.0 to 113 mg/L with a median of 4.0 mg/L in the lower Ozark aquifer (fig. 121; table 45). Various reports have commented on potential higher salinity groundwater in the lower Ozark aquifer, where it dips steeply south of the Springfield-Salem Plateaus toward the Arkansas River. Lamonds (1972) stated that groundwater in the southern extent of the lower Ozark aquifer was assumed to be highly mineralized but did not provide spatial information on salinity gradients or saltwater-freshwater transition zones. MacDonald and others (1977) stated that chloride increases with the regional gradient toward the Arkoma Basin and calculated salinity concentrations ranging from 2,000 to 3,000 mg/L using formation density and induction-electric logs. Imes and Emmett (1994) stated that the lower Ozark aquifer was saline only in the region between the Boston Mountains and the Arkansas River. Prior and others (1999) stated that most wells advanced into the lower Ozark aquifer in the Boston Mountains were reported to contain brine and hypothesized that deeper wells in the extreme southern Ozark Plateaus probably would encounter increased water salinity. A general spatial trend was noted for increases in chloride to the south (fig. 117). Wells with the highest chloride concentrations, which are located near the southern boundary of the Springfield Plateau (Boone Formation), may represent an approximate southern boundary of usable fresh groundwater in the lower Ozark aquifer. No spatial trends were apparent for chloride concentrations in the upper Ozark aquifer.

In summary, the Ozark aquifer comprises carbonate formations that have weathered to form a karst terrain, which increases vulnerability to surface-derived contaminants. Because agriculture in the form of dairy and beef cattle, poultry, and swine operations is the dominant land use in the Ozark Plateaus, nutrients, bacteria, and pesticides pose the greatest threat to groundwater quality. Elevated nitrate concentrations were noted in groundwater from the upper and lower Ozark aquifer, in spite of the fact that the lower Ozark aquifer is confined and well depths generally are more than 1,000 ft. The thin soils and karst features associated with the Ozark aquifer coupled with insufficient casing appear to facilitate the transport of agricultural contaminants to the upper and lower Ozark aquifers. An important protection and management conclusion based on these data is that sufficient casing for isolating groundwater from the more vulnerable Springfield Plateau aquifer may prevent influx of surface-derived contaminants into the upper Ozark aquifer in this area of the Ozark Plateaus.

## Summary

Aquifers in Arkansas that currently serve or have served as important sources of water supply were described with respect to existing State and Federal groundwater protection and management programs, geology, hydrologic characteristics, water use, water levels, deductive analyses, and projections of aquifer conditions using groundwater models, and water quality for 16 aquifers. State and Federal protection and management programs were described according to regulatory oversight, management strategies, and ambient groundwater-monitoring programs that currently are in place for assessing and protecting groundwater resources throughout the State. Information was compiled and summarized from about 550 historical and recent publications that describe the hydrology and geochemistry of each of the aquifers. Additionally, more than 8,000 sites with groundwater-quality data were obtained from the U.S. Geological Survey National Water Information System and the Arkansas Department of Environmental Quality databases and entered into a spatial database to investigate distribution and trends in groundwater chemical constituents for each of the aquifers.

The 16 aquifers of the State are divided into two major physiographic regions: the Coastal Plain of eastern Arkansas and the Interior Highlands of western Arkansas. Aquifers in the Coastal Plain comprise Cenozoic-age strata consisting primarily of Cretaceous, Tertiary, and Quaternary sands, gravels, silts, and clays, with groundwater primarily produced from coarse-grained sands and gravels within these aquifers. Except for isolated areas of Quaternary alluvial deposits that serve as valuable sources of groundwater supply, aquifers of the Interior Highlands predominantly consist of fractured sandstone, shale, chert, and carbonate rocks. These rocks are well indurated and primary porosity is low. Secondary porosity is created by weathering, fracturing, and dissolution, resulting in relatively low storage and low well yields from aquifers of the Interior Plains.

Groundwater in the Coastal Plain of Arkansas represents one of the most valuable natural resources in the State, driving the economic engines of agriculture, while also supplying abundant water for commercial, industrial, and public-water supply. In terms of age from youngest to oldest, the aquifers of the Coastal Plain include: Quaternary alluvial aquifers including the Mississippi River Valley alluvial aquifer, the Jackson Group, and the Cockfield, Sparta, Cane River, Carrizo, Wilcox, Nacatoch, Ozan, Tokio, and Trinity aquifers.

The Mississippi River Valley alluvial aquifer is the most important aquifer in terms of total groundwater used in Arkansas. Arkansas ranks fourth nationally in groundwater use, and 94 percent of all groundwater used in Arkansas is from the Mississippi River Valley alluvial aquifer. Water-use rates continue to increase for this aquifer; rates in 2010 from the aquifer were approximately 7,400 million gallons per day (Mgal/d). Intensive use has led to (1) severe water-level declines resulting in deep cones of depression in the potentiometric surface, (2) rates of pumping that exceed recharge and are unsustainable in many areas, and (3) designation of critical groundwater area status for the aquifer in several areas of eastern Arkansas. These conditions have led to development of alternate water supplies, including construction of major surface-water diversions and the drilling of deeper wells into the Sparta aquifer to supplement irrigation water demands. Water quality generally is good throughout the aquifer. However, elevated iron concentrations in most areas preclude use of the aquifer for public-supply, commercial, and industrial purposes without treatment. Elevated salinity additionally occurs in different areas of eastern Arkansas, resulting from upwelling of high-salinity water from underlying formations or evapotranspiration in clay-rich backswamp areas.

The Jackson Group in south-central Arkansas is formally designated as a regional confining unit, though serving as a locally important aquifer for domestic and farm supply for six counties up through the 1990s. Low well yields and poor water quality, in addition to wider availability of public-supply sources, have resulted in no known use from the aquifer at the time of this report.

The Cockfield is a principal aquifer in southeastern Arkansas and had a reported use of approximately 19 Mgal/d in 2010. This aquifer serves dominantly as source of domestic supply but has been used for small public-supply systems. It has been increasingly used over the years as a public supply and more recently for irrigation. Groundwater in the outcrop area has low pH and dissolved solids, elevated nitrate and iron concentrations, and is a calcium-bicarbonate water type. Groundwater downdip from the outcrop area is affected by cation exchange and transitions to a sodium-bicarbonate water type. Compared to the outcrop area, groundwater downdip has higher pH and increasing dissolved solids and lower nitrate and iron with more strongly reducing conditions further along the flow path. An area of elevated salinity occurs in Chicot County with chloride concentrations as high as 1,800 mg/L that results from upwelling of saline water from great depths. Elevated sulfate concentrations in the central part of the aquifer were attributed to leakage of high-sulfate groundwater from the Jackson Group.

The Sparta aquifer is the second most important aquifer in Arkansas in terms of volume of use and provided approximately 196 Mgal/d of water in 2010. The aquifer was used in the past dominantly as a source of public and industrial supply, although irrigation use has increased over the years in response to critically declining water levels in the Mississippi River Valley alluvial aquifer. Pumping rates that exceed recharge rates have resulted in severe water-level declines and the formation of eight separate cones of depression in the potentiometric surface. Groundwater from the Sparta aquifer generally is of very high quality; however, isolated areas contain slightly elevated chloride concentrations resulting from upwelling of high-salinity water from underlying formations. Changes in geochemistry result from a transitioning of calcium-bicarbonate to a sodium-bicarbonate water type along the flow path. There also are concomitant increases in dissolved solids, decreases in iron, and decreases in nitrate with changes in redox conditions along the flow path.

The other aquifers of the Coastal Plain, the Cane River, Carrizo, Wilcox, Nacatoch, Ozan, Tokio, and Trinity aquifers, generally are used as important local sources of domestic, industrial, and public supply. In terms of reported water use, the Wilcox is recognized as the most important of these aquifers with a reported water use in 2010 of approximately 37 Mgal/d. All other aquifers have reported uses of less than 4 Mgal/d each. Use of groundwater from the Cane River, Carrizo, Tokio, and Trinity aquifers is solely in and near the respective outcrop areas in southeastern Arkansas. These aquifers all exhibit increasing salinity at various distances downdip from the outcrop areas that renders the groundwater unusable for most purposes. Water use for the Nacatoch and Wilcox aquifers also is restricted to areas in and near to the outcrop area with salinity increasing in the downdip direction in southwestern Arkansas. However, there is a higher percentage of sand in these aquifers in the northeastern part of the State that results in high quality water and in greater use of the aquifers in this region. Increasing sand percentages also occur for the Cane River and Carrizo Formations in the northeastern part of the State. However, these sands cannot be distinguished from and are included as part of the Sparta aquifer in this region. An increase in salinity downdip from the outcrop area for all of these aquifers in southwestern Arkansas was attributed to possible residual salinity from original marine depositional environments. In southwestern Arkansas, all of these aquifers had groundwater with low pH, high iron, and were of a calcium-bicarbonate water type in and near the outcrop area. The groundwater transitions to a sodium-bicarbonate water type with increasing dissolved solids, pH, and salinity, as well as lower iron and nitrate concentrations in the downdip direction of flow.

The Interior Highlands of northern and western Arkansas has less reported groundwater use than other areas of the State. This is the result of a combination of factors including (1) prevalent and increasing use of surface water, (2) less intensive agricultural uses, (3) lower population and industry densities, (4) less potential yield of the resource, and (5) lack of detailed reporting. The overall lower well yields from aquifers of the Interior Highlands result in domestic supply as the dominant use, with minor industrial, public, and commercial-supply use. When large volumes are required for public and industrial supply with a growing population, surface water supplies the majority of these water needs. However, surface water is not available for large expanses of the rugged and remote Interior Highlands, so locally available groundwater is a critical, though small-scale water resource. The aquifers of the Interior Highlands generally occur in shallow, fractured, well-indurated, structurally modified bedrock compared to the relatively flat-lying, unconsolidated sediments of the Coastal Plain.

Spatial trends in groundwater geochemistry of the Interior Highlands differ greatly from trends noted for aquifers of the Coastal Plain. In the Coastal Plain, the prevalence of long regional flow paths resulted in regionally predictable and mappable geochemical changes. In the Interior Highlands, groundwater moves along short, topographically controlled flow paths (from hilltops to valleys) within small watersheds. Consequently, dense data coverage from numerous wells would be required to effectively characterize these small groundwater basins and to define small-scale geochemical changes along any given flow path. Dominant changes in geochemistry for the Ouachita aquifer and the Western Interior Plains confining system were attributed to (1) rock type, (2) residence time along individual flow paths, and (3) resultant rock/water interaction and changes in redox zonation. Generally, groundwater evolves along flow paths from a calcium- to a sodium-bicarbonate water type, with increasing reducing conditions that result in denitrification, elevated iron and manganese, and ultimately to production of methane in the more geochemically evolved and strongest reducing conditions.

In the Ozark and Springfield Plateau aquifers, rapid influx of surface-derived contaminants such as nitrogen, coupled with little to no attenuation processes, is attributed to the karst landscape developed on Mississippian- and Ordovician-age carbonate rocks. Agriculture in the form of beef and dairy cattle, swine, and poultry operations is the predominant land use in this region of steep topography and thin soils. There is a high degree of connectivity between the surface water and groundwater, expressed in the occurrence of sinkholes, solution fractures, caves, losing streams, large springs, and other karst features. This kart-derived interconnection leads to nutrients, bacteria, and other surface-derived contaminants associated with agricultural activities posing the greatest threat to groundwater quality in the Ozark aquifer. A direct correlation was noted for increasing nitrate concentrations with increasing percentage of agricultural land use for the Springfield Plateau and Ozark aquifers. Additionally, areas with a higher density of karst features were shown to have higher nitrate concentrations than areas with less karst features. Even in areas of similar agricultural land use, the presence of karst features was shown to account for approximately 12 percent of the variation between nitrate concentrations (12 percent greater in areas with dense karst features) for increasing agricultural land use.

# References

Ackerman, D.J., 1987a, Generalized potentiometric surface of the aquifers in the Cockfield Formation, southeastern Arkansas, spring 1980: U.S. Geological Survey Water-Resources Investigations Report 87–4212, 1 sheet.

Ackerman, D.J., 1987b, Generalized potentiometric surface of the aquifers in the Sparta-Memphis aquifer, eastern Arkansas, spring 1980: U.S. Geological Survey Water-Resources Investigations Report 87–4282, 1 sheet.

Ackerman, D.J., 1989a, Hydrology of the Mississippi River Valley alluvial aquifer, South-Central United States—A preliminary assessment of the regional flow system: U.S. Geological Survey Water-Resources Investigations Report 88–4028, 74 p.

Ackerman, D.J., 1989b, Potentiometric surfaces of the Mississippi River Valley alluvial aquifer in eastern Arkansas, spring 1972 and 1980: U.S. Geological Survey Water-Resources Investigations Report 88–4075, 1 sheet.

Ackerman, D.J., 1990, Hydrology of the Mississippi River Valley alluvial aquifer, South-Central United States: U.S. Geological Survey Water-Resources Investigations Report 90–358, 228 p.

Ackerman, D.J., 1996, Hydrology of the Mississippi River Valley alluvial aquifer, South-Central United States: U.S. Geological Survey Professional Paper 1416–D, 56 p.

Adamski, J.C., 1987, The effect of agriculture on the quality of ground water in a karstified carbonate terrain, northwest Arkansas: Fayetteville, University of Arkansas, M.S. thesis, 124 p.

Adamski, J.C., 1996, Radium and radon in ground water of the Ozark region in Arkansas, Kansas, Missouri, and Oklahoma: U.S. Geological Survey Fact Sheet 181–96, 1 sheet.

Adamski, J.C., 1997, Nutrients and pesticides in ground water of the Ozark Plateaus in Arkansas, Kansas, Missouri, and Oklahoma: U.S. Geological Survey Water-Resources Investigations Report, 96–4313, 28 p.

Adamski, J.C., 2000, Geochemistry of the Springfield Plateau aquifer of the Ozarks Plateaus Province in Arkansas, Kansas, Missouri, and Oklahoma, U.S.A.: Hydrogeological Processes, v. 14, p. 849–866.

Adamski, J.C., Petersen, J.C., Freiwald, D.A., and Davis, J.V., 1995, Environmental and hydrologic setting of the Ozarks Plateaus study unit, Arkansas, Kansas, Missouri, and Oklahoma: U.S. Geological Survey Water-Resources Investigations Report 94–4022, 69 p.

Agricultural Research Service, 2013, The ARS pesticide properties database: Agricultural Research Service, accessed January 17, 2013, at http://www.ars.usda.gov/services/docs.htm?docid=14199.

Albin, D.R., 1960, Special ground-water report number 1, Murfreesboro area: Arkansas Geological and Conservation Commission in cooperation with the U.S. Geological Survey, 22 p.

Albin, D.R., 1964, Geology and ground-water resources of Bradley, Calhoun, and Ouachita Counties, Arkansas: U.S. Geological Survey Water-Supply Paper 1779–G, 32 p.

Albin, D.R., 1965, Water-resources reconnaissance of the Ouachita Mountains, Arkansas: U.S. Geological Survey Water-Supply Paper 1809–J, 14 p.

Albin, D.R., Hines, M.S., and Stephens, J.W., 1967, Water resources of Jackson and Independence Counties, Arkansas: U.S. Geological Survey Water-Supply Paper 1839–G, 29 p.

Albin, D.R., Stephens, J.W., and Edds, Joe, 1967, Ground-water levels in deposits of Quaternary and Tertiary age, spring 1965: Arkansas Geological Survey Water Resources Summary, no. 4, 10 p.

Aley, T.J., 1988, Complex radial flow of ground water in flat-lying residuum-mantled limestone in the Arkansas Ozarks: Proceedings, Second Environmental Problems in Karst Terranes and Their Solutions, National Water Well Association Conference, p. 159–170.

Aley, T.J., and Aley, Cathy, 1987, Groundwater study—Ozarks National Scenic Riverways: Ozark Underground Laboratory, Protem, Mo., National Park Service Contract CX 6000–4–0083, 222 p.

Alley, W.M., Healy, R.W., LaBaugh, J.W., and Thomas, E.R., 2002, Flow and storage in groundwater systems: Science, v. 296, no. 5575, p. 1985–1990.

Alley, W.M., Reilly, T.E., and Franke, O.L, 1999, Sustainability of ground-water resources: U.S. Geological Survey Circular 1186, 79 p.

Andrоes, D., 2006, The origin and extent of quartz overgrowth cements in anomalous Eocene sandstones and siltstones within the Wilcox Group on Crowley’s Ridge: Fayetteville, University of Arkansas, M.S. thesis, 148 p.

Appelo, C.A.J., and Postma, Dieke, 1999, Geochemistry, groundwater, and pollution: Brookfield, Vt., A.A. Bakema Publishers, 536 p.

Arkansas Agriculture Department, 2013, About the aquaculture division: Arkansas Agriculture Department, accessed March 11, 2013, at http://aad.arkansas.gov/aquaculture/Pages/default.aspx.

Arkansas Department of Environmental Quality, 1981, Groundwater—Elements of an Arkansas State groundwater quality protection strategy: Arkansas Department of Environmental Quality Water Division, v. 1, 96 p. (Also available at http://www.adeq.state.ar.us/water/branch_planning/publications.htm.)

