OKLAHOMA WATER RESOURCES BOARD
OWRB
the water agency

Arbuckle-Simpson Hydrology Study

Annual Report
Federal Fiscal Year 2006

Prepared by Noel Osborn

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Oklahoma Water Resources Board

In Cooperation With

U.S. Bureau of Reclamation
U.S. Geological Survey
Oklahoma State University
University of Oklahoma
The Oklahoma Climatological Survey
Chickasaw Nation

CONTENTS

ARBUCKLE-SIMPSON HYDROLOGY STUDY
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INTRODUCTION

The Arbuckle-Simpson Hydrology Study (Study) is a five-year, comprehensive study of the Arbuckle-Simpson aquifer and associated springs and streams in south-central Oklahoma. The Study is funded through a 50/50 state/federal cost-share agreement with the U.S. Bureau of Reclamation (Bureau) and the Oklahoma Water Resources Board (OWRB). A multidisciplinary team of researchers from various agencies and universities is working together to understand the geology and hydrology of the region.

Now beginning the fourth year of the investigation, the team has made considerable progress in obtaining information necessary to determine how much water can be withdrawn from the Arbuckle-Simpson aquifer while protecting springs and streams. To date, the investigation has focused on monitoring and evaluating various aspects of the aquifer system, which include characterizing groundwater and surface water flow, quantifying the hydrologic budget, and defining the geologic framework. This report describes the Study, progress through September 30, 2006, initial findings, problems, and upcoming activities.

BACKGROUND

The Arbuckle-Simpson aquifer, which underlies more than 500 square miles in south central Oklahoma, is the principal water source for approximately 39,000 people in Ada, Sulphur, and others in the region. The aquifer is also the source of a number of important springs in the region, including Byrds Mill Spring, Ada’s primary drinking water source, and those in the Chickasaw National Recreation Area (CNRA), the destination for about 3.4 million visitors each year. The U.S. Environmental Protection Agency has designated the aquifer’s eastern portion as a Sole Source Aquifer, a mechanism to protect drinking water supplies in areas with limited water supply alternatives.

Early in 2002, communities in Canadian County seeking future supply proposed to pump as much as 80,000 acre-feet of water per year from the aquifer and transport it to central Oklahoma. Although Oklahoma water law considers groundwater the private property of the landowner, local residents, citizens’ groups, and the National Park Service were concerned that large-scale withdrawals of water from the Arbuckle-Simpson aquifer would cause groundwater levels to decline, resulting in declining flow in streams and springs.

In response to growing concerns, the State Legislature passed Senate Bill 288 in May 2003. SB 288 places a moratorium on municipal use outside the region until the OWRB conducts a comprehensive study to determine the maximum annual yield that will not reduce the natural flow of water from springs or streams emanating from the aquifer. Because current Oklahoma water law does not take into account the hydrologic interaction between surface and groundwater, the legislation sets a new precedent in Oklahoma water law.

OVERVIEW OF STUDY

Purpose and Objectives

The purpose of the Arbuckle-Simpson Hydrology Study is 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.

Specific objectives are:

1. Characterize the 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 study area's surface hydrology, including stream and spring discharge, runoff, and base flow, and the relationship of surface water to groundwater.
3. Construct a digital groundwater/surface water flow model of the 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 principal streams; identify potential sources of natural contamination as well as areas most vulnerable to contamination.
5. Construct network stream models for the Clear Boggy Creek, Blue River and Lower Washita River stream systems for use in the allocation of water rights.
6. Propose water management options, consistent with state groundwater and stream water laws, which address water rights issues, pumping impacts on springs and stream base flows and water quality, and water supply development.

Participants

Coordinated by the OWRB, research is being conducted by several state and federal agencies and universities. Cooperators and participants in the Study include the U.S. Bureau of Reclamation (Bureau), U.S. Geological Survey (USGS), U.S. Environmental Protection Agency (U.S. EPA), Oklahoma State University (OSU), the University of Oklahoma (OU), Oklahoma Geological Survey (OGS), The Oklahoma Climatological Survey (OCS), National Park Service (NPS), Chickasaw and Choctaw Nations, U.S. Fish and Wildlife Service (FWS), Oklahoma Department of Environmental Quality (ODEQ), Oklahoma Department of Wildlife Conservation, Citizens for the Protection of the Arbuckle-Simpson Aquifer (CPASA), The Nature Conservancy (TNC), area landowners, local communities, organizations, and water users. Table 1 lists cooperating agencies and lead researchers.

