Oklahoma Water Resources Board

Arbuckle-Simpson Hydrology Study

Final Report to the U.S. Bureau of Reclamation

Oklahoma Water Resources Board

Prepared in cooperation with:
U.S. Geological Survey
Oklahoma State University
University of Oklahoma

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Final Report to the U.S. Bureau of Reclamation

In accordance with Cooperative Agreement No. 03FC601814

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EXECUTIVE SUMMARY

The Oklahoma Water Resources Board, in collaboration with the U.S. Bureau of Reclamation, the U.S. Geological Survey, Oklahoma State University, and the University of Oklahoma, conducted a comprehensive investigation of the Arbuckle-Simpson aquifer in south-central Oklahoma. The six-year investigation, termed the "Arbuckle-Simpson Hydrology Study", was conducted between 2003 and 2009 to obtain information necessary to determine how much water can be withdrawn from the aquifer while protecting springs and streams.

The Arbuckle-Simpson aquifer is exposed at the surface in three uplifted areas, designated as the western, central, and eastern Arbuckle-Simpson aquifers for this investigation. The area where the aquifer is exposed at the surface (outcrop) encompasses about 520 square miles, but in some areas, where fresh groundwater flows beneath shallower geologic units, the aquifer extends beyond the outcrop. The freshwater zone of the aquifer is known to extend beneath younger geologic units in an area west of Sulphur and the Chickasaw National Recreation Area. The total area of the Arbuckle-Simpson aquifer, as defined for this investigation, is about 600 square miles.

The investigation was designed as an aquifer-scale assessment of water resources for the allocation of water rights. Most of the data collection and modeling efforts were focused on the eastern Arbuckle-Simpson aquifer, because the data needed to build the groundwater-flow model are sparse in the western and central Arbuckle-Simpson aquifer, the eastern Arbuckle-Simpson aquifer is the largest part of the aquifer, most of the current water use from the aquifer is from the eastern Arbuckle-Simpson aquifer, and most of the streams and springs sourced from the aquifer are located on the eastern Arbuckle-Simpson aquifer. The western and central aquifers were addressed with more general methods.

A multidisciplinary team of researchers employed several methods to obtain and interpret information on the climate, geology, groundwater, and streamflow. Methods included monitoring groundwater, surface water, and climatic conditions; evaluating petroleum-related information; drilling test wells; conducting aquifer tests; geophysics; geochemistry; isotopic age dating of groundwater; tree-ring analysis; and modeling of groundwater, surface water, and geology. These research efforts resulted in the production of more than 30 reports and provide the basis to predict the impacts of groundwater withdrawals on streamflow and to test various water management strategies.

A digital groundwater-flow model of the eastern Arbuckle-Simpson aquifer was developed and used to test conceptual models of the aquifer and to predict the consequences of aquifer-scale groundwater withdrawals on streamflow. Agreement of the groundwater-flow model and independently derived parameters indicates the model is a reasonable representation of the groundwater flow system. The calibrated eastern Arbuckle-Simpson groundwater-flow model was used to estimate the effects of potential groundwater withdrawals on Blue River and Pennington Creek streamflows and baseflows. Simulations were conducted of groundwater withdrawals distributed uniformly across the aquifer for water years 2004 through 2008. Three simulations of

distributed withdrawals were tested, allocating groundwater withdrawals as equal proportionate shares of 0.125, 0.250, and 0.392 (acre-feet/acre)/year.

Major accomplishments for the Arbuckle-Simpson Hydrology Study are listed below:

- A public involvement plan was developed to keep cooperators and stakeholders informed of the Study's progress. Information was distributed through a variety of media including fact sheets, newsletters, press releases, videos, field trips, and presentations.

- The Arbuckle Data Viewer online mapping application was developed to provide the public with ready-access to data collected for the Study.

- Three USGS stream gages and the Fittstown Mesonet weather station were installed for the Study. The stream gages provided five years of streamflow records, which were used to estimate aquifer recharge. The Mesonet station includes a 257-foot observation well, which was installed to monitor groundwater level along with other hydroclimatic data.

- Eight quarterly stream and groundwater synoptic measurement events were conducted between January 2004 and February 2007. The water-level measurements were used to create potentiometric surface maps to delineate subsurface watersheds, revealing that some subsurface watersheds are substantially different from the surface watersheds.

- A geochemical investigation of the Arbuckle-Simpson aquifer was conducted to characterize the groundwater quality at an aquifer scale, describe the chemical evolution of groundwater as it flows from recharge areas to discharge in streams and springs, and to determine the residence time of groundwater in the aquifer. Geochemical inverse modeling determined a set of reactions that account for the compositions of the mineralized waters in the Chickasaw National Recreation Area.

- Information collected during the exploration for petroleum (including well records for over 1,150 petroleum exploration wells, lithologic and geophysical logs, cores and bit cuttings) was used to determine thicknesses and spatial distribution of hydrogeologic units, lithology, fluid types, and aquifer properties.

- A 1,820-foot test well was drilled to gain information regarding lithology, stratigraphy, aquifer properties, vertical flow gradients, and water chemistry in the lower portion of the Arbuckle-Simpson aquifer. The deep test well provided the unique opportunity to collect representative rock and water samples, conduct water flow measurements, and log the borehole with a modern suite of geophysical logs from a fresh borehole.

- Several geophysical techniques (including gravity and magnetic surveys, seismic testing, electrical resistivity imaging, and helicopter electromagnetic surveys) were used to characterize the subsurface geology and evaluate groundwater flow through the highly faulted, structurally complex, carbonate aquifer. A pre-existing seismic survey on the eastern Arbuckle-Simpson aquifer provided evidence that faults extend to basement at an estimated depth of 3,500 feet.

- A digital three-dimensional hydrogeologic framework model was constructed to quantify the geometric relationships of the geologic units within the eastern Arbuckle-Simpson aquifer and provide the geologic framework needed to construct a regional groundwater-flow model. The hydrogeologic framework model greatly improved the final groundwater-flow model and our understanding of the Arbuckle-Simpson aquifer.
- Effects of Earth tides and barometric pressure on water-level fluctuations were analyzed to determine specific storage, storage coefficient, and porosity of the aquifer.
- A distributed hydrologic model was used to develop the hydrologic budgets for the Blue River basin and for the adjacent Clear and Muddy Boggy basins. Precipitation data taken from bias-corrected radar were used as hourly input values to model the recharge for the period January 1994 to April 2007.
- Aquifer recharge was determined by analyzing streamflow records from three stream gages (Blue River near Connerville, Pennington Creek near Reagan, and Honey Creek below Turner Falls).
- A 300-year tree-ring chronology was developed and used to reconstruct streamflow and precipitation of the region.
- A river-basin network model was developed to assess the impact of groundwater withdrawals on downstream surface water rights.
- An instream flow assessment was conducted to quantify fish habitat in spring runs of the Blue River and Pennington Creek.
- A digital groundwater-flow model of the eastern portion of the aquifer was developed to test conceptual models of the aquifer and to predict the consequences of aquifer-scale groundwater withdrawals on streamflow.

The purpose of this report is to describe the scope of the study and to summarize major activities, problems, and accomplishments. Detailed descriptions of research activities and results are documented in the many reports submitted to the Oklahoma Water Resources Board. In particular, the U.S. Geological Survey Scientific Investigations Report: "Hydrogeology and Simulation of Groundwater Flow in the Arbuckle-Simpson Aquifer, South-Central Oklahoma" by Christenson and others (in review) will provide a synthesis of much of the hydrogeologic research as well as model simulation results.

INTRODUCTION

The Arbuckle-Simpson aquifer underlies more than 500 square miles in south-central Oklahoma and provides water for municipal, mining, irrigation, fisheries, recreation, and wildlife conservation purposes. The eastern portion of the aquifer provides drinking water to approximately 39,000 people in Ada, Sulphur, and the surrounding area. The U.S. Environmental Protection Agency (EPA) designated the eastern portion of the aquifer as a sole source aquifer, because it is the principal source of drinking water in the area. The Arbuckle-Simpson aquifer is the source of a number of important springs in the region, including Byrds Mill Spring, Ada's primary drinking water supply, and springs in the Chickasaw National Recreation Area (CNRA). Several headwater streams originating in the aquifer, including Blue River, Pennington, Mill, Travertine, Honey, and Hickory Creeks, originate in the aquifer, and are sustained throughout the year by groundwater discharge to springs and seeps.

Because of concerns that large-scale withdrawals of groundwater could result in declining flow in streams and springs, the State Legislature passed Senate Bill 288 in May 2003. The bill imposes a moratorium on the issuance of any temporary groundwater permits for municipal or public water supply outside of any county that overlies a "sensitive sole source groundwater basin". The Arbuckle-Simpson aquifer is considered a "sensitive sole source groundwater basin" because the EPA designated the eastern Arbuckle-Simpson aquifer as a "sole source aquifer" in 1989. Senate Bill 288 states that the moratorium will remain in effect until the Oklahoma Water Resources Board (OWRB) completes a hydrologic investigation of the Arbuckle-Simpson aquifer and approves a maximum annual yield that will not reduce the natural flow of water from springs or streams emanating from the aquifer. Prior to approval of permits for groundwater use within the basin, SB 288 also requires the OWRB to find that the proposed use is not likely to degrade or interfere with springs or streams emanating from the aquifer.

The Arbuckle-Simpson Hydrology Study (referred to as "Study" in this report) was conducted between 2003 and 2009 to obtain information necessary to determine how much water can be withdrawn from the aquifer while protecting springs and streams. A multidisciplinary team of researchers employed several methods to obtain and interpret information on the climate, geology, groundwater, and streamflow. A key component of the Study was the development of a digital groundwater-flow model by the U.S. Geological Survey. The model, which simulates groundwater flow and discharge to streams, was used to estimate the effects of aquifer-scale groundwater withdrawals on streamflow.

The purpose of this report is to describe the scope of the Study and to summarize major activities, problems, and accomplishments. Detailed descriptions of research activities and results are documented in the many reports submitted to the OWRB and listed in the *Reports* section at the end of this report. In particular, the U.S. Geological Survey (USGS) Scientific Investigations Report: "Hydrogeology and Simulation of Groundwater Flow in the Arbuckle-Simpson Aquifer, South-Central Oklahoma" by Christenson and others (in review) will provide a synthesis of much of the hydrogeologic research as well as model simulation results.

STUDY OVERVIEW

Purpose and Objectives

The purpose of the Arbuckle-Simpson Hydrology Study was to acquire understanding of the region's hydrology to enable development and implementation of an effective water resource management plan that protects the region's springs and streams.

As stated in the Cooperative Agreement with the U. S. Bureau of Reclamation (Agreement No. 03FC601814, dated August 14, 2003), specific objectives were to include, but not be limited to the following:

1. Characterize the Arbuckle-Simpson aquifer in terms of geologic setting, aquifer boundaries, hydraulic properties (hydraulic conductivity, transmissivity, storage coefficient), water levels, groundwater flow, recharge, discharge, and water budget.
2. Characterize the surface hydrology of the study area in terms of stream and spring discharge, runoff, and baseflow, and the relationship of surface water to groundwater.
3. Construct a digital, transient groundwater/surface water flow model of the Arbuckle-Simpson aquifer system to be used in evaluating the allocation of water rights and in simulating management options.
4. Determine the chemical quality of the aquifer and of the principal streams and identify potential sources of natural contamination. Delineate areas of the aquifer that are most vulnerable to contamination.
5. Construct network stream models for the Clear Boggy Creek, Blue River and Lower Washita River stream systems to be used in the allocation of water rights.
6. Review and develop recommendations for water resources management in the this region taking into account water rights issues, the potential impacts of pumping on springs and the stream baseflows, water quality and water supply development, all in accordance with the Oklahoma Groundwater and Stream Water Laws.

Study Area

The study area for the Arbuckle-Simpson Hydrology Study consists of the Arbuckle-Simpson aquifer and adjacent areas in south-central Oklahoma (Figure 1). The study area encompasses portions of Murray, Pontotoc, Johnston, Carter, Coal, Garvin, and Marshall Counties. The area where the aquifer is exposed at the surface (outcrop) encompasses about 520 square miles, but in some areas, where fresh groundwater flows beneath shallower geologic units, the aquifer extends beyond the outcrop. Determining the extent of fresh groundwater (considered by the OWRB to have dissolved solids content less than 5,000 milligrams per liter) in the subsurface was beyond the scope of the Study. However, freshwater from the Arbuckle-Simpson aquifer is produced from wells in an area west of Sulphur and the CNRA. As determined in this investigation, the water chemistry changes quickly west of the freshwater zone, and becomes saline (Christenson, Hunt, and Parkhurst, 2009). The area where the freshwater zone of the aquifer is known to extend beneath younger geologic units is termed "Arbuckle-Simpson aquifer subcrop" in this report and is shown on Figure 1. The total area of the Arbuckle-Simpson aquifer, as defined for this investigation, is about 600 square miles.

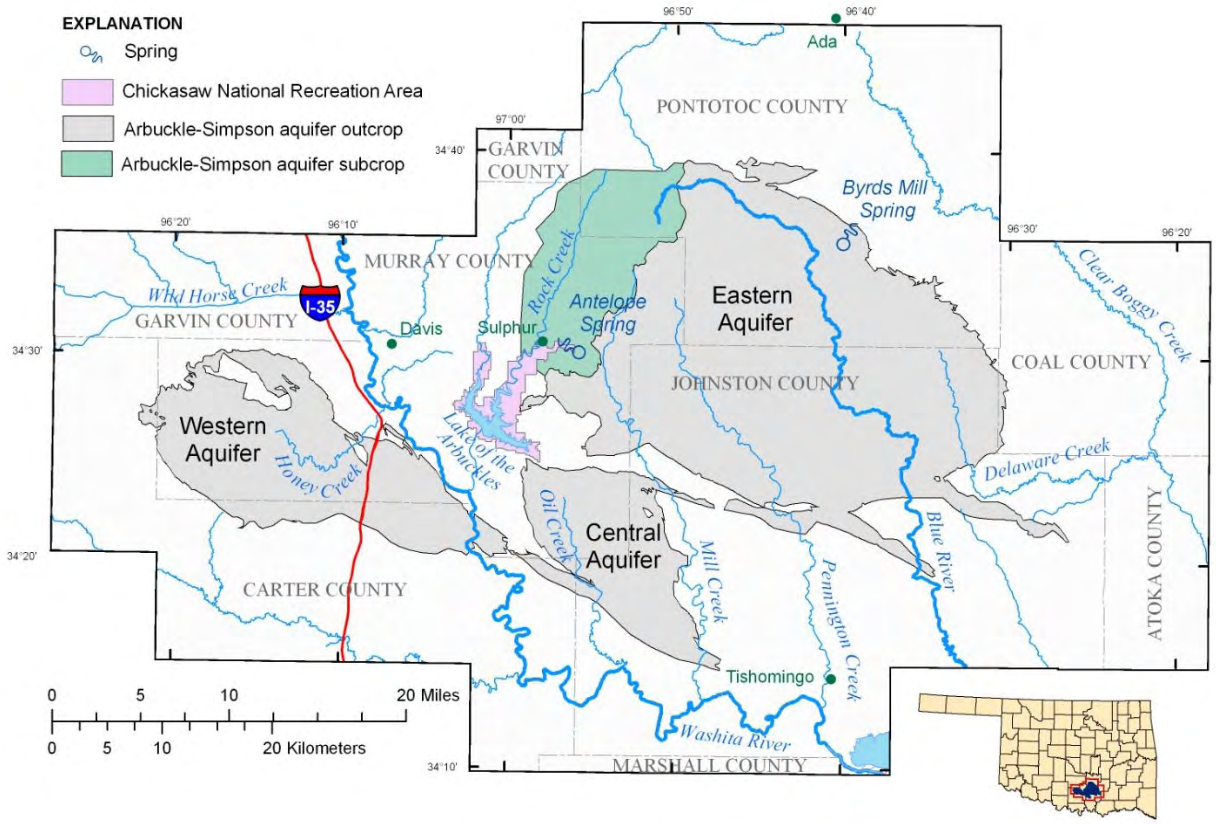

Figure 1. Study area of the Arbuckle-Simpson Hydrology Study.

The aquifer is exposed at the surface in three uplifted areas, which generally correspond to three prominent geologic features: the Arbuckle, Tishomingo, and Hunton anticlines. During the investigation, Study participants referred to these areas by the anticline names, but this terminology caused confusion when discussing specific structural features. Thus, a decision was made to designate the three areas as the western, central, and eastern Arbuckle-Simpson aquifers, which correspond to the Arbuckle, Tishomingo, and Hunton anticline areas, respectively (Figure 1).

Topography over the western Arbuckle Simpson aquifer is very rugged and is characterized by a series of northwest-trending ridges formed on intensely folded strata. The highest elevation in the western Arbuckle Simpson aquifer is 1,377 feet. Three miles to the east the Washita River flows at an elevation of 770 feet, resulting in a local relief of 607 feet. The central and eastern Arbuckle Simpson aquifers are characterized by gently rolling plains formed on relatively flat-lying rocks.

The study area is largely rural. Data from the 2000 Census indicate that the population in the study area is about 45,000. Population on and near the outcrop of the Arbuckle-Simpson aquifer is about 3,000. Towns in the study area include Sulphur, Davis, and Tishomingo. Ada and Ardmore, the larger cities in the region, lie just outside of the study area.

Land overlying the aquifer is characterized by rough stony land, which is suited to the grazing of livestock. The most important industries, outside from those related to agriculture, are mining and tourism and recreation. Several quarries on or near the aquifer produce limestone, dolomite, granite, and sand for commercial purposes. Tourism and recreation are important to the economy of the area. Recreational facilities include Lake of the Arbuckles, Chickasaw National Recreation Area, Turner Falls Park, the Blue River Public Fish and Hunting Area, and several youth camps.

Hydrogeologic Setting

The Arbuckle-Simpson aquifer lies in the Arbuckle Mountains Uplift geologic province, which is commonly referred to as the Arbuckle Mountains. The Arbuckle Mountains consist of folded and faulted Proterozoic and Cambrian igneous rocks and Paleozoic sedimentary rocks ranging in age from Cambrian through Late Pennsylvanian (Figure 2). The Arbuckle Mountains consist of a series of northwest-southeast trending structures that are separated from each other by major Paleozoic fault zones. Structural deformation is greatest in the western Arbuckle-Simpson aquifer, where vertical and overturned beds occur. Structural deformation is much less pronounced in the central and eastern Arbuckle-Simpson aquifers, where the rocks are more flat lying (dips less than 20 degrees), and are deformed mainly by block faulting. The Arbuckle-Simpson aquifer is contained within three major rock units of Upper Cambrian to Middle Ordovician age: the Timbered Hills, Arbuckle, and Simpson Groups. These are described below, from youngest to oldest.

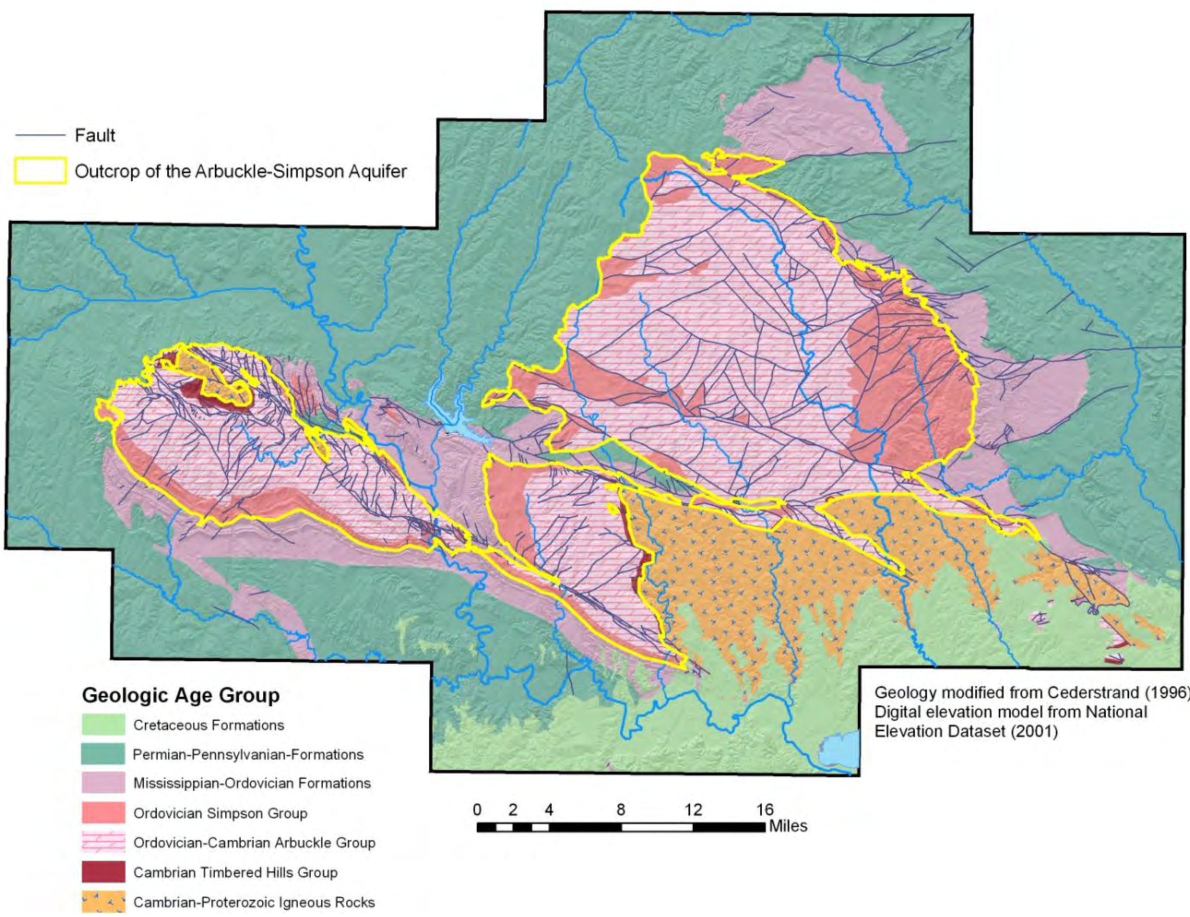

Figure 2. Generalized surface geology of the Arbuckle-Simpson aquifer.

The Cambrian-age Timbered Hills Group is the lowermost geologic unit of the aquifer. The Timbered Hills Group is exposed only in small areas in the Arbuckle-Simpson aquifer and consists of up to 700 feet of limestone, dolomite, and sandstone. Although rocks in the Timbered Hills Group comprise part of the Arbuckle-Timbered Hills aquifer in western Oklahoma, little is known about the water-bearing properties of the Timbered Hills Group in the Arbuckle Mountains. There is no identifiable confining layer that separates the Timbered Hills Group from the Arbuckle Group, and thus the Timbered Hills is assumed to be part of the same groundwater-flow system.

The Arbuckle Group of Late Cambrian to Early Ordovician age comprises the major portion of the aquifer and consists of a thick sequence of carbonate rocks (limestone and dolostone). The Arbuckle Group ranges in thickness from 6,700 feet in the western Arbuckle-Simpson aquifer to less than 4,000 feet in the eastern Arbuckle-Simpson aquifer. Water occurs in cavities, solution channels, fractures, and intercrystalline porosity present in the limestone and dolostone.

The Simpson Group of Early to Late Ordovician age is the uppermost geologic unit of the aquifer. The Simpson Group is characterized by thick beds of cleanly washed quartzose sandstone interbedded with limestones, dolostones, and shales. The Simpson Group is up to 2,300 feet thick in the western Arbuckle-Simpson aquifer, but generally is less than 1,000 feet in the eastern Arbuckle-Simpson aquifer. Water in the Simpson Group occurs in pore spaces between the sand grains in the sandstones.

The Arbuckle-Simpson aquifer is confined below by basement igneous rocks, consisting of Cambrian rhyolites and Proterozoic granites. In areas where the top of the aquifer dips below the surface, it is confined above by younger rocks of various ages. For modeling purposes, the geologic units were grouped into four hydrostratigraphic units (rock units that have reasonably similar hydrologic properties): basement, Arbuckle-Timbered Hills, Simpson, and post-Simpson. The time-stratigraphic, rock-stratigraphic, hydrogeologic, and model hydrostratigraphic units associated with the aquifer are listed in Table 1.

The Arbuckle-Simpson aquifer receives water primarily from infiltration of precipitation on the outcrop area. Generally, groundwater flows from topographically high areas to low areas, where it discharges to springs and streams. Where the Arbuckle-Simpson aquifer dips beneath rocks of lower permeability, the aquifer is confined, and wells that penetrate below the confining layer may be artesian. Several artesian wells flow in the valley of Rock Creek, near Sulphur. The most well known artesian well is Vendome Well in the CNRA.

Many springs discharge from the Arbuckle-Simpson aquifer. The USGS National Water Information System (NWIS) database lists 140 springs in the study area (Figure 3). Springs are unique ecosystems that provide habitat for a wide diversity of aquatic and terrestrial life. Spring habitats differ from other flowing-water systems in that they have constant flow and temperature, exist as small and isolated habitat areas, and have a general lack of large predators. Arbuckle-Simpson springs provide water for drinking water, livestock, fisheries, and recreation. Some springs, such as those at CNRA, have cultural and historical significance. Byrds Mill Spring, which flows about 8,000 gallons per minute (gpm), is the largest spring in Oklahoma and serves as the primary water supply for the City of Ada.

Table 1. Comparison of time-stratigraphic, hydrogeologic, and model hydrostratigraphic units in the Arbuckle-Simpson aquifer

<table>
<tr><th>Time-Stratigraphic</th><th colspan="2">Rock-Stratigraphic Unit</th><th>Hydrogeologic Unit</th><th>Model Hydrostratigraphic</th></tr>
<tr><td>Pennsylvanian to Late Ordovician</td><td colspan="2">Post-Simpson Geologic Units, Undifferentiated</td><td>Upper Confining Unit</td><td>Post-Simpson</td></tr>
<tr><td rowspan="5">Middle Ordovician</td><td rowspan="5">Simpson Group</td><td>Bromide Formation</td><td rowspan="13">Arbuckle-Simpson Aquifer</td><td rowspan="5">Simpson</td></tr>
<tr><td>Tulip Creek Formation</td></tr>
<tr><td>McLish Formation</td></tr>
<tr><td>Oil Creek Formation</td></tr>
<tr><td>Joins Formation</td></tr>
<tr><td rowspan="4">Early Ordovician</td><td rowspan="6">Arbuckle Group</td><td>West Spring Creek Formation</td><td rowspan="8">Arbuckle-Timbered Hills</td></tr>
<tr><td>Kindblade Formation</td></tr>
<tr><td>Cool Creek Formation</td></tr>
<tr><td>McKenzie Hill Formation</td></tr>
<tr><td rowspan="4">Late Cambrian</td><td>Signal Mountain Formation
Butterly Dolomite</td></tr>
<tr><td>Fort Sill Limestone
Royer Dolomite</td></tr>
<tr><td rowspan="2">Timbered Hills Group</td><td>Honey Creek Limestone</td></tr>
<tr><td>Reagan Sandstone</td></tr>
<tr><td>Middle Cambrian</td><td colspan="2">Colbert Rhyolite</td><td rowspan="2">Basement Confining Layer</td><td rowspan="2">Basement</td></tr>
<tr><td>Proterozoic</td><td colspan="2">Tishomingo Granite, Troy Granite, granodiorite, and granitic gneiss</td></tr>
</table>