Arkansas Department of Environmental Quality, 2012, Integrated water quality monitoring and assessment report (draft): Arkansas Department of Environmental Quality, Water Division, prepared pursuant to Sections 305b and 303d of the Federal Water Pollution Control Act, accessed May 10, 2013, at http://www.adeq.state.ar.us/water/reports_data.htm.

Arkansas Department of Environmental Quality, 2013a, Remedial action trust fund, State priority list: Technical Branch, Hazardous Waste Division, accessed May 10, 2013, at http://www.adeq.state.ar.us/hazwaste/branch_tech/.

Arkansas Department of Environmental Quality, 2013b, Arkansas Brownfield Program: Arkansas Department of Environmental Quality, accessed May 10, 2013, at http://www.adeq.state.ar.us/hazwaste/bf/brownfield/.

Arkansas Department of Environmental Quality, 2013c, The Elective Sites Cleanup Program: Enforcement and Inspection Branch, Hazardous Waste Division accessed May 10, 2013, at http://www.adeq.state.ar.us/hazwaste/branch_ie/.

Arkansas Department of Environmental Quality, 2013d, List of publications: Water Division, Water Quality Planning Branch, accessed May 3, 2013, at http://www.adeq.state.ar.us/water/branch_planning/publications.htm.

Arkansas Department of Health, 1990, Wellhead protection program, State of Arkansas: Department of Health, Division of Engineering, September 1990.

Arkansas Department of Health, 2009, Source water assessment and protection programs: Arkansas Department of Health, Division of Engineering, Source Water Protection Program, accessed April 3, 2013, at http://www.healthy.arkansas.gov/programsServices/environmentalHealth/Engineering/sourceWaterProtection/Pages/default.aspx.

Arkansas Department of Health, 2013, Drinking water information for Arkansas: Arkansas Department of Health, accessed April 3, 2013, at http://www.healthy.arkansas.gov/eng/autoupdates/pwslist0.htm.

Arkansas Game and Fish Commission, 1998, Arkansas wildlife—A history, K. Sutton, ed.: University of Arkansas Press, 328 p.

Arkansas Geological Commission, 1980, Ground-water levels in observation wells in Arkansas, spring, 1980: Arkansas Geological Commission in cooperation with the U.S. Geological Survey Water Resources Summary, no. 15, 45 p.

Arkansas Industrial Development Commission, 1980, Directory of manufacturers in Arkansas, 1980: Arkansas Industrial Development Commission publication, 180 p.

Arkansas Natural Resources Commission, 1990, Water management, Arkansas water plan, available at http://anrc.ark.org/divisions/water-resources-management/arkansas-water-plan.

Arkansas Natural Resources Commission, 1996, The designation of the Sparta aquifer within Bradley, Calhoun, Columbia, Ouachita, and Union Counties as a critical groundwater area: accessed May 31, 2013, at http://www.anrc.arkansas.gov/Rules%20and%20Regulations/orders/1995-1_designation_of_sparta_as%20cgwap.pdf.

Arkansas Natural Resources Commission, 1999, Arkansas nonpoint source management plan, 1998–2001, as amended: Little Rock, Ark., Arkansas Natural Resources Commission.

Arkansas Natural Resources Commission, 2005, Rules for the protection and management of groundwater, Title IV, effective 2005: Little Rock, Ark., Arkansas Natural Resources Commission.

Arkansas Natural Resources Commission, 2009, Order designating the Cache critical groundwater area: Arkansas Natural Resources Commission, accessed May 31, 2013, at http://www.anrc.arkansas.gov/Rules%20and%20Regulations/orders/nea_critical_gw_designation_2009.pdf.

Arkansas Natural Resources Commission, 2011, Water law in Arkansas: Little Rock, Ark., Arkansas Natural Resources Commission, 58 p.

Arkansas Natural Resources Commission, 2012a, Arkansas ground-water protection and management report for 2011: Little Rock, Ark., Arkansas Natural Resources Commission, 139 p.

Arkansas Natural Resources Commission, 2012b, Status report to the Arkansas Legislative Council on the Grand Prairie area: Demonstration Project and Bayou Meto Water Management District Irrigation Project, accessed April 2, 2013, at http://www.arkleg.state.ar.us/assembly/2011/Meeting%20Attachments/000/I10445/Exhibit%20H.9%20-%20ANRC%20-%20Status%20Report.pdf.

Arkansas Natural Resources Commission, 2013a, Arkansas groundwater protection and management report for 2012, a supplement to the Little Rock, Ark., Arkansas Water Plan: Arkansas Natural Resources Commission, 57 p.

Arkansas Natural Resources Commission, 2013b, Fact sheet on well metering law: Arkansas Natural Resources Commission, accessed November 25, 2013, at https://static.ark.org/eeuploads/anrc/fact_sheet_act_1426.pdf.

Arkansas Oil and Gas Commission, 2013, General rules and regulations, effective February 8, 2013: Little Rock, Ark., Arkansas Oil and Gas Commission, accessed April 2, 2013, at http://www.aogc.state.ar.us.

Arkansas Pollution Control and Ecology Commission, 1993, Regulation no. 1—Regulation for the prevention of pollution by salt water and other oil field wastes produced by wells in all fields or pools, effective March, 16, 1993: Little Rock, Ark., Arkansas Pollution Control and Ecology Commission, accessed April 4, 2013, at http://www.adeq.state.ar.us/regs.

Arkansas Pollution Control and Ecology Commission, 2002, Regulation no. 20—The Arkansas surface coal mining and reclamation code as revised, effective September 26, 2002: Little Rock, Ark., Arkansas Pollution Control and Ecology Commission, accessed April 4, 2013, at http://www.adeq.state.ar.us/regs.

Arkansas Pollution Control and Ecology Commission, 2005, Regulation no. 17—Arkansas underground injection control code, effective February 14, 2005: Little Rock, Ark., Arkansas Pollution Control and Ecology Commission, accessed April 4, 2013, at http://www.adeq.state.ar.us/regs.

Arkansas Pollution Control and Ecology Commission, 2006, Regulation no. 29—Brownfields redevelopment as revised, effective March 3, 2006: Little Rock, Ark., Arkansas Pollution Control and Ecology Commission, accessed April 4, 2013, at http://www.adeq.state.ar.us/regs.

Arkansas Pollution Control and Ecology Commission, 2008, Regulation no. 22—Solid waste management rules, effective April 26, 2008: Little Rock, Ark., Arkansas Pollution Control and Ecology Commission, accessed April 4, 2013, at http://www.adeq.state.ar.us/regs.

Arkansas Pollution Control and Ecology Commission, 2009, Regulation no. 12—Storage tank regulations as revised, effective December 28, 2009: Little Rock, Ark., Arkansas Pollution Control and Ecology Commission, accessed April 4, 2013, at http://www.adeq.state.ar.us/regs.

Arkansas Pollution Control and Ecology Commission, 2011a, Regulation no. 34—State water permit regulation, effective September 26, 2011: Little Rock, Ark., Arkansas Pollution Control and Ecology Commission, accessed April 4, 2013, at http://www.adeq.state.ar.us/regs.

Arkansas Pollution Control and Ecology Commission, 2011b, Regulation no. 2—Regulation establishing water quality standards for surface waters of the State of Arkansas as revised, effective September 26, 2011: Little Rock, Ark., Arkansas Pollution Control and Ecology Commission, accessed April 4, 2013, at http://www.adeq.state.ar.us/regs.

Arkansas Pollution Control and Ecology Commission, 2012a, Regulation no. 23—Hazardous waste management as revised, effective August 12, 2012: Little Rock, Ark., Arkansas Pollution Control and Ecology Commission, accessed April 4, 2013, at http://ww.adeq.state.ar.us/regs.

Arkansas Pollution Control and Ecology Commission, 2012b, Regulation no. 5—Liquid animal waste management systems as revised, effective June 22, 2012: Little Rock, Ark., Arkansas Pollution Control and Ecology Commission, accessed April 4, 2013, at http://www.adeq.state.ar.us/regs.

Arkansas Pollution Control and Ecology Commission, 2012c, Regulation no. 15—The Arkansas open-cut mining and land reclamation code as revised, effective September 15, 2012: Little Rock, Ark., Arkansas Pollution Control and Ecology Commission, accessed April 4, 2013, at http://www.adeq.state.ar.us/regs.

Arkansas Pollution Control and Ecology Commission, 2012d, Regulation no. 30—Arkansas remedial action trust fund hazardous substances site priority list, effective August 12, 2012: Little Rock, Ark., Arkansas Pollution Control and Ecology Commission, accessed April 4, 2013, at http://www.adeq.state.ar.us/regs.

Arkansas Soil and Water Conservation Commission, 1991, Identification of ground-water vulnerability areas in Arkansas: Little Rock, Ark., Arkansas Soil and Water Conservation Commission, 12 p.

Arkansas State Board of Health, 2012a, Rules and regulations pertaining to public water systems as revised, effective March 23, 2012: Little Rock, Ark., Arkansas State Board of Health, accessed March 30, 2013, at http://www.healthy.arkansas.gov/programsServices/environmentalHealth/Engineering/Pages/RulesRegulations.

Arkansas State Board of Health, 2012b, Rules and regulations pertaining to public water systems as revised, effective March 23, 2012: Little Rock, Ark., Arkansas State Board of Health, Department of Health Center for Local Public Health Branch, Engineering Section, accessed March 30, 2013, at http://www.healthy.arkansas.gov/programsServices/environmentalHealth/Engineering/Pages/RulesRegulations.

Arkansas State Planning Board, 1939, Arkansas water resources: Little Rock, Ark., Arkansas State Planning Board, 92 p.

Arkansas State Plant Board, 2013, Arkansas ground water, groundwater pesticide database: Arkansas State Plant Board, accessed January 17, 2013, at http://plantboard.arkansas.gov/Pages/default.aspx.

Arkansas Water Study Commission, 1956, Water in Arkansas—A report on the surface water resources in Arkansas: Prepared at the Discretion of the General Assembly of Arkansas, 55 p.

Arkansas Water Well Construction Commission, 2011, Arkansas Water Well Construction Act, chapter 50 of the Arkansas Code, Title 17: Arkansas Water Well Construction Commission, accessed on May 10, 2013, at http://www.arkansas.gov/awwcc/2011_law.pdf.

Arthur, J.K., 2001, Hydrogeology, model description, and flow analysis of the Mississippi River alluvial aquifer in northwestern Mississippi: U.S. Geological Survey Water-Resources Investigations Report, 2001–4035, 47 p.

Arthur, J.K., and Taylor, R.E., 1990, Definition of the geohydrologic framework and preliminary simulation of the ground-water flow in the Mississippi embayment aquifer system, Gulf Coastal Plain, United States: U.S. Geological Survey Water-Resources Investigations Report 86–4364, 97 p.

Arthur, J.K., and Taylor, R.E., 1998, Ground-water flow analysis of the Mississippi embayment aquifer system, South-Central United States: U.S. Geological Survey Professional Paper, 1416–I, 148 p.

Baker, N.T., 1990, Summary and analysis of water-use data collection in eastern Arkansas: U.S. Geological Survey Water-Resources Investigations Report 90–4177, 25 p.

Baker, N.T., Manning, C.A., and Beavers, E.A., 1991, Inventory of public water supplies in Arkansas: U.S. Geological Survey Open-File Report 91–247, 157 p.

Baker, R.C., 1955, Arkansas' ground-water resources: Arkansas Geological and Conservation Commission in cooperation with the U.S. Geological Survey Circular, no. 1, 16 p.

Baker, R.C., Hewitt, F.A., and Billingsley, G.A., 1948, Ground-water resources of the El Dorado area, Union County, Arkansas: University of Arkansas Bulletin, v. 42, no. 12, 39 p.

Bangladesh Agricultural Development Corporation, 1992, Final report of the Deep Tubewell II Project, v. 2.1, Natural Resources: Report prepared for the Bangladesh Agricultural Development Corporation and Overseas Development Administration (United Kingdom), Mott MacDonald Ltd. and Hunting Technical Services, 401 p.

Barlow, P.M., and Leake, S.A., 2012, Streamflow depletion by wells—Understanding and managing the effects of groundwater pumping on streamflow: U.S. Geological Survey Circular 1376, 84 p.

Basile-Doelsch, D.I., Meunier, J.D., and Parron, Claude, 2005, Another continental pool in the terrestrial silicon cycle: Nature, v. 433, no. 7024, p. 399–402.

Bates, B.C., Kundzewicz, Z.W., Wu, Shaohong, and Palutikof, J.P., 2008, Climate change and water: Geneva, Switzerland, Technical Paper VI of the Intergovernmental Panel on Climate Change (IPCC), IPCC Secretariat, 210 p.

Beaver Water District, 2010, Beaver Lake and its watershed: Beaver Water District, accessed October 9, 2012, at http://www.bwdh2o.org/.

Bedinger, M.S., Emmett, L.F., and Jeffery, H.G., 1963, Ground-water potential of the alluvium of the Arkansas River between Little Rock and Fort Smith, Arkansas: U.S. Geological Survey, Water-Supply Paper, 1669–L, 29 p.

Bedinger, M.S., and Jeffery, H.G., 1964, Ground water in the Lower Arkansas River Valley, Arkansas: U.S. Geological Survey Water-Supply Paper 1669–V, 17 p.

Bedinger, M.S., and Reed, J.E., 1961, Geology and ground-water resources of Desha and Lincoln Counties, Arkansas: Arkansas Geology and Conservation Commission Water Resources Circular 6, 129 p.

Bedinger, M.S., Stephens, J.W., and Edds, Joe, 1960, Decline of water levels in the Pine Bluff area: U.S. Geological Survey in cooperation with Arkansas Geological and Conservation Commission Special Ground-Water Report Number 2, 10 p.

Bell, Robert, 2010, History of U.S. aquaculture has roots in Arkansas: Arkansas Business, accessed December 11, 2012, http://www.arkansasbusiness.com/article/36243/history-of-us-aquaculture-has-roots-in-arkansas?page=all.

Bolyard, S.E., 2007, Migration of landfill contaminants in a tilted-block mantled-karst setting in northwestern Arkansas: Fayetteville, University of Arkansas, M.S. thesis, 69 p.

Boswell, E.H., Cushing, E.M., Hosman, E.L., and Jeffery, H.G., 1968, Quaternary aquifers in the Mississippi embayment, with discussion on quality of the water: U.S. Geological Survey Professional Paper 448–E, 15 p.

Boswell, E.H., Moore, G.K., MacCary, L.M., Jeffery, H.G., and others, 1965, Water resources of the Mississippi embayment—Cretaceous aquifers in the Mississippi embayment, with discussions on quality of the water: U.S. Geological Survey Professional Paper 448–C, 37 p.

Bowman, Steve, and Wright, Steve, 1999, Arkansas Duck Hunter's Almanac: Fayetteville, Ark., Ozark Delta Press, 272 p.

Brahana, J.V., 1982, Two-dimensional digital groundwater model of the Memphis Sand and equivalent units, Tennessee, Arkansas, Mississippi: U.S. Geological Survey Open-File Report 82–99, 55 p.

Brahana, J.V., and Broshears, R.E., 1989, Hydrogeology and ground-water flow in the Memphis and Fort Pillow aquifers in the Memphis area, Tennessee: U.S. Geological Survey Water-Resources Investigations Report 89–4131, 56 p.

Brahana, J.V., and Davis, R.K., 1998, Methodology for delineating ground-water recharge areas of springs in the carbonate-rock terrane of northwest Arkansas, and application to five separate spring basins within the region, *in* Davis, R.K., Brahana, J.V., and Johnston, J.S., eds., Ground water in northwest Arkansas—Minimizing nutrient contamination from non-point sources in karst terrane: Final report for tasks 94–300 and 95–300 to Arkansas Soil and Water Conservation Commission for EPA, Project #C9996103–02 and C9996102–03, 56 p.

Brahana, J.V., Gonthier, G.J., and Remsing, L.M., 1991, Hydrogeologic data for Boone County, Arkansas: U.S. Geological Survey Open-File Report 91–518, 36 p.

Brahana, J.V., Leidy, V.A., Lindt, J.M., and Hodge, S.A., 1993, Hydrogeologic data for Carroll County, Arkansas: U.S. Geological Survey Open-File Report 93–150, 32 p.

Brahana, J.V., and Mesko, T.O., 1988, Hydrogeology and preliminary assessment of regional flow in the upper Cretaceous and adjacent aquifers in the northern Mississippi embayment: U.S. Geological Survey Water-Resources Investigations Report, 87–4000, 65 p.

Brahana, J.V., Tennyson, Rodney, Terry, Jim, Hays, P.D., and Pollock, Erik, 2009, Reactivated basement faulting as a hydrogeologic control of hypogene speleogenesis in the southern Ozarks of Arkansas, U.S.A., *in* Stafford, Kevin, ed., Advances in hypogene karst studies: National Cave and Karst Research Institute Symposium 1, p. 99–110.

Brahana, J.V., Ting, T.E., Mohammed Al-Qinna, Murdoch, J.F., Davis, R.K., Laincz, Jozef, Killingbeck, J.J., Szilvagyi, Eva, Doheny-Skubic, Margaret, Chaubey, Indrajeet, Hays, P.D., and Thomas, Gregg, 2005, Quantification of hydrologic budget parameters for the vadose zone and epikarst in mantled karst, *in* Kuniansky, E.L., ed., U.S. Geological Survey Karst Interest Group, Proceedings, Rapid City, South Dakota, September 12–15, 2005: U.S. Geological Survey Scientific Investigations Report 2005–5160, p. 144–152.