A technical peer review team consisting of experts from various agencies reviews the scope of work and provides advice to ensure the use of sound science and appropriate methods. The team consists of Scott Christenson (USGS), Dr. Todd Halihan (OSU), Dr. Neil Suneson (OGS), and Dr. Randall Ross (EPA). Serving as liaisons between the team and various stakeholders are Dick Scalf, representing CPASA and Clayton Jack, representing landowners over the aquifer.

A surface water committee was created 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 includes representatives of the USGS, NPS, OSU, TNC, Oklahoma Department of Environmental Quality, Oklahoma Department of Wildlife Conservation, U.S. Fish and Wildlife Service, and area landowners.

Table 1. Cooperating agencies and lead researchers in the Arbuckle-Simpson Hydrology Study

Agency	Lead Researcher/ Contact	Activities
USGS	Scott Christenson	Groundwater flow modeling; geochemistry; aquifer characterization
	Bob Blazs	Stream gages
	Andrew Hunt, David Parkhurst	Geochemistry
	Charles Blome	Geologic modeling
	Dan Scheirer	Geophysics
OSU	Todd Halihan	Fault and aquifer characterization; literature review
	Jim Puckette	Geologic characterization; evaluation of petroleum information
	Surinder Sahai	Seismic data
	Beth Caniglia	Environmental sociology
	Bill Fisher	Instream flow
OU	Aondover Tarhule	Tree-ring chronology
	Baxter Vieux	Rainfall-runoff modeling
	Roger Young	Geophysics
OWRB	Noel Osborn	Study oversight and coordination; groundwater monitoring; spring and well inventory; water use
	Bob Fabian	Project administrator
	Monty Porter	Streamflow monitoring
	Mike Sughru	GIS applications and data management
	Andy Scurlock	Data management
	Brian Vance	Public involvement
Bureau	Collins Balcombe	Bureau oversight; NEPA and NHPA compliance
OCS	Chris Fiebrich	Mesonet weather station
EPA Kerr Lab	Randall Ross	Geophysical logging
NPS	Sue Braumiller, Jennifer Back	CNRA monitoring

Time Line

The Study was initiated in August 2003, when the cooperative agreement between the OWRB and Bureau was signed. The Study consists of three primary phases: field investigation, modeling, and evaluation of water management options. The first three years of the proposed five-year study were devoted primarily to field investigation (Phase I). Now entering the fourth year of the Study, the primary focus will be on developing the groundwater and surface water models and evaluating minimum instream flow requirements (Phase II). The last year of study (Phase III) will be devoted to evaluating various water management options (Table 2).

Table 2. Time line of phases in the Arbuckle-Simpson Hydrology Study

Calendar Year	2003		2004				2005				2006				2007				2008			
Phases	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
I. Field Investigation																						
II. Modeling																						
III. Management Options																						

STUDY AREA

The study area for the Arbuckle-Simpson Hydrology Study consists of the aquifer outcrop and adjacent areas in the Arbuckle Mountains in south-central Oklahoma (Figure 1). The study area encompasses portions of Murray, Pontotoc, Johnston, Carter, Coal, Garvin, and Marshall Counties. The outcrop of the aquifer encompasses about 500 square miles, but the full extent of the aquifer is unknown. In some places, such as near Sulphur, the aquifer extends into the subsurface beneath shallower formations.