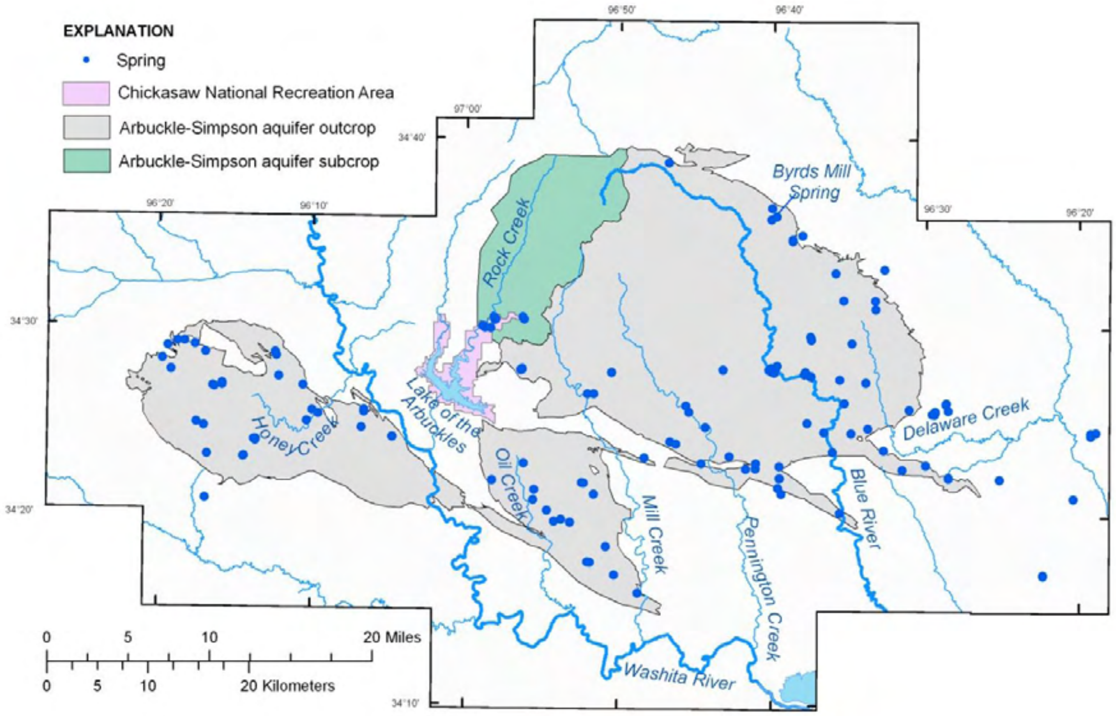

Figure 3. Springs listed in the USGS National Water Information System database within the Arbuckle-Simpson aquifer study area.

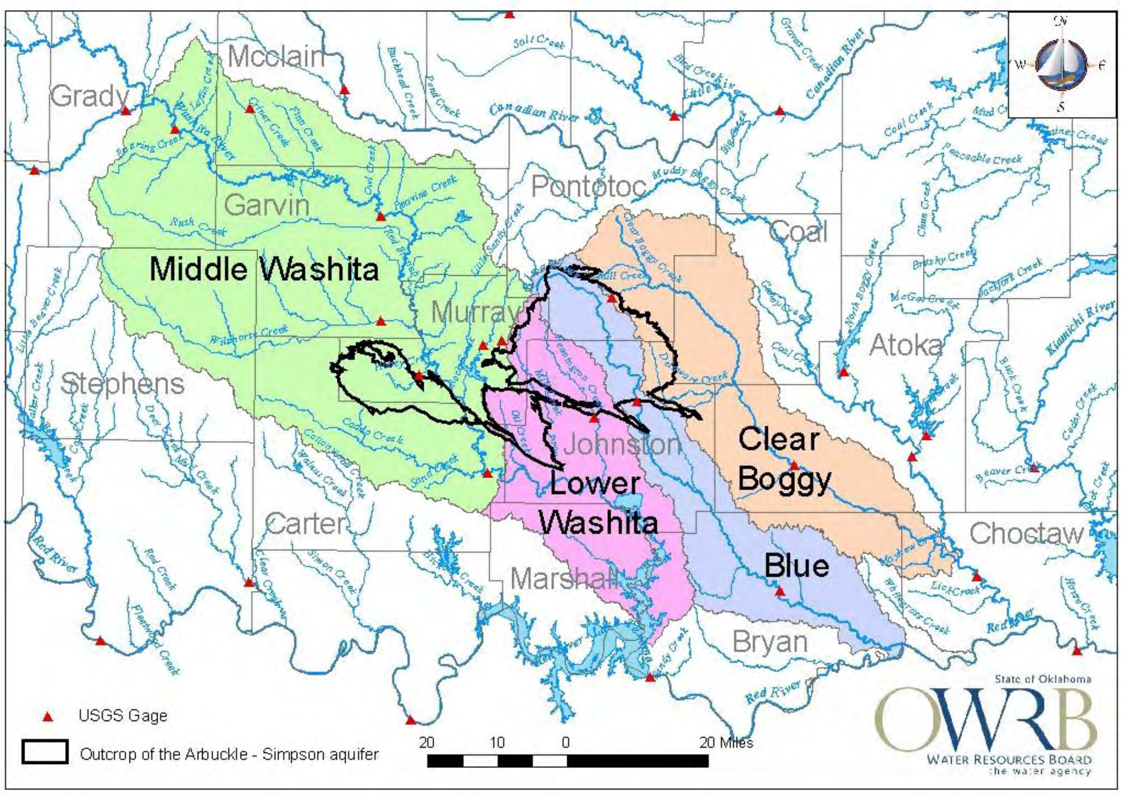

Figure 4. Watersheds in the area of investigation for the Arbuckle-Simpson Hydrology Study.

Springs and seeps sustain flow in several headwater streams originating in the aquifer, such as the scenic Blue River and Honey Creek at Turner Falls. Blue River, which drains a large part of the eastern Arbuckle-Simpson aquifer, is the largest stream that originates within the study area and the only free-flowing river in Oklahoma. Other perennial streams include Pennington, Mill, Travertine, Delaware, Byrds Mill, and Oil Creeks. Major streams emanating from the aquifer are within four watersheds: the Middle Washita, Lower Washita; Blue, and Clear Boggy watersheds (Figure 4).

Previous Investigations

Fairchild, Hanson, and Davis (1990) describe the hydrology of the Arbuckle-Simpson aquifer in Oklahoma Geological Survey (OGS) Circular 91. USGS conducted the fieldwork for the investigation from 1977 to 1979, which consisted of stream gaging, water-level measurements, water quality sampling, and aquifer tests. The hydrology of the Chickasaw National Recreation Area is described by Hanson and Cates (1994). The fieldwork for this investigation was conducted from 1985 to 1987, and was limited to about a 20-square mile area in and immediately adjacent to CNRA. Other hydrologic investigations have been conducted in the aquifer (for example, Barthel, 1985; Harp and McLin, 1986; Wold, 1986; Savoca and Bergman, 1994), but are limited in scope.

The geology of the Arbuckle Mountains has been extensively studied (for example, Denison, 1997; Ham, 1950; Ham, 1973; Johnson, 1991; Perry, 1989; Ragland and Donovan, 1991). Most geological maps of the area derive from Ham and McKinley (1954). However, most geologic information has been obtained from the western Arbuckle-Simpson aquifer along the Interstate 35 road cuts and from petroleum data outside of the aquifer boundaries. Subsurface geologic information over the eastern Arbuckle-Simpson aquifer is especially sparse, and the geologic framework of the aquifer is poorly understood.

Despite the previous hydrologic and geologic studies, very little was known about the aquifer's ability to store and transmit water, and there was insufficient information to predict the response of springs and streams to groundwater withdrawals.

Scope and Approach

The Study was designed as an aquifer-scale assessment of water resources for the allocation of water rights. This was due to the spatial scale of available data that can be obtained within the budget and time frame of the Study and to the nature of Oklahoma water law, which appropriates equal proportionate shares of groundwater over the entire aquifer, or groundwater "basin".

Most of the data collection and modeling efforts were focused on the eastern Arbuckle-Simpson aquifer, because the data needed to build the groundwater-flow model are sparse in the western and central Arbuckle-Simpson aquifer, the eastern Arbuckle-Simpson aquifer is the largest part of the aquifer, most of the current water use from the aquifer is from the eastern Arbuckle-Simpson aquifer, and most of the streams and springs sourced from the aquifer are located on the eastern Arbuckle-Simpson aquifer. The western and central aquifers were addressed with more general methods.

Many types of information are required to understand the hydrology of the Arbuckle-Simpson aquifer. For example, climatic factors, such as precipitation, evaporation, and soil moisture, determine the amount of water available for recharging the aquifer. Geologic information is necessary to evaluate groundwater flow through the highly faulted, structurally complex, carbonate aquifer. Stratigraphy, structure, fracture properties, karst features, diagenesis, burial history, and migration of fluids can affect aquifer storage and how water moves through the aquifer. Groundwater movement through the aquifer is affected by the distribution of hydraulic head and aquifer hydraulic properties and by groundwater withdrawal. Continuous streamflow measurements are necessary to establish baseline conditions and to determine volumes attributed to baseflow, recharge, and runoff.

In addition to understanding the hydrologic system, management of the Arbuckle-Simpson aquifer requires other types of information. For example, information regarding ecosystems and critical habitat for flora and fauna is commonly used to evaluate minimum streamflows. Understanding the range of climatic variability and the potential long-term changes in climate is necessary to sustain water availability for water use and the environment in times of drought. For the regulation of water withdrawals, historical patterns of water supply (drought and flood cycles and period of recurrence) and water withdrawals should be examined.

A multidisciplinary team of researchers employed several methods to obtain and interpret the necessary information. Methods included monitoring of climate, surface water, and groundwater; evaluating petroleum-related information; drilling test wells; conducting aquifer tests; geophysics; geochemistry; isotopic age dating of groundwater; tree-ring analysis; and modeling of groundwater, surface water, and geology. These data and interpretations provide the basis to predict the impacts of groundwater withdrawals on streamflow and to test various water-use strategies.

Funding

The proposed study was estimated to take five years to complete, with a budget of 5.15 million dollars. The actual Study was completed in six years, with a total budget of $3.9 million, which was funded primarily through a 50/50 state/federal cost-share agreement with the U.S. Bureau of Reclamation (Bureau). The cost breakdown of allocated state and federal monies from August 2003 through September 2009 is shown in Table 2.

Table 2. Arbuckle-Simpson Hydrology Study cost breakdown August 2003 through September 2009

	State	Federal	Total
Personnel	338,246.25	338,246.24	676,492.49
Fringe	184,206.38	184,206.38	368,412.76
Travel	14,798.03	14,798.02	29,596.05
Equipment	81,931.85	81,931.85	163,863.70
Supplies	69,798.33	69,798.33	139,596.66
Contractual	1,025,776.70	1,025,776.70	2,051,553.40
Indirect Costs	251,499.44	251,499.45	502,998.89
Totals	**1,966,256.98**	**1,966,256.97**	**3,932,513.95**

In addition to allocated monies, the Study received considerable assistance, both financial and in-kind, from a number of sources. USGS contributed a minimum of $45,000 towards the drilling of the deep test well and provided in-kind services for the geochemical work by covering personnel costs for the geochemists. The Chickasaw Nation contributed approximately $27,000 annually to pay for the operation and maintenance costs for three USGS stream gages. The most significant in-kind contribution was the development of a three-dimensional geologic model by USGS, at no cost to the Study. The geologic modeling effort, which cost about $250,000, was funded by the USGS Earth Surface Processes Team in Denver. Other in-kind services included U.S. EPA, Robert S. Kerr Laboratory in Ada, Oklahoma, which donated the expertise of Dr. Randall Ross and the facility's geophysical logging equipment to log wells and Dr. Ann Keeley to analyze water samples for bacteria. Devon Energy provided funds to Dr. Roger Young and Breanne Kennedy, from Oklahoma University (OU), to conduct a three-dimensional seismic survey on the eastern Arbuckle-Simpson aquifer. Sue Braumiller with the National Park Service (NPS) measured stream and spring flows in CNRA to supplement the synoptic stream measurements collected by OWRB staff.

Several companion studies augmented the Arbuckle-Simpson Hydrology Study. For example, USGS Western Region Geophysical Investigations, under contract with the NPS, conducted two geophysical investigations of the CNRA. The USGS Earth Surface Processes Team and Crustal Imaging and Characterization Team, in cooperation with other state and federal agencies, funded a helicopter electromagnetic and magnetic (HEM) survey over four areas in the eastern Arbuckle-Simpson aquifer. Information obtained from these geophysical investigations was incorporated into the hydrogeologic framework model.

The Oklahoma Water Resources Research Institute provided research grants for two studies that complemented the Arbuckle-Simpson Hydrology Study. Researchers from Oklahoma State University (OSU) and OU collaborated on one study: *Determination of fracture density in the Arbuckle-Simpson aquifer from ground-penetrating radar and resistivity data* (Cemen, Young, and Halihan, 2008). OSU Environmental sociologist Dr. Beth Caniglia received two grants to help fund her study, *Science, Development and Public Opinion: The Adjudication of Groundwater Policy for the Arbuckle-Simpson Aquifer* (Caniglia, 2007).

Participants

The Arbuckle-Simpson Hydrology Study was conducted by the OWRB in cooperation with USGS, OSU, OU, and Oklahoma Climatological Survey (OCS) in accordance with interagency agreements. The Bureau contracted with Hydrosphere Resource Consultants to conduct stream management models. Cooperative projects and contracts funded by allocated funds for the Study are listed in Table 3.

Table 3. Cooperative projects funded by the Arbuckle-Simpson Hydrology Study

Cooperator	Lead Researcher	Task
USGS	Scott Christenson	Geochemical investigation Analysis of aquifer tests Drilling and testing observation well Groundwater flow model
	Bob Blazs	Stream gaging
	David Smith	Airborne geophysical interpretation
	Chuck Blome	Three-dimensional hydrogeologic model
OSU	Todd Halihan	Literature review and data compilation Fracture flow and fracture property analysis Water quality data analysis Aquifer characterization Epikarst analysis Earth-tide analysis
	Jim Puckette	Geologic characterization and evaluation of petroleum information
	Bill Fisher	Instream flow assessment
OU	Baxter Vieux	Determining aquifer recharge with distributed hydrologic model
	Aondover Tarhule	Hydroclimatic reconstruction using tree rings
	Roger Young	Analysis of seismic reflection data
OCS	Chris Fiebrich	Mesonet weather station
Hydrosphere Resources Consultants	Ben Harding	Stream water management network model

OWRB staff coordinated and assisted with the efforts of cooperators and participants; conducted public involvement activities (including meetings, field trips, newsletters, press releases, quarterly reports, web site, and videos); compiled spatial data for the study area and served as the clearinghouse and repository for the Geographic Information System (GIS) layers; conducted several field activities (such as water-level and stream monitoring, and inventories of springs and artesian wells), compiled and analyzed water use data, and conducted research on the geology and hydrology of the Arbuckle-Simpson aquifer. The Bureau ensured federal regulatory compliance and provided assistance with technical issues and public involvement activities.

A technical peer review team, consisting of experts from four agencies, was formed to review the scope of work and provide advice to ensure the use of sound science and appropriate methods. The team consisted of Scott Christenson, with the USGS, Dr. Neil Suneson, with the OGS, Dr. Todd Halihan, with OSU, and Dr. Randall Ross, with the EPA Robert S. Kerr Laboratory. Serving as liaisons between the team and various stakeholders were Dick Scalf, representing Citizens for the Protection of the Arbuckle-Simpson Aquifer (CPASA) and Clayton Jack, representing landowners over the aquifer.

A surface water committee was created in January 2006 to evaluate potential instream flow regimes of major streams that could be implemented in accordance with Senate Bill 288. Chaired by Derek Smithee, chief of the OWRB's Water Quality Division, the committee included representatives of the USGS, NPS, OSU, The Nature Conservancy (TNC), Oklahoma Department of Environmental Quality (ODEQ), Oklahoma

Department of Wildlife Conservation, Oklahoma Conservation Commission, U.S. Fish and Wildlife Service (FWS), and area landowners.

In addition to the cooperators and participants discussed above, many organizations participated in the Study. These included OSU Extension Service, Arbuckle Master Conservancy District, and CPASA. Finally, the Arbuckle-Simpson Hydrology Study would not have been possible without the assistance of the many land owners, municipalities, and operators of rural water districts, who provided access to their property, wells, and springs during this investigation.

METHODS

Public Involvement

Controversy over the proposed sale of water from the aquifer created a high level of interest in the study from citizens, stakeholders, municipalities, and organizations. With the Bureau's assistance, the OWRB developed a public involvement plan in 2003 to keep cooperators and stakeholders informed of the Study's activities and results. Specific goals of the plan were to:

1. Identify and involve individuals, groups, and organizations with diverse interests in the aquifer at the onset and throughout the Study.
2. Identify all issues and concerns early in the process.
3. Help stakeholders understand the goals of the Study.
4. Provide stakeholders with pertinent information to keep them informed of the investigation and results and to help them form educated opinions.
5. Provide forums to facilitate public involvement in the planning and decision-making process.
6. Review and use input and provide feedback to the public.

Information was distributed through a variety of media including fact sheets, newsletters, press releases, videos, field trips, email updates, and presentations. To insure widespread availability of information on the Study, OWRB developed an Arbuckle-Simpson web site (http://www.owrb.ok.gov/studies/groundwater/arbuckle_simpson/arbuckle_study.php).

To "kick-off" the Study, the peer review team discussed the scientific challenges of the investigation at a special Arbuckle-Simpson symposium held in conjunction with the 2003 Governor's Water Conference. In January 2004, the Bureau assisted in facilitating a meeting with federal and state agencies to inform them of the Study; to identify concerns, issues, and level of interest; and to solicit information that could be of use to the Study. Also in 2004, OWRB staff and the technical peer review team led a field trip to the Arbuckle-Simpson aquifer area for OWRB Board of Directors and the public.

In December 2007, the OWRB launched the Arbuckle Data Viewer, an online mapping application that allows Study participants and the public to examine and download data collected for the Study. The data viewer can be accessed through the OWRB's Water Information Mapping System (WIMS) web site at www.owrb.ok.gov/maps/server/wims.php.

In February 2008, OWRB staff and Board members, along with various representatives of state and federal agencies, stakeholders, and researchers, toured the Edwards aquifer area near San Antonio. The Oklahoma group visited the Texas Water Development Board and Edwards Aquifer Authority to learn about the aquifer and the strategies utilized for its management.

On August 18, 2009, OWRB held an informal public meeting in Ada to present the findings of the Study and to solicit input on management strategies. The 5-hour meeting was attended by more than 300 citizens including landowners, legislators, municipalities, special interest groups, and federal, state, and local agencies.

Data Management

Because researchers from several organizations were collecting, using, and interpreting various types of information and data, a system for sharing and managing these data was essential. In June 2004, Study participants with OWRB, OSU, and USGS drafted a data management plan in order to provide researchers, decision makers, and the public access to the data and information necessary to evaluate water management options of the Arbuckle-Simpson aquifer. Types of data and information collected for the Study included documents, spatial data, and environmental data (measured or collected data).

Under a cooperative agreement with the OWRB, OSU compiled more than 300 references for journal articles, theses, dissertations, and books. Bibliographic data were compiled in an EndNotes database, and scanned documents were provided as Adobe PDF files. The database, available as a series of six compact discs, provided researchers with ready access to pertinent information.

Oil-Law Records Corporation of Oklahoma City provided a dataset of almost 15,000 records of oil and gas wells at no cost to the Study. The dataset is from the Natural Resources Information System (NRIS) database, and contains information on well location, completion, and depths of geologic units.

Integral to the data management plan was a geographic information system (GIS) to store, analyze, and display spatial data. ESRI ArcGIS was used as a spatial database. OWRB served as the clearinghouse and repository for the GIS layers and associated metadata. OWRB staff compiled and documented GIS layers for a study area boundary, updated surficial geology, faults, outcrop area of the aquifer rocks, and 30-meter Digital Elevation Models. The development of the online Arbuckle Data Viewer (described in the *Public Involvement* section of this report) greatly facilitated data sharing of spatial and environmental data.

Managing the various environmental data proved to be difficult. OSU and OWRB staff invested in EnivroData software to manage various environmental data. However, the software was not well adapted for managing spatial data or the wide range of data types used in the Study. One student from OSU utilized the EnivroData software to compile existing water chemistry data, but otherwise, cooperators used their own data management systems. Data collected by OWRB staff are stored in OWRB databases and are accessible from the OWRB web site. USGS data are stored in the NWIS database and are easily obtained from USGS web sites. Data collected by other cooperators were generally stored in desktop spreadsheet files and were later submitted to OWRB.

MONITORING

The monitoring program for the Study encompassed climatic, groundwater, and stream variables. Project monitoring stations used during the course of the Study included one Mesonet weather station, 17 wells for monitoring continuous water levels, and three USGS stream gages. The locations of these and other active monitoring stations are shown on Figure 5. In addition to the continuous measurements collected at these stations, discharge from streams and water levels in wells were measured periodically and during quarterly synoptic events.

Much of the analysis of the Arbuckle-Simpson Hydrology Study used data from water years 2004 through 2008 (October 1, 2003 through September 30, 2008). Precipitation during these water years is representative of long-term conditions, as indicated by annual precipitation records for Ada. Ada's average annual precipitation for water years 2004-08 was 38.82 inches, which was only 0.47 inches below the 1911-2008 long-term average precipitation of 39.29 inches (Figure 6). Ada's precipitation for water years 2004, 2006, and 2008 was below the long-term average, while water years 2005 and 2007 were above average.

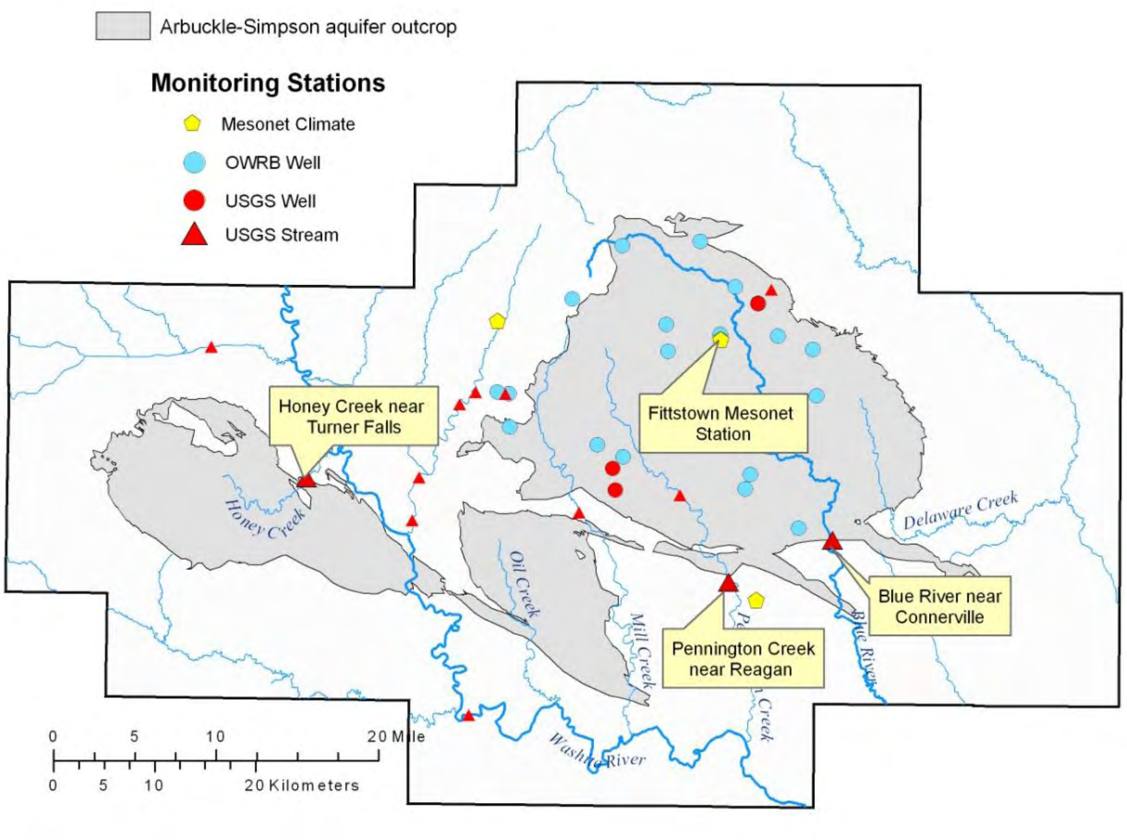

Figure 5. Monitoring stations in the Arbuckle-Simpson Hydrology Study area in 2003-2009.

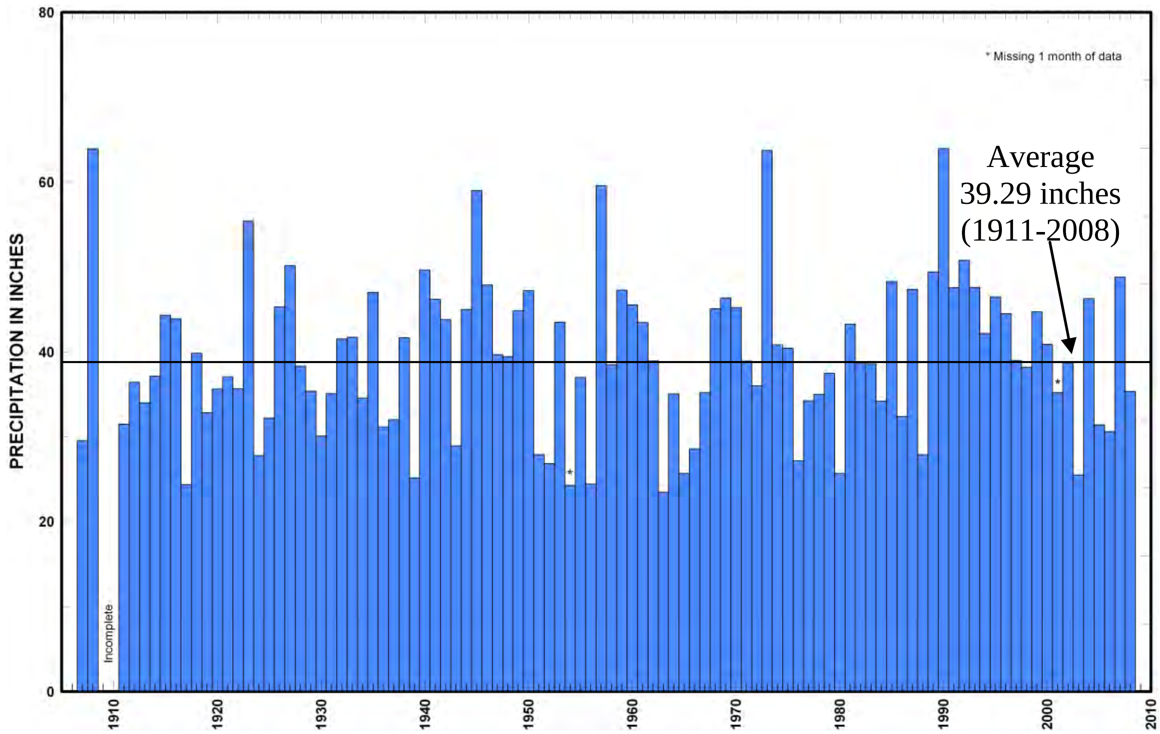

Figure 6. Annual precipitation at Ada, Oklahoma, 1907 to 2008.

Climate

Climatic factors such as precipitation, evaporation, temperature, wind speed, soil temperature, and soil moisture affect groundwater recharge and streamflow, and are thus necessary in evaluating the hydrologic budget. Regionally, these parameters are monitored by the Oklahoma Mesonet, a world-class network of over 110 automated measuring stations covering Oklahoma. Measurements at each station include precipitation, temperature, barometric pressure, relative humidity, wind speed and direction, solar radiation, soil temperature, and soil moisture. Mesonet stations in the study area include Sulphur, Tishomingo, and Fittstown.

The Fittstown Mesonet weather station was commissioned on May 12, 2005, to collect climatic data for the Study. Maintained by OCS, the Fittstown station is the only Mesonet station on the outcrop area of the Arbuckle-Simpson aquifer. In October 2005, OWRB staff installed a 257-foot observation well at the Fittstown Mesonet site and equipped the well with a continuous water-level recorder. Real-time climatic data and water-level elevations can be viewed on the Mesonet web site www.mesonet.org. These data provide researchers with information essential to understanding the aquifer and how it responds to variations in precipitation and other climatic factors.

Groundwater

OWRB staff installed pressure transducers and data loggers in 17 wells during the course of the study to collect continuous water-level measurements. Existing, unused wells were selected on the basis of long-term accessibility. Period of record for continuous water-level data began in June 2004. The continuous groundwater-level measurements provided information on how the aquifer responds to various stresses, such as precipitation and pumping, and were used to calculate aquifer recharge, to determine aquifer properties due to Earth tides and barometric-pressure, and to calibrate the groundwater-flow model.

In addition to the Study observation wells, the USGS maintains three continuous, real-time groundwater-observation wells. Of primary importance is the USGS Fittstown groundwater-observation well. Monitored since 1959, the well holds the longest record of continuous water-level measurements in the study area. The USGS also maintains two groundwater-observation wells near the Town of Mill Creek as part of a monitoring and management plan for Meridian Aggregates Co. The National Park Service maintains two observation wells in the CNRA.

Streamflow

The USGS installed three real-time stream gages specifically for the Study: Pennington Creek near Reagan (07331300), Blue River near Connerville (07332390), and Honey Creek below Turner Falls (07329780). The Pennington Creek and Blue River gages were installed in October 2003, and the Honey Creek gage was installed in October 2004. These gages were installed near the edge of the aquifer at optimal locations for determining groundwater discharge from the aquifer. The three Study gages are in addition to other USGS gages at Byrds Mill Spring, Antelope Spring, and Rock Creek at Sulphur. The USGS maintains two stream gages for the Meridian Aggregates monitoring and management plan: one on Mill Creek near the town of Mill Creek and the other on Pennington Creek east of the town of Mill Creek. All USGS gage data are available in real time through the USGS NWIS web site: http://waterdata.usgs.gov/nwis.

From April 2004 to August 2006, OWRB staff conducted periodic monitoring of 12 stream stations on Blue River and Delaware, Honey, Mill, Oil, and Pennington Creeks. Nine stations were equipped with wire-weight gages installed on bridges, and three stations were equipped with staff gages or tape-down points. One of the stations, located on the upper reach of Blue River, was upgraded for continuous monitoring in February 2005. Point discharge measurements and field parameters were measured during a variety of flow conditions, and rating curves were developed for most stations. The OWRB stream monitoring stations were decommissioned in August 2006. In September 2006, USGS installed gages at two of the periodic monitoring stations (Mill Creek near the town of Mill Creek, and Pennington Creek east of the town of Mill Creek) for the Meridian Aggregates monitoring and management plan. All stream data collected for the Study are available through the online Arbuckle Data Viewer at www.owrb.ok.gov/maps/server/wims.php.

Synoptic Measurements

In addition to the continuous and periodic measurements, OWRB staff conducted synoptic measurements of water levels and stream discharge. The synoptic measurements were conducted over short time periods during baseflow conditions when there was no surface runoff. Data obtained from the synoptic measurements provide a "snapshot" of the water table and streamflow for a specific time and were used to construct potentiometric maps, determine change in aquifer storage, determine recharge rates, and calibrate the groundwater-flow model.

OWRB staff conducted eight quarterly stream and groundwater synoptic measurement events between January 2004 and February 2007. Three of the quarterly stream synoptic events were conducted over the entire aquifer during winter months, when discharge and water quality measurements were collected from 90 sites on streams emanating from the western, central, and eastern Arbuckle-Simpson aquifers. The locations of the discharge measurements are shown on Figure 7. The other quarterly stream synoptic events were conducted primarily on the eastern Arbuckle-Simpson aquifer. All groundwater synoptic events were conducted in only the eastern Arbuckle-Simpson aquifer, using a network of about 100 used and unused wells.

In addition to the quarterly synoptic measurements, three stream-specific synoptic events were conducted to gain additional information on Honey Creek, Washita River, and Blue River. Table 4 lists the synoptic events conducted for the Study.

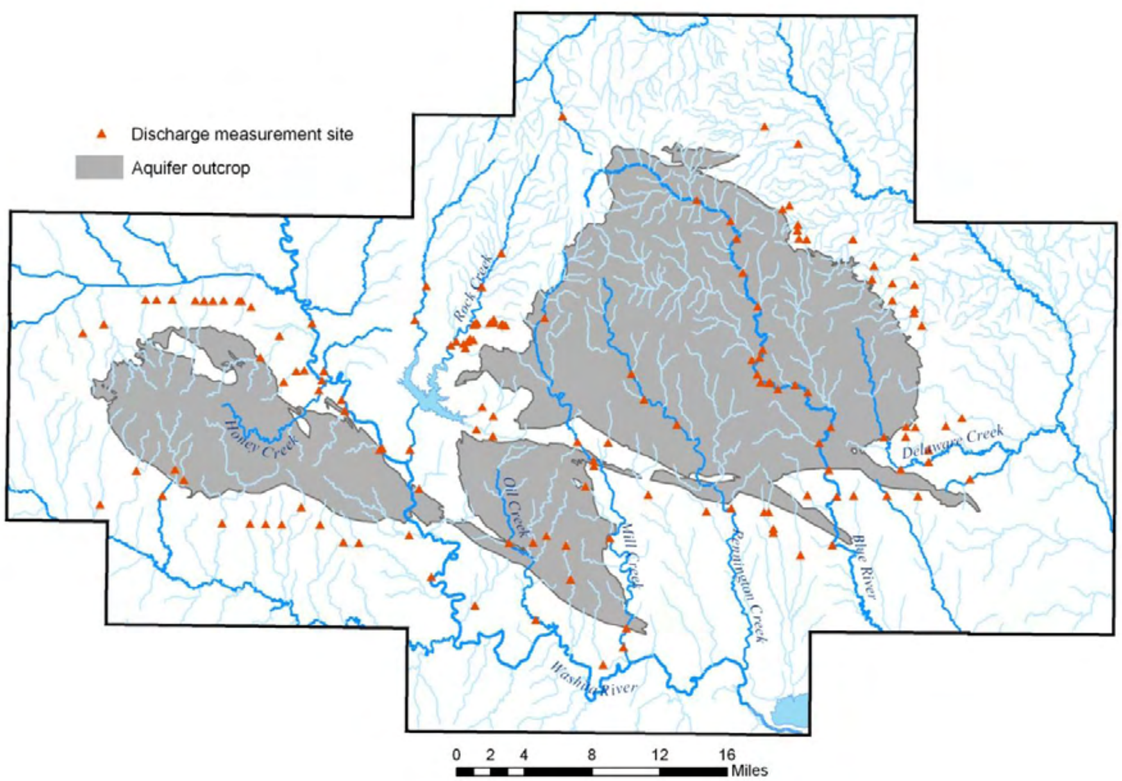

Figure 7. Locations of synoptic discharge measurements of streams on or near the Arbuckle-Simpson aquifer.

Table 4. Synoptic measurement events conducted for the Arbuckle-Simpson Hydrology Study

Date	Area	Type
January 15-16, 2004	Eastern Arbuckle-Simpson	Stream
July 23, 2004	Honey Creek	Stream
September 13-14, 2004	Washita River	Stream
January 17-26, 2005	Aquifer-Wide	Stream
March 23-24, 2005	Eastern Arbuckle-Simpson	Groundwater
March 28-30, 2005	Blue River	Stream
June 22-23, 2005	Eastern Arbuckle-Simpson	Groundwater
September 21-25, 2005	Eastern Arbuckle-Simpson	Stream
September 22-24, 2005	Eastern Arbuckle-Simpson	Groundwater
December 11-17, 2005	Aquifer-Wide	Stream
December 12-13, 2005	Eastern Arbuckle-Simpson	Groundwater
March 24-29, 2006	Eastern Arbuckle-Simpson	Groundwater
March 28-30, 2006	Eastern Arbuckle-Simpson	Stream
June 21-22, 2006	Eastern Arbuckle-Simpson	Groundwater
June 19-21, 2006	Eastern Arbuckle-Simpson	Stream
September 5-7, 2006	Eastern Arbuckle-Simpson	Stream
September 7-8, 2006	Eastern Arbuckle-Simpson	Groundwater
December 18-19, 2006	Eastern Arbuckle-Simpson	Groundwater
February 19-22, 2007	Aquifer-Wide	Stream

RESEARCH

Several research activities were conducted to quantify the various components necessary in understanding the hydrogeology of the aquifer: the geologic framework, geochemistry, groundwater-flow system, hydrologic budget, streamflow, and climate. Many of the research activities were a collaborative effort between various scientists and agencies. Because of the Study's team approach, the research activities are described below by research topic rather than by cooperative agreement or specific researcher. It is not the intent of this report to describe in detail the research methodologies and results. Instead, descriptions are documented in the many reports submitted to the OWRB and listed in Appendix A. Final reports to the OWRB are available on the Arbuckle-Simpson web site. The USGS Scientific Investigations Report: "Hydrogeology and Simulation of Groundwater Flow in the Arbuckle-Simpson Aquifer, South-Central Oklahoma" by Christenson and others (in review) will provide a synthesis of much of the hydrogeologic research and simulation results from the groundwater-flow model.

Hydrogeologic Framework

Any water-resource assessment of an aquifer must take into account the hydrogeologic framework, which defines the physical geometry and rock types in the subsurface through which water flows. The subsurface hydrogeologic framework of the eastern Arbuckle-Simpson aquifer was poorly defined prior to this study because of the complex geology of the aquifer and sparse well data in the deeper portions of the aquifer. Thus, considerable effort was dedicated to characterizing the hydrogeologic framework of the aquifer.

A variety of geologic and geophysical approaches were used to improve the understanding of the hydrogeologic framework of the eastern Arbuckle-Simpson aquifer. Data obtained from drilling water supply and petroleum exploration wells were evaluated to understand down-hole lithology and stratigraphy, and to estimate the thickness, spatial distribution, porosity, and types of pore fluids of hydrostratigraphic units. Surface, subsurface, and airborne geophysical techniques were applied to provide additional insight into the subsurface geology. The geologic and geophysical data were then integrated with existing information to develop a three-dimensional hydrogeologic framework model.

Deep Test Well

A tremendous effort was invested in planning, drilling and testing a deep test well. The purpose of drilling and testing the well was to gain information regarding reservoir characteristics, stratigraphy, aquifer properties, vertical flow gradients, and water chemistry in the lower portion of the Arbuckle-Simpson aquifer. The drilling site was located on the Spears Ranch in section 23-01S-06EI, Johnston County, which is west of Connerville and approximately 1,300 feet from Blue River. The Spears Ranch site was selected because it is in the outcrop of the Arbuckle Group, along a gaining section of Blue River, and not close to a major fault.

Regulatory Issues

The Bureau ensured compliance with the National Environmental Protection Act (NEPA) and National Historical Preservation Act (NHPA). OWRB ensured compliance with the disposal of produced water. Oklahoma Department of Environmental Quality did not require a wastewater discharge permit, but requested the use of Best Management Practices to minimize the amount of sediment entering Blue River or its tributary. To this end, a berm constructed from hay bales was placed on the discharge channel. The berm acted as a filter, trapping the finer cuttings while letting water seep through. Water that passed through the berm ran over the land surface for approximately 200 to 250 feet before entering the tributary to Blue River. OWRB staff conducted periodic monitoring for turbidity, pH, and conductivity during the drilling process to ensure that unacceptable amounts of cuttings and sediment did not enter Blue River.

Drilling

OWRB contracted with the USGS Research Drilling Project to drill a well to a maximum depth of 3,000 feet, the approximate limit of the USGS Gardner-Denver 17-W rig, and to collect water samples at varying depths. USGS and OWRB staff provided oversight during all well drilling and construction activities.

USGS began drilling the Spears 1 test well September 14, 2005. The well was drilled to a depth of 628 feet using air-percussion and air-rotary methods, and then abandoned due to drilling difficulties resulting from excess produced water. USGS moved the drilling rig about 160 feet east of the initial well and on September 25, 2005 commenced drilling the Spears 2 test well. Drilling continued using standard air rotary methods to a depth of

1,473 feet, at which point the engine broke down, and on October 26 the rig was moved to Ardmore for repairs. Drilling resumed on November 16 and continued until November 30. Drilling of the Spears 2 test well ceased at a depth of 1,820 feet when excessive water volume made drilling with air prohibitive and available funds were expended. Produced water was estimated to be between 1,000 and 1,200 gpm at this depth. The borehole was left uncased below a 35-foot length surface casing.

Drilling of the two test wells was hampered by several mechanical and technical problems, the primary of which was the pneumatic hammer's inability to effectively drill when large volumes of water were encountered. Drilling was able to continue to greater depths using standard air rotary techniques, but with much slower penetration rates than those achieved using the pneumatic hammer.

Well Testing

Several tests and analyses were conducted on the wells, including geochemical sampling, geophysical logging, and examination of rock cuttings. Information gained from these tests provided researchers with a greater understanding of the geologic and hydrologic characteristics of the aquifer.

USGS collected high-quality water samples from discreet depths in the Spears 2 test well to create a geochemical profile. The initial plan was to sample 5-6 zones as the hole was drilled using single conductor packer tests. When a test interval was reached, USGS stopped drilling to retrieve the drill string, insert the single-packer system, inflate the packer, and test the interval between the packer and the bottom of the test well. Testing consisted of measuring the hydraulic head and collecting water-quality samples. Three zones were sampled in this manner. However, drilling foam was present in the produced water, even after purging the well overnight, which indicated that the samples were contaminated with air from the drilling process. Thus, the samples were not analyzed, and a decision was made to return in the future to adequately purge the hole and complete the sampling with a down-hole sampler or with straddle packers.

USGS returned to the site in July 2006, to complete the sampling of the Spears 2 test well. Single and double (straddle) packer tests were used to sample five discreet zones at various depths in the well. Water samples were collected for a comprehensive suite of analytes, including field parameters (pH, specific conductance, temperature, dissolved oxygen, alkalinity), major cations and anions, trace elements, oxygen and hydrogen isotopes, nutrients, noble gases, and tritium. Analyses of the water samples indicate that the water was considered fresh, with uniform major-ion and trace-element chemistry from all depths. The average dissolved solids concentration of the five sampled intervals was 325 mg/L. Results of the geochemical sampling are discussed in Christenson, Hunt, and Parkhurst (2009).

Geophysical logging of the two wells was conducted by Dr. Randall Ross with the EPA Robert S. Kerr Laboratory. The logging suite included natural-gamma, spontaneous-potential, normal-resistivity (64 in. long-normal; 16 in. short-normal), lateral-resistivity (48 in.), single-point resistance, 3-arm caliper, P-wave sonic, acoustic televiewer, fluid-temperature, fluid-resistivity, and electromagnetic borehole flowmeter. As a result of hole collapse, the logging tools were only able to reach about 1,335 feet deep. Caliper logs were run before geochemical sampling to assist in selecting placement of the packer.

Data obtained from geophysical logging were used for stratigraphic correlation with logs of numerous petroleum wells in the area; to determine physical properties of the rock matrix and the contained fluids; to characterize fractures; and to obtain hydraulic properties.

Bit cuttings collected from surface to total depth at 10-foot intervals provided a representative sample of the subsurface strata. The cuttings were examined visually, tested chemically, and x-rayed to determine the chemical composition, lithology, and characteristics of the pore network. Bit cuttings from seven 10-foot intervals were made into thin sections and analyzed further. Stratigraphic boundaries or formation boundaries within the Arbuckle Group were determined by comparing the lithotypes represented in the bit cuttings and the gamma-ray log character with the descriptions and wireline logs of a recently drilled deep petroleum exploration well and published descriptions of the Arbuckle Group. Analyses and interpretation of the geophysical logs, bit cuttings, and stratigraphy are discussed in Puckette (2009).

The deep test well project provided the unique opportunity to drill a fresh borehole, collect representative rock samples, conduct water flow measurements and log the borehole with a modern suite of geophysical logs. Although the final depth of investigation by drilling did not reach the original objective, and hole collapse further limited the depth of wireline log investigations, the various types of data analyzed in this project provided much information on the aquifer.

Analysis of Petroleum Data

Information collected during the exploration for petroleum was used to augment the limited aquifer data provided by water supply wells. Types of data included lithologic and geophysical logs to determine thicknesses and spatial distribution of hydrogeologic units, cores and bit cuttings to determine lithology, reports from cable-tool-drilled wells, drill stem test and well completions that establish fluid types in flow units, calculations of fluid properties from geophysical log curves, pore morphology and rock architecture determined from core, and quantified porosity measurements from core and geophysical logs. In all, well records for over 250 water supply wells and 1,150 petroleum exploration wells were examined (Puckette, Halihan, and Faith, 2009).

Geophysical Methods

Several types of geophysical data were collected and analyzed to characterize the hydrogeologic framework of the Arbuckle-Simpson aquifer. A variety of ground, airborne, and subsurface geophysical methods were conducted over the aquifer, including electrical resistivity, gravity, magnetic, ground penetrating radar, seismic, and helicopter electromagnetic surveys.

Electrical Resistivity Imaging (ERI) provided subsurface information of up to 200 meters in depth. ERI data were used to locate fault traces and measure fault orientations for several major faults; to evaluate background properties of the major lithologies; and to evaluate a borehole technique. ERI data were also used to evaluate the thickness, conductivity and storage properties of the epikarst zone (the weathered layer of carbonate rock that lies beneath the soil and above the zone of saturation) in specific study areas of the eastern Arbuckle-Simpson aquifer (Halihan and others, 2009; Riley, 2007; Sample, 2008).

The USGS conducted an airborne (helicopter) electromagnetic/magnetic (HEM) survey over four areas in the eastern Arbuckle-Simpson aquifer in March, 2007. The HEM survey provided subsurface details of the electrical resistivity of the geology up to 150 meters in depth. Electromagnetic data acquired from the survey were used to more precisely locate mapped faults, to identify shallow faults that have no recognizable surface expression, to refine the lithostratigraphic units, and to map the depth and extent of shallow epikarst.

The HEM data from Block B (overlying the City of Ada's well field) and Block D (overlying the Spears test well site) were analyzed for the Arbuckle-Simpson Hydrology Study. First, the data were inverted to give resistivity depth inversion (RDI) profiles. Then, individual RDIs were closely examined to determine geologic structures and contacts, and occurrences of epikarst. The HEM results were corroborated using the analysis and interpretation of ERI surveys performed independently by OSU investigators (Smith, Deszcz-Pan, and Smith, 2009).

The deeper portion of the Arbuckle-Simpson aquifer, ranging from 900-3,500 feet, was studied with gravity and seismic data. Gravity surveys were conducted to identify subsurface faults and the depth to basement. Scheirer and Hosford Scheirer (2006) used gravity data to define the buried extensions of major faults beneath CNRA. A pre-existing seismic survey on the eastern Arbuckle-Simpson aquifer provided evidence that faults extend to basement at an estimated depth of 3,500 feet (Kennedy, 2008; Young, Kennedy, and Russian, 2009).

Fracture Property Analysis

An evaluation of the aquifer's fracture characteristics was undertaken to evaluate the controls that fractures exert on the regional flow system. GIS data for streams and faults were evaluated in the context of hydraulic and outcrop data in the aquifer. The evaluation of vertical fracturing included geophysical (seismic, gravity, and electrical methods) and thermal data (Mouri, 2006; Halihan, Mouri, and Puckette, 2009).

Three-Dimensional Hydrogeologic Framework Model

A digital three-dimensional hydrogeologic framework model was constructed to quantify the geometric relationships of the hydrostratigraphic units within the eastern Arbuckle-Simpson aquifer. The hydrogeologic framework model depicts the volumetric extent of the aquifer and provides the hydrostratigraphic layer thickness and elevation data needed to construct a regional groundwater-flow model. Primary data used to define the faults and hydrostratigraphic surfaces in the model were obtained from geophysical logs, cores, and cuttings from 126 water and petroleum wells. Data from the model were exported to MODFLOW-2000 groundwater-flow modeling software. The exported data included the elevation of the top of the four model hydrostratigraphic units, the land-surface elevation, and the thickness of the Arbuckle-Timbered Hills, Simpson, and the post-Simpson units (Christenson and others, in review).

Geochemical Investigation

USGS conducted a geochemical investigation of the Arbuckle-Simpson aquifer to characterize the groundwater quality at an aquifer scale, to describe the chemical evolution of groundwater as it flows from recharge areas to discharge in streams and springs, and to determine the residence time of groundwater in the aquifer.

To describe the water quality of the aquifer, water samples were collected from 24 wells and 6 springs, including Byrds Mill Spring, in the western, central, and eastern Arbuckle-Simpson aquifers. In addition, water samples were collected from five distinct zones in the Spears 2 test well to create a geochemical profile with depth. To help understand the chemistry and flow system for the mineralized springs and artesian wells of the CNRA, a sample of brine was collected from an oil well, completed in the Simpson Group about 4 miles west of Sulphur.

The suite of analytes for most samples included major cations and anions, trace metals, nutrients, bacteria, oxygen and hydrogen isotopes, chlorofluorocarbons (CFCs), strontium isotopes, noble gases, and tritium. A few samples of water from wells or springs that were suspected to have long flowpaths were analyzed for carbon-14.

The chemical analyses were used as input to geochemical models to describe the chemical evolution of the water as it moves through the aquifer. Age-dating tracers were used to determine the approximate time of recharge and residence time of groundwater in the aquifer. Carbon-14, helium-3/tritium, and chlorofluorocarbons were used to calculate groundwater ages, recharge temperatures, and mixtures of groundwater in the Arbuckle-Simpson aquifer. Concentrations of dissolved argon, neon, and xenon in water samples were used to determine the temperature of the water when it recharged the aquifer. Geochemical inverse modeling determined a set of reactions that account for the compositions of the mineralized waters in the CNRA. Results of the geochemistry investigation are presented in Christenson, Hunt, and Parkhurst (2009); a short summary is available in a fact sheet by Christenson and others (2009).

Groundwater Flow System

Several methods were used to quantify groundwater flow and aquifer hydraulic properties in the eastern Arbuckle-Simpson aquifer. These methods and the interpretive results will be published in the USGS Scientific Investigations Report: “Hydrogeology and Simulation of Groundwater Flow in the Arbuckle-Simpson Aquifer, South-Central Oklahoma” by Christenson and others (in review). A brief summary of the methods are discussed below.

Groundwater Flow

As described in the *Monitoring* section of this report, OWRB staff synoptically measured water levels in wells completed in the eastern Arbuckle-Simpson aquifer quarterly during 2005 and 2006. Water-level measurements and wellhead elevations from these synoptic measurements, and from a previous synoptic event conducted in 1995, were used to create potentiometric surface maps. The potentiometric surface maps were then analyzed to delineate subsurface watersheds. Subsurface watersheds, which represent the area within the subsurface that contributes flowing groundwater to a specific point, were delineated for seven primary discharge areas on the eastern Arbuckle-Simpson aquifer:

Blue River, Byrds Mill Spring, Delaware Creek, Mill Creek, Pennington Creek, Sheep Creek, and Rock Creek. Results indicate that some subsurface watersheds are substantially different from the surface watersheds (Christenson and others, in review).

Aquifer Hydraulic Parameters

Aquifer hydraulic parameters, such as transmissivity, hydraulic conductivity, storativity, and specific yield, help define the flow characteristics of the aquifer. Aquifer hydraulic parameters were determined using multiple, independent methods, including aquifer tests, analysis of groundwater and surface-water hydrographs, and analysis of water-level fluctuations resulting from Earth tides. Both site-specific and regional methods were employed.

One site-specific method was the use of geophysical log measurements from wells to determine porosity. Puckette, Halihan, and Faith (2009) determined porosity of the Oil Creek and McLish Sandstones in the study area using geophysical log measurements from wells that were logged with density, neutron or sonic porosity tools.

Another site-specific method was the use of aquifer tests to determine transmissivity and storage coefficient. USGS and OWRB staff worked with the City of Ada to conduct a test by equipping the City's production wells and surrounding wells with water-level recorders. Several attempts failed due to rain that occurred during the test or to City personnel not notifying USGS prior to turning on the production well. An aquifer test was successfully conducted using two Murray County Rural Water District wells. The test ran from June 8 to June 9, 2006, when a production well was pumped for 24 hours at an average rate of 518 gpm. A test well, located 63 feet from the production well, was equipped with a pressure transducer and data logger that recorded the water level every minute.

Three regional methods were applied to determine hydraulic characteristics of the aquifer. One method entailed analyzing continuous stream gage and groundwater-level data to determine recharge, storage, diffusivity, and transmissivity on the scale of surface-water basins. Another method entailed calculating the storage coefficient of the aquifer as the ratio of the recharge from individual recharge events to the corresponding change in head in a well. The most novel regional approach used water-level fluctuations in observation wells due to Earth tides and barometric-pressure to determine specific storage, storage coefficient, and porosity of the aquifer. For this analysis, Rahi and Halihan (2009) evaluated water-level fluctuations in 14 observation wells of variable depths and variable time intervals.

Hydrologic Budget

The quantification of various hydrologic budget components is important for managing and understanding the water resources of the Arbuckle-Simpson aquifer. The hydrologic budget states that the difference between the rates of water flowing into and out of a hydrologic unit is balanced by a change in water storage:

Flow In-Flow Out = Change in Storage.

Most water enters the Arbuckle-Simpson aquifer as recharge from infiltration of precipitation. Water leaves the aquifer as discharge to streams and springs (baseflow), evapotranspiration, and groundwater withdrawals. Methods used to determine the components of the hydrologic budget for the Arbuckle-Simpson aquifer are described below.

Distributed Hydrologic Model

The hydrologic budgets for the Blue River basin and for the adjacent Clear and Muddy Boggy basins were computed by accounting for precipitation that becomes baseflow discharge from the aquifer, direct runoff, and evapotranspiration. A physics-based distributed hydrologic model was used to develop time series and climatologic quantities of runoff at gaged and ungaged locations in the three basins. Precipitation data taken from bias-corrected radar were used as hourly input values to model the recharge for the period January 1994 to April 2007 (Vieux and Moreno, 2008).

A 500-meter resolution distributed hydrologic model was constructed for the Blue River basin in order to reconstruct streamflow through simulation of direct runoff and estimation of synthetic baseflow at gaged and ungaged locations (Calderon, 2006). The model was refined to improve the soil model representation of hydraulic conductivity, soil depth, effective porosity, and wetting front suction. A refined, 200-meter resolution model was then constructed for the portion of the Blue River basin that overlies the eastern Arbuckle-Simpson aquifer. The model provided accurate estimation of direct runoff for the period 2003-2007 at the USGS gage station Blue River near Connerville as compared to observed cumulative volume.

The calibrated model was used to generate annual gridded infiltration maps for the period 1994-2006, extending the period to encompass the entire analysis period. Gridded infiltration was interpreted from the model and validated for the period 2004-2006 using a water balance at Connerville. Grids of infiltration and actual evapotranspiration were used to derive distributed groundwater recharge over the Blue River subsurface watershed (Vieux and Moreno, 2008; Moreno, 2009).

Estimation of runoff in the Clear and Muddy Boggy Basins was performed for identification of available water resources in these two basins where aquifer discharge and recharge are not major components of the water budget. Seasonal water balances were constructed at the gauging stations Clear Boggy near Caney, Muddy Boggy near Farris, and Muddy Boggy near Unger using available hydrometeorological data. A 500-meter resolution distributed hydrologic model was constructed for these basins and calibrated at the station Clear Boggy near Caney for the period May 2005 to May 2007. This model was used to estimate available water resources at internal ungaged locations (Vieux and Moreno, 2008).

Aquifer Recharge

Inflow to the Arbuckle-Simpson aquifer (recharge) is primarily from infiltration of precipitation, with a very small amount from vertical leakage in the aquifer subcrop. Water does not enter the aquifer from streamflow originating outside the aquifer or from lateral groundwater flows from adjacent aquifers. Outflow from the aquifer (discharge) is primarily to springs and streams, with a smaller amount to well withdrawals and evapotranspiration of groundwater from riparian vegetation. Because most inflows to the Arbuckle-Simpson aquifer are limited to the aquifer outcrop, and because most outflows are to streams, the Arbuckle-Simpson aquifer is particularly well-suited for estimating aquifer recharge. Streamflow measured at the aquifer boundaries provides an accounting of groundwater leaving the aquifer and can be used as a proxy for estimating recharge.

The primary method used in this investigation to estimate recharge to the Arbuckle-Simpson aquifer was a recession-curve-displacement technique (using computer program RORA) that analyzes streamflow records from stream gages. Records from three gages were used for this analysis: Blue River near Connerville, Pennington Creek near Reagan, and Honey Creek below Turner Falls. These gages were installed for the Study and were constructed near the edge of the aquifer at locations optimized for recharge calculations. To express the recharge as a rate, the calculated recharge values were divided by the area of the subsurface watershed that discharged to the stream gage (described in the *Groundwater Flow* section of this report). Recharge rates and recharge zones were refined during the calibration of the groundwater-flow model, and are described in Christenson and others (in review).

Groundwater Withdrawals

OWRB staff evaluated groundwater withdrawals from the Arbuckle-Simpson aquifer. Reported groundwater withdrawals were compiled, verified, and analyzed from water use reports submitted to OWRB by permitted users of groundwater in the aquifer. Annual use data were compiled for the years 1964-2008, and monthly use data were compiled for the years 1994-2008. Annual groundwater use for non-permitted household purposes was estimated based on population and average household use, and groundwater use for non-permitted livestock was estimated based on head of cattle and average consumption rates. Staff visited production wells to verify well locations and pumping schedules. Results of the water use analysis are summarized in an OWRB fact sheet (2009).

OWRB staff conducted an inventory of flowing artesian wells in the Sulphur area. Staff reviewed historical records and documented existing sites by obtaining global positioning system (GPS) locations, photographs, and flow rates. Of the estimated 40 flowing wells that were drilled in the area since 1889, less than 20 wells are still flowing. Total discharge from these wells is currently about 1,000 gpm, of which about 600 gpm (968 acre-feet per year) is from Vendome Well in the CNRA.

Streamflow Reduction

Senate Bill 288 requires the OWRB to determine a maximum annual yield of groundwater that will not reduce the natural flow of water from springs or streams emanating from the aquifer. The mandate imposed by Senate Bill 288 is open to interpretation because it does not state how the reduction of natural flow of water from springs or streams is to be determined. A couple of methods, discussed below, were used to evaluate streamflow reduction.

River Basin Network Flow Model

A river basin network flow model was developed as a tool for OWRB staff to evaluate the impact of groundwater withdrawals on downstream water rights for the Clear Boggy, Blue, and Lower Washita watersheds. The model was constructed to simulate the operation of all permitted water rights along the streams in priority. Over 190 water demands were represented, including 124 irrigators and 17 public water supplies. Groundwater inflows can be adjusted using either specific time series data from outside sources, such as from the Arbuckle-Simpson groundwater model, or using basin-wide adjustments to the baseflow. The model also allows the user to adjust the length of the growing season and the consumptive use of agricultural water users, which could vary with climate in the future (Hydroshpere Resource Consultants, 2007).

Instream Flow Assessment

An instream flow assessment was conducted in 2007 and 2008 to quantify the effect of reduced streamflows on fish habitat in spring-fed streams of the Arbuckle-Simpson aquifer. These spring habitats are considered to be groundwater dependent ecosystems because without the surface expression of groundwater they would not exist in their current form. The species assemblages of the springs are unique in southern Oklahoma because spring habitats provide a consistent source of clean and clear water with minimal temperature fluctuation. The Instream Flow Incremental Methodology (IFIM) was used to assess instream flow requirements of selected fishes on Spring Creek and Blue River, and the Physical Habitat Simulation System (PHABSIM) was used to model habitat of spring-dependent fish species. The IFIM is the most commonly applied and comprehensive instream flow assessment technique used by state and federal agencies.

The instream flow assessment modeled habitat on Spring Creek and Blue River of four spring-dependent fish species: two minnows, southern redbelly dace (*Phoxinus erthyrogaster*) and redspot chub (*Nocomis asper*); and two darters, least darter (*Etheostoma microperca*) and orangethroat darter (*Etheostoma spectabile*). The study sites included two spring-fed streams, one larger stream (Spring Creek) with high groundwater inputs, and a river (Blue River) with both groundwater and surface water inputs that is adjacent to the small spring-fed streams. Spring Creek, a tributary of Pennington Creek, was selected to represent a lower-order stream system than Blue River. Results from this study are reported in Seilheimer and Fisher (2008).

A second instream flow assessment was conducted in 2009 on Mill Creek streams and springs to provide information that could be used by OWRB to assess minimum instream flow requirements for Mill Creek. Three fish species were used in the analysis: orangethroat darter (*Etheostoma spectabile*), southern redbelly dace (*Phoxinus erthyrogaster*), and spotted bass (*Micropterus punctulatus*). The study sites included two sections of main channel in Mill Creek and two spring-fed streams, located adjacent to the channel segments. Results from this study are reported in Seilheimer and Fisher (2009).

Indicators of Hydrologic Alteration

The Indicators of Hydrologic Alteration (IHA) program, developed by The Nature Conservancy, was used to quantify patterns in the flow regimes of selected streams draining the Arbuckle-Simpson aquifer. Gaged streams used in the analysis were Blue River, Pennington Creek, Honey Creek, Travertine Creek, and Byrds Mill Spring. In general, it was found that these streams had stable baseflows that flowed even in the most extreme drought cycles. These streams had strong seasonal variability with lower baseflows in the summer (August through October) and higher baseflows in winter

(January through June). Gages on springs tended to be quite stable, and did not show seasonal variation. The flows at these sites were most influenced by long-term patterns in precipitation (Tejan and Haase, 2008).

Hydroclimatic Reconstruction

A hydroclimatic reconstruction of the Arbuckle-Simpson aquifer using tree-ring chronology was used to gain insight into the long-term pattern of climatic variability predating instrumental records. Reconstructed precipitation and streamflow data were used to investigate the occurrence and frequency of periods of rainfall deficit. The tree-ring chronology developed specifically for this study is based on 31 living Post Oak (*Quercus stellata*) tree samples and is 229-years (1775-2004). The chronology agrees very strongly with an existing chronology for the study area that extends from 1700-1995. Combining the two chronologies resulted in a new 304-year chronology from 1700-2004. This chronology was calibrated against instrumental monthly precipitation and streamflow, for the Arbuckle-Simpson aquifer area. The calibration model was then used to reconstruct precipitation and streamflow back to 1700.

The magnitude of drought that occurs on average once in 5 years was used as the threshold for extracting droughts from the reconstructed series. For the five-year drought, the threshold for total precipitation is less than or equal to 22 inches, and the threshold for streamflow is 1,545 cubic feet per second (cfs). Using the above thresholds, statistical analyses were used to determine the frequency, duration, and intensity of droughts in the Arbuckle-Simpson aquifer. Results of the hydroclimatic reconstruction and drought analysis are reported in Tarhule (2009).

Groundwater-Flow Model

Key to the Study was the development of a digital groundwater-flow model of the aquifer, which was used to test conceptual models of the aquifer and to predict the consequences of aquifer-scale groundwater withdrawals on streamflow. The modeling effort was an integral part of the investigation since the inception of the Study, when early model simulations were conducted to test the conceptual model of the aquifer and to identify data gaps.

A groundwater-flow model of the eastern Arbuckle-Simpson aquifer was developed and calibrated on the basis of information collected during the Arbuckle-Simpson Hydrology Study and previous investigations. This information includes: (1) the geologic history of the aquifer; (2) lithologic, stratigraphic, and tectonic geologic information about the aquifer; (3) climatic data; (4) geochemical data and interpretations; (5) three-dimensional hydrogeologic framework modeling of the aquifer; (6) hydraulic properties of and recharge to the aquifer; (7) water levels measured in wells; (8) stream gaging data for the major streams; (9) streamflow measurements for major and minor streams in the study area; and (10) groundwater withdrawal rates. A comprehensive report documenting the development and application of the groundwater-flow model of the eastern Arbuckle-Simpson aquifer and the supporting hydrologic and geologic data and analysis will be published in Christenson and others (in review). A brief description of the model is presented below.

The MODFLOW-2000 groundwater-flow model, developed by the USGS, was used to simulate groundwater flow and discharge to streams and springs in the eastern Arbuckle-Simpson aquifer. The groundwater-flow model is designed to provide scientific information that can be used to assist in managing water in accordance with Oklahoma groundwater law, which permits groundwater to be withdrawn based on determinations of the maximum annual yield of the aquifer. Thus, the model is designed to work at the aquifer scale, not at the scale of individual wells. The eastern Arbuckle-Simpson groundwater-flow model was divided horizontally into uniform 200 meter by 200 meter model cells. The model was divided vertically into six layers in order to simulate the three-dimensional movement of groundwater in the aquifer. The top and thickness of the post-Simpson, Simpson, and Arbuckle-Timbered Hills hydrostratigraphic units, as well as the elevation of the land surface and top of the basement rocks, were exported from the hydrogeologic framework model (described in the *Geologic Interpretation* section of this report). The model domain extends west of the aquifer outcrop, in the vicinity of Sulphur, to simulate flow in the aquifer subcrop, which is overlain by the post-Simpson hydrostratigraphic unit (Figure 8).

Aquifer hydraulic properties represented in the model are horizontal hydraulic conductivity, vertical anisotropy (the ratio of horizontal to vertical hydraulic conductivity), and specific storage. The hydraulic properties were assigned to three zones based on the post-Simpson, Simpson, and Arbuckle-Timbered Hills model hydrostratigraphic units. Recharge was distributed in the model into four zones based on the model hydrostratigraphic unit at the land surface: post-Simpson, Simpson, Arbuckle-Timbered Hills (north of Sulphur fault), and Arbuckle-Timbered Hills (south of Sulphur fault). Groundwater discharge from the aquifer to streams was simulated with the MODFLOW drain package.

The steady-state model was calibrated to a set of synoptic head and flow observations made in August 1995. Calibration of the steady-state model was done using the parameter estimation process in MODFLOW-2000. The model was calibrated to transient conditions for the 5-year time period starting October 1, 2003 through September 30, 2008, corresponding to water years 2004 through 2008. Recharge initially was set to the daily recharge computed by the RORA program but adjusted during the calibration process to match streamflows recorded at Blue River near Connerville and Pennington Creek near Reagan.

The aquifer hydraulic parameters derived from the groundwater model are similar to aquifer hydraulic parameters determined for the Arbuckle-Simpson aquifer independently by other methods, such as aquifer tests, analyses of groundwater and surface-water hydrographs, and age dating. Agreement of the groundwater-flow model and independently derived parameters indicates the model is a reasonable representation of the groundwater-flow system. In particular, the storage coefficient derived from the transient groundwater-flow model is similar to independent analyses of storage coefficients. The small storage coefficient means that only small volumes of water are available from aquifer storage.

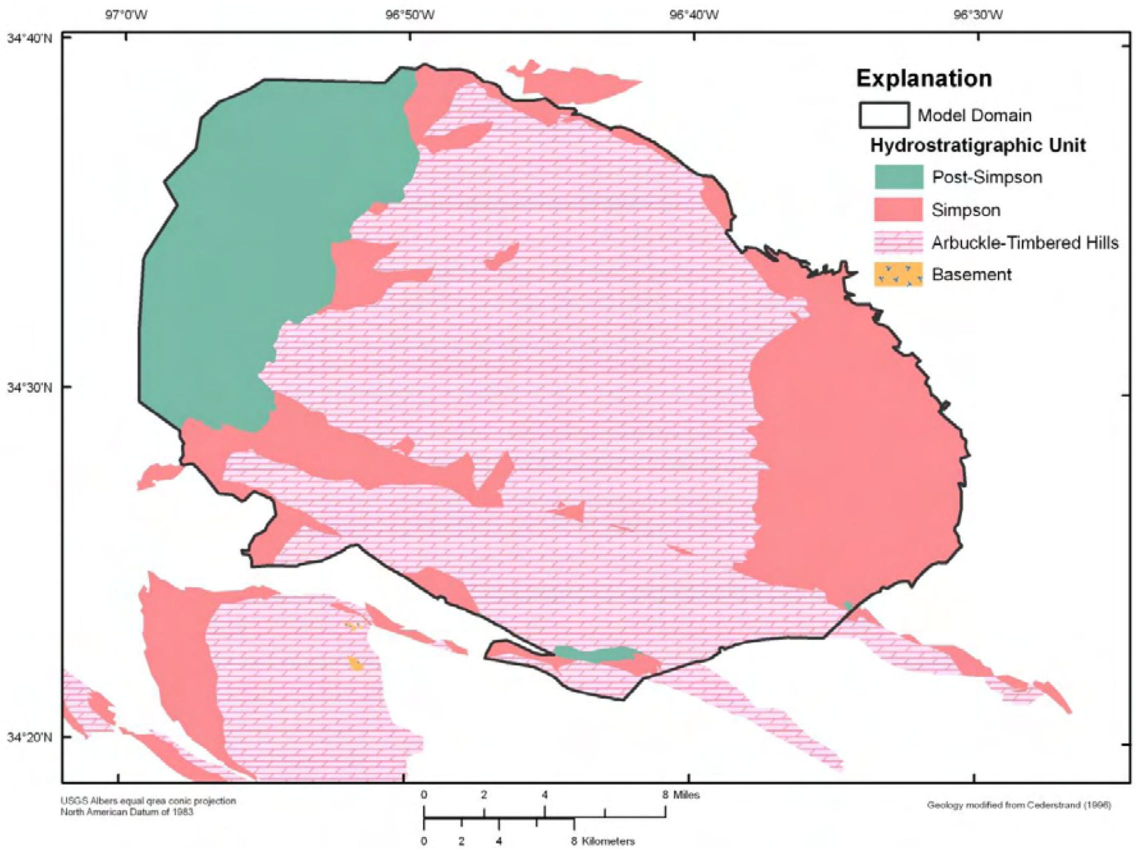

Figure 8. Eastern Arbuckle-Simpson aquifer MODFLOW model domain and model hydrostratigraphic units.

The calibrated eastern Arbuckle-Simpson groundwater-flow model was used to estimate the effects of potential groundwater withdrawals on Blue River and Pennington Creek streamflows and baseflows. Simulations were conducted of groundwater withdrawals distributed uniformly across the aquifer for water years 2004 through 2008. Three simulations of distributed withdrawals were tested, allocating groundwater withdrawals as equal proportionate shares of 0.125, 0.250, and 0.392 (acre-feet/acre)/year.

Simulating distributed withdrawal rates as an equal proportionate share results in very small withdrawals from each cell when wells are placed in every model cell. For example, simulating an equal proportionate share of 0.125 (acre-feet/acre)/year uses a withdrawal rate of only 1.09 gpm in August in each 200 meter by 200 meter model cell. Development of withdrawals from wells is unlikely to occur in this manner, so a test to demonstrate the difference between simulating withdrawals in a distributed manner (an equal proportionate share) and concentrated withdrawals of groundwater was conducted. For this test, groundwater was withdrawn from a single model cell near the center of the eastern Arbuckle-Simpson aquifer in volumes equivalent to 0.125, 0.250, and 0.392 (acre-feet/acre)/year. This test demonstrated that concentrated pumping of groundwater may lessen the effects of withdrawals on some streams but will increase the effect on other streams (Christenson and others, in review).

PROBLEMS

Funding

The greatest challenges of the Study were due to the method of funding, which was based on year-to-year allocations from state and federal governments. Planning, obtaining contracts, and purchasing were difficult due to the uncertainty of amounts allocated from year to year. The fact that the state and federal governments operate on different fiscal years (July 1 and October 1, respectively) added another complication. Furthermore, the State's allocated funds are provided through the gross production tax, from which the amount available is often uncertain until the end of the state fiscal year. Other problems encountered during the Study are discussed briefly below.

Equipment

Minor problems with equipment were encountered during the field investigation. Early in the Study, equipment at two OWRB stream monitoring stations was vandalized: The wire-weight gage on the Blue River near Connerville was damaged twice, and the wire-weight gage on Mill Creek near Ravia was destroyed. To remedy this problem, OWRB installed custom-made steel boxes to house the gages at vulnerable sites. Other problems encountered in the field investigation included failure of water-level monitoring equipment installed in observation wells, landowners using observation wells in time of drought, equipment damage from animals, and pump damage in private wells from taking water-level measurements.

Inaccessible Property

Following the passage of SB 288, some of the landowners overlying the aquifer filed a lawsuit against the OWRB to protest the State's moratorium of their permit applications. These landowners refused to grant access to their land and wells for the purposes of collecting information for the Study. As a result, a significant portion of the eastern Arbuckle-Simpson aquifer was not available for the investigation. Despite this inconvenience, the study team was able to work around the apparent data gap. Synoptic water-level measurements collected in 1995 provided adequate coverage of the area for delineating the potentiometric surface, to which the steady-state groundwater-flow model was calibrated. Furthermore, well reports, bit cuttings, and geophysical logs were available through the OGS for some deep historic wells on the private lands.

Anschutz Seismic Data

Under a cooperative agreement with OWRB and OSU, Dr. Surinder Sahai purchased from Anschutz Exploration Corporation a license agreement for digital data from a seismic line shot over the northern portion of the eastern Arbuckle-Simpson aquifer. The data and information provided on the seismic line (such as basement boundary and fault locations) were considered to be of critical importance for use in the geologic interpretation, 3-D geologic modeling, and the groundwater-flow model. Unfortunately, Dr. Sahai left OSU in May 2007, before analyzing the data.

Dr. Sahai's departure from OSU left in question the status of the license agreement and access to the data by other cooperators. After discussing the issue with OWRB legal staff, Anschutz agreed to grant cooperating researchers associated with the Arbuckle-Simpson Hydrology Study the same right of usage of the seismic data and derivatives as the Licensee (OSU), provided that the cooperators would be bound by the terms of the original license. Under a cooperative agreement with OWRB and OU, and in compliance with the license agreement, Dr. Roger Young received data copies of all files from OSU and completed the processing, analysis, and interpretation of the seismic data.

Deep Test Well

Considerable effort was devoted to drilling and testing a deep test well. The plan was to drill to a maximum depth of 3,000 feet, which is the approximate limit of the USGS Research Drilling Project's Gardner-Denver 17-W rig, with the hope of determining the base of the aquifer. The drilling project was hampered by several mechanical and technical problems, the primary of which was the pneumatic hammer's inability to effectively drill when large volumes of water were encountered. Eventually the volume of produced water forced the drillers to switch from drilling with an air hammer to much slower air rotary methods. After the second attempt, drilling of the Spears 2 test well ceased at a depth of 1,820 feet when excessive water volume made drilling with air prohibitive and available funds were expended.

The geochemical sampling for the test well was not performed as planned, because of fear that the water samples were contaminated by air from the drilling. OWRB and USGS staff researched other methods for deepening the Spears test well or drilling a different deep test well in order to collect depth-stratified samples that would not be contaminated with drilling fluid. Unfortunately, funds were not available for continued drilling. Instead, USGS returned to the site seven months later to complete the sampling of the Spears 2 test well using packer tests. During the time the uncased well was left open, the deeper portion of the hole collapsed, and the logging tools were only able to reach about 1,335 feet deep. Although the final depth of investigation by drilling did not reach the original objective and hole collapse further limited the depth of wireline log investigations and water sampling, the various types of data analyzed in this project provided much information on the aquifer.

PLANS

After reviewing suggested strategies from the August 18 public meeting and working with stakeholders, OWRB staff will make recommendations to the Board for the maximum annual yield and other management strategies. If approved, the Board will then issue a Tentative Order for the maximum annual yield. One or more formal public hearings on the Tentative Order must be held in the area of the Arbuckle-Simpson Groundwater Basin before the Board can issue a Final Order determining the maximum annual yield of the basin.

Researchers and study participants agree that long-term monitoring of the aquifer is critical for water management of the area. Monitoring stations installed specifically for the Arbuckle-Simpson Hydrology Study, and currently in use, consist of three USGS stream gages (Blue River near Connerville, Pennington Creek near Reagan, and Honey Creek below Turner Falls), the Fittstown Mesonet weather station, and four water-level observation wells equipped with continuous data loggers. The Chickasaw Nation and

USGS cooperative funds will cover the operating costs for the three USGS stream gages, and OWRB will cover the maintenance of the Fittstown Mesonet weather station and monitoring of four water-level observation wells through State Fiscal Year 2010. Continued monitoring after June 30, 2010 will depend on funding.

SUMMARY

The Oklahoma Water Resources Board, in collaboration with the U.S. Bureau of Reclamation, the U.S. Geological Survey, Oklahoma State University, and the University of Oklahoma, conducted a comprehensive investigation of the Arbuckle-Simpson aquifer in south-central Oklahoma. The six-year investigation, termed the "Arbuckle-Simpson Hydrology Study", was funded primarily by federal funds through the U. S. Bureau of Reclamation appropriation, and matching funds from the State of Oklahoma. Cooperative agreements with the Bureau were in effect from August 14, 2003 to September 30, 2009.

The Study was the most comprehensive hydrologic investigation ever conducted in Oklahoma. This was due to several factors. Because of the controversial issues and natural scenic beauty of the area, there was much public interest and political involvement. In addition, the science was difficult due to the complex geologic setting of highly faulted, carbonate aquifer. Finally, as the focus of groundwater investigations evolves from assessing water availability to predicting the impacts of groundwater withdrawals on streamflow, scientists require more sophisticated information and methods to determine the effects of proposed water-use strategies.

A multidisciplinary team of researchers worked together to obtain information necessary to determine how much water can be withdrawn from the aquifer while protecting springs and streams. The team consisted of more than 30 scientists, including hydrologists, geologists, geophysicists, geochemists, biologists, engineers, meteorologists, and environmental sociologists. Researchers produced more than 30 reports regarding the Study, including 2 USGS Scientific Investigation Reports, 8 theses, and 13 final reports in accordance with interagency cooperative agreements (Appendix A).

Several methods were employed to obtain and interpret information on the climate, geology, groundwater, and streamflow. Methods included monitoring of climate, surface water, and groundwater; evaluating petroleum-related information; drilling a deep test well; conducting aquifer tests; geophysics; geochemistry; isotopic age dating of groundwater; and modeling of groundwater, surface water, and geology. Many of the methods employed new technology and had not been used before by OWRB for hydrologic investigations. New methods used in the Arbuckle-Simpson Hydrology Study include distributed hydrologic modeling with radar data; tree-ring analysis to reconstruct hydroclimatic conditions; three-dimensional hydrogeologic framework modeling; instream flow assessments, river-basin network modeling, installation of a Mesonet weather station, Earth-tide analysis, and airborne geophysical surveys.

Key to the Study was the development of a digital groundwater-flow model of the eastern Arbuckle-Simpson aquifer, which was used to test conceptual models of the aquifer and to predict the consequences of aquifer-scale groundwater withdrawals on streamflow. Agreement of the groundwater-flow model and independently derived parameters indicates the model is a reasonable representation of the groundwater flow system. Three simulations of distributed withdrawals were tested, allocating groundwater withdrawals as equal proportionate shares of 0.125, 0.250, and 0.392 (acre-feet/acre)/year. Also tested was the effect of concentrated groundwater withdrawals, as opposed to distributed withdrawals, on streamflow.

Major accomplishments for the Arbuckle-Simpson Hydrology Study are listed below:

- A public involvement plan was developed to keep cooperators and stakeholders informed of the Study's progress. Information was distributed through a variety of media including fact sheets, newsletters, press releases, videos, field trips, and presentations.

- The Arbuckle Data Viewer online mapping application was developed to provide the public with ready-access to data collected for the Study.

- Three USGS stream gages and the Fittstown Mesonet weather station were installed for the Study. The stream gages provided five years of streamflow records, which were used to estimate aquifer recharge. The Mesonet station includes a 257-foot observation well, which was installed to monitor groundwater level along with other hydroclimatic data.

- Eight quarterly stream and groundwater synoptic measurement events were conducted between January 2004 and February 2007. The water-level measurements were used to create potentiometric surface maps to delineate subsurface watersheds, revealing that some subsurface watersheds are substantially different from the surface watersheds.

- A geochemical investigation of the Arbuckle-Simpson aquifer was conducted to characterize the groundwater quality at an aquifer scale, describe the chemical evolution of groundwater as it flows from recharge areas to discharge in streams and springs, and to determine the residence time of groundwater in the aquifer. Geochemical inverse modeling determined a set of reactions that account for the compositions of the mineralized waters in the Chickasaw National Recreation Area.

- Information collected during the exploration for petroleum (including well records for over 1,150 petroleum exploration wells, lithologic and geophysical logs, cores and bit cuttings) was used to determine thicknesses and spatial distribution of hydrogeologic units, lithology, fluid types, and aquifer properties.

- A 1,820-foot test well was drilled to gain information regarding lithology, stratigraphy, aquifer properties, vertical flow gradients, and water chemistry in the lower portion of the Arbuckle-Simpson aquifer. The deep test well provided the unique opportunity to collect representative rock and water samples, conduct water flow measurements, and log the borehole with a modern suite of geophysical logs from a fresh borehole.

- Several geophysical techniques (including gravity and magnetic surveys, seismic testing, electrical resistivity imaging, and helicopter electromagnetic surveys) were used to characterize the subsurface geology and evaluate groundwater flow through the highly faulted, structurally complex, carbonate aquifer. A pre-existing seismic survey on the eastern Arbuckle-Simpson aquifer provided evidence that faults extend to basement at an estimated depth of 3,500 feet.

- A digital three-dimensional hydrogeologic framework model was constructed to quantify the geometric relationships of the geologic units within the eastern Arbuckle-Simpson aquifer and provide the geologic framework needed to construct a regional groundwater-flow model. The hydrogeologic framework model greatly improved the final groundwater-flow model and our understanding of the Arbuckle-Simpson aquifer.
- Effects of Earth tides and barometric pressure on water-level fluctuations were analyzed to determine specific storage, storage coefficient, and porosity of the aquifer.
- A distributed hydrologic model was used to develop the hydrologic budgets for the Blue River basin and for the adjacent Clear and Muddy Boggy basins. Precipitation data taken from bias-corrected radar were used as hourly input values to model the recharge for the period January 1994 to April 2007.
- Aquifer recharge was determined by analyzing streamflow records from three stream gages (Blue River near Connerville, Pennington Creek near Reagan, and Honey Creek below Turner Falls).
- A 300-year tree-ring chronology was developed and used to reconstruct streamflow and precipitation of the region.
- A river-basin network model was developed to assess the impact of groundwater withdrawals on downstream surface water rights.
- An instream flow assessment was conducted to quantify fish habitat in spring runs of the Blue River and Pennington Creek.
- A digital groundwater-flow model of the eastern portion of the aquifer was developed to test conceptual models of the aquifer and to predict the consequences of aquifer-scale groundwater withdrawals on streamflow.

In conclusion, the Arbuckle-Simpson Hydrology Study greatly advanced the state of knowledge of the geology, hydrology, and many other aspects of the aquifer. Study results provide a sound understanding of aquifer recharge, discharge, and groundwater flow through the aquifer. A digital groundwater-flow model of the eastern Arbuckle-Simpson aquifer enables OWRB to predict the consequences of groundwater withdrawals on streamflow. Most importantly, the results of this investigation provide the information necessary for decision makers and stakeholders to make informed, science-based decisions regarding management of the water resources of the Arbuckle-Simpson aquifer.

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