Brahana, J.V., 2011a, Karst hydrogeology of the southern Ozarks *in* Kuniansky, E.L., ed., U.S. Geological Survey Karst Interest Group, Proceedings, Fayetteville, Ark., April 26–29, 2011: U.S. Geological Survey Scientific Investigations Report 2011–5031, p. 119

Brahana, J.V., 2011b, Ten relevant karst hydrogeologic insights gained from 15 years of in situ field studies at the Savoy Experimental Watershed *in* Kuniansky, E.L., ed., U.S. Geological Survey Karst Interest Group, Proceedings, Fayetteville, Ark., April 26–29, 2011: U.S. Geological Survey Scientific Investigations Report 2011–5031, p. 132–141

Branner, G.C., 1937, Data on springs in Arkansas: Arkansas Geological and Conservation Commission unnumbered series, 127 p.

Brannon, J.C., Podosek, F.A., and Cole, S.C., 1996, Radiometric dating of Mississippi Valley-type ore deposits, *in* Sangster, D.F., ed., Carbonate hosted lead-zinc deposits: Society of Economic Geologists Special Publication 4, p. 536–545.

Broom, M.E., Kraemer, T.F., and Bush, W.V., 1984, A reconnaissance study of the saltwater contamination in the El Dorado aquifer, Union County, Arkansas: U.S. Geological Survey Water-Resources Investigations Report 84–4012, 47 p.

Broom, M.E., and Lyford, F.P., 1981, Alluvial aquifer of the Cache and St. Francis River Basins, northeastern Arkansas: U.S. Geological Survey Open-File Report 81–476, 48 p.

Broom, M.E., and Lyford, F.P., 1982, Alluvial aquifer of the Cache and St. Francis River Basins, northeastern Arkansas: Arkansas Geological Commission Circular No. 13, 48 p., 13 pls.

Broom, M.E., and Reed, J.E., 1973, Hydrology of the Bayou Bartholomew alluvial aquifer-stream system, Arkansas: U.S. Geological Survey Open-File Report 73–34, 91 p.

Bryant, C.T., Ludwig, A.H., and Morris, E.E., 1985, Ground-water problems in Arkansas: U.S. Geological Survey Water-Resources Investigations Report 85–4010, 24 p.

Buckalew, A.R., and Buckalew, R.B., 1974, The discovery of oil in south Arkansas, 1920–1924: Arkansas Historical Quarterly, v. 32, p. 195–208.

Caplan, W.M., 1954, Subsurface geology and related oil and gas possibilities of northeastern Arkansas: Arkansas Resources and Development Commission Bulletin 20, 124 p.

Caplan, W.M., 1960, Subsurface geology of pre-Everton rocks in northern Arkansas: Arkansas Geological and Conservation Commission Information Circular 21, 17 p.

Cardon, G.E., and Mortvedt, J.J., 2001, Salt affected soils: Fort Collins, Colo., Colorado State University Cooperative Extension Service, 5 p.

Chapelle, F.H., 2001, Ground-water microbiology and geochemistry (2d ed.): New York, John Wiley and Sons, Inc., 477 p.

Chapelle, F.H., Bradley, P.M., Thomas, M.A., and McMahon, P.B., 2009, Distinguishing iron-reducing from sulfate-reducing conditions: Ground Water, v. 47, no. 2, p. 300–305.

Chowdhury, A.A.F., 2002, The impact of the acreage allotment program on rice farming: International Advances in Economic Research, v. 8, no. 1, p. 49–57.

Clark, B.R., and Hart, R.M., 2009, The Mississippi Embayment Regional Aquifer Study (MERAS)—Documentation of a groundwater-flow model constructed to assess water availability in the Mississippi embayment: U.S. Geological Survey Scientific Investigations Report 2009–5172, 61 p.

Clark, B.R., Hart, R.M., and Gurdak, J.J., 2011a, Groundwater availability of the Mississippi embayment: U.S. Geological Survey Professional Paper 1785, 62 p.

Clark, B.R., Westerman, D.A., and Fugitt, D.T., 2011b, Simulation of the effects of groundwater withdrawals on water-level altitudes in the Sparta aquifer in the Bayou Meto-Grand Prairie area of eastern Arkansas, 2007–37: U.S. Geological Survey Scientific Investigations Report 2011–5215, 9 p.

Clark, B.R., Westerman, D.A., and Fugitt, D.T., 2013, Enhancements to the Mississippi Embayment Regional Aquifer Study (MERAS) groundwater flow model and simulations of sustainable water-level scenarios: U.S. Geological Survey Scientific Investigations Report 2013–5161, 36 p.

Cole, E.F., and Morris, E.E., 1986, Water resources of the Ouachita National Forest, Arkansas: U.S. Geological Survey Water-Resources Investigations Report 86–4166, 1 sheet.

Conrad, T.A., 1856, Observations on the Eocene deposit of Jackson, Mississippi, with descriptions of thirty-four new species of shells and corals: Philadelphia Academy of Natural Sciences, Proceedings, v. 7, p. 257–258.

Cordova, R.M., 1963, Reconnaissance of the ground-water resources of the Arkansas Valley region: U.S. Geological Survey Water-Supply Paper 1669–BB, 33 p.

Coughlin, T.L., 1975, Geologic and environmental factors affecting groundwater chemistry in north-central Washington County, Arkansas: Fayetteville, University of Arkansas, M.S. thesis, 130 p.

Counts, H.B., 1957, Ground-water resources of parts of Lonoke, Prairie, and White Counties, Arkansas: Arkansas Geology and Conservation Commission Water Resources Circular 5, 65 p.

Counts, H.B., and Engler, K., 1954, Changes in water levels in deposits of Quaternary age in eastern Arkansas from 1938–1953: University of Arkansas, Agriculture Experiment Station Report Series 42, 11 p.

Counts, H.B., Tait, D.B., Klein, H., and Billingsley, G.A., 1955, Ground-water resources in a part of southwestern Arkansas: Arkansas Geological Commission Water Resources Circular, no. 2, 35 p.

Cox, G.D., Ogden, A.E., and Slavik, Gretta, 1980, Contamination of Boone-St. Joe Limestone groundwater by septic tanks and chicken houses: Arkansas Academy of Science Proceedings, v. 34, p. 41–44.

Cox, R.T., 2009, Ouachita, Appalachian, and ancestral Rockies deformations recorded in mesoscale structures on the foreland Ozark plateaus: Tectonophysics, v. 474, no. 3–4, p. 674–683.

Crider, A.F., 1906, Drainage of wetlands in Arkansas by wells: U.S. Geological Survey Water-Supply Paper 160, p. 54–58.

Crider, A.F., and Johnson, L.C., 1906, Summary of the underground-water resources of Mississippi: U.S. Geological Survey Water-Supply Paper 159, 86 p.

Cushing, E.M., Boswell, B.H., and Hosman, R.L., 1964, General geology of the Mississippi embayment: U.S. Geological Survey Professional Paper 448–B, 28 p.

Czarnecki, J.B., 2006a, Effects of proposed additional ground-water withdrawals from the Mississippi River Valley alluvial aquifer on water levels in Lonoke County, Arkansas: U.S. Geological Survey Scientific Investigations Report 2006–5275, 6 p.

Czarnecki, J.B., 2006b, Simulation of various management scenarios of the Mississippi River Valley alluvial aquifer in Arkansas: U.S. Geological Survey Scientific Investigations Report 2006–5052, 14 p.

Czarnecki, J.B., 2007, Simulated ground-water withdrawals by Cabot WaterWorks from the Mississippi River Valley alluvial aquifer, Lonoke County, Arkansas: U.S. Geological Survey Scientific Investigations Report 2007–5030, 39 p.

Czarnecki, J.B., 2008, Evaluation of selected model constraints and variables on simulated sustainable yield from the Mississippi River Valley alluvial aquifer system in Arkansas: U.S. Geological Survey Scientific Investigations Report 2008–5138, 21 p.

Czarnecki, J.B., 2009, Effects of potential changes in groundwater withdrawals from the Sparta aquifer on water-level altitudes in Jefferson County, Arkansas: U.S. Geological Survey Scientific Investigations Report 2009–5234, 8 p.

Czarnecki, J.B., 2010, Groundwater-flow assessment of the Mississippi River Valley alluvial aquifer of northeastern Arkansas: U.S. Geological Survey Scientific Investigations Report 2010–5210, 33 p.

Czarnecki, J.B., Bolyard, S.E., Hart, R.M., and Clark, J.M., 2014, Digital surfaces and thicknesses of selected hydrogeologic units within the Ozark Plateaus aquifer system, northwestern Arkansas: U.S. Geological Survey Scientific Investigations Report 2013–5208, 25 p.

Czarnecki, J.B., Clark, B.R., and Reed, T.B., 2003, Conjunctive-use optimization model of the Mississippi River Valley alluvial aquifer of northeastern Arkansas: U.S. Geological Survey Water-Resources Investigations Report 03–4230, 29 p.

Czarnecki, J.B., Clark, B.R., and Stanton, G.P., 2003, Conjunctive-use optimization model of the Mississippi River Valley alluvial aquifer of southeastern Arkansas: U.S. Geological Survey Water-Resources Investigations Report 03–4233, 26 p.

Czarnecki, J.B., Gillip, J.A., Jones, P.M., and Yeatts, D.S., 2009, Groundwater-flow model of the Ozark Plateau aquifer system, northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma: U.S. Geological Survey Scientific Investigations Report 2009–5148, 62 p.

Czarnecki, J.B., Hays, P.D., and McKee, P.W., 2012, The Mississippi River Valley alluvial aquifer in Arkansas—A sustainable water resource?: U.S. Geological Survey Fact Sheet 041–02, 4 p.

Czarnecki, J.B., Pugh, A.L., and Blackstock, J.M., 2013, Potentiometric surface of the Ozark aquifer in northern Arkansas, 2010: U.S. Geological Survey Scientific Investigations Report 2014–5013, 16 p.

Czarnecki, J.B., and Schrader, T.P., 2013, Effects of recent climate variability on groundwater levels in eastern Arkansas: U.S. Geological Survey Scientific Investigations Report 2012–5258, 17 p.

Dall, W.H., 1898, A table of the North American Tertiary horizons, correlated with one another and those of Western Europe, with annotations: U.S. Geological Survey 18th Annual Report, part 2, p. 323–348.

Dane, C.H., 1929, Upper Cretaceous formations of southwestern Arkansas: Arkansas Geological Survey Bulletin 1, 215 p.

Davies, J., and Exley, C., 1992, Hydrochemical character of the main aquifer units of central and north-eastern Bangladesh and possible toxicity of groundwater to fish and humans, final report: British Geological Survey Technical Report WD/92/43R, 70 p.

Davis, R.K., Brahana, J.V., and Johnston, J.S., 2000, Ground water in northwest Arkansas—Minimizing nutrient contamination from non-point sources in karst terrane: Fayetteville, Ark., University of Arkansas, Arkansas Water Resources Center, no. MSC–288, 69 p.

Davis, R.K., Hamilton, S., and Brahana, J.V., 2005, Escherichia coli survival in springs and streams of mantled karst aquifers, northwest Arkansas: Journal of American Water Resources Association, v. 41, n. 6, p. 1279–1287.

Davis, R.K., and Shephard, S., 2010, Beaver Lake and its watershed 2010, Beaver Water District, 44 p., accessed October 9, 2012, at http://www.bwdh2o.org/wp-content/uploads/2012/03/2010-FINAL-Beaver-Lake-Watershed-Report.pdf.

Dintelmann, D., Gutierrez, M., and Gouzie, D., 2006, Groundwater potentiometric decline in the Springfield, Missouri area: Environmental Geology, v. 50, no. 4, p. 541–549.

Dollof, J.H., Rozendal, R.A., Siratovich, E.N., Swain, F.M., Jr., and Woncik, J., 1967, Subsurface upper Cretaceous stratigraphy of southwestern Arkansas: Gulf Coast Association of Geological Survey Transactions, v. 17, p. 76–104.

Drogue, C., 1980, Essai d'identification d'un type de structure de magasins carbonates fissures: Application à l'interprétation de certains aspects du fonctionnement hydrogéologìque: Mém sér Soc Géol France, v. 11, p. 101–108.

Edds, Joe, and Fitzpatrick, D.J., 1984a, Maps showing the altitude of the potentiometric surface and changes in the water levels of the alluvial aquifer in eastern Arkansas, spring 1983: U.S. Geological Survey Water-Resources Investigations Report 84–4264, 1 sheet.

Edds, Joe, and Fitzpatrick, D.J., 1984b, Maps showing altitude of the potentiometric surface and changes in water levels of the Sparta Sand and Memphis Sand aquifers in eastern Arkansas, spring 1983: U.S. Geological Survey Water-Resources Investigations Report 84–4265, 1 sheet.

Edds, Joe, and Fitzpatrick, D.J., 1985, Maps showing altitude of the potentiometric surface and changes in water levels of the Sparta Sand and Memphis Sand aquifers in eastern Arkansas, spring 1984: U.S. Geological Survey Water-Resources Investigations Report 85–4223, 1 sheet.

Edds, Joe, and Fitzpatrick, D.J., 1986, Maps showing altitude of the potentiometric surface and changes in water levels of the Sparta Sand and Memphis Sand aquifers in eastern Arkansas, spring 1985: U.S. Geological Survey Water-Resources Investigations Report 86–4084, 1 sheet.

Edds, Joe, and Fitzpatrick, D.J., 1989, Altitude of the potentiometric surface and changes in water levels in the Sparta-Memphis aquifer in eastern and southern Arkansas, spring 1986: U.S. Geological Survey Water-Resources Investigations Report 88–4042, 1 sheet.

Edds, Joe, and Remsing, L.M., 1986, Ground-water levels in Arkansas, spring 1986: U.S. Geological Survey Open-File Report 86–406–W, 62 p.

Emmett, L.F., Skelton, John, Luckey, R.R., and Miller, D.E., and others, 1978, Water resources and geology of the Springfield area, Missouri: Missouri Department of Natural Resources, 160 p.

Encyclopedia of Arkansas, 2013, Lake Georgia-Pacific *in* The encyclopedia of Arkansas history and culture: Encyclopedia of Arkansas, Central Arkansas Library System, accessed September 10, 2013, at http://www.encyclopediaofarkansas.net/encyclopedia/media-detail.aspx?mediaID=7071.

Engle, C.R., 2012, Aquaculture *in* The encyclopedia of Arkansas history and culture: Encyclopedia of Arkansas, Central Arkansas Library System, accessed April 13, 2013, at http://www.encyclopediaofarkansas.net/encyclopedia/entry-detail.aspx?entryID=3640.

Engler, Kyle, 1958, Water levels in rice irrigation wells in the Grand Prairie region: Arkansas Farm Research, May–June 1958, v. 7, 12 p.

Engler, Kyle, Bayley, F.H., and Sniegocki, R.T., 1963, Studies of artificial recharge in the Grand Prairie region, Arkansas environment and history: U.S. Geological Survey Water-Supply Paper 1615–A, 32 p.

Engler, Kyle, Thompson, D.G., and Kazmann, R.G., 1945, Groundwater supplies for rice irrigation in the Grand Prairie region, Arkansas: University of Arkansas, College of Agriculture, Agricultural Experiment Station Bulletin, no. 457, 56 p.

Fancher, G.H., and Mackay, D.K., 1946, Secondary recovery of petroleum in Arkansas: Report to the 56th General Assembly of the State of Arkansas under the auspices of the Arkansas Oil and Gas Commission, p. 245–250.

Fenneman, N.M., 1938, Physiography of eastern United States: New York, McGraw-Hill Book Co., Inc., 714 p.

Fetter, C.W., 1988, Applied hydrogeology (2d ed.): New York, Macmillan Publishing Company, 592 p.

Fisk, H.N., 1944, Geological investigation of the alluvial aquifer of the lower Mississippi River: U.S. Department of the Army, Mississippi River Commission, 78 p.

Fisk, H.N., 1947, Fine-grained alluvial deposits and their effects on Mississippi River activity: U.S. Army Corps of Engineers, Waterways Experiment Station, 82 p.

Fitzpatrick, D.J., 1985, Occurrence of saltwater in the alluvial aquifer in the Boeuf-Tensas Basin, Arkansas: U.S. Geological Survey Water-Resources Investigations Report 85–4029, 1 sheet.

Fitzpatrick, D.J., 1990, A preliminary assessment of the potential for artificial recharge in eastern Arkansas: U.S. Geological Survey Water-Resources Investigations Report 90–4123, 31 p.

Fitzpatrick, D.J., Kilpatrick, J.M., and McWreath, Harry, 1990, Geohydrologic characteristics and simulated response to pumping stresses in the Sparta aquifer in east-central Arkansas: U.S. Geological Survey Water-Resources Investigations Report 88–4201, 50 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: New Jersey, Prentice-Hall, 604 p.

Freiwald, D.A., 1984, Average annual precipitation and runoff in Arkansas, 1951–80: U.S. Geological Survey Water-Resources Investigations Report 84–4363, 1 sheet.