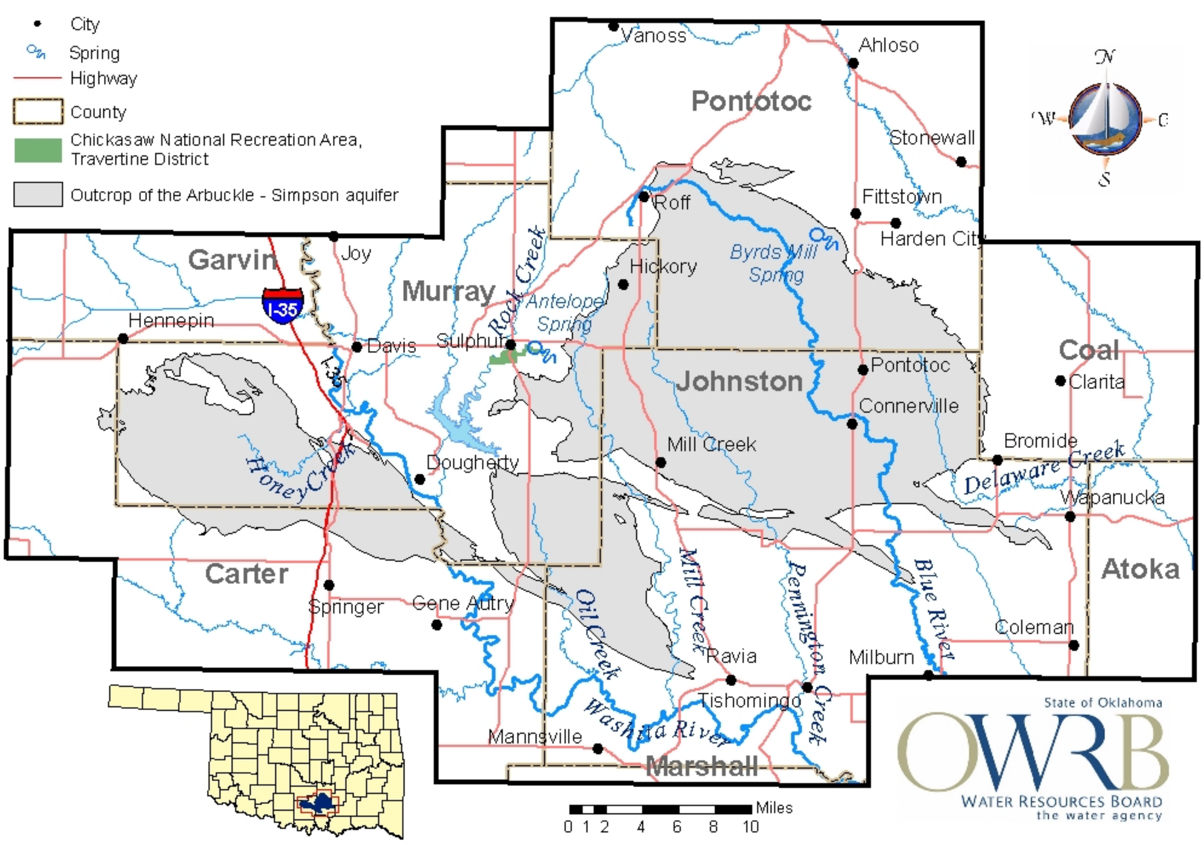

Figure 1. Study area for the Arbuckle-Simpson Hydrology Study.

Hydrogeologic Setting

Rocks comprising the Arbuckle-Simpson aquifer are exposed at the land surface in three uplifted areas, which for the purposes of this study, are referred to as the Arbuckle, Tishomingo, and Hunton Anticline areas (Figure 2). The southwestern area is on the Arbuckle Anticline, a geological structure that was formed 300 million years ago when intensive folding and faulting of a thick sequence of Paleozoic rocks formed the ancestral Arbuckle Mountains. Originally rising several thousand feet above the surrounding plains, the mountains have been eroded to their present-day maximum relief of 600 feet. Topography over the steeply dipping strata is very rugged. Road cuts along Interstate 35 provide unique views of the thick sequence of Paleozoic rocks and complex structure of the Arbuckle Anticline. The eastern area is on several structural features, of which the Hunton Anticline is the most prominent, and the central area is on the Tishomingo Anticline. The structural deformation on these two anticlines is much less pronounced than on the Arbuckle Anticline, and the topography consists of gently rolling plains formed on relatively flat-lying rocks.

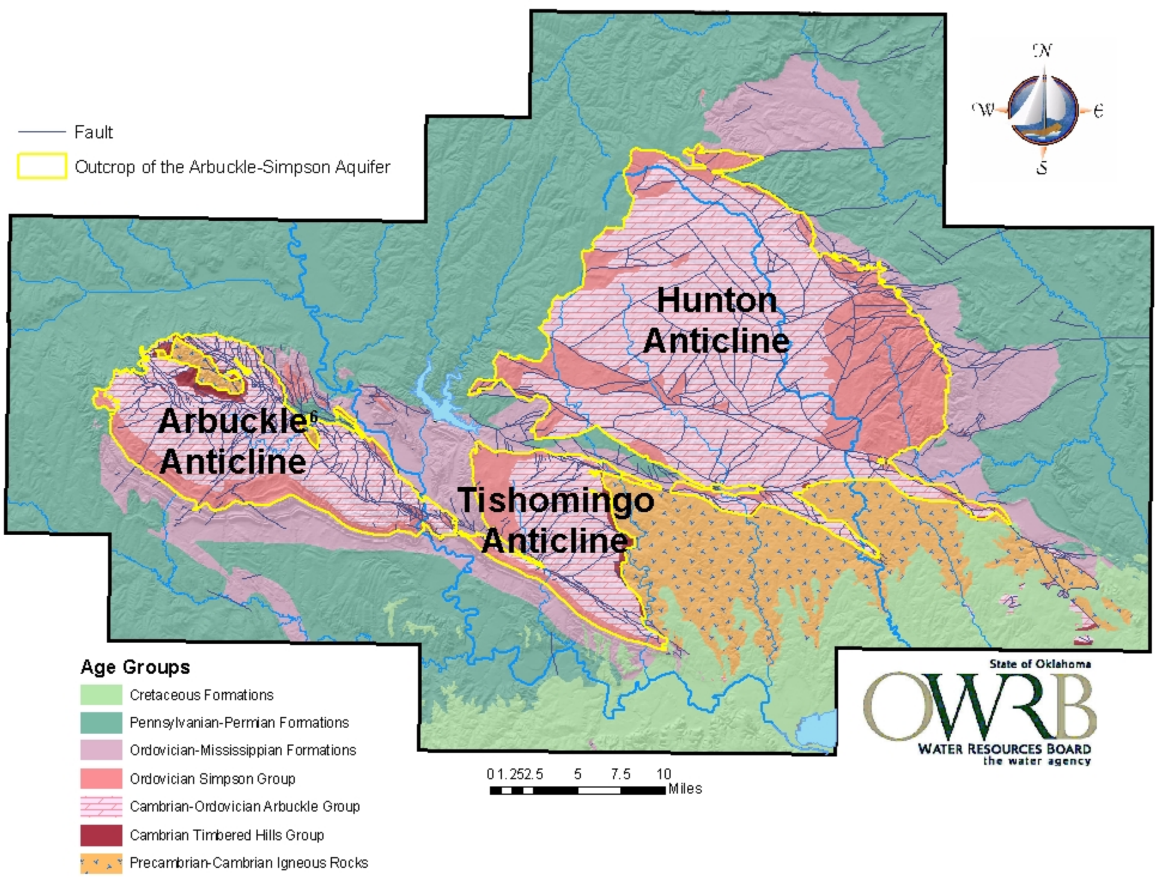

Figure 2. Generalized surface geology and outcrop areas of the Arbuckle-Simpson aquifer.

The Arbuckle-Simpson aquifer occurs within three major rock units of Upper Cambrian to Middle Ordovician age: the Simpson, Arbuckle, and Timbered Hills Groups. The aquifer is confined below by basement igneous rocks, consisting of Cambrian age rhyolite and Precambrian granites. In areas where the top of the aquifer dips below the surface, it is confined above by younger rocks of various ages. The geologic and hydrogeologic units associated with the aquifer are listed in the stratigraphic section (Table 3).

The Simpson Group is the youngest, uppermost geologic unit of the aquifer. Present over about one third of the outcrop area, the Simpson Group ranges in thickness from less than 1,000 ft in the Hunton Anticline area to 2,300 ft in the Arbuckle Anticline area. The Simpson Group is comprised of five formations, four of which consist of a basal sandstone overlain by limestones and dolