Minor Alluvial Aquifers in Coastal Plain

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

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

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

Red River Alluvial Aquifer

Hydrogeologic Setting

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

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

Water Use

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

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

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

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

Water Quality

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

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

Ouachita-Saline Rivers Alluvial Aquifer

Hydrogeologic Setting

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

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

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

Water Quality

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

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

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

Jackson Group

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

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

Hydrogeologic Setting

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

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

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

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

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

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

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

Water Use

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

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

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

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

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

Water Quality

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

General Geochemistry and Water Type

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

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

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

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

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

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

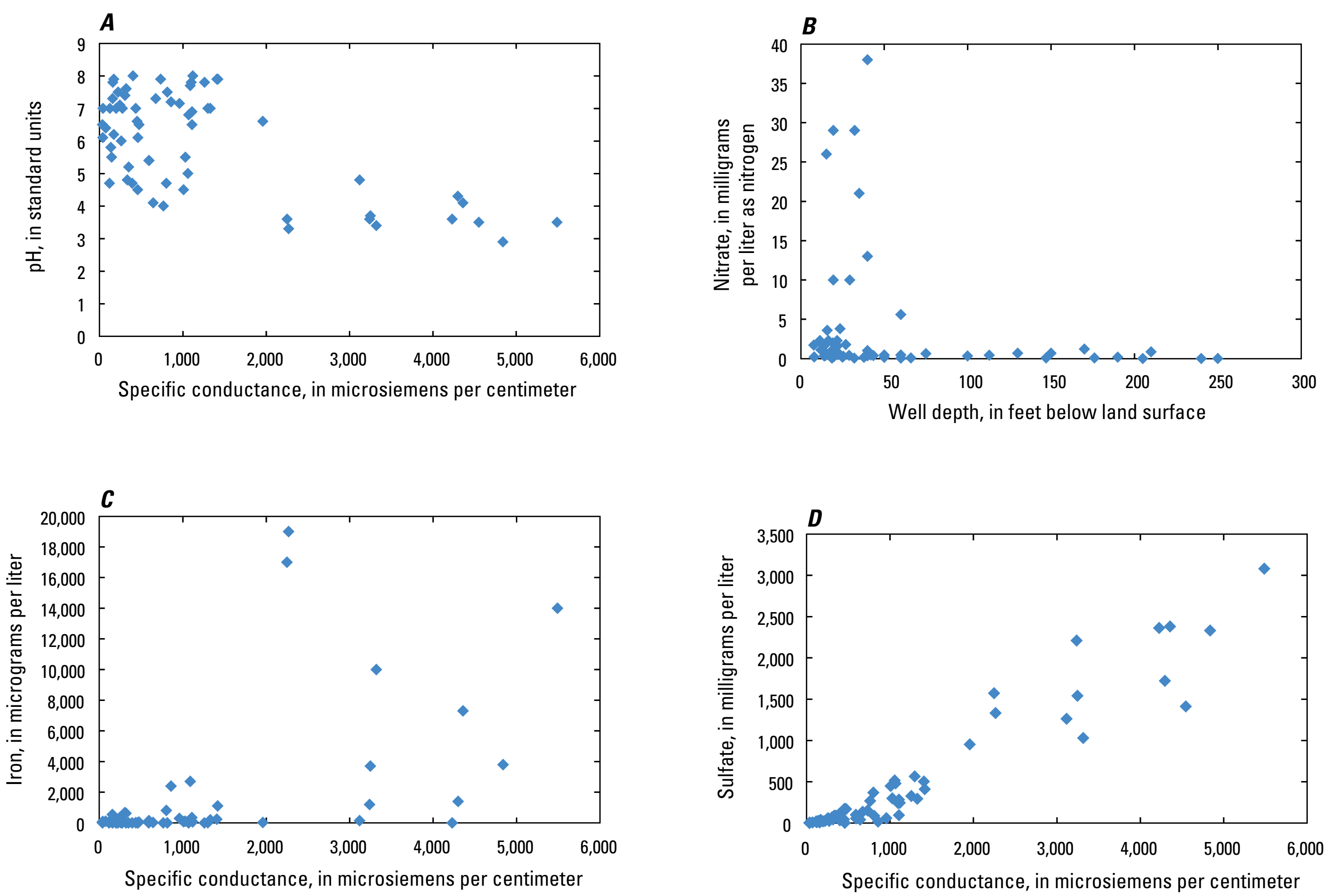


Figure 32. Graphs showing relation of *A*, specific conductance and pH; *B*, well depth and nitrate; *C*, specific conductance and iron; and *D*, specific conductance and sulfate in groundwater from Jackson Group in southeastern Arkansas.

Nitrate

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

Iron

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

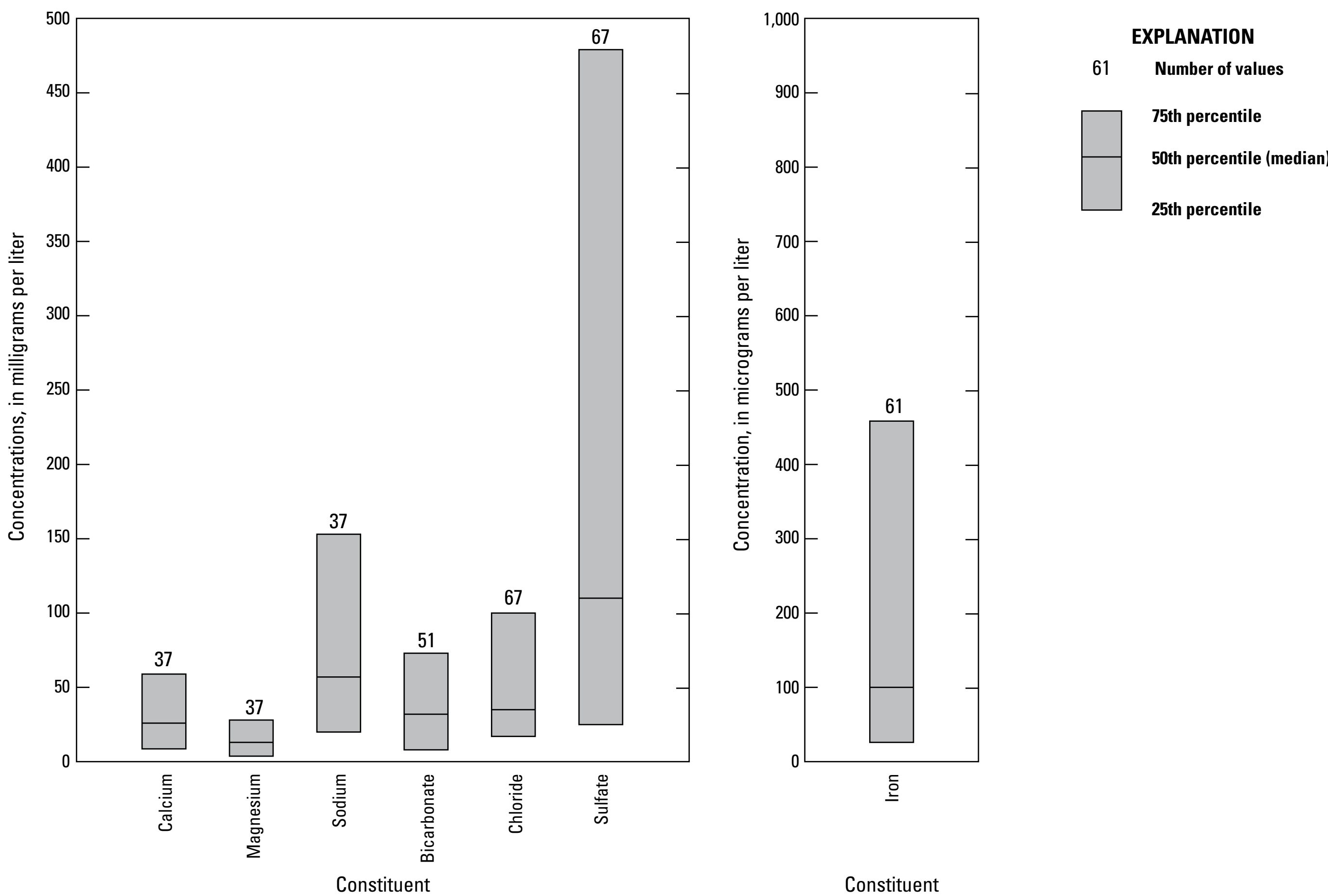


Figure 33. Interquartile range for selected chemical constituents in groundwater from the Jackson Group in southeastern Arkansas.

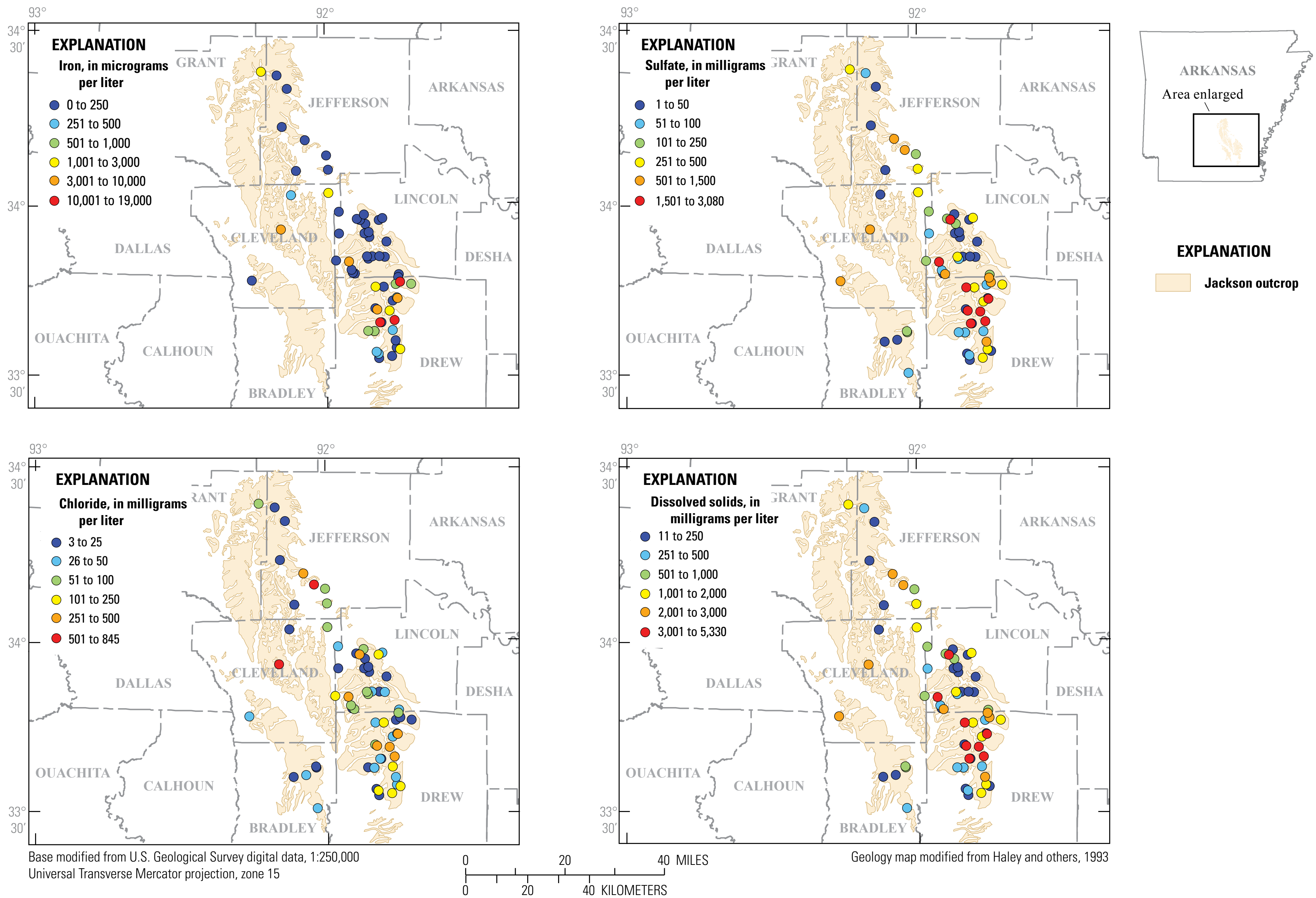


Figure 34. Spatial distribution of selected chemical constituents in groundwater from the Jackson Group in southeastern Arkansas.

Sulfate

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

Chloride

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

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

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

Cockfield Aquifer

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

Geologic Setting

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

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

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

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

Hydrologic Characteristics

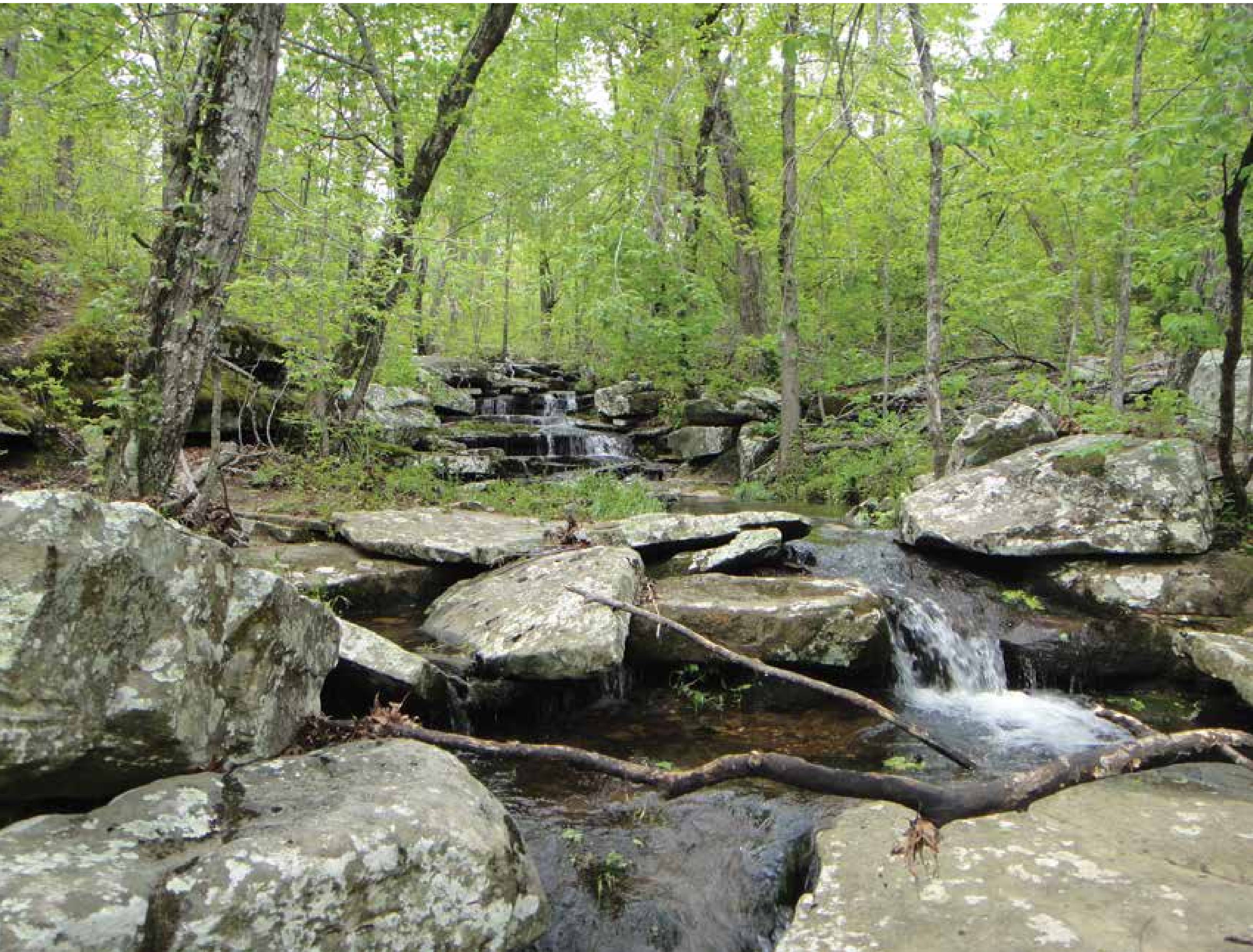
Recharge to the Cockfield aquifer is from precipitation on the outcrop and leakage through the overlying Mississippi River Valley alluvial aquifer in the subcrop area (fig. 3). Surface water in the area of outcrop also is a potential recharge source (Hosman and others, 1968; Broom and others, 1984; Petersen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

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

Water Use

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

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



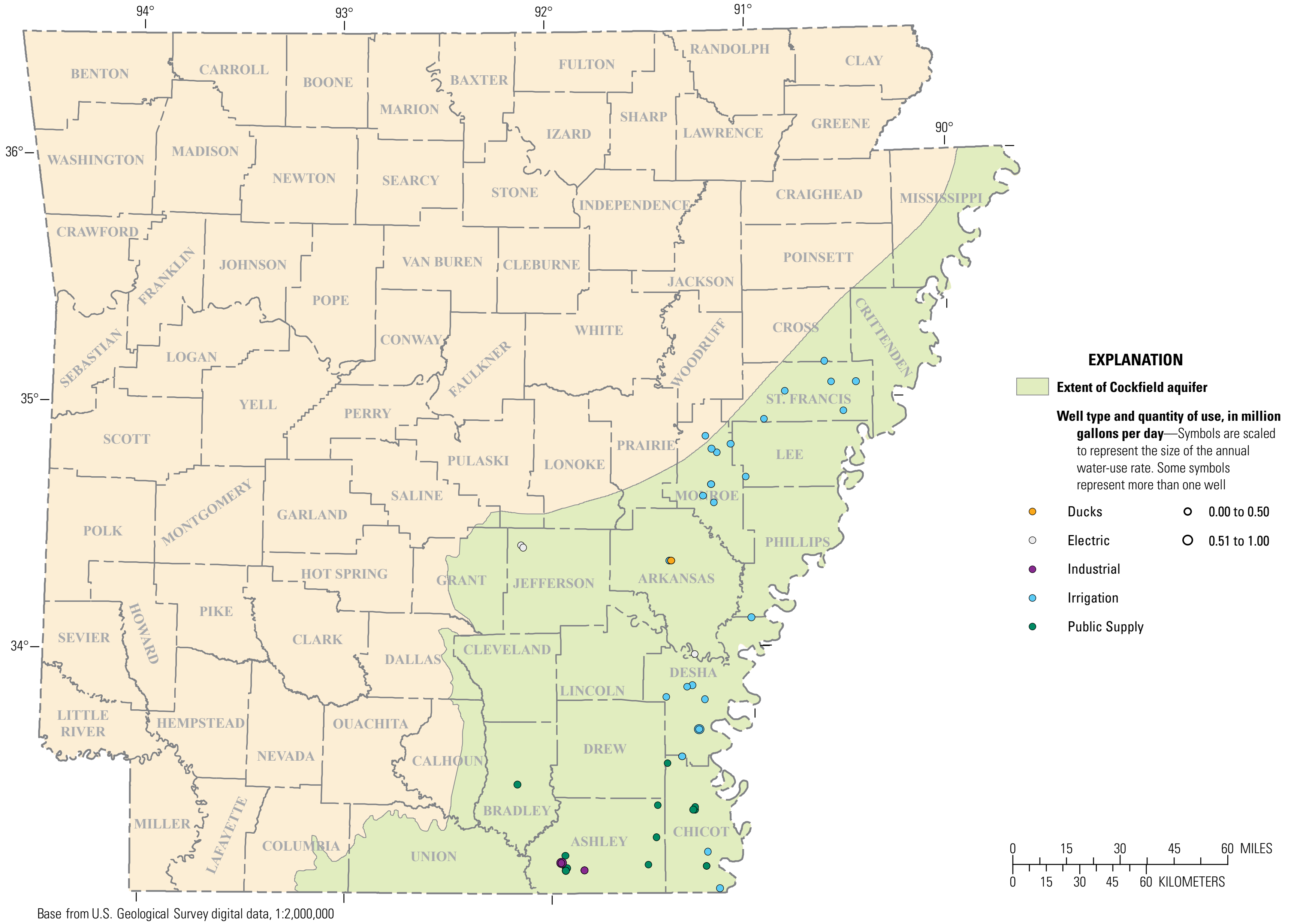


Figure 35. Wells with reported water use from the Cockfield aquifer in Arkansas, 2010.

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

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

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

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

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

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

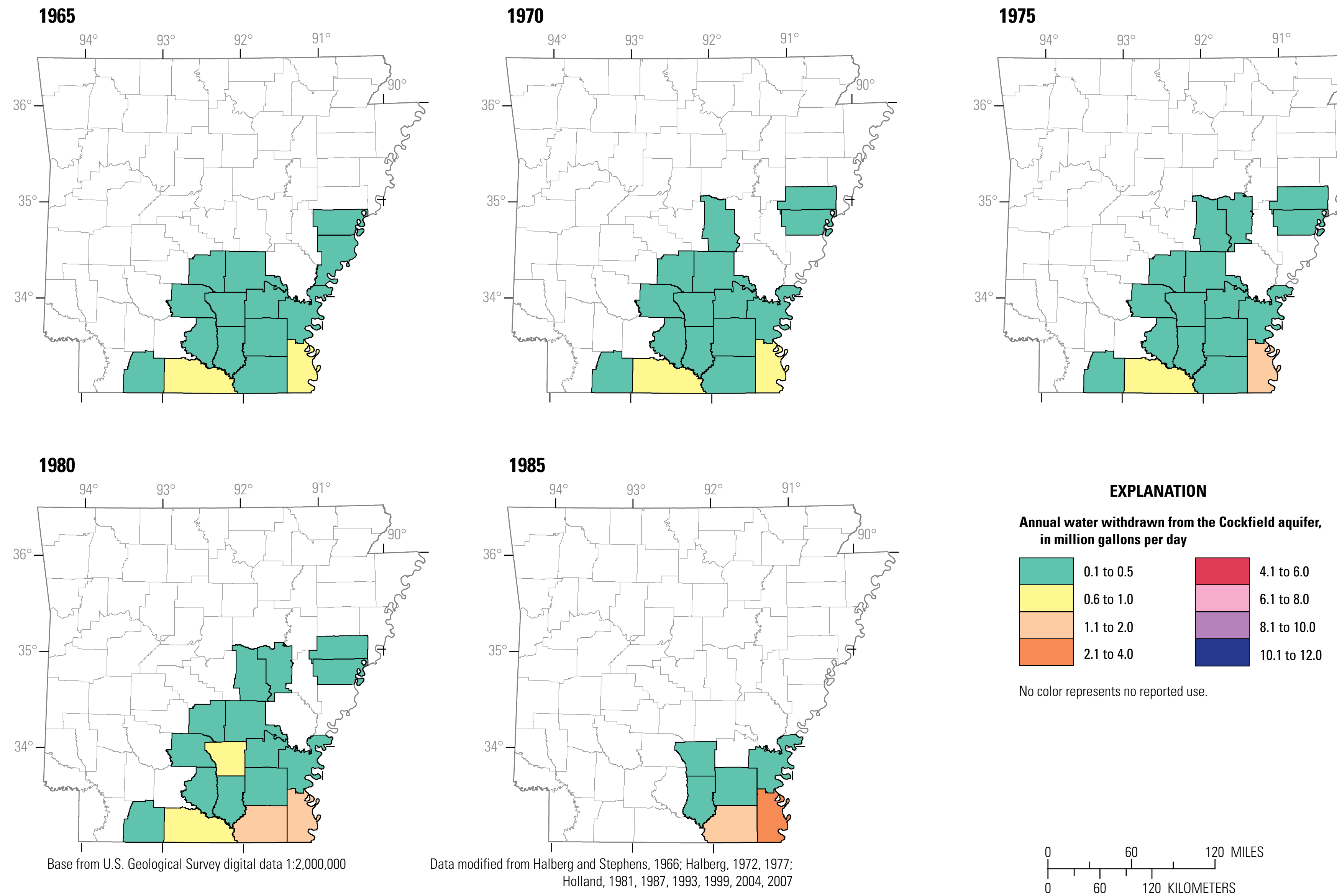


Figure 36. Water-use rates for the Cockfield aquifer in southeastern Arkansas from 1965 to 2010.

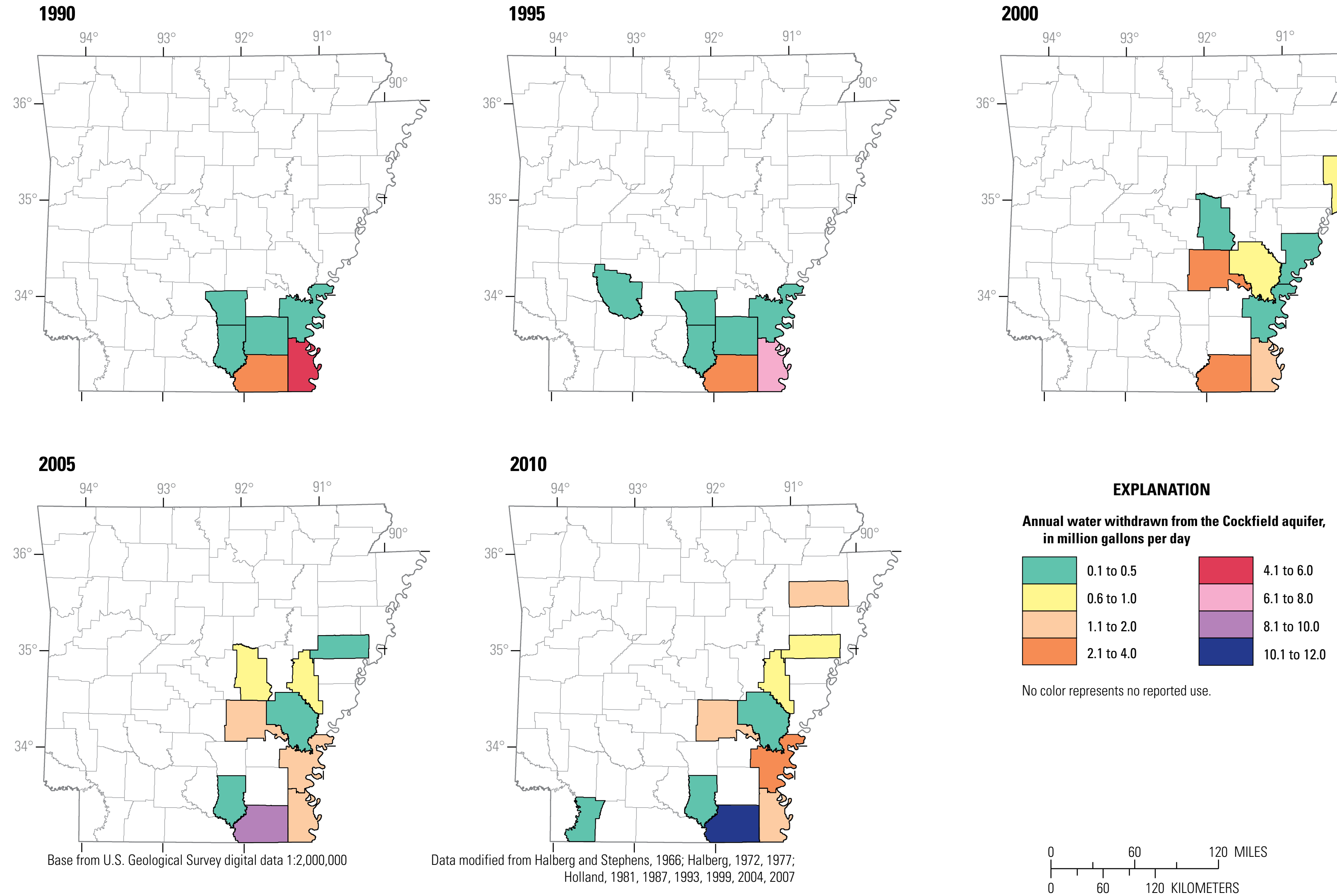


Figure 36. Water-use rates for the Cockfield aquifer in southeastern Arkansas from 1965 to 2010.—Continued

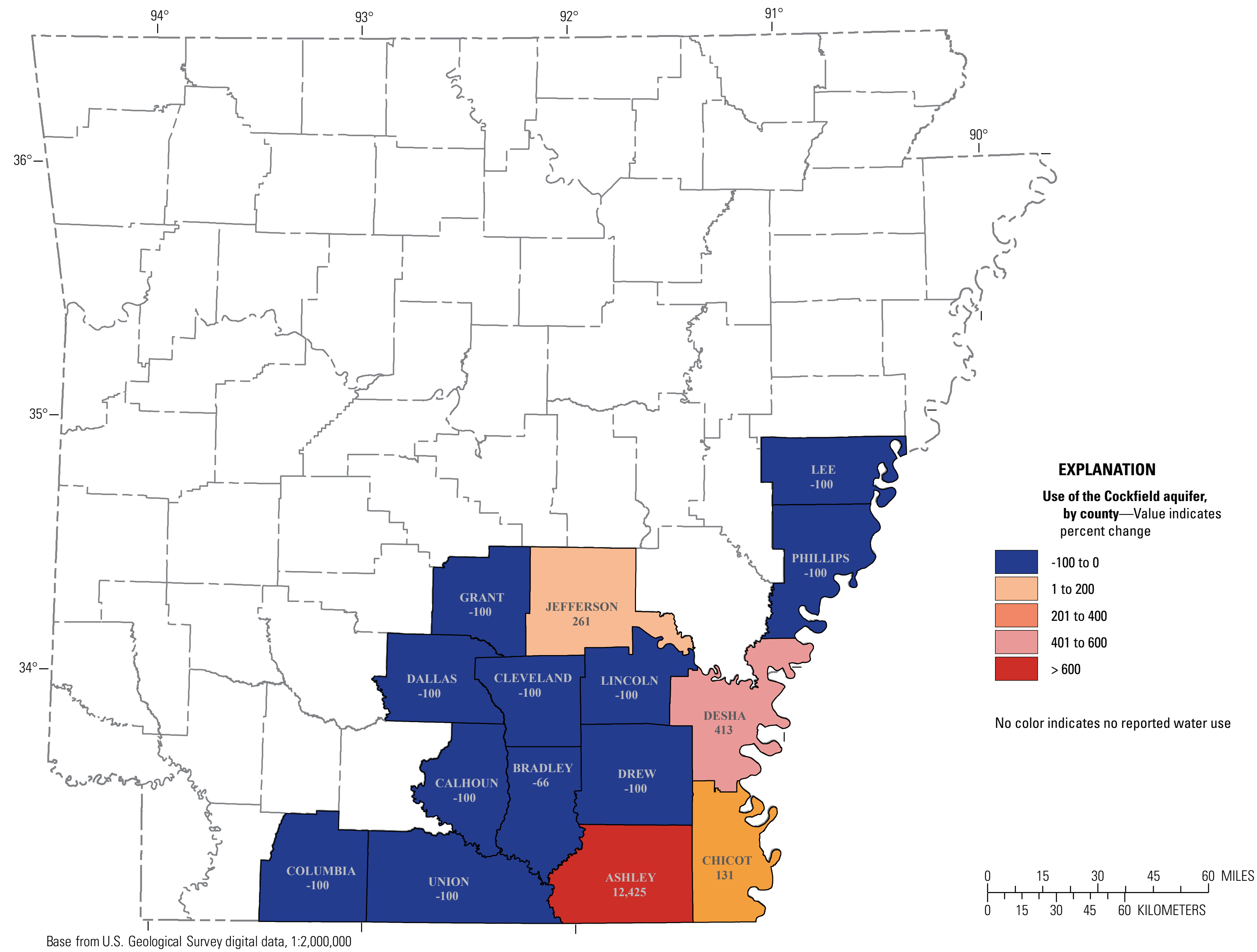


Figure 37. Change in percentage of water use from the Cockfield aquifer in southeastern Arkansas from 1965 to 2010.

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

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

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

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

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

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

Water Levels

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

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

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

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

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

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

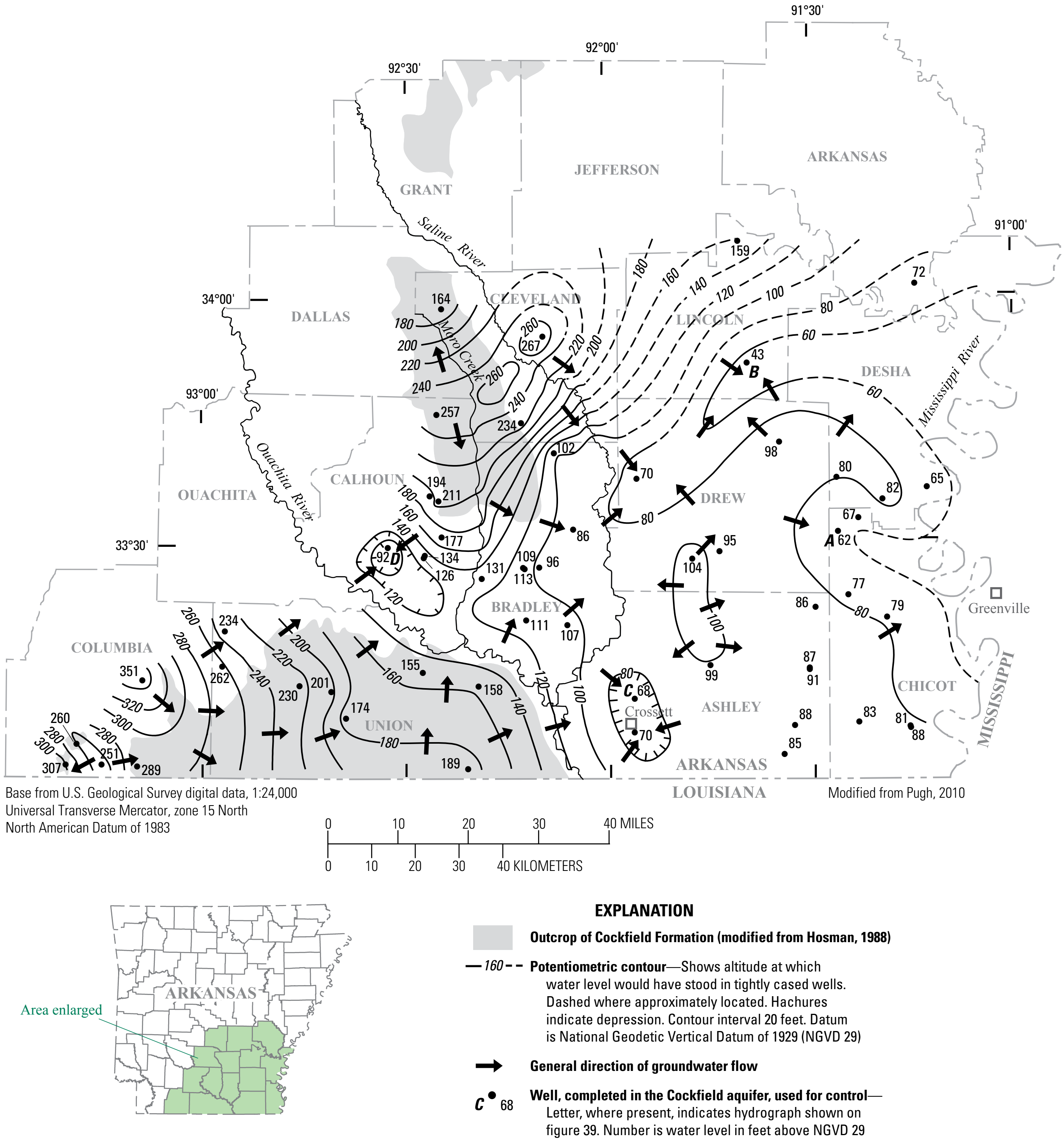


Figure 38. Potentiometric surface of the Cockfield aquifer in Arkansas, 2009.

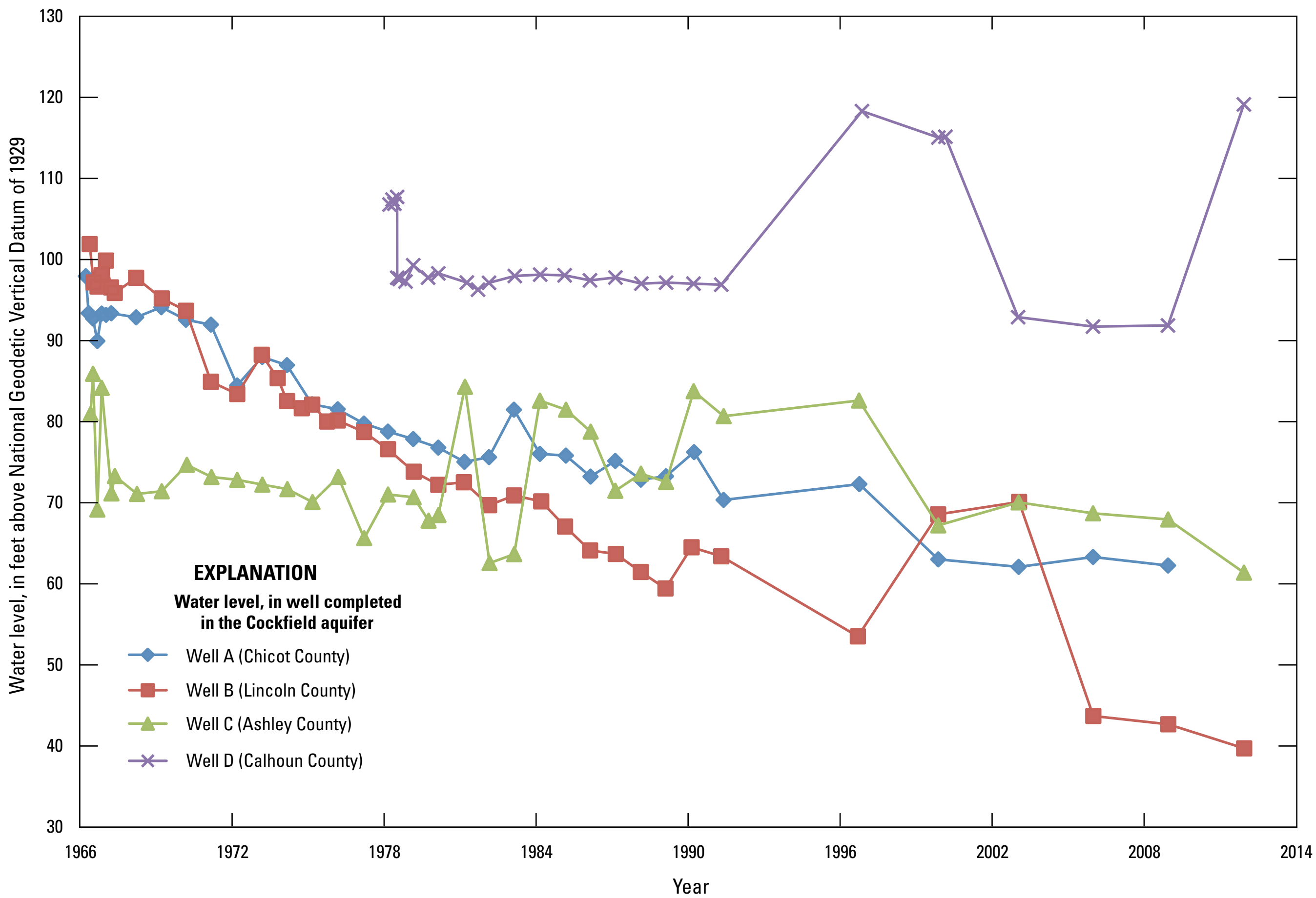


Figure 39. Hydrographs of water levels in wells completed in the Cockfield aquifer in southeastern Arkansas.

Water Quality

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

General Geochemistry and Water Type

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

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

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

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

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

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

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

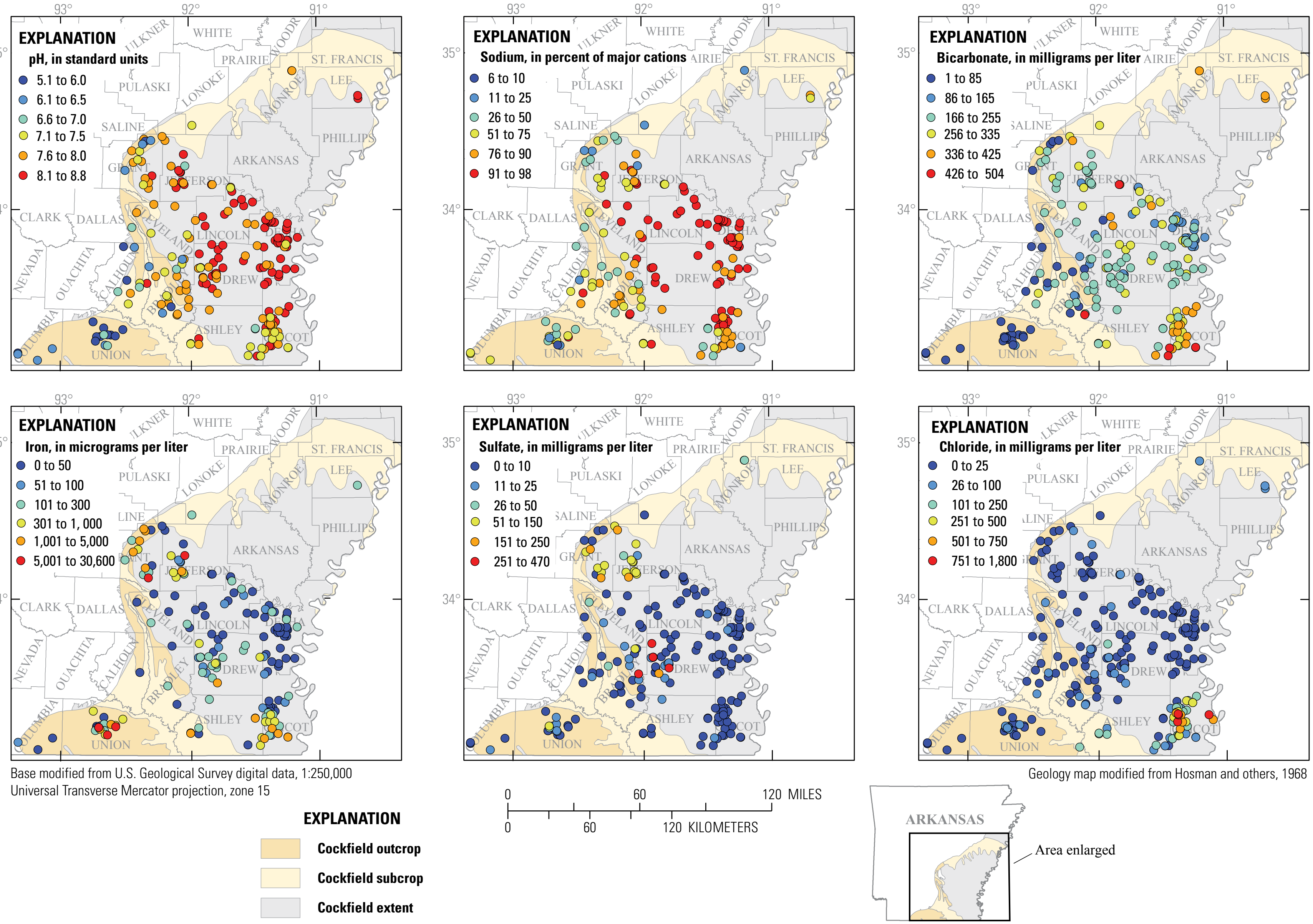


Figure 40. Spatial distribution of selected chemical constituents for groundwater from the Cockfield aquifer in southeastern Arkansas.

Iron

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

Nitrate

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

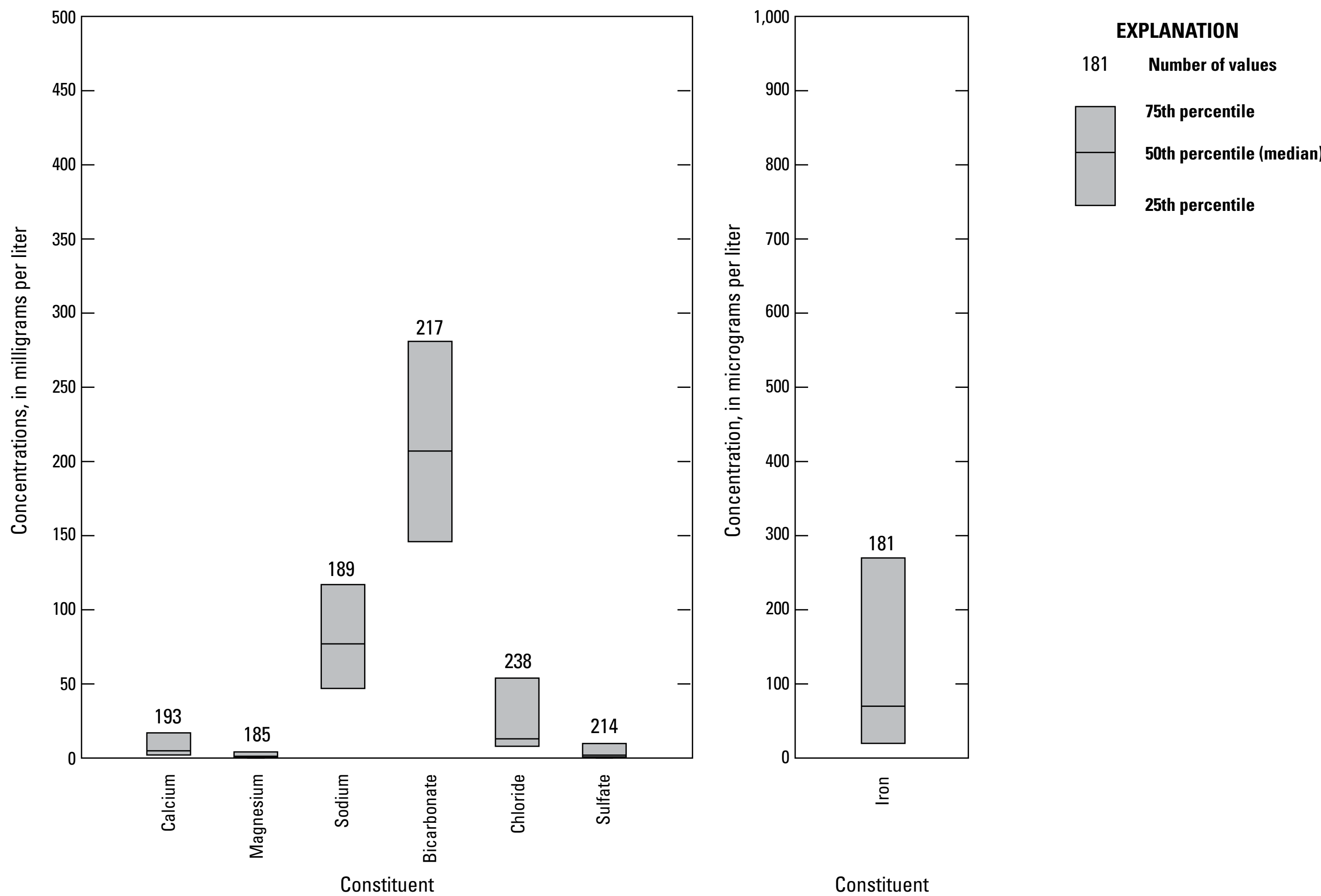


Figure 41. Box plots showing interquartile range of selected chemical constituents in groundwater from the Cockfield aquifer in southeastern Arkansas.

Sulfate

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

Chloride

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

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

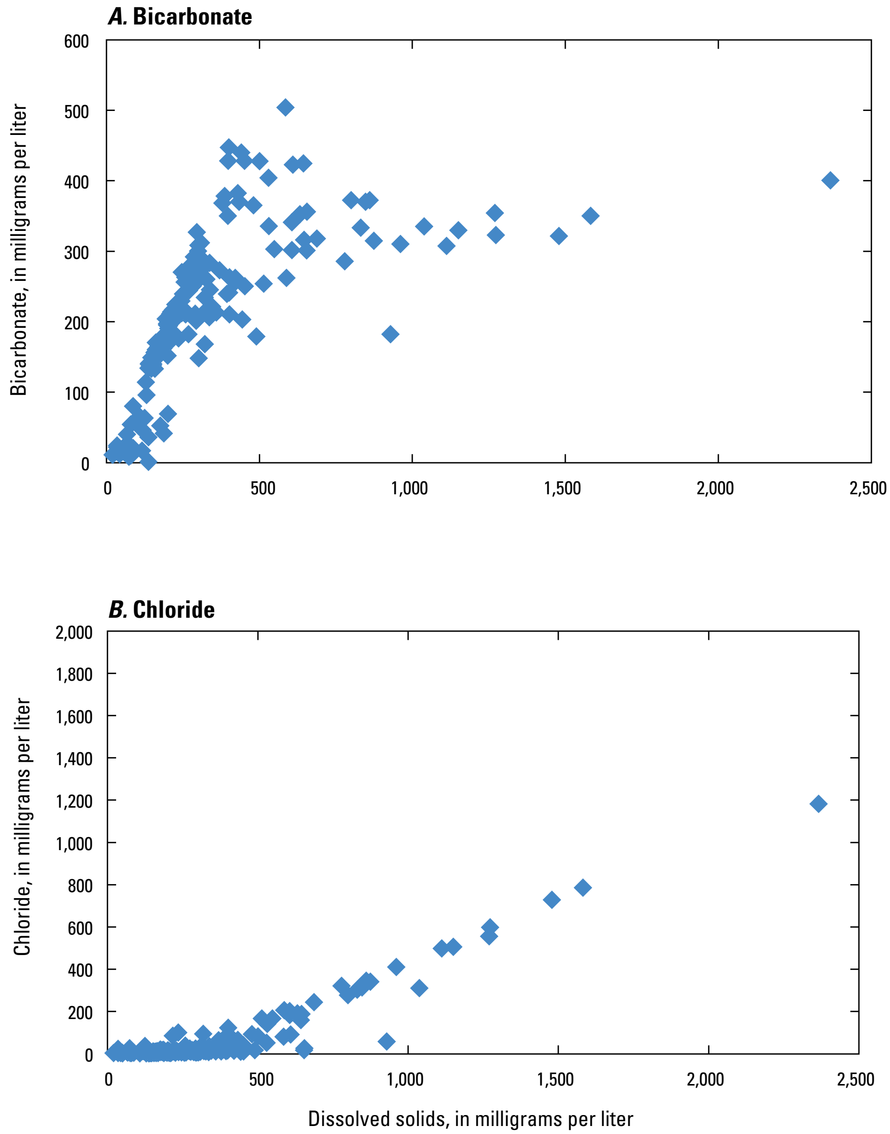


Figure 42. Graphs showing relation of concentrations of dissolved solids to *A*, bicarbonate and *B*, chloride in groundwater from the Cockfield aquifer in southeastern Arkansas.

Sparta Aquifer

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

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

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

Geologic Setting

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

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

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

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

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

Hydrologic Characteristics

Hydraulic properties vary widely in the Sparta aquifer, and the highest transmissivity is tied to the thickest sand intervals, not necessarily the highest sand percentage (Payne, 1968). Hosman and others (1968) reported transmissivity of the Sparta aquifer ranging from 1,800 to 17,400 ft²/d, storage coefficients ranging from 0.0002 to 0.0024, hydraulic conductivity ranging from about 11 to 110 ft/d, and specific capacities ranging from 7 to 14 (gal/min)/ft. Plebuch and Hines (1969) reported well yields as high as 700 gal/min and transmissivities from 3,200 to 15,400 ft²/d.

Pugh (2008a) summarized aquifer-test data from the Sparta aquifer as follows: based on data from 16 sites, the average specific capacity was 61.7 (gal/min)/ft with a minimum of 0.13 (gal/min)/ft and a maximum of 439 (gal/min)/ft; based on data from 33 sites, the average transmissivity was 7,990 ft²/d with a minimum of 23 ft²/d and a maximum of 31,000 ft²/d; based on data from 3 sites, the average hydraulic conductivity was 13.1 ft/d with a minimum of 1.7 ft/d and a maximum of 29 ft/d; and based on data from 17 sites, the average storage coefficient was 0.00209 with a minimum of 0.000017 and a maximum of 0.03. Pugh (2008a) also reported that the Sparta aquifer commonly yields 1,000 gal/min to wells, and that yields may exceed 1,900 gal/min. A transmissivity of nearly 7,400 ft²/d and a storage coefficient of 0.0009 were reported from the Sparta aquifer in St. Francis County (Hosman and others, 1968). Data from 23 aquifer tests in northern Arkansas (listed under Memphis Sand) throughout the northern Mississippi embayment show transmissivity ranging from 2,700 to 54,000 ft²/d, and storage coefficients ranging from 0.0001 to 0.2 (Brahana and Broshears, 1989).

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

Water Use

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

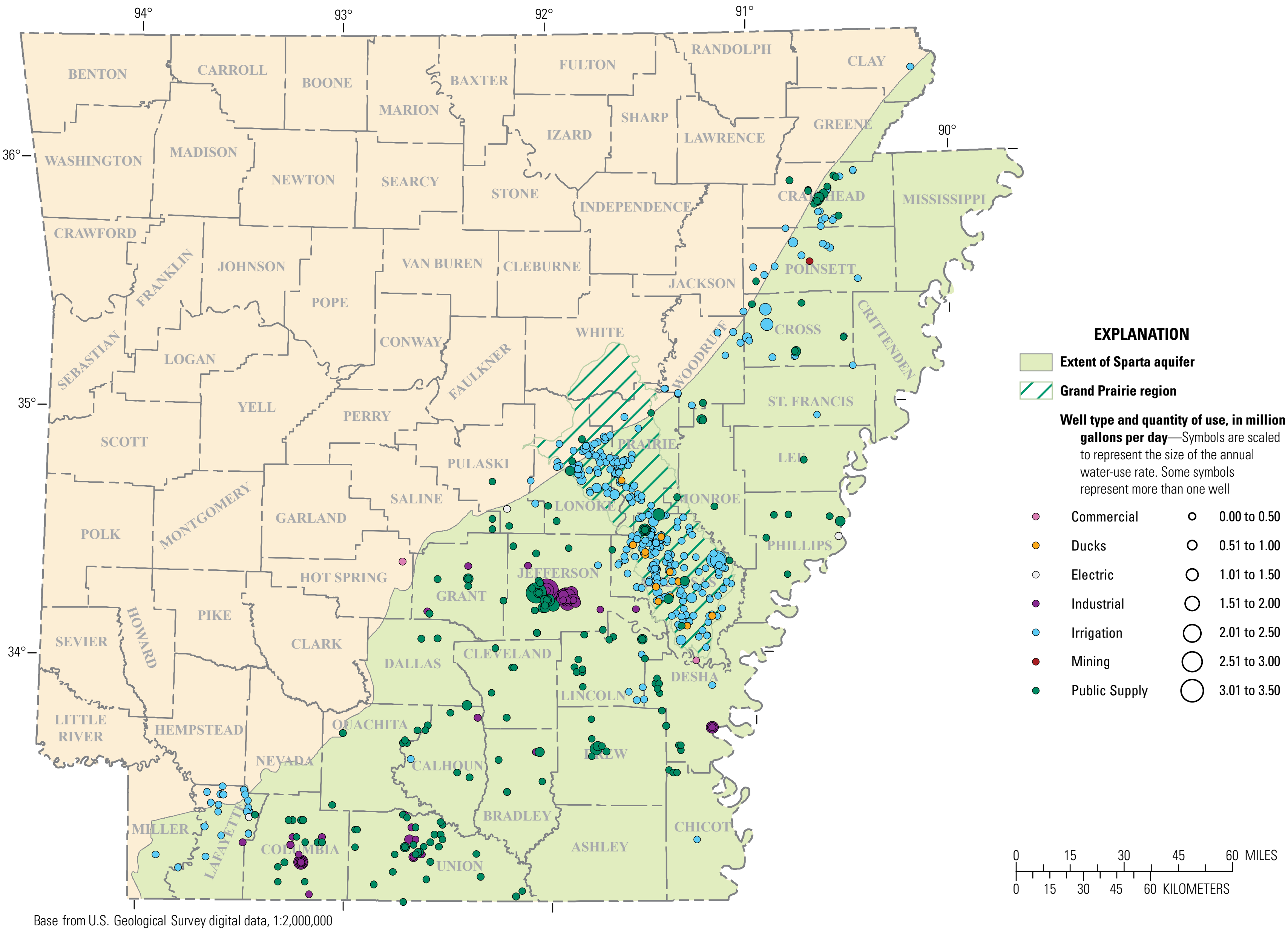


Figure 43. Wells with reported water use from the Sparta aquifer in Arkansas, 2010.

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

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

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

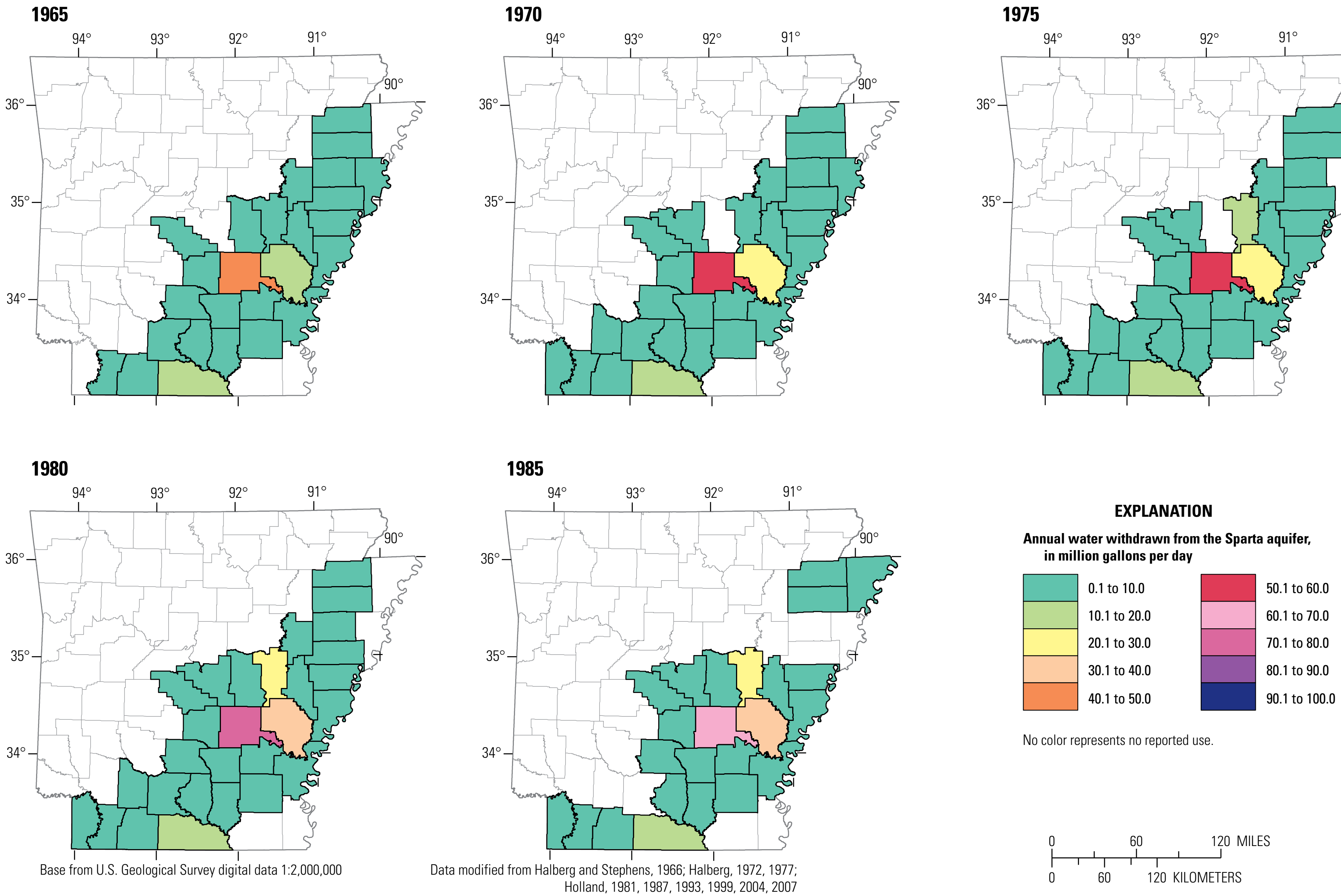


Figure 44. Water-use rates for the Sparta aquifer in Arkansas from 1965 to 2010.

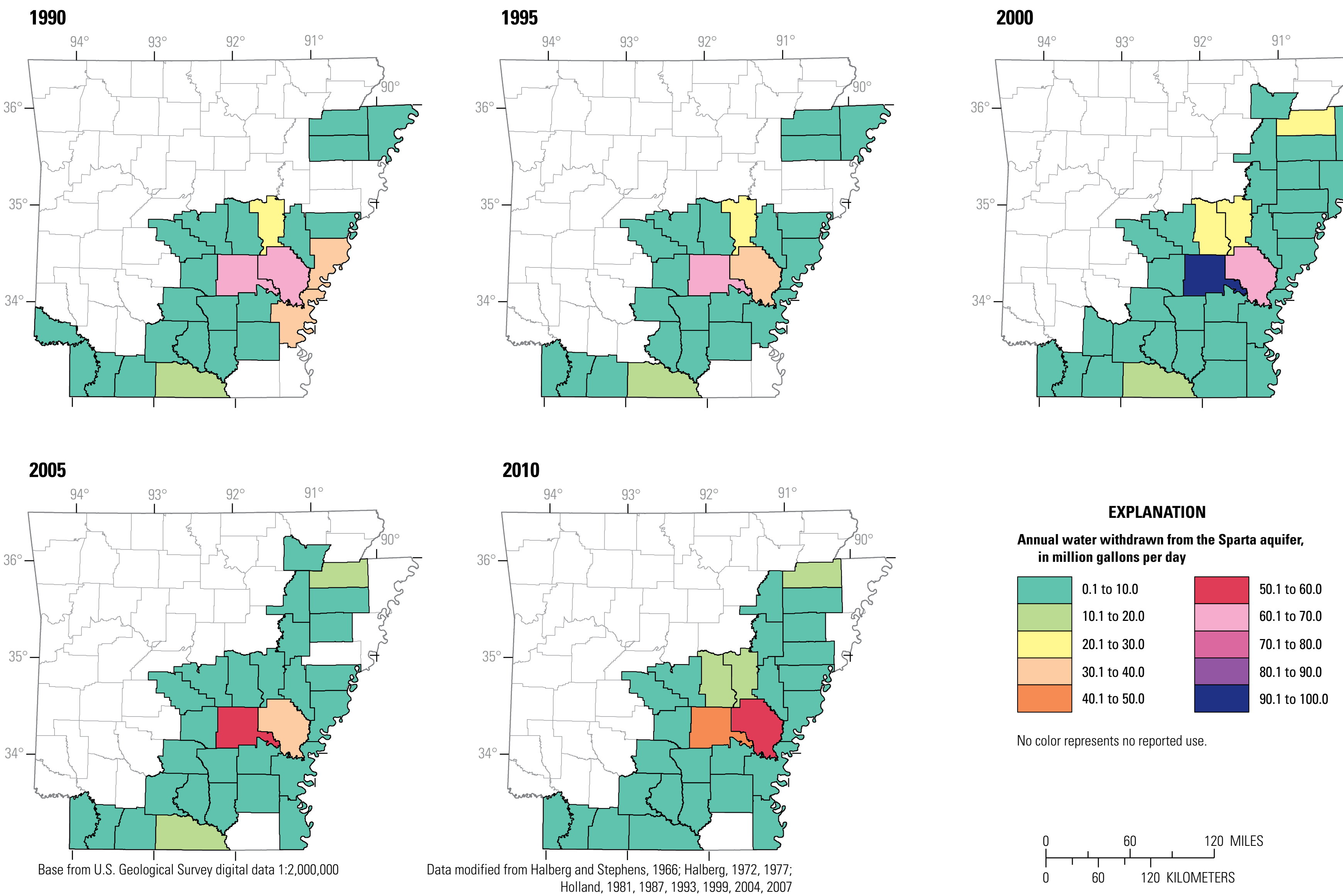


Figure 44. Water-use rates for the Sparta aquifer in Arkansas from 1965 to 2010.—Continued

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

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

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

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

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

Domestic and Public Supply

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

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

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

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

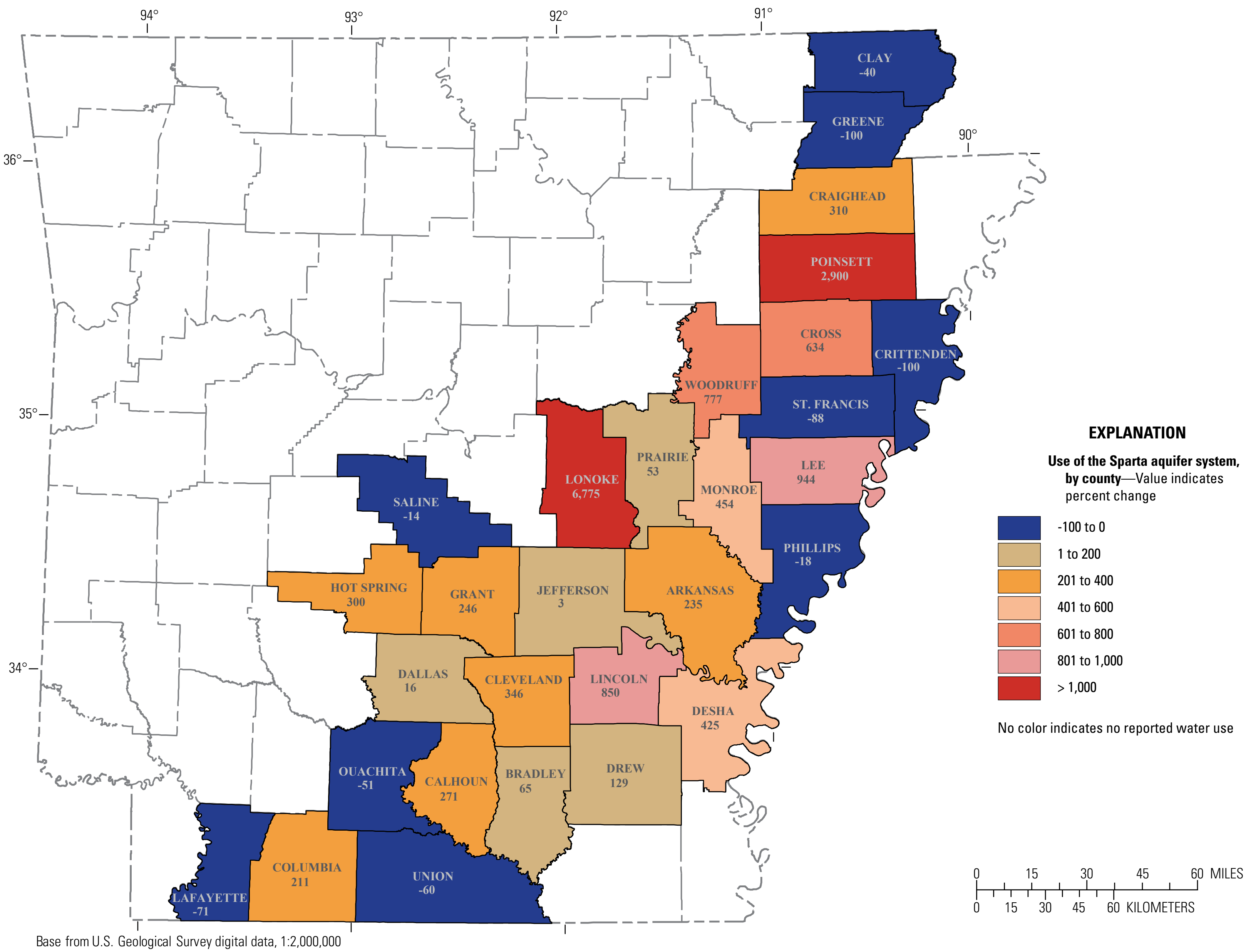


Figure 45. Change in percentage of water use from the Sparta aquifer in Arkansas from 1965 to 2010.

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

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

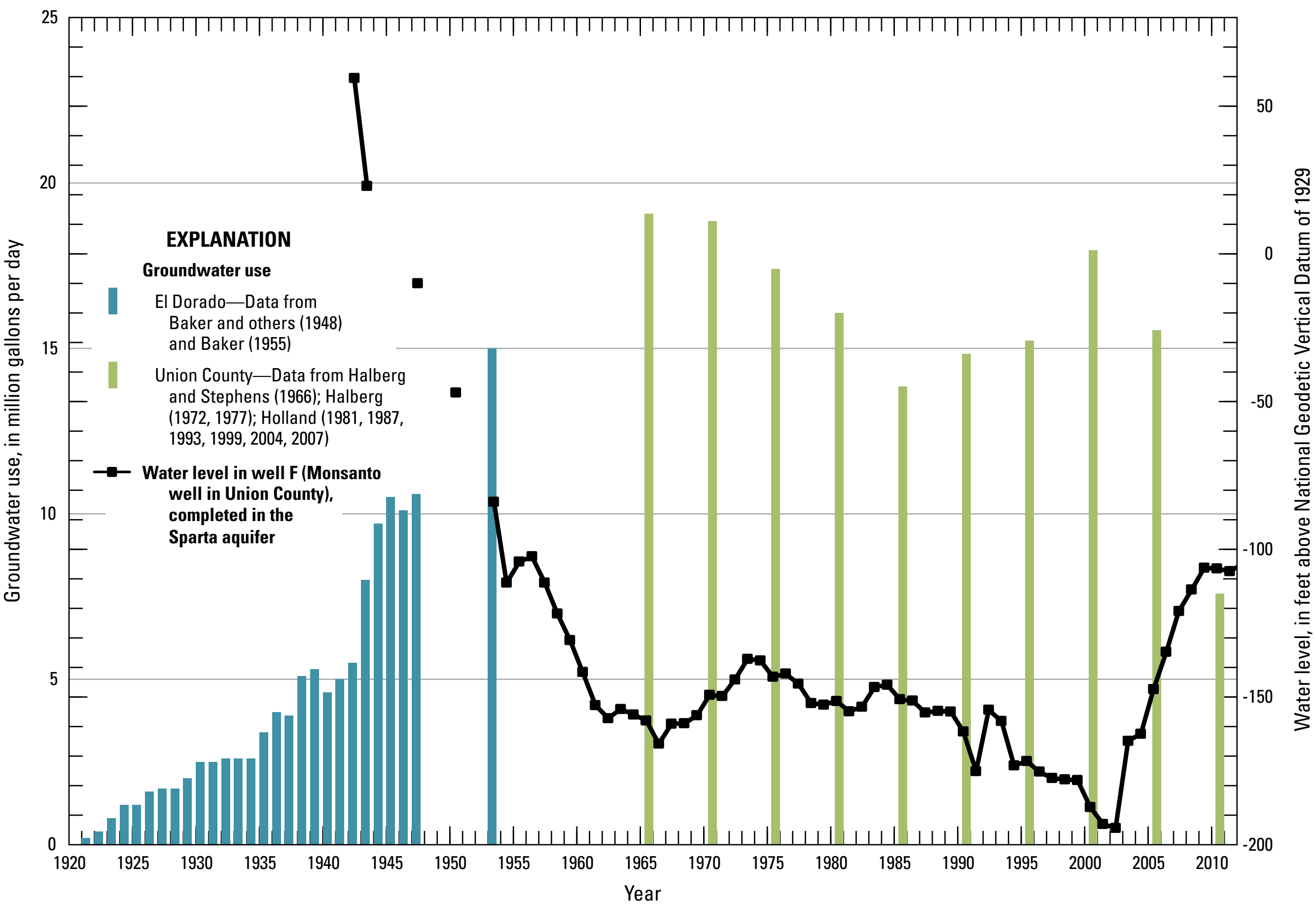


Figure 46. Hydrograph showing water use in the Sparta aquifer from the city of El Dorado and Union County and water levels in the Monsanto well (location shown as well F on fig. 49) in the Sparta aquifer near El Dorado, Union County, Arkansas.

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

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

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

Irrigation

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

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

Industrial Use

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

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

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

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

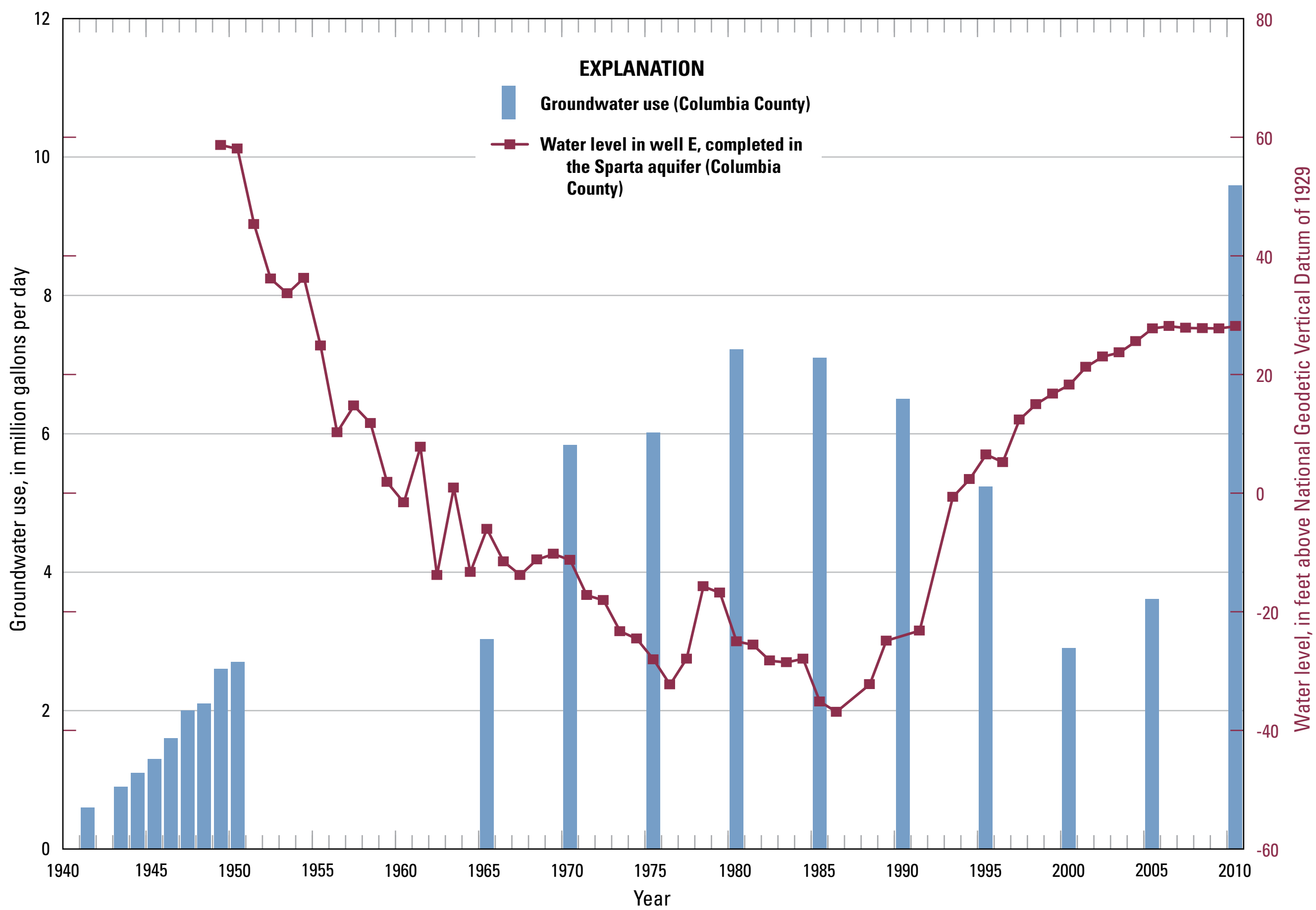


Figure 47. Hydrograph showing water use and water levels in well E (location shown on fig. 49) in the Sparta aquifer in Columbia County, Arkansas.

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

Water Levels

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

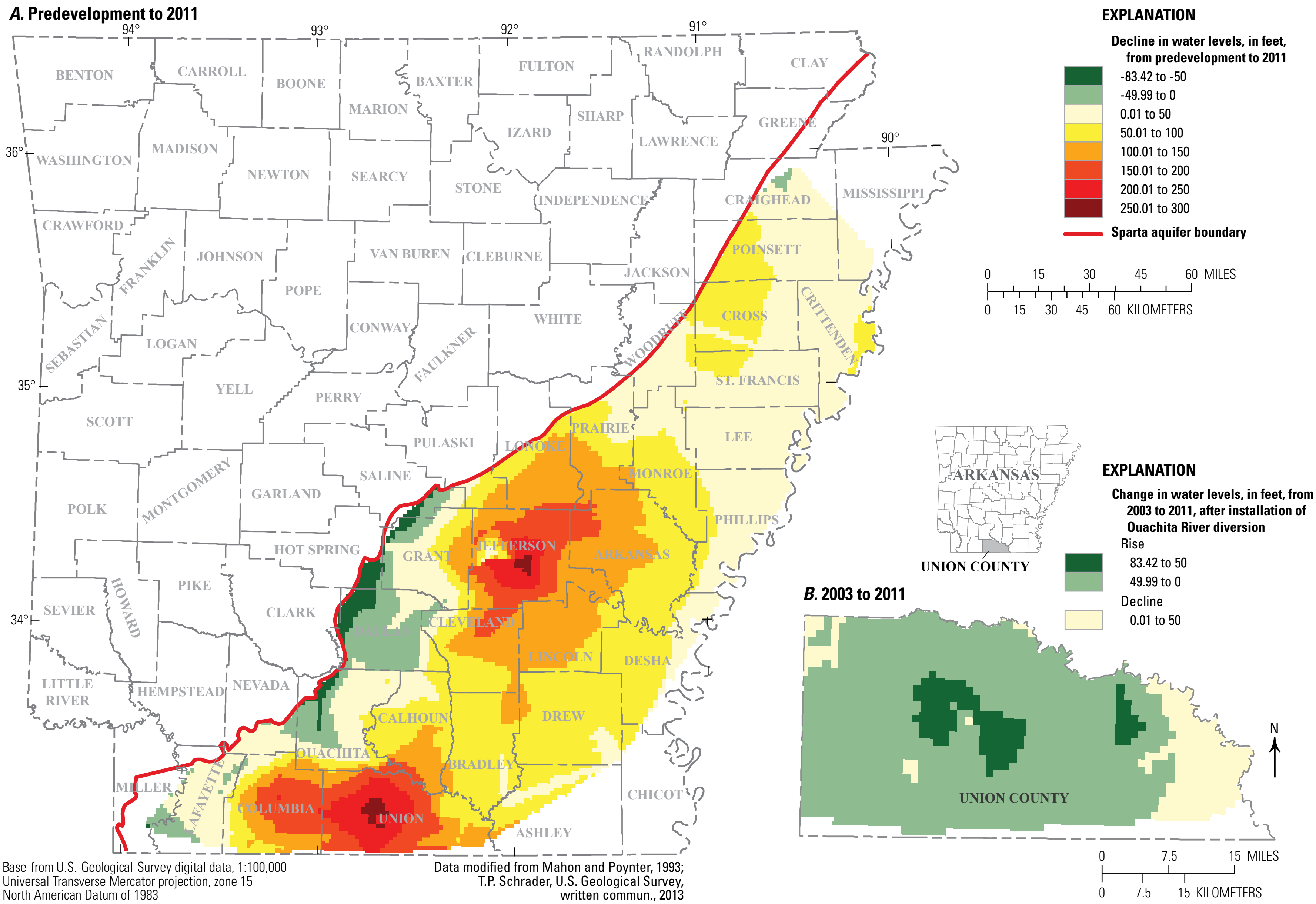


Figure 48. *A*, change in water levels for the Sparta aquifer in Arkansas from predevelopment to 2011; *B*, change in water levels for the Sparta aquifer in Union County from 2003 to 2011.

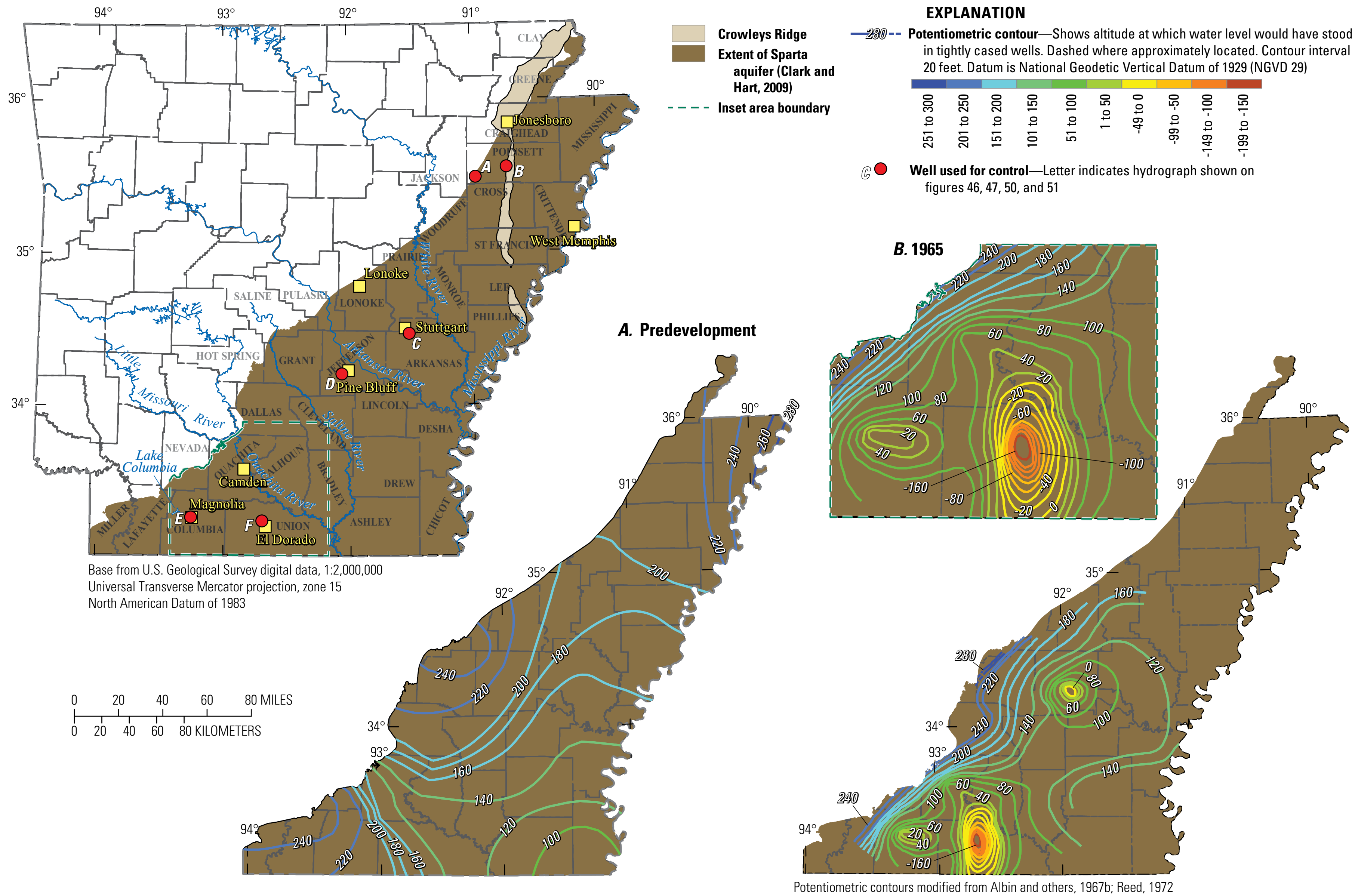


Figure 49. Selected potentiometric contours of water levels in the Sparta aquifer in Arkansas.

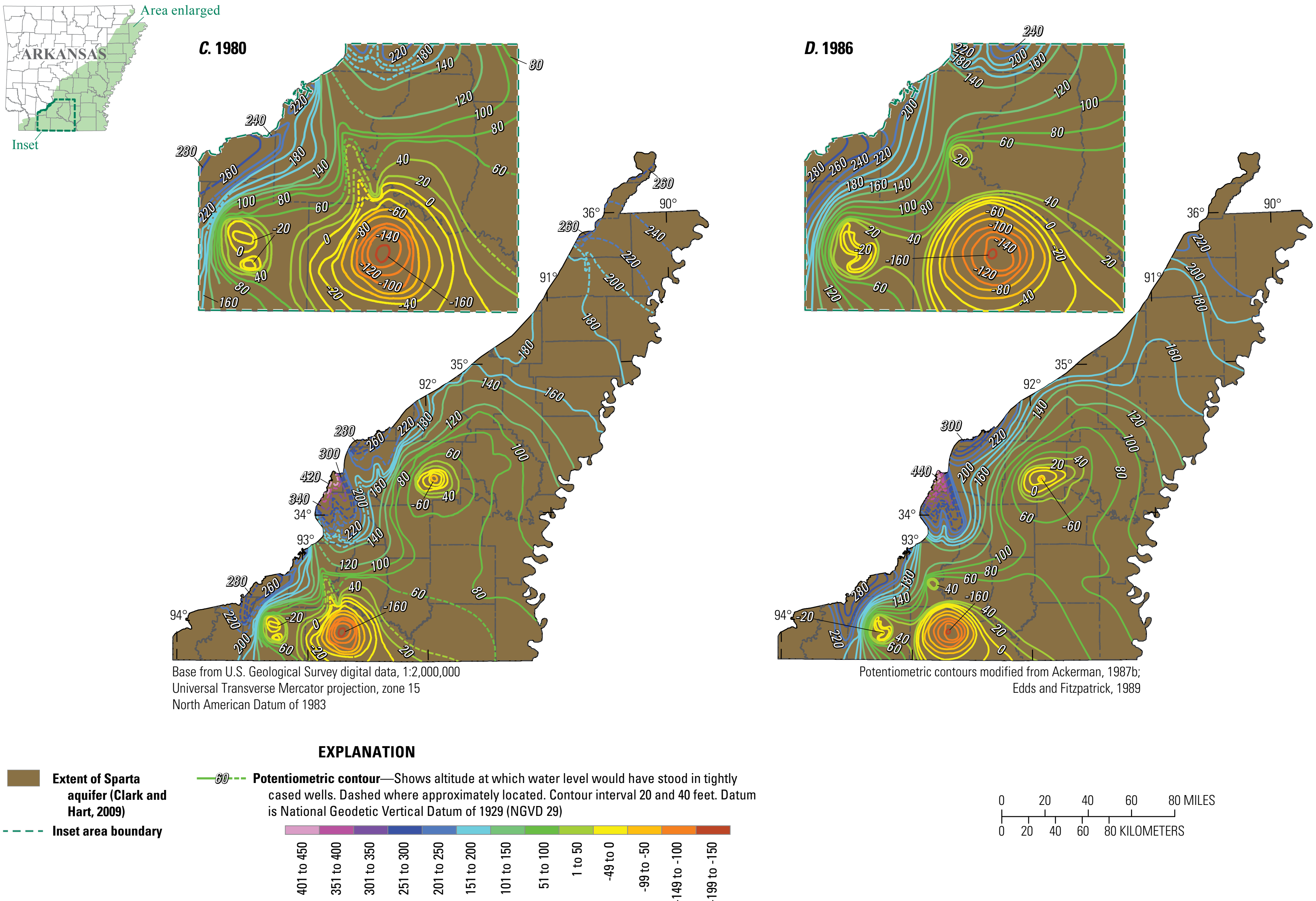
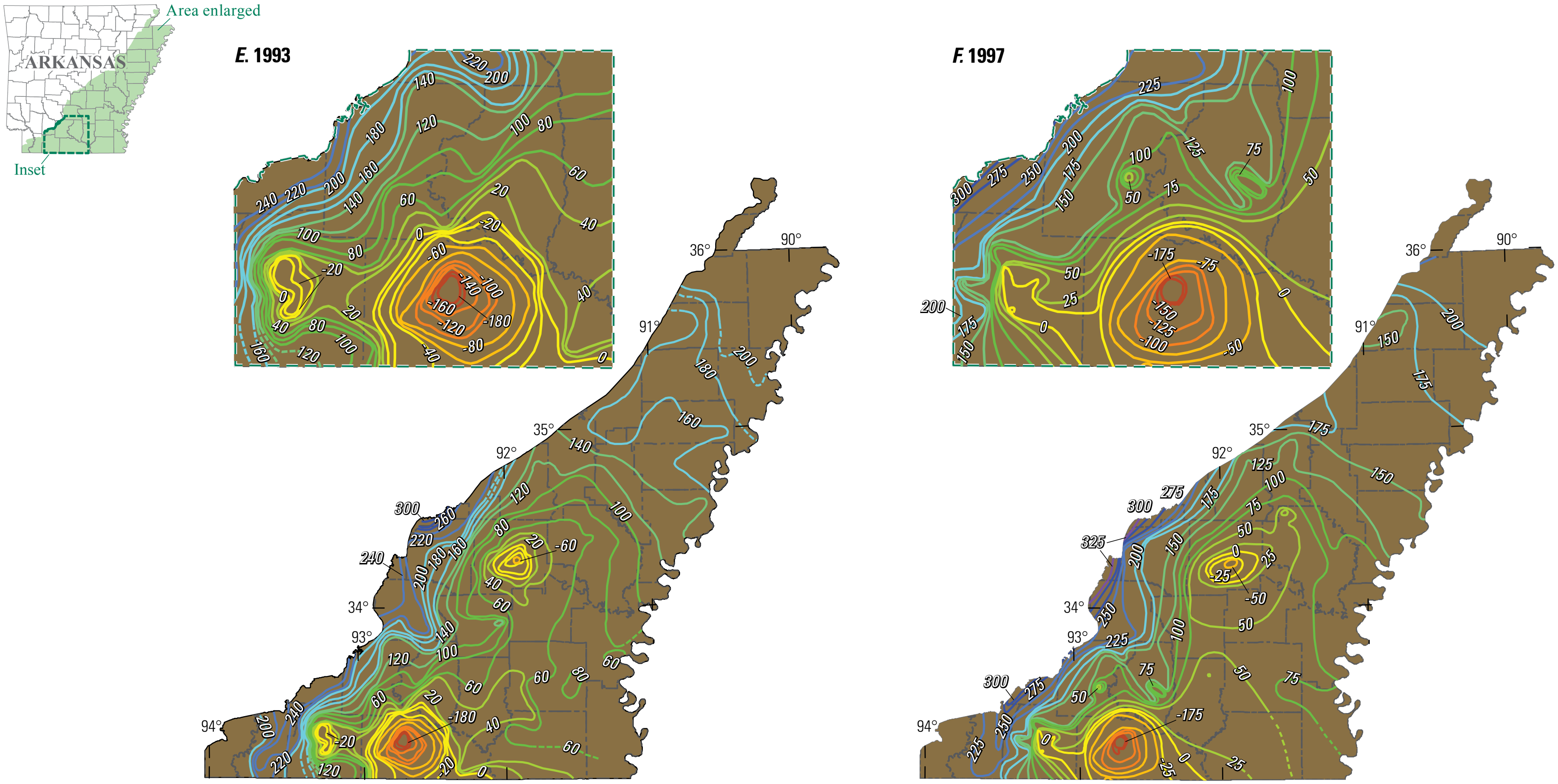


Figure 49. Selected potentiometric contours of water levels in the Sparta aquifer in Arkansas.—Continued



Base from U.S. Geological Survey digital data, 1:2,000,000
Universal Transverse Mercator projection, zone 15
North American Datum of 1983

Potentiometric contours modified from Westerfield, 1995; Joseph, 1997

EXPLANATION

Extent of Sparta aquifer (Clark and Hart, 2009)

Inset area boundary

180 **Potentiometric contour**—Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour intervals 20 and 25 feet. Datum is National Geodetic Vertical Datum of 1929 (NGVD 29)

301 to 350
251 to 300
201 to 250
151 to 200
101 to 150
51 to 100
1 to 50
-49 to 0
-99 to -50
-149 to -100
-199 to -150

0 20 40 60 80 MILES
0 20 40 60 80 KILOMETERS

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

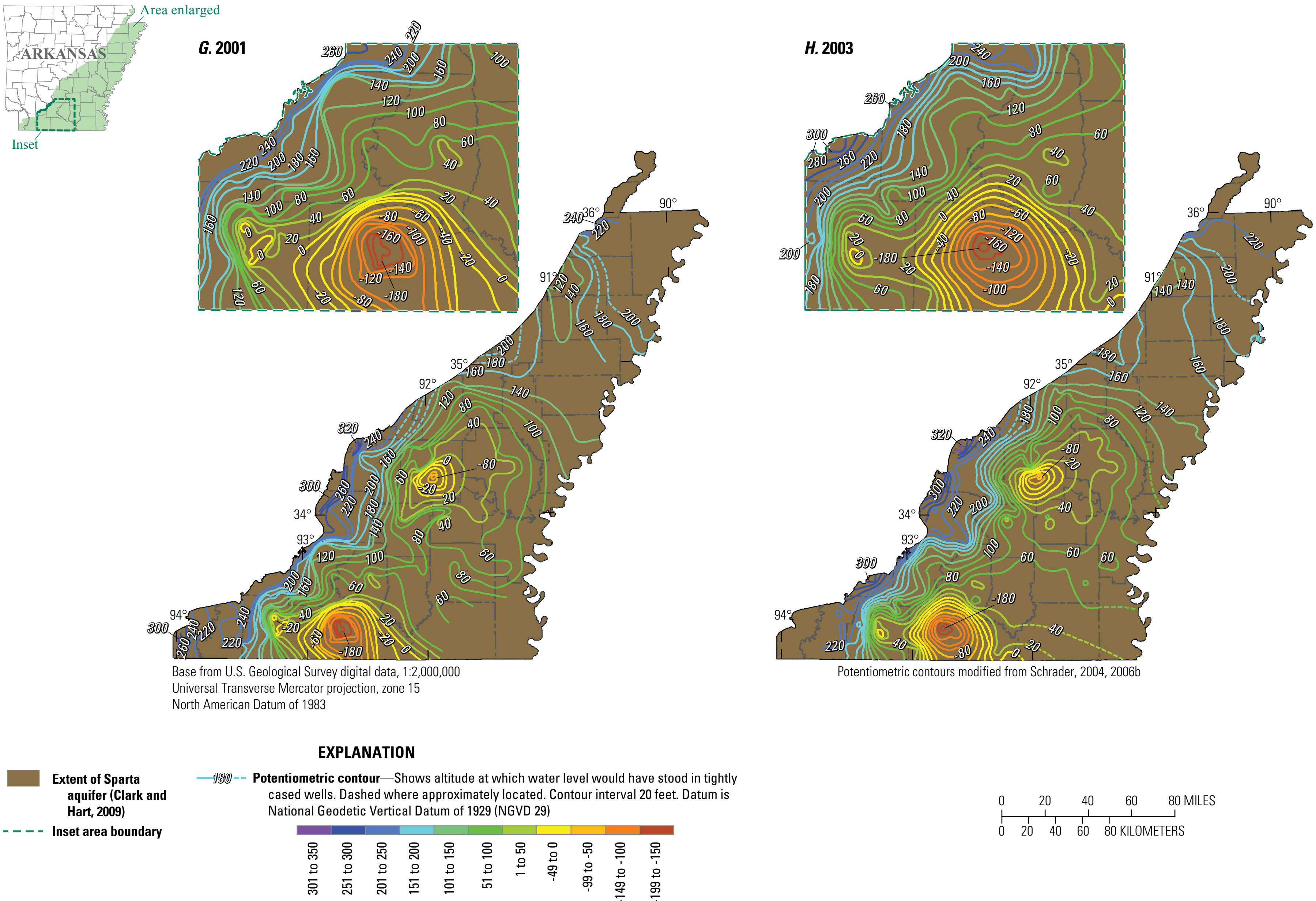


Figure 49. Selected potentiometric contours of water levels in the Sparta aquifer in Arkansas.—Continued

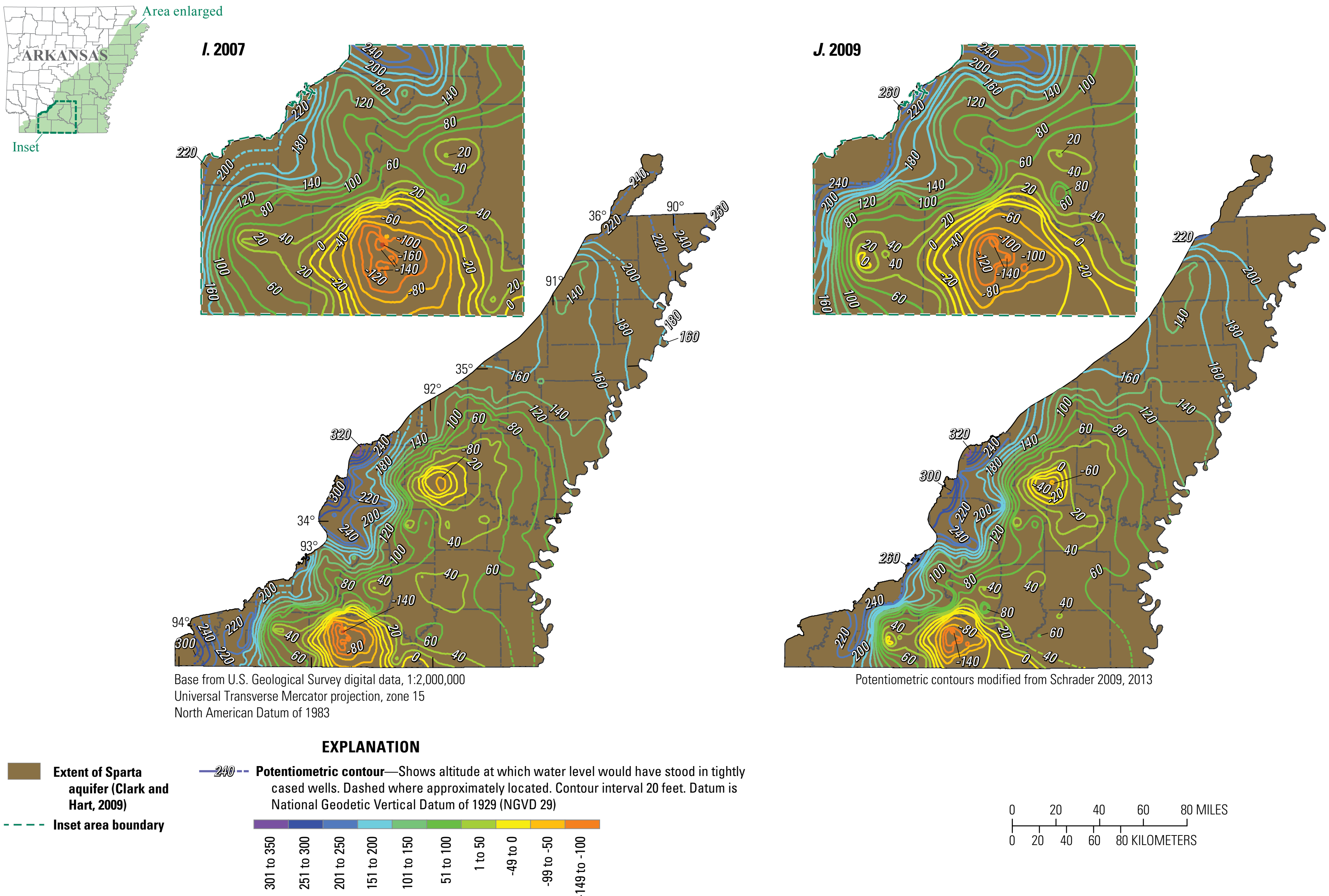


Figure 49. Selected potentiometric contours of water levels in the Sparta aquifer in Arkansas.—Continued

Northeastern Arkansas

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

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

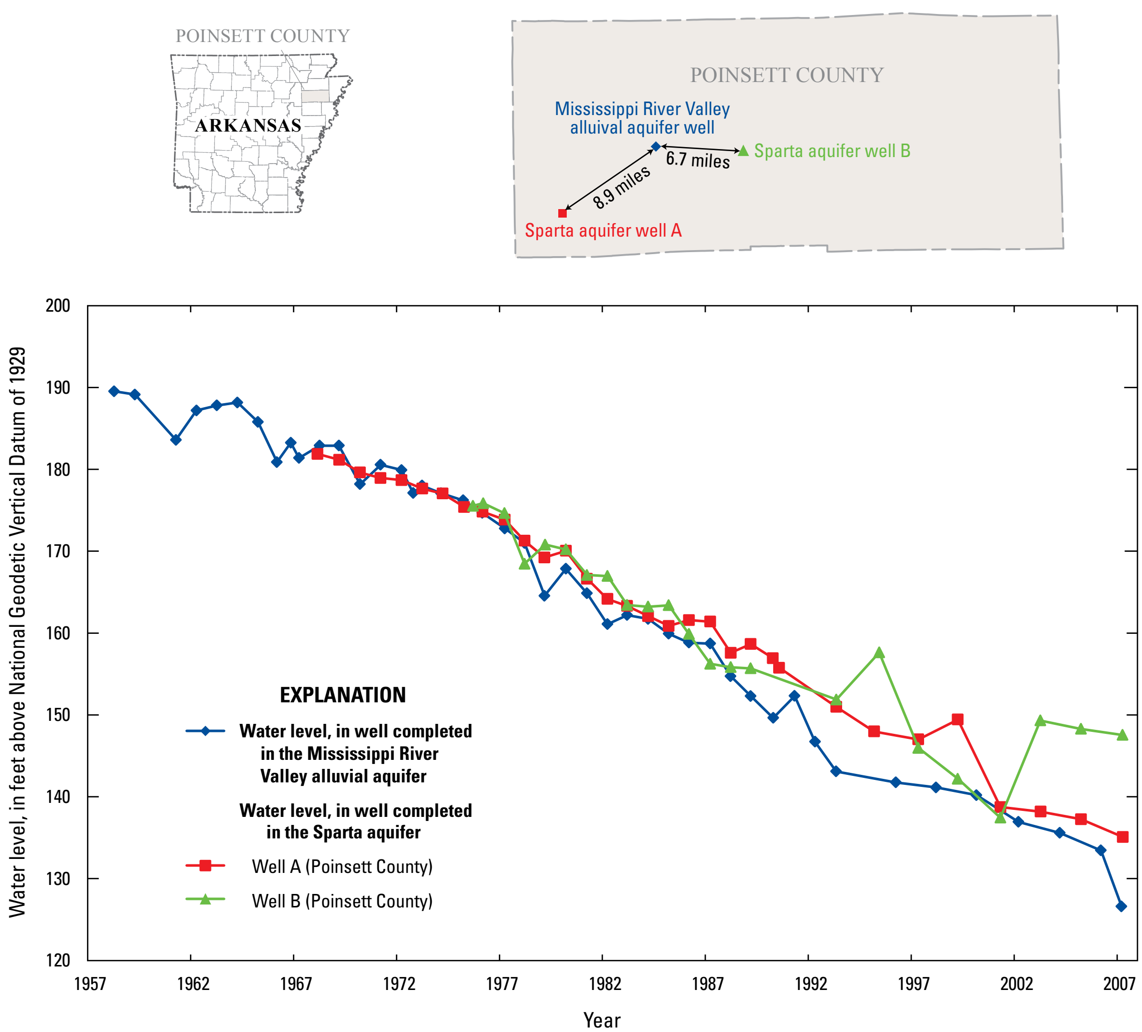


Figure 50. Hydrographs showing water levels in wells A and B in the Sparta aquifer (locations of wells shown on fig. 49) and water levels in a well in the Mississippi River Valley alluvial aquifer in Poinsett County, Arkansas.

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

Grand Prairie and Jefferson County

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

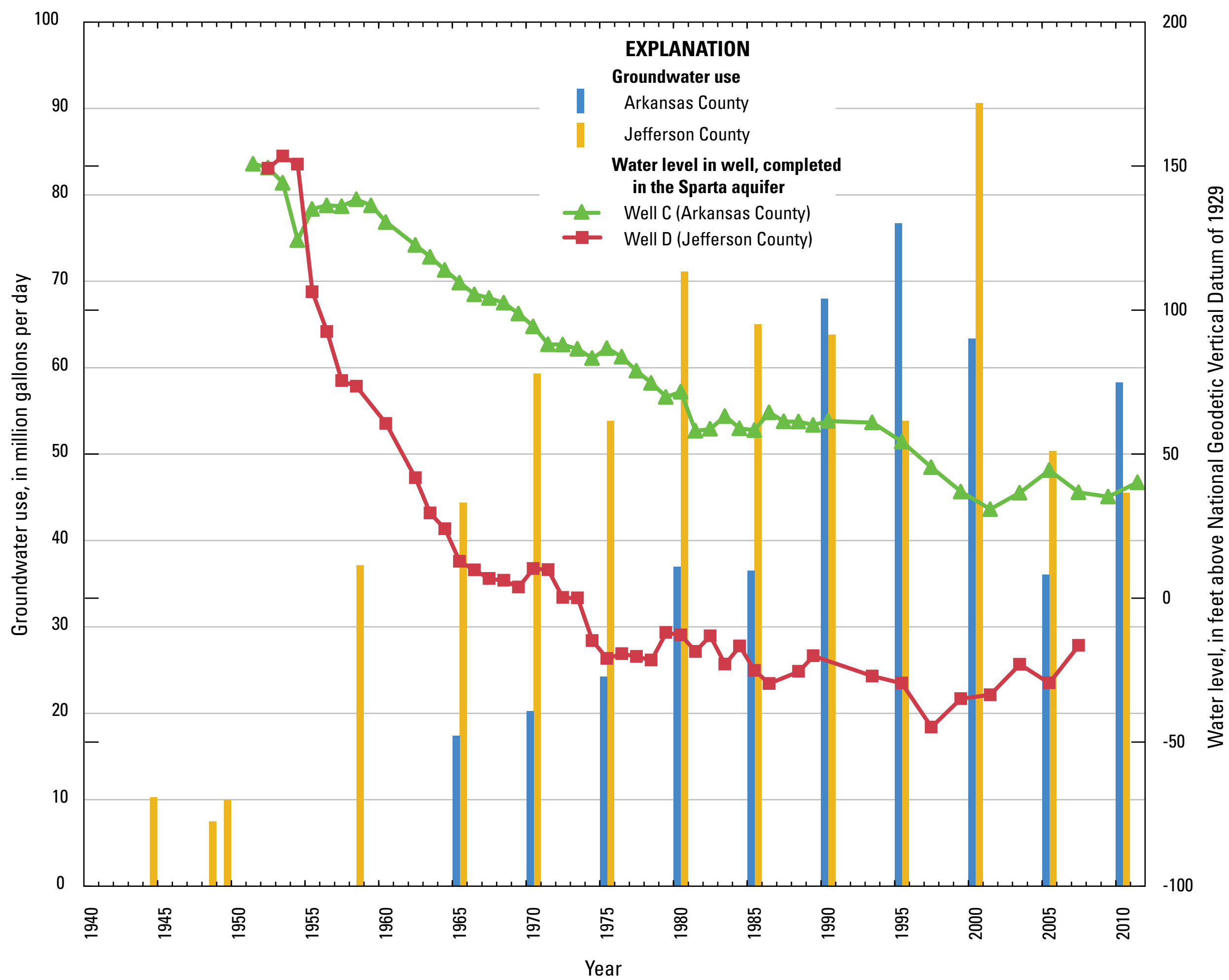


Figure 51. Hydrographs showing water use and water levels in wells C and D (locations of wells shown on fig. 49) in the Sparta aquifer in Arkansas and Jefferson Counties, Arkansas.

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

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

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

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

Southern Arkansas

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

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

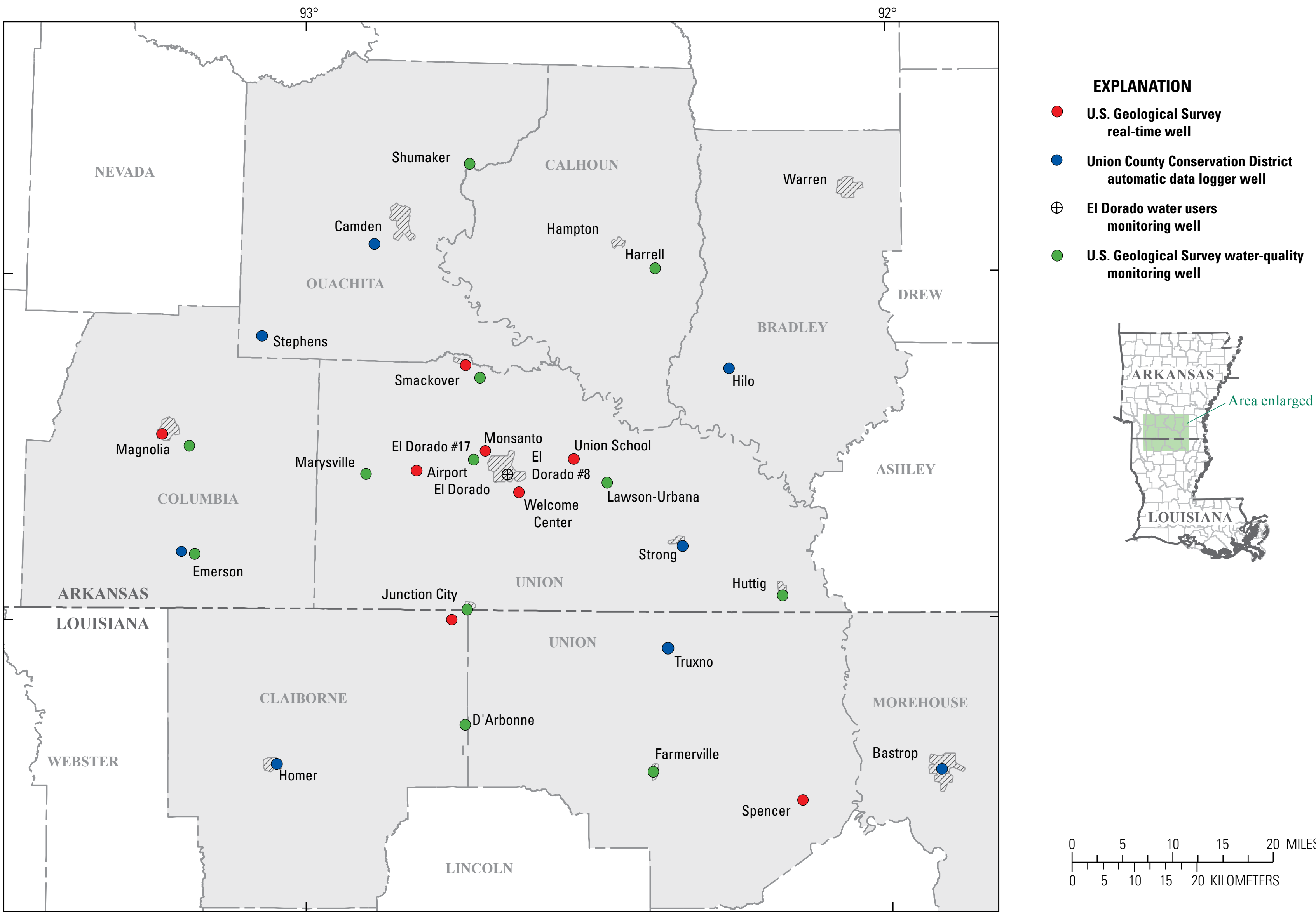
In the El Dorado (Union County) area, water levels for the Sparta aquifer dropped 240 ft from 1922 to 1953, while water use over that same period increased from less than 1 Mgal/d to 15 Mgal/d (Baker, 1955). Industrialization began in earnest following World War II, and dramatic water-level declines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

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

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

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

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



Base from U.S. Geological Survey digital data

Data modified from Freiwald and Johnson, 2007

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

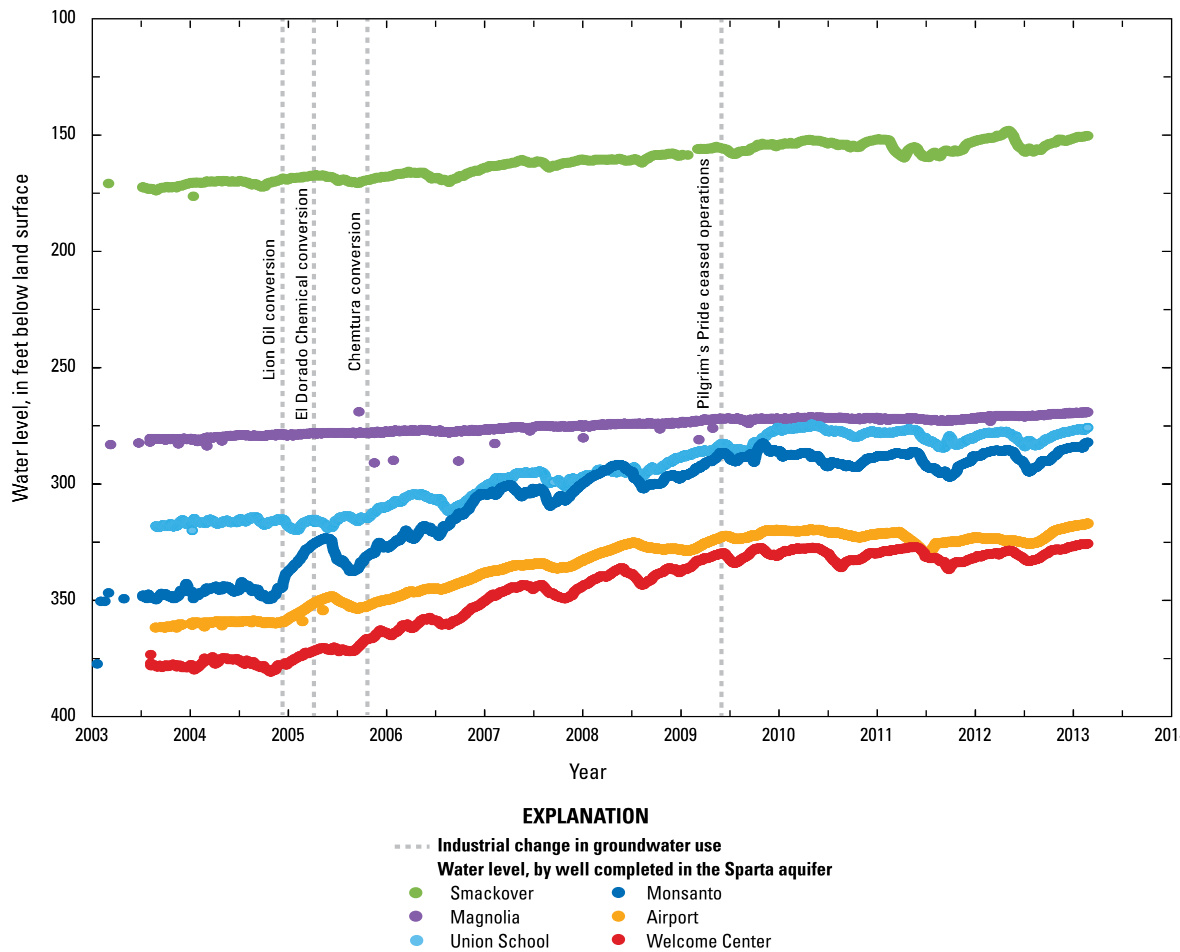


Figure 53. Hydrographs showing effects of change in industrial groundwater use on water levels in wells (location of wells shown in fig. 52) completed in the Sparta aquifer in southern Arkansas.

Deductive Analyses, Projections of Aquifer Conditions, and Sustainable Use

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

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

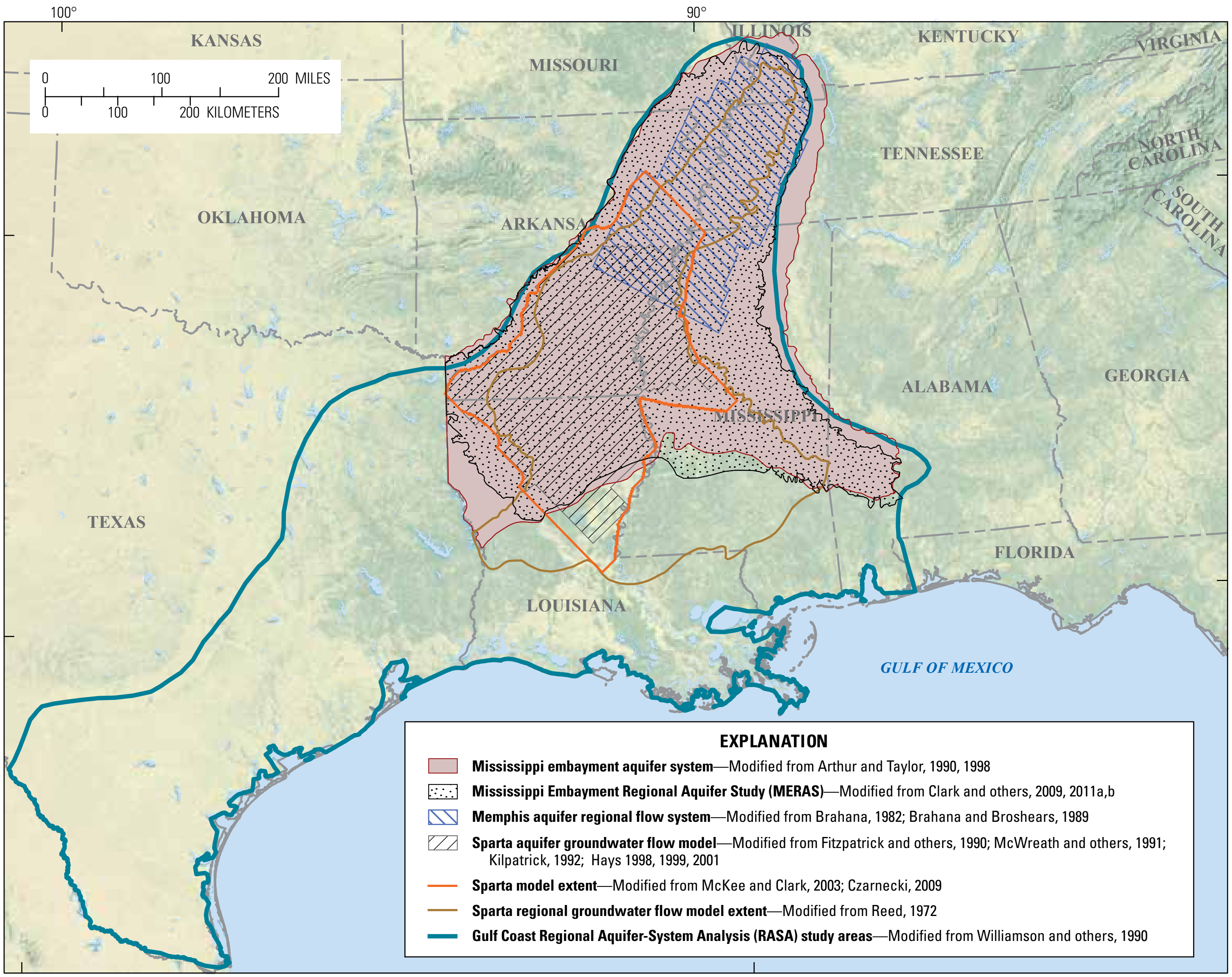
Long-term water-level declines and imminent problems associated with the extensive development of groundwater as a resource led to development of a regional analog groundwater-flow model of the Sparta aquifer in the late 1960s (Reed, 1972). The model was used to simulate the effects of potential increases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

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

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

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

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



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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Water Quality

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

General Geochemistry and Water Type

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

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

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

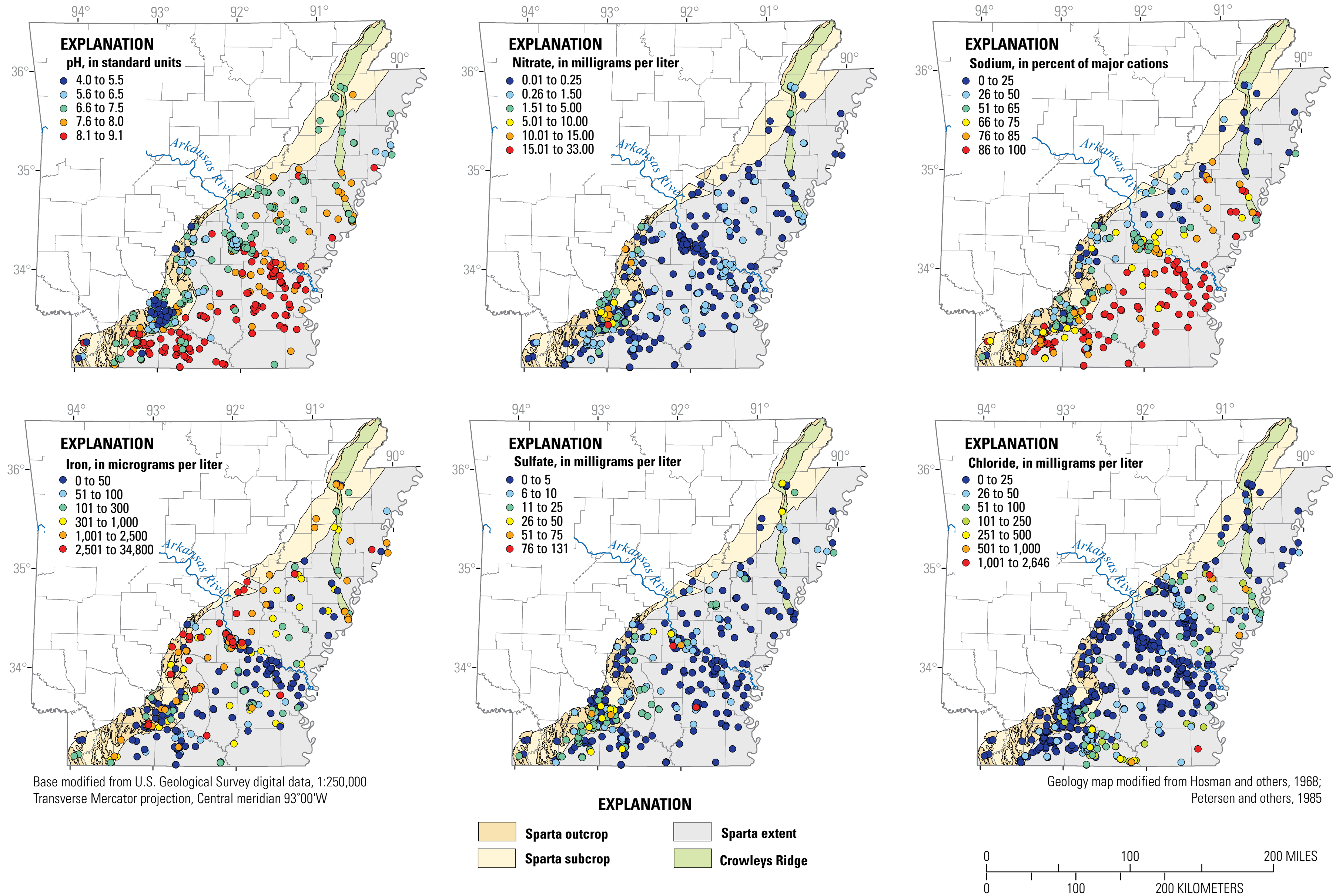


Figure 55. Spatial distribution of selected chemical constituents for groundwater from the Sparta aquifer in Arkansas.

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

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

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

Nitrate

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

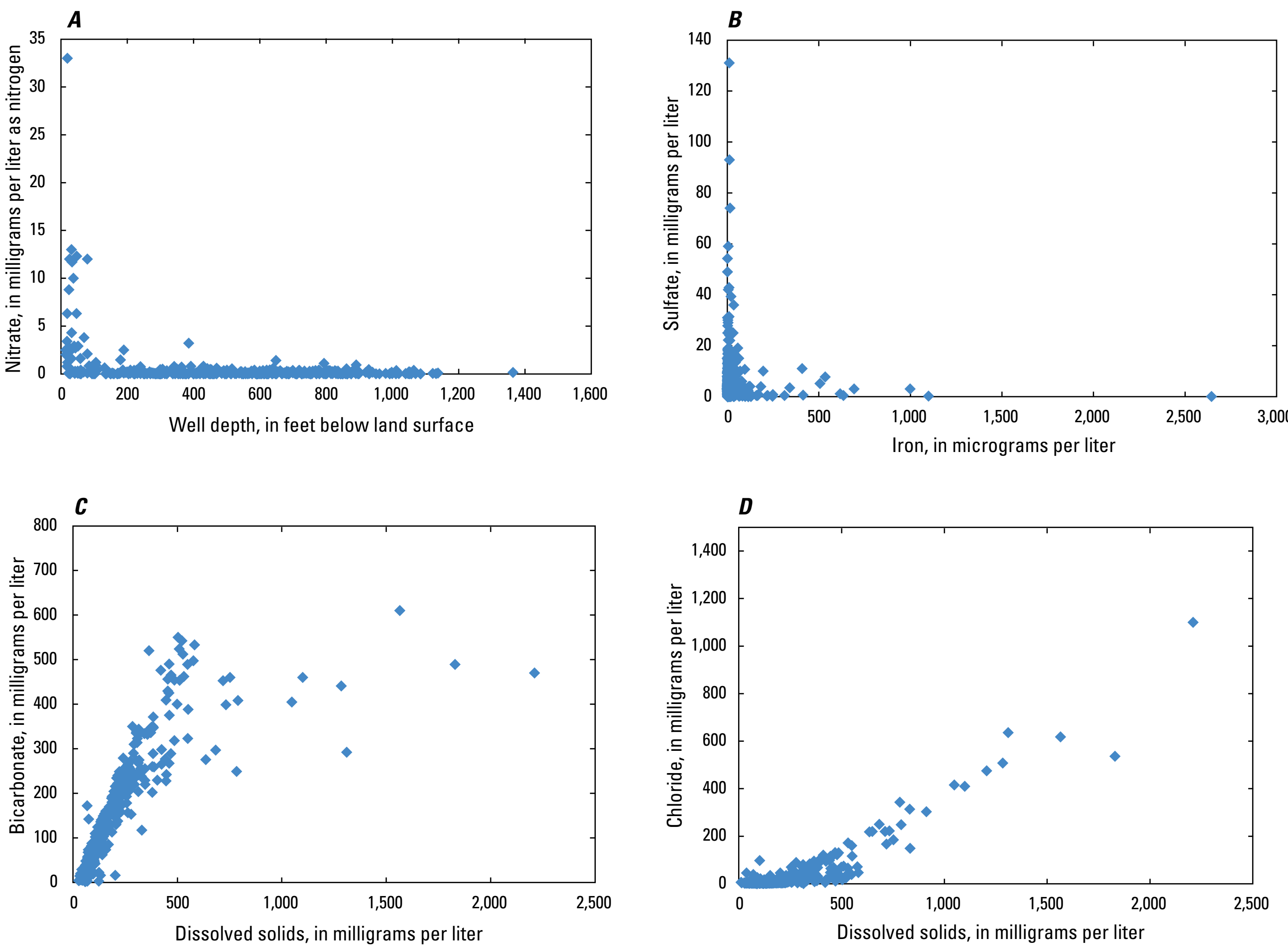


Figure 56. Relation between *A*, well depth and nitrate; *B*, iron and sulfate; *C*, dissolved solids and bicarbonate; and *D*, dissolved solids and chloride for groundwater from the Sparta aquifer in Arkansas.

Iron

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

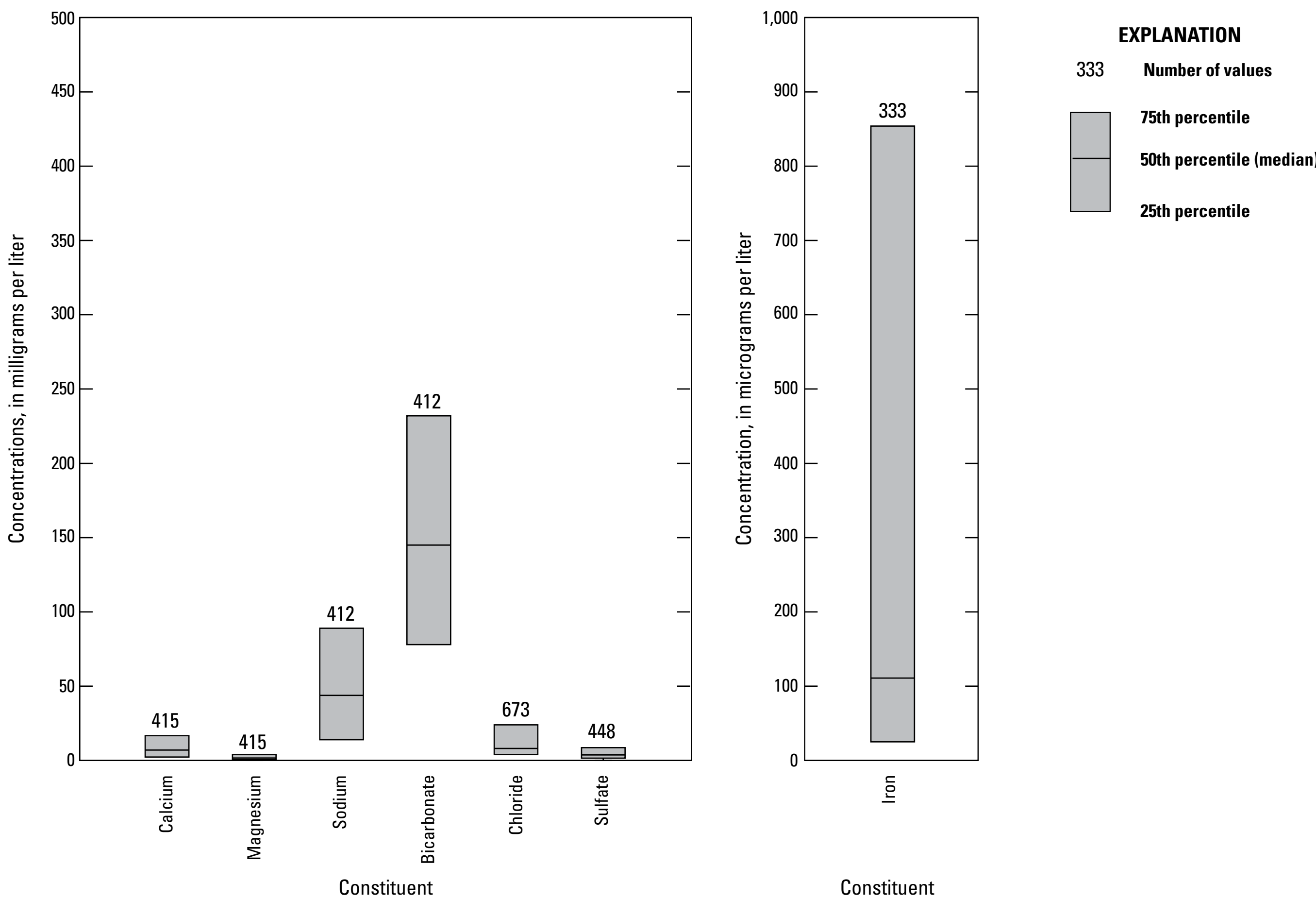


Figure 57. Interquartile range of selected chemical constituents for groundwater from the Sparta aquifer in Arkansas.

Sulfate

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

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

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

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

Chloride

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

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

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

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

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

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

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

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

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

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

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

Cane River Aquifer

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

Geologic Setting

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

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

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

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

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

Hydrologic Characteristics

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

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

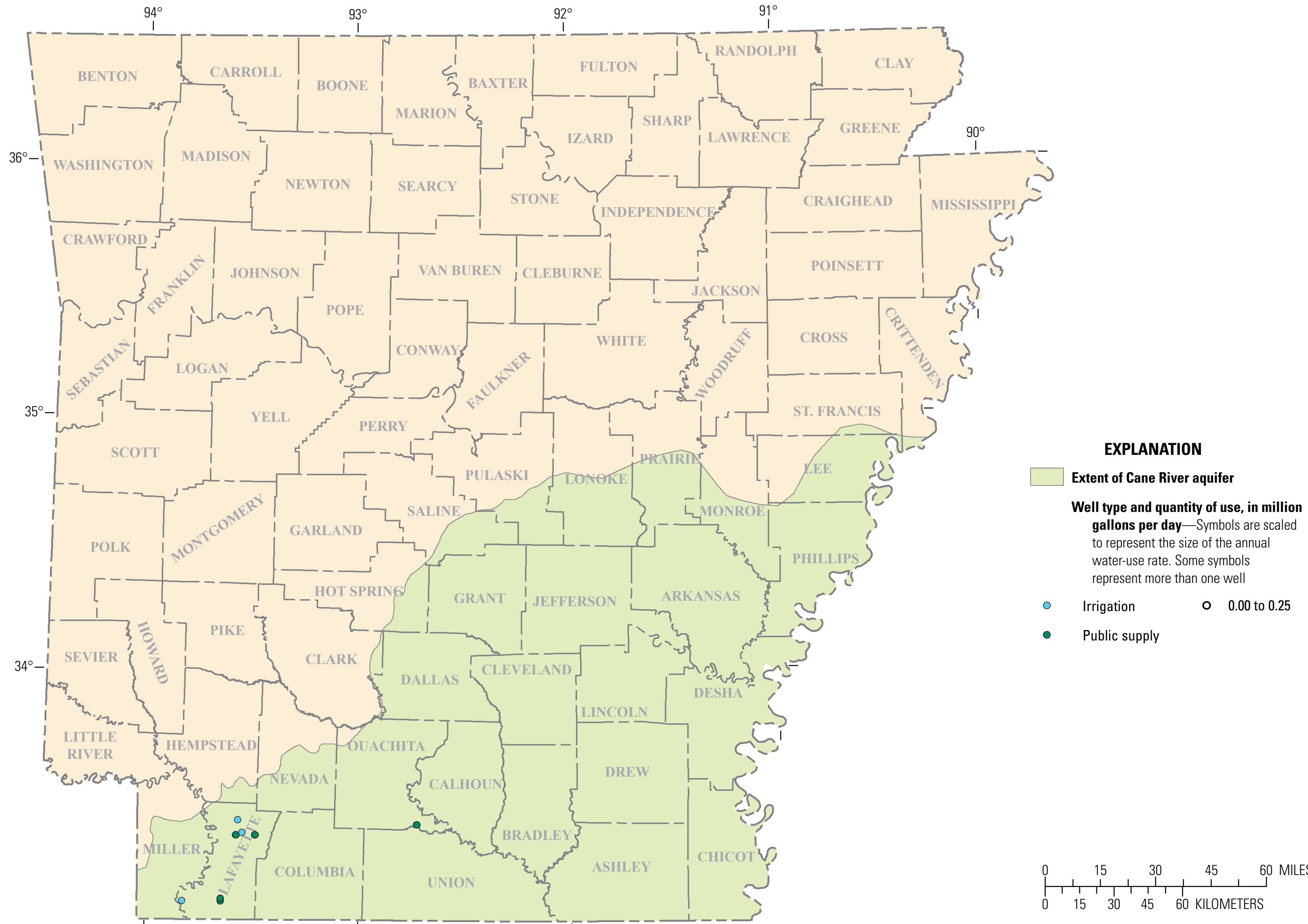
Yields of the Cane River are variable but are sufficient for public supply in the smaller towns in southwestern Arkansas. Public-supply wells for three cities in Lafayette County produced 120, 300, and 920 gal/min (Ludwig, 1972), and two public-supply wells in Dallas County each produced 50 gal/min (Plebuch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

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

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

Water Use

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



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

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

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

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

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

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

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

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

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

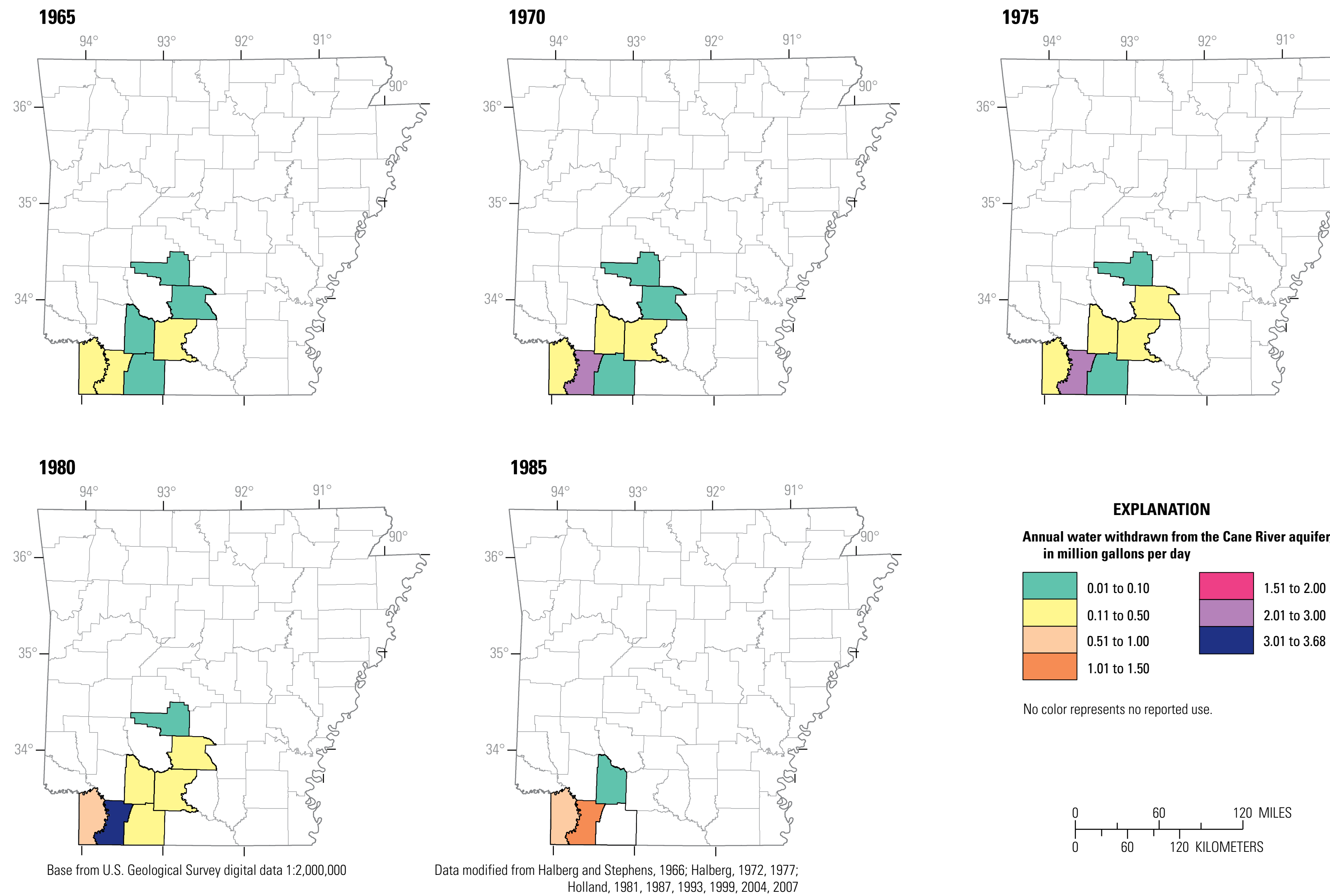


Figure 59. Water-use rates for the Cane River aquifer in Arkansas from 1965 to 2010.

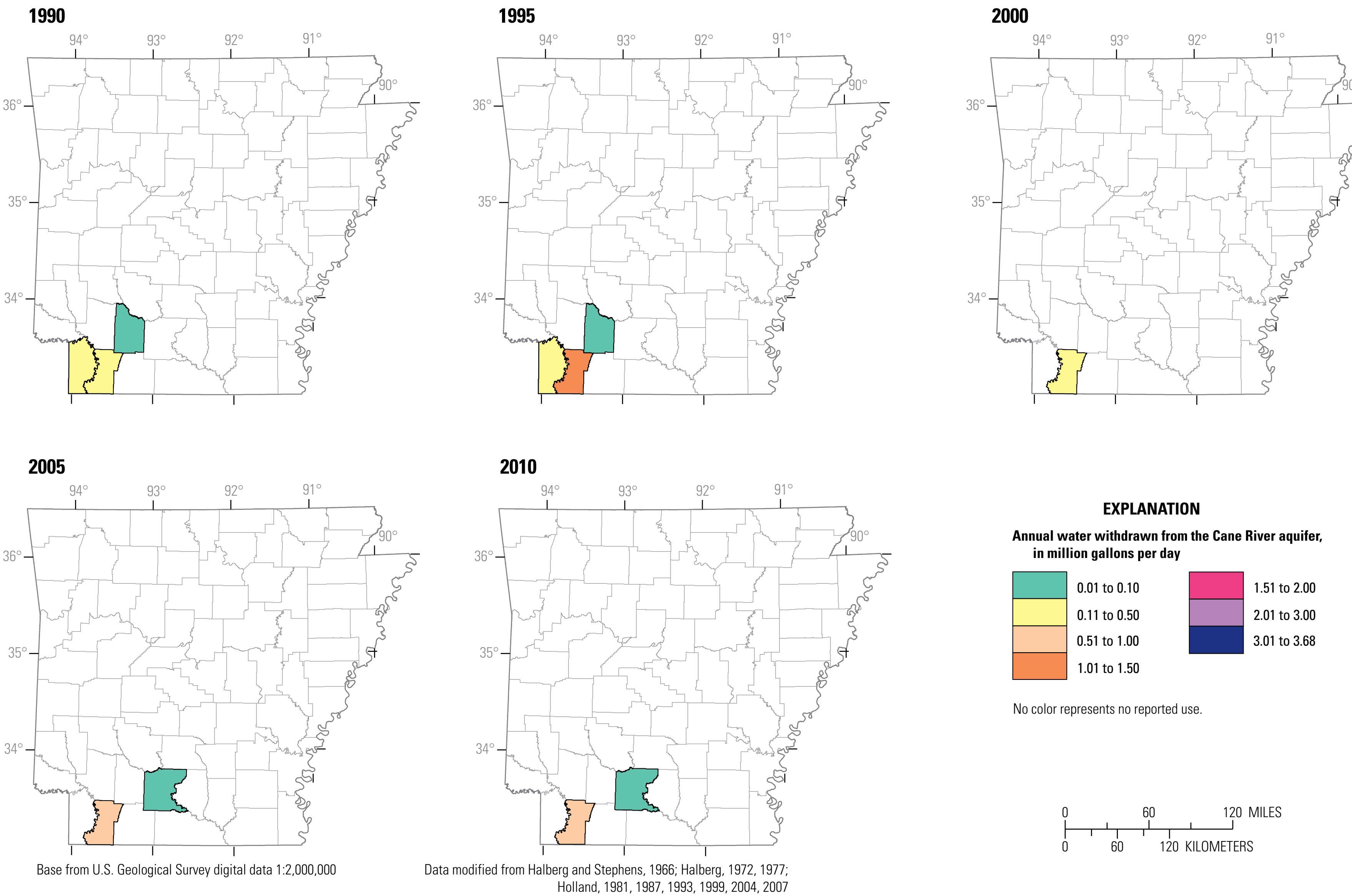


Figure 59. Water-use rates for the Cane River aquifer in Arkansas from 1965 to 2010.—Continued

Water Quality

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

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

General Geochemistry and Water Type

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

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

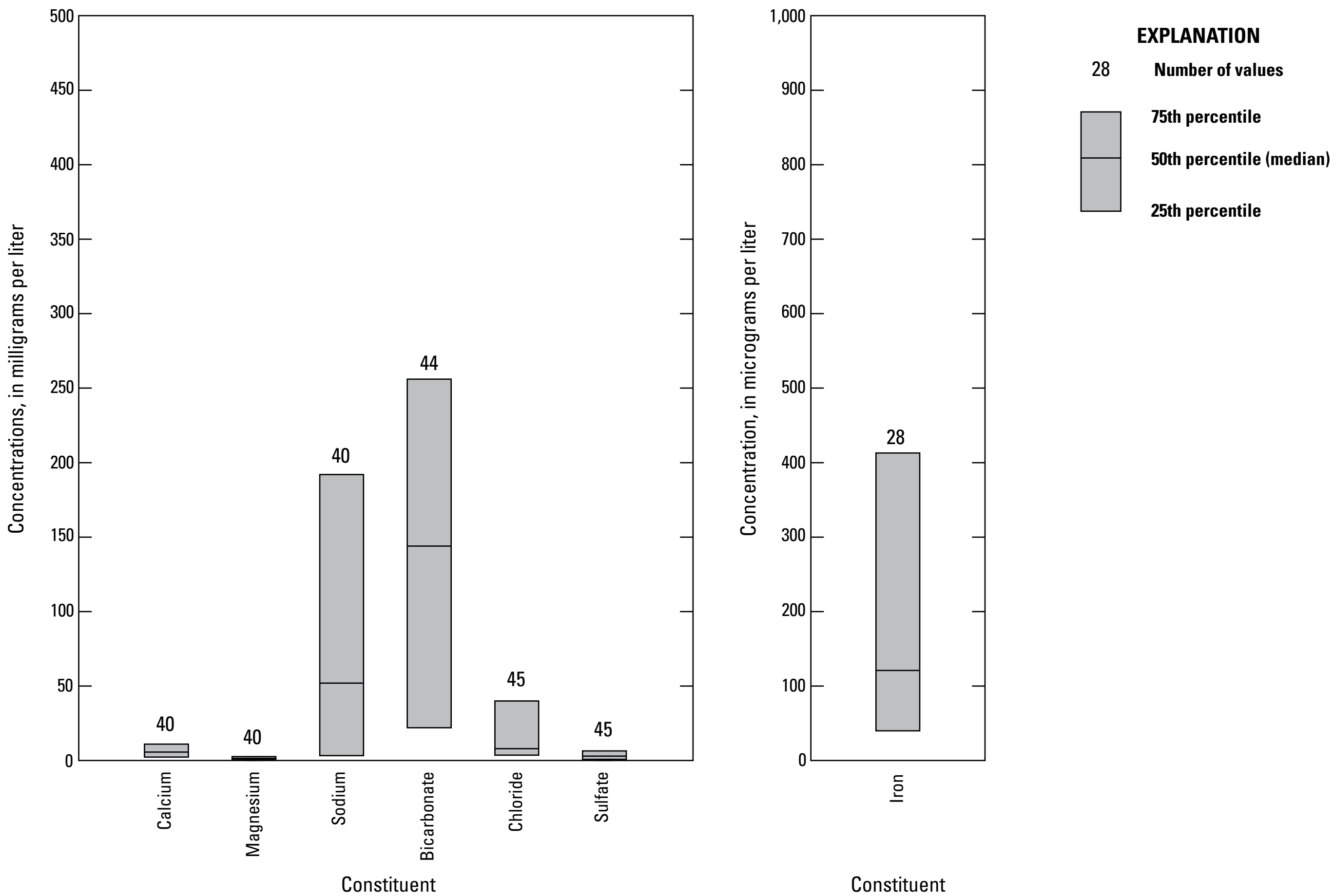


Figure 60. Interquartile range of selected chemical constituents for groundwater from the Cane River aquifer in Arkansas.

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

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

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

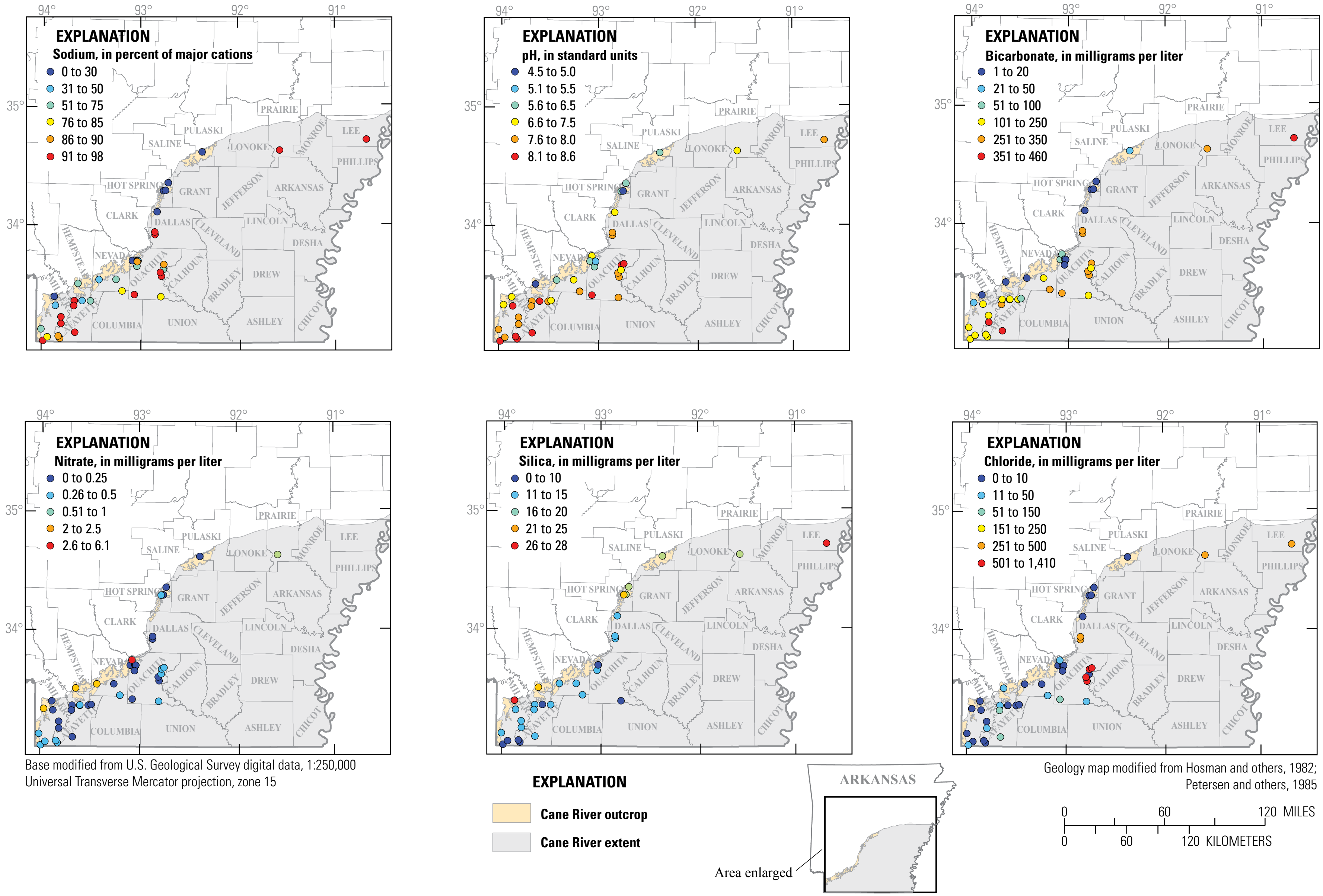


Figure 61. Spatial distribution of selected chemical constituents for groundwater from the Cane River aquifer in Arkansas.

Nitrate

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

Iron

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

Silica

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

Sulfate

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

Chloride

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

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

Carrizo Aquifer

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

Geologic Setting

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

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

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

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

Hydrologic Characteristics

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

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

Water Use

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

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

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

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

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

Water Quality

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

General Geochemistry and Water Type

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

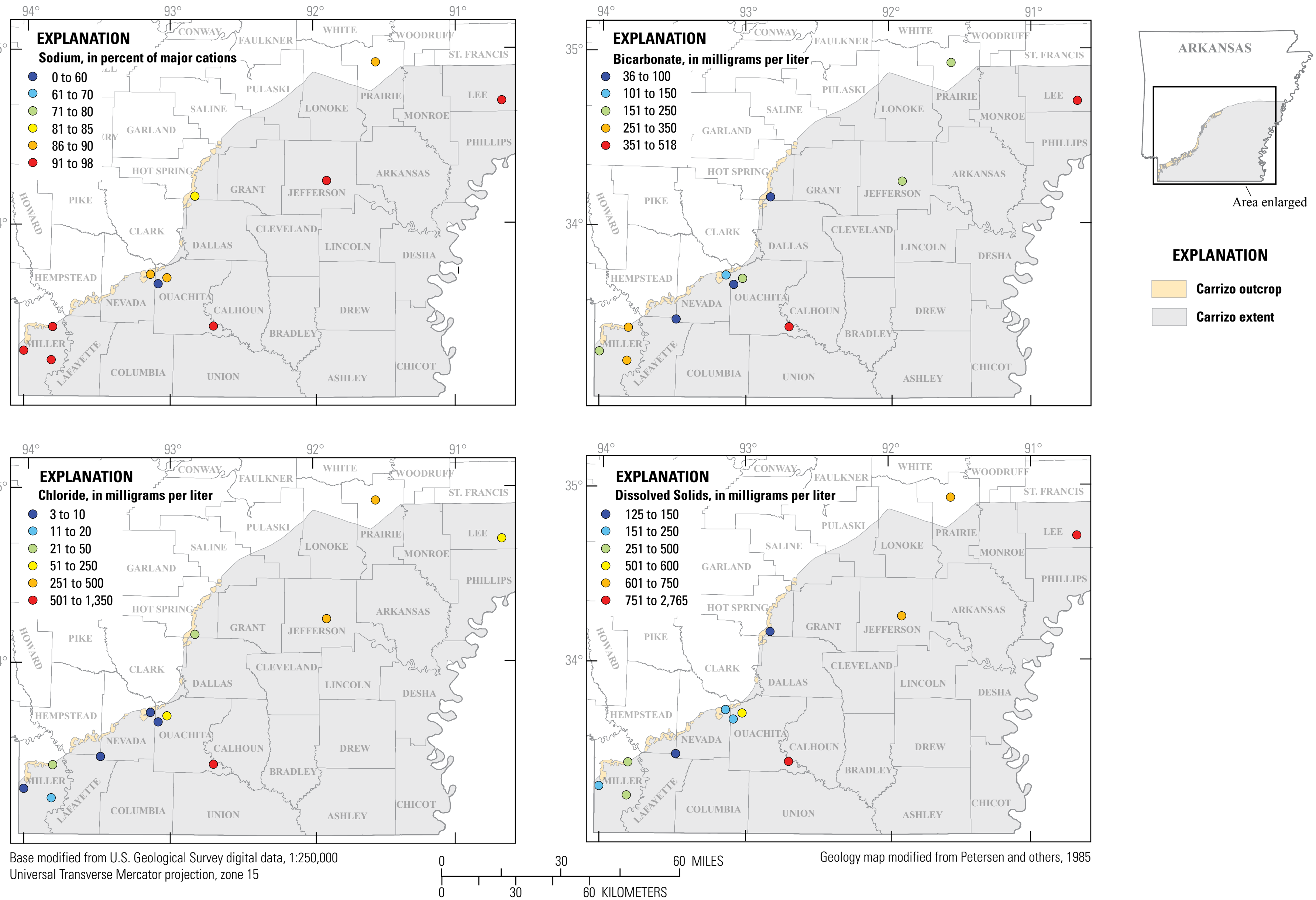


Figure 62. Spatial distribution of selected chemical constituents for groundwater from the Carrizo aquifer in Arkansas.

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

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

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

Nitrate

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

Iron

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

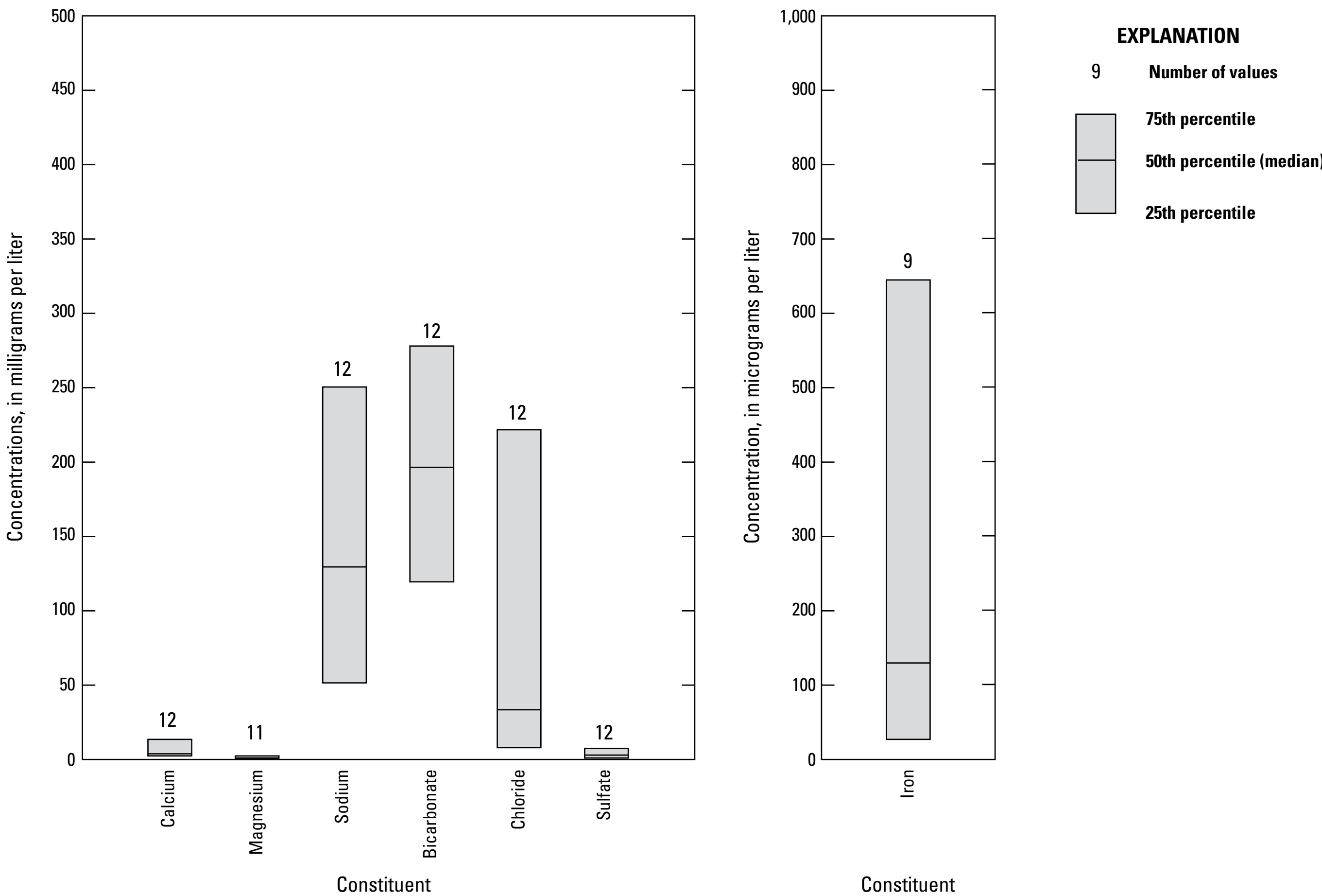


Figure 63. Interquartile range of selected chemical constituents for groundwater from the Carrizo aquifer in Arkansas.

Sulfate

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

Chloride and Dissolved Solids

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

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

Wilcox Aquifer

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

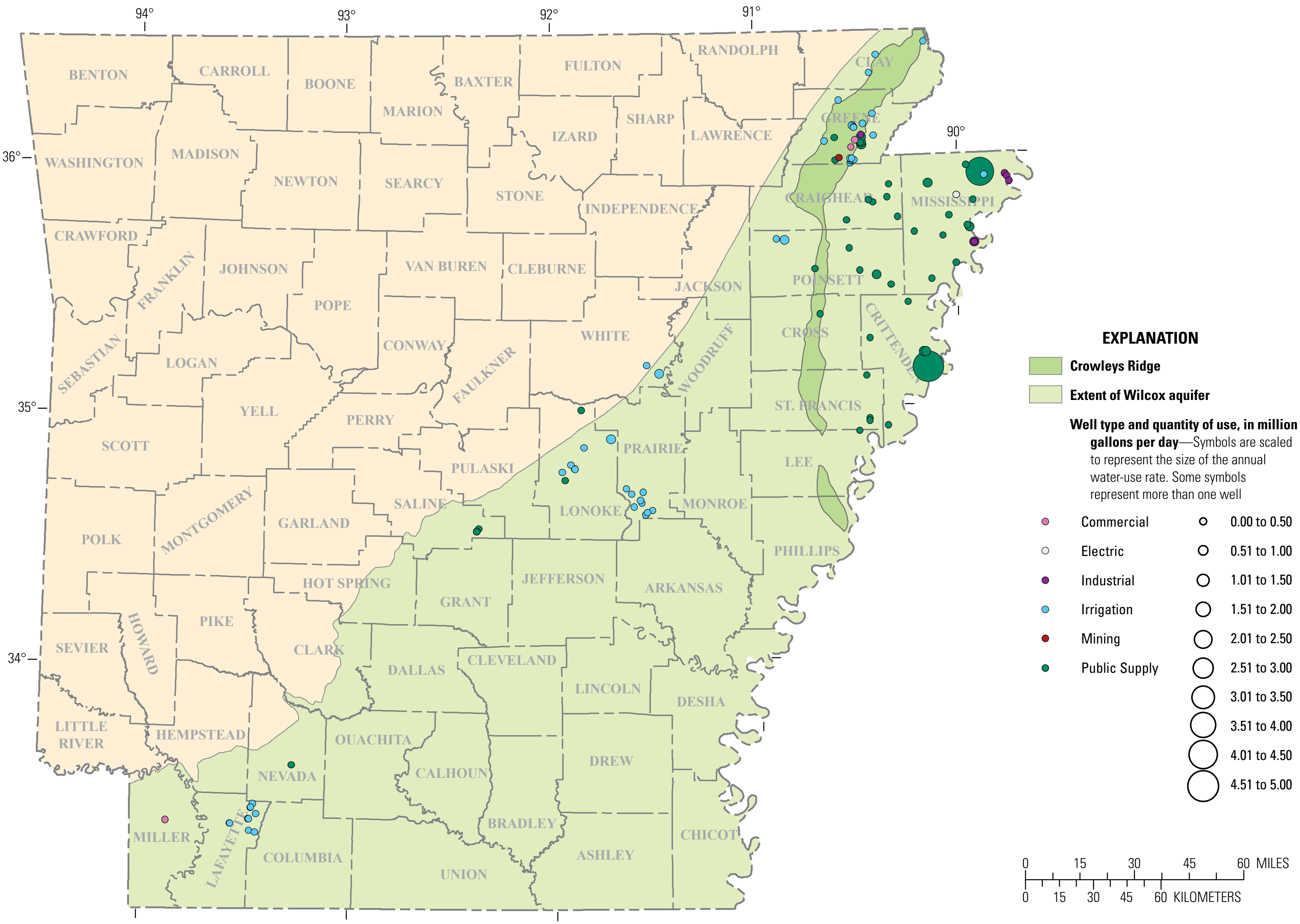
Geology

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

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

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

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



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

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

Hydrologic Characteristics

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

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

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

Water Use

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

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

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

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

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

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

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

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

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

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

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

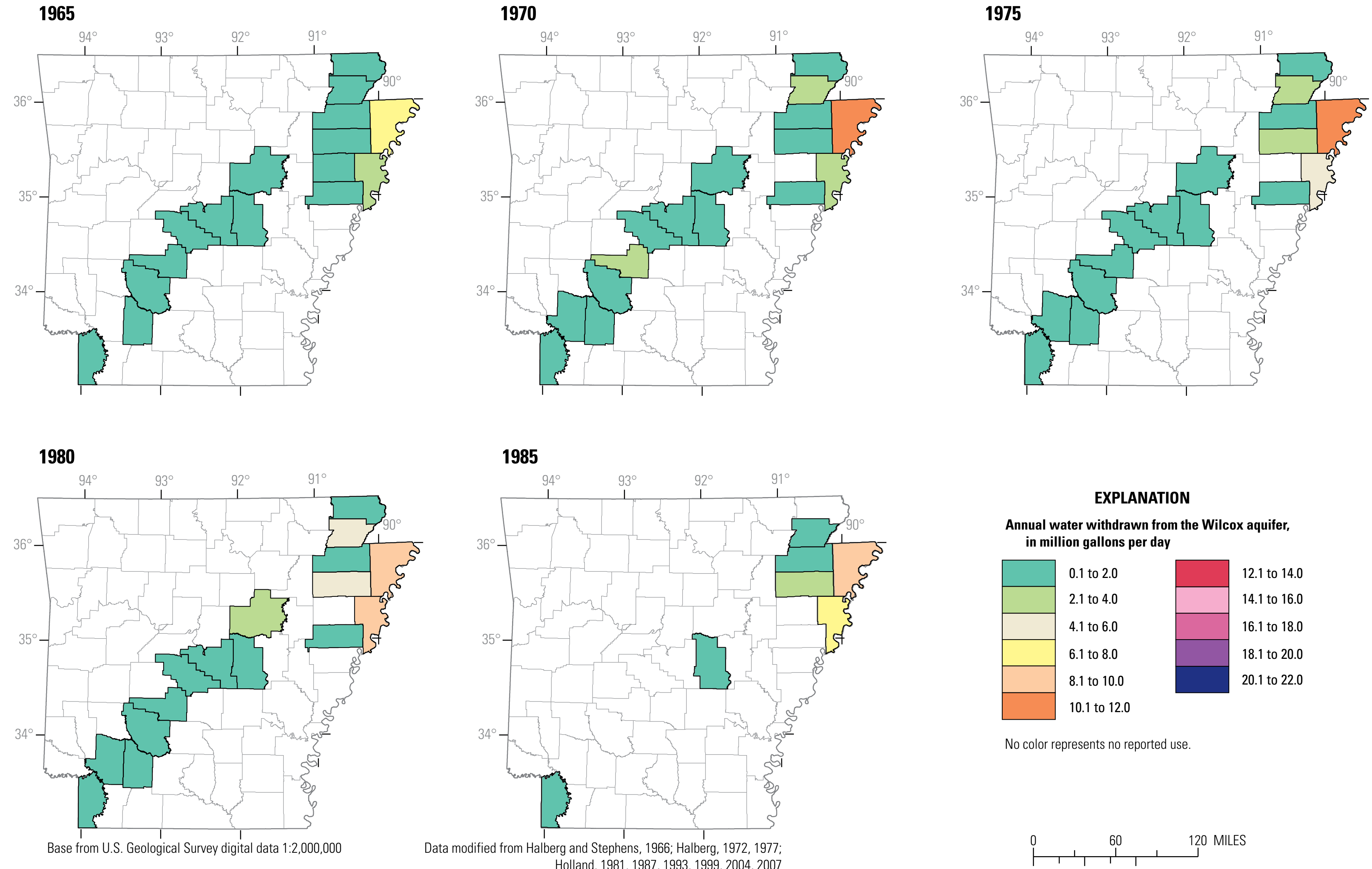
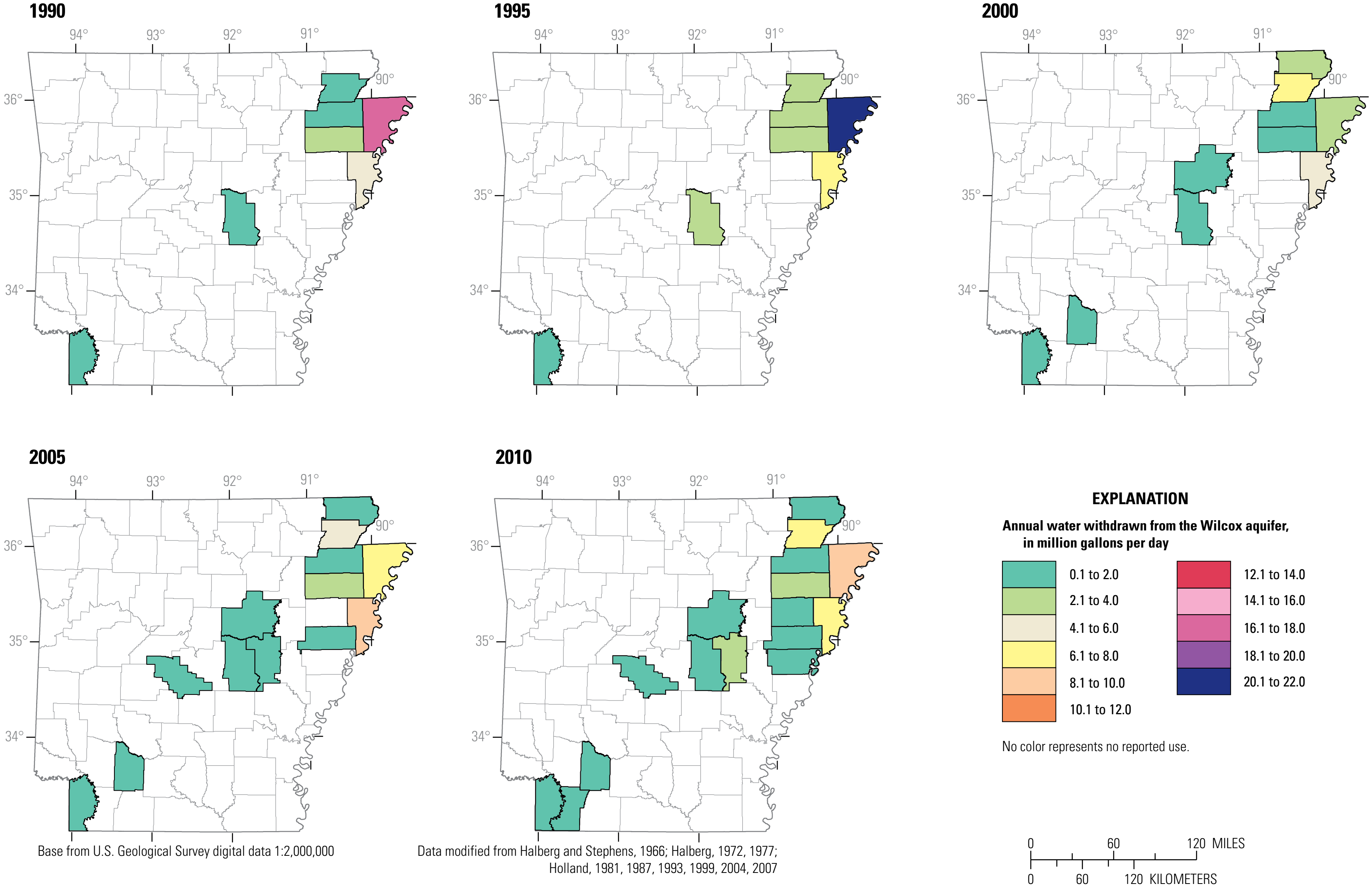


Figure 65. Water-use rates for the Wilcox aquifer in Arkansas from 1965 to 2010.



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

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

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

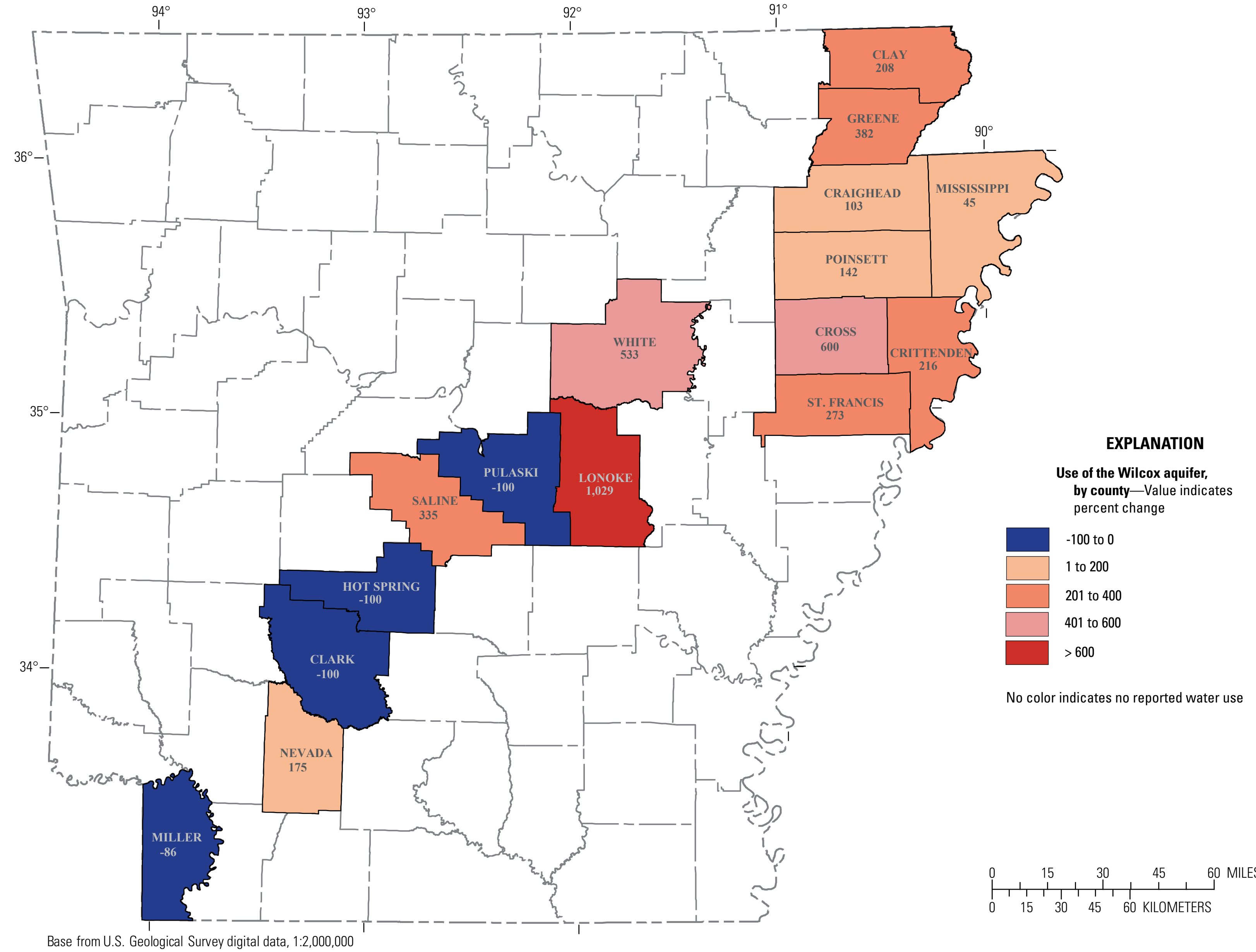


Figure 66. Change in percentage of water use from the Wilcox aquifer in Arkansas from 1965 to 2010.

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

Water Levels

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

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

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

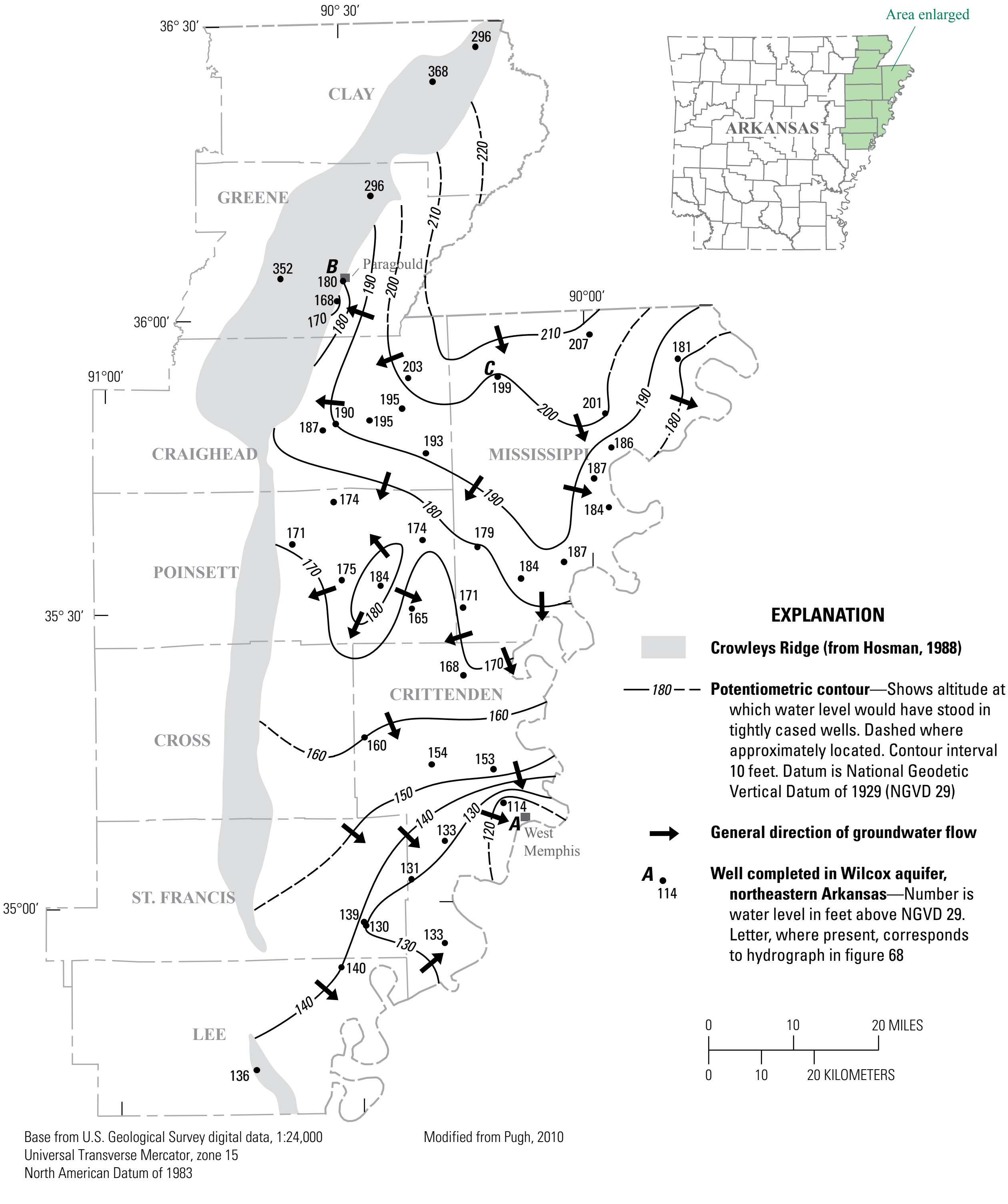


Figure 67. Potentiometric surface of the Wilcox aquifer in Arkansas, 2009.

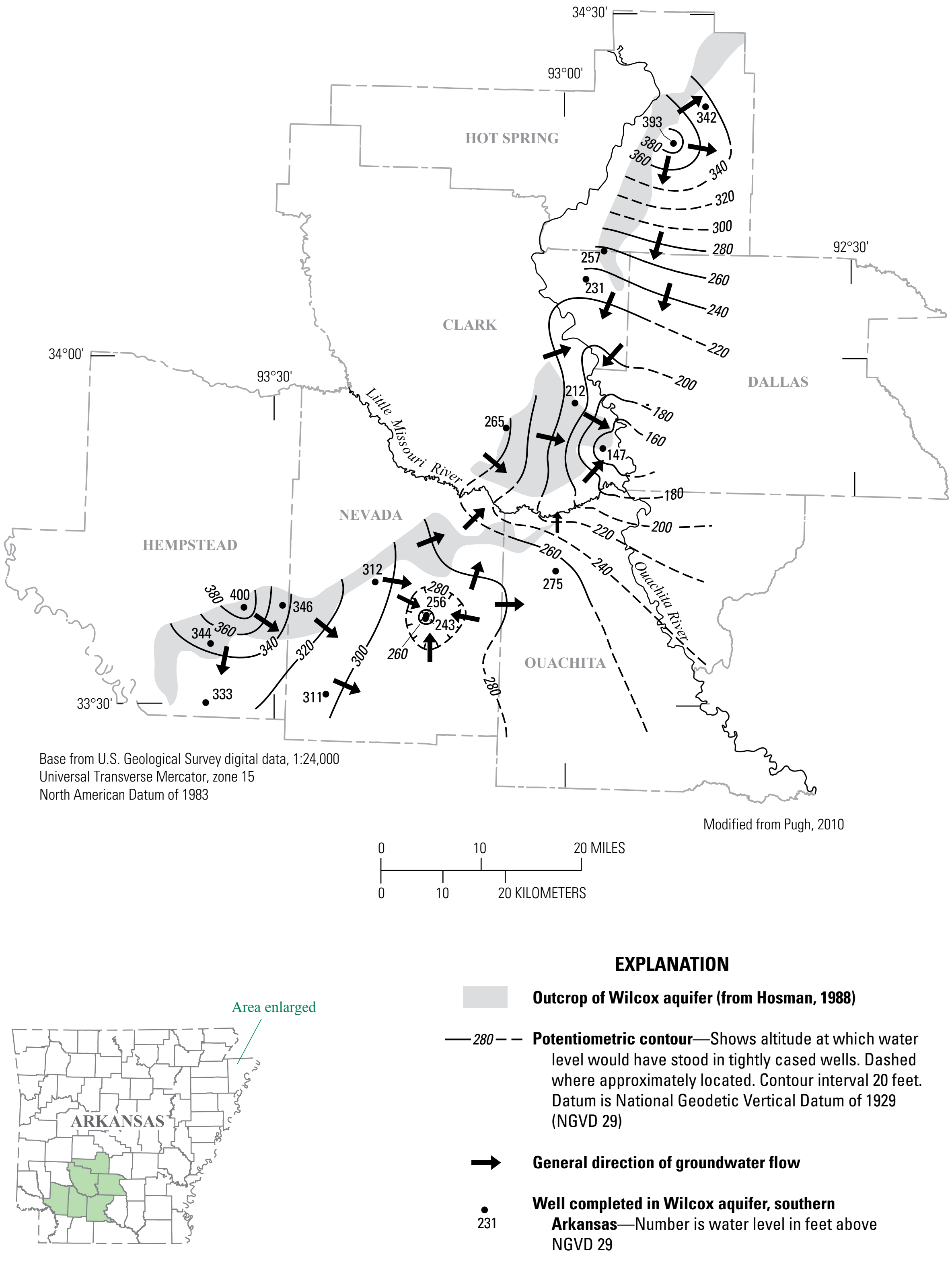


Figure 67. Potentiometric surface of the Wilcox aquifer in Arkansas, 2009.—Continued

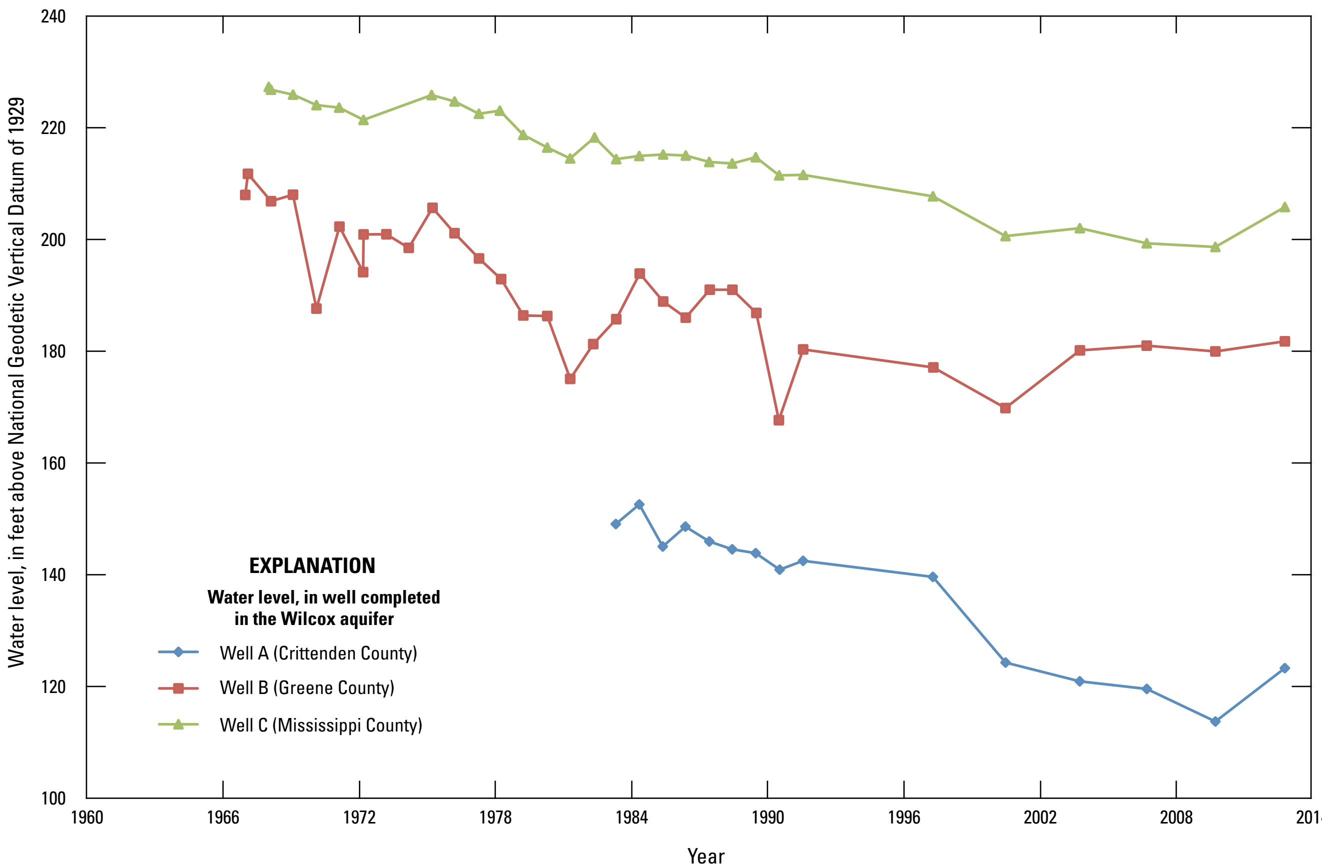


Figure 68. Hydrographs of water levels in wells completed in the Wilcox aquifer in Arkansas.

Water Quality

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

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

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

General Geochemistry and Water Type

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

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

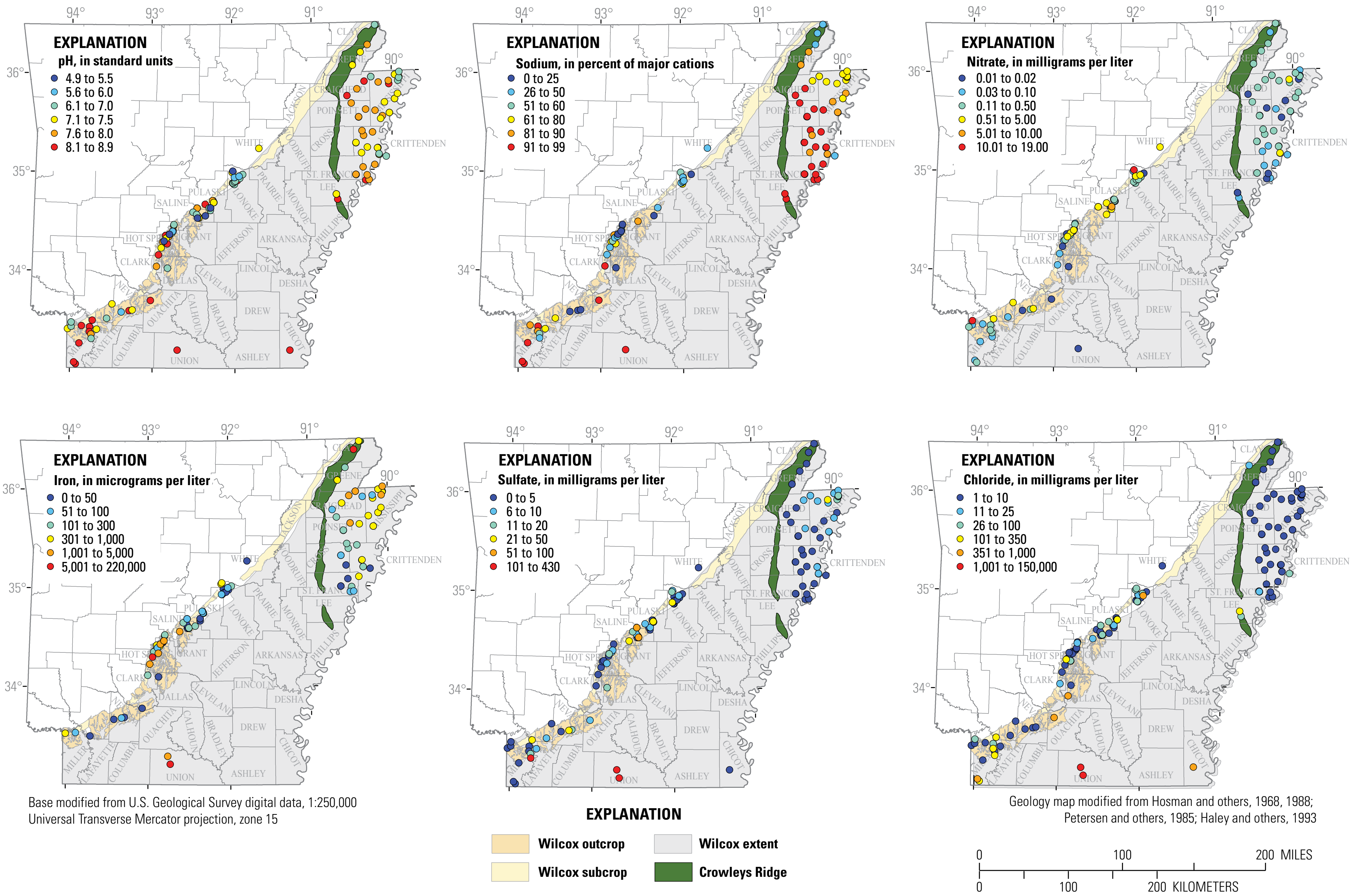


Figure 69. Spatial distribution of selected chemical constituents in groundwater from the Wilcox aquifer in Arkansas.

Nitrate

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

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

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

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

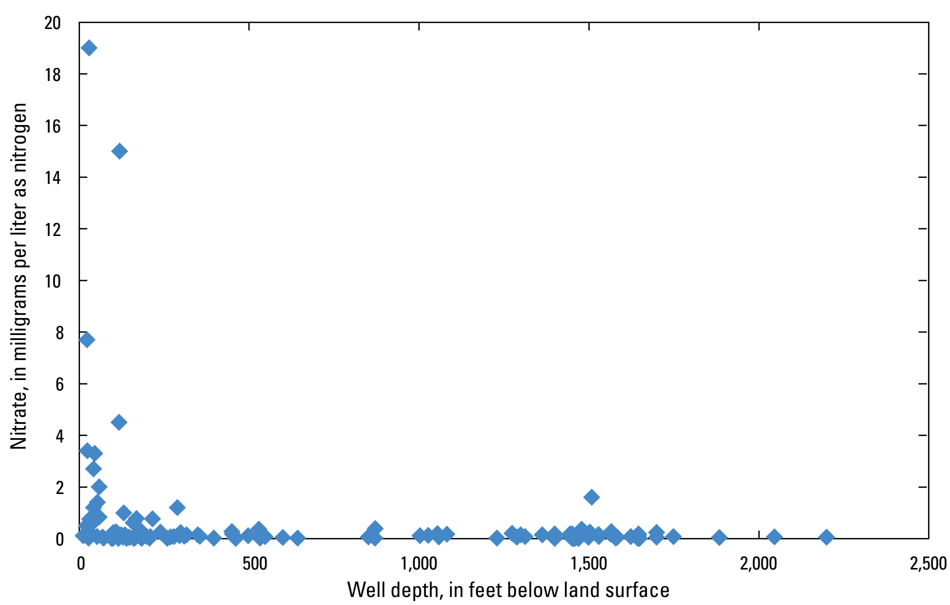


Figure 70. Relation of well depth and nitrate in groundwater from the Wilcox aquifer in Arkansas.

Iron

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

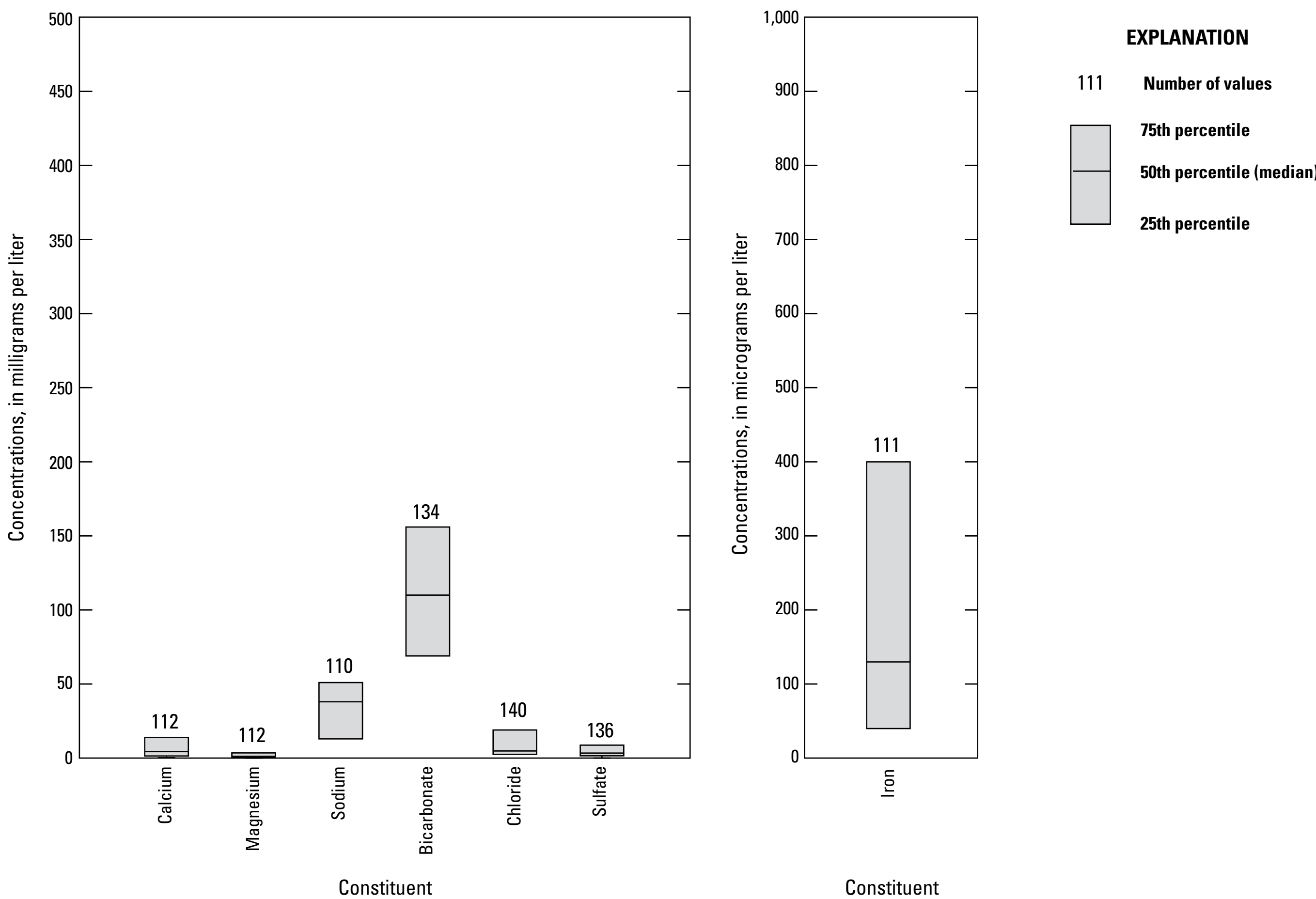


Figure 71. Interquartile range of selected chemical constituents in groundwater from the Wilcox aquifer in Arkansas.

Sulfate

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

Chloride and Dissolved Solids

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

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

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

Nacatoch Aquifer

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

Geology

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

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

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

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

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

Hydrologic Characteristics

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

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

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

Water Use

Use of the Nacatoch aquifer has been restricted to areas near its outcrop and subcrop areas in southwestern and northeastern Arkansas, respectively. The water is considered too saline for use in other areas, such as Craighead, Jackson, Monroe, and Poinsett Counties (Albin and others, 1967a; Hines and others, 1972; Broom and Lyford, 1981). Few early wells were completed in the Nacatoch in east-central Arkansas (Stephenson and Crider, 1916). Water-use reports since 1965 show use only in Clay, Greene, and Lawrence Counties in northeastern Arkansas (fig. 72). Primary use of the aquifer has been for public and industrial supply. Domestic wells also tap the aquifer in eastern Lawrence and southeastern Randolph Counties (Lamonds, 1969). Countywide domestic use is attributed to the primary aquifer present in the county, therefore domestic use for Randolph County would not be attributed the Nacatoch aquifer and is not presented in table 32. Poor water-quality downdip from the outcrop area has restricted the aquifer's use in parts of southwestern Arkansas (Terry and others, 1986).

Veatch (1906) reported that the Nacatoch aquifer had been extensively developed in southwestern Arkansas and stated "over a thousand wells" had been developed between Arkadelphia (Clark County) and Texarkana (Miller County), which was most likely an overestimation because later work recorded just over 400 wells completed in the aquifer (Boswell and others, 1965). Many wells that were flowing artesian wells had been abandoned and allowed to flow because of the lack of concern for conserving this resource (Veatch, 1906). Other flowing artesian wells were present in the Nacatoch in southern Clark County (Boswell and others, 1965; Plebuch and Hines, 1969), but yields and water levels in the aquifer were declining as a consequence of unrestricted artesian flows.

Water use from the Nacatoch aquifer has varied over the years. Boswell and others (1965) reported 1.2 Mgal/d were produced prior to 1965, primarily by municipalities and industries in southwestern Arkansas. Use of groundwater from the aquifer increased 174 percent from 1965 to 1980 (table 32), the peak year for use of water from the Nacatoch aquifer. Use decreased from 1980 to 1995, jumped to a second high in 2000, and again decreased after 2000. Water use from the aquifer in 2010 was approximately 66 percent public supply, 4 percent for industrial supply, 10 percent for electric supply, and the remainder for mining, domestic, and livestock uses (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). As of 2010, 33 wells completed in the Nacatoch were registered in ARWUDBS.

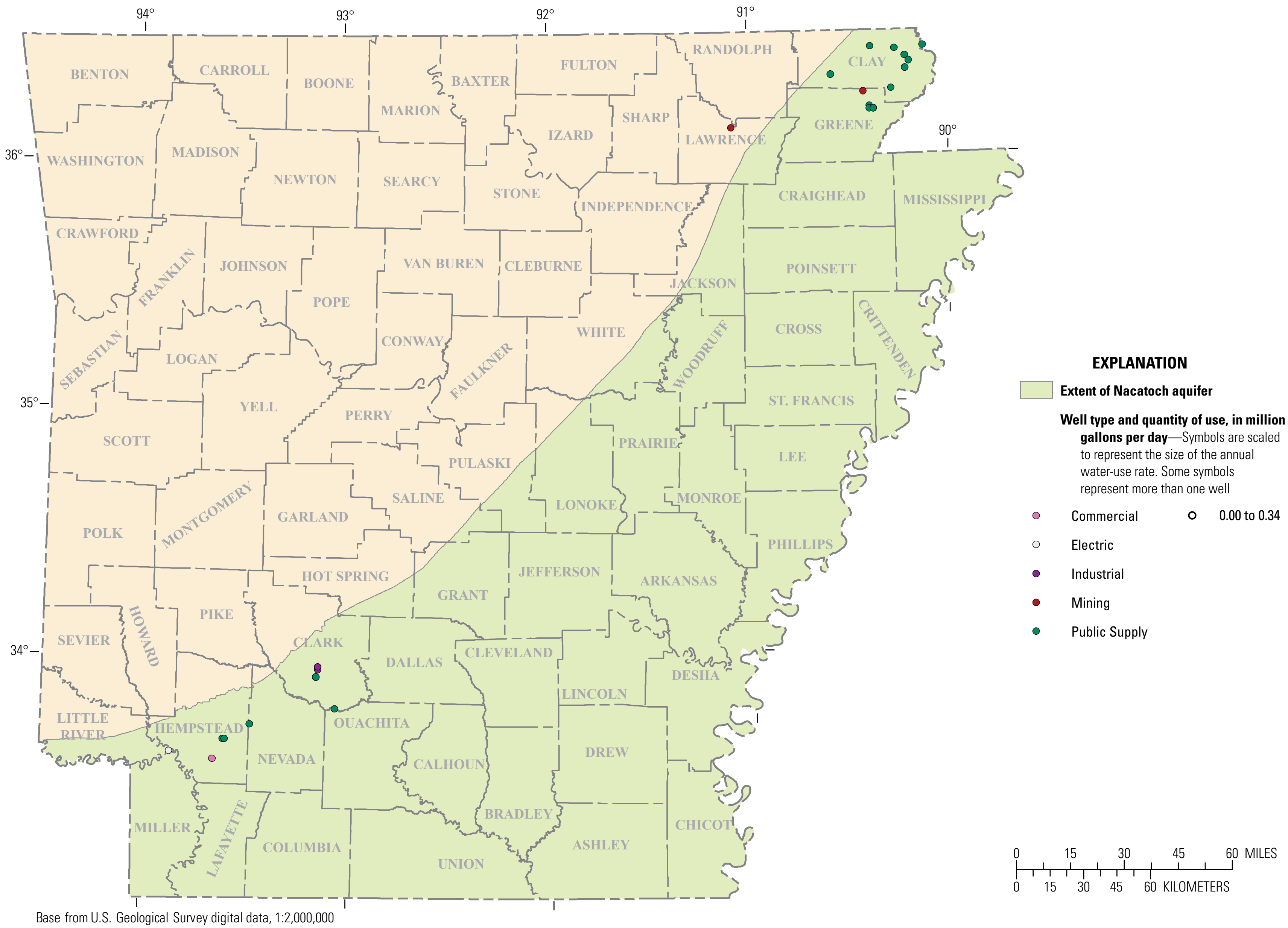


Figure 72. Wells with reported water use from the Nacatoch aquifer in Arkansas, 2010.

Table 32. Water use from the Nacatoch aquifer in Arkansas, 1965–2010.

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

County	1965	1970	1975	1980	1985	1990	1995	2000	2005	2010
Clay	0.25	0.51	0.63	1.55	1.13	1.98	1.72	[1]1.28	0.97	1.22
Greene	0.00	0.06	0.08	0.16	0.09	0.23	0.00	[1]0.40	0.48	0.46
Lawrence	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Northeast total	**0.25**	**0.57**	**0.71**	**1.71**	**1.22**	**2.21**	**1.72**	**[1]1.68**	**1.46**	**1.69**
Clark	0.44	0.55	0.64	1.73	0.91	0.29	0.34	0.54	0.43	0.15
Hempstead	1.12	1.72	1.44	1.98	0.15	0.20	0.32	1.83	1.92	1.29
Hot Spring	0.00	0.00	0.00	0.24	0.00	0.00	0.00	0.00	0.00	0.00
Howard	0.00	0.14	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Little River	0.20	0.04	0.04	0.06	0.00	0.00	0.00	0.00	0.00	0.00
Miller	0.14	0.03	0.04	0.06	0.00	0.00	0.00	0.00	0.00	0.00
Nevada	0.21	0.45	0.55	0.68	1.11	0.44	0.36	[1]0.08	0.18	0.21
Ouachita	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Southwest total	**2.11**	**2.93**	**2.93**	**4.75**	**2.17**	**0.93**	**1.02**	**[1]2.45**	**2.54**	**1.66**
Total	**2.36**	**3.50**	**3.64**	**6.46**	**3.39**	**3.14**	**2.74**	**[1]4.13**	**4.00**	**3.35**

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

Northeastern and southwestern Arkansas generally exhibited the same patterns of water use from the Nacatoch aquifer. Hempstead County generally had the most use in southwestern Arkansas and Clay County in northeastern Arkansas (fig. 73). Southwestern Arkansas had the greatest use in 1980, and northeastern Arkansas had the greatest use in 1990. Groundwater use in southwestern Arkansas usually was more than in northeastern Arkansas except for reporting years 1990, 1995, and 2010. From 1965 to 2010, use decreased in southwestern Arkansas, while use increased in northeastern Arkansas (fig. 74; table 32).

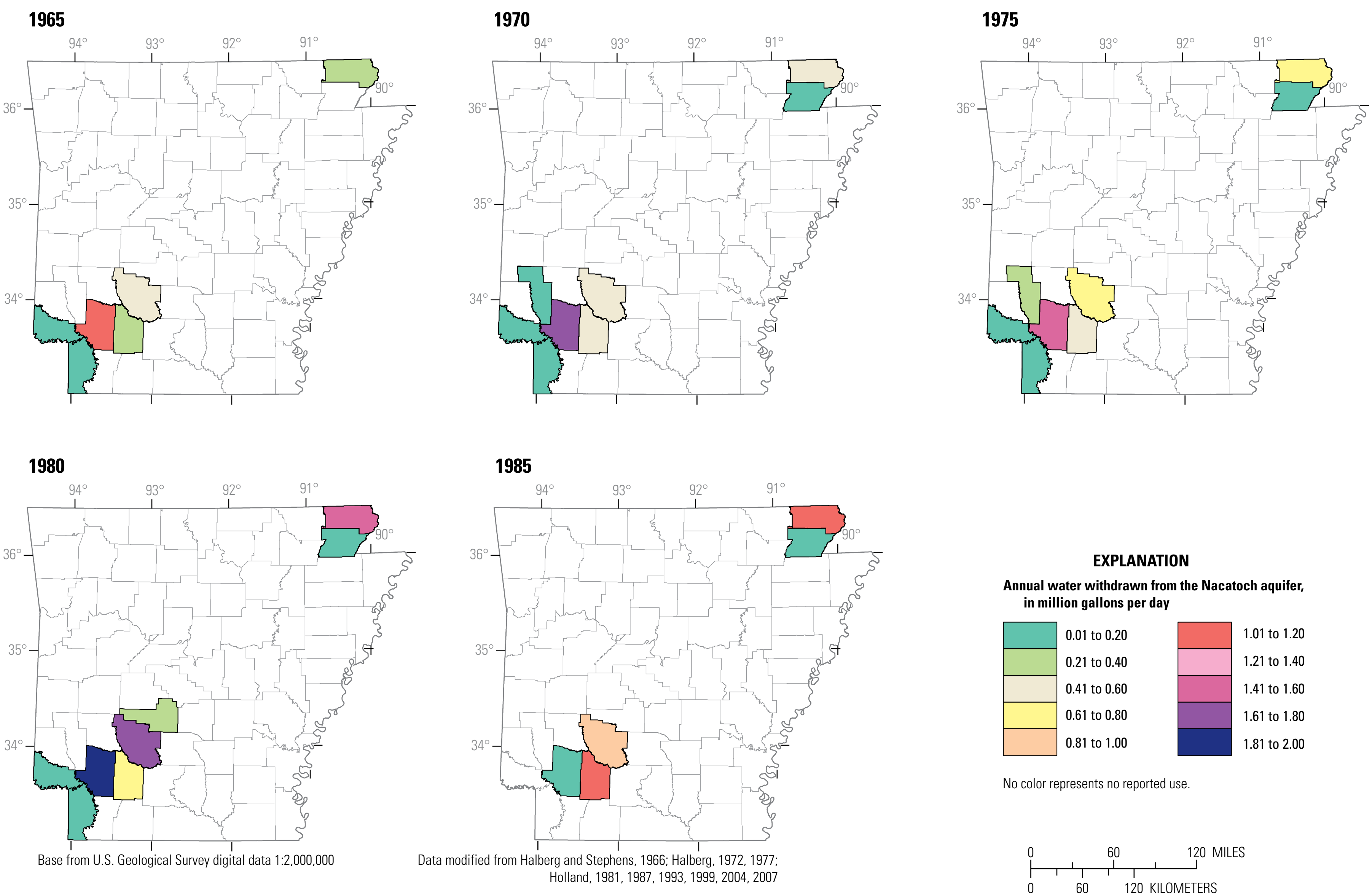


Figure 73. Water-use rates for the Nacatoch aquifer in Arkansas from 1965 to 2010.

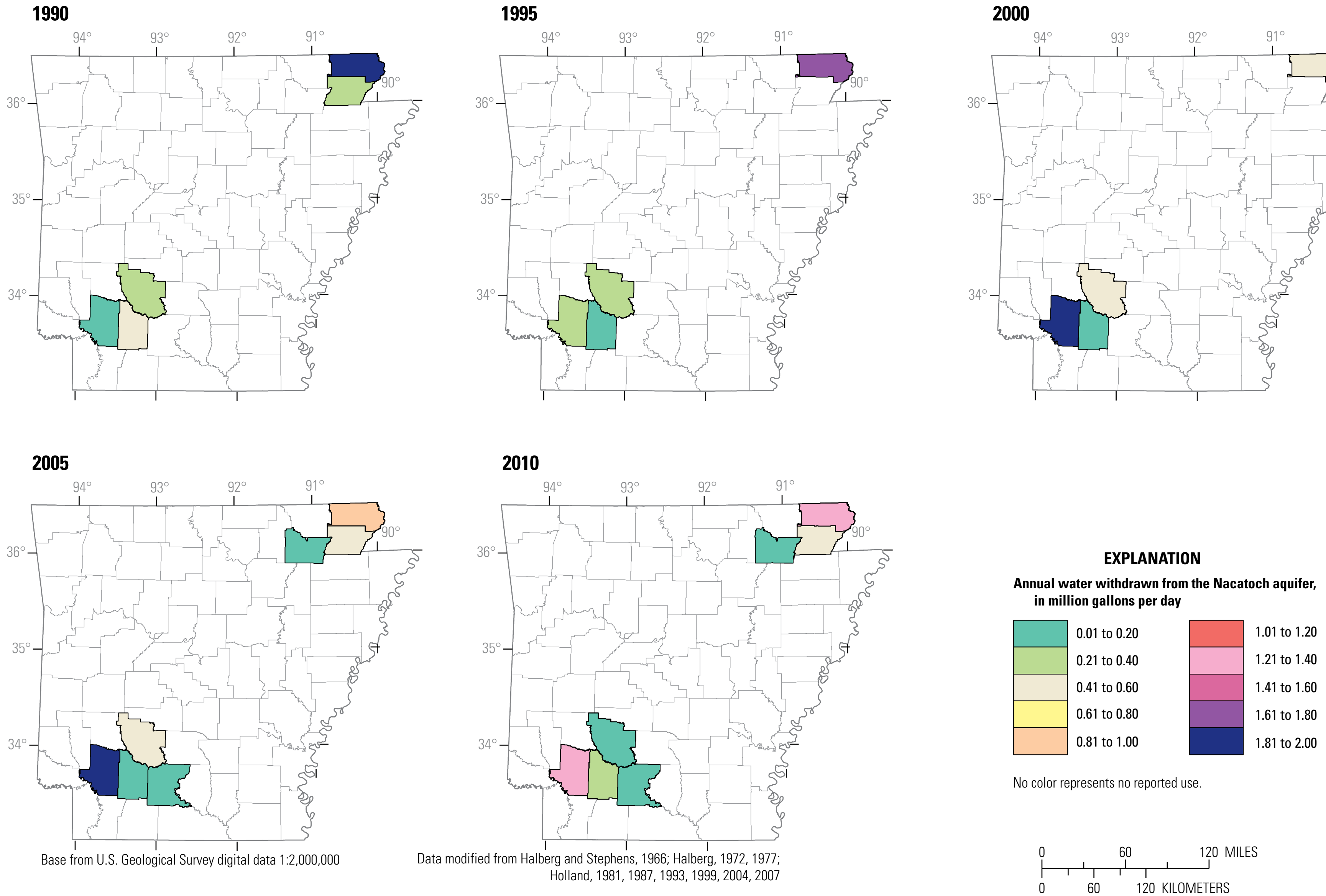


Figure 73. Water-use rates for the Nacatoch aquifer in Arkansas from 1965 to 2010.—Continued

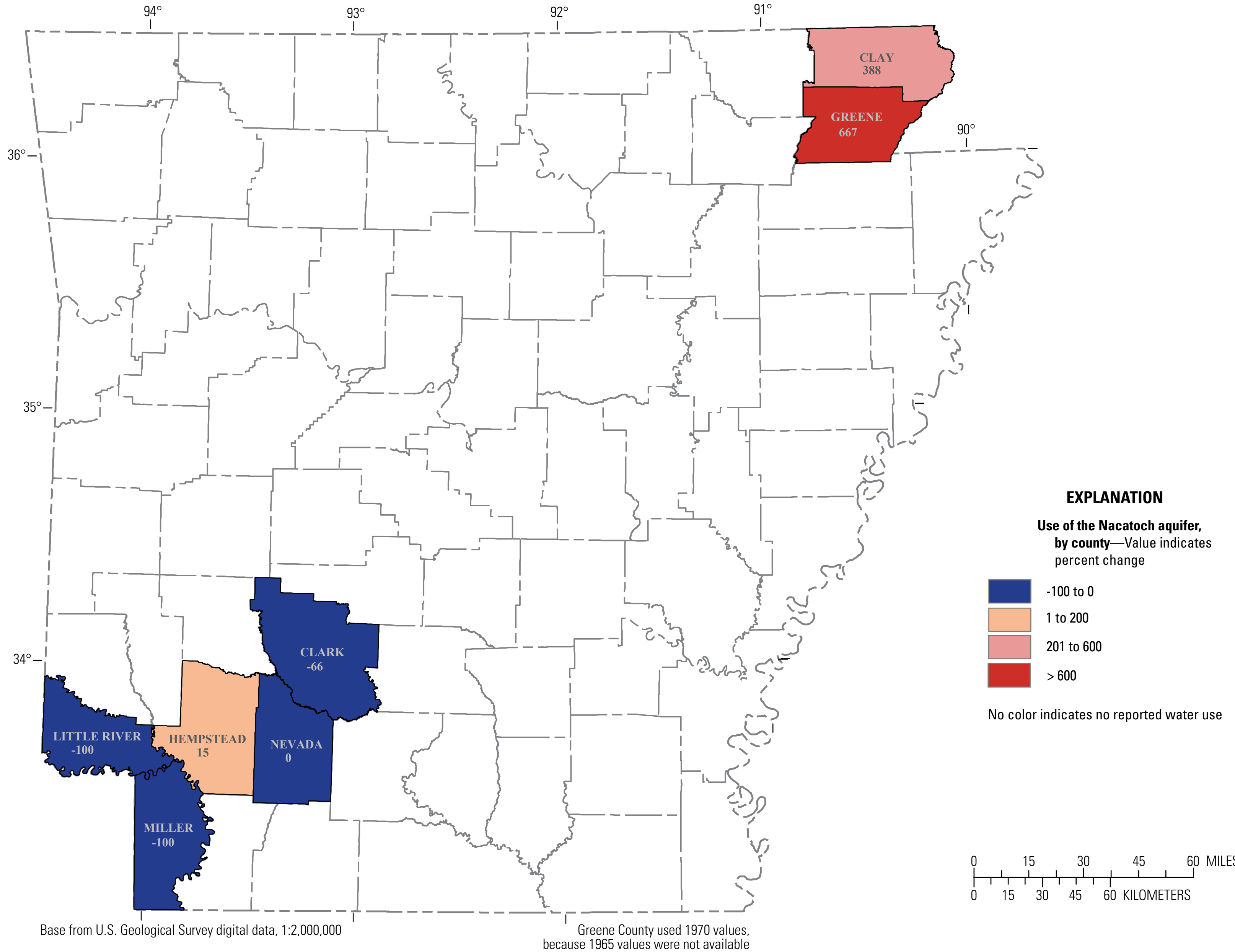


Figure 74. Change in percentage of water use from the Nacatoch aquifer in Arkansas from 1965 to 2010.

Public Supply

Water use from the Nacatoch aquifer for public supply currently (2013) is greater in northeastern Arkansas than in southwestern Arkansas. Clay County Regional Water District is the largest user of the Nacatoch for public supply with a total of 0.64 Mgal/d, which accounted for approximately 19 percent of total Nacatoch water use in 2010. Piggott (0.35 Mgal/d) and Rector (0.17 Mgal/d) in Clay County were other large users in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). The well in Piggott was drilled in 1923 and, at one point, was a flowing artesian well (Hale and others, 1947).

Hope (Hempstead County) is the largest user for public supply in southwestern Arkansas, using 15 percent of the total water withdrawn from the aquifer. Hope completed two wells in the Nacatoch in 1933, after completing one well in the Tokio aquifer in 1918 (Hale and others, 1947; Counts and others, 1955). Hope has drilled additional wells into both aquifers over the years but now supplements its groundwater with surface water.

Prescott (Nevada County) drilled two wells in the Nacatoch aquifer in 1925 and 1948 (Hale and others, 1947; Counts and others, 1955) but currently (2013) withdraws water only from the Little Missouri River. Water use for Nevada County decreased (fig. 73) after Prescott switched water sources between 1985 and 1990. Smaller communities in the area, including Gurdon (Clark County) and Emmet (Nevada County), tap the aquifer for public supply. Also, a school district in Hempstead County continues to use a well drilled in 1948 (Counts and others, 1955; Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

Industry

Industrial use from the Nacatoch aquifer in Clark County was dominated by lumber and paper companies in the mid-1900s. Counts and others (1955) recorded five different lumber companies with wells withdrawing from the aquifer. Lumber-processing facilities currently (2013) depend on the aquifer in Clark County. Ice and gas companies also were recorded users of the aquifer. In 2010, the largest single use of the aquifer was for cooling water at a powerplant in Hempstead County. In northeastern Arkansas, mining interests are active users of the aquifer in Greene and Lawrence Counties.

Water Levels

Southwestern Arkansas has experienced water-level declines in the Nacatoch aquifer since its early and intense development. During early development, many flowing artesian wells were unrestricted and allowed to flow freely, causing a decline in water levels of approximately 7 ft over 17 years near Prescott (Nevada County) (Veatch, 1906). Veatch (1906) created a potentiometric-surface map from water levels measured in 1902. Water levels were highest north of Hope at the northern limit of the aquifer outcrop and decreased to the south.

The ANRC and USGS monitor water levels in the Nacatoch aquifer as part of a long-term, statewide program (Schrader, 1998, 1999, 2007b; Schrader and Scheiderer, 2004; Schrader and Blackstock, 2010; Schrader and Rogers, 2013). In southwestern Arkansas, recent potentiometric-surface maps have shown the same pattern as in Veatch (1906), where groundwater-surface altitudes gradually decrease from the outcrop of the aquifer to the south (Schrader and Blackstock, 2010). Water levels in some wells declined by approximately 40 ft at Hope from 1942 to 1969 as a result of large groundwater withdrawals, mostly for public supply and industry. A cone of depression has been documented in this area since 1967 (Ludwig, 1973; Schrader, 1999; Schrader and Scheiderer, 2004; Schrader and Blackstock, 2010). Water levels rose in well A near the cone of depression at Hope in 2010 (figs. 75 and 76), corresponding to decreasing water use in Hempstead County. The 2011 potentiometric surface depicts a cone of depression near Hope (fig. 76).

Two other cones of depression in the Nacatoch aquifer potentiometric surface were noted in southern Clark and north-central Hempstead Counties (fig. 76). The Clark County depression was first identified in 2002 (Schrader and Scheiderer, 2004), whereas the Hempstead County depression was first identified in 2008 (Schrader and Blackstock, 2010). Groundwater altitudes in each of these depressions have dropped a foot since construction of the 2005 potentiometric-surface map (Schrader, 2007b).

In well B, near Prescott (Nevada County), water levels declined more than 30 ft from the mid-1950s to the mid-1970s (figs. 75 and 76). Dramatic water-level rises of approximately 70 ft were later identified in well B from 1985 to 1990, when the drinking-water supply of Prescott switched from groundwater to the Little Missouri River (Schrader and Blackstock, 2010). Water levels have stabilized since the early 1990s.

Water-level declines in wells completed in the Nacatoch aquifer in northeastern Arkansas were recorded in Clay (well C) and Greene (well D) Counties from the 1960s and 1970s until the late 1990s (figs. 75 and 76). Water levels have stabilized since 1990 with the decrease in use of the Nacatoch aquifer (table 32). Interestingly, a localized potentiometric high that had not been noted previously appeared in the 2011 surface in southeastern Clay County (fig. 76).

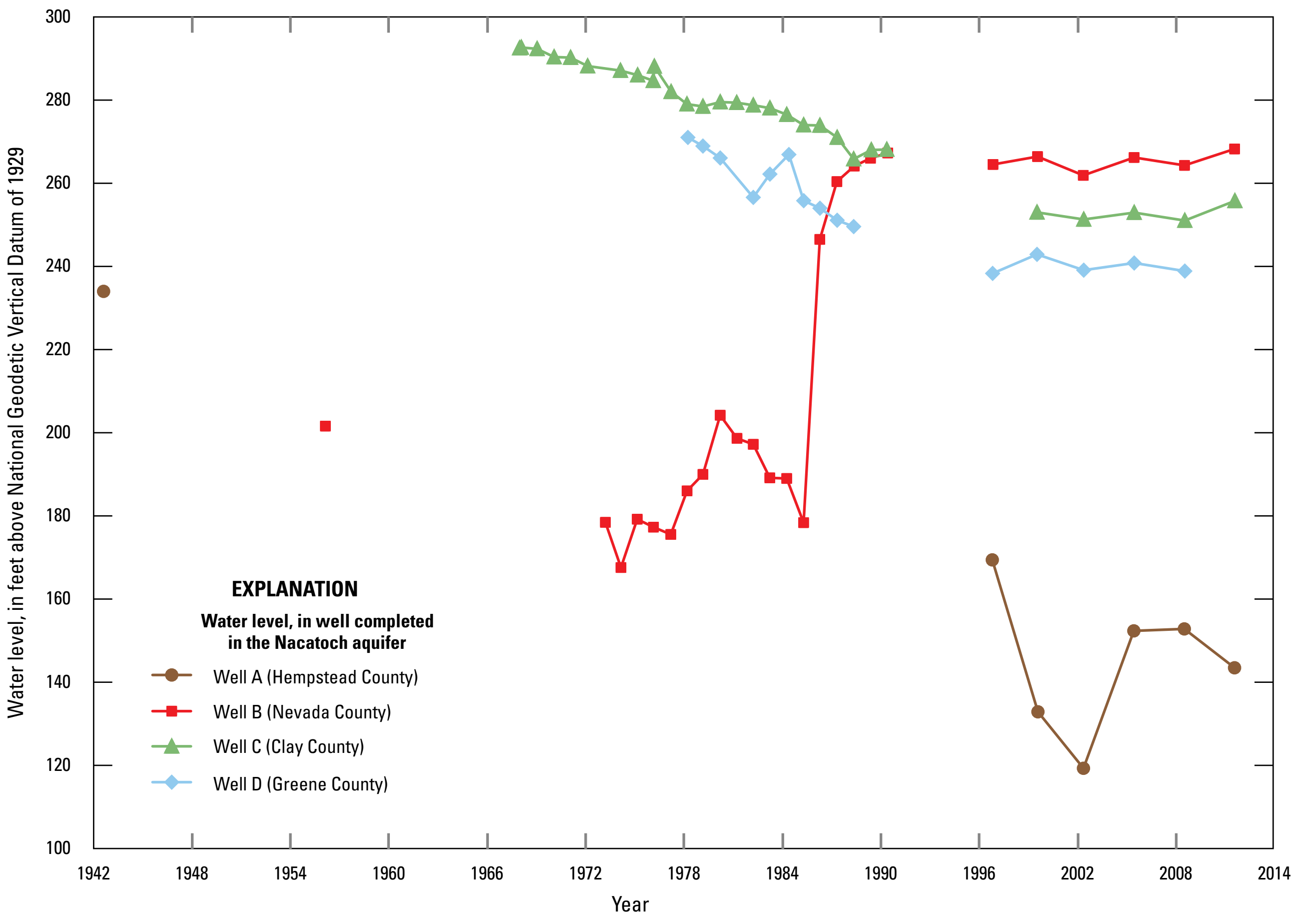


Figure 75. Hydrographs of water levels in wells completed in the Nacatoch aquifer in Arkansas.

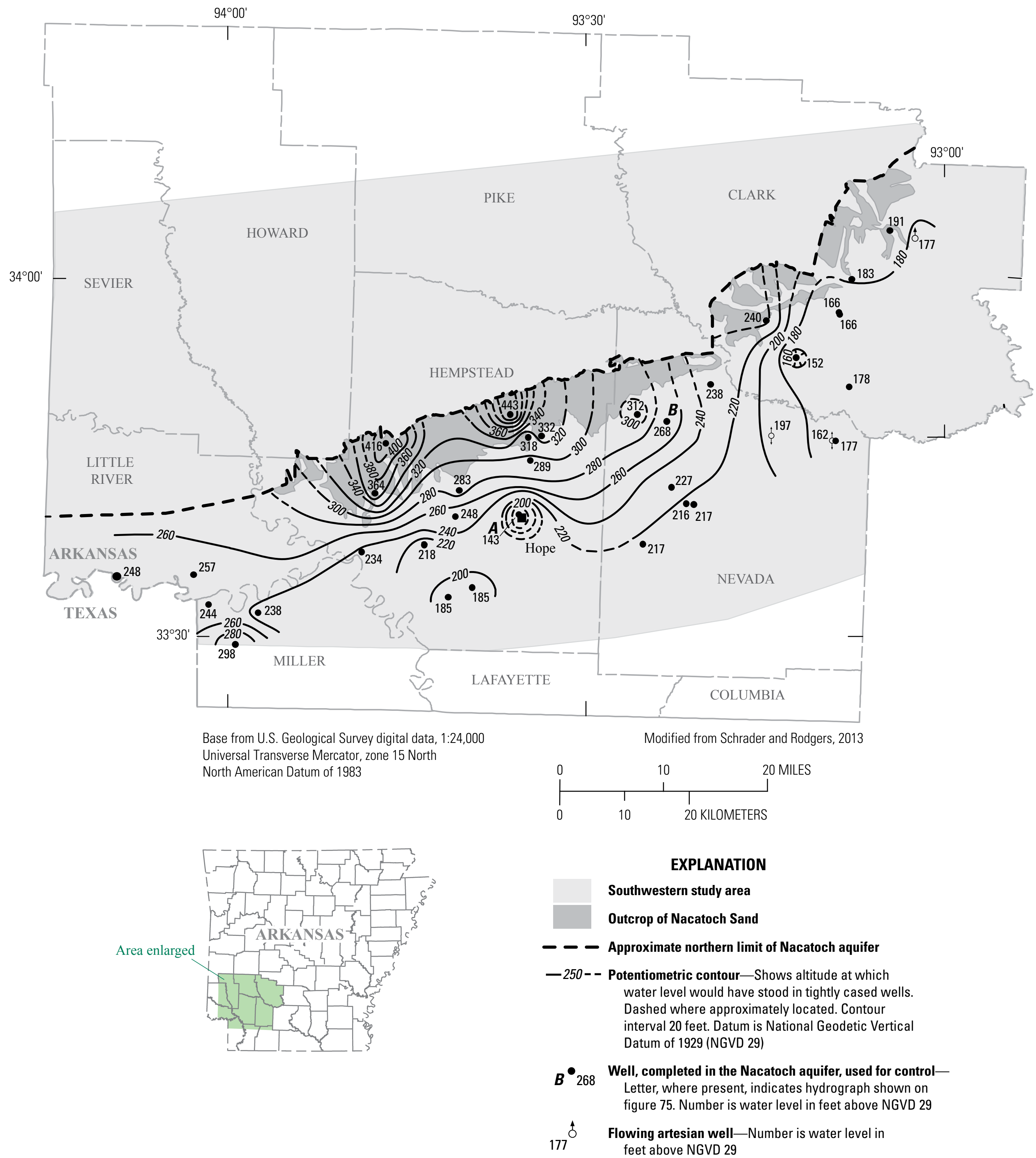


Figure 76. Potentiometric surface of the Nacatoch aquifer in Arkansas, February–March 2011.

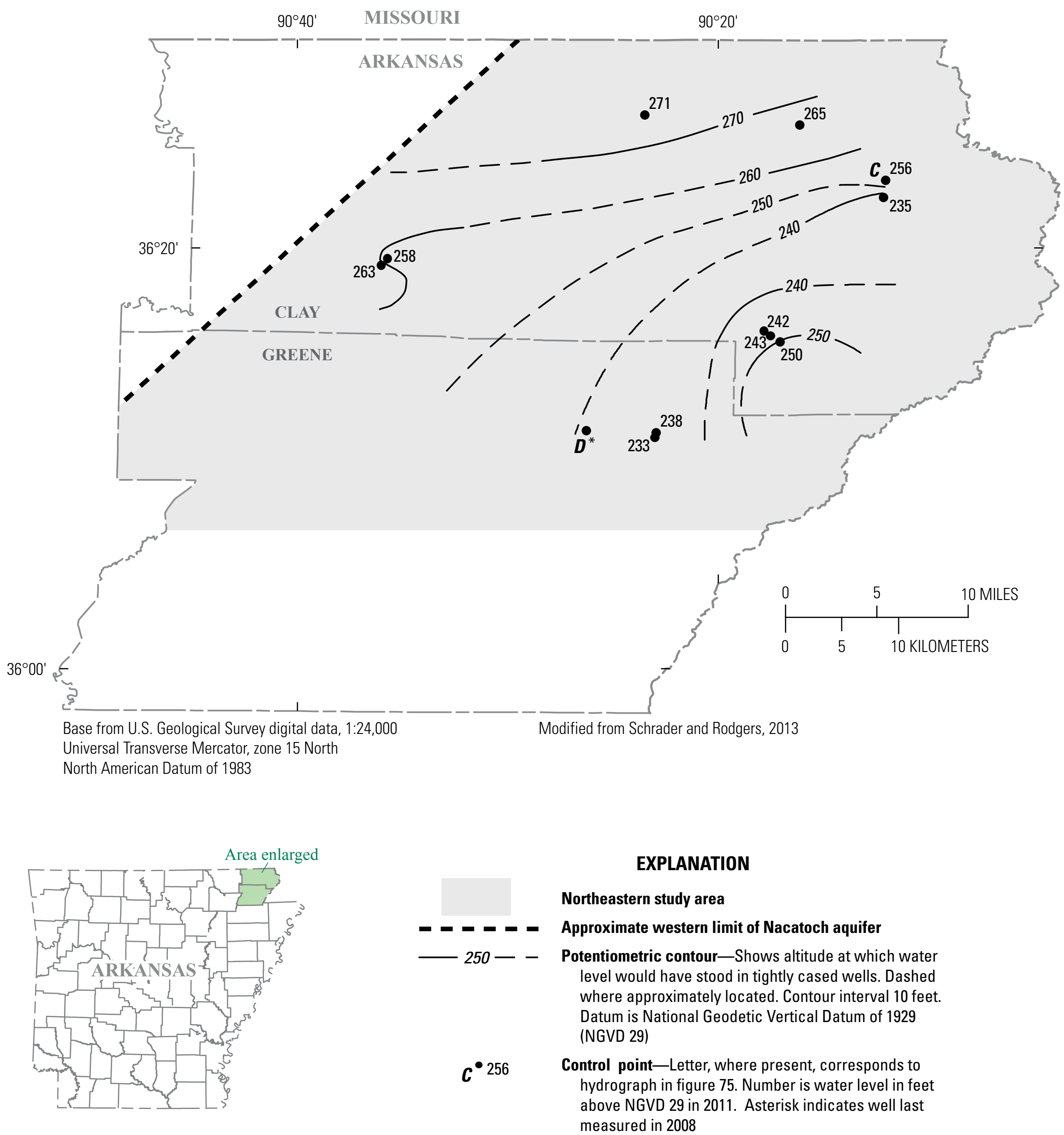


Figure 76. Potentiometric surface of the Nacatoch aquifer in Arkansas, February–March 2011.—Continued

Water Quality

The Nacatoch aquifer is an important source of groundwater in the southwestern part of the State. It is also a good-quality source of water in the extreme northeastern part of the State. Geological controls on lithology and structure explain its occurrence and viability as an aquifer in these areas. The Nacatoch crops out in a narrow band in the southwestern part of the State, extending from western Hempstead County to northeastern Clark County (fig. 77).

Freshwater occurs almost solely in an isolated area in and near this area of outcrop (Terry and others, 1986). The upper part of the Nacatoch is composed of sand and is the principal water-bearing part of the formation in this area (Counts and others, 1955; Ludwig, 1973). Counts and others (1955) noted that water quality in the Nacatoch varied considerably in southwestern Arkansas. Within 2–20 mi from the outcrop area, the groundwater was too salty for most uses. The change in water quality along flow paths downgradient from the recharge area is gradual in some areas, degrading to unusable over 20 mi, or abrupt, changing from less than 100 mg/L to greater than 1,000 mg/L in less than 4 mi. Similarly, Plebuch and Hines (1969) stated that chloride concentrations in Clark County were low but increased rapidly downgradient to concentrations unsuitable for most uses within 2–17 mi from the outcrop. Within a distance of 3 mi along the northeastern edge of the outcrop area in Clark County, chloride concentrations were noted to increase from 7.0 to 7,560 mg/L and dissolved solids from 92 to 12,300 mg/L. Near the outcrop area in Hempstead, Little River, and Nevada Counties, groundwater was soft or moderately hard with low chloride concentrations (Ludwig, 1972). Downgradient from the outcrop area, however, sodium and chloride concentrations increased with a concomitant increase in dissolved solids. Counts (1955) hypothesized that because the Nacatoch was a marine deposit, the original salt content had never been flushed completely from the formation, accounting for the higher salinity in the downgradient and deeper parts of the aquifer. Groundwater from the Nacatoch generally had very low iron concentrations (Counts and others, 1955; Ludwig, 1973) as well as low sulfate and nitrate concentrations (Counts and others, 1955).

The Nacatoch aquifer provides a productive source of groundwater in the southwestern part of the State near the outcrop (hereinafter referred to as the “southwestern extent” of the aquifer). This is because of the higher sand content in the upper unit compared to the lower unit of the Nacatoch that consists of a mixture of interbedded clays, marls, and sands (Counts and others, 1955; Plebuch and Hines, 1969). The lithology in central Arkansas consists of bluish-gray, calcareous, fossiliferous sandstones and clays (Stephenson and Crider, 1916). Elevated dissolved-solids concentrations in groundwater from this area render the water unusable (Boswell and others, 1965; Petersen and others, 1985). In northeastern Arkansas (hereinafter referred to as the “northeastern extent” of the aquifer), the sand content of the Nacatoch increases to 40–60 percent, and the aquifer once again becomes a viable aquifer (Renfroe, 1949; Caplan, 1954; Lamonds and others, 1969). The Nacatoch is a silty and fine-grained sand in Jackson County but transitions to a clean, medium- to coarse-grained sand in Clay, Greene, and Lawrence Counties. The aquifer thickens in these counties to approximately 200 ft and yields are as much as 500 gal/min in parts of Clay and Greene Counties. In Craighead County, the aquifer yielded slightly saline to brine water, and one sample in Monroe County contained chloride concentrations of 21,500 mg/L (Broom and Lyford, 1981). Because the northeastern extent contained only 8 of 132 wells in the combined water-quality database used for this report, most of the following detailed discussion, especially with respect to spatial trends for the various constituents, is confined to the southwestern extent of the aquifer.

General Geochemistry and Water Type

The Nacatoch aquifer is similar to other Cretaceous and Tertiary aquifers and tends to have increasing pH values along the flow path resulting from increased dissolution of carbonate minerals. The Nacatoch is somewhat unique, however, in that only 1 of 129 samples, including samples from wells in the outcrop area, had a pH value less than 7.0 (value of 4.7). Because the average pH of precipitation for southern Arkansas is approximately 4.7 standard units (Kresse and Fazio, 2002), pH values for Cretaceous and Tertiary aquifers often are much lower than 7.0 for many shallow wells in the recharge (outcrop) area. Downgradient from the outcrop area, pH values tend to increase along a given flow path as a result of buffering by carbonate minerals. Values of pH for groundwater from the Nacatoch ranged upward to 9.0 with a median of 8.4 (table 33). Only 25 of 129 samples had pH values less than 8.0. Lower groundwater velocities coupled with an abundance of carbonate minerals throughout the formation may result in dissolution of carbonates and associated buffering of acidic recharge within a relatively short distance along the flow path. Additionally, many of the wells completed in the Nacatoch produce from sands at relatively great depths. Out of 129 wells with well-depth information, only 13 were less than 100 ft deep, and 39 wells were more than 500 ft deep with a maximum of 2,231 ft in depth. The increased vertical distance and traveltime of infiltrating recharge water allows greater time for rock/water interaction, including dissolution of carbonate minerals.

The lowest pH values (4.7–7.5) in the Nacatoch aquifer occurred in or near the outcrop area and trended progressively upward to values exceeding 8.0 in the downgradient (southeasterly) direction of flow (fig. 77). Because pH generally increases with increasing dissolution of carbonates along the flow path, bicarbonate concentrations generally followed the trend of increasing pH. The lowest concentrations (less than 200 mg/L) occurred in and near the outcrop and progressively increased in the downgradient direction of flow. The highest bicarbonate concentrations were in wells located in the eastern and western sections of the outcrop area in the southwestern extent of the aquifer (fig. 77).

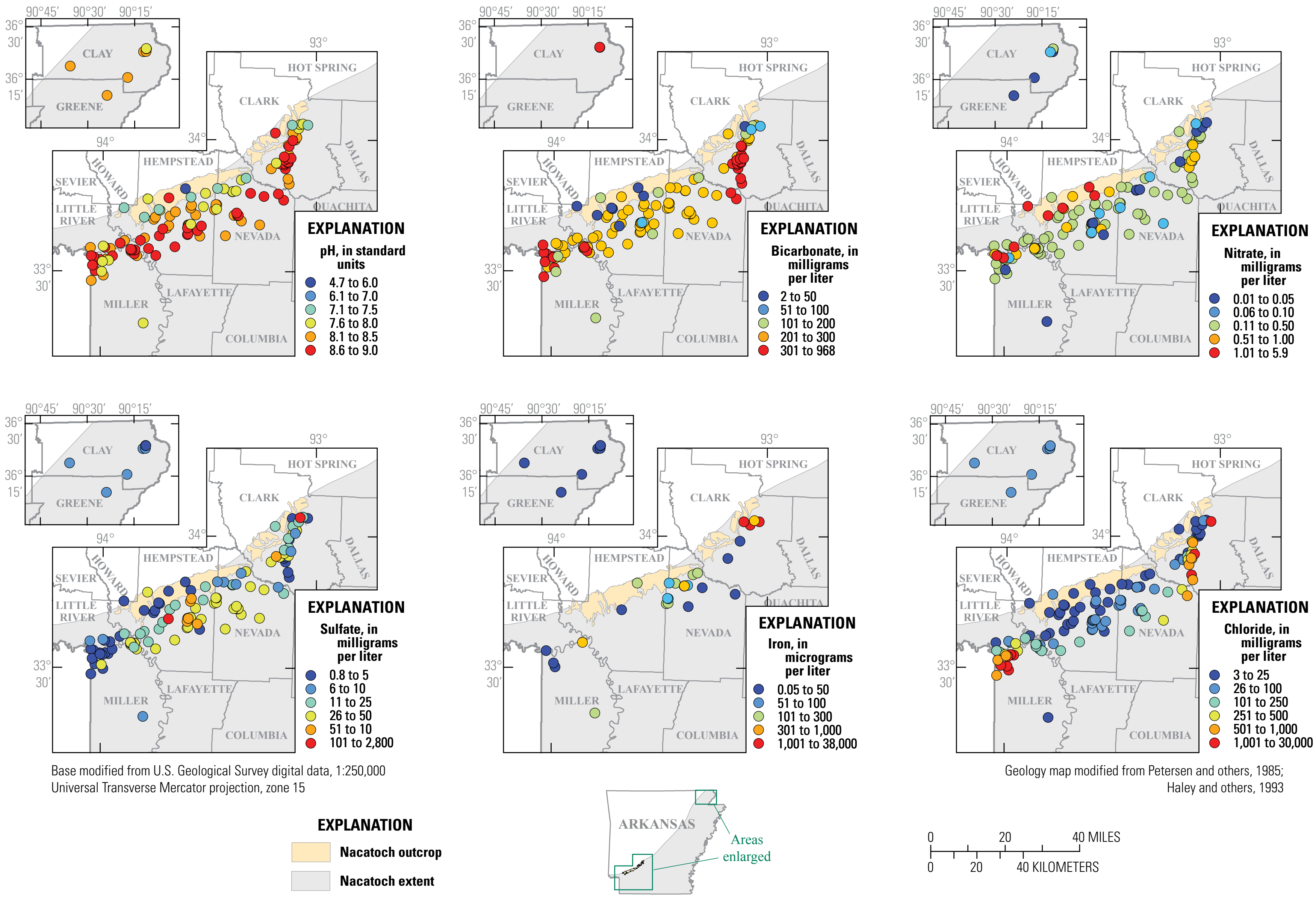


Figure 77. Spatial distribution of selected chemical constituents for groundwater from the Nacatoch aquifer in Arkansas.

Table 33. Descriptive statistics for selected chemical constituents in groundwater from the Nacatoch aquifer in Arkansas.

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

Constituent or characteristic	Minimum	Median	Maximum	Standard deviation	Number of wells
Calcium (mg/L)	1.0	17	2,100	438	40
Magnesium (mg/L)	0.1	3.1	570	97	40
Sodium (mg/L)	6.5	168	20,000	3,740	40
Potassium (mg/L)	0.8	3.0	119	27.5	40
Bicarbonate (mg/L)	2.0	260	968	118	123
Chloride (mg/L)	3.0	45	30,000	4,240	132
Sulfate (mg/L)	0.8	21	2,800	251	131
Silica (mg/L)	7.4	13	63	13.6	41
Nitrate (mg/L as nitrogen)	0.01	0.25	5.9	0.78	127
Dissolved solids (mg/L)	94	444	55,400	10,900	40
Iron (µg/L)	0.05	80	38,000	6,200	38
Manganese (µg/L)	0.13	10	1,800	382	21
Arsenic (µg/L)	0.03	0.52	1.0	0.48	6
Hardness (mg/L as calcium carbonate)	4.0	33	6,700	807	131
Specific conductance (µS/cm)	38	706	53,000	6,080	130
pH (standard units)	4.7	8.4	9.0	0.6	129

Rock/water interactions in the aquifer can change the major chemical composition and resulting water type along the groundwater-flow path. The exchange of calcium for sodium on solid exchange sites certainly is one of the most important processes affecting inorganic chemistry in aquifers of the Coastal Plain (Kresse and Fazio, 2002; Kresse and Clark, 2008; Kresse and others, 2012) Only 32 sites had sufficient data for calculating percent sodium of total cations in the Nacatoch aquifer. These data, however, were sufficient to note general trends in water type. Generally, sites with sodium less than 50 percent of the total cations, indicating a calcium-bicarbonate water type, were located in or less than about 1 mi from the outcrop area. Sites further downgradient had sodium percentages more than 50 percent and ranging upward to 99 percent (not shown on fig. 77).

Nitrate

Nitrate concentrations were extremely low in most samples from the Nacatoch aquifer. Nitrate concentrations ranged from 0.01 to 5.9 mg/L as nitrogen with a median of 0.25 mg/L (table 33). No concentrations exceeded the Federal MCL of 10.0 mg/L as nitrogen (U.S. Environmental Protection Agency, 2009). Out of 127 sites, 118 had nitrate concentrations less than 1.0 mg/L, of which 106 were less than 0.5 mg/L. The highest nitrate concentrations were in and near the outcrop area in the southwestern extent, with the lowest (less than 0.5 mg/L as nitrogen) occurring downgradient from the outcrop area (fig. 77). In the vicinity of the outcrop, well depths are shallower, and all nitrate concentrations greater than 2.0 mg/L occurred in wells with depths of 60 ft or less (fig. 78). All groundwater samples from the northeastern extent had nitrate concentrations less than 0.5 mg/L. Similar to other aquifers in the Coastal Plain, the highest nitrate concentrations tend to occur in and near the outcrop area. Well depths are shallow in these areas, and the aquifer is more vulnerable to surface (fertilizers, applied animal waste) and shallow subsurface (septic tanks) sources of nitrate.

Iron

Iron is ubiquitous in groundwater for aquifers throughout the State and can present problems for most uses. Groundwater from the Nacatoch aquifer, however, contained some of the lowest iron concentrations for any aquifer in the State. Iron concentrations ranged from 0.05 to 38,000 µg/L with a median of 80 µg/L (fig. 79; table 33). Only 8 of 38 samples had iron concentrations exceeding the secondary drinking-water regulation of 300 µg/L (U.S. Environmental Protection Agency, 2009). All samples from the northeastern extent (Clay and Greene Counties) had iron concentrations less than 50 µg/L. Most of the highest iron concentrations (ranging up to 7,400 µg/L) were in the extreme northeastern part of the outcrop area in Clark County (fig. 77), with the highest concentration of 38,000 µg/L from an unused oil-exploration well in Union County (not shown on map). Downgradient from the outcrop area, iron concentrations were generally less than 100 µg/L. Higher iron concentrations in and near the outcrop area were noted for other Cretaceous and Tertiary aquifers. Lower concentrations downgradient from outcrop areas were attributed to iron-sulfide mineralization as a dominant control on iron solubility (see sections on Sparta and Cockfield aquifers for detailed discussion).

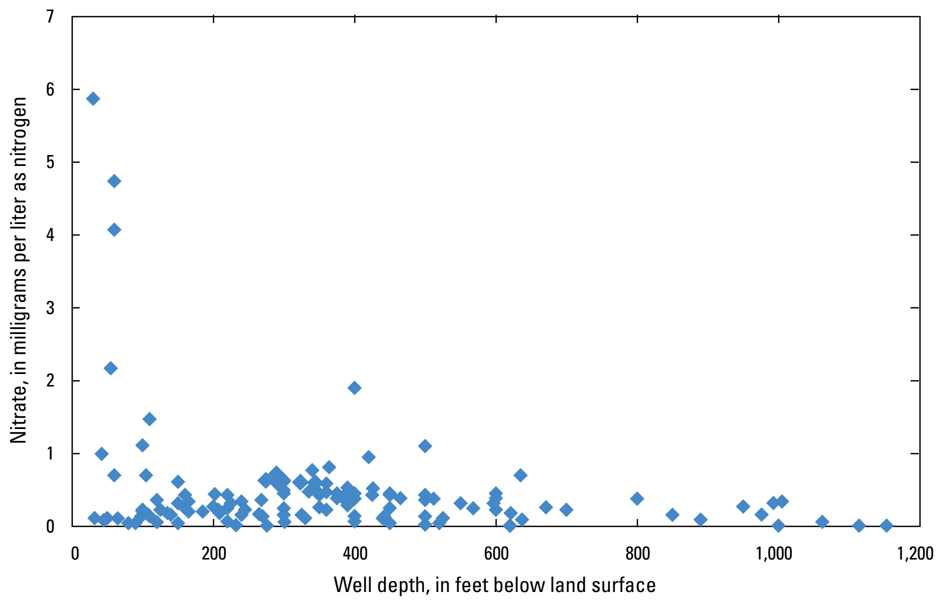


Figure 78. Relation of well depth and nitrate concentrations in groundwater from the Nacatoch aquifer in Arkansas.

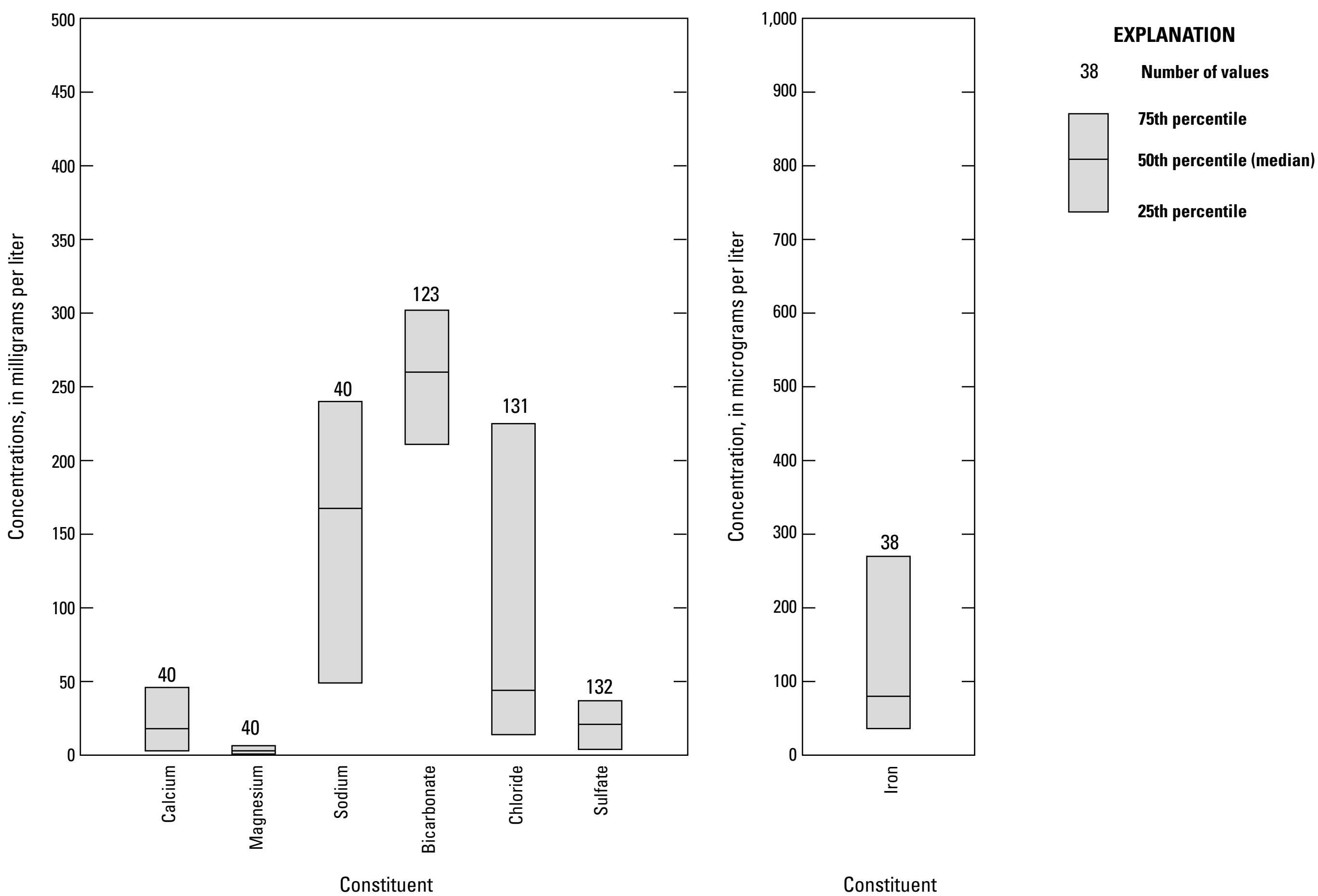


Figure 79. Interquartile range of selected chemical constituents in groundwater from the Nacatoch aquifer in Arkansas.

Sulfate

Earlier reports (Counts and others, 1955; Ludwig, 1972) noted the low concentrations of nitrate, iron, and sulfate concentrations in groundwater from the Nacatoch aquifer. Inspection of data compiled for this report confirmed these observations. Sulfate concentrations ranged from 0.8 to 2,800 mg/L with a median of 21 mg/L (fig. 79; table 33). Of 131 samples with sulfate concentration data, 118 (90 percent) were less than 50 mg/L, 55 (42 percent) were less than 10 mg/L, and 35 (27 percent) were less than 5 mg/L. Only three samples had sulfate concentrations greater than the secondary drinking-water regulation of 250 mg/L (U.S. Environmental Protection Agency, 2009). These three samples were (1) from unused oil-exploration wells in Union County (not shown on figures), (2) were not used as water-supply sources, and (3) were far removed from the outcrop area where high-salinity, high-dissolved-solids groundwater is known to occur. In and near the outcrop area, sulfate concentrations generally were less than 50 mg/L (fig. 77). The lowest concentrations (less than 5 mg/L) were from wells in the outcrop area and along the extreme eastern (Clark County) and western (Little River and Miller Counties) parts of the southwestern extent of the aquifer (regardless of proximity to outcrop area). This distribution was the inverse of that observed for bicarbonate concentrations, which were highest in the extreme eastern and western part of the outcrop area (fig. 77). In the central part of the outcrop area (Hempstead and Nevada Counties), sulfate concentrations generally were lowest and increased downgradient. Higher clay content and gypsum mineralization in the central part of the aquifer may account for the higher sulfate concentrations downgradient from the outcrop area. However, data on mineralogy, redox zonation, or other aquifer characteristics were not available to make definitive statements in regard to specific rock/water interaction that would explain occurrence and spatial distribution for sulfate or other constituents. All samples from wells in the northeastern extent had sulfate concentrations less than 10 mg/L.

Chloride

Increasing salinity downgradient from the outcrop area in the southwestern extent of the Nacatoch aquifer is documented in numerous earlier reports (Counts and others, 1955; Plebuch and Hines, 1969; Ludwig, 1973; Terry and others, 1986). Data collected for this report corroborate these earlier studies and reveal a strong spatial component to the occurrence and distribution of elevated chlorides. Although chloride concentrations generally increased downgradient from the outcrop area in Hempstead and Nevada Counties, the gradient is not as sharp as noted for sites in the southwestern and northeastern parts of the outcrop area (fig. 77). Groundwater in Hempstead and Nevada Counties has chloride concentrations that are below the secondary drinking-water regulation of 250 mg/L as far as 13 mi from the outcrop area. Thus, good-quality, low-salinity groundwater can be extracted in a much broader area in these counties. However, much sharper concentration gradients and higher concentrations are noted for groundwater from sites located in the western and eastern parts of the outcrop area. Chloride concentrations sharply increased in a southeasterly direction in Miller County from 355 mg/L, to 565 mg/L, and finally to 1,670 mg/L, all within a distance of 0.7 mi. In the eastern part of the outcrop area (Clark County), one well containing a chloride concentration of 7,560 mg/L was less than 0.8 mi from the outcrop area and less than 1.5 mi from a well containing a chloride concentration of only 10 mg/L.

Four exploratory wells in Union County contained chloride concentrations ranging from 3,500 to 30,000 mg/L. These wells were at a distance of approximately 60 mi from the outcrop area, where high salinity would be expected in the Nacatoch aquifer (not shown on fig. 77). Samples from all wells in the northeastern extent (Clay and Greene Counties) contained chloride concentrations less than 100 mg/L. One well located in Monroe County (not shown on fig. 77) was located in an area of high salinity that occupies a narrow band extending from Prairie County, through Monroe County, and into Lee County. This area was noted in past publications as containing high salinity that affected all Quaternary- and Tertiary-age aquifers (Stephenson and Criner, 1916; Counts, 1957; Halberg and Reed, 1964; Morris and Bush, 1986). See the section on Mississippi River Valley alluvial and Sparta aquifers for detailed information on this area of high salinity groundwater.

In summary, the Nacatoch aquifer is a viable and important source of water for parts of the southwestern and extreme northeastern parts of the State. In the southwestern extent, freshwater mainly is obtained from areas in or near to the outcrop area. This is especially true for the eastern and western parts of the outcrop area. Salinity increases in a downgradient direction from the outcrop area to a point where the groundwater is not suitable for most uses. Gradients of increasing chloride concentrations are sharpest in the western and eastern parts of the outcrop, with a larger area of freshwater downgradient from the outcrop area in the central part of the outcrop area. Concentrations of sulfate, iron, and nitrate generally are very low throughout the Nacatoch aquifer. Values for pH, bicarbonate, and sodium tend to increase downgradient from the outcrop area as a result of mineral dissolution coupled to cation exchange.

Ozan Aquifer

The Cretaceous-age Ozan Formation comprises an aquifer that is used in isolated parts of southwestern Arkansas. This aquifer is not listed in any regional reports, is one of the least-used aquifers, and contains some of the poorest-quality groundwater of any aquifer in the State. For purposes of this report, the saturated part of the Ozan Formation will be referred to hereinafter as the “Ozan aquifer.”

Hydrogeologic Setting

The Ozan Formation is a mixed limey, clayey, and primarily sand unit that ranges in thickness from 0 to about 200 ft thick. The Ozan unconformably overlies the Brownstone Marl and grades conformably into the Annona Chalk above (Dane, 1929; Boswell and others, 1965). The formation is difficult to differentiate from the underlying Brownstone Marl but in some areas can be distinguished by a glauconitic sand bed (known as the Buckrange sand lentil) at the base of the formation or by a common occurrence of smooth, convex oyster shells (Dane, 1929; Counts and others, 1955; Plebuch and Hines, 1969). The upper part of the Ozan consists of gray sandy marl with a few beds of sand and sandy limestone. The formation changes facies from a sandy clay and marl to a chalk and marl in Little River County (Counts and others, 1955).

A considerable change in sea depth occurred in Arkansas following the Lower Cretaceous. While Lower Cretaceous units in Arkansas dominantly were nearshore deposits, deepening water resulted in more clayey and carboniferous sediments being deposited during the Upper Cretaceous (Veatch, 1906), resulting in the formation of mainly marls and chalks. The base of the Ozan shows evidence of nearly continuous, very slow deposition, indicating a period of nondeposition as an explanation of the unconformity at the base. The upper part of the Ozan indicates increased sediment supply, as evidenced by the increased sand content and micaceous nature of the sediment.

The Ozan Formation outcrop extends from northeastern Clark County towards the southwest into Oklahoma. The outcrop is from 1 to 4 mi wide and is covered by terrace and alluvial deposits through large areas (Boswell and others, 1965). From central Union County eastward, the sand content and thickness increase rapidly, indicating an approach to the sea strand line and the presence of a sedimentary trough (Dollof and others, 1967). While the extent is limited, an equivalent of the formation does appear at depth in northeastern Arkansas. In this area, the formation ranges up to 150 ft thick and consists of a dark-gray, silty to sandy, micaceous, calcareous marl with shale layers.

Hydrologic Characteristics

Hydrologic data for the Ozan aquifer are limited because of its lack of importance as a regional water supply. Most wells completed in the Ozan are used for domestic water supply (Boswell and others, 1965). Aquifer yields are limited, and the water is highly mineralized. Most producing wells are located in Clark County (Counts and others, 1955), and some of these were listed as flowing artesian wells (Plebuch and Hines, 1969); however, most of these wells are no longer flowing, possibly because of decades of unrestricted flow. A few wells are completed in Hempstead and Sevier Counties, but the water in these counties is not suitable for drinking. A flowing artesian well yielding approximately 1 gal/min was noted in Sevier County (Counts and others, 1955). The Ozan dominantly receives recharge in the outcrop area.

Zachry and others (1986) investigated the potential of injecting wastewaters from petroleum exploration into Cretaceous aquifers in southern Arkansas, demonstrating the poor water quality in this area. They concluded that the variability of sand thickness and sand distribution prevented confident prediction of lateral movement of water within the Nacatoch, Ozan, and Tokio Formations. Vertical movement towards Tertiary aquifers was projected to be slow or nonexistent. Fractures were hypothesized to provide for enhancement of potential lateral movement of water within the formation but would have little influence on vertical movement into Tertiary aquifers as a result of the characteristics of the confining units.

Water Use

Eleven domestic wells were recorded in Clark County, and 2 other wells were recorded in Hempstead and Sevier County, but their use was restricted because of high chloride concentrations (Counts and others, 1955; Boswell, 1965). Plebuch and Hines (1969) estimated that 0.13 Mgal/d was withdrawn from the Ozan aquifer in Clark County in 1965. Water-use data for the Ozan are only available from 1965 to 1980 (table 34), and no use has been reported for this aquifer thereafter.

Water Quality

Wells completed in the Ozan aquifer occur dominantly in the outcrop area, which extends along an extremely narrow band extending from western Little River County (near the State border) through northeastern Clark County. The Ozan contains some of the poorest quality water of any of the aquifers in the Coastal Plain. Limited use of groundwater from the Ozan has been cited in several reports. Plebuch and Hines (1969) noted that the aquifer generally contained groundwater with dissolved-solids concentrations of more than 1,000 mg/L in Clark County and was used only because no other water source was available. Counts and others (1955) noted that the aquifer yielded only small amounts of highly mineralized water for domestic purposes, although

Table 34. Water use from the Ozan aquifer in southwestern Arkansas, 1965–80.

[Data from Halberg and Stephens (1966); Halberg (1972, 1977); Holland (1981). Only counties with published data for consumption of groundwater from the Ozan aquifer are shown]

County	1965	1970	1975	1980
Clark	0.13	0.15	0.19	0.52

noting that some of the water was not suitable for even that purpose. Boswell and others (1965) reported that even groundwater from the Ozan outcrop area contained dissolved-solids concentrations of more than 1,000 mg/L and that it was an important aquifer only in Clark County because no other water source was present.

As a consequence of limited use, the Ozan aquifer has received limited attention in terms of aquifer characterization and documentation of water quality. Older reports contain sparse water-quality information, and most of this information is related to salinity problems. Counts and others (1955) reported chloride concentrations ranging from 32 to 2,100 mg/L in the Ozan aquifer. One well in Sevier County was reported as containing a chloride concentration of 1,100 mg/L and was not used at the time of sampling. Only wells in Hempstead County yielded less mineralized water, containing dissolved-solids concentrations from 400 to 500 mg/L (Counts and others, 1955). Boswell and others (1965) calculated dissolved-solids concentrations from specific conductance values and cited a range from 600 to greater than 4,000 mg/L.

General Geochemistry and Water Type

Only 14 sites had water-quality data from the Ozan aquifer. These data dominantly included major anions (bicarbonate, chloride, sulfate), nitrate, and field parameters including pH and specific conductance; only 2 wells contained information related to major cations (calcium, magnesium, sodium, potassium). Thus, no meaningful analysis can be made with regard to water type. However, certain assumptions can be made in regard to the evolution of geochemistry with existing data, and these are discussed further in "Conceptual Model of Groundwater Geochemical Evolution" at the end of this section.

Values of pH ranged from 6.8 to 8.6 with a median of 8.3 (table 35). All pH values except one were greater than 7.5. No trends were noted in the spatial distribution of pH, except that the highest values tend to occur in the eastern part of the aquifer in Clark County (fig. 80). Generally, areas of higher pH correlated to areas of higher bicarbonate concentrations, indicating dissolution of carbonate minerals as a primary catalyst for buffering the low pH of rainwater and increasing pH. However, the distribution and concentrations of other anions indicate additional rock/water reactions and possible mixing with other water sources to explain the evolution of groundwater geochemistry. For instance, several sites with low bicarbonate concentrations were in the extreme eastern extent of the aquifer in Clark County, but samples from these wells exhibit some of the highest pH values and highest sulfate concentrations (fig. 80). Further discussion on the occurrence and distribution of the major anions is found below.

Nitrate

Nitrate concentrations ranged from 0.02 to 1.9 mg/L as nitrogen with a median of 0.43 mg/L (table 35). All concentrations were below the MCL of 10 mg/L. Insufficient data were available to assess any relations of nitrate with depth. However, wells with nitrate concentrations exceeding 0.5 mg/L were less than 200 ft below the land surface. Well depths ranged up to 380 ft.

Table 35. Descriptive statistics for selected chemical constituents in groundwater from the Ozan aquifer in southwestern Arkansas.

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

Constituent or characteristic	Minimum	Median	Maximum	Standard deviation	Number of wells
Calcium (mg/L)	0.8	3.4	6.0	2.6	2
Magnesium (mg/L)	0.35	1.32	2.3	0.97	2
Sodium (mg/L)	33.6	477	920	443	2
Potassium (mg/L)	1.62	2.21	2.8	0.59	2
Bicarbonate (mg/L)	96	261	560	154	14
Chloride (mg/L)	5.3	479	2,100	771	14
Sulfate (mg/L)	4.9	230	517	151	14
Silica (mg/L)	11.1	12.1	13	0.95	2
Nitrate (mg/L as nitrogen)	0.02	0.43	1.9	0.54	12
Dissolved solids (mg/L)	136	1,230	2,330	1,090	2
Iron (µg/L)	20	600	1,180	580	2
Manganese (µg/L)	19.8	19.8	19.8	0.13	1
Arsenic (µg/L)	0.03	0.03	0.03	0.03	1
Hardness (mg/L as calcium carbonate)	6.0	98	400	128	13
Specific conductance (µS/cm)	213	2,550	7,200	2,370	14
pH (standard units)	6.8	8.3	8.6	0.4	14

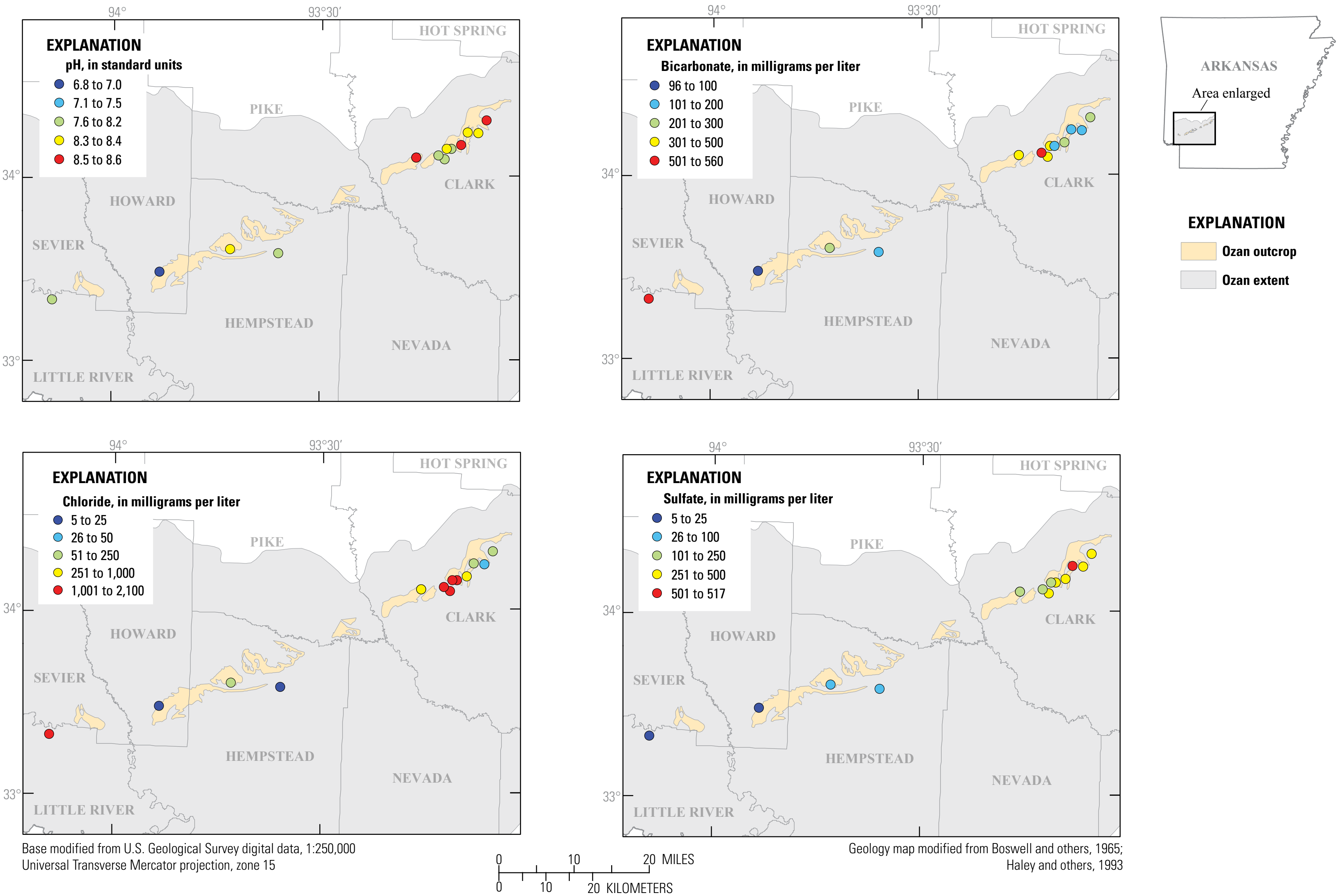


Figure 80. Spatial distribution of selected chemical constituents in groundwater from the Ozan aquifer in southwestern Arkansas.

Iron

Only two wells had iron analyses, with concentrations of 20 and 1,180 µg/L. These two samples reveal that iron concentrations vary widely, similar to other Cretaceous and Tertiary aquifers of the Coastal Plain. Typically, iron concentrations in Coastal Plain aquifers tend to be higher in the outcrop area and decrease downgradient. This is attributed to increasing reducing conditions and formation of iron-sulfide minerals along the flow path. However, data were inadequate to make any assessment of the spatial distribution of iron for the Ozan aquifer.

Sulfate

Sulfate concentrations ranged from 4.9 to 517 mg/L with a median of 230 mg/L, which is the highest median sulfate concentration of any aquifer in the State (fig. 81; table 35). However, groundwater from the Jackson Group (table 21) contained the overall highest sulfate concentrations of any aquifer. A general relation was observed between sulfate and bicarbonate concentrations. Four wells had sulfate concentrations greater than 300 mg/L (ranging upward to 517 mg/L) with associated bicarbonate concentrations that were less than 300 mg/L. Conversely, five wells had sulfate concentrations less than 300 mg/L and associated bicarbonate concentrations that were greater than 400 mg/L (upward to 542 mg/L) (fig. 82*A*).

Chloride

Chloride concentrations ranged from 5.3 to 2,100 mg/L with a median of 479 mg/L (fig. 81; table 35). Chloride exceeded the Federal secondary drinking-water regulation of 250 mg/L (U.S. Environmental Protection Agency, 2009) dominantly at sites located in central Clark County with the exception of one site located in northeastern Little River County that had a chloride concentration of 1,100 mg/L (fig. 80). Six wells with chloride concentrations

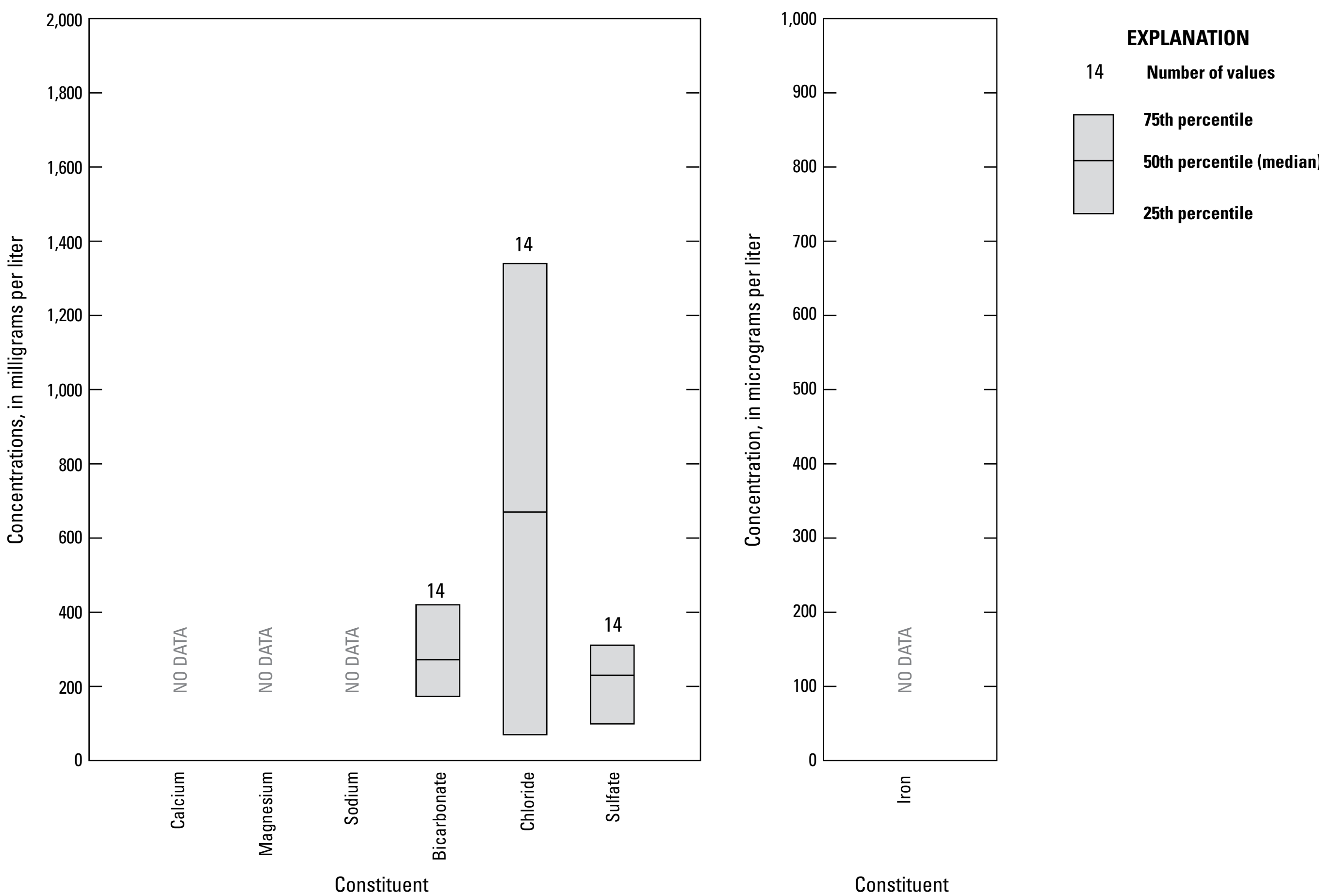


Figure 81. Interquartile range of selected chemical constituents in groundwater from the Ozan aquifer in southwestern Arkansas.

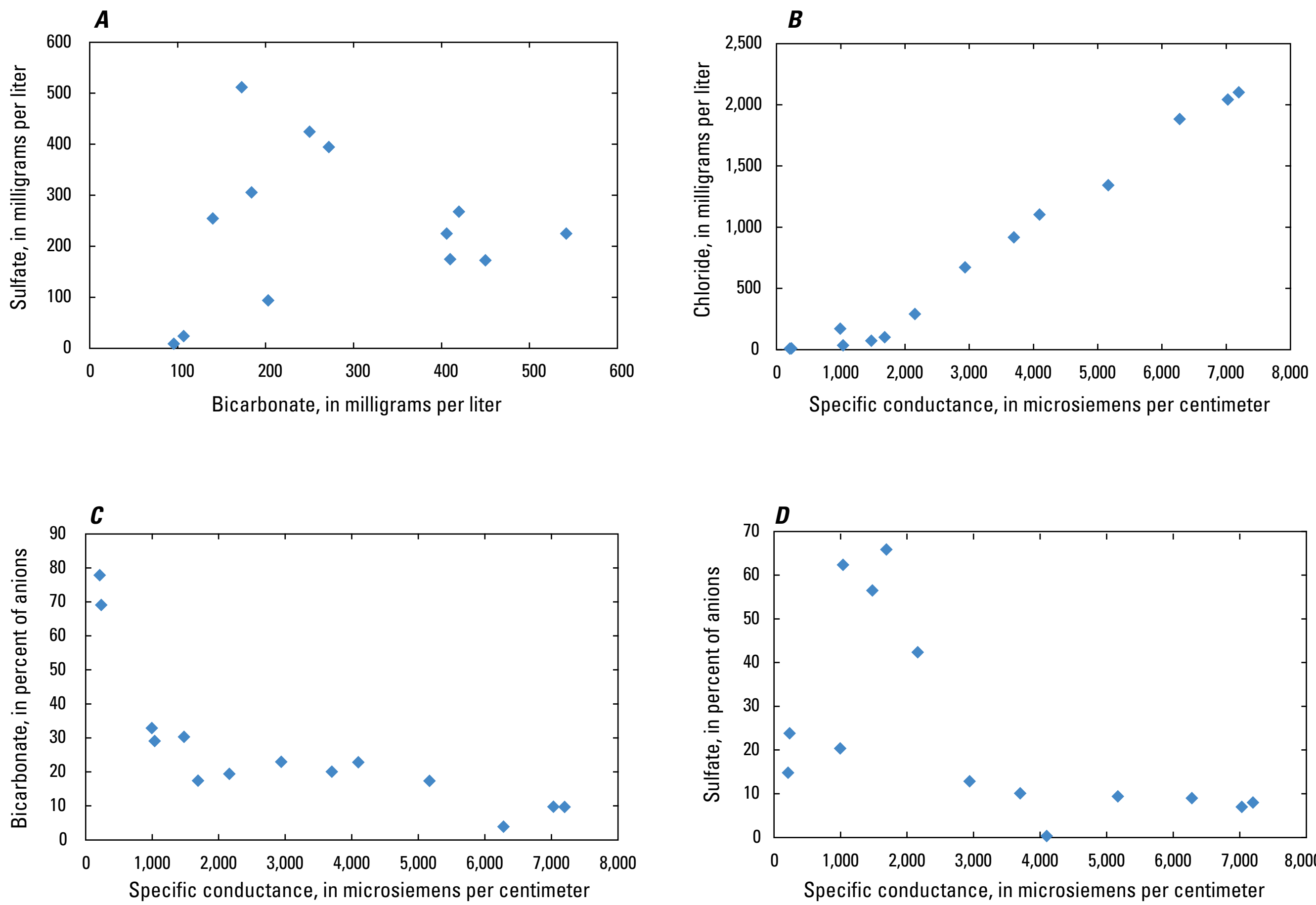


Figure 82. Relation of *A*, bicarbonate and sulfate; relation of specific conductance and *B*, chloride; *C*, percent bicarbonate; and *D*, percent sulfate in groundwater from the Ozan aquifer in southwestern Arkansas.

exceeding 250 mg/L in Clark County ranged in depth from 150 to 360 ft. These were located in the outcrop area, and the depths are relatively shallow compared to other high-chloride occurrences in Cretaceous and Tertiary aquifers in southwestern Arkansas. Because the outcrop generally represents the area of recharge and shallow well depths, flushing of residual salinity would normally occur resulting in lower chloride concentrations. Other Cretaceous formations generally contained freshwater in and near the outcrop with higher salinity occurring downgradient. No mechanisms for the cause of high chloride were provided in older reports. The authors also cannot provide mechanisms confidently because of the lack of information for this unusual occurrence. Counts and others (1955) noted the low well yields from a dominant sandy-clay facies of the Ozan in the area of outcrop, and one plausible explanation for elevated chloride concentrations may be that residual connate water in the high percentage clayey deposits of the Ozan Formation have not been sufficiently flushed over time. Another possible explanation is that elevated chloride concentrations result from the upwelling of high-salinity groundwater from underlying formations.

Conceptual Model of Groundwater Geochemical Evolution

Although only two samples had analysis of dissolved solids, all samples had field specific conductance, which is a reasonable proxy for assessing changes in constituent concentrations with increased residence time in the aquifer. Specific conductance and chloride show a positive linear relation when specific conductance values exceed 2,000 µS/cm (fig. 82*B*). Analysis of the geochemical data shows that bicarbonate or sulfate is the dominant anion (by weight) for specific conductance values less than approximately 2,000 µS/cm. Therefore, certain assumptions can be made in regard to geochemical evolution of groundwater in the Ozan aquifer based on extensive review of other aquifers in the Coastal Plain.

Groundwater from the Ozan aquifer appears to be dominated by bicarbonate in the early stages along the groundwater flow path with short residence time within the aquifer. This is reflected in two samples with bicarbonate greater than 50 percent of anions and values of specific conductance less than 1,000 µS/cm (fig. 82*C*). A sharply decreasing trend is noted for percent bicarbonate when specific conductance is greater than 1,000 µS/cm. Therefore, this fits the model of early-stage carbonate-mineral dissolution observed for many aquifers of the State. This model typically results in a calcium-bicarbonate to sodium-bicarbonate water type with increased carbonate dissolution and cation exchange. For samples with specific conductance values between approximately 1,000 and 2,200 µS/cm, sulfate is the dominant anion (fig. 82*D*). Groundwater with higher sulfate than bicarbonate concentrations is theorized to be derived from dedolomitization processes in the aquifer, in which gypsum dissolution leads to calcite precipitation (see sections on Tokio and Trinity aquifers). Groundwater with specific conductance values exceeding approximately 2,200 µS/cm has chloride as the dominant anion (ranging from 64 to 87 percent of total anions). Chloride additionally exhibits a positive linear relation with specific conductance for specific conductance values greater than 2,200 µS/cm (fig. 82*B*). The increasing chloride concentration may result from dissolution of residual salts (or saline water) that have not been flushed from the original marine deposits or from leakage of high-salinity water from underlying formations. Thus, one model of geochemical evolution of groundwater in the Ozan aquifer is carbonate dissolution in the early phases resulting in a bicarbonate water type, transitioning to a sulfate-dominated water type with dissolution of gypsum, and eventually to a chloride water type by mixing with high-salinity water. Groundwater with elevated chloride concentrations would be expected to contain elevated sodium (sodium-chloride type water), which is a concern for consumptive use (U.S. Environmental Protection Agency, 2009). One groundwater sample contained chloride and sodium concentrations of 1,100 mg/L and 920 mg/L, respectively, which may be a problem for individuals with a restricted sodium diet.

In summary, groundwater from the Ozan aquifer is some of the least used and poorest quality water in the State. Several reports mentioned that use of the aquifer as a domestic source was predicated on the fact that no other water source was available. High chloride concentrations occur in groundwater within the outcrop area of the Ozan aquifer, which is atypical of most Cretaceous and Tertiary aquifers of the Coastal Plain. Elevated sulfate concentrations and pH from wells located in the northeastern extent are attributed to possible gypsum dissolution coupled to calcite precipitation.

Tokio Aquifer

Cretaceous formations in Arkansas (Nacatoch Sand, Ozan Formation, Tokio Formation, and the Trinity Group) and the aquifers comprised by these formations are not included in any of the regional hydrogeologic framework models of the Mississippi embayment (Arthur and Taylor, 1990; Hosman and Weiss, 1991; Hart and others, 2008; Clark and Hart, 2009); however, the Tokio was included in the hydrologic investigations atlas for Segment 5 (Arkansas, Louisiana, and Mississippi) of Renken (1998) as the Tokio-Woodbine aquifer. The aquifer is referred to as the Tokio aquifer in various USGS water-use and water-level reports referenced herein; the most recent being Holland (2007) and Schrader and Rodgers (2013). This report will follow this terminology and for purpose of this report, the saturated part of the Tokio Formation yielding groundwater to wells in Arkansas will be referred to hereinafter as the “Tokio aquifer.”

Geology

The Tokio Formation is a Cretaceous-age, clastic formation primarily comprising sand and gravel units with interbedded clay and marl, ranging in thickness from 50 to more than 300 ft (Boswell and others, 1965). The Tokio Formation initially was included with strata named as the Bingen Sand by Hill (1888). Stephenson (1927) divided the Bingen Sand into the Tokio Formation and the Woodbine Formation, discarding the term Bingen Sand. During the Cretaceous age, a considerable change of sea depth occurred in Arkansas after deposition of the Lower Cretaceous formations. While deepening water resulted in more clayey and carboniferous rocks being deposited during the Upper Cretaceous, Lower Cretaceous units in Arkansas, including the Tokio Formation, mainly were nearshore deposits (Veatch, 1906).

The Tokio Formation unconformably overlies consolidated rocks of Mississippian and Pennsylvanian age in Clark and northeastern Nevada Counties (Plebuch and Hines, 1969); overlies the Trinity Group in Pike, Nevada, Miller, and most of Hempstead Counties (Petersen and others, 1985); and overlies the Woodbine Formation in Little River, Sevier, Howard, and northwestern Hempstead Counties (Boswell and others, 1965). The Tokio is overlain by the Brownstown Marl, although in an area of Union County, the Brownstone Marl is absent and the Tokio is overlain by the Ozan Formation (Boswell and others, 1965; Zachry and others, 1986). The formation outcrops from Clark County southwestward to Sevier County and attains a maximum width of about 10 mi in Howard County (Schrader and Blackstock, 2010). The Tokio consists of discontinuous, interbedded gray clay and poorly sorted crossbedded sands, lignite, and scattered carbonaceous materials. In some areas, there is a prominent basal gravel (Counts and others, 1955; Boswell and others, 1965; Dollof and others, 1967; Plebuch and Hines, 1969; Petersen and others, 1985).

The Tokio Formation dips at about 60 ft/mi to the southeast away from the outcrop and ranges in thickness from 50 to more than 300 ft (Boswell and others, 1965), obtaining its maximum thickness in Miller County (Dollof and others, 1967). A fault zone through the Tokio occurs across Miller, Little River, Lafayette, Hempstead, Nevada, Ouachita, Calhoun, and Bradley Counties (Petersen and others, 1985, pl. 8). Dane (1929) identified the Tokio as a nearshore marine deposit. The presence of lignite and terrestrial plant fossils indicates nearshore deposition. The basal gravel is interpreted as a beach deposit formed by a transgressing sea with the gravel mainly being reworked from older Cretaceous formations (Dane, 1929).

In southern Sevier County and parts of Howard and Hempstead Counties, the Tokio comprises three distinct aquifers, including a basal sand that grades to gravel to the east and two upper sands (Boswell and others, 1965). Toward the east, the clay layers separating the sands thin, and the sands merge into a single massive sand aquifer, which is prevalent over most of Hempstead, southern Pike, and northern Nevada Counties.

Hydrologic Characteristics

The Tokio aquifer receives direct recharge at its outcrop and from the overlying alluvial deposits where it subcrops (Boswell and others, 1965). At its outcrop, the Tokio weathers into a sandy soil, facilitating percolation of surface and rainwater into the sand (Counts and other, 1955). Well depths and yields vary throughout the aquifer. Ludwig (1972) listed well depths ranging from less than 30 ft to 1,200 ft below land surface for parts of Hempstead, Lafayette, and Little River Counties. Most wells in the Tokio have low yields, but some produce 150–300 gal/min. Many are flowing artesian wells that typically produce less than 20 gal/min. The Tokio is the most important source of water from flowing artesian wells in southwestern Arkansas. Wells in central Hempstead County yield as much as 300 gal/min. Wells flowing at rates as much as 90 gal/min occur adjacent to streams (Counts and others, 1955). Wells in northwestern Little River County penetrated a 15- to 20-ft thick, water-bearing sand that produced yields of less than 10 gal/min (Ludwig, 1973). The prevalence of artesian wells in the Tokio indicates that the aquifer is confined away from the outcrop and the potentiometric surface is above land surface. An aquifer test in southern Howard County resulted in a transmissivity of about 170 ft^2/d and a storage coefficient of 0.000044. A test using a public-supply well in Hempstead County resulted in a transmissivity of about 600 ft^2/d (Boswell and others, 1965).

Water Use

The Tokio aquifer dominantly has been used as a source of domestic water supply. Counts and others (1955) recorded 143 domestic wells in the Tokio aquifer in Clark, Hempstead, Howard, Nevada, Pike, and Sevier Counties in southwestern Arkansas. Many of these wells originally were flowing. An estimated 66 percent of water was lost from the total 3 Mgal/d that was withdrawn in southwestern Arkansas as a result of uncontrolled flowing artesian wells (Boswell and others, 1965). Domestic-supply and livestock use continued into the late 1960s and early 1970s in Clark County and northwestern Little River County near Winthrop (Plebuch and Hines, 1969; Ludwig, 1973). For 2010, there were 18 wells registered in ARWUDBS from the Tokio (fig. 83). Current (2013) use is for domestic purposes in Hempstead County and for livestock purposes in Howard County.

Several towns in southwestern Arkansas have used the Tokio aquifer for public supply. Hope (Hempstead County) tapped the aquifer in 1918 (Hale and others, 1947). Hope drilled additional wells into the Nacatoch aquifer in 1933 (Hale and others, 1947). The city continues to use groundwater from this and the Nacatoch aquifers but supplements with surface water. Hope withdrew 1.83 Mgal/d, which was 64 percent of its total public-supply use from this aquifer in 2010 (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Other small communities in the area including Okolona (Clark County), Mineral Springs (Howard County), Blevins (Hempstead County), and Ben Lomond (Sevier County) tap the Tokio for public supply. Prescott (Nevada County) formerly had one well in the Tokio, which was completed in 1912, and two wells in the Nacatoch (Counts and others, 1955) but now solely withdraws water from the Little Missouri River. Also, wells historically were used at several schools in the area (Counts and others, 1955).

A small amount of industrial use, including gas production near Prescott, a cement company in Howard County, and a handful of lumber operations occurred in the past (Counts and others, 1955). Current industrial use of the aquifer only occurs in Miller County (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

Historical use of the Tokio aquifer by county is listed in table 36. Use of groundwater from the aquifer increased about 200 percent from 1965 to 1980 (fig. 84), the peak year for use of water from the aquifer. Use decreased from 1980 to 1995 and then jumped to a second high in 2000. Since 2000, water use from the Tokio has declined. Approximately 73 percent of water used from the Tokio aquifer is for public supply, 7 percent for industrial use, and the remainder for domestic and livestock uses (Terrance W. Holland, U.S. Geological Survey, written commun., 2012).

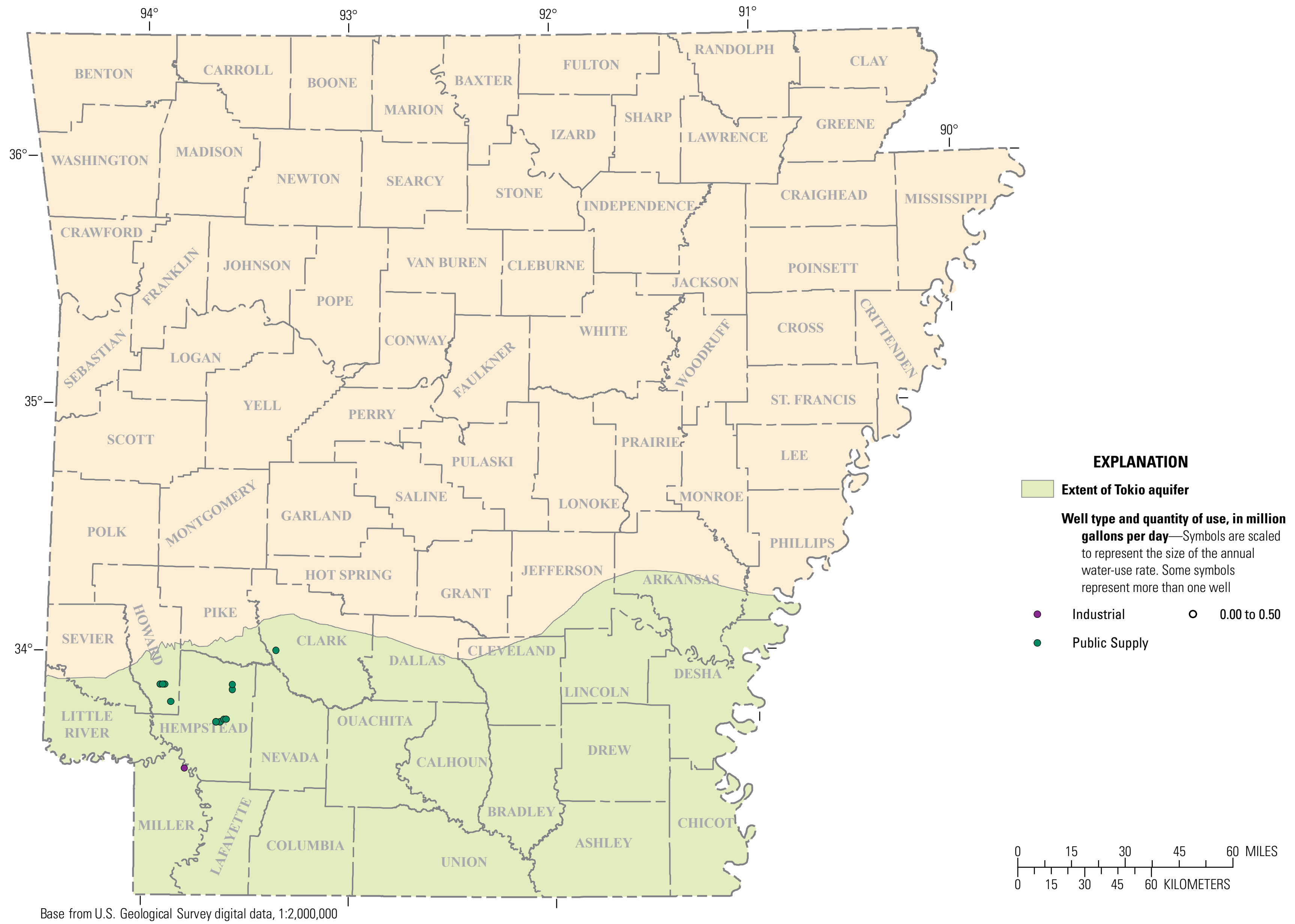


Figure 83. Wells with reported water use for the Tokio aquifer in Arkansas, 2010.

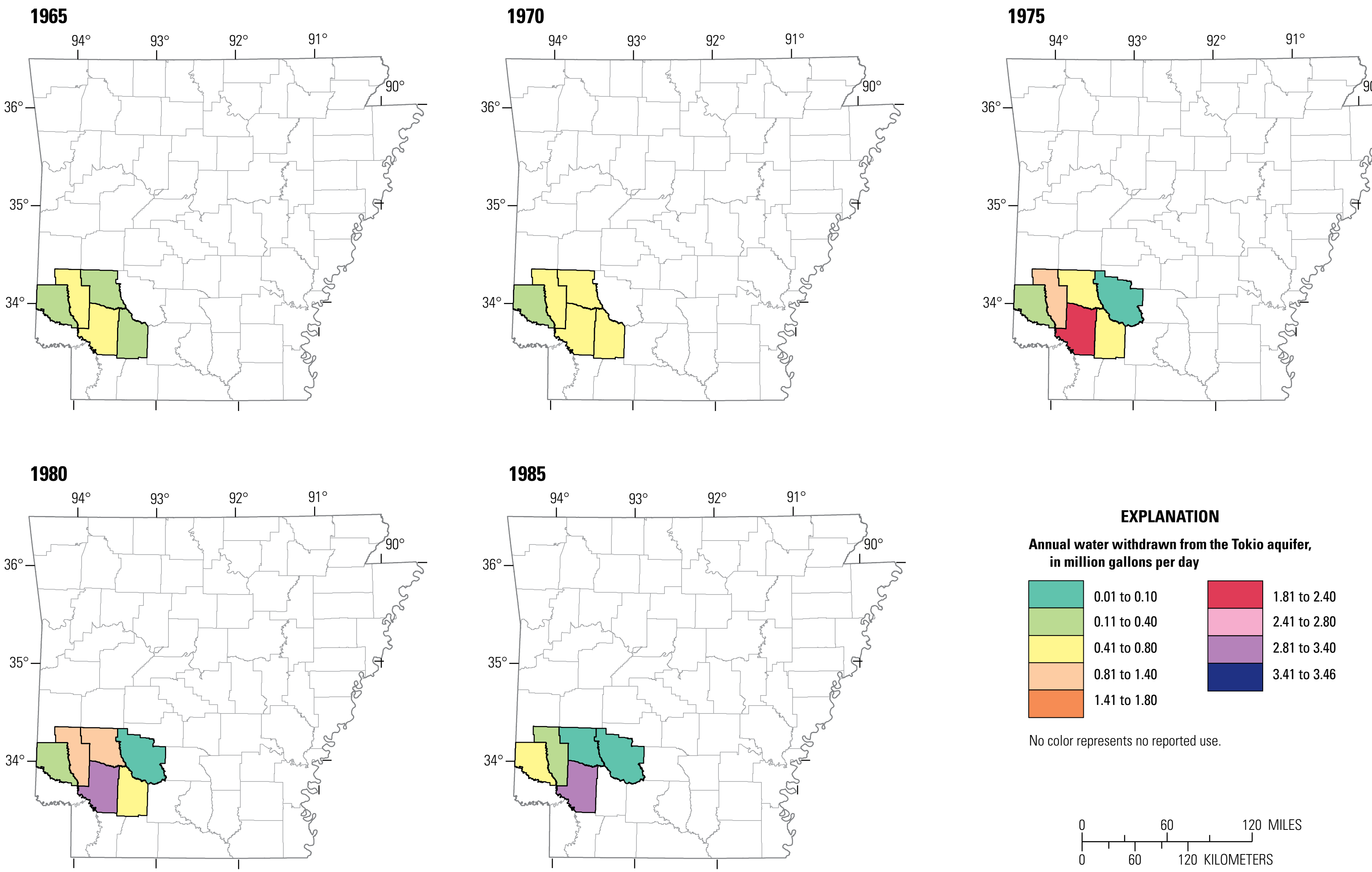
Table 36. Water use from the Tokio aquifer in Arkansas, 1965–2010.

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

County	1965	1970	1975	1980	1985	1990	1995	2000	2005	2010
Clark	0.00	0.00	0.02	0.06	0.04	0.01	0.01	[1]0.06	0.07	0.06
Hempstead	0.67	0.68	2.15	3.00	2.86	1.10	1.66	3.46	2.10	2.12
Howard	0.69	0.62	0.97	1.11	0.14	0.00	0.00	[1]0.06	0.50	0.54
Miller	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15
Nevada	0.37	0.47	0.55	0.68	0.00	0.00	0.00	0.00	0.00	0.00
Pike	0.12	0.41	0.43	0.82	0.06	0.03	0.02	0.00	0.00	0.00
Sevier	0.15	0.17	0.25	0.35	0.79	1.15	0.54	2.36	1.73	0.00
Total	**2.00**	**2.35**	**4.37**	**6.02**	**3.89**	**2.29**	**2.23**	[1]**5.94**	[2]**4.40**	**2.87**

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

[2]In the 2005 report, 0.08 million gallons per day in Sharp County was inadvertently reported as being withdrawn from the Tokio aquifer when it should have been applied to the Everton Formation. Therefore, the published total is slightly different from Holland (2007).



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

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

Figure 84. Water-use rates for the Tokio aquifer in Arkansas from 1965 to 2010.

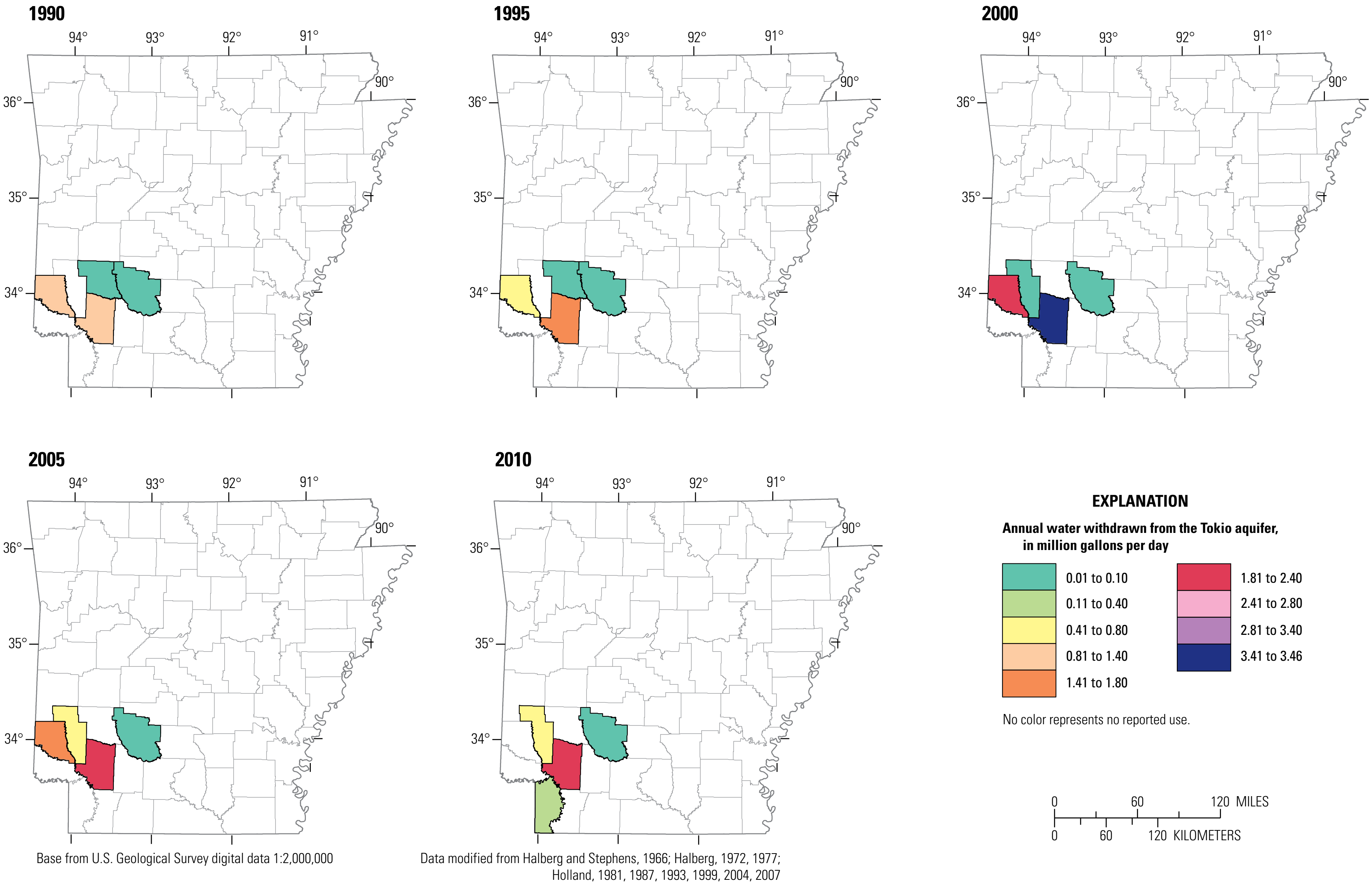


Figure 84. Water-use rates for the Tokio aquifer in Arkansas from 1965 to 2010.—Continued

Water Levels

Long-term ANRC and USGS cooperative monitoring has documented water-level changes in the Tokio aquifer (Schrader, 1998, 1999, 2007b; Schrader and Scheiderer, 2004; Schrader and Blackstock, 2010; Schrader and Rogers, 2013). The potentiometric surface for the Tokio aquifer is highest within the outcrop area in northeastern Howard County (fig. 85), with groundwater flowing to the south and primarily southeast (Counts and others, 1955; Boswell and others, 1965; Plebuch and Hines, 1969; Petersen and others; 1985; Schrader and Blackstock, 2010; Schrader and Rodgers, 2013). No appreciable changes in water levels were noted between the 1996, 1999, and 2001 investigations (Schrader and Scheiderer, 2004), but the addition of a single well changed the position of the 300-ft contour in Howard County for the 2008 potentiometric-surface map (Schrader and Blackstock, 2010). A cone of depression in southern Howard County appeared in the 2011 potentiometric surface (fig. 85). Many reports cite the possibility of a cone of depression forming 5 mi northwest of Hope; however, data are insufficient in the southern part of the study area to confirm this situation (Schrader, 2007; Schrader and Blackstock, 2010; Schrader and Rodgers, 2013). Ludwig (1973) previously reported that large withdrawals from Prescott and Hope did not appear to affect the potentiometric surface between 1950 and 1968.

Water levels in well A (figs. 85 and 86) near the possible cone of depression northwest of Hope have declined with increasing use. A large decline was documented between 1990 and 2000, when water use increased from 1.10 Mgal/d to 3.46 Mgal/d in Hempstead County, a 215-percent increase. Water levels additionally appear to have slowly declined at Prescott; water-level changes in well B previously have been associated with changes in water use in Nevada County. Water levels near the outcrop and artesian-flow areas have remained relatively constant since the 1950s (well C in northeastern Hempstead County and well D in southwestern Howard County; figs. 85 and 86).

Water Quality

Similar to other Tertiary-age aquifers in southwestern Arkansas, water quality varies with flow direction as controlled by formation dips to the southeast. The Tokio aquifer crops out in a narrow band from southeastern Sevier through western Clark Counties with a small, isolated outcrop located in extreme western Little River County. Most producing wells are located within the larger outcrop belt. Chloride concentrations increased to the southeast in the downgradient (downdip) direction of groundwater flow (Counts and others, 1955; Plebuch and Hines, 1969; Ludwig, 1972). Counts and others (1955) stated that bicarbonate and sulfate were high, indicating a moderately high sodium-bicarbonate to sodium-sulfate water type. Plebuch and Hines (1969) and Ludwig (1973) listed groundwater from the Tokio as a soft to moderately hard, sodium-bicarbonate water type throughout most of its extent, except for areas of increased chloride concentration downgradient from the outcrop area. Iron concentrations were cited as being high in some areas, ranging up to 54 mg/L (Counts and others, 1955; Ludwig, 1972).

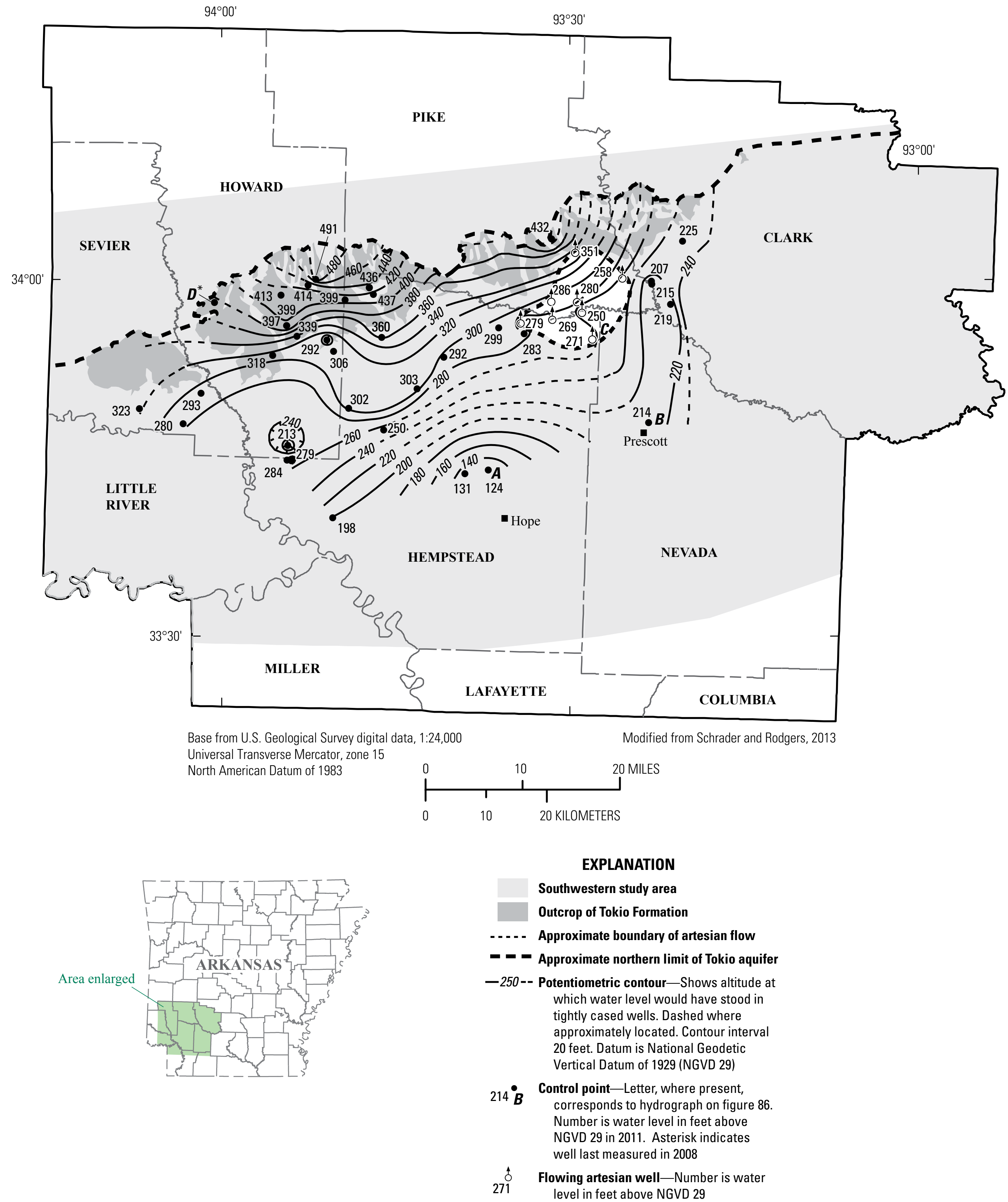


Figure 85. Potentiometric surface of the Tokio aquifer in Arkansas, spring 2011.

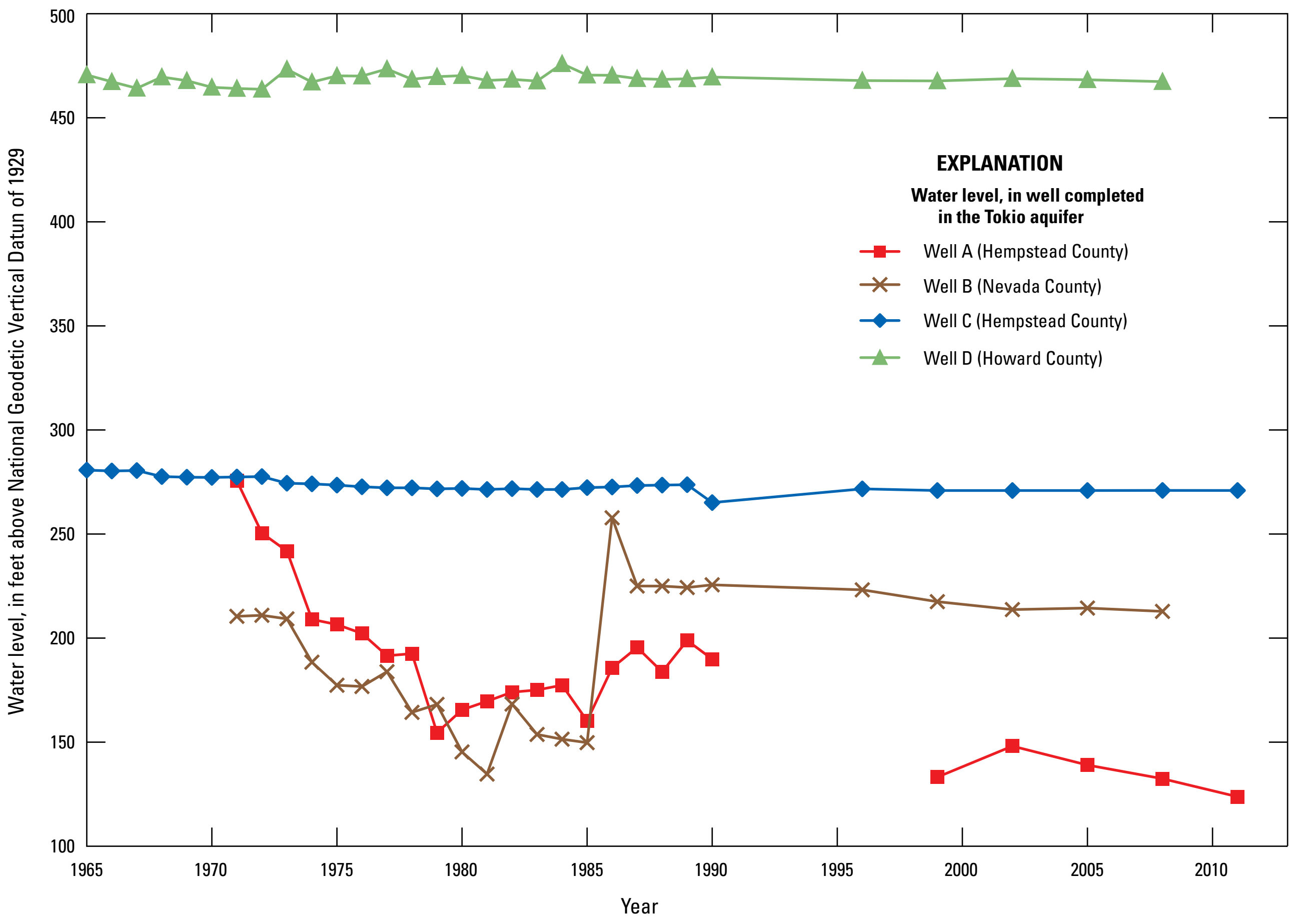


Figure 86. Hydrographs of water levels in wells completed in the Tokio aquifer in Arkansas.

General Geochemistry and Water Type

Similar to other Cretaceous- and Tertiary-age aquifers reviewed in this report, pH values generally were lowest in the outcrop area, reflecting rainwater recharge values. Values of pH increased abruptly within short distances in the downgradient direction of flow as buffered by dissolution of aquifer carbonate minerals (fig. 87). Values of pH ranged from 5.4 to 9.1 standard units with a median of 8.3 (table 37). The median value demonstrates the high-pH characteristic of Tokio groundwater. Only 20 of 158 samples were less than 7.0, and 102 of the 158 samples were greater than 8.0. Values of pH were highest, greater than 8.5, in the southwestern and northeastern outcrop areas. In the southwestern part of the outcrop area, bicarbonate concentrations were very low, which is at odds with application of the carbonate buffering explanation of high pH mentioned earlier. In this area, sulfate was the dominant anion. Detailed discussion of sulfate geochemistry and explanation of high pH values in the southwestern area are found in the “Sulfate” section below.

Most Cretaceous and Tertiary aquifers have sodium as the dominant cation downgradient from their respective outcrop areas, and the Tokio aquifer follows this pattern. Only 29 samples had sufficient major cation data for calculating percent sodium of total cations (in milliequivalents per liter). Samples having percent sodium less than 50 percent of the total cations were from wells in the outcrop area at the origin of the groundwater flow path where groundwater is less geochemically evolved (fig. 87). At the beginning of the flow path, calcium is often the dominant cation, and cation-exchange processes have not appreciably affected groundwater chemistry. The exchange of calcium for sodium on solid-phase exchange sites increases sodium in solution at the expense of calcium, and groundwater transitions ultimately from a calcium- to a sodium-bicarbonate water type along a given flow path. Fifteen samples had greater than 90 percent sodium. All of these wells were located within 2–5 mi of the outcrop area except for one site located on the southern edge of the outcrop area in Howard County.

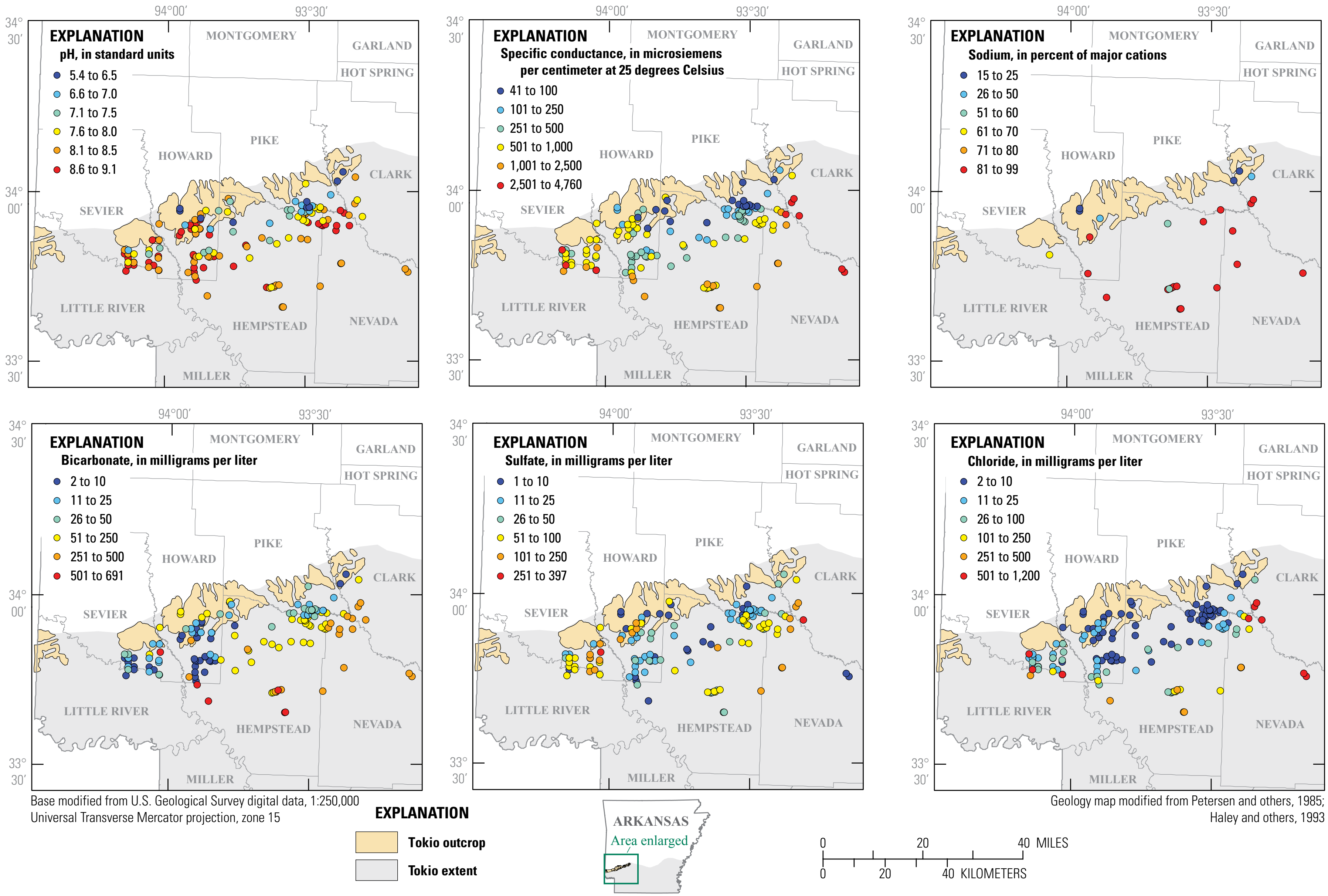


Figure 87. Spatial distribution of selected chemical constituents in groundwater from the Tokio aquifer in Arkansas.

Table 37. Descriptive statistics for selected chemical constituents in groundwater from the Tokio aquifer in Arkansas.

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

Constituent or characteristic	Minimum	Median	Maximum	Standard deviation	Number of wells
Calcium (mg/L)	0.7	5.3	66	14.8	29
Magnesium (mg/L)	0.07	1.2	9.2	1.95	29
Sodium (mg/L)	1.99	196	694	204	29
Potassium (mg/L)	0.7	2.62	29	5.3	28
Bicarbonate (mg/L)	2.0	27	691	152	156
Chloride (mg/L)	2.3	11	1,200	205	159
Sulfate (mg/L)	1.0	31	397	59.4	158
Silica (mg/L)	4.8	13.2	28.5	6.1	26
Nitrate (mg/L as nitrogen)	0.01	0.18	4.1	0.41	154
Dissolved solids (mg/L)	52	498	1,820	502	29
Iron (µg/L)	0.05	80	4,000	736	117
Manganese (µg/L)	0.13	4.09	2,100	446	21
Arsenic (µg/L)	0.03	0.03	0.03	0.03	6
Hardness (mg/L as calcium carbonate)	2.0	48	700	135	155
Specific conductance (µS/cm)	41	435	4,760	808	159
pH (standard units)	5.4	8.3	9.1	0.8	158

Nitrate

Nitrate concentrations in 154 samples generally were low in samples from the Tokio aquifer, ranging from 0.01 to 4.1 mg/L as nitrogen with a median of 0.18 mg/L (table 37). All samples were below the Federal MCL of 10 mg/L as nitrogen (U.S. Environmental Protection Agency, 2009). Typical of other aquifers in the Coastal Plain, higher nitrate concentrations generally were in or near outcrop areas, with low concentrations downgradient. Three of the four samples with nitrate concentrations greater than 1.0 mg/L were in the outcrop area. There was a relatively greater density of nitrate concentrations more than 0.5 mg/L in the southwestern part of the aquifer. Overall low nitrate concentrations precluded an effective relation between nitrate and well depth. However, the two highest nitrate concentrations of 2.0 and 4.1 mg/L were in wells with depths of 25 and 16 ft. Well depths ranged upward to 1,500 ft.

Iron

The Tokio aquifer generally had the lowest median and maximum iron concentrations of any of the Cretaceous- and Tertiary-age aquifers in Arkansas. Iron concentrations ranged from 0.05 to 4,000 µg/L with a median of 80 µg/L (fig. 88; table 37). The median concentration is below the Federal secondary drinking-water regulation of 300 µg/L (U.S. Environmental Protection Agency, 2009). Iron concentrations generally were lower in and near the outcrop area, although no strong spatial trend was evident for iron concentrations. Several wells that had concentrations exceeding 1,000 µg/L were located 6 mi or more downdip from the outcrop area. Ludwig (1973) stated that elevated iron concentrations were not necessarily indicative of iron originating in the Tokio aquifer; instead, he hypothesized it resulted from a mixing of water in uncased wells from shale formations overlying the Tokio. This could explain the lack of spatial trends noted for other Cretaceous and Tertiary aquifers, such as higher iron concentrations in outcrop areas.

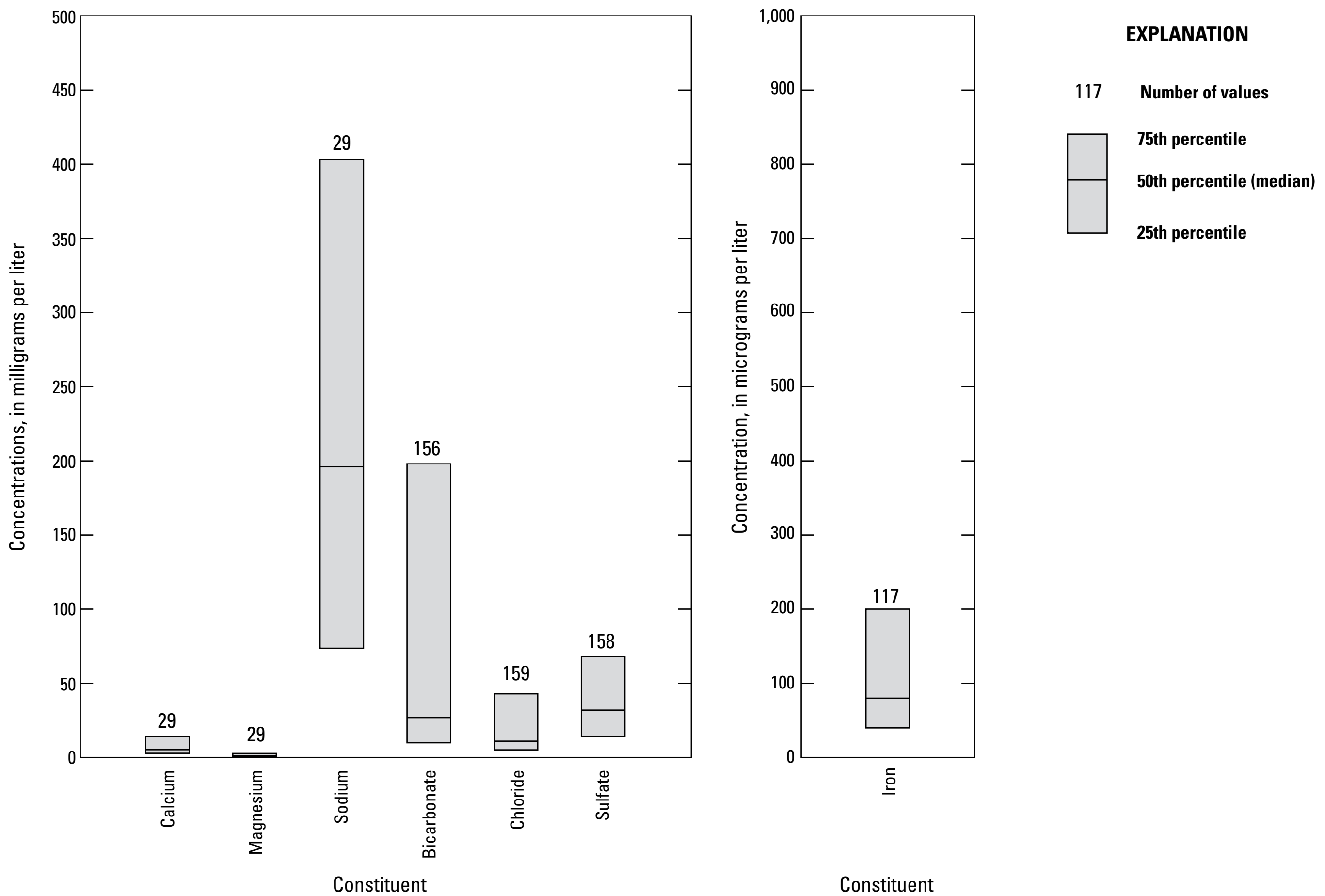


Figure 88. Box plots showing interquartile range for selected chemical constituents in groundwater from the Tokio aquifer in Arkansas.

Sulfate

Sulfate concentrations for the Tokio aquifer ranged from 1.0 to 397 mg/L with a median of 31 mg/L (fig. 88; table 37). This median concentration was an order of magnitude higher than in the Sparta, Cockfield, Carrizo, Cane River, and Wilcox aquifers. Only the Ozan and Jackson Group aquifers had higher sulfate concentrations, with medians of 230 and 110 mg/L, respectively. Therefore, the Tokio exhibits a wider range and higher concentrations of sulfate compared to other Cretaceous and Tertiary aquifers. Counts (1955) stated that bicarbonate and sulfate concentrations frequently were high in the Tokio, indicating a moderately high sodium-bicarbonate to sodium-sulfate water type. However, Ludwig (1972) had little mention of elevated sulfate in the aquifer. The spatial distribution of sulfate suggests very different geochemical processes controlling groundwater-evolution trends in various parts of the Tokio.

Prior to this discussion, a review of general salinity trends is useful. Conceptually, salinity is represented by the quantity of dissolved salts in water, which is directly related to the dissolved-solids concentration. Only 29 of 160 wells with water-quality data had analyses for dissolved solids. However, 159 of the wells had specific conductance values. Specific conductance exhibited a strong linear relation with dissolved solids with a coefficient of determination (R^2) value of 0.99 (fig. 89*A*) from a regression analysis (Helsel and Hirsch, 2002), making specific conductance an excellent proxy for dissolved solids by the equation:

$$\underline{DS} = (0.556 \times \underline{SC}) + 35.7 \qquad (1)$$

where

$\underline{DS}$ is the concentration of dissolved solids in milligrams per liter, and

$\underline{SC}$ is the specific conductance in microsiemens per centimeter.

An inspection of the spatial distribution of specific conductance values revealed steep gradients for increases in groundwater salinity downgradient from the outcrop area (fig. 87). Specific conductance values exceeding

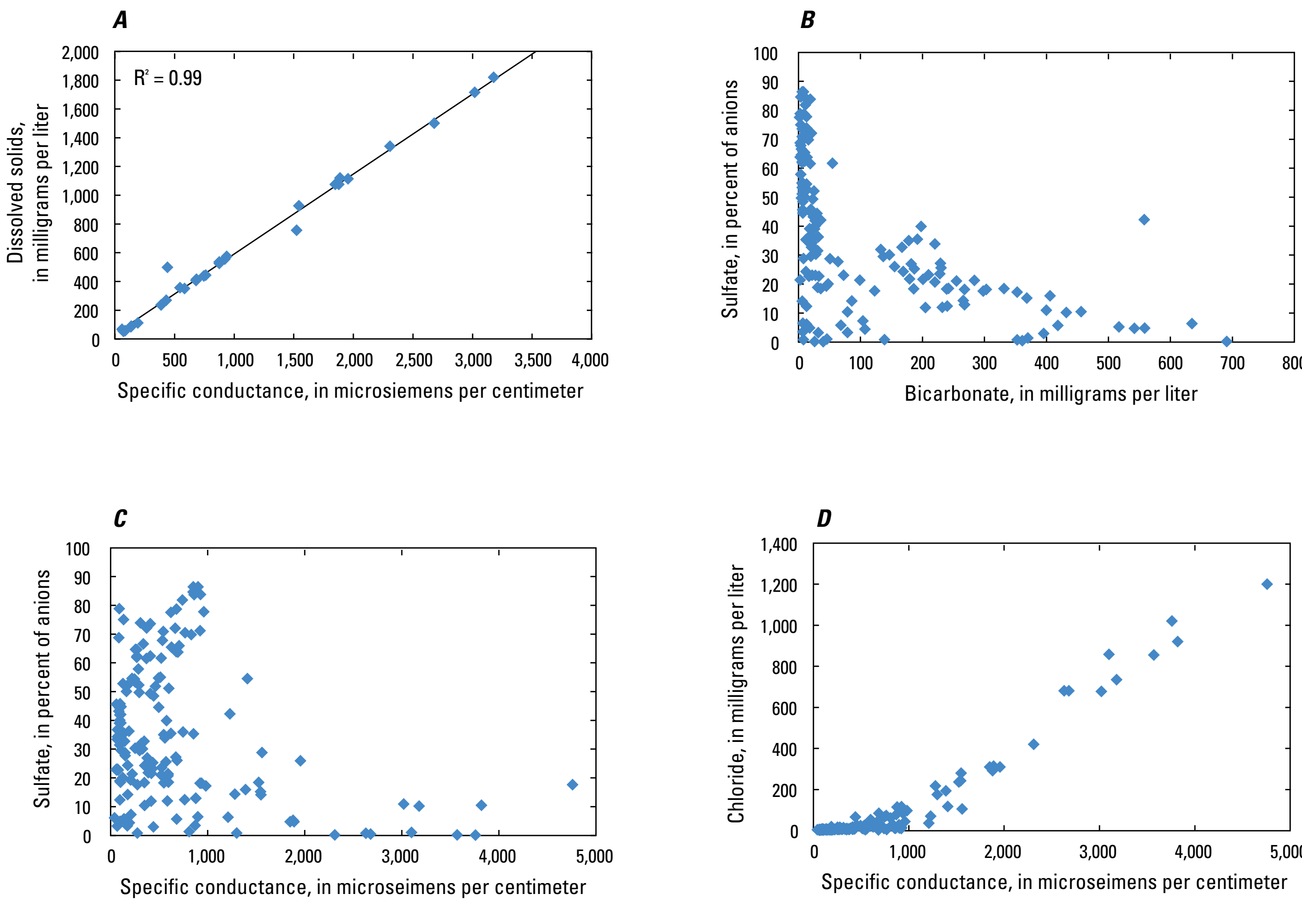


Figure 89. Relation of *A*, specific conductance and dissolved solids; *B*, sulfate and bicarbonate; *C*, specific conductance and sulfate; and *D*, specific conductance and chloride in groundwater from the Tokio aquifer in Arkansas.

2,500 µS/cm are located within 1–5 mi of the outcrop areas in the southwestern and northeastern parts of the aquifer. Conversely, no values exceeding 2,500 µS/cm are noted in the central part. Even as far as 15–20 mi from the outcrop area, specific conductance values are less than 2,500 µS/cm in the central part of the aquifer. This situation is similar to the Nacatoch aquifer, which exhibited sharper salinity gradients in the southwestern and northeastern parts of the aquifer compared to the central part.

These abrupt increases in salinity, indicated by increases in specific conductance, appear to be the result of different processes in the southwestern and northeastern areas of the aquifer. In the northeastern part of the aquifer, the higher-conductance groundwater is dominated by chloride and bicarbonate as the major anions. Six samples have chloride concentrations exceeding 500 mg/L, and 14 samples have bicarbonate concentrations exceeding 250 mg/L and ranging upward to 432 mg/L (fig. 87). The increase in salinity in the northeastern area is similar to other Cretaceous aquifers, where salinity tends to increase within short distances in the downgradient direction of flow. There usually is a clear transition from a calcium- or sodium-bicarbonate water in and near the outcrop area to a sodium-chloride water type downgradient. In the extreme southwestern part of the aquifer, sulfate is the dominant anion, rather than bicarbonate or chloride. Only 4 of 27 wells in the southwestern part of the aquifer had chloride concentrations exceeding 250 mg/L, and all but 2 wells had bicarbonate concentrations less than 50 mg/L (many less than 10 mg/L) (fig. 87). When sulfate was the dominant anion (sulfate greater than 50 percent of anions in milliequivalents per liter), bicarbonate concentrations generally were less than approximately 25 mg/L. An inverse relation was noted between percent sulfate and bicarbonate concentrations (fig. 89*B*). Additionally, sulfate-dominated groundwater generally occurred in less mineralized water. When sulfate was the dominant anion, conductance values generally were less than approximately 800 µS/cm (fig. 89*C*), which correlates to a dissolved-solids concentration of about 480 mg/L. Thus, sulfate concentrations did not increase with increasing dissolved solids along the flow path, typical of other Cretaceous aquifers, but rather constitutes the major anion chemistry in this area.

For Arkansas aquifers, bicarbonate concentrations generally exceed sulfate concentrations. One mechanism that results in high (greater than 20 mg/L) sulfate concentrations is diffusion from fine-grained sediments. Fine-grained sediments often contain several hundred milligrams per liter of sulfate, whereas concentrations in coarse-grained sediments are less than 50 mg/L (Chapelle, 2001). Although abundant clays are noted for most of the Cretaceous formations in southwestern Arkansas, this mechanism does not account for the increases in sulfate with concomitant decreases in bicarbonate concentrations. This mechanism also does not explain the high pH values (greater than 8.5 standard units) in this area.

A second viable mechanism that results in elevated sulfate concentrations is dedolomitization. Sacks (1996) noted that high-sulfate groundwater in Florida was controlled by gypsum and dolomite dissolution linked with calcite precipitation. This process, referred to as dedolomitization, accounts for increased sulfate concentrations with concomitant decreases in bicarbonate for several areas of the country (Appelo and Postma, 1999). Gypsum (a mineral composed of calcium and sulfate) is cited as a source of sulfate in other Cretaceous and Tertiary aquifers in southwestern Arkansas. Thus, dedolomitization provides a plausible explanation for elevated sulfate that is consistent with the geochemistry of groundwater, particularly bicarbonate and chloride, in the southwestern part of the aquifer. Only a limited number of samples had major cation chemistry (table 37) including calcium, magnesium, sodium (29 samples), and potassium (28 samples), whereas most samples had major anion chemistry including bicarbonate (156), chloride (159) and sulfate (158). This precludes detailed analysis of mineral equilibrium constraints on resulting groundwater geochemistry. Availability of more detailed geochemical data sets would enable such an analysis and provide a more confident determination of dissolved-species sources.

Chloride

Similar to other Cretaceous aquifers in southwestern Arkansas, salinity was noted to increase to the southeast in the downdip direction of groundwater flow (Counts and others, 1955; Plebuch and Hines, 1969; Ludwig, 1973). Chloride exhibited a positive, linear relation with specific conductance values greater than 1,000 µS/cm, indicating dominance of chloride in the higher salinity groundwater (fig. 89*D*). The elevated salinity in southern Arkansas led Zachry and others (1986) to investigate the potential of injecting wastewaters from petroleum exploration into Cretaceous aquifers in southern Arkansas as the groundwater was too saline for other uses.

Chloride concentrations from the Tokio aquifer ranged from 2.3 to 1,200 mg/L with a median of 11 mg/L (fig. 88; table 37). This median concentration is capable of being derived naturally from evapotranspiration of infiltrating precipitation (Kresse and Fazio, 2002). Similar to the Nacatoch aquifer, gradients of increasing salinity are sharper along the northeastern and southwestern parts of the aquifer. Chloride concentrations exceeding 500 mg/L occurs within 1–5 mi of the outcrop area in the western and eastern parts of the aquifer. In the central part of the aquifer, chloride concentrations are less than approximately 300 mg/L as much as 20 mi from the outcrop area (fig. 87). Thus, the central part of the aquifer affords a much larger area of low-salinity groundwater for various uses. There was no variation in formation structure or dominant stratigraphy to explain the observed chloride distribution. Further investigations into the spatial variation in geochemistry for the Tokio aquifer ultimately will require a more indepth analysis of stratigraphy, sediment mineralogy, and redox zonation.

In summary, good-quality water is obtained from the Tokio aquifer throughout much of its extent. Sharp increases in salinity are noted in the extreme southwestern and northeastern parts of the aquifer, limiting use at distances more than approximately 5 mi downdip from the outcrop area. In the central part of the aquifer, salinity increases are more gradual, affording a larger area of low-salinity, high-quality water for multiple uses. In the southwestern part of the aquifer, sulfate is the dominant anion. Dedolomitization is a likely process that may account for the high-sulfate, low-bicarbonate groundwater in this area of the aquifer; however, this theory requires further analysis to achieve greater confidence.

Trinity Aquifer

Cretaceous formations in Arkansas (Nacatoch Sand, Ozan Formation, Tokio Formation, and the Trinity Group) and the aquifers comprised by these formations are not included in any of the regional hydrogeologic framework models of the Mississippi embayment (Arthur and Taylor, 1990; Hart and others, 2008; Clark and Hart, 2009). Although the Nacatoch was included in the Gulf Coast RASA by Hosman and Weiss (1991), no older Cretaceous formations were included in their model. Renken (1998) included the Trinity as a minor aquifer in the Ground Water Atlas of the United States for Segment 5 (Arkansas, Louisiana, and Mississippi). USGS water-use reports referenced herein record use from the “Trinity aquifer,” although it accounts for the lowest use of any aquifer in Arkansas. For purpose of this report, the saturated part of the Trinity Group yielding water to wells will be referred to hereinafter as the “Trinity aquifer.” The following sections describe the geology, hydrologic characteristics, use, water levels, and water quality of the Trinity aquifer in Arkansas.

Geologic Setting

The Trinity Group is a sequence of clastic rocks ranging from less than 100 ft thick in outcrop areas to more than 1,000 ft thick at downdip locations. The Trinity is a locally important aquifer in southwestern Arkansas and comprises six distinct units (Counts and others, 1955). The basal unit is the Pike Gravel, overlain by the Delight Sand, overlain by the

Dierks Limestone, overlain by the Holly Creek Formation, overlain by the De Queen Limestone, and finally overlain by the Paluxy Sand. The three important water-bearing sands of the Trinity are the Pike Gravel, the Ultima Thule Gravel Member of the Holly Creek Formation, and the Paluxy Sand Formation (Boswell and others, 1965).

The Trinity Group is named for type exposures on the Trinity River in Texas. The Lower Cretaceous Series Trinity Group unconformably overlies rocks of Paleozoic age and is unconformably overlain by the Upper Cretaceous Woodbine and Tokio Formations (Miser and Purdue, 1919; Boswell and others, 1965). The Trinity crops out in a belt 5–10 mi wide that extends from Pike County westward into southeastern Oklahoma. The outcrop is irregular and may cap outlying hills (Veatch, 1906; Counts and others, 1955; Boswell and others, 1965). The strike of the beds is generally westward, and the dip is generally to the south at about 50 ft/mi. The dip increases to the south and may exceed 100 ft/mi (Miser and Purdue, 1919). The Trinity attains a maximum thickness of more than 2,500 ft (Boswell and others, 1965).

The Pike Gravel is the thickest and most persistent gravel unit of the Trinity Group. It consists of rounded pebbles and cobbles intermixed and interbedded with sand and clay (Counts and others, 1955). The Pike Gravel is a resistant unit and forms an even, though dissected, southward-dipping upland. The gravel is composed mainly of dense white, gray, brown, black, or red novaculite and lesser amounts of quartz, quartzite, and sandstone gravel. The Pike Gravel ranges in thickness from 20 to 50 ft thick near the outcrop to a maximum known thickness of about 100 ft downdip (Miser and Purdue, 1919; Counts and others, 1955).

The Ultima Thule Gravel is similar in lithology to the Pike Gravel but is comprised of finer materials (Boswell and others, 1965). The sand and clay separating the Ultima Thule and Pike gravels thin to the west and the Ultima Thule rests directly on the Pike Gravel or Paleozoic rocks into Oklahoma (Miser and Purdue, 1919). The Ultima Thule Gravel thickens to the west, reaching a maximum thickness of approximately 40 ft near the State line (Counts and others, 1955). The Paluxy Sand generally consists of well-sorted, fine white sand interbedded with clay and limestone and local gravel lenses (Boswell and others, 1965). The Paluxy Sand has a maximum thickness of about 900 ft. The Paluxy Sand is present in southern Howard and Sevier Counties (Boswell and others, 1965).

The lowest beds of the Trinity Group represent nearshore deposits of the advancing Cretaceous sea that were followed by overlying limestone and marls indicating deeper waters. The upper sand represents shallow-water conditions, which mark the beginning of the Upper Cretaceous (Veatch, 1906).

Hydrologic Characteristics

The upper Paluxy Sand is the principal water-bearing sand in the group. Well yields range from 0 to 200 gal/min, and flowing artesian wells were common at lower altitudes. A flowing artesian well in the Saline River bottoms in Sevier County yielded about 100 gal/min (Counts and others, 1955). Counts and others (1955) provided a table that listed 16 of 35 wells as “flowing.” Public-supply wells in western Sevier County generally are completed in the upper and lower gravels at depths of 145–450 ft and have reported yields as high as 200 gal/min. Flowing artesian wells that yield from 1 to 50 gal/min were reported in Howard County (Counts and others, 1965). Wells screened in the Pike Gravel in southern Pike County initially were under flowing artesian conditions but ceased to flow as potentiometric surfaces declined with large withdrawals and overpumping. One aquifer test showed a transmissivity of about 1,300 ft^2/d and a storage coefficient of about 0.00004 (Boswell and others, 1965). In Pike County, the Trinity is a calcareous clay with little potential to yield water. The Trinity aquifer receives recharge in the outcrop area, and the direction of groundwater flow is southward (Boswell and others, 1965).

Water Use

The Trinity aquifer is present in several counties in southwestern Arkansas, but the clayey sediments common throughout the extent impede its use from a water-quality and yield standpoint. Five wells are recorded in the ARWUDBS for this aquifer in 2010 (fig. 90). Multiple wells in the outcrop area were also in use for domestic and livestock supply but do not meet registration requirements.

Veatch (1906) reported a scattering of well completion attempts into the Trinity aquifer in southwestern Arkansas, but only one well was completed in central Howard County. Counts and others (1955) reported 37 wells completed in the Trinity aquifer, including public-supply wells at Murfreesboro (Pike County), DeQueen, Horatio, Lockesburg (Sevier County), and Mineral Springs (Howard County). The public-supply well for the town of Horatio was drilled in 1921. Public-supply wells were drilled for Murfreesboro and Mineral Springs in the mid-1930s (Hale and others, 1947). Horatio and Lockesburg continue (2013) to use the Trinity aquifer (fig. 90), Murfreesboro uses the Little Missouri River, and Mineral Springs uses groundwater from the Tokio aquifer. Albin (1960) estimated that Murfreesboro used 0.07 Mgal/d in 1960, which quickly increased to 0.215 Mgal/d in the later 1960s because of increased industrial demands.

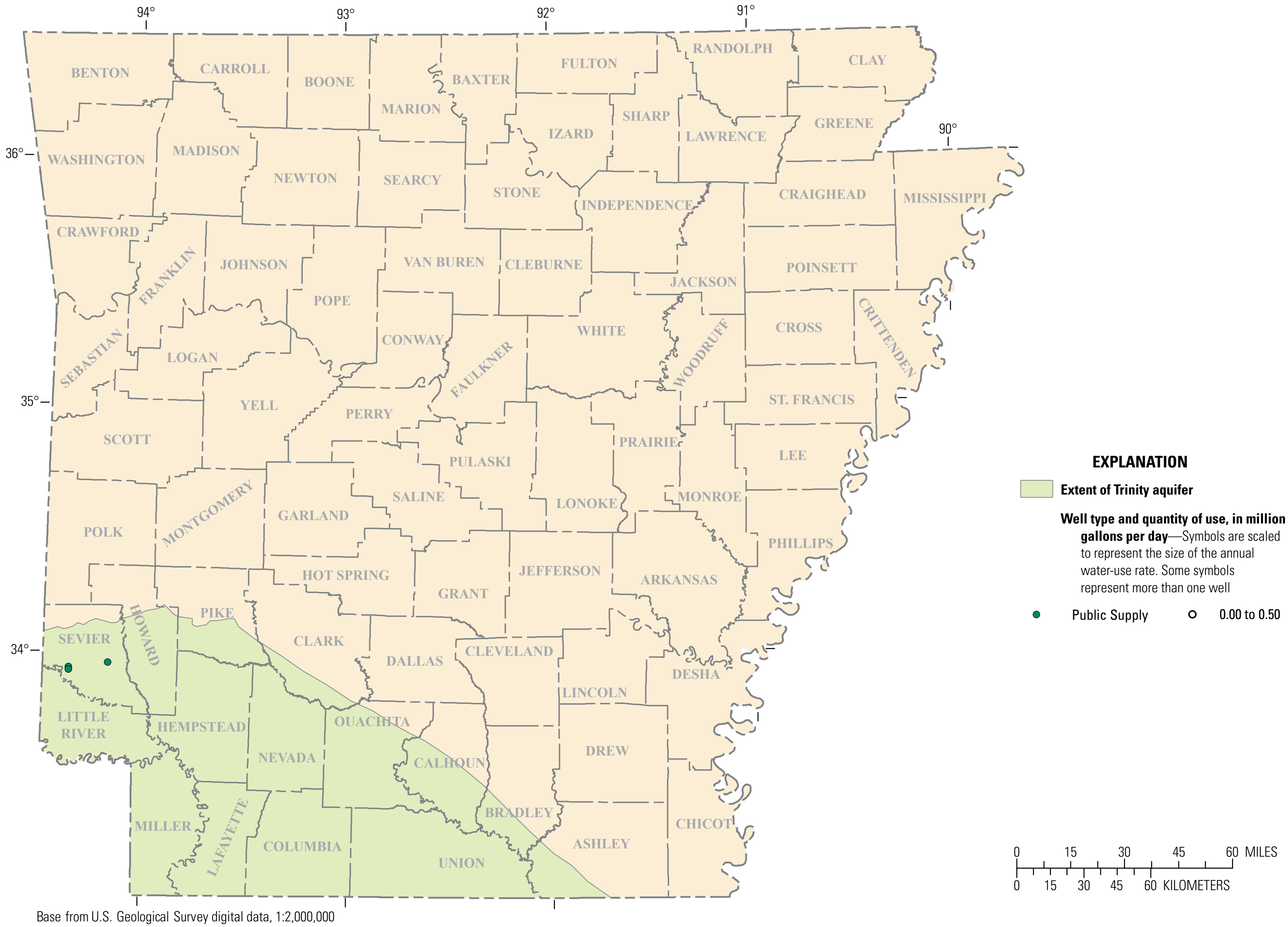


Figure 90. Wells with reported groundwater use for the Trinity aquifer in Arkansas, 2010.

Use of the Trinity aquifer has been restricted to a few counties in southwestern Arkansas (figs. 90–91). Estimated use from the aquifer in 2010 was available only for Columbia and Sevier Counties with a combined total of 0.86 Mgal/d (table 38). Sevier County generally had the most use. Although no data were published for Sevier County from 1985 through 1995, Horatio and Lockesburg were assumed to have used the aquifer for public supply. Approximately 20 percent of water used from the Trinity in Sevier County is for public supply (Terrance W. Holland, U.S. Geological Survey, written commun., 2012). Domestic use of the Trinity is still (2013) widespread and common; however, water use is assumed to be underestimated because domestic wells are not required to be registered. In addition, livestock wells generally do not meet the minimum-use requirement for registration. In 1990–2000, water use attributed to those two purposes was reported for Howard County (fig. 90).

Water Levels

The Trinity aquifer is recharged by infiltration of precipitation in the outcrop area. The direction of flow is southward with regional dip of the formation (Boswell and others, 1965). Water levels have not been monitored following measurements taken by Boswell and others (1965) in the mid-1960s. High rates of withdrawal from the Trinity probably contributed to potentiometric-head declines in formerly flowing artesian wells with water-level declines of more than 40 ft below the land surface in the mid-1960s (Boswell and others, 1965).

Water Quality

The Trinity aquifer crops out in an east-west trending band from western Sevier County to near the southeastern extent of Pike County. Only 32 wells with limited water-quality data were available, and these data were from wells located only in Sevier and Howard Counties. Generally, water quality from the Trinity is good, although chloride and sulfate can be somewhat elevated locally (Counts and others, 1955; Boswell and others, 1965). Counts and others (1955) noted that although sulfate concentrations generally were less than 30 mg/L, a few samples had sulfate concentrations exceeding 100 mg/L. Chloride concentrations generally were below 10 mg/L, except for one sample that exceeded 100 mg/L. Boswell and others (1965) reported that groundwater varied from a calcium-magnesium bicarbonate to a sodium-bicarbonate water type and that dissolved-solids concentrations usually were less than 300 mg/L, indicating overall good quality water.

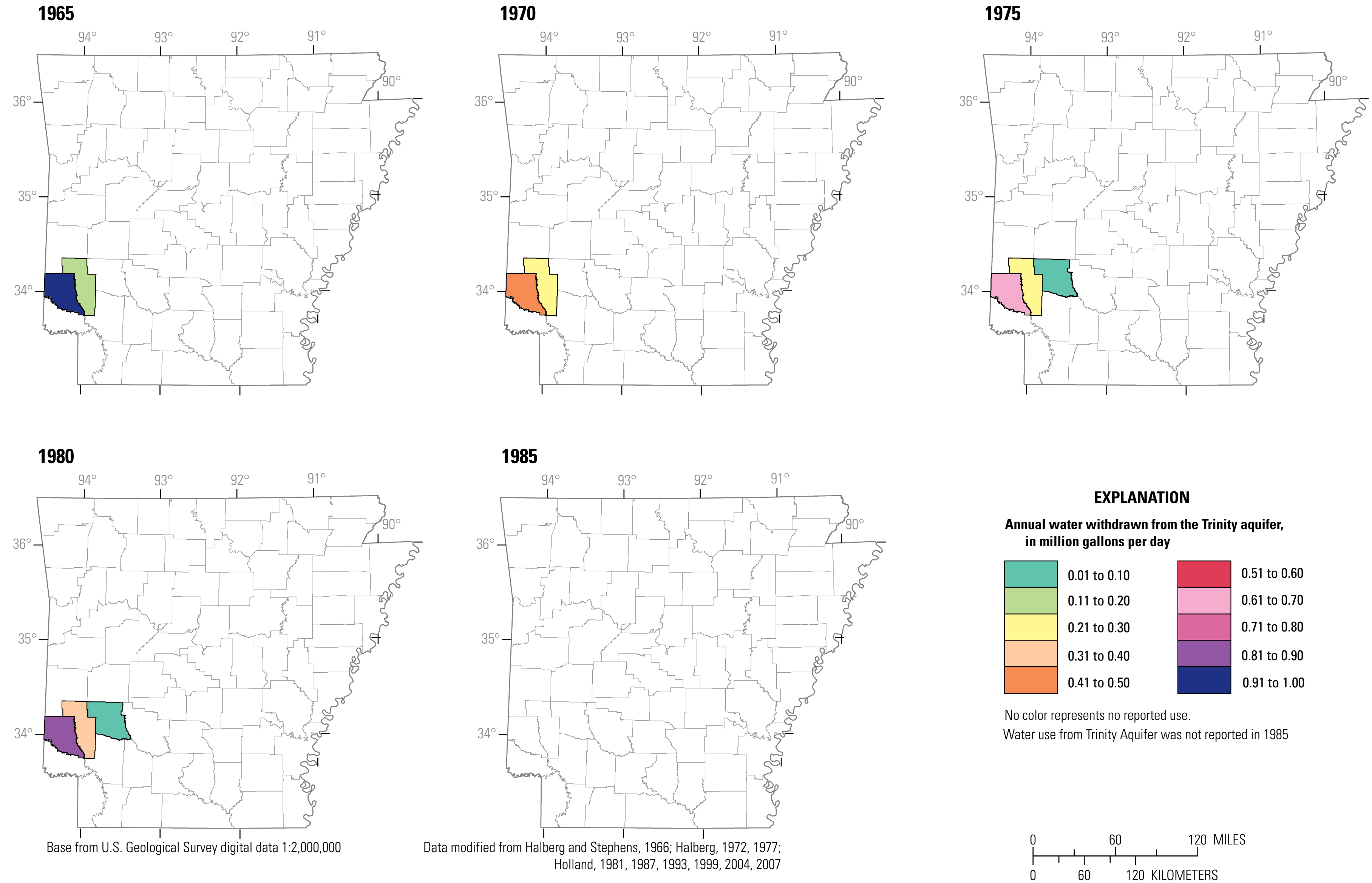


Figure 91. Water-use rates for the Trinity aquifer in Arkansas from 1965 to 2010.

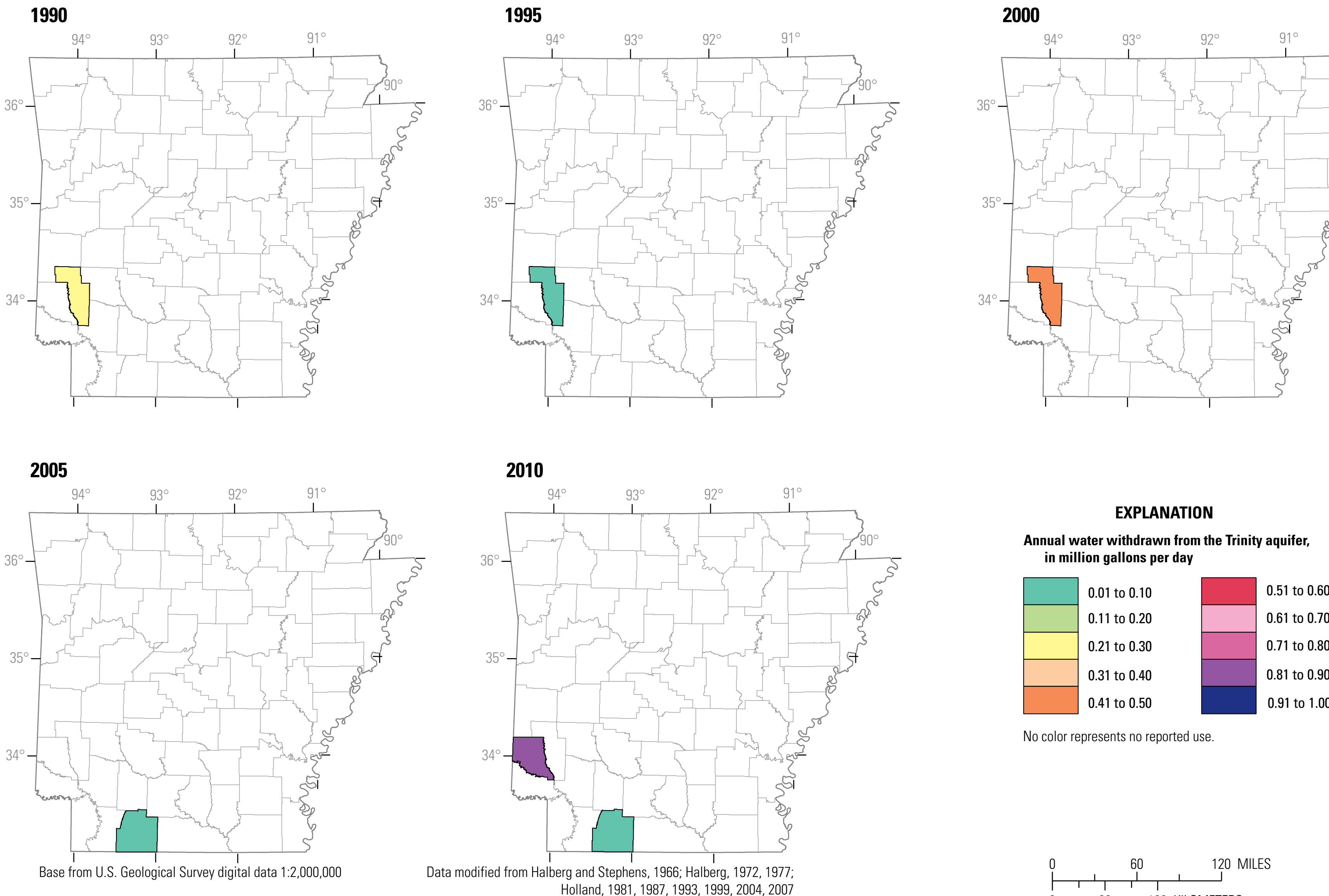


Figure 91. Water-use rates for the Trinity aquifer in Arkansas from 1965 to 2010.—Continued

Table 38. Water use from the Trinity aquifer in Arkansas, 1965–2010.

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

County	1965	1970	1975	1980	[1]1985	1990	1995	2000	2005	2010
Columbia	0.00	0.00	0.00	0.00	--	0.00	0.00	0.00	0.03	0.02
Howard	0.13	0.22	0.30	0.35	--	0.23	0.08	0.42	0.00	0.00
Pike	0.00	0.00	0.01	0.02	--	0.00	0.00	0.00	0.00	0.00
Sevier	0.99	0.49	0.65	0.89	--	0.00	0.00	[2]0.94	[2]0.16	0.84
Total	**1.12**	**0.71**	**0.96**	**1.26**	**--**	**0.23**	**0.08**	**1.36**	**0.19**	0.86

[1]Water use from the Trinity aquifer was not reported in 1985.

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

General Geochemistry and Water Type

Generally, groundwater from the Trinity aquifer is of a calcium-magnesium water type, transitioning to a sodium-bicarbonate water type downdip from the outcrop area, similar to other Cretaceous- and Tertiary-age aquifers in southern Arkansas. Sodium was less than 50 percent of the total cations for locations in the outcrop area. Groundwater from wells at a distance from 5 to 25 mi downdip from the outcrop area contained as much as 98 percent sodium (fig. 92). Values of pH ranging from 6.2 to 7.5 occur only in the outcrop area. Values of pH from about 5 to 20 mi downgradient from the outcrop area generally were greater than 8.5 and ranged upward to 9.2 (fig. 92).

For many aquifers in Arkansas, bicarbonate concentrations tend to increase with increasing pH and dissolved-solids concentrations, indicating dissolution of carbonate minerals. Therefore, groundwater tends to evolve toward a strongly bicarbonate water type with bicarbonate accounting for the highest percentage of total anions at higher dissolved-solids concentrations. The only exception to this situation is when groundwater is affected by saltwater intrusion or mixing with poor-quality groundwater. Several geochemical relations indicate that reactions other than simple dissolution of carbonate minerals affect groundwater geochemical evolution in the Trinity aquifer. This is discussed in greater detail later in this section.

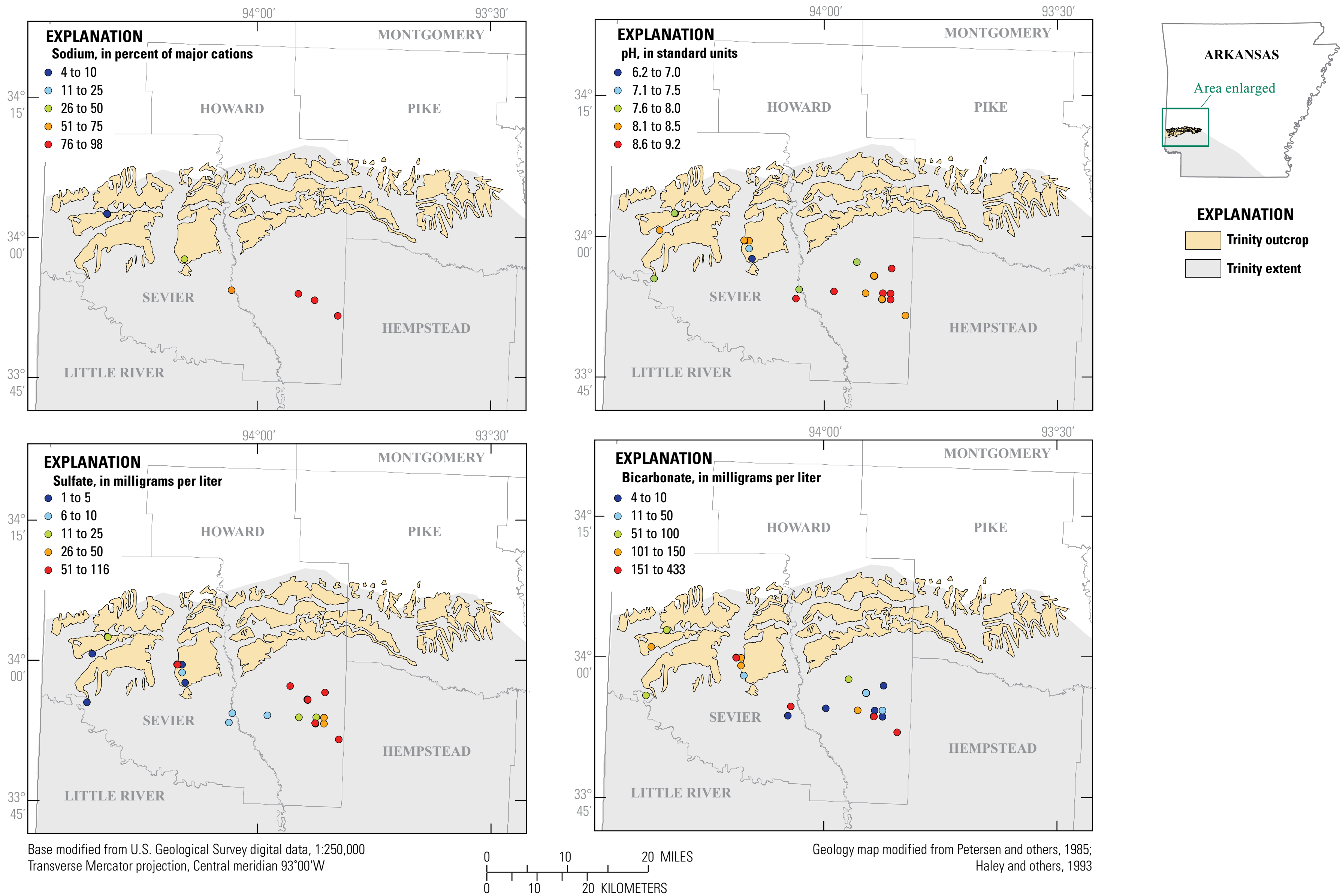


Figure 92. Spatial distribution of selected chemical constituents in groundwater from the Trinity aquifer in Arkansas.

Nitrate

Nitrate concentrations generally are low in the Trinity aquifer. Nitrate concentrations ranged from 0.04 to 29 mg/L in 26 samples with a median of 0.26 mg/L as nitrogen (table 39). One well, only 25 ft deep, exceeded a nitrate concentration of 1.0 mg/L with a nitrate concentration of 29 mg/L. Two wells, 130 ft and 260 ft northwest of the 25-ft deep well, had nitrate concentrations less than 0.5 mg/L, indicating the elevated nitrate for the 25-ft well was from an extremely localized source of nitrogen.

Iron

Iron concentrations are extremely low in the Trinity aquifer with a median of 60 µg/L for 29 samples (fig. 93; table 39). Only one groundwater sample exceeded the Federal secondary drinking-water regulation of 300 µg/L (U.S. Environmental Protection Agency, 2009). This sample was taken from a well located in the outcrop area. Iron concentrations for several Cretaceous and Tertiary aquifers were noted to have higher iron concentrations in their outcrop areas compared to increasing concentrations downgradient, resulting from possible changes in redox conditions along the flow path.

Sulfate

Sulfate concentrations ranged from 1.0 to 116 mg/L with a median of 16 mg/L (fig. 93; table 39). Concentrations exceeded 25 mg/L in seven wells located approximately 5–17 mi from the outcrop area in the southeastern part of the aquifer in southern Howard County (fig. 92), with five of these wells exceeding 50 mg/L. In this same area, all chloride concentrations were less than 15 mg/L, and bicarbonate concentrations generally were lower than sulfate concentrations (fig. 92). For other Cretaceous aquifers, salinity increased downdip from the outcrop area with chloride as the dominant anion. Increasing chloride concentrations generally result from ineffective flushing of residual marine-derived salinity or upwelling of high-salinity water from underlying formations. Six of seven wells exceeding 25 mg/L sulfate in this area had sulfate concentrations exceeding that of chloride and bicarbonate. Therefore, some process is thought to have accounted for the increased sulfate. This situation also was noted for the Tokio aquifer for an area in southeastern Sevier County, where increases in sulfate with concomitant decreases in bicarbonate were attributed to dedolomitization mechanisms (see section on “Tokio aquifer”). Although further research is required to validate such assumptions, dedolomitization appears to be the most likely process accounting for the chemistry of groundwater where sulfate is the anion of highest concentration in the Trinity aquifer.

Table 39. Descriptive statistics for selected chemical constituents in groundwater from the Trinity aquifer in Arkansas.

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

Constituent or characteristic	Minimum	Median	Maximum	Standard deviation	Number of wells
Calcium (mg/L)	0.4	13	54	20.7	9
Magnesium (mg/L)	0.2	2.2	11	4.38	9
Sodium (mg/L)	3.6	8.5	261	89.6	9
Potassium (mg/L)	1.24	2.8	9.3	2.32	9
Bicarbonate (mg/L)	4.0	67	433	109	30
Chloride (mg/L)	3.0	6.0	695	124	30
Sulfate (mg/L)	1.0	16	116	34.6	30
Silica (mg/L)	10	12	16	1.89	9
Nitrate (mg/L as nitrogen)	0.04	0.26	29	5.6	26
Dissolved solids (mg/L)	42	192	683	189	9
Iron (µg/L)	0.05	60	2,200	544	29
Manganese (µg/L)	4.29	4.29	4.29	0.13	1
Arsenic (µg/L)	0.03	0.03	0.03	0.03	1
Hardness (mg/L as calcium carbonate)	8.0	185	440	114	30
Specific conductance (µS/cm)	75	501	2,650	458	30
pH (standard units)	6.2	8.4	9.2	0.6	30

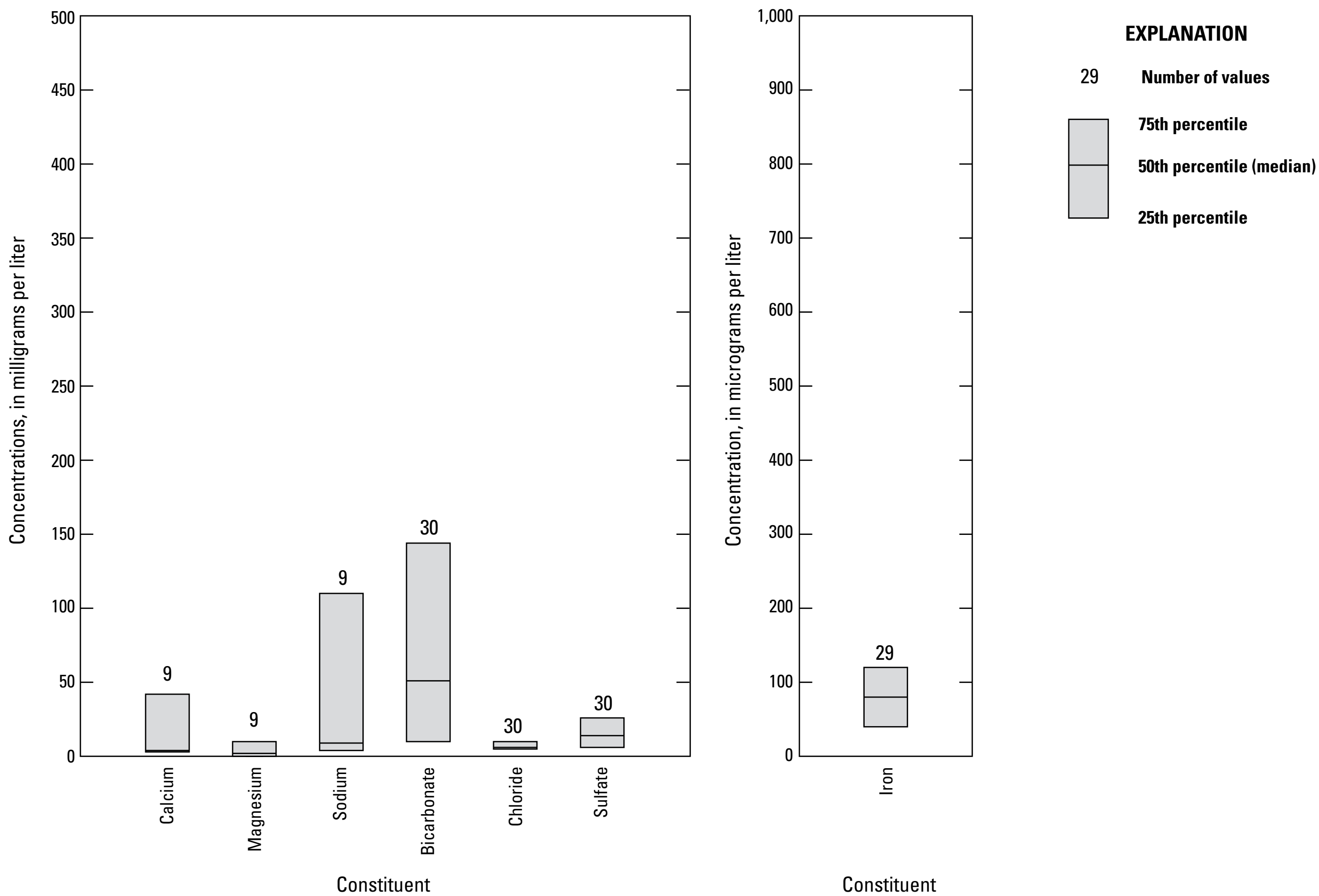


Figure 93. Interquartile range of selected chemical constituents in groundwater from the Trinity aquifer in Arkansas.

Chloride

All but one chloride concentration was less than or equal to 15 mg/L, even as far as 13 mi from the outcrop area in southern Howard County. The one sample had an elevated chloride concentration of 695 mg/L and was from a shallow 25-ft well in Sevier County. Counts and others (1955) described this well as "almost dry." If the well was completed in a low-permeable, clayey section of the Trinity, it is possible that salinity originated during deposition in a marine environment that had not been adequately flushed. Because of the overall low chloride concentrations in higher yielding wells in the area, the geochemistry of groundwater from this well is simply an anomaly but assists in understanding localized water-quality problems in other aquifers of the Coastal Plain that have varying amounts of clay interbedded with sand lenses. In the absence of anthropogenic effects on water quality, poor-quality, higher-salinity groundwater often is explained by mixing with groundwater bound in low-permeable, clay-rich deposits that experience inadequate flushing of residual connate water at the time of deposition. The overall low salinity in samples from wells throughout the aquifer suggests that any saline water that originated in more permeable sands has been adequately flushed.

In summary, good-quality groundwater is found throughout the Trinity aquifer. Sulfate concentrations can be locally elevated, although all concentrations were less than the 250 mg/L secondary drinking-water regulation. Wells with elevated sulfate generally had low bicarbonate concentrations, which is hypothesized as resulting from dedolomitization processes. All chloride concentrations but one were less than or equal to 15 mg/L at distances as great as 15 mi from the outcrop area, demonstrating the low overall salinity in the aquifer.