Freiwald, D.A., 1987, Streamflow gain and loss of selected streams in northern Arkansas: U.S. Geological Survey Water-Resources Investigations Report 86–4185, 4 sheets.

Freiwald, D.A., and Grosz, G.D., 1988, Effects of fluctuating river-pool stages on ground-water levels in the adjacent alluvial aquifer in the lower Arkansas River, Arkansas: U.S. Geological Survey Water-Resources Investigations Report 87–4279, 14 p.

Freiwald, D.A., and Johnson, S.F., 2007, Monitoring of Sparta aquifer recovery in southern Arkansas and northern Louisiana, 2003–07: U.S. Geological Survey Fact Sheet 2007–3102, 4 p.

Freiwald, D.A., and Plafcan, Maria, 1987, Ground-water levels in Arkansas, spring 1987: U.S. Geological Survey Open-File Report 87–459, 66 p.

Frezon, S.E., and Glick, E.E., 1959, Pre-Atoka rocks of northern Arkansas: U.S. Geological Survey Professional Paper 314–H, 18 p.

Funkhouser, J.E., Little, P.R., Brahana, J.V., Kresse, T.M., Anderson, M., Formica, S., and Huetter, T., 1999, Methodology to study the effects of animal production in mantled karst aquifers of the southern Ozarks, *in* Palmer, A.N., Palmer, M.V., and Sasowsky, I.D., eds., Karst modeling: Special Publication 5, Karst Waters Institute, Charles Town, W. Va., p. 255–258.

Gates, J.B., 2005, Groundwater irrigation in the development of the Grand Prairie rice industry, 1896–1950: Papers in the Earth and Atmospheric Sciences, paper 172, p. 394–413.

Ghasemizadeh, Reza, Hellweger, Ferdinand, Butscher, Christoph, Padilla, Ingrid, Vesper, Dorothy, Field, Malcolm, and Alshawabkeh, Akram, 2012, Review—Groundwater flow and transport modeling of karst aquifers, with particular reference to the North Coast Limestone aquifer system of Puerto Rico: Hydrogeology Journal, v. 20, no. 8, p. 1441–1461.

Ghil, Michael, 2002, Natural climate variability, *in* MacCraken, M.C., and Perry, J.S., eds., Encyclopedia of global environmental change—Volume 1, the Earth system—Physical and chemical dimensions of global environmental change: Chichester, John Wiley and Sons, p. 544–549.

Gillip, J.A., 2007, The effects of land-use change on water quality and speleogenesis in Ozark cave systems—A paired cave study of Civil War and Copperhead Caves, northwestern Arkansas: Fayetteville, University of Arkansas, M.S. thesis, 77 p.

Gillip, J.A., and Czarnecki, J.B., 2009, Validation of a ground-water flow model of the Mississippi River Valley alluvial aquifer using water-level and water-use data for 1998–2005 and evaluation of water-use scenarios: U.S. Geological Survey Scientific Investigations Report 2009–5040, 22 p.

Gilmour, J.T., 2000, Water quality in rice production: B.R. Wells Rice Research Studies 2000, Arkansas Agricultural Experiment Station Research Series, no. 485, p. 171–177.

Gonthier, G.M., 2003, Quality of ground water in Pleistocene and Holocene subunits of the Mississippi River Valley alluvial aquifer, 1998: U.S. Geological Survey Water-Resources Investigations Report 03–4202, 84 p.

Gonthier, G.M., and Mahon, G.L., 1993, Thickness of the Mississippi River Valley confining unit, eastern Arkansas: U.S. Geological Survey Water-Resources Investigations Report 92–4121, 4 sheets.

Gordon, Mackenzie, Jr., Tracey, J.I., Jr., and Ellis, M.W., 1958, Geology of the Arkansas bauxite region: U.S. Geological Survey Professional Paper 299, 268 p.

Gott, J.D., 1975, Soil survey of Mark Twain National Forest area, Missouri: U.S. Department of Agriculture, Soil Survey Report, p. 47–50.

Griffis, C.L., 1972, Groundwater surface-water integration study in the Grand Prairie of Arkansas: Arkansas Water Resources Research Center, no. 11, 330 p.

Grohskopf, J.G., and McCracken, Earl, 1949, Insoluble residues of some Paleozoic formations of Missouri, their preparation, characteristics, and application: Missouri Geological Survey and Water Resources Report of Investigations, no. 10, 39 p.

Grosz, G.D., Terry, J.E., and Hall, A.P., 1988, Hydrology of the lower Little Red River, Arkansas, and a procedure for estimating available streamflow: U.S. Geological Survey Water-Resources Investigations Report 88–4008, 106 p.

Guccione, M.J., Prior, W.L., and Rutledge, E.M., 1986, The Tertiary and Quaternary geology of Crowley's Ridge—A guidebook: Arkansas Geological Commission Guidebook 86–4, 39 p.

Halberg, H.N., 1972, Use of water in Arkansas, 1970: State of Arkansas Geological Commission, Water Resources Summary, no. 7, 17 p.

Halberg, H.N., 1977, Use of water in Arkansas, 1975: State of Arkansas Geological Commission Water Resources Summary, no. 9, 28 p.

Halberg, H.N., Bryant, C.T., and Hines, M.S., 1968, Water resources of Grant and Hot Spring Counties, Arkansas: U.S. Geological Survey Water-Supply Paper 1857, 64 p.

Halberg, H.N., and Reed, J.E., 1964, Ground water resources of eastern Arkansas in the vicinity of U.S. Highway 70: U.S. Geological Survey Water-Supply Paper 1779–V, 38 p.

Halberg, H.N., and Stephens, J.W., 1966, Use of water in Arkansas, 1965: State of Arkansas Geological Commission Water Resources Summary, no. 5, 12 p.

Hale, H., 1926, City water supplies of Arkansas: Fayetteville, Ark., University of Arkansas Engineering Experiment Station Bulletin, no. 2, 100 p.

Hale, H., Baker, R.C., Walling, I.W., Parrish, D.M., Billingsley, G.A., 1947, Public water supplies of Arkansas: Fayetteville, Ark., University of Arkansas Bulletin, Research Series, no. 11, 104 p.

Haley, B.R., Glick, E.E., Bush, W.V., Clardy, B.F., Stone, C.G., Woodward, M.B., and Zachry, D.L., 1993, Geologic map of Arkansas: U.S. Geological Survey, 1 sheet.

Hall, A.P., and Holland, T.W., 1984, Water use in Arkansas, 1981: U.S. Geological Survey Water Resources Investigation 84–4070, 1 sheet.

Hanson, R.T., Newhouse, M.W., and Dettinger, M.D., 2004, A methodology to assess relations between climatic variability and variations in hydrologic time series in the southwestern United States: Journal of Hydrology, v. 287, no. 1–4, p. 252–269.

Harrington, A.D., and Childers, R.A., 1985, Arkansas directory of manufacturers (1984 ed.): Arkansas Industrial Development Foundation, 324 p.

Hart, R.M., and Clark, B.R., 2008, Geophysical log database for the Mississippi Embayment Regional Aquifer Study (MERAS): U.S. Geological Survey Scientific Investigations Report 2008–5192, 8 p.

Hart, R.M., Clark, B.R., and Bolyard, S.E., 2008, Digital surfaces and thicknesses of selected hydrogeologic units within the Mississippi Embayment Regional Aquifer Study (MERAS): U.S. Geological Survey Scientific Investigations Report 2008–5098, 33 p.

Harvey, E.J., 1980, Ground water in the Springfield-Salem Plateaus of southern Missouri and northern Arkansas: U.S. Geological Survey Water-Resources Investigations 80–101, 66 p.

Hays, P.D., 1999, Sustainable yield estimation for the Sparta aquifer in Union County, Arkansas: U.S. Geological Survey Water-Resources Investigations Report 99–4274, 18 p.

Hays, P.D., 2000, Sustainable-yield estimation for the Sparta Aquifer in Union County, Arkansas: U.S. Geological Survey Water-Resources Investigations Report 99–4274, 17 p.

Hays, P.D., 2001, Simulated response to recharge augmentation of the Sparta aquifer in southeastern Arkansas: U.S. Geological Survey Water-Resources Investigations Report 01–4039, 14 p.

Hays, P.D., and Fugitt, D.T., 1999, The Sparta aquifer in Arkansas' critical ground-water areas—Response of the aquifer to supplying future water needs: U.S. Geological Survey Water-Resources Investigations Report 99–4075, 6 p.

Hays, P.D., Lovelace, J.K., and Reed, T.B., 1998, Simulated response to pumping stress in the Sparta aquifer of southeastern Arkansas and north-central Louisiana, 1998–2027: U.S. Geological Survey Water-Resources Investigations Report 98–4121, 25 p.

Hays, P.D., and McKee, P.W., 2003, The Sparta aquifer—A sustainable regional resource?: U.S. Geological Survey Fact Sheet FS–111–02, 4 p.

Healy, R.W., 2010, Estimating groundwater recharge: Cambridge, New York, Cambridge University Press, 256 p.

Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chap. A3, 522 pages.

Hem, J.D., 1989, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Henry, C., Daniels, M., and Hardke, J., 2013, Water management, *in* Hardke, J.T., ed., Arkansas rice production handbook: University of Arkansas Cooperative Extension Service, Little Rock, Ark., p. 103–122.

Hewitt, F.A., Baker, R.C., and Billingsley, G.A., 1949, Ground-water resources of Ashley County, Arkansas: Arkansas University, Institute of Science and Technology, Research Series 14, 35 p.

Hill, R.T., 1888, The Neozoic geology of southwestern Arkansas, *in* Annual report of the Geological Survey of Arkansas: Little Rock, Ark., Press Printing Co., v. 2, p. 1–259.

Hines, M.S., 1975, Flow-duration and low-flow frequency determinations of selected Arkansas streams: Arkansas Geological Survey, Water Resources Circular 12, 66 p.

Hines, M.S., Plebuch, R.O., and Lamonds, A.G., 1972, Water resources of Clay, Greene, Craighead, and Poinsett Counties, Arkansas: U.S. Geological Survey Hydrologic Atlas 337, 2 maps.

Hobza, C.M., 2005, Ground-water quality near a swine waste lagoon in a mantled karst terrane in northwestern Arkansas: Fayetteville, University of Arkansas, M.S. thesis, 76 p.

Holland, T.W., 1981, Use of water in Arkansas, 1980: State of Arkansas Geological Commission Water Resources Summary, no. 14, 30 p.

Holland, T.W., 1987, Use of water in Arkansas, 1985: State of Arkansas Geological Commission Water Resources Summary, no. 16, 27 p.

Holland, T.W., 1993, Water use in Arkansas, 1990: U.S. Geological Survey Open-File Report 93–48, 9 p.

Holland, T.W., 1999, Water use in Arkansas, 1995: U.S. Geological Survey Open-File Report 99–188, 1 sheet.

Holland, T.W., 2004, Estimated water use in Arkansas, 2000: U.S. Geological Survey Scientific Investigations Report 2004–5230, 31 p.

Holland, T.W., 2007, Water use in Arkansas, 2005: U.S. Geological Survey Scientific Investigations Report 2007–5241, 32 p.

Holland, T.W., and Hall, A.P., 1986, Water use in Arkansas, 1982: U.S. Geological Survey Water-Resources Investigations Report 85–4282, 1 sheet.

Holman, I.P., 2006, Climate change impacts on groundwater recharge—Uncertainty, shortcomings, and the way forward?: Hydrogeology Journal, v. 14, no. 5, p. 637–647.

Hon, Rudolph, Doherty, Kevin, Davidson, Thomas, Brandon, W.C., Stein, C.L., and McTigue, D.F., 2002, Arsenic sources and pathways in the overburden of central Massachusetts: Arsenic in New England—A Multi-Discipline Scientific Conference, Manchester, N.H., May 29–31, 2002, 2 p.

Hosman, R.L., 1964, The Carrizo Sand, a potential aquifer in south-central Arkansas: U.S. Geological Survey Professional Paper 501–D, p. 158–160.

Hosman, R.L., 1982, Outcropping Tertiary units in southern Arkansas: U.S. Geological Survey Miscellaneous Investigations Series I–1405, 1 sheet.

Hosman, R.L., 1988, Geohydrologic framework, Gulf Coastal Plain: U.S. Geological Survey Hydrologic Investigations Atlas HA–695, 2 sheets.

Hosman, R.L., 1996, Regional stratigraphy and subsurface geology of Cenozoic deposits, Gulf Coastal Plain, South-Central United States: U.S. Geological Survey Professional Paper 1416–G, 35 p.

Hosman, R.L., Long, A.T., Lambert, T.W., Jeffery, H.G., and others, 1968, Tertiary aquifers in the Mississippi embayment, with discussions of quality of the water: U.S. Geological Survey Professional Paper 448–D, 29 p.

Hosman, R.L., and Weiss, J.S., 1991, Geohydrologic units of the Mississippi embayment and Texas coastal uplands aquifer systems, South-Central United States: U.S. Geological Survey Professional Paper 1416–B, 19 p.

Howe, W.B., and Konig, J.W., 1961, The stratigraphic succession in Missouri: Missouri Geologic Survey and Water Resources Division, v. 40, 185 p.

Hudson, M.R., and Cox, R.T., 2003, Late Paleozoic tectonics of the southern Ozark dome, *in* Cox, R.T., comp., Field trip guidebook for joint South-Central and Southeastern sections: Geological Society of America, Tennessee Division of Geology Report of Investigations 51, p. 15–32.

Hudson, M.R., Mott, D.N., Turner, K.J., and Murray, K.E., 2005, Geologic controls on a transition between karst aquifers at Buffalo National River, northern Arkansas, *in* Kuniansky, E.L., 2005, U.S. Geological Survey Karst Interest Group Proceedings, Rapid City, S.D., September 12–15, 2005: U.S. Geological Survey Scientific Investigations Report 2005–5160, p. 143.

Hudson, M.R., and Turner, K.J., 2007, Geologic map of the Boxley quadrangle, Newton and Madison Counties, Arkansas: U.S. Geological Survey Scientific Investigations Map 2991, 1:24,000 scale.

Hudson, M.R., Turner, K.J., and Bitting, C., 2011, Geology and karst landscapes of the Buffalo National River area, northern Arkansas, *in* Kuniansky, E.L., ed., U.S. Geological Survey Karst Interest Group Proceedings, Fayetteville, Ark., April 26–29, 2011: U.S. Geological Survey Scientific Investigations Report 2011–5031, p. 191–212.

Hudson, M.R., Turner, K.J., and Trexler, C.C., 2009, Regional joint analysis for the Buffalo National River area of northern Arkansas—Implications for tectonic history and landscape influence: Geological Society of America Abstracts with Programs, v. 41, no. 7, p. 367.

Huetter, T.A., Van Schaik, E.J., and Kresse, T.M., 1997, Report on the third sampling of the Omaha Monitoring Area: Arkansas Department of Pollution Control and Ecology, WQ97–06–3, 44 p.

Huff, G.F., and Bonck, J.P., 1993, Saltwater in shallow aquifers in east-central and northeastern Louisiana and southeastern Arkansas: U.S. Geological Survey Open-File Report 93–494, 29 p.

Hunrichs, R.A., 1983, Identification and classification of perennial streams of Arkansas: U.S. Geological Survey Water-Resources Investigations Report 83–4063, 1 sheet.

Imes, J.L., and Emmett, L.F., 1994, Geohydrology of the Ozark Plateaus aquifer system in parts of Missouri, Arkansas, Oklahoma, and Kansas: U.S. Geological Survey Professional Paper 1414–D, 127 p.

Imes, J.L., and Fredrick, B.S., 2002, Using dye-tracing and chemical analyses to determine effects of a wastewater discharge to Jam Up Creek on water quality of Big Spring, southeastern Missouri, 2001: U.S. Geological Survey Fact Sheet 103–02, 1 sheet.

Imes, J.L., and Kleeschulte, M.J., 1996, Seasonal groundwater level changes (1990–1993) and flow patterns in the Fristoe unit of the Mark Twain National Forest, southern Missouri: U.S. Geological Survey Water-Resources Investigations Report 95–4096, 1 sheet.

Imes, J.L., and Smith, B.J., 1990, Areal extent, stratigraphic relation, and geohydrologic properties of regional geohydrologic units in southern Missouri: U.S. Geological Survey Hydrologic Investigations Atlas HA–711–I, 3 sheets, scale 1:750,000.

Jagucki, M.L., Katz, B.G., Crandall, C.A., and Eberts, S.M., 2009, Assessing the vulnerability of public-supply wells to contamination—Floridian aquifer system near Tampa, Florida: U.S. Geological Survey Fact Sheet 2009–3062, 6 p.

Johnson, Sherrel, 2004, Ouachita River alternative water supply project: Union County Water Conservation Board, accessed June 13, 2013, at http://ucwcb.org/.

Joseph, R.L., 1998a, Potentiometric surface of the Sparta aquifer in eastern and south-central Arkansas, and the Memphis Aquifer in east-central Arkansas, October 1996–July 1997: U.S. Geological Survey Scientific Investigations Report 97–4282, 19 p.

Joseph, R.L., 1998b, Potentiometric surfaces of aquifers in the Cockfield Formation in southeastern Arkansas and the Wilcox Group in southern and northeastern Arkansas, October 1996–July 1997: U.S. Geological Survey Water-Resources Investigations Report 98–4084, 19 p.

Joseph, R.L., 1999, Status of water levels and selected water-quality conditions in the Mississippi River Valley alluvial aquifer in eastern Arkansas, 1998: U.S. Geological Survey Water-Resources Investigations Report 99–4035, 54 p.

Joseph, R.L., 2000, Status of water levels and selected water-quality conditions in the Sparta and Memphis aquifers in eastern and south-central Arkansas, 1999: U.S. Geological Survey Scientific Investigations Report 2000–4009, 34 p.

Kaliba, A.R., and Engle, C.R., 2006, Chicot County, Arkansas—The economic impact of the catfish industry: University of Arkansas at Pine Bluff Cooperative Extension Program ETB257, 13 p.

Keener, R., 1972, Septic tank contamination of groundwater: University of Arkansas, Fayetteville, Ark., 23 p.

Kenny, J.F., Barber, N.L., Hutson, S.S., Linsey, K.S., Lovelace, J.K., and Maupin, M.A., 2009, Estimated use of water in the United States in 2005: U.S. Geological Survey Circular 1344, 52 p.

Kilpatrick, J.M., 1992, Simulated response to future pumping in the Sparta aquifer, Union County, Arkansas: U.S. Geological Survey Water-Resources Investigations Report 91–4161, 25 p.

Kilpatrick, J.M., and Ludwig, A.H., 1990a, Ground-water resources of the Arkansas River Basin in Arkansas: U.S. Geological Survey Open-File Report 88–725, 45 p.

Kilpatrick, J.M., and Ludwig, A.H., 1990b, Ground-water resources of the upper White River Basin in Arkansas: U.S. Geological Survey Open-File Report 88–724, 48 p.

Kindinger, J.L., Davis, J.B., Flocks, J.G., 2000, Subsurface characterization of selected water bodies in the St. Johns River Water Management District, Northeast Florida: U.S. Geological Survey Open-File Report 2000–180, 7 p.

Kinniburgh, D.G., and Smedley, P.L, eds., 2001, Arsenic contamination of groundwater in Bangladesh, final report: British Geological Survey, BGS Report WC–00–19, v. 2, 267 p.

Klaer, F.H., Jr., 1940, Memphis, *in* Meinzer, O.E., Wenzel, L.K., and others, Water levels and artesian pressure in observation wells in the United States in 1940, pt. 2, southeastern States: U.S. Geological Survey Water-Supply Paper 907, p. 92–101.

Klein, Howard, Baker, R.C., and Billingsley, G.A., 1950, Ground-water resources of Jefferson County, Arkansas: Arkansas University, Institute of Science and Technology Research Series 19, 44 p.

Kleiss, B.A., Coupe, R.H., Gonthier, G.J., and Justus, B.J., 2000, Water quality in the Mississippi embayment, Mississippi, Louisiana, Arkansas, Missouri, Tennessee, and Kentucky, 1995–98: U.S. Geological Survey Circular 1208, 36 p., accessed June 13, 2013, at http://pubs.water.usgs.gov/circ1208/.

Kline, S.W., 2003, A model for groundwater flow in the alluvial aquifer of the Arkansas River at Dardanelle, Arkansas: Arkansas Geological Commission Water Resources Circular, Issue 18, 70 p.

Kline, S.W., Kresse, T.M., Fazio, J.A., Prior, W.L., Hanson, W.D., Miller, R.A., and Treece, T.M., 2006, The Arkansas River's alluvial aquifer in central Arkansas—Physical hydrology of the aquifer at Dardanelle [abs.]: Fayetteville, Ark., Proceedings of the Arkansas Water Resources Center Annual Conference, accessed May 13, 2013, at http://www.uark.edu/depts/awrc/Publications/2006AWRCConference/TrifoldLF.pdf.

Knierim, K.J., Pollock, E.D., and Hays, P.D., 2011, Using labeled isotopes to trace groundwater flowpaths in a northwestern Arkansas cave, *in* Kuniansky, E.L., ed., U.S. Geological Survey Karst Interest Group Proceedings, Fayetteville, Ark., April 26–29, 2011: U.S. Geological Survey Scientific Investigations Report 2011–5031, p. 67–73.

Knierim, K.J., Pollock, E.D., and Hays, P.D., 2013, Using isotopes of dissolved inorganic carbon species and water to separate sources of recharge in a cave spring, northwestern Arkansas, USA: Acta Carsologica, v. 42, p. 261–276.

Knight, R.D., 1954, The Gunter Member of the Gasconade Formation (Lower Ordovician) in southern Missouri: Missouri Geological Survey and Water Resources Report of Investigations, no. 17, p. 51–56.

Konikow, L.F., 2013, Groundwater depletion in the United States (1900−2008): U.S. Geological Survey Scientific Investigations Report 2013−5079, 63 p., accessed June 13, 2013, at http://pubs.usgs.gov/sir/2013/5079.

Kresse, T.M., 1991, A hydrogeological and geochemical site characterization of a proposed landfill site, Searcy County, Arkansas: Groundwater Journal, v. 29, no. 3, p. 444.

Kresse, T.M., and Clark, B.R., 2008, Occurrence, distribution, sources, and trends of elevated chloride concentrations in the Mississippi River Valley alluvial aquifer in southeastern Arkansas: U.S. Geological Survey Scientific Investigations Report 2008–5193, 34 p.

Kresse, T.M., and Fazio, J.A., 2002, Pesticides, water quality, and geochemical evolution of ground water in the alluvial aquifer, Bayou Bartholomew Basin, Arkansas: Arkansas Department of Environmental Quality, Water Quality Report WQ02–05–1, 111 p.

Kresse, T.M., and Fazio, J.A., 2003, Occurrence of arsenic in ground waters of Arkansas and implications for source and release mechanisms: Arkansas Department of Pollution Control and Ecology, Water Quality Report WQ03–03–01, 35 p.

Kresse, T.M., and Fazio, J.A., 2004, Groundwater quality and geochemistry in the Strawberry River watershed in northeast Arkansas: Arkansas Department of Environmental Quality Water Quality Report WQ04–01–1, 54 p.

Kresse, T.M., Fazio, J.A., Hays, P.D., and Stanton, G.P., 2000, Sources of saltwater intrusion in the alluvial aquifer in parts of Chicot County, Arkansas: Proceedings of Environmental Hydrology of the Arkansas Water Resource Center Annual Conference, April 4–5, 2000, Fayetteville, Ark., p. 1–6.

Kresse, T.M., Fazio, J.A., Miller, R.A., and Kline, S.W., 2006, The Arkansas River's alluvial aquifer in central Arkansas—Geochemistry of the aquifer at Dardanelle [abs.]: Fayetteville, Ark., Proceedings of the Arkansas Water Resources Center Annual Conference, accessed September 29, 2012, at http://www.uark.edu/depts/awrc/Publications/2006AWRCConference/TrifoldLF.pdf.

Kresse, T.M., and Hays, P.D., 2009, Geochemistry, comparative analysis, and physical and chemical characteristics of the thermal waters east of Hot Springs National Park, Arkansas, 2006–2009: U.S. Geological Survey Scientific Investigations Report 2009–5263, 48 p.

Kresse, T.M., Hays, P.D., Hudson, M.R., and Kaufman, J.E., 2011, The influence of land use and occurrence of sinkholes on nitrogen transport in the Ozark Plateaus in Arkansas and Missouri, *in* Kuniansky, E.L., ed., U.S. Geological Survey Karst Interest Group Proceedings, Fayetteville, Ark., April 26–29, 2011: U.S. Geological Survey Scientific Investigations Report 2011–5031, 212 p.

Kresse, T.M., and Huetter, T.A., 1999, Ground-water resources and water quality in the vicinity of Pine Bluff municipal area, Jefferson County, Arkansas: Arkansas Department of Environmental Quality, Water Quality Report WQ99–10–1, 79 p.

Kresse, T.M., and Van Schaik, E.J., 1996, Preliminary results of pesticide investigation, Augusta, Arkansas: Arkansas Department of Pollution Control and Ecology, Water Quality Report WQ96–11–1, 44 p.

Kresse, T.M., Van Schaik, E.J., Wise, Jim, and Huetter, T.A., 1997, Occurrence of pesticides in alluvial aquifer of eastern Arkansas: Arkansas Department of Pollution Control and Ecology, Water Quality Report WQ97–10–1, 39 p.

Kresse, T.M., Warner, N.R., Hays, P.D., Down, Adrian, Vengosh, Avner, and Jackson, R.B., 2012, Shallow groundwater quality and geochemistry in the Fayetteville Shale gas-production area, north-central Arkansas, 2011: U.S. Geological Survey Scientific Investigations Report 2012–5273, 31 p.

Krinitzsky, E.L., and Wire, J.C., 1964, Ground water in alluvium of Lower Mississippi Valley (upper and central areas): U.S. Army Corps of Engineers, Waterways Experiment Station Technical Report 3–658, v. 1–2, 400 p.

Kundzewicz, Z.W., Mata, L.J., Arnell, N.W., Döll, P., Kabat, P., Jiménez, B., Miller, K.A., Oki, T., Sen, Z., and Shiklomanov, I.A., 2007, Freshwater resources and their management, *in* Parry, M.L., Canziani, O.F., Palutikof, J.P., Linden, P.J. van der, and Hanson, C.E., eds., Climate change 2007—Impacts, adaptation and vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom, p. 173–210.

Laincz, Jozef, 2011, Investigation of nitrate processing in the interflow zone of mantled karst, northwestern Arkansas, *in* Kuniansky, E.L., ed., U.S. Geological Survey Karst Interest Group Proceedings, Fayetteville, Ark., April 26–29, 2011: U.S. Geological Survey Scientific Investigations Report 2011–5031, p. 75–83.

Lamonds, A.G., 1972, Water-resources reconnaissance of the Ozark plateaus province, northern Arkansas: U.S. Geological Survey Hydrologic Atlas 383, 2 sheets.

Lamonds, A.G., Hines, M.S., and Plebuch, R.O., 1969, Water resources of Randolph and Lawrence Counties, Arkansas: U.S. Geological Survey Water-Supply Paper 1879–B, 45 p.

Lamonds, A.G., and Stephens, J.W., 1969, Water resources data for the Ozark Plateaus Province, Arkansas: U.S. Geological Survey Unnumbered Open-File Report, 18 p.

Lautier, Jeffrey, 1981, Geology of the subsurface Eocene Cockfield Formation in southern Allen Parish, Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 31, p. 125–133.

Leach, D.L., and Rowan, E.L., 1986, Genetic link between Ouachita foldbelt tectonism and Mississippi Valley-type lead-zinc deposits of the Ozarks: Geology, v. 14, p. 931–935.

Leidy, V.A., and Morris, E.E., 1990a, Ground-water quality and preliminary assessment of the potential for contamination beneath agricultural lands in central Lonoke County, Arkansas: U.S. Geological Survey Water-Resources Investigations Report 90–4099, 31 p.

Leidy, V.A., and Morris, E.E., 1990b, Hydrogeology and quality of ground water in the Boone Formation and Cotter Dolomite in karst terrain of northwestern Boone County, Arkansas: U.S. Geological Survey Water-Resources Investigations Report 90–4066, 57 p.

Leidy, V.A., and Taylor, R.E., 1992, Overview of susceptibility of aquifers to contamination, Union County, Arkansas: U.S. Geological Survey Water-Resources Investigations Report 92–4094, 95 p.

Looney, J.W., 1990, An update on Arkansas water law—Is the riparian rights doctrine dead?: Arkansas Law Review, v. 43, p. 643–708.

Looney, J.W., 1995, Enhancing the role of water districts in ground water management and surface water utilization in Arkansas: Arkansas Law Review, v. 48, p. 573–630.

Ludwig, A.H., 1973, Water resources of Hempstead, Lafayette, Little River, Miller, and Nevada Counties, Arkansas: U.S. Geological Survey Water-Supply Paper 1998, 41 p.

Ludwig, A.H., 1992, Flow duration and low-flow characteristics of selected Arkansas streams: U.S. Geological Survey Water-Resources Investigations Report 92–4026, 77 p.

Ludwig, A.H., and Terry, J.E., 1980, Methods and applications of digital-model simulation of the Red River alluvial aquifer, Shreveport to the mouth of the Black River, Louisiana: U.S. Geological Survey Water-Resources Investigations Report 79–114, 103 p.

Macaulay, Calum, 2005, Low temperature quartz cementation of the Upper Cretaceous white sandstone of Lochaline, Argyll, Scotland: Department of Geology and Geophysics, University of Edinburgh, Departmental Publication 4, 4 p.

MacDonald, H.C., Jeffus, H.M., Steele, K.F., Coughlin, T.L., Kerr, K.M., and Wagner, G.H., 1976, Groundwater pollution in Arkansas: University of Arkansas at Fayetteville, Arkansas Agricultural Experiment Station Special Report, no. 25, 7 p.

MacDonald, H.C., Zachry, D.L., Jeffus, H.C., 1977, Northern Arkansas groundwater inventory: Arkansas Water Resources Center, Fayetteville, Ark., no. MSC–26, 186 p.

Macfarlane, P.A., and Hathaway, L.R., 1987, The hydrogeology and chemical quality of groundwaters from the lower Paleozoic aquifers in the tri-State region of Kansas, Missouri, and Oklahoma: Kansas Geological Survey Groundwater Series 9, 37 p.

Mack, L.E., 1963, Water law in Arkansas: Arkansas Industrial Development Commission and Arkansas University Industrial Research and Extension Center, 74 p.

MacKichan, K.A., 1951, Estimated use of water in the United States, 1950, U.S. Geological Survey: U.S. Geological Survey Circular 115, 13 p.

MacKichan, K.A., 1957, Estimated use of water in the United States, 1955, U.S. Geological Survey: U.S. Geological Survey Circular 398, 18 p.

Mahon, G.L., and Ludwig, A.H., 1990, Simulation of ground-water flow in the Mississippi River Valley alluvial aquifer in eastern Arkansas: U.S. Geological Survey Water-Resources Investigations Report 89–4145, 26 p.

Mahon, G.L., and Poynter, D.T., 1993, Development, calibration, and testing of ground-water flow models for the Mississippi River Valley alluvial aquifer in eastern Arkansas using one-square-mile cells: U.S. Geological Survey Water-Resources Investigations Report 92–4106, 33 p., 11 pls.

Mahon, G.L., Terry, J.E., and Peralta, R.C., 1989, Water-resources development alternatives for the Mississippi alluvial plain in eastern Arkansas: Proceedings of the 25th Annual Conference of the American Water Resources Association (AWRA), Herndon, Va., p. 31–35.

Mahon, J.C., 1979, The history of Riceland Foods: Craighead County Historical Quarterly, v. 17, p. 10–17.

Manger, W.L., 1983, The geologic provinces of Arkansas: Arkansas Naturalist, v. 1, no. 7, p. 1–6.

Marshall, A.S., 2005, Establishing a land subsidence observation network using static and kinematic GPS in the Grand Prairie region of eastern Arkansas: Fayetteville, University of Arkansas, M.S. thesis, 57 p.

Marshall, David, Brahana, J.V., and Davis, R.K., 1998, Resuspension of viable sediment-bound enteric pathogens in shallow karst aquifers, *in* Brahana, J.V., Eckstein, Yoram, Ongley, L.K., Schneider, Robert, and Moore, J.E., eds., Gambling with groundwater—Physical, chemical, and biological aspects of aquifer-stream relations: Las Vegas, Nevada, International Association of Hydrogeologists/American Association of Hydrogeologists, Proceedings, p. 179–186.

McArthur, J.M., Ravenscroft, Peter Safiullah, S., and Thirlwall, M.F., 2001, Arsenic in groundwater—Testing pollution mechanisms for sedimentary aquifers in Bangladesh: Water Resources Research, v. 37, no. 1, p. 109–117.

McFarland, J.D., 2004, Stratigraphic summary of Arkansas: Arkansas Geological Commission Information Circular 36, 38 p.

McFarland, J.D., Bush, W.V., Wise, O.A., and Holbrook, D.F., 1979, A guidebook to the Ordovician-Mississippian rocks of north-central Arkansas: Arkansas Geological Commission GB–79–1, 25 p.

McFarland, M.L., Lemon, R.G., and Stichler, C.R., 1998, Irrigation water quality—Critical salt levels for peanuts, cotton, corn and grain sorghum: Texas Agricultural Extension Service, Texas A&M University, 4 p.

McFarland, J.D., and Prior, William, 2005, North Arkansas ground water investigations—Cave City Graben area: Arkansas Geological Commission, Water Resources Summary 17, 17 p.

McGee, W.J., 1888, Three formations of the Middle Atlantic Slope: American Journal of Science, v. 35, no. 206, p. 120–143.

McGraw, K., Popp, J., and Miller, W., 2012, Economic contribution of agriculture to the Arkansas economy in 2010: University of Arkansas Cooperative Extension Service Research Report 991, 49 p.

McGuiness, C.L., 1951, Water law with special reference to ground water: U.S. Geological Survey Circular 117, 30 p.

McKee, P.W., and Clark, B.R., 2003, Development and calibration of a ground-water flow model for the Sparta aquifer of southeastern Arkansas and north-central Louisiana and simulated response to withdrawals, 1998–2027: U.S. Geological Survey Water-Resources Investigations Report 03–4132, 68 p.

McKee, P.W., Clark, B.R., and Czarnecki, J.B., 2004, Conjunctive-use optimization and sustainable-yield estimation for the Sparta aquifer of southeastern Arkansas and north-central Louisiana: U.S. Geological Survey Water-Resources Investigations Report 03–4231, 30 p.

McKnight, E.T., 1935, Zinc and lead deposits of northern Arkansas: U.S. Geological Survey Bulletin 853, 311 p.

McQueen, H.S., 1931, Insoluble residues as a guide in stratigraphic studies: Missouri Bureau of Geology and Mines, 56th Biennial Report of the State Geologist, 1929–1930, app. 1, p. 102–131.

McWreath, H.C., III, Nelson, J.D., and Fitzpatrick, D.J., 1991, Simulated response to pumping stresses in the Sparta aquifer, northern Louisiana and southern Arkansas: Louisiana Department of Transportation and Development Water Resources Technical Report No. 51, 51 p.

Melton, R.W., 1976, The regional geohydrology of the Roubidoux and Gasconade Formations, Arkansas and Missouri: Fayetteville, University of Arkansas, M.S. thesis, 160 p.

Merrill, R.K., Sims, J.J., Jr., Gann, D.E., and Liles, K.J., 1985, Newton County geology and mineral resources [Mississippi]: Mississippi Office of Geology Bulletin, no. 126, 108 p.

Mesko, T.O., and Imes, J.L., 1995, Discharge of ground water along the Ozark escarpment in southeastern Missouri and northeastern Arkansas: U.S. Geological Survey Water-Resources Investigations Report 95–4103, 12 p.

Meyer, Meyer, LeCroix, Hixson, Inc.; Lazenby and Associates; Louisiana Tech University School of Business; URS Corporation; Smoot, C.W.; and Frye-Magee, 2002, Sparta groundwater study—A study commissioned by the Sparta Groundwater Conservation District Commission, final report: Sparta Groundwater Conservation District Commission, 93 p.

Miser, H.D., and Purdue, A.H., 1919, Gravel deposits of the De Queen and Caddo Gap quadrangles, Arkansas-Oklahoma: U.S. Geological Survey Bulletin 690–B, p. 15–30.

Morgan, R., 2012, Water supply and source water protection issues in northwest Arkansas, *in* Annual Watershed and Research Conference, 2012, Proceedings: Arkansas Water Resources Center, accessed September 29, 2012, at http://www.uark.edu/depts/awrc/conference.html.

Morris, E.E., and Bush, W.V., 1986, Extent and source of saltwater intrusion into the alluvial aquifer near Brinkley, Arkansas, 1984: U.S. Geological Survey Water-Resources Investigations Report 85–4322, 123 p.

Mott, D.N., Hudson, M.R., and Aley, T.J., 1999, Nutrient loads traced to interbasin groundwater transport at Buffalo National River, Arkansas, *in* Harmon, D., ed., Proceedings of the 10th Conference on Research and Resource Management in Parks and Public Lands, George Wright Society, Hancock, Mich., p. 114–121.

Mott, D.N., Hudson, M.R., and Aley, T.J., 2000, Hydrologic investigations reveal interbasin recharge contributes significantly to detrimental nutrient loads at Buffalo National River, Arkansas, *in* Proceedings of Arkansas Water Resources Center Annual Conference MSC–284, Fayetteville, Ark., p. 13–20.

Mueller, S.H., Goldfarb, R.J., Farmer, G.L., Sanzolone, R., Adams, M., and Theodorakus, P., 2001, A seasonal study of the arsenic and groundwater geochemistry in Fairbanks, Alaska: U.S. Geological Survey Workshop on Arsenic in the Environment, Denver, Colo., February 2001, 4 p.

Murray, K.E., and Hudson, M.R., 2002, Three-dimensional geologic framework modeling for a karst region in the Buffalo National River, Arkansas, *in* Kuniansky, E.L., ed., U.S. Geological Survey Karst Interest Group Proceedings, Atlanta, Ga., August 20–22, 2002: U.S. Geological Survey Scientific Investigations Report 02–4174, 89 p.

Muse, P.S., 1982, Ground-water resource evaluation of southwest Washington County, Arkansas: Fayetteville, University of Arkansas, M.S. thesis, 175 p.

National Research Council, 2002, Estimating water use in the United States—A new paradigm for the National Water-Use Information Program: The National Academies Press, Washington, D.C., 190 p., accessed May 3, 2013, at http://www.nap.edu/catalog/10484.html.

National Wildlife Federation, 2014, Ecosystem services: National Wildlife Federation, accessed March 7, 2014, at http://www.nwf.org/Wildlife/Wildlife-Conservation/Ecosystem-Services.aspx.

Neely, B.L., Jr., 1991, Arkansas floods and droughts *in* Paulson, R.W., Chase, E.B., Roberts, R.S., and Moody, D.W., compilers, National Water Summary 1988–89—Hydrologic events and floods and droughts: U.S. Geological Survey Water Supply Paper 2375, p. 189–195.

Nichols, T.W., Vendrell, P.F., and Steele, K.F., 1993, Completion report, Arkansas State pesticides in ground water monitoring project: Fayetteville, Ark., Arkansas Water Resources Center, Miscellaneous Report no. 136, 50 p.

Nichols, T.W., Vendrell, P.F., Steele, K.F., and Scott, H.D., 1996, Completion report, Arkansas State pesticides in ground water monitoring project—Phase V, vulnerable areas in Jackson, Monroe, Lawrence, and Lonoke Counties: Fayetteville, Ark., Arkansas Water Resources Center, Miscellaneous Report no. 199, 100 p.

Nickson, R.T., McArthur, J.M., Ravenscroft, Peter, Burgess, W.G., and Ahmed, K.M., 2000, Mechanism of arsenic release to groundwater, Bangladesh and West Bengal: Applied Geochemistry, v. 15, no. 2000, p. 403–413.

Nordstrom, D.K., Alpers, C.N., Ptacek, C.J., and Blowes, D.W., 2000, Negative pH and extremely acidic mine waters from Iron Mountain, California: Environmental Science and Technology, v. 34, p. 254–258.

Nunn, J.A., and Lin, Guichang, 2002, Insulating effect of coals and organic rich shales—Implications for topography driven fluid flow, heat transport, and genesis of ore deposits in the Arkoma Basin and Ozark Plateau: Basin Research, v. 14, no. 2, p. 129–145.

Nuttall, Thomas, 1821, A journal of travels into the Arkansas Territory during the year 1819: Philadelphia, Pennsylvania, T.H. Palmer, 296 p.

Ogden, A.E., 1979, Hydrogeologic and geochemical investigation of the Boone-St. Joe Limestone aquifer in Benton County, Arkansas: Fayetteville, Ark., Arkansas Water Resources Center, no. PUB–0068, 133 p.

Onellion, F.E., 1956, Geology and ground-water resources of Drew County, Arkansas: Arkansas Geology and Conservation Commission, Water Resources Circular 4, 32 p.

Onellion, F.E., and Criner, J.H., Jr., 1955, Ground-water resources of Chicot County, Arkansas: Arkansas Geology and Conservation Commission Water Resources Circular 3, 27 p.

Orndorff, R.C., Weary, D.J., and Harrison, R.W., 2006, The role of sandstone in the development of an Ozark karst system, south-central Missouri: Geological Society of America Special Papers, 404, p. 31–38.

Ozark Mountain Regional Public Water Authority, 2013, Project history: Ozark Mountain Regional Public Water Authority, accessed March 2, 2013, at http://www.ozarkmountainregionalpwa.org/project-history.html.

Palmer, A.N., 2011, Paleokarst of the U.S.A.—A brief review, *in* Kuniansky, E.L., ed., U.S. Geological Survey Karst Interest Group Proceedings, Fayetteville, Ark., April 26–29, 2011: U.S. Geological Survey Scientific Investigations Report 2011–5031, p. 7–15.

Parker, J.S., 2001, A changing landscape—Environmental conditions and consequences of the 1920s: Arkansas Historical Quarterly, v. 60, no. 1, p. 30–52.

Parr, D.L., 1987, The effect of season and rain events on the chemistry of selected spring water in limestone terrain, Washington County, Arkansas: Fayetteville, University of Arkansas, M.S. thesis, 135 p.

Payne, J.N., 1968, Hydrologic significance of the lithofacies of the Sparta Sand in Arkansas, Louisiana, Mississippi, and Texas: U.S. Geological Survey Professional Paper 569–A, 17 p.

Payne, J.N., 1970, Geohydrologic significance of lithofacies of the Cockfield Formation of Louisiana and Mississippi and the Yegua Formation of Texas: U.S. Geological Survey Professional Paper 569–B, 14 p.

Payne, J.N., 1972, Hydrologic significance of lithofacies of the Cane River Formation or equivalents of Arkansas, Louisiana, Mississippi, and Texas: U.S. Geological Survey Professional Paper 569–C, 17 p.

Payne, J.N., 1975, Geohydrologic significance of lithofacies of the Carrizo Sand of Arkansas, Louisiana, and Texas and the Meridian Sand of Mississippi: U.S. Geological Survey Professional Paper 569–D, 11 p.

Peralta, R.C., Cantiller, R.R.A., and Mahon, G.L., 1992, Maximizing sustainable ground water withdrawals comparing accuracy and computational requirements for steady- and unsteady-state digital modeling approaches, *in* Subitzky, Seymour, ed., Selected papers in the hydrologic sciences, 1988–1992: U.S. Geological Survey Water-Supply Paper 2340, p. 63–74.

Peralta, R.C., Cantiller, R.R.A., and Terry, J.E., 1995, Optimal large-scale conjunctive water-use planning—Case study: Journal of Water Resources Planning and Management, v. 121, no. 6, p. 471–478.

Peralta, R.C., Yazdanian, A., Killian, P.J., and Shulstad, R.N., 1985, Future Quaternary groundwater accessibility in the Grand Prairie—1993: University of Arkansas, Agricultural Experiment Station Bulletin, no. 877, 37 p.

Petersen, J.C., 1988, Statistical summary of selected water-quality data (water years 1975 through 1985) for Arkansas rivers and streams: U.S. Geological Survey Water-Resources Investigations Report 88–4112, 189 p.

Petersen, J.C., Broom, M.E., and Bush, W.V., 1985, Geohydrologic units of the Gulf Coastal Plain in Arkansas: U.S. Geological Survey Water-Resources Investigations Report 85–4116, 20 p.

Peterson, E.W., Davis, R.K., Brahana, J.V., and Orndorff, H.A., 2000, 17-β Estradiol as an indicator of animal waste contamination in mantled karst aquifers: Journal of Environmental Quality, v. 29, no. 3, p. 826–834.

Peterson, E.W., Davis, R.K., Brahana, J.V., and Orndorff, H.A., 2002, Movement of nitrate through regolith covered karst terrane, northwest Arkansas: Journal of Hydrology, v. 256, p. 35–47.

Plafcan, Maria, 1985, Ground-water levels in the alluvial aquifer in eastern Arkansas, 1984: U.S. Geological Survey Open-File Report 85–569, 26 p.

Plafcan, Maria, 1986, Ground-water levels in the alluvial aquifer in eastern Arkansas, 1985: U.S. Geological Survey Open-File Report 86–242, 29 p.

Plafcan, Maria, 1987, Ground-water levels in the alluvial aquifer in eastern Arkansas, 1986: U.S. Geological Survey Open-File Report 87–545, 31 p.

Plafcan, Maria, and Edds, Joe, 1986, Water level and saturated thickness maps of the alluvial aquifer in eastern Arkansas, 1984: U.S. Geological Survey Water-Resources Investigations Report 86–4014, 1 sheet.

Plafcan, Maria, and Fugitt, D.T., 1987, Water level maps of the alluvial aquifer in eastern Arkansas, 1985: U.S. Geological Survey Water-Resources Investigations Report 86– 4178, 1 sheet.

Plafcan, Maria, and Remsing, L.M., 1989, Water level maps of the alluvial aquifer in eastern Arkansas, 1986: U.S. Geological Survey Water-Resources Investigations Report 88–4067, 1 sheet.

Plebuch, R.O., 1961, Fresh water aquifers of Crittenden County, Arkansas: U.S. Geological Survey Water Resources Circular, no. 8, 65 p.

Plebuch, R.O., 1962, Changes in ground-water levels in deposits of Quaternary age in northeastern Arkansas: U.S. Geological Survey Water Resources Summary, no. 3, 10 p.

Plebuch, R.O., and Hines, M.S., 1967, Water resources of Pulaski and Saline Counties, Arkansas: U.S. Geological Survey Water-Supply Paper 1839–B, 25 p.

Plebuch, R.O., and Hines, M.S., 1969, Water resources of Clark, Cleveland, and Dallas Counties, Arkansas: U.S. Geological Survey Water-Supply Paper 1879–A, 32 p.

Pollock, E.D., Knierim, K.J., Hays, P.D., 2011, Seasonal carbon dynamics in a northwestern Arkansas cave—Linking climate and cave conditions: U.S. Geological Survey Karst Interest Group, U.S. Geological Survey Scientific Investigations Report 2011–5020, p. 37–43.

Prior, W.L., Howard, J.M., McFarland, J.D., and Hill, S.S., 1999, Roubidoux Formation and Gunter Sandstone Member of the Gasconade Formation, major aquifers in northern Arkansas: Arkansas Geological Commission, Water Resources Circular, no. 17, 45 p.

Pugh, A.L., 1998, Potentiometric surface of the Ozark aquifer in northern Arkansas, 1995: U.S. Geological Survey Water-Resources Investigations Report 98–4000, 7 p.

Pugh, A.L., 2008a, Summary of aquifer test data for Arkansas—1940–2006: U.S. Geological Survey Scientific Investigations Report 2008–5149, 33 p.

Pugh, A.L., 2008b, Potentiometric surface of the Ozark aquifer in northern Arkansas, 2007: U.S. Geological Survey Scientific Investigations Report 2008–5137, 16 p.

Pugh, A.L., 2010, Potentiometric surfaces and water-level trends in the Cockfield (upper Claiborne) and Wilcox (lower Wilcox) aquifers of southern and northeastern Arkansas, 2009: U.S. Geological Survey Scientific Investigations Report 2010–5014, 47 p.

Pugh, A.L., Westerfield, P.W., and Poynter, D.T., 1997, Thickness of the Mississippi River Valley alluvial aquifer in eastern Arkansas: U.S. Geological Survey Water-Resources Investigations Report 97–4049, 1 sheet.

Pugh, A.L., and Westerman, D.A., 2014, Mean annual, seasonal, and monthly precipitation and runoff in Arkansas, 1951–2011: U.S. Geological Survey Scientific Investigations Report 2014–5006, 40 p.

Pulley, H.J., and Beyrouty, C.A., 1996, Effect of salt type on soybean growth: Arkansas Soil Fertility Studies, Arkansas Agricultural Experiment Station Research Series, no. 45, p. 84–87.

Purdue, A.H., 1905, Water resources of the contact region between the Paleozoic and Mississippi embayment deposits in northern Arkansas: U.S. Geological Survey Water-Supply Paper 145, p. 88–119.

Purdue, A.H., 1910, The collecting area of the waters of the hot springs, Hot Springs, Arkansas: Journal of Geology, v. 18, p. 279–285.

Purdue, A.H., and Miser, H.D., 1916, Description of Eureka Springs and Harrison quadrangles (Arkansas-Missouri): U.S. Geological Survey Geologic Atlas, Folio 202, 21 p.

Quatrochi, P.M., 1996, Groundwater jurisdiction under the Clean Water Act—The tributary groundwater dilemma: Boston College Environmental Affairs Law Review, v. 23, accessed April 2, 2013, at http://lawdigitalcommons.bc.edu/ealr/vol23/iss3/.

Ragsdale, J.G., 2003, Oil development in south Arkansas, 1921–2001: South Arkansas Historical Journal, v. 3, p. 18–24, accessed May 1, 2013, at http://www.southark.edu/old/index.php/volumes-1-4.

Ravenscroft, Peter, 2003, An overview of the hydrogeology of Bangladesh, *in* Rahman, A.A, and Ravenscroft, P., eds., Groundwater resources and development in Bangladesh—Background to the arsenic crisis, agricultural potential and the environment: Dhaka, Bangladesh Centre for Advanced Studies, University Press Ltd., p. 43–86.

Reed, J.E., 1972, Analog simulation of water-level declines in the Sparta Sand, Mississippi embayment: U.S. Geological Survey Hydrologic Atlas 434, map, scale 1:250,000.

Reed, J.E., and Broom, M.E., 1979, Digital model of the Bayou Bartholomew alluvial aquifer-stream system, Arkansas: U.S. Geological Survey Open-File Report 79–685, 37 p.

Reed, T.B., 2003, Recalibration of a ground-water flow model of the Mississippi River Valley alluvial aquifer of northeastern Arkansas, 1918–1998, with simulations of water levels caused by projected ground-water withdrawals through 2049: U.S. Geological Survey Water-Resources Investigations Report 03–4109, 58 p.

Reed, T.B., 2004, Status of water levels and selected water-quality conditions in the Mississippi River Valley alluvial aquifer in eastern Arkansas, 2002: U.S. Geological Survey Scientific Investigations Report 2004–5129, 53 p.

Reilly, T.E., Dennehy, K.F., Alley, W.M., and Cunningham, W.L., 2008, Ground-water availability in the United States: U.S. Geological Survey Circular 1323, 70 p.

Renfroe, C.A., 1949, Petroleum exploration in eastern Arkansas with selected well logs: Arkansas Resources and Development Commission Bulletin 14, 159 p.

Renken, R.A., 1998, Groundwater atlas of the United States—Segment 5, Arkansas, Louisiana, Mississippi: U.S. Geological Survey Hydrologic Atlas 730–F, 28 p.

Richards, J.M., 2010, Groundwater-flow model and effects of projected groundwater use in the Ozark Plateaus aquifer system in the vicinity of Greene County, Missouri—1907–2030: U.S. Geological Survey Scientific Investigations Report 2010–5227, 106 p.

Richards, J.M., and Mugel, D.N., 2008, Potentiometric surface of the Ozark aquifer near Springfield, Missouri, 2006–07: U.S. Geological Survey Scientific Investigations Map 3003, 1 sheet.

Robinson, J.A., and Brooks, J.M., 2010, Public water-supply systems and associated water use in Tennessee, 2005: U.S. Geological Survey Open-File Report 2010–1226, 100 p.

Rosencrantz, F.L., 1946, The rice industry in Arkansas: The Arkansas Historical Quarterly, v. 5, no. 2, p. 123–137.

Ryals, G.N., 1980, Potentiometric maps of the Sparta Sand, northern Louisiana and southern Arkansas, 1900, 1965, 1975, and 1980: U.S. Geological Survey Open-File Report 80–1180, 1 map.

Ryling, R.W., 1960, Ground-water potential of Mississippi County, Arkansas: U.S. Geological Survey Water Resources Circular, no. 7, 87 p.

Sacks, L.A., 1996, Geochemical and isotopic composition of ground water with emphasis on sources of sulfate in the Upper Floridian aquifer in parts of Marion, Sumter, and Citrus Counties, Florida: U.S. Geological Survey Water-Resources Investigations Report 95–4251, 47 p.

Saucier, R.T., 1994, Geomorphology and Quaternary geologic history of the Lower Mississippi Valley, volume I: U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss., 400 p.

Scheiderer, R.M., and Freiwald, D.A., 2006, Monitoring the recovery of the Sparta aquifer in southern Arkansas and northern Louisiana: U.S. Geological Survey Fact Sheet 2006–3090, 4 p.

Schrader, T.P., 1998, Status of water levels in aquifers in the Nacatoch Sand and Tokio Formation of southwestern Arkansas, 1996: U.S. Geological Survey Water-Resources Investigations Report 98–4130, 22 p.

Schrader, T.P., 1999, Status of water levels in aquifers in the Nacatoch Sand of southwestern and northeastern Arkansas and the Tokio Formation of southwestern Arkansas, 1999: U.S. Geological Survey Water-Resources Investigations Report 99–4208–A, 23 p.

Schrader, T.P., 2001a, Potentiometric surface of the Ozark aquifer in northern Arkansas, 2001: U.S. Geological Survey Water-Resources Investigations Report 01–4233, 11 p.

Schrader, T.P., 2001b, Status of water levels and selected water-quality conditions in the Mississippi River Valley alluvial aquifer in eastern Arkansas, 2000: U.S. Geological Survey Water-Resources Investigations Report 01–4124, 52 p.

Schrader, T.P., 2004, Status of water levels and selected water-quality conditions in the Sparta-Memphis aquifer in Arkansas, spring–summer 2001: U.S. Geological Survey Scientific Investigations Report 2004–5055, 57 p.

Schrader, T.P., 2005, Potentiometric surface of the Ozark aquifer in northern Arkansas, 2004: U.S. Geological Survey Water-Resources Investigations Report 2005–5208, 10 p.

Schrader, T.P., 2006a, Status of water levels and selected water-quality conditions in the Mississippi River Valley alluvial aquifer in eastern Arkansas, 2004: U.S. Geological Survey Scientific Investigations Report 2006–5128, 82 p.

Schrader, T.P., 2006b, Status of water levels and selected water-quality conditions in the Sparta-Memphis aquifer in Arkansas, spring–summer 2003: U.S. Geological Survey Scientific Investigations Report 2006–5021, 43 p.

Schrader, T.P., 2007a, Potentiometric surfaces and water-level trends in the Cockfield and Wilcox aquifers of southern and northeastern Arkansas, 2006: U.S. Geological Survey Scientific Investigations Report 2007–5218, 28 p.

Schrader, T.P., 2007b, Status of water levels in aquifers in the Nacatoch Sand of southwestern and northeastern Arkansas and the Tokio Formation of southwestern Arkansas, February 2005: U.S. Geological Survey Scientific Investigations Report 2007–5024, 22 p.

Schrader, T.P., 2008a, Water levels and selected water-quality conditions in the Mississippi River Valley alluvial aquifer in eastern Arkansas, 2006: U.S. Geological Survey Scientific Investigations Report 2008–5092, 72 p.

Schrader, T.P., 2008b, Potentiometric surface in the Sparta-Memphis aquifer of the Mississippi embayment, spring 2007: U.S. Geological Survey Scientific Investigations Map 3014, 1 sheet.

Schrader, T.P., 2009, Water levels and selected water-quality conditions in the Sparta-Memphis aquifer (middle Claiborne aquifer), spring–summer 2007: U.S. Geological Survey Scientific Investigations Report 2009–5207, 24 p.

Schrader, T.P., 2010, Water levels and selected water-quality conditions in the Mississippi River Valley alluvial aquifer in eastern Arkansas, 2008: U.S. Geological Survey Scientific Investigations Report 2010–5140, 71 p., 2 pls.

Schrader, T.P., 2013, Water levels and water quality in the Sparta-Memphis aquifer (middle Claiborne aquifer) in Arkansas, spring–summer 2009: U.S. Geological Survey Scientific Investigations Report 2013–5100, 51 p., 2 pls, accessed September 10, 2013, at http://pubs.usgs.gov/sir/2013/5100/.

Schrader, T.P., 2014, Water levels and water quality in the Sparta-Memphis aquifer (middle Claiborne aquifer) in Arkansas, spring–summer 2011: U.S. Geological Survey Scientific Investigations Report 2014–5044, 44 p., 2 pls, accessed June 25, 2014, at http://dx.doi.org/10.3133/sir20145044.

Schrader, T.P., and Blackstock, J.M., 2010, Water levels in aquifers in the Nacatoch Sand of southwestern and northeastern Arkansas and the Tokio Formation of southwestern Arkansas, spring 2008: U.S. Geological Survey Scientific Investigations Report 2010–5238, 22 p.

Schrader, T.P., and Jones, J.S., 2007, Status of water levels and selected water-quality conditions in the Sparta-Memphis aquifer in Arkansas and the status of water levels in the Sparta aquifer in Louisiana, spring 2005: U.S. Geological Survey Scientific Investigations Report 2007–5029, 50 p.

Schrader, T.P., and Joseph, R.L., 2000, Potentiometric surface of the Cockfield aquifer in southeastern Arkansas and the Wilcox aquifers in southern and northeastern Arkansas, 2000: U.S. Geological Survey Water-Resources Investigations Report 2000–4206, 22 p.

Schrader, T.P., and Rodgers, K.D., 2013, Water levels in aquifers in the Nacatoch Sand of southwestern and northeastern Arkansas and the Tokio Formation of southwestern Arkansas, February–March 2011: U.S. Geological Survey Scientific Investigations Report 2013–5130, 21 p.

Schrader, T.P., and Scheiderer, R.M., 2004, Status of water levels in aquifers in the Nacatoch Sand of southwestern and northeastern Arkansas and the Tokio Formation of southwestern Arkansas, 2002: U.S. Geological Survey Water-Resources Investigations Report 2003–4284, 24 p.

Scott, H.D., Ferguson, J.A., Hanson, Linda, Fugitt, Todd, and Smith, Earl, 1998, Agricultural water management in the Mississippi Delta Region of Arkansas: University of Arkansas, Arkansas Agricultural Experiment Station Research Bulletin, no. 959, 100 p.

Scott, H.D., Selim, H.M., and Johnson, A.B., 2000, MLRA 134—Southern Mississippi Valley silty uplands, *in* Water and chemical transport in soils of the southern U.S.A.: Southern Cooperative Bulletin, no. 395.

Sharif, M.U., Davis, R.K., Steele, K.F., Kim, B., Hays, P.D., Kresse, T.M., and Fazio, J.A., 2008, Distribution and variability of redox zones controlling spatial variability of arsenic in the Mississippi River Valley alluvial aquifer, southeastern Arkansas: Journal of Contaminant Hydrology, v. 99, p. 49–67.

Sharif, M.U., Davis, R.K., Steele, K.F., Kim, B., Hays, P.D., Kresse, T.M., and Fazio, J.A., 2011, Surface complexation modeling for predicting solid phase arsenic concentrations in the sediments of the Mississippi River Valley alluvial aquifer, Arkansas, U.S.A.: Applied Geochemistry, v. 26, p. 496–504.

Sharif, M.U., Davis, R.K., Steele, K.F., Kim, B., Kresse, T.M., and Fazio, J.A., 2008, Inverse geochemical modeling of groundwater evolution with emphasis on arsenic in the Mississippi River Valley alluvial aquifer, Arkansas, U.S.A.: Journal of Hydrology, v. 350, p. 41–55.

Signor, D.C., Growitz, D.J., and Kam, W., 1970, Annotated bibliography on artificial recharge of ground water, 1955–67: U.S. Geological Survey Water-Supply Paper 1990, 141 p.

Skinner, J.H., 1984, Clarification of the definition of aquifer in 40 CFR 260.10: Memorandum from John H. Skinner, Director, Office of Solid Waste, U.S. Environmental Protection Agency, 4 p.

Smith, C.R., and Steele, K.F., 1990, Nitrate concentrations of ground water Benton County, Arkansas: Fayetteville, Ark., Arkansas Water Resources Center, no. MSC–073, 48 p.

Smith, M.C., Massey, J.H., Branson, J., Epting, J.W., Pennington, D., Tacker, P.L., Thomas, J., Vories, E.D., and Wilson, C., 2007, Water use estimates for various rice production systems in Mississippi and Arkansas: Irrigation Science, v. 25, p. 141–147.

Sniegocki, R.T., 1953, Plans for the first year's work on the artificial recharge project, Grand Prairie region, Arkansas: U.S. Geological Survey Open-File Report, 16 p.

Sniegocki, R.T., 1963a, Geochemical aspects of artificial recharge in the Grand Prairie region, Arkansas: U.S. Geological Survey Water-Supply Paper 1615–E, 41 p.

Sniegocki, R.T., 1963b, Problems in artificial recharge through wells in the Grand Prairie region, Arkansas: U.S. Geological Survey Water-Supply Paper 1615–F, 25 p.

Sniegocki, R.T., 1964, Hydrology of a part of the Grand Prairie region, Arkansas: U.S. Geological Survey Water-Supply Paper 1615–B, 72 p.

Sniegocki, R.T., Bayley, F.H., and Engler, K., 1963, Equipment and controls used in studies of artificial recharge in the Grand Prairie region, Arkansas: U.S. Geological Survey Water-Supply Paper 1615–C, 39 p.

Sniegocki, R.T., Bayley, F.H., Engler, K., and Stephens, J.W., 1965, Testing procedures and results of studies of artificial recharge in the Grand Prairie region, Arkansas: U.S. Geological Survey Water-Supply Paper 1615–G, 56 p.

Sniegocki, R.T., and Reed, J.E., 1963, Principals of siphons with respect to the artificial-recharge studies in the Grand Prairie region, Arkansas: U.S. Geological Survey Water-Supply Paper 1615–D, 19 p.

Snyder, R.W., 1976, Stratigraphy of the Roubidoux and Gasconade Formations of northern Arkansas: Fayetteville, University of Arkansas, M.S. thesis, 65 p.

Southwest Arkansas Water District, 2013, Our history: Southwest Arkansas Water District, accessed January 12, 2013, at http://www.swawd.com/history.

Spooner, W.C., 1935, Oil and gas geology of the Gulf Coastal Plain in Arkansas: Arkansas Geological Survey, Bulletin 2, 516 p.

Stanton, G.P., 1993, Processes and controls affecting anisotropic flow in the Boone-St. Joe aquifer in northwest Arkansas: Fayetteville, University of Arkansas, M.S. thesis, 217 p.

Stanton, G.P., 1997, Potentiometric surface and specific conductance of the Sparta and Memphis aquifers in eastern Arkansas, 1995: U.S. Geological Survey Water-Resources Investigations Report 97–4119, 126 p.

Stanton, G.P., and Clark, B.R., 2003, Recalibration of a ground-water flow model of the Mississippi River Valley alluvial aquifer in southeastern Arkansas, 1918–1998, with simulations of hydraulic heads caused by projected ground-water withdrawals through 2049: U.S. Geological Survey Water-Resources Investigations Report 03–4232, 48 p.

Stanton, G.P., Joseph, R.L., and Pugh, A.L., 1998, Status of water levels and selected water-quality conditions in the Mississippi River Valley alluvial aquifer in eastern Arkansas, 1994–1996: U.S. Geological Survey Water-Resources Investigations Report 98–4131, 72 p.

Stanton, J.S., Peterson, S.M., and Fienen, M.N., 2010, Simulation of groundwater flow and effects of groundwater irrigation on stream base flow in the Elkhorn and Loup River Basins, Nebraska, 1895–2055—Phase two: U.S. Geological Survey Scientific Investigations Report 2010–5149, 78 p., 1 app.

State Review of Oil and Natural Gas Environmental Regulations, 2012, Arkansas hydraulic fracturing State review: Arkansas Oil and Gas Commission, accessed on April 2, 2013, at http://www.aogc.state.ar.us/notices/AR_HFR_FINAL.pdf.

Steele, K.F., 1981, Groundwater quality and mineral deposits relationships in the Ozark Mountains: Fayetteville, Ark., Water Resources Research Center, no. PUB–077, 59 p.

Steele, K.F., 1983, Chemistry of the springs of the Ozark Mountains, northwestern Arkansas: Fayetteville, Ark., Arkansas Water Resources Research Center, no. 98, 48 p.

Steele, K.F., and Adamski, J.C., 1987, Land use effects on ground water quality in carbonate rock terrain: Fayetteville, Ark., Arkansas Water Resources Research Center, no. 129, 71 p.

Steele, K.F., Clayton, W.R., Nichols, T.W., and Vendrell, P.F., 1993, Completion report, pesticide and nitrate monitoring results for Craighead, Mississippi, and Poinsett Counties, Arkansas—Phase II: Fayetteville, Ark., Arkansas Water Resources Center, no. MSC–200, 27 p.

Steele, K.F., Hill, S.S., Nichols, T.W., Scott, H.D., Vendrell, P.F., and Lin, H.S., 1994, Completion report—Ground water monitoring project for Arkansas, phase III: Fayetteville, Ark., Arkansas Water Resources Center, no. MSC–197, 59 p.

Steele, K.F., and McCalister, W.K., 1990, Nitrate concentrations of ground water from limestone and dolomitic aquifers in the northeastern Washington County area, Arkansas: Fayetteville, Ark., Water Resources Research Center, no. MSC–68, 33 p.

Steele, K.F., Widmann, R.K., Wickliff, D.S., and Parr, D.L., 1985, The effect of rainstorm events on spring water chemistry in limestone terrane: Association of Ground Water Scientists and Engineers, Southern Regional Ground Water Conference, National Water Well Association, Proceedings, p. 51–65.

Steinbrugge, G.W., Heiple, L.R., Rogers, N., and Sniegocki, R.T., 1954, Groundwater recharge by means of wells: University of Arkansas, Agricultural Experimental Station Publication, 119 p.

Stephens, J.W., and Halberg, H.N., 1961, Use of water in Arkansas, 1960: State of Arkansas Geological and Conservation Commission Water Resources Summary, no. 4, 8 p.

Stephenson, L.W., 1927, Notes on stratigraphy of the upper Cretaceous formations of Texas and Arkansas: Bulletin of the American Association of Petroleum Geologists, v. 11, p. 8.

Stephenson, L.W, and Crider, A.F., 1916, Geology and ground waters of northeastern Arkansas, *with a discussion of* Dole, R.B., The chemical character of the waters: U.S. Geological Survey Water-Supply Paper 399, 315 p.

Stoffell, Barry, Appold, M.S., Wilkinson, J.J., McClean, N.A., and Jeffries, T.E, 2008, Geochemistry and evolution of Mississippian Valley-type mineralizing brines from the tri-State and northern Arkansas districts determined by LA–ICP–MS microanalysis of fluid inclusions: Economic Geology, v. 103, no. 7, p. 1411–1435.

Stone, C.G., and Bush, W.V., 1984, General geology and mineral resources of the Caddo River watershed: Arkansas Geological Commission, Information Circular 29, 32 p.

Stone, Nathan, and Selden, George, 2006, Aquaculture alternatives in Arkansas: University of Arkansas at Pine Bluff Cooperative Extension Program FSA9055, 8 p.

Sullavan, J.N., 1974, Drainage areas of streams in Arkansas—White River Basin: U.S. Geological Survey Unnumbered Open-File Report, 123 p.

Sumner, D.M., and Wasson, B.E., 1990, Geohydrology and simulated effects of large ground-water withdrawals on the Mississippi River alluvial aquifer in northwestern Mississippi: U.S. Geological Survey Water-Supply Paper 2292, 60 p.

Tacker, Phil, Langston, J., Ferguson, J., and Vories, E., 1994, Water management: Rice Production Handbook, University of Arkansas Cooperative Extension Service MP 192, p. 55–63.

Tacker, Phil, Vories, E.D., and Carman, D., 2010, Water supply problems and solutions in the Grand Prairie region of Arkansas: American Society of Agricultural and Biological Engineers Conference Proceedings, Phoenix, Ariz., December 5–8, 2010, 8 p.

Tait, D.B., Backer, R.C., and Billingsley, G.A., 1953, The ground-water resources of Columbia County, Arkansas—A reconnaissance: U.S. Geological Survey Circular 241, 25 p.

Tennyson, Rodney, Terry, Jim, Brahana, J.V., Hays, P.D., and Pollock, Erik, 2008, Tectonic control of hypogene speleogenesis in the Southern Ozarks—Implications for NAWQA and beyond, *in* Kuniansky, E.L., ed., U.S. Geological Survey Karst Interest Group Proceedings, Bowling Green, Ky., May 27–29, 2008: U.S. Geological Survey Scientific Investigations Report 2008–5023, 142 p.

Terry, J.E., Bryant, C.T., Ludwig, A.H., and Reed, J.E., 1979, Water-resources appraisal of the south Arkansas lignite area: U.S. Geological Survey Open-File Report 79–924, 162 p.

Terry, J.E., Bryant, C.T., Ludwig, A.H., and Reed, J.E., 1986, Water-resources appraisal of the south-Arkansas lignite area: Arkansas Geological Commission Information Circular 28–D, 162 p.

The New York Times, 1907, Roosevelt pleads for water routes: The New York Times, accessed January 17, 2013, at http://query.nytimes.com/mem/archivefree/pdf?res=F10B14F8345417738DDDAC0894D8415B878CF1D3.

Thompson, D.G., 1931, Ground-water supplies for rice irrigation in the Grand Prairie region, Arkansas: U. S. Department of the Interior Press Mem. 49844, 21 p.

Thompson, D.G., 1936, Arkansas Grand Prairie Region, *in* Metnzer, O.E., and Wenzel, L.K., ed., Water levels and artesian pressure in observation wells in the United States in 1935: U.S. Geological Survey Water-Supply Paper 777, p. 5–17.

Ting, T.E., 2005, Assessing bacterial transport, storage and viability in mantled karst of northwest Arkansas using clay and Escherichia coli labeled with lanthanide series metals: Ph.D. Dissertation, University of Arkansas, Fayetteville, 558 p.

Truman, H.S., 1949, Letter to the speaker concerning irrigation in the Grand Prairie area of Arkansas *in* Peters, Gerhard, and Woolley, J.T., The American presidency project: Accessed June 2, 2013, at http://www.presidency.ucsb.edu/ws/?pid=13275.

Turner, K.J., and Hudson, M.R., 2008, Improved understanding of a karst aquifer system through utilization of a 3D geologic model, Buffalo National River, Arkansas: Geological Society of America Abstracts with Programs, v. 40, no. 3, p. 36.

Turner, K.J., Hudson, M.R., Murray, K.E., and Mott, D.N., 2007, Three-dimensional geologic framework model for a karst aquifer system, Hasty and Western Grove quadrangles, northern Arkansas: U.S. Geological Survey Scientific Investigations Report 2007–5095, 12 p., CD digital archive.

Turner, J.P., Saunders, J.A., and Cook, R.B., 2002, Petrographic evidence for amorphous silica precursors and geomicrobiologic processes in silicified and pyritized Holocene wood: Paper 216–9, Geological Society of America Annual Meeting, 2002, Programs with Abstract, p. 493.

Union County Water Conservation Board, 2007, Sparta aquifer recovery study Union County, Arkansas: Final Report to the EPA, 67 p.

University of Arkansas at Little Rock Water Study Task Force, 2000, Water for our future: Overcoming regional paralysis, 114 p., accessed June 2, 2013, at http://ualr.edu/provost/water.pdf.

University of Arkansas Division of Agriculture, 2013, Economic contribution of Arkansas Agriculture, 36 p., accessed June 2, 2014, at http://www.uaex.edu/division/docs/Economic_Contribution_2013.pdf.

U.S. Army Corps of Engineers, 1977, Pine Bluff metropolitan area, Arkansas: Summary of Water Supply Studies, Interim Report, Vicksburg District, 33 p.

U.S. Army Corps of Engineers, 2007, Grand Prairie region and Bayou Meto Basin, Arkansas: General Reevaluation Report, 118 p., accessed March 11, 2013, at http://www.mvm.usace.army.mil/Portals/51/docs/missions/projects/Bayou%20Meto/Volume%2001.pdf.

U.S. Army Corps of Engineers, 2010, Reallocation of water storage at Bull Shoals Lake, Arkansas: Ozark Mountain Regional Public Water Authority and Marion County Region Water District, 362 p., accessed August 28, 2013, at http://www.swl.usace.army.mil/Portals/50/docs/planningandenvironmental/BShoals_OzarkWS_FEA_FONSI_20100817%20.pdf.

U.S. Army Corps of Engineers, 2013a, National inventory of dams: U.S. Army Corps of Engineers, accessed May 1, 2013, at http://geo.usace.army.mil/pgis/f?p=397:1:0.

U.S. Army Corps of Engineers, 2013b, Review plan for Grand Prairie Area Demonstration Project, Grand Prairie region, Arkansas P2# 109425—Implementation phase: U.S. Army Corps of Engineers, 25 p., accessed April 2, 2013, at http://www.mvm.usace.army.mil/Portals/51/docs/PPPMD/Peer%20Review%20Plans/Grand_Prairie_Review_Plan.pdf.

U.S. Department of Agriculture, 2006, USDA roles in market-based environmental stewardship: Natural Resources Conservation Service, USDA Department Regulation no. 5600–003.

U.S. Department of Agriculture, 2010, State facts sheets—Arkansas: U.S. Department of Agriculture, accessed August 17, 2013, at http://www.ers.usda.gov/StateFacts/AR.htm.

U.S. Department of Agriculture, 2011, Arkansas 2011 State agriculture overview: U.S. Department of Agriculture, accessed April 20, 2013, at http://www.nass.usda.gov/Statistics_by_State/Ag_Overview/AgOverview_AR.pdf.

U.S. Department of Agriculture, 2012, National Agricultural Statistics Service Quick Stats: U.S. Department of Agriculture, accessed April 20, 2012, at http://quickstats.nass.usda.gov/.

U.S. Environmental Protection Agency, 1984, Classification of injection wells, section 146.5 of subpart A of part 6 146, underground injection control program—Criteria and standards: U.S. Code of Federal Regulations, Title 40, Part 146, July 1, 1984, p. 371–372.

U.S. Environmental Protection Agency, 1988, 40 CFR Parts 280 and 281, Technical standards and corrective action requirements for owners and operators of underground storage tanks (UST), Federal Register, v. 53, no. 185, 165 p.

U.S. Environmental Protection Agency, 1994a, Review, approval, and evaluation of State management plans: Office of Prevention, Pesticides, and Toxic Substances, EPA 735–B–93–005b, 42 p.

U.S. Environmental Protection Agency, 1994b, Assessment, prevention, monitoring, and response components of State management plans: Office of Prevention, Pesticides, and Toxic Substances, EPA 735–B–93–005c, 219 p.

U.S. Environmental Protection Agency, 2001, 40 CFR Parts 9, 141, and 142, National Primary Drinking Water Regulations—Arsenic and clarification to compliance and new source contaminants monitoring, final rule: Federal Register, v. 66, no. 14, 94 p.

U.S. Environmental Protection Agency, 2009, 2009 Edition of the drinking water standards and health advisories: Office of Water, Washington, D.C., EPA 822–R–09–011, 12 p.

U.S. Environmental Protection Agency, 2010, Hydraulic fracturing research study: Office of Research and Development, EPA/600/F–10/002, accessed July 30, 2013, at http://www.epa.gov/tp/pdf/hydraulic-fracturing-fact-sheet.pdf.

U.S. Environmental Protection Agency, 2013, CERCLIS public access database: U.S. Environmental Protection Agency, Superfund Site Information, NPL Listing for Arkansas, accessed May 13, 2013, at http://cfpub.epa.gov/supercpad/cursites/srchsites.cfm.

U.S. Geological Survey, 2013a, Changes in water-use categories: U.S. Geological Survey, accessed June 3, 2013, at http://water.usgs.gov/watuse/WU-Category-Changes.html.

U.S. Geological Survey, 2013b, USGS water data for the Nation: USGS National Water Information System (NWIS), accessed August 29, 2013, at http://waterdata.usgs.gov/nwis.

Van den Heuvel, P., 1979, Petrography of the Boone Formation, northwest Arkansas: Fayetteville, University of Arkansas, M.S. thesis, 92 p.

Vandike, J.E., 1997, Guidebook to the geology and hydrology of the Current River Basin: Missouri Division of Geology and Land Survey, 27 p.

Van Schaik, E.J., and Kresse, T.M., 1994, Report on the third sampling of the El Dorado, Pine Bluff, and Lonoke Prototypes: Arkansas Department of Pollution Control and Ecology, WQ94–10–1, 45 p.

Van Schaik, E.J., and Kresse, T.M., 1995, Report on the third sampling of the Jonesboro Prototype: Arkansas Department of Pollution Control and Ecology, WQ95–11–1, 28 p.

Van Schaik, E.J., and Kresse, T.M., 1996, Report on the third sampling of the Brinkley Prototype: Arkansas Department of Pollution Control and Ecology, WQ96–02–1, 40 p.

Vardy, Renee, 2011, Characterization of urban impact on water quality of karst springs in Eureka Springs, Arkansas, *in* Kuniansky, E.L., ed., U.S. Geological Survey Karst Interest Group Proceedings, Fayetteville, Ark., April 26–29, 2011: U.S. Geological Survey Scientific Investigations Report 2011–5031, p. 44–53.

Vaughn, T.W., 1895, The stratigraphy of northwestern Louisiana: American Geologist, v. 15, p. 205–229.

Veatch, A.C., 1906, Geology and underground water resources of northern Louisiana and southern Arkansas: U.S. Geological Survey Professional Paper 46, 422 p.

Vories, E.D., Tacker, P.L., and Hogan, Robert, 2005, Multiple inlet approach to reduce water requirements for rice production: Applied Engineering in Agriculture, v. 21, no. 4, p. 611−616.

Wagner, D.M., 2007, In-situ assessment of waste storage effectiveness in karst using stable isotope biogeochemistry: Fayetteville, University of Arkansas, M.S. thesis, 58 p.

Wagner, G.H., and Steele, K.F., 1985, Metal concentrations in the groundwater of the Ouachita Mountains, Arkansas, U.S.A.: Water, Air, and Soil Pollution, v. 25, p. 339–347.

Wagner, G.H., Steele, K.F., and Zachry, D.L., 1975, Trace metal and major elements in water-soluble rocks of northwest Arkansas: Arkansas Water Resources Center, Fayetteville, Ark, no. PUB–036, 55 p.

Warner, N.R., Kresse, T.M., Hays, P.D., Down, A., Karr, J.D., Jackson, R.D., and Vengosh, A., 2013, Geochemical and isotopic variations in shallow groundwater in areas of the Fayetteville Shale development, north-central Arkansas: Applied Geochemistry, v. 35, p. 207–220.

Webb, G.E., 1994, Paleokarst, paleosol, and rocky-shore deposits at the Mississippian-Pennsylvanian unconformity, northwestern Arkansas: Geological Society of America Bulletin, May 1994, v. 106, no. 5, p. 634–648.

Weeks, W.B., 1938, South Arkansas stratigraphy with emphasis on the older Coastal Plain beds: American Association of Petroleum Geologists Bulletin, v. 22, p. 972–978.

Westerfield, P.W., 1989, Ground-water levels in the alluvial aquifer in eastern Arkansas, 1987: U.S. Geological Survey Open-File Report 89–64, 32 p.

Westerfield, P.W., 1990, Water-level maps of the Mississippi River Valley alluvial aquifer in eastern Arkansas, 1987: U.S. Geological Survey Water-Resources Investigations Report 90–4089, 1 sheet.

Westerfield, P.W., 1994, Potentiometric-surface maps of the Cockfield and lower Wilcox aquifers in Arkansas, 1991: U.S. Geological Survey Water-Resources Investigations Report 93–4137, 2 sheets.

Westerfield, P.W., 1995, Potentiometric surface of the Sparta and Memphis aquifers in eastern Arkansas, April through July 1993, U.S. Geological Survey Scientific Investigations Report 95–4000, 1 sheet.

Westerfield, P.W., and Baxter, C.R., 1990a, Ground-water levels in the alluvial aquifer in eastern Arkansas, 1988: U.S. Geological Survey Open-File Report 90–383, 32 p.

Westerfield, P.W., and Baxter, C.R., 1990b, Ground-water levels in the alluvial aquifer in eastern Arkansas, 1989: U.S. Geological Survey Open-File Report 90–558, 35 p.

Westerfield, P.W., and Baxter, C.R., 1990c, Water level maps of the Mississippi River Valley alluvial aquifer in eastern Arkansas, 1987: U.S. Geological Survey Open-File Report 90–4089, 1 sheet.

Westerfield, P.W., and Gonthier, G.J., 1993, Water-level maps of the Mississippi River Valley alluvial aquifer in eastern Arkansas, 1989: U.S. Geological Survey Water-Resources Investigations Report 92–4120, 1 sheet.

Westerfield, P.W., and Poynter, D.T., 1993, Ground-water levels in the alluvial aquifer in eastern Arkansas, 1992: U.S. Geological Survey Open-File Report 93–96, 25 p., 1 sheet.

Westerfield, P.W., and Poynter, D.T., 1994, Water-level maps of the Mississippi River Valley alluvial aquifer in eastern Arkansas, spring, 1993: U.S. Geological Survey Open-File Report 93–374, 1 sheet.

Westerfield, P.W., and Touschner, S.T., 1991, Ground-water levels in the alluvial aquifer in eastern Arkansas, 1990: U.S. Geological Survey Open-File Report 91–248, 35 p.

Westerfield, P.W., and Touschner, S.T., 1992, Ground-water levels in the alluvial aquifer in eastern Arkansas, 1991: U.S. Geological Survey Open-File Report 92–46, 24 p.

Westerfield, P.W., and Touschner, S.T., 1993, Ground-water levels in the alluvial aquifer in eastern Arkansas, 1992: U.S. Geological Survey Open-File Report 93–96, 25 p.

Whitfield, M.S., Jr., 1975, Geohydrology and water quality of the Mississippi River alluvial aquifer, northeastern Louisiana: Louisiana Department of Public Works Water Resources Technical Report, no. 10, 29 p.

Wickliff, D.S., 1988, The effects of rainstorm events on the water chemistry of a river with emphasis on the heavy metal content: Fayetteville, University of Arkansas, M.S. thesis, 95 p.

Widmann, R.K., 1982, Episodic and seasonal effects of rainfall on spring water chemistry in a limestone terrane: Fayetteville, University of Arkansas, M.S. thesis, 110 p.

Wilbert, L.J., Jr., 1953, The Jacksonian stage in southeastern Arkansas: Arkansas Resources and Development Commission, Division of Geology Bulletin 19, 125 p.

Williams, F.C., 2012, Agriculture: Encyclopedia of Arkansas, accessed December 4, 2012, at http://www.encyclopediaofarkansas.net/encyclopedia/entry-detail.aspx?search=1&entryID=385.

Williamson, A.K., Grubb, H.F., and Weiss, J.S., 1990, Groundwater flow in the Gulf Coast aquifer systems, south-central United States—A preliminary analysis: U.S. Geological Survey Water-Resources Investigations Report 89–4071, 124 p.

Wilson, C.E., Jr., and Branson, J.W., 2002, Trends in Arkansas rice production, *in* Rice research studies 2002: Arkansas Agricultural Experiment Station Research Series 504, p. 15–17.

Wilson, C.E., Jr., Frizzell, D.L., Slaton, N.A., and Norman, R.J., 1997, Influence of seeding rates on rice salinity tolerance: B.R. Wells Rice Research Studies 1997, Arkansas Agricultural Experiment Station Research Series 460, p. 175–179.

Yeatts, D.S., 2004, Potentiometric Surfaces in the Cockfield and Wilcox aquifers of southern and northeastern Arkansas, 2003: U.S. Geological Survey Scientific Investigations Report 2004–5169, 29 p.

Zachry, D.L., Steele, K.F., Wood, L.J., and Johnston, D.H., 1986, Stratigraphy and hydrology of upper Cretaceous and Tertiary strata, Columbia and Union Counties, Arkansas: University of Arkansas, Fayetteville, Ark., 74 p.

Zimmerman, R.K., 1992, Fractured Smackover limestone in northeast Louisiana—Implications for hydrocarbon exploitation: Gulf Coast Association of Geological Societies Transactions, v. 42, p. 401–412.

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