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

By Timothy M. Kresse[1], Phillip D. Hays[1], Katherine R. Merriman[1], Jonathan A. Gillip[1], D. Todd Fugitt[2], Jane L. Spellman[3], Anna M. Nottmeier[1], Drew A. Westerman[1], Joshua M. Blackstock[1], and James L. Battreal[2]

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).

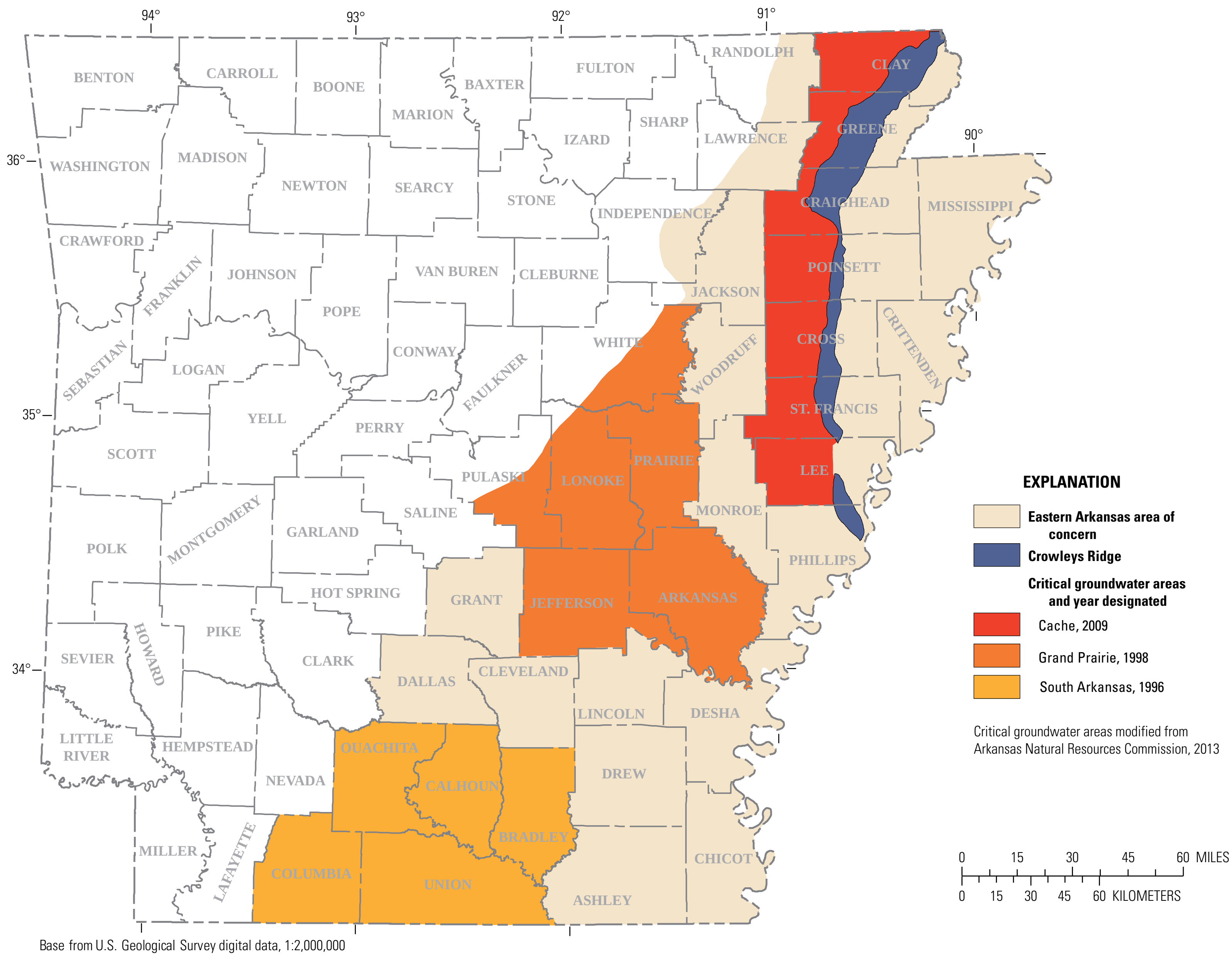


Figure 1. Location of critical groundwater areas in eastern Arkansas and counties referenced in this report.

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

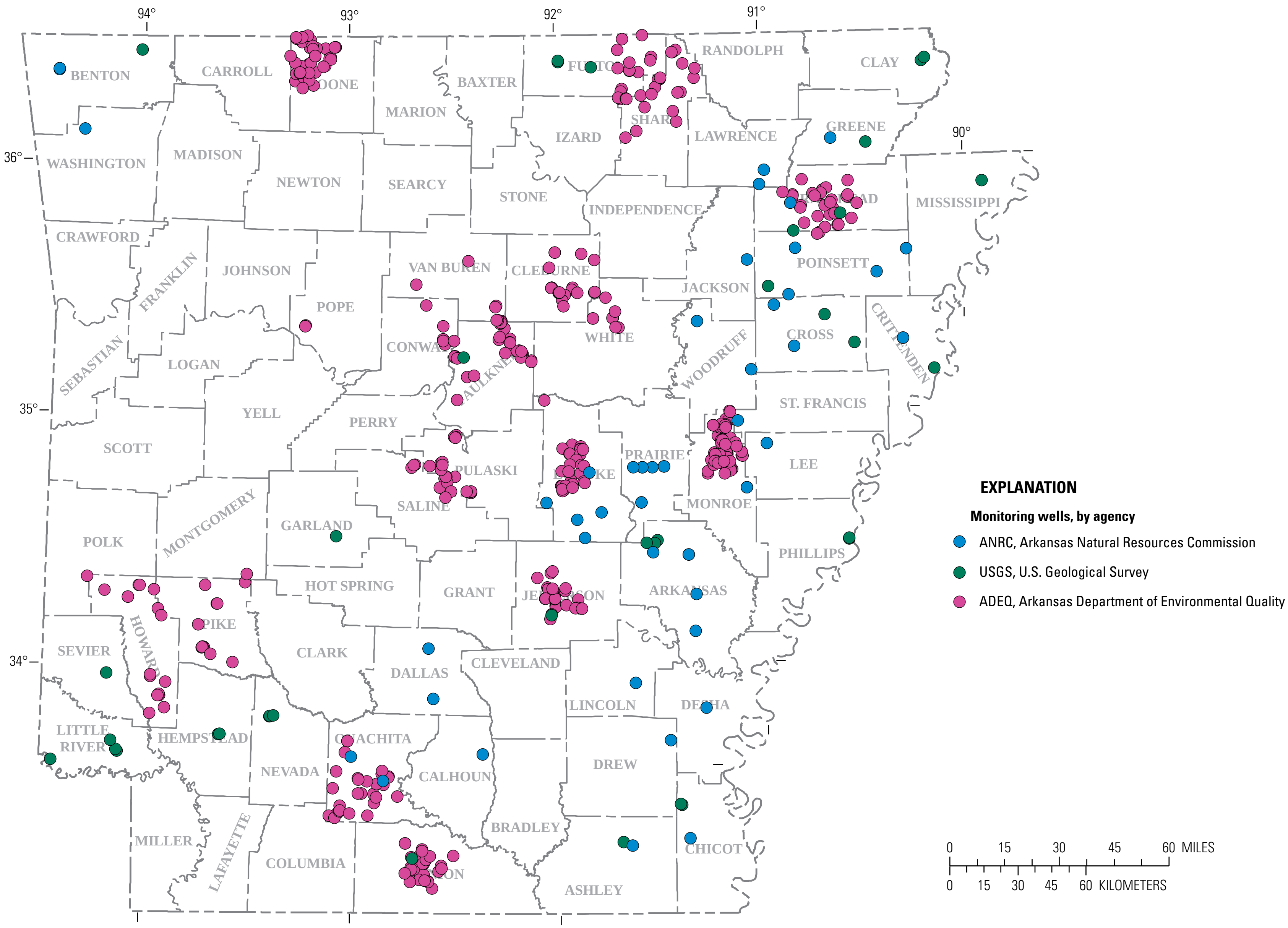
The ADH currently (2013) maintains a database of approximately 1,300 wells that are sampled every 3 years for inorganic, organic (for example, pesticides, herbicides, volatile organic compounds, and semi-volatile organic compounds), and radiological contaminants. However, treated water predominantly 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).

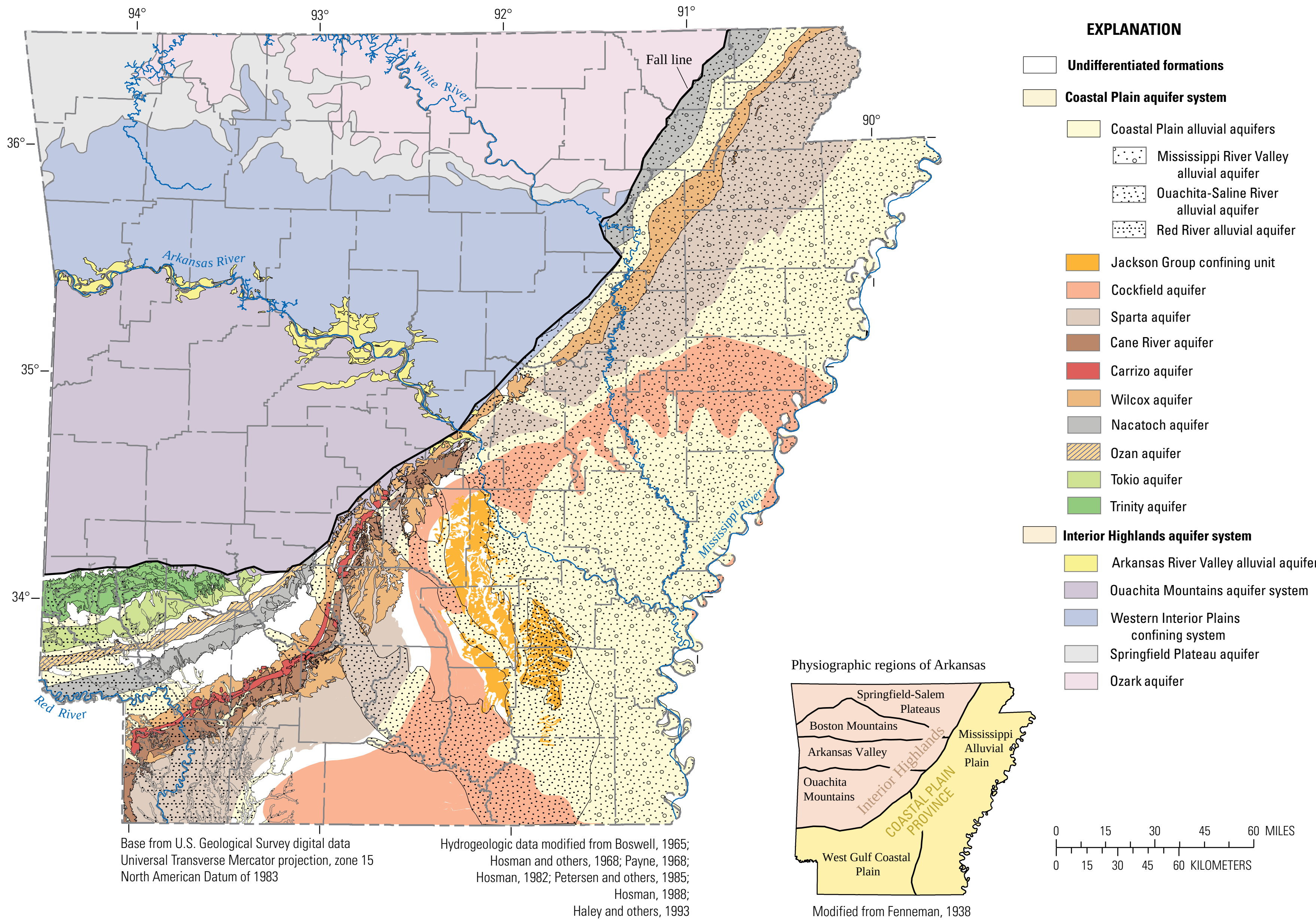


Figure 3. Combined outcrop, subcrop areas, and physiographic regions for the 16 aquifers serving as major and minor sources of groundwater supplies throughout Arkansas.

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.

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

[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 Hartshorne Sandstone Atoka Formation Bloyd Shale Hale Formation	Western Interior Plains confining system
	Mississippian	Pitkin Limestone Fayetteville Shale Batesville Sandstone Moorefield Formation	
		Boone Formation St. Joe Limestone Member	Springfield Plateau aquifer
	Devonian	Chattanooga Shale	Ozark confining unit
		Clifty Limestone Penters Chert	Upper Ozark aquifer
	Silurian	Lafferty Limestone St. Clair Limestone Brassfield Limestone	
	Ordovician	Cason Shale Fernvale Limestone Kimmswick Limestone Plattin Limestone Joachim Dolomite St. Peter Sandstone Everton Formation Smithville Formation Powell Dolomite Cotter Dolomite Jefferson City Dolomite	
		Roubidoux Formation Gasconade Dolomite Gunter Sandstone Member	Lower Ozark aquifer
		Van Buren Formation	
	Cambrian	Eminence Dolomite Potosi Dolomite	
		Doe Run Dolomite Derby Dolomite Davis Formation	St. Francois confining unit
		Bonneterre Formation Reagan Sandstone 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.

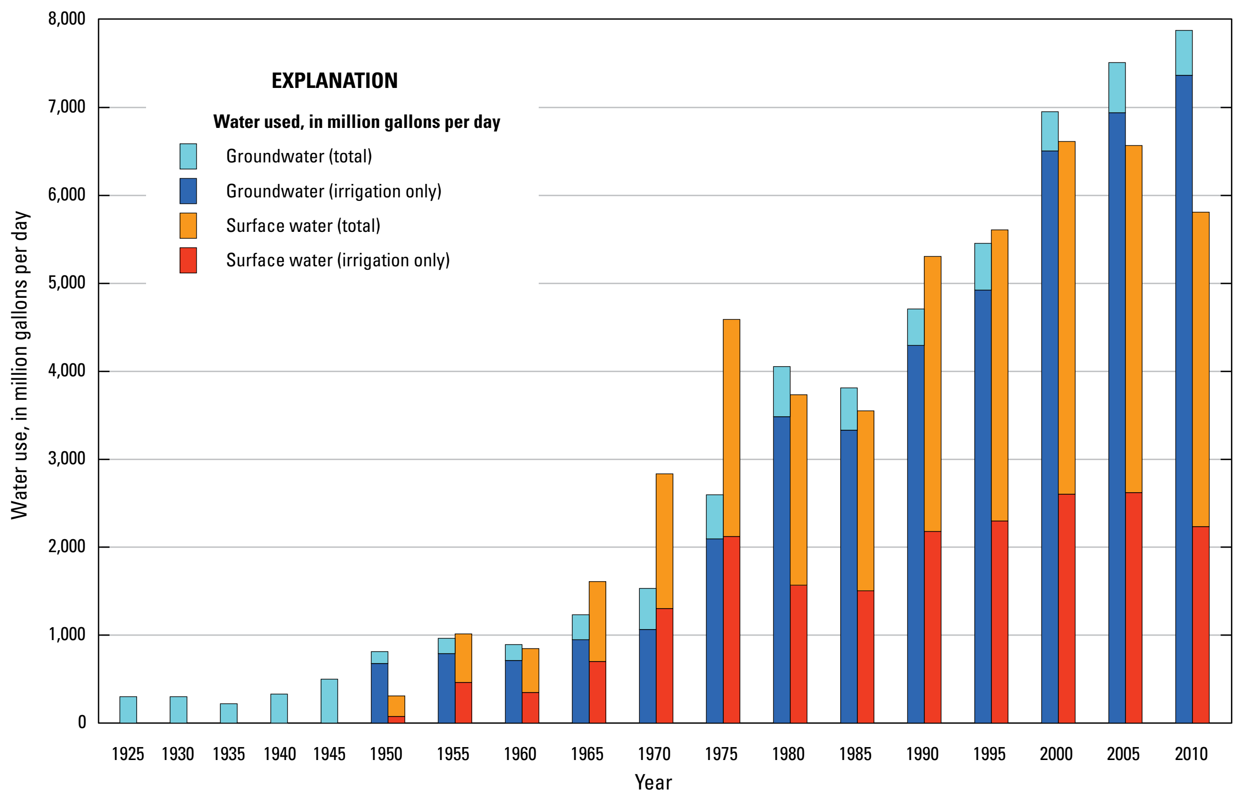
[8]In the 1985 water-use report, aquaculture was combined into the livestock category.

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.



Data from MacKichan (1951, 1957); Baker (1955); Arkansas Water Study Commission (1956); Stephens and Halberg (1961); Halberg and Stephens (1966); Halberg (1972, 1977); Holland (1981, 1987,1993, 1999, 2004, 2007). Water use for nonconsumptive use by hydroelectric generation was not included.

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.

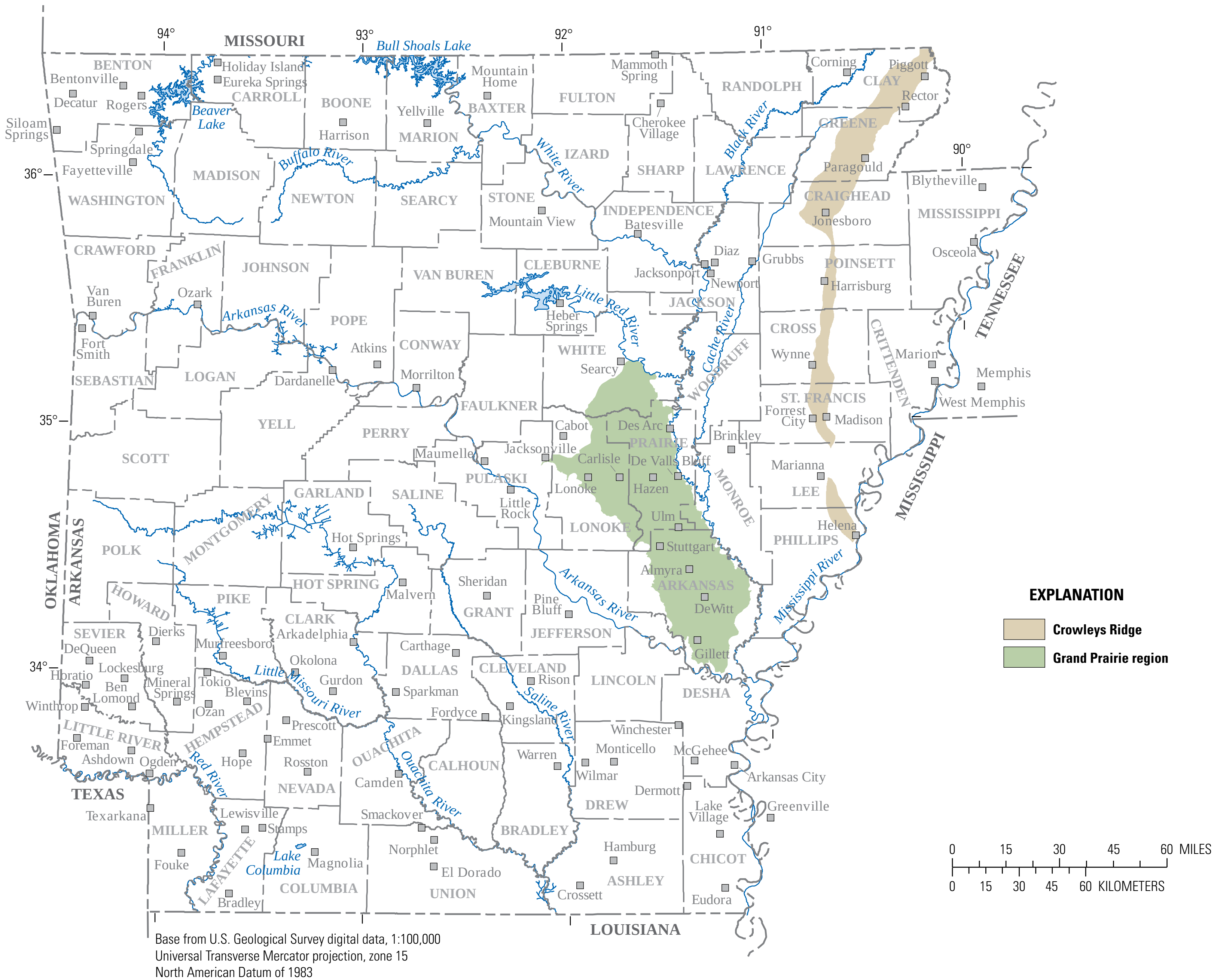
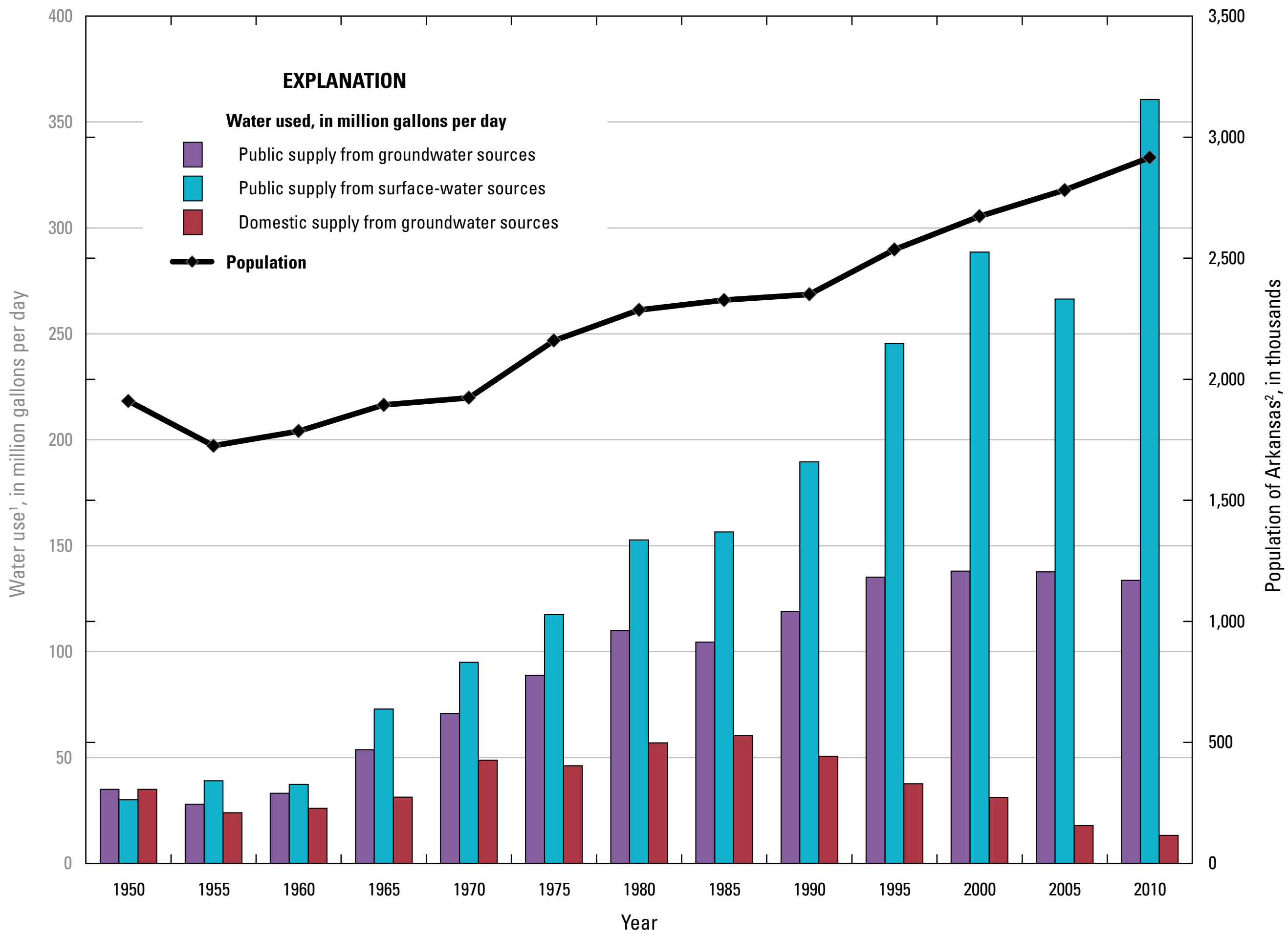


Figure 5. Location of Arkansas cities and major rivers referenced in this report.



[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).

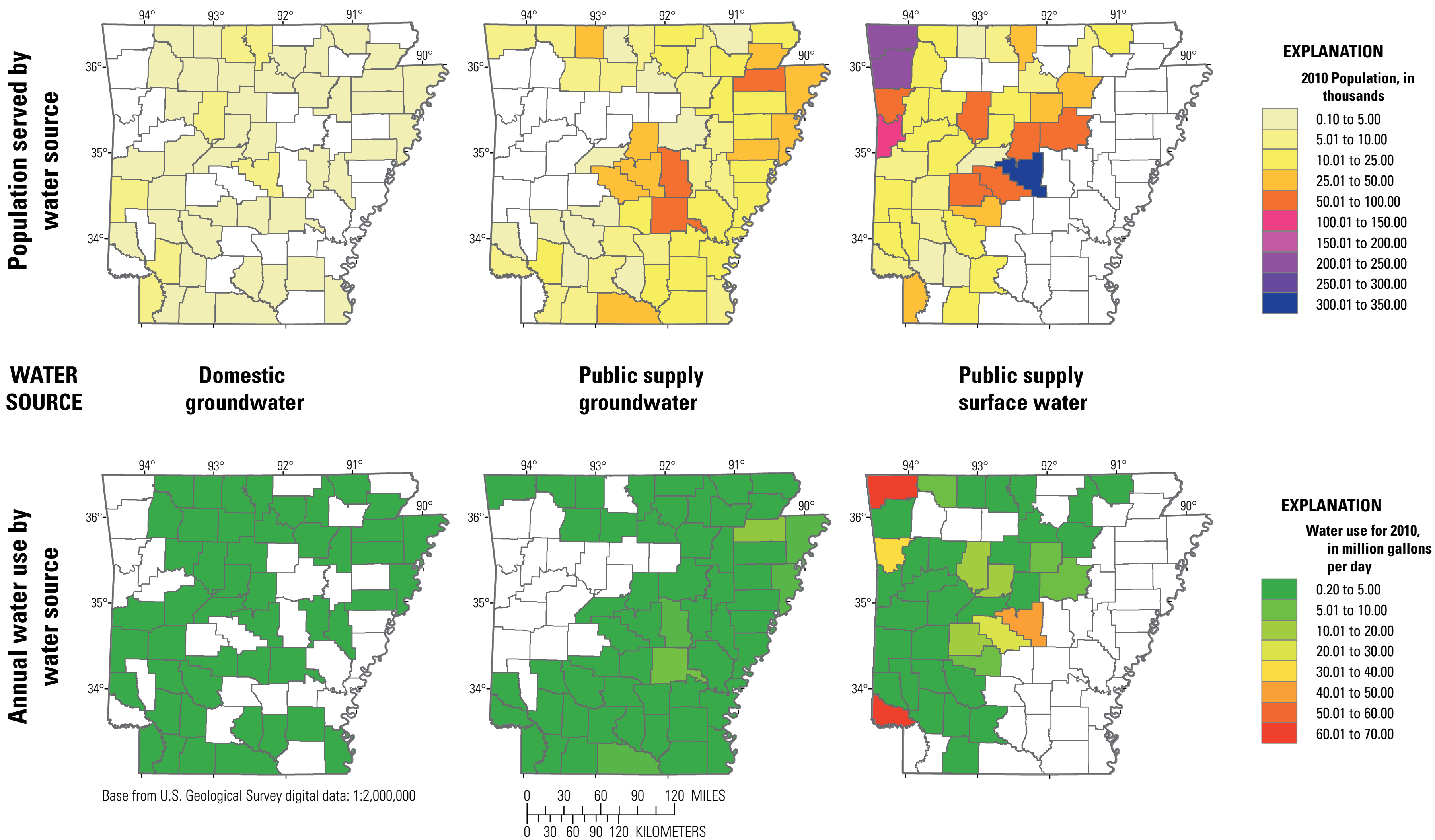


Figure 7. Population, in thousands, by water source (domestic groundwater, public supply groundwater or public supply surface water) and water use, in million of gallons per day, by water source in Arkansas, 2010.

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 waterfowl 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).

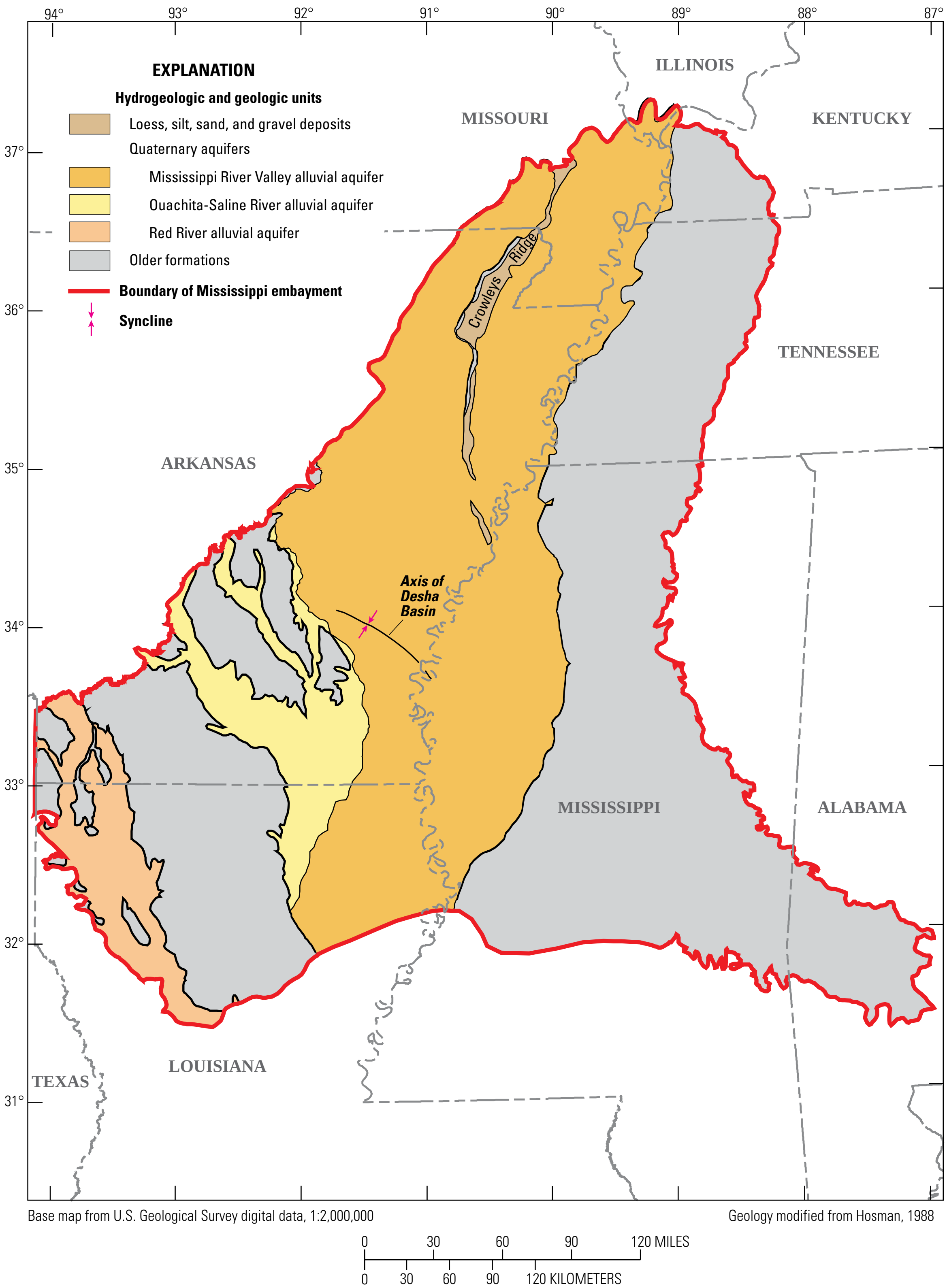


Figure 8. Extent of the Mississippi embayment with location of Quaternary aquifers.

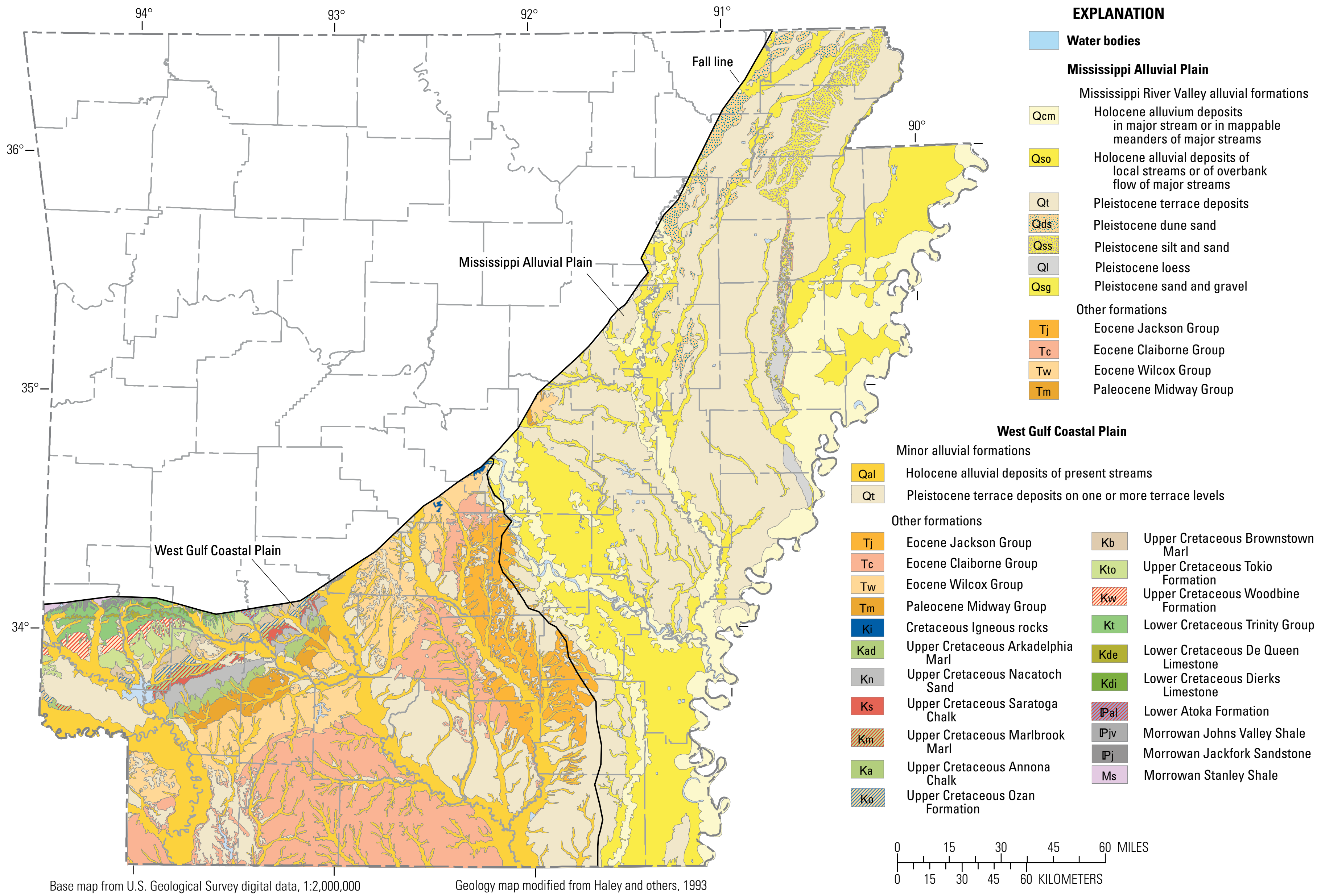


Figure 9. Surface geology of the West Gulf Coastal Plain and Mississippi Alluvial Plain in southern and eastern Arkansas.

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.

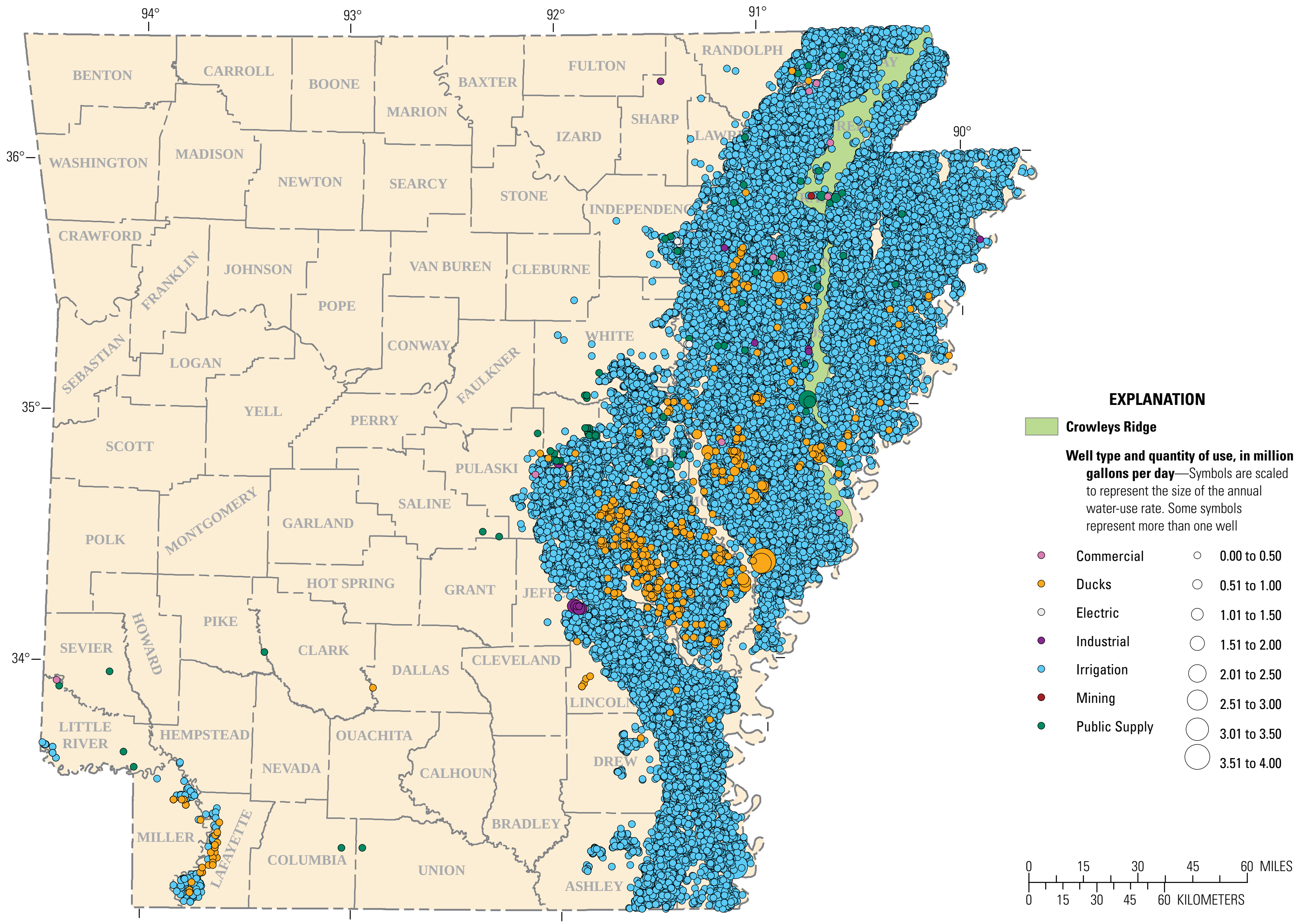
Water-use rates for the Mississippi River Valley alluvial aquifer have increased steadily from 1965 to 2010 (fig. 11). The majority of the increase is attributed to irrigation, which has increased consistently over time for all reported water-use data (fig. 4). In 1965, the average water use by county 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.



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

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

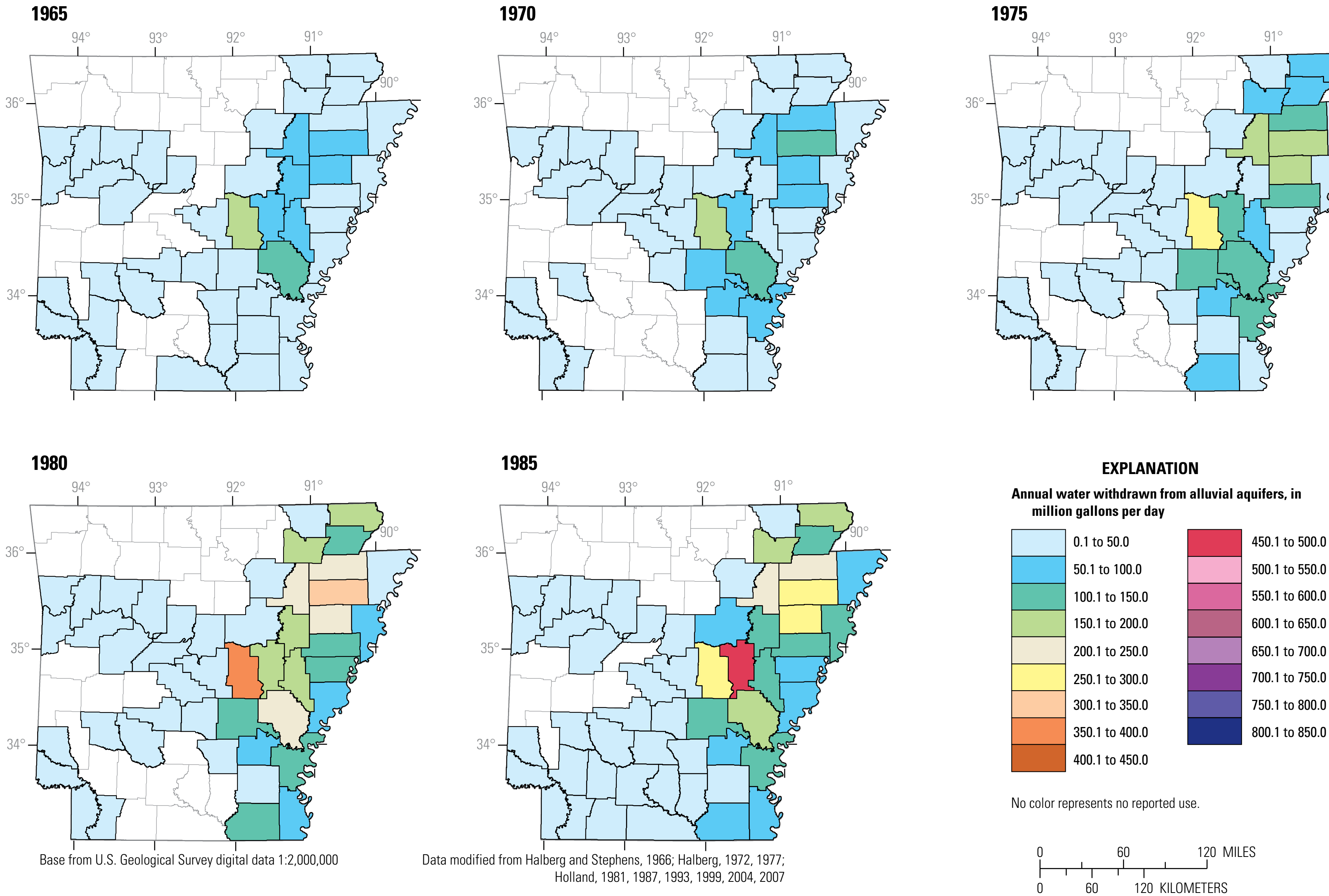


Figure 11. Water use from alluvial aquifers in Arkansas from 1965 to 2010.

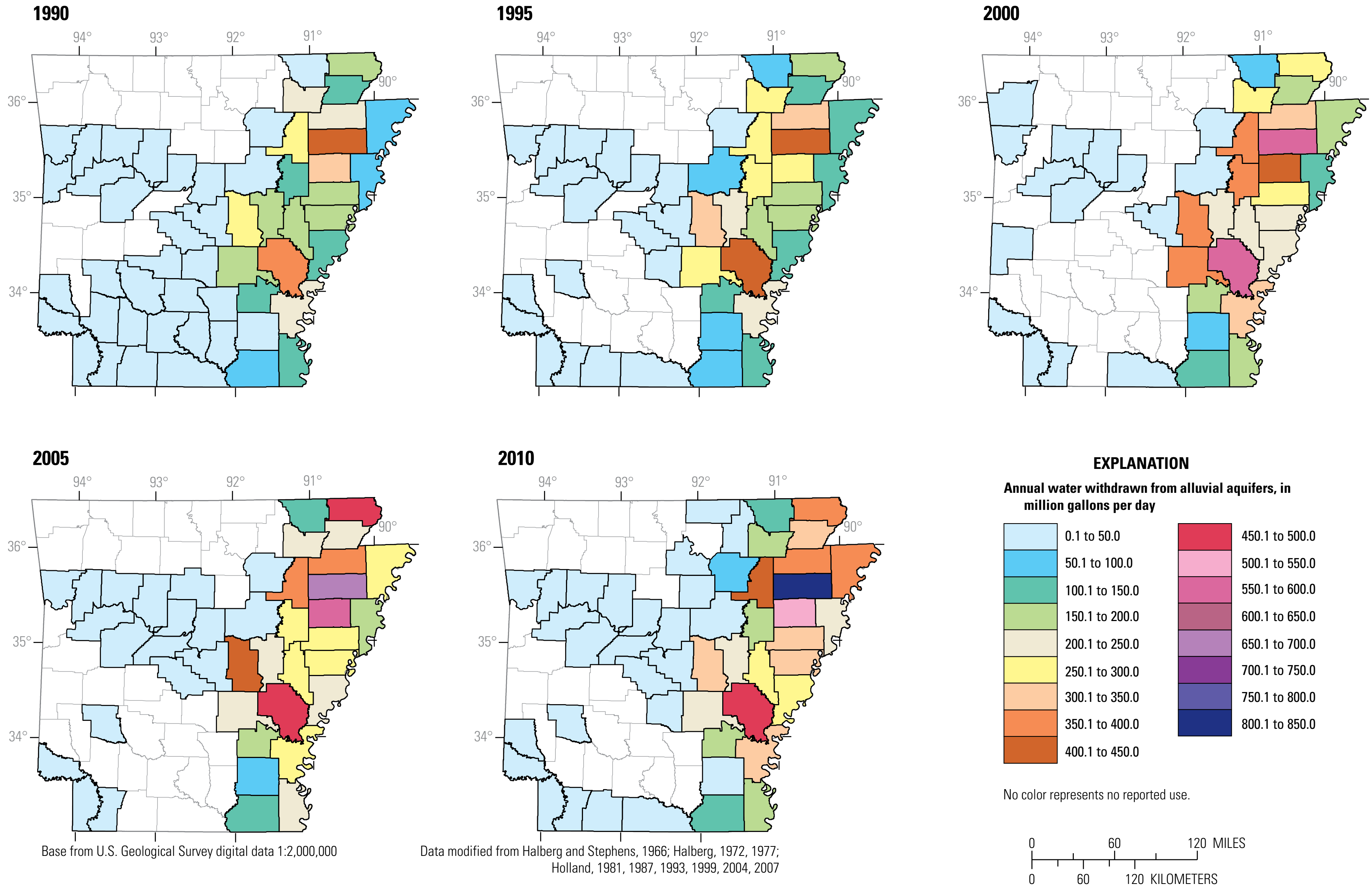


Figure 11. Water use from alluvial aquifers in Arkansas from 1965 to 2010.—Continued

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

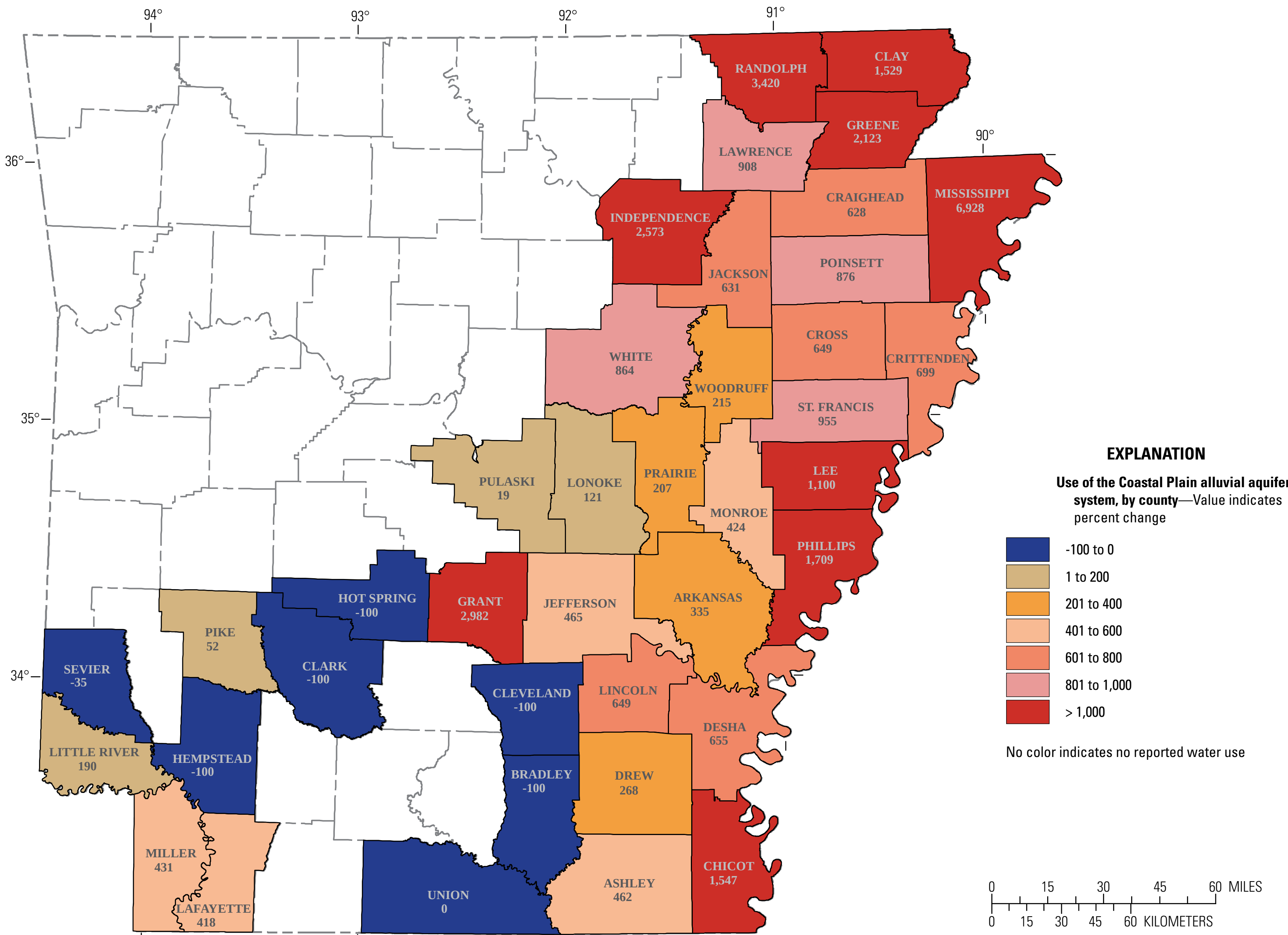
[Data from Halberg and Stephens (1966); Halberg, (1972, 1977); Holland (1981, 1987, 1993, 1999, 2004, 2007). Units are million gallons per day]

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**



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

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

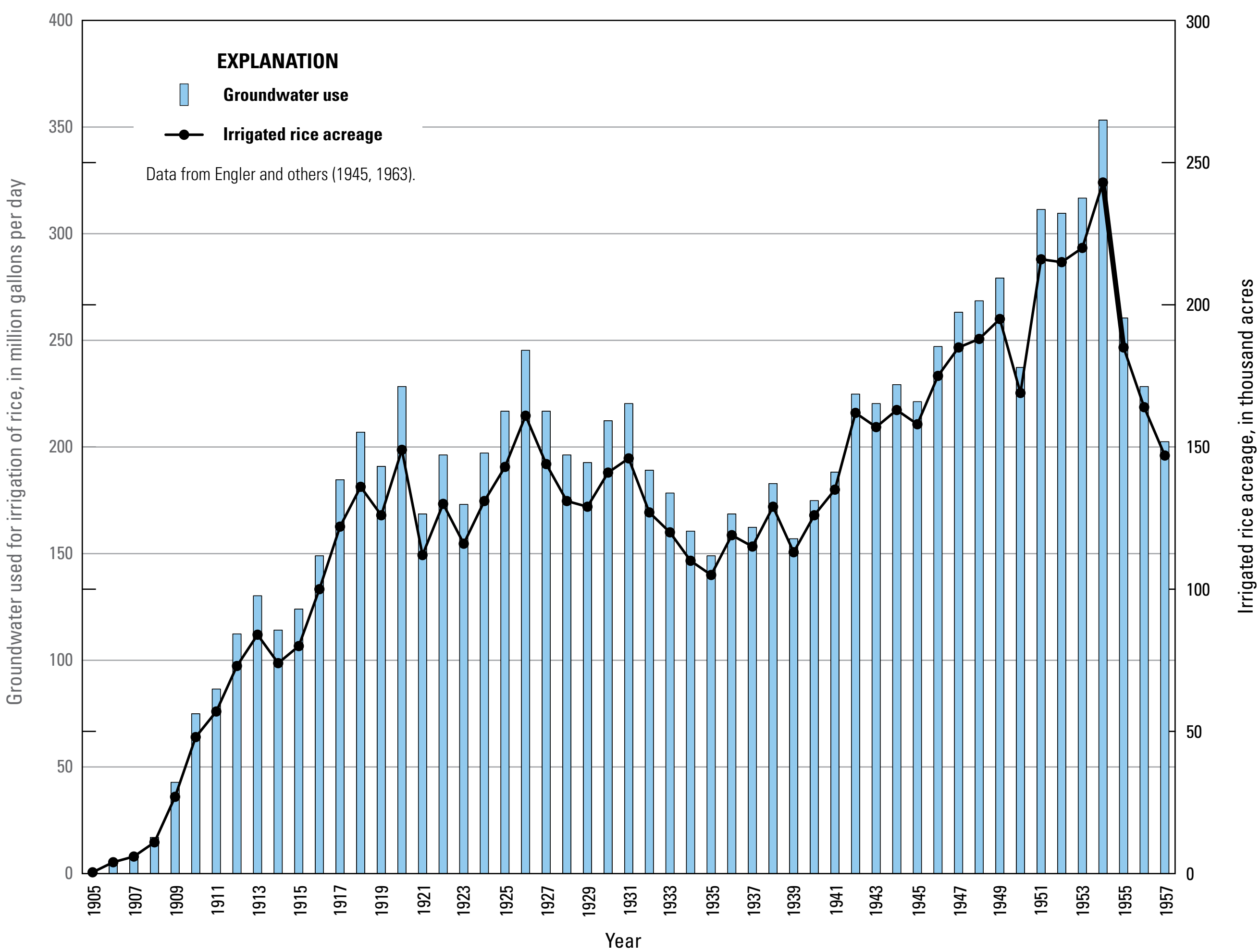


Figure 13. Rice acreage and corresponding irrigation water use from Mississippi River Valley alluvial aquifer in the Grand Prairie region of Arkansas, 1905–57.

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).

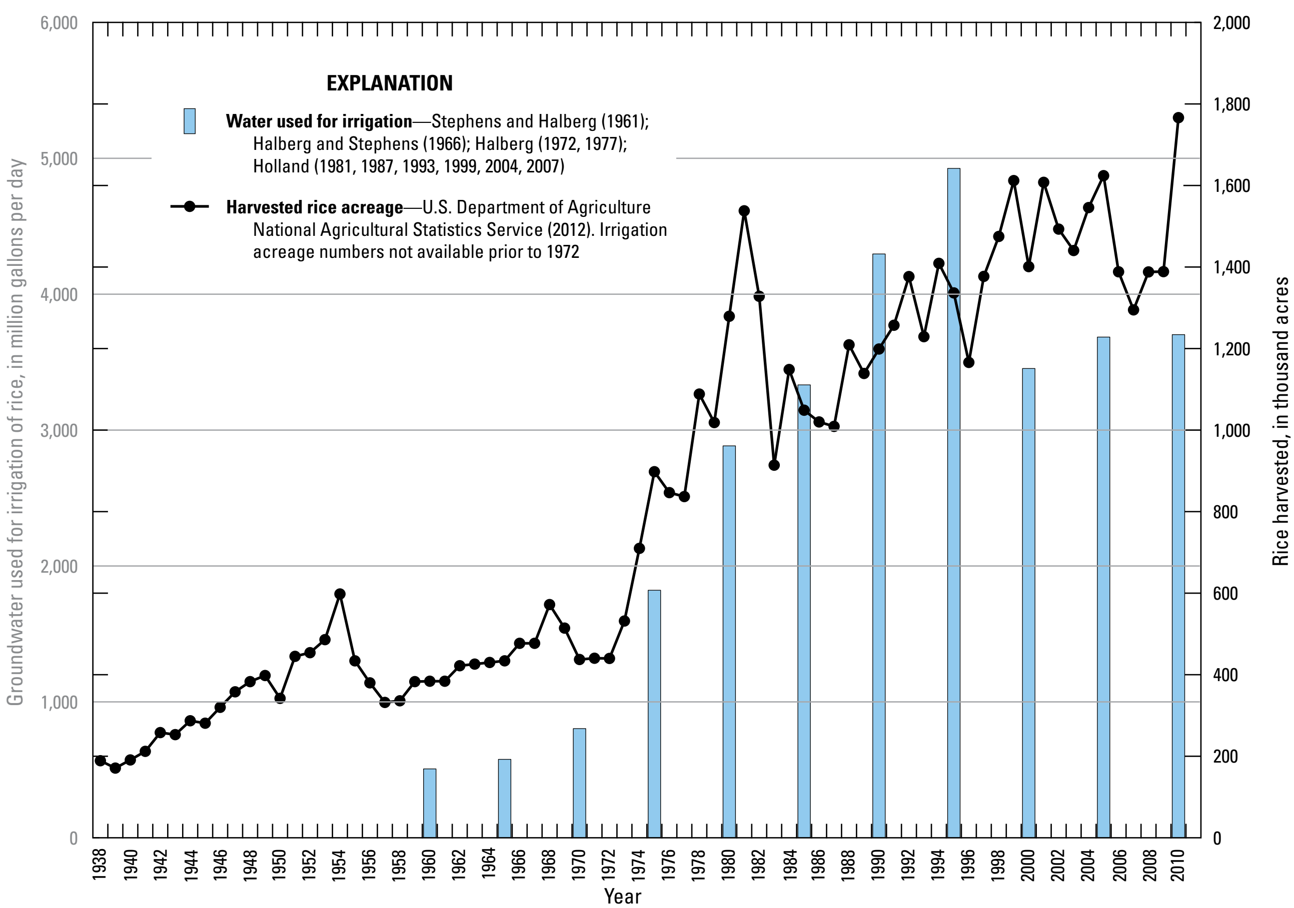


Figure 14. Acres of rice harvested and groundwater use for irrigation of rice in Arkansas.

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

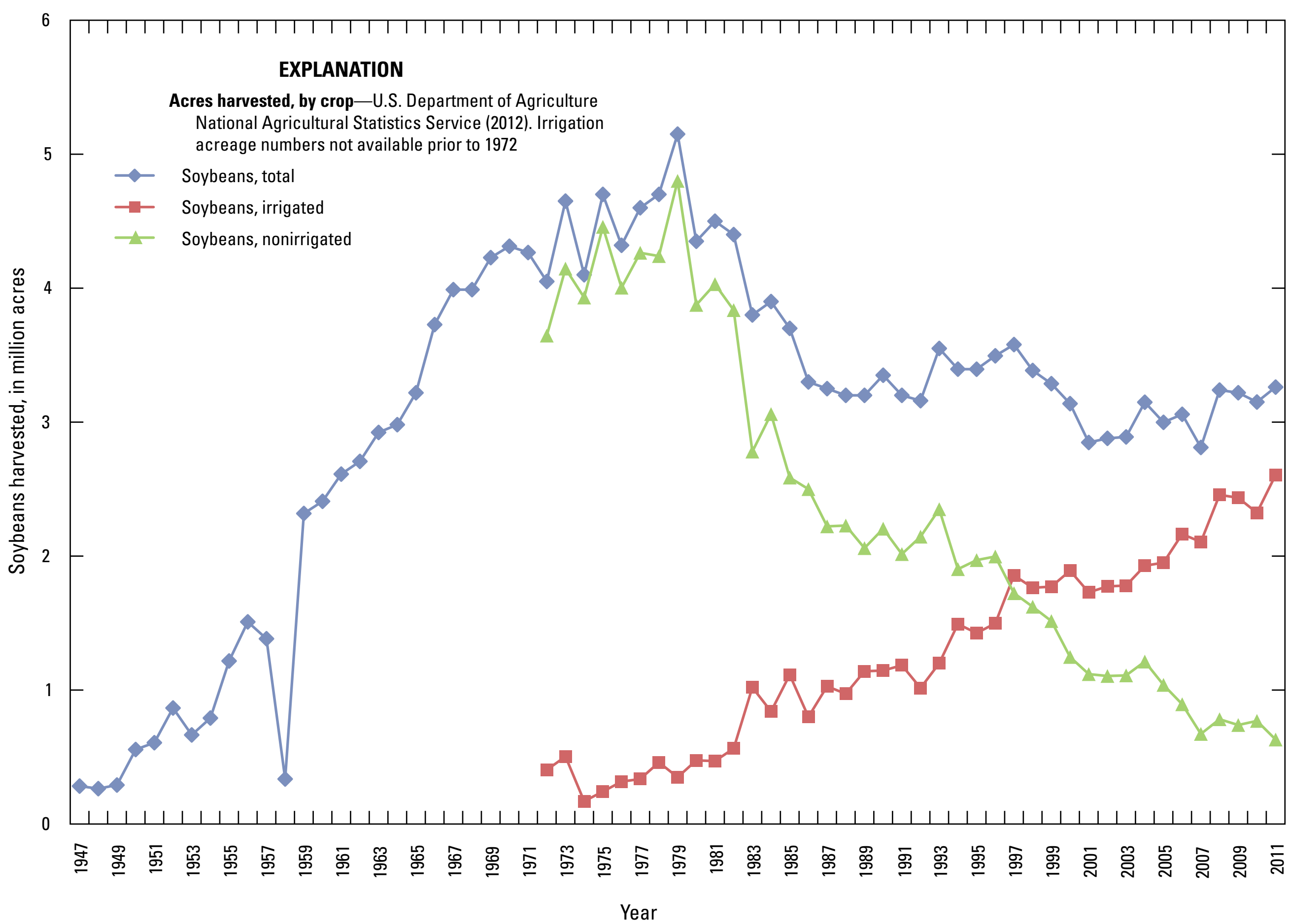


Figure 15. Acres harvested of irrigated and nonirrigated soybeans for Arkansas.

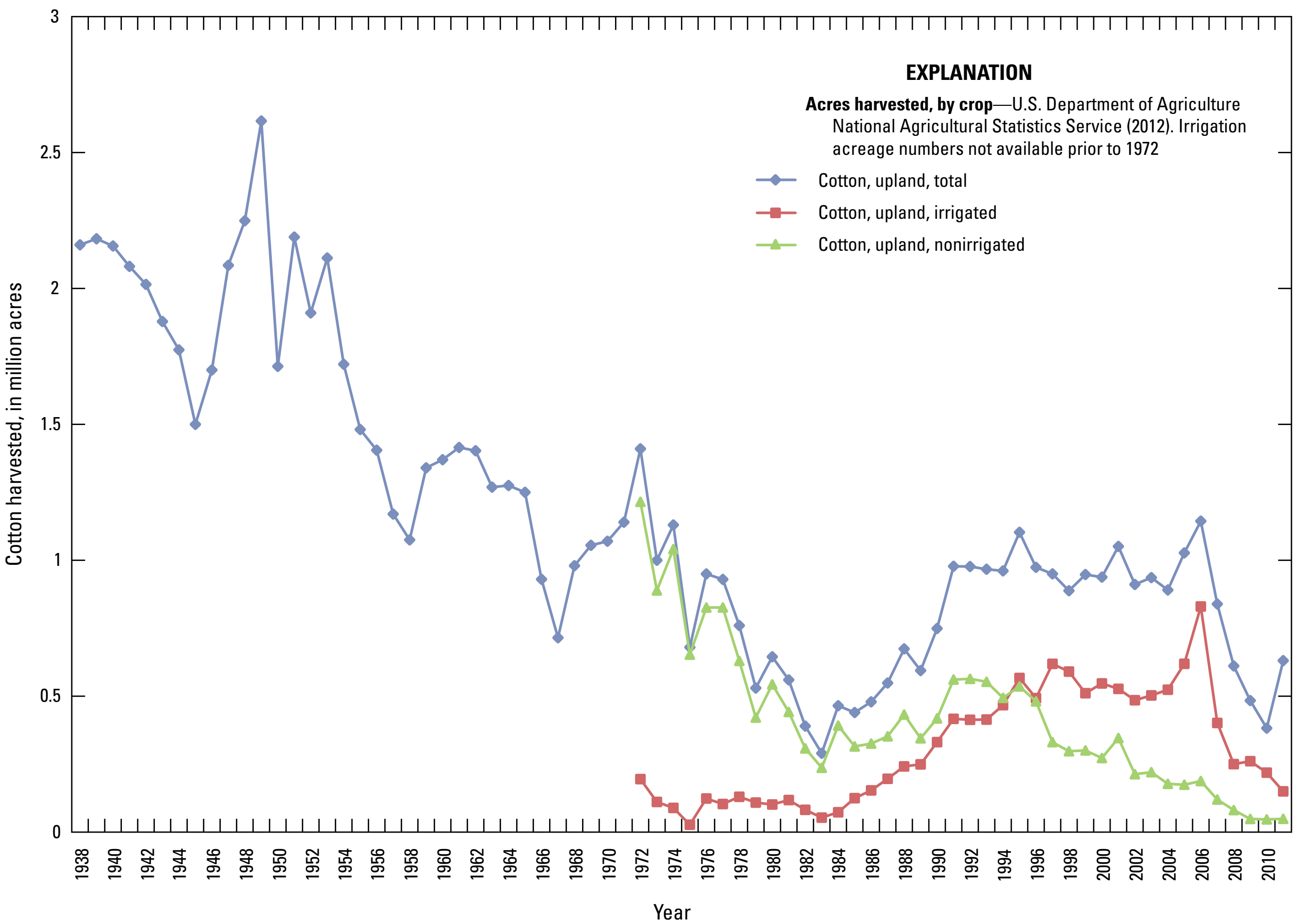


Figure 16. Acres harvested of irrigated and nonirrigated cotton for Arkansas.

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*).

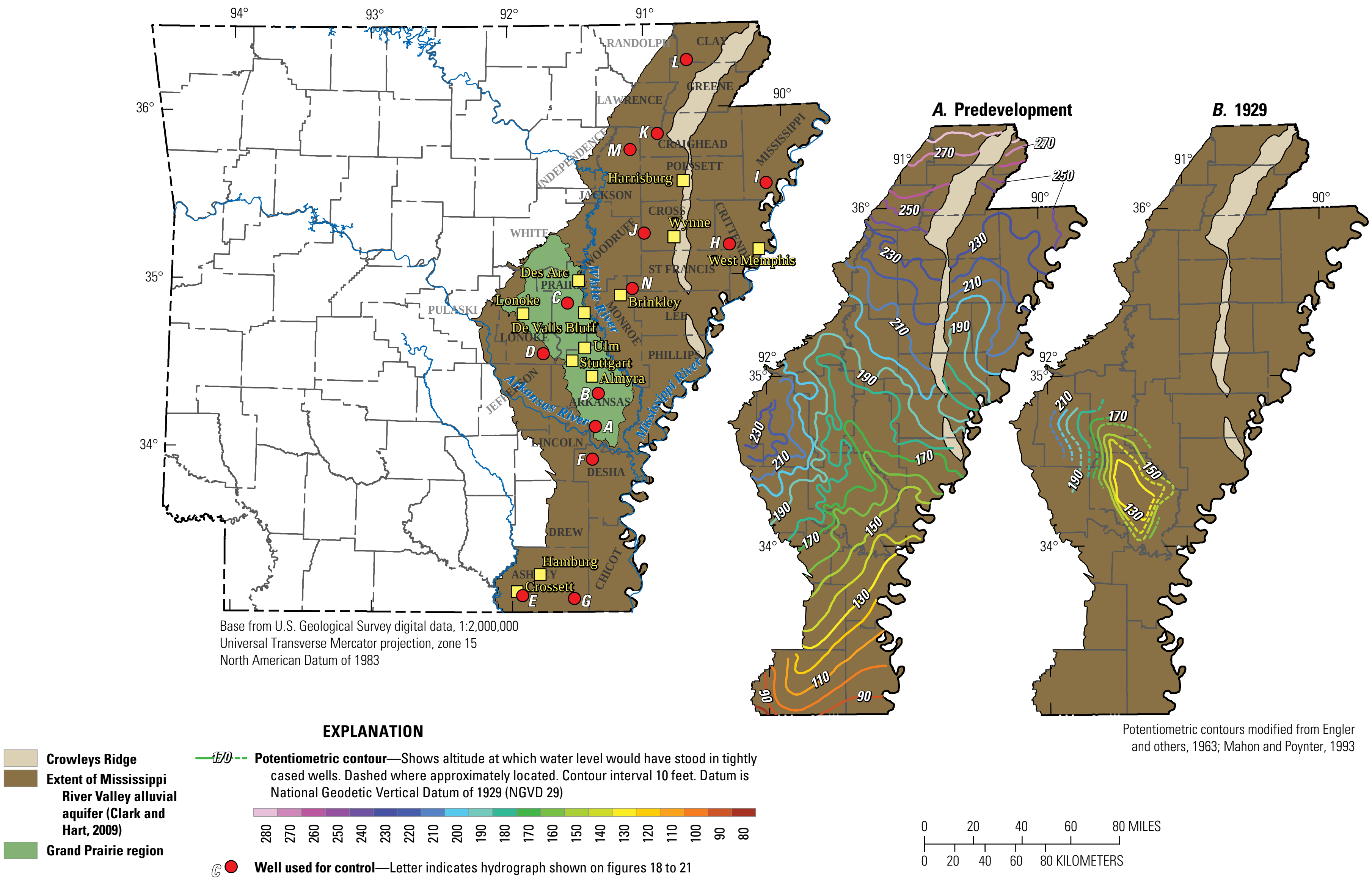


Figure 17. Selected potentiometric contours of water levels for selected time periods in the Mississippi River Valley alluvial aquifer in Arkansas. *A*, predevelopment; *B*, 1929; *C*, 1938; *D*, 1944; *E*, 1953 and 1955; *F*, 1961 and 1962; *G*, 1965; *H*, 1972; *I*, 1980; *J*, 1992; *K*, 1998; *L*,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

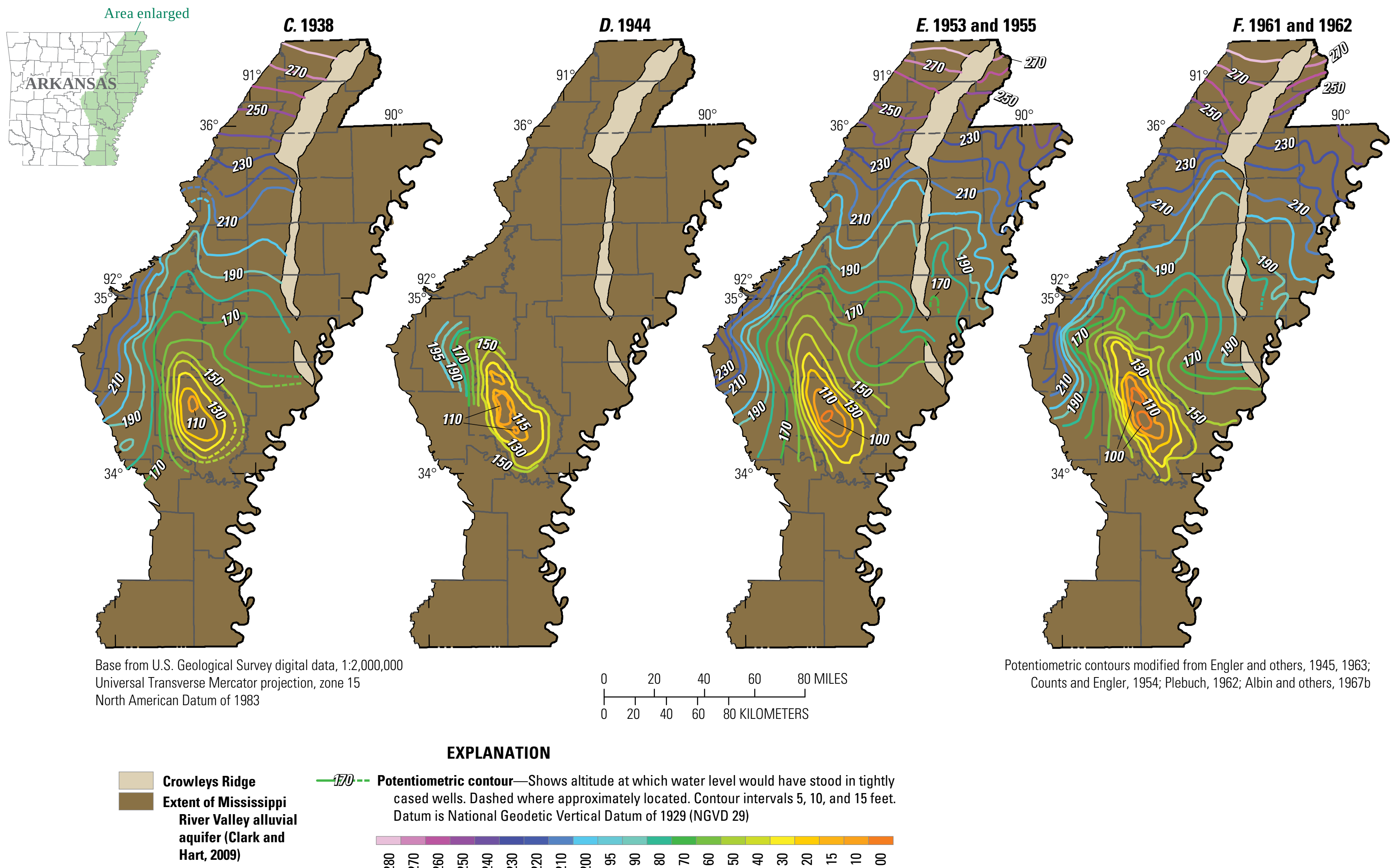


Figure 17. Selected potentiometric contours of water levels for selected time periods in the Mississippi River Valley alluvial aquifer in Arkansas. *A*, predevelopment; *B*, 1929; *C*, 1938; *D*, 1944; *E*, 1953 and 1955; *F*, 1961 and 1962; *G*, 1965; *H*, 1972; *I*, 1980; *J*, 1992; *K*, 1998; *L*,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

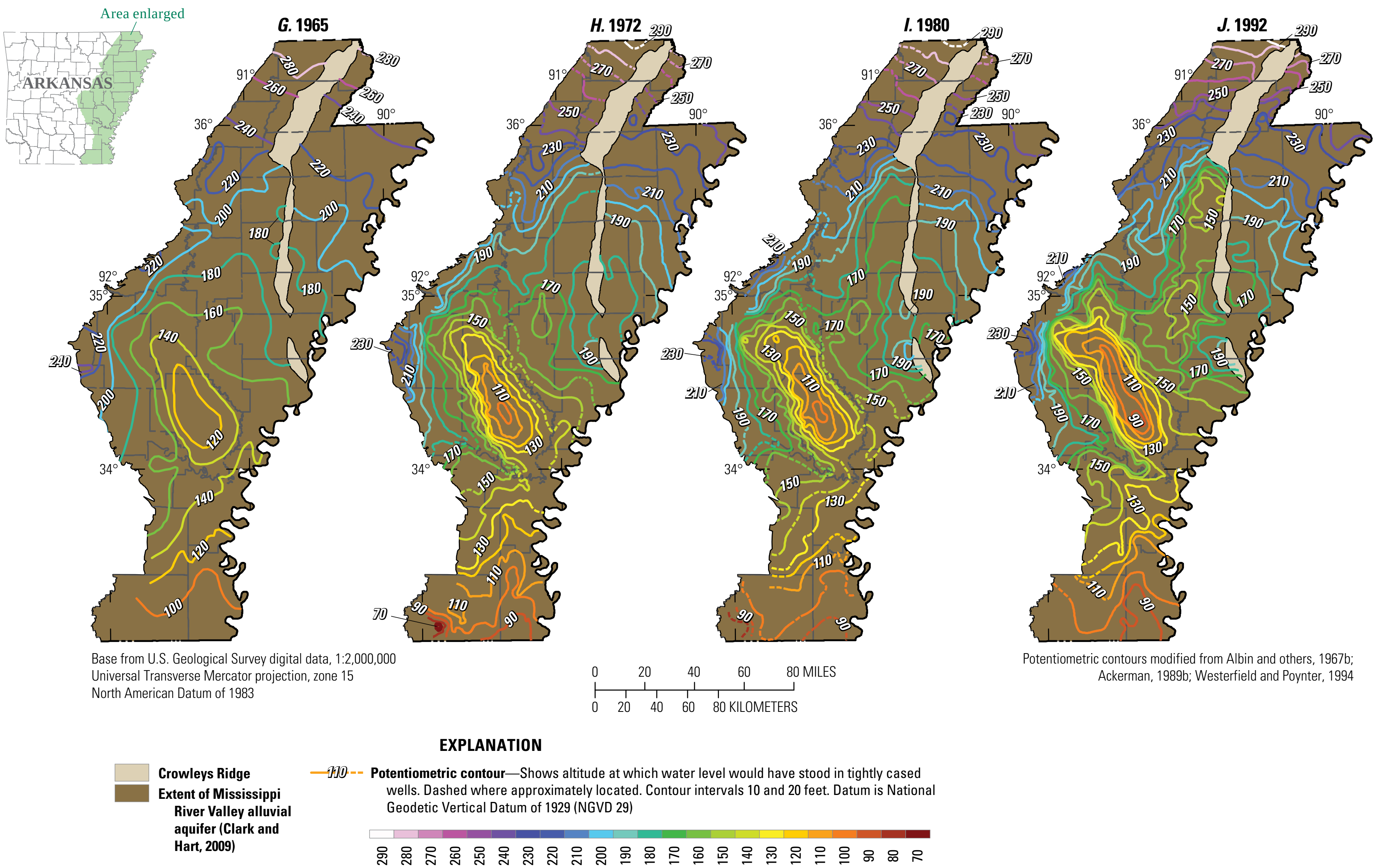


Figure 17. Selected potentiometric contours of water levels for selected time periods in the Mississippi River Valley alluvial aquifer in Arkansas. *A*, predevelopment; *B*, 1929; *C*, 1938; *D*, 1944; *E*, 1953 and 1955; *F*, 1961 and 1962; *G*, 1965; *H*, 1972; *I*, 1980; *J*, 1992; *K*, 1998; *L*,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

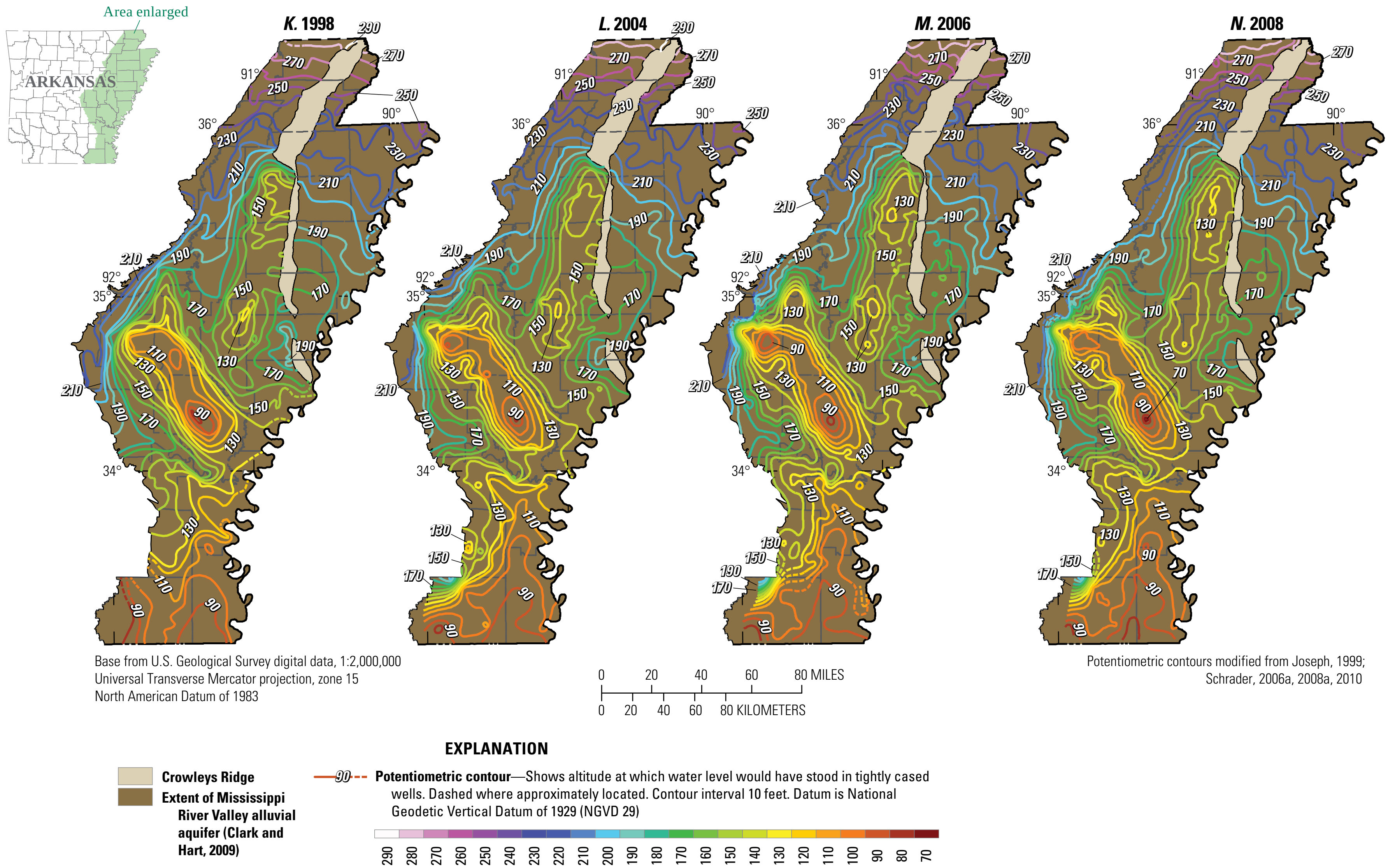


Figure 17. Selected potentiometric contours of water levels for selected time periods in the Mississippi River Valley alluvial aquifer in Arkansas. *A*, predevelopment; *B*, 1929; *C*, 1938; *D*, 1944; *E*, 1953 and 1955; *F*, 1961 and 1962; *G*, 1965; *H*, 1972; *I*, 1980; *J*, 1992; *K*, 1998; *L*,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

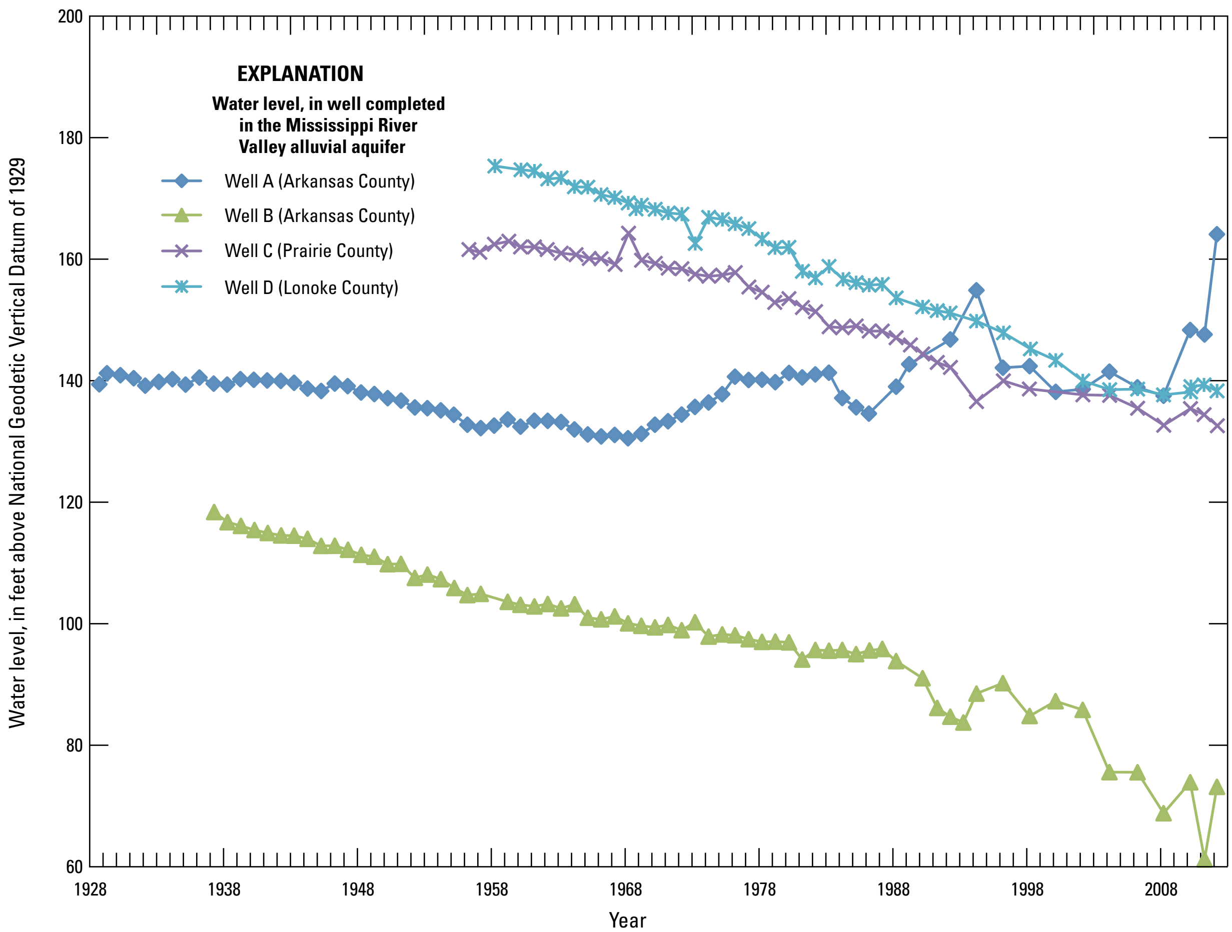


Figure 18. Hydrograph of water levels in wells completed in Mississippi River Valley alluvial aquifer in the Grand Prairie region of Arkansas.

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*).

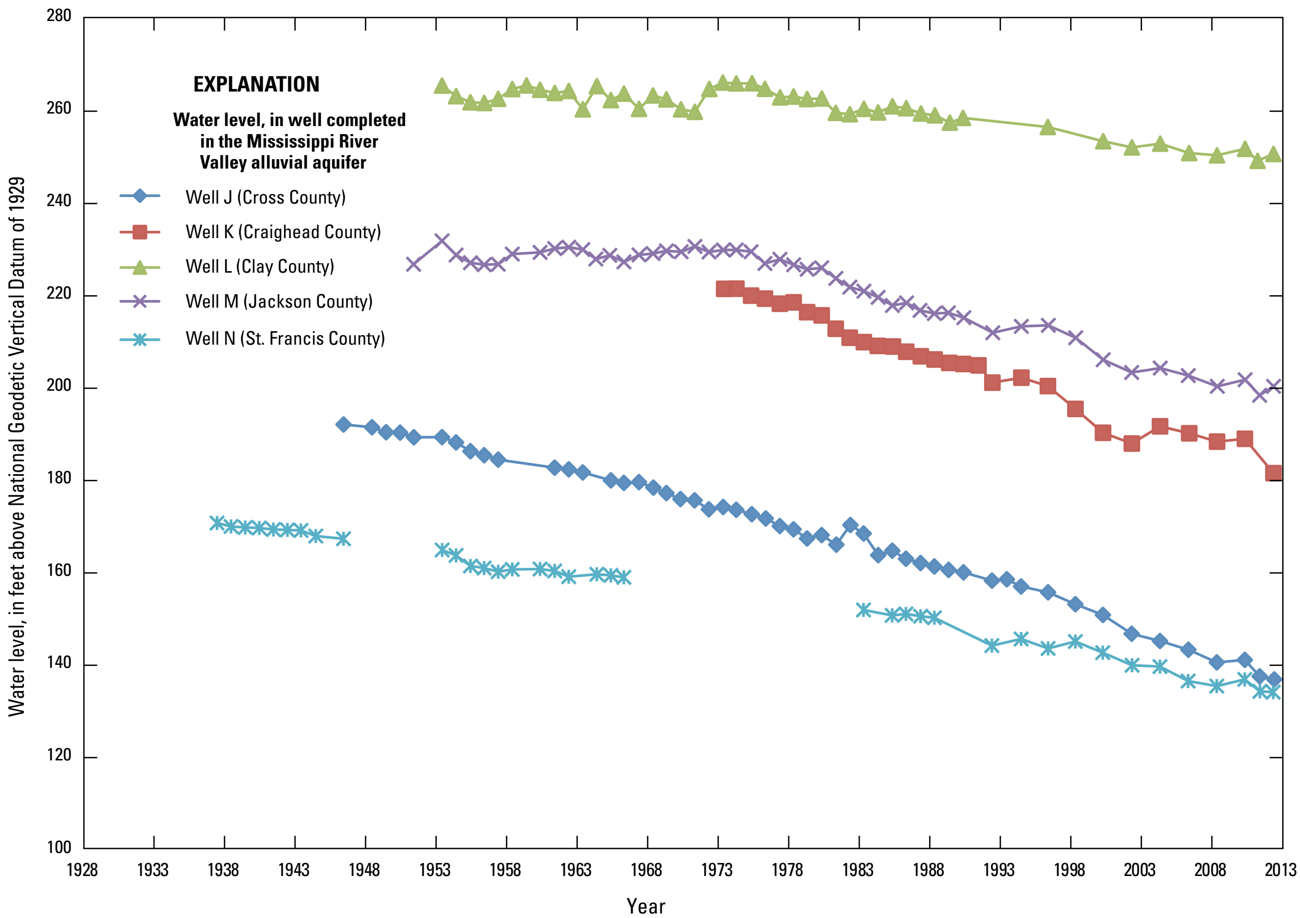


Figure 19. Hydrographs of water levels in wells completed in the Mississippi River Valley alluvial aquifer west of Crowleys Ridge in northeastern Arkansas.

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.

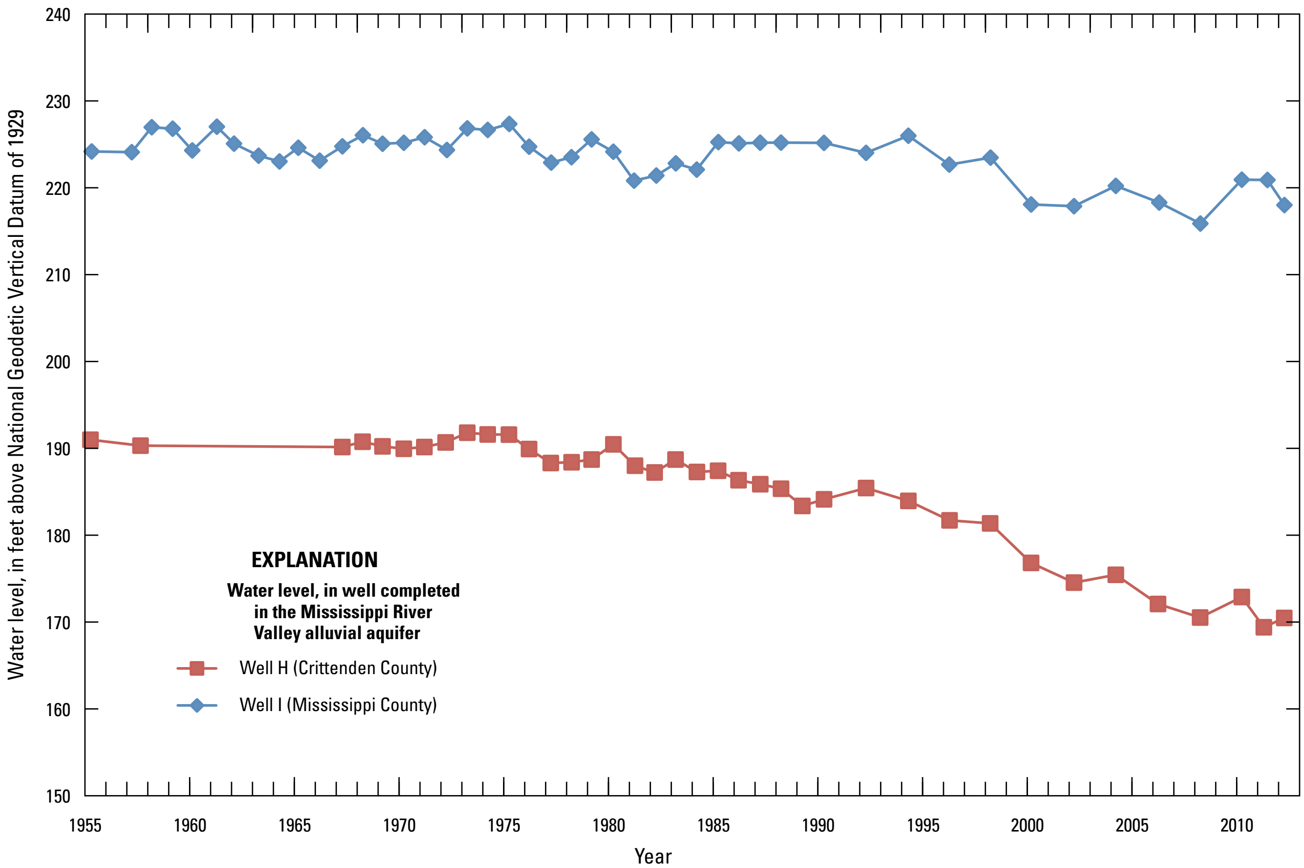


Figure 20. Hydrographs of water levels in wells completed in the Mississippi River Valley alluvial aquifer east of Crowleys Ridge in northeastern Arkansas.

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.

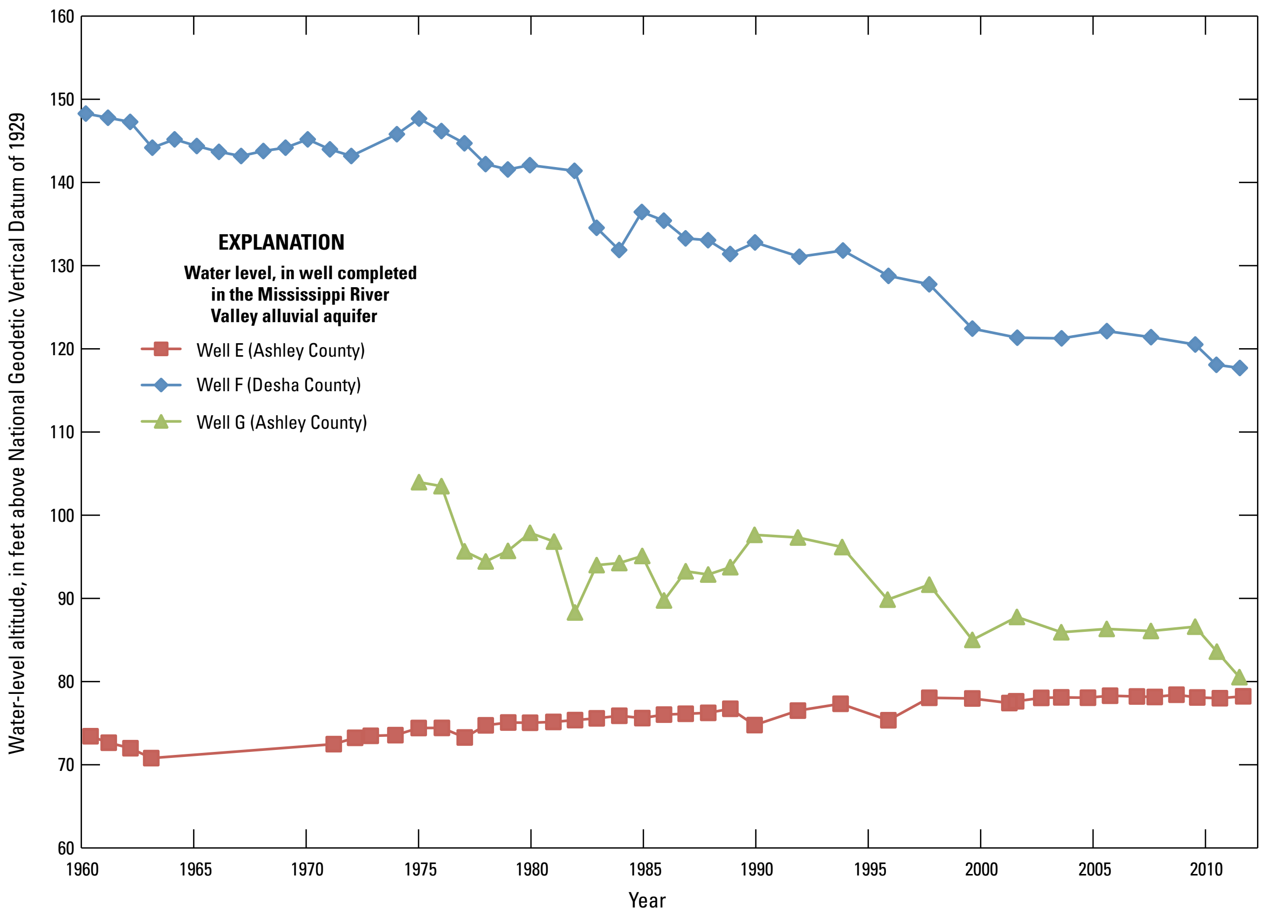


Figure 21. Hydrographs of water levels in wells completed in the Mississippi River Valley alluvial aquifer in southeastern Arkansas.

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.

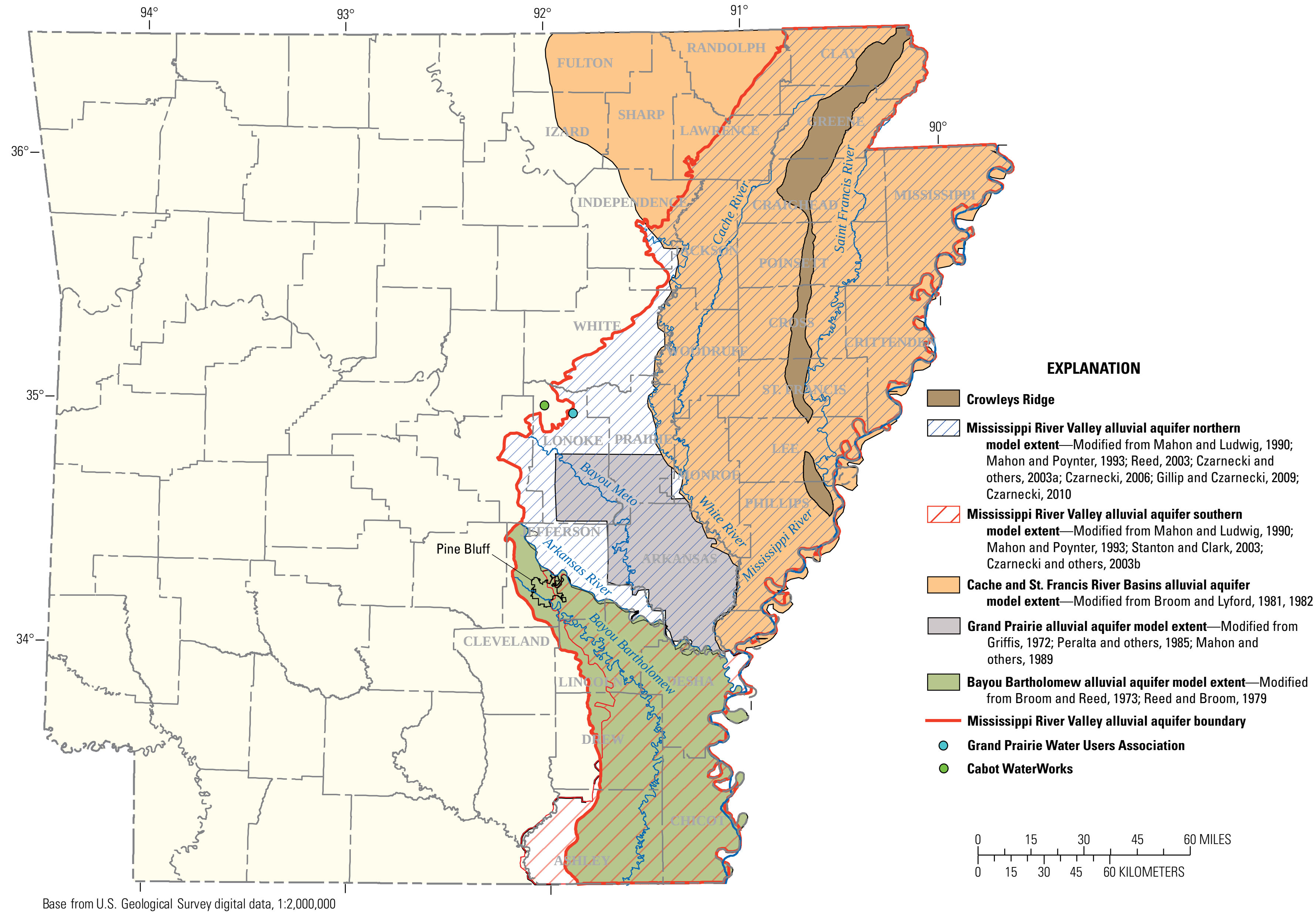


Figure 22. Areal extents for all groundwater flow-simulation models conducted in the Mississippi River Valley alluvial aquifer in eastern Arkansas.

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.

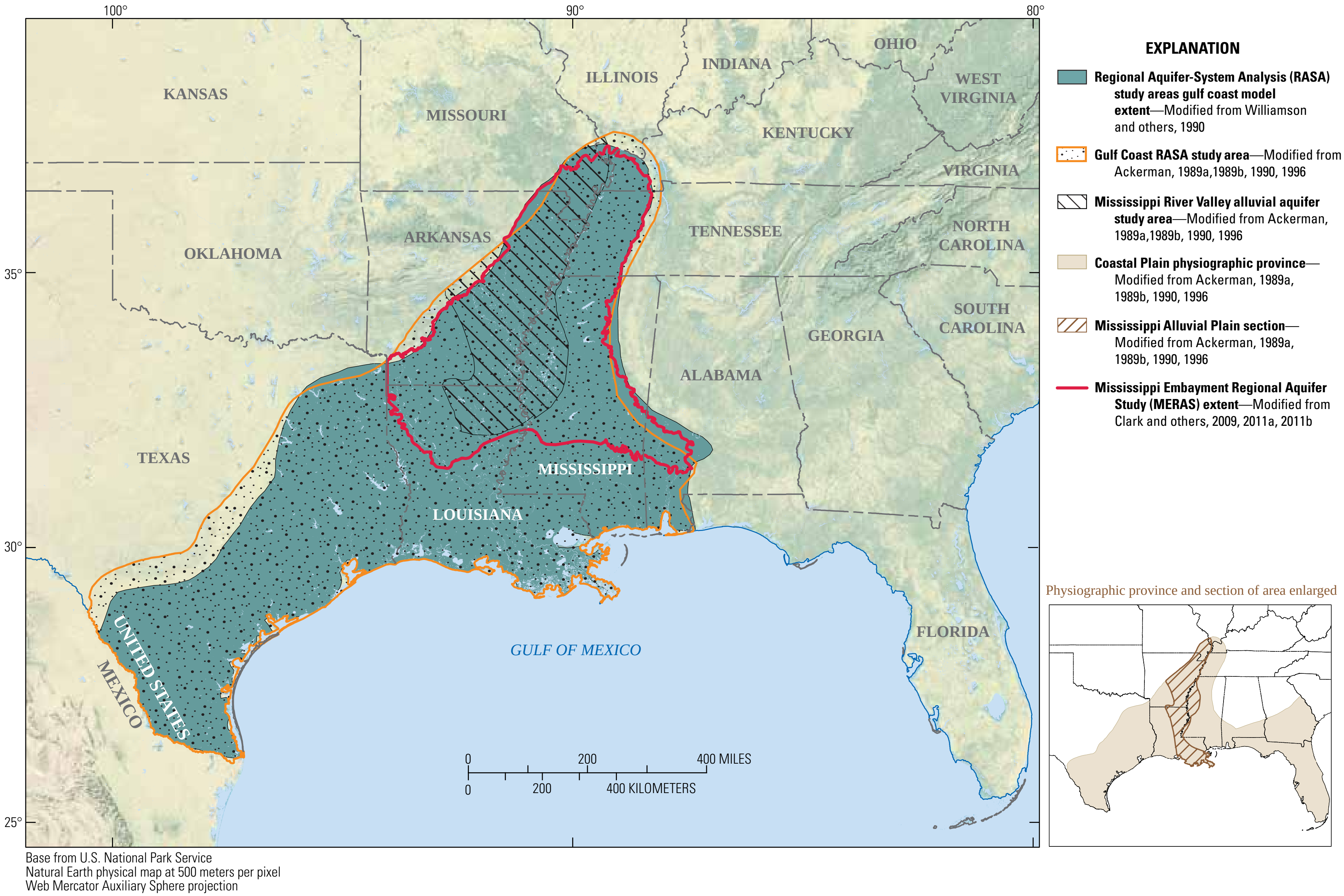


Figure 23. Spatial extent of the Mississippi Embayment Regional Aquifer-System Analysis study including the Mississippi River Valley alluvial aquifer study area.

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.

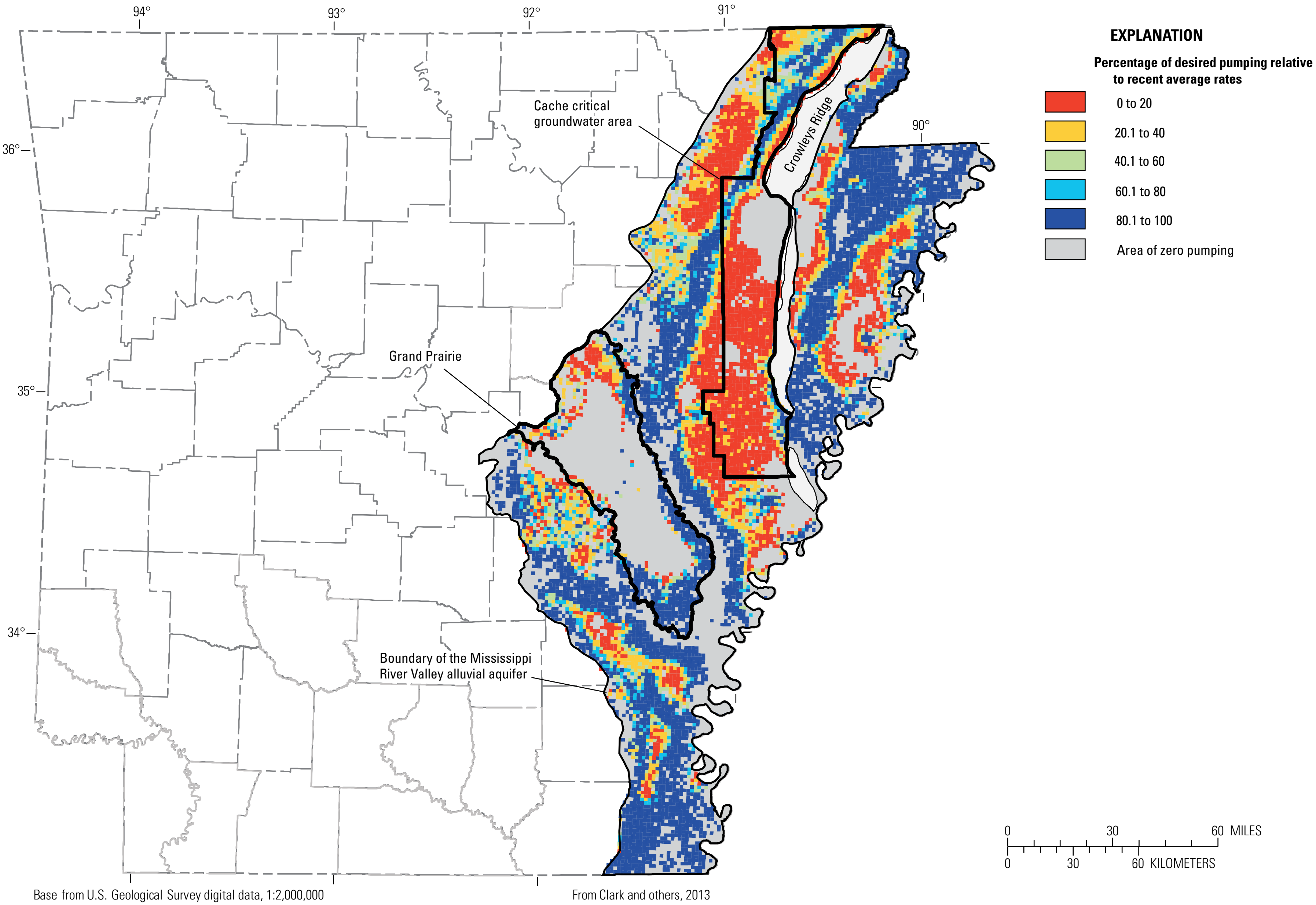


Figure 24. Percentage of recent average annual pumping from the Mississippi River Valley alluvial aquifer with reductions for surface-water diversions simulated in scenario 3 of Clark and others (2013).

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).

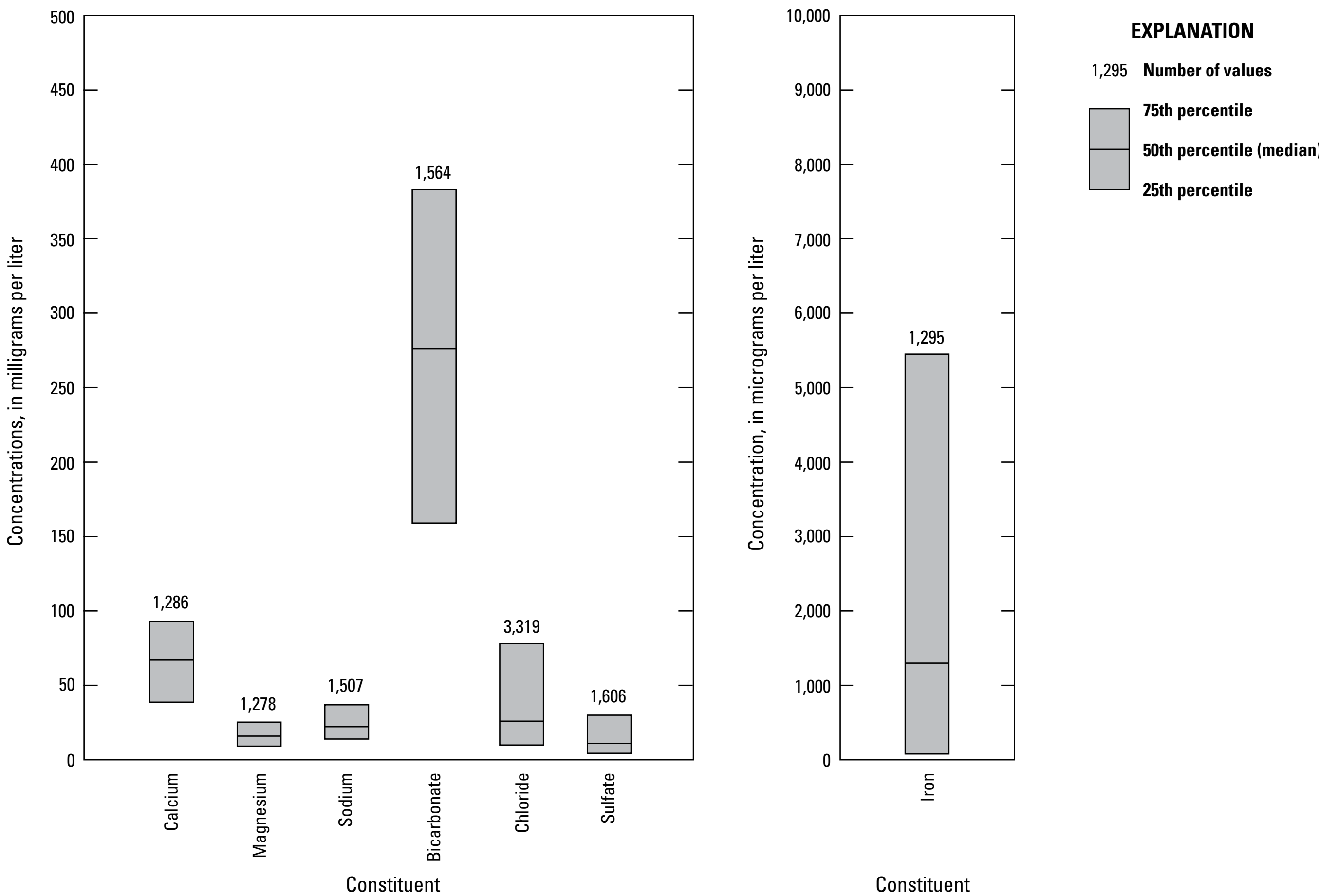


Figure 25. Interquartile range of selected chemical constituents in groundwater from alluvial deposits in the Coastal Plain of southern and eastern Arkansas.

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.

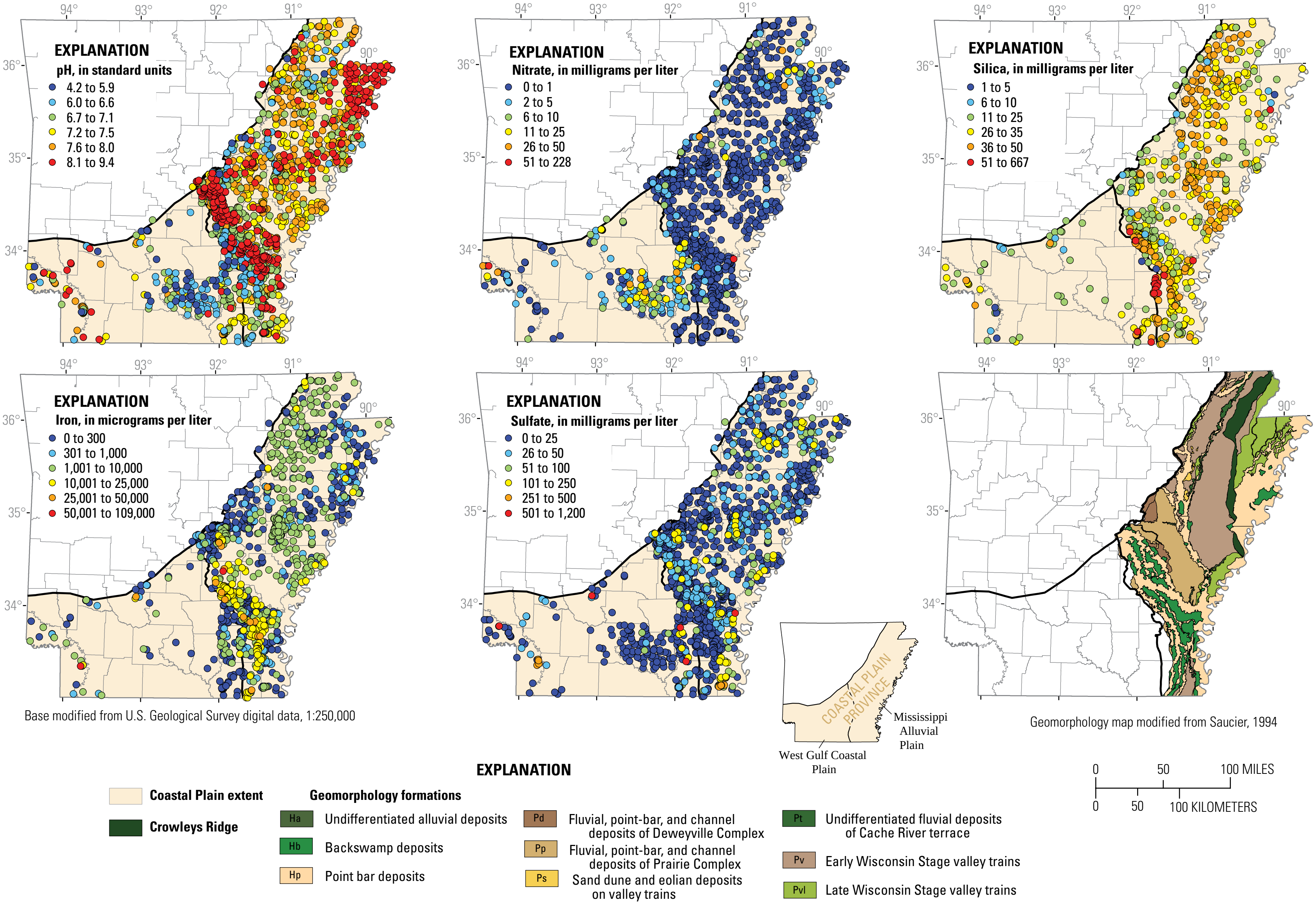


Figure 26. Spatial distribution of selected chemical constituents in groundwater from alluvial deposits in the Coastal Plain of southern and eastern Arkansas.

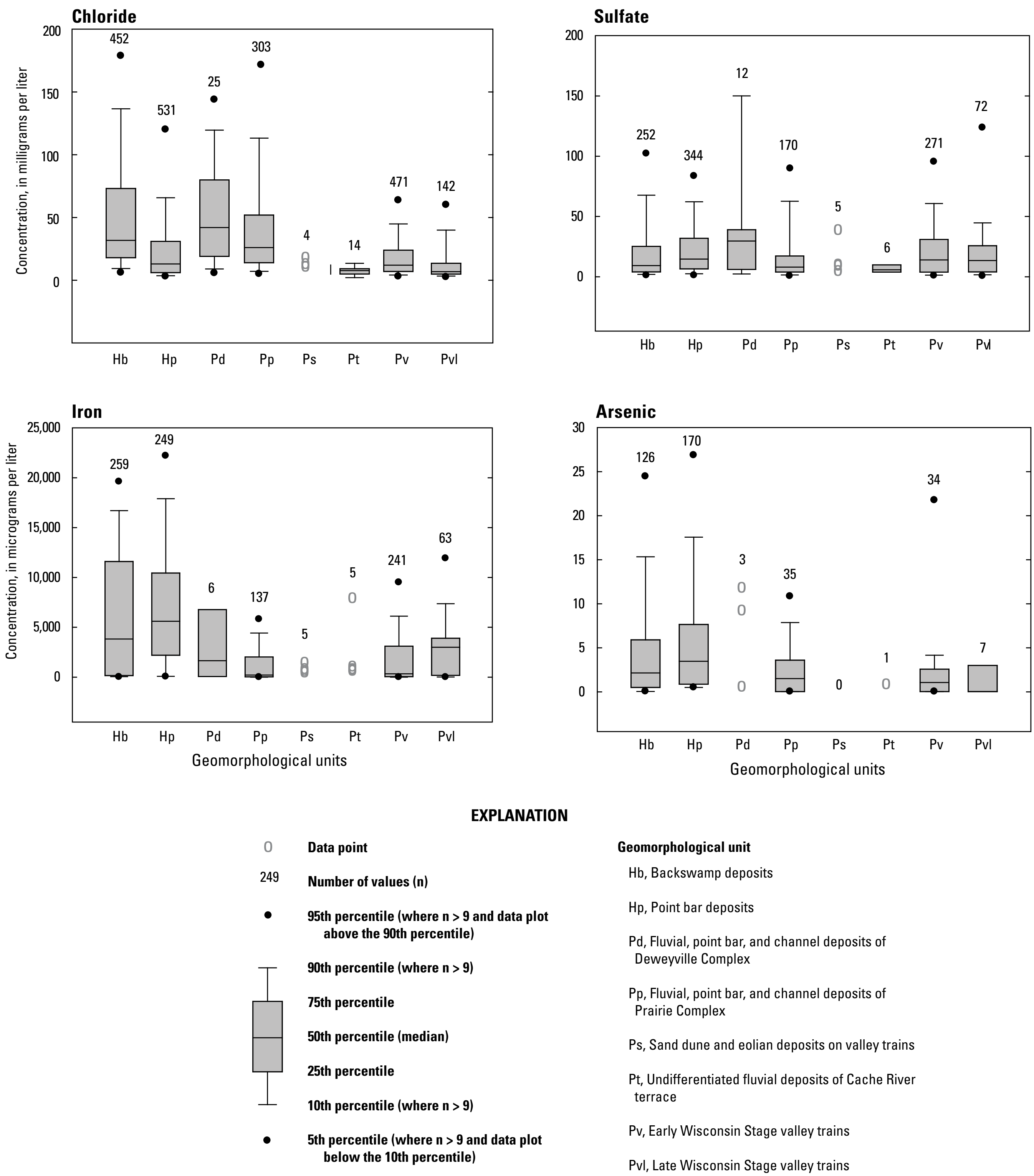


Figure 27. Selected chemical constituents in groundwater from alluvial deposits as related to geomorphological units in the Mississippi Alluvial Plain of eastern Arkansas.

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.

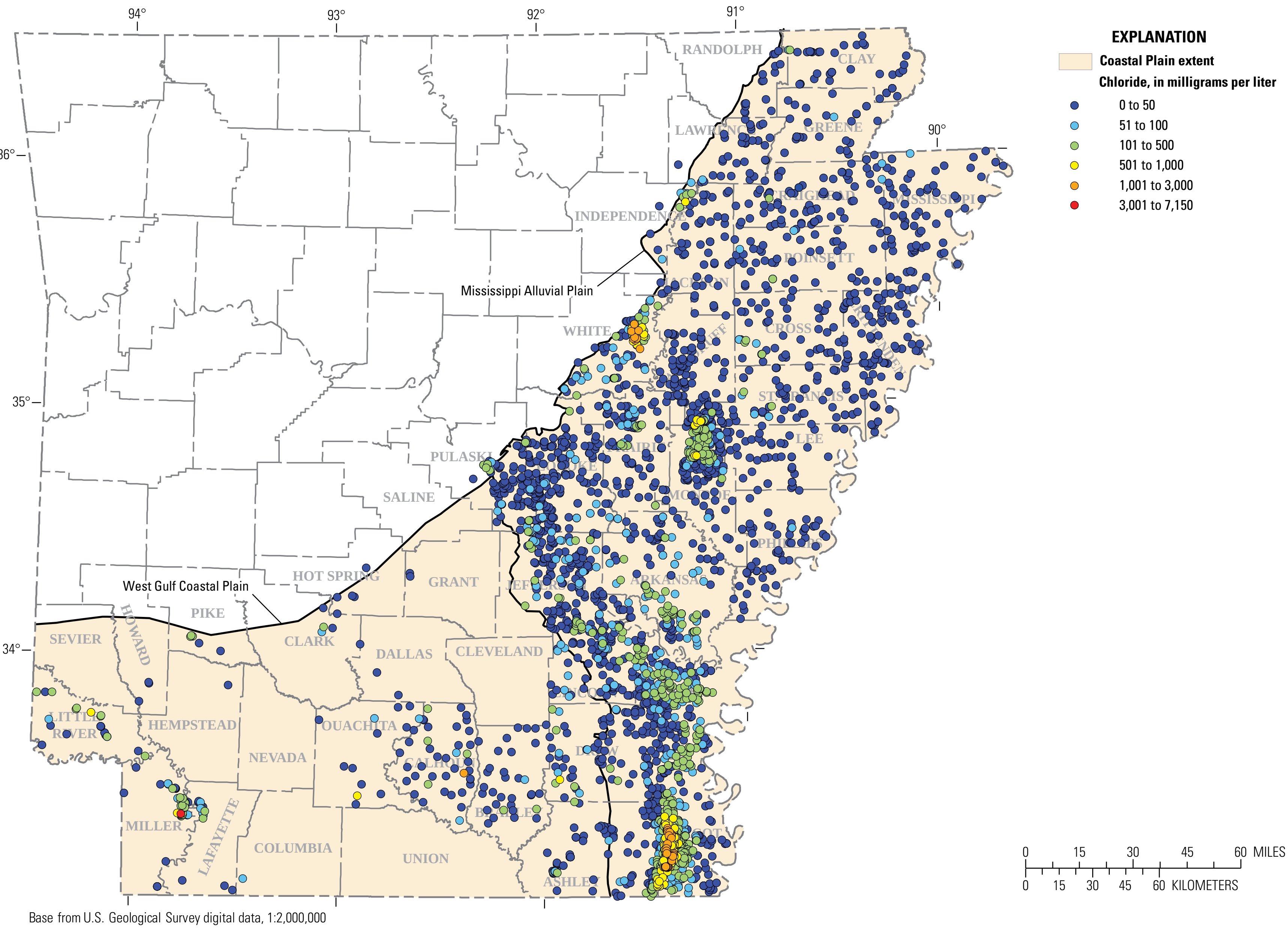


Figure 28. Distribution of chloride concentrations in groundwater from alluvial deposits of the Coastal Plain in Arkansas.

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.

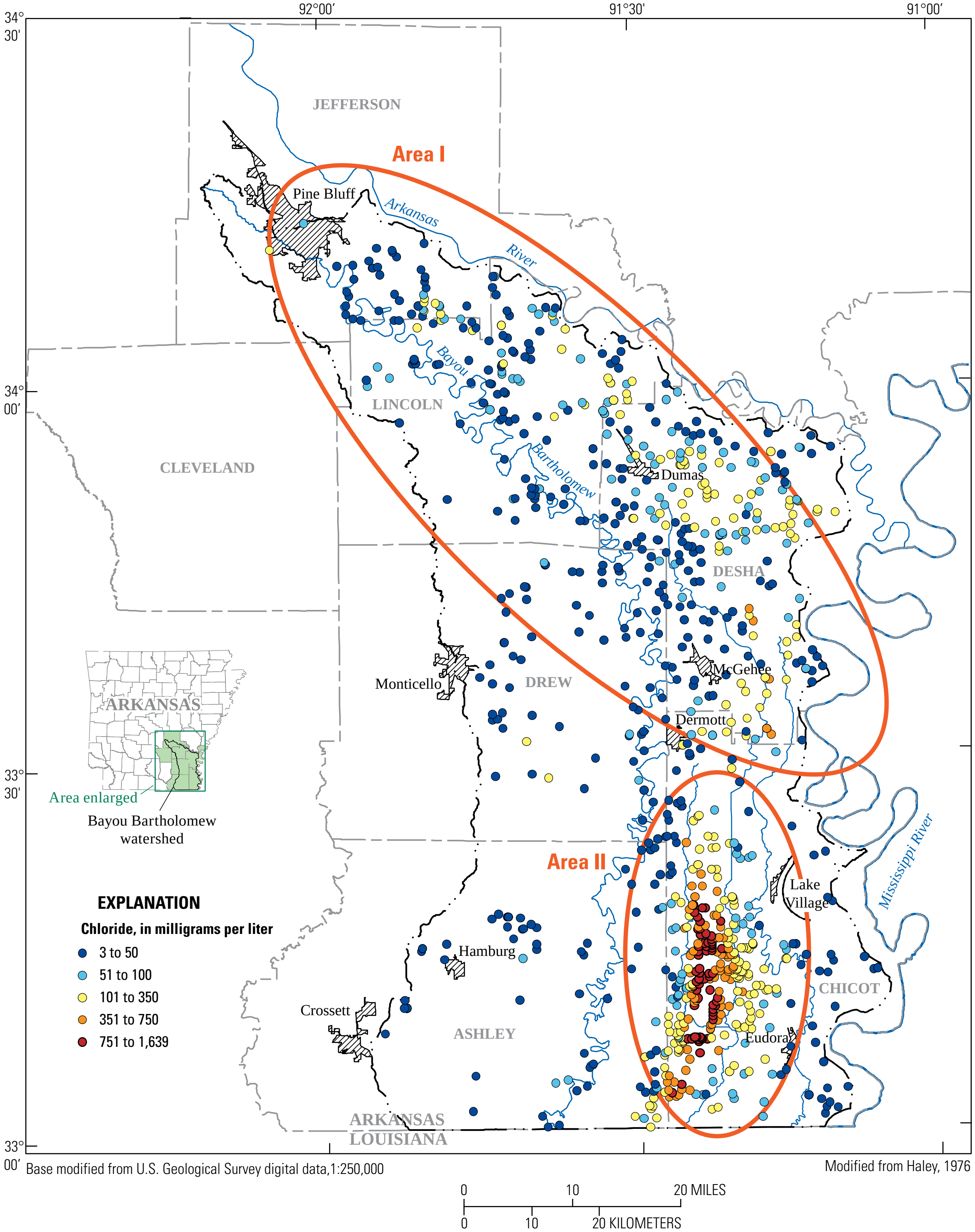


Figure 29. Distribution of chloride concentrations in groundwater from the Mississippi River Valley alluvial aquifer in Bayou Bartholomew watershed of southeastern Arkansas (from Kresse and Clark, 2008).

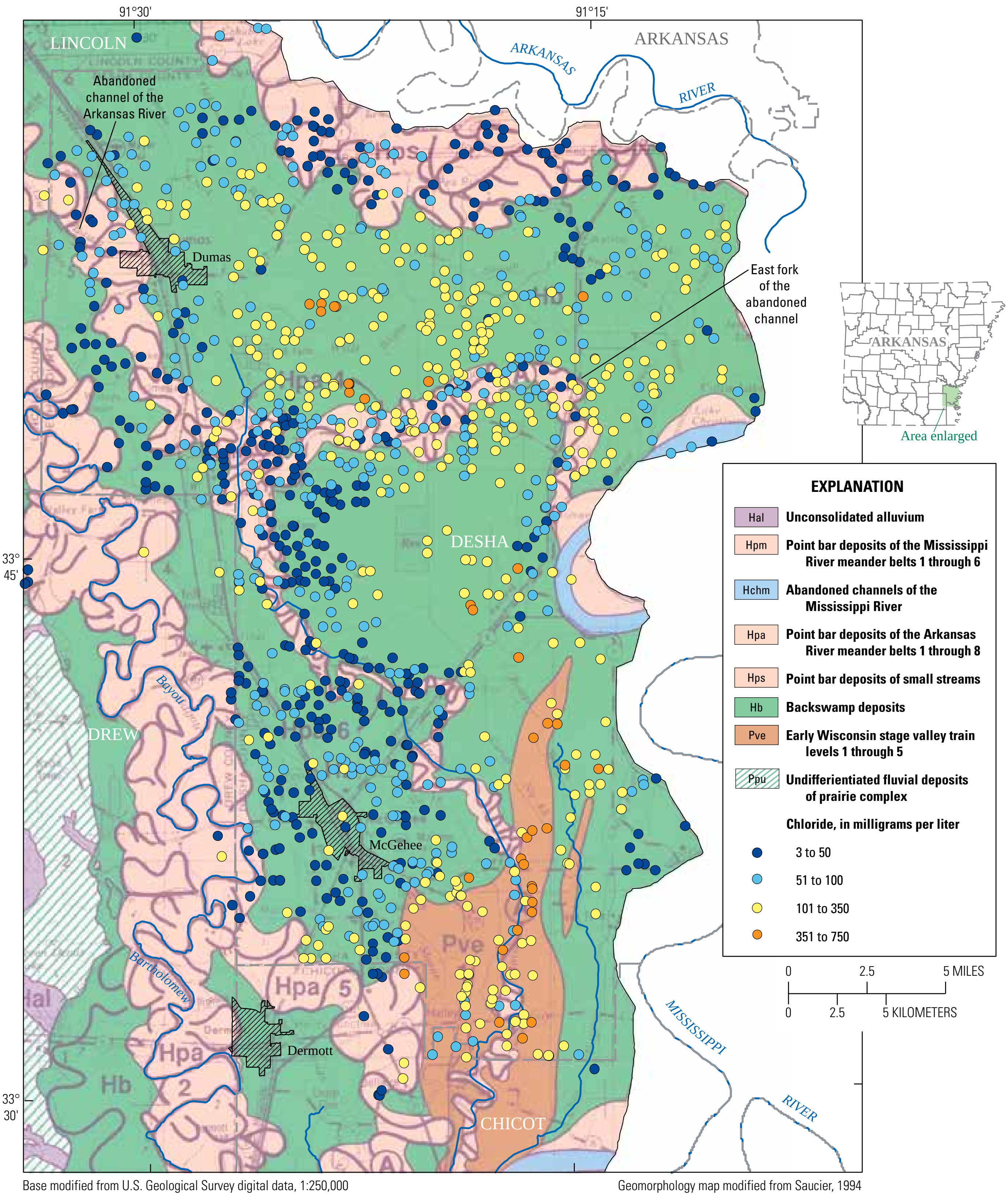


Figure 30. Distribution of chloride concentrations in groundwater from the Mississippi River Valley alluvial aquifer overlain onto a map of Quaternary geomorphological landforms (from Kresse and Clark, 2008).

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.

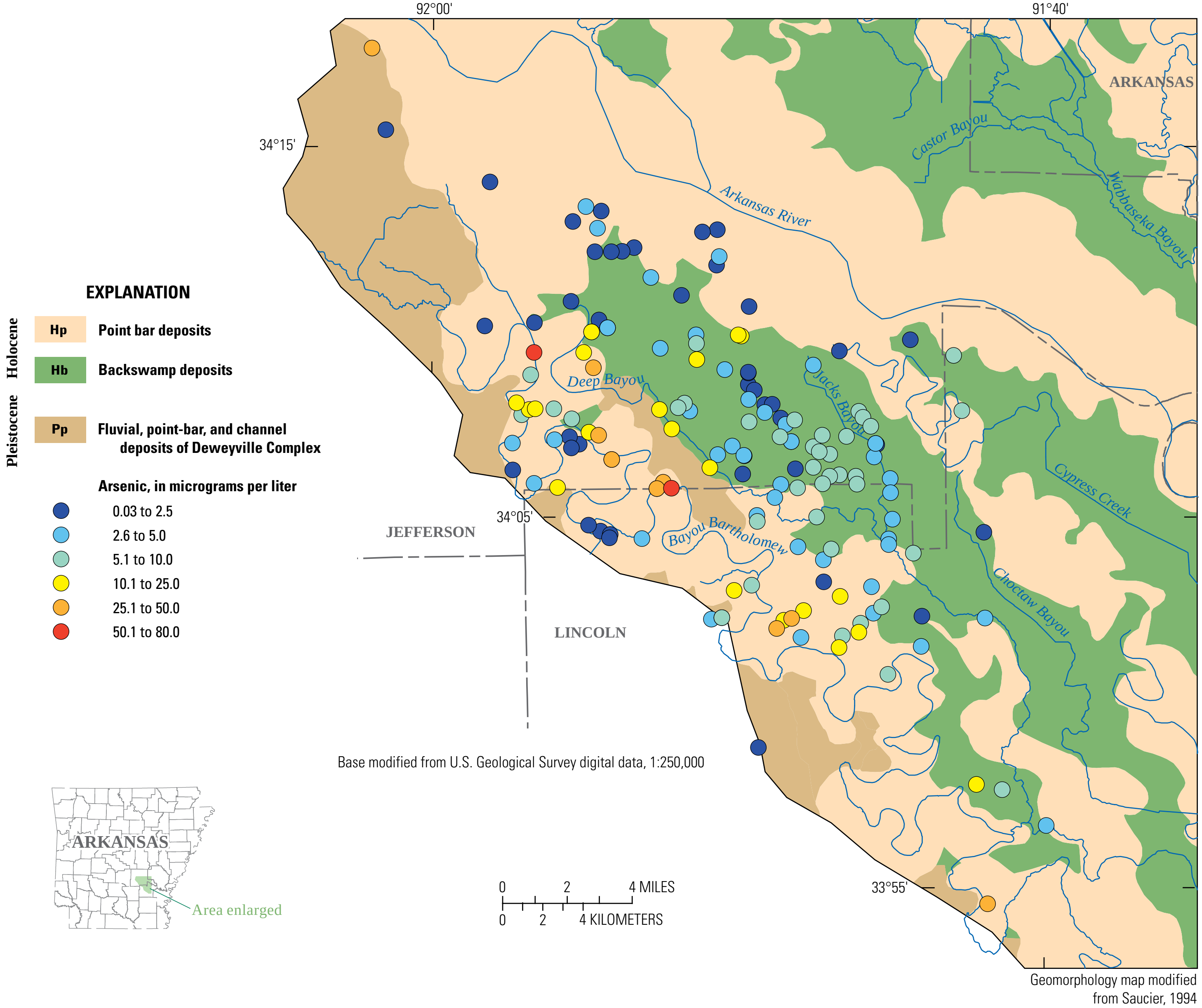


Figure 31. Distribution of arsenic concentrations in groundwater from the Mississippi River Valley alluvial aquifer overlain onto a map of Quaternary geomorphological landforms.

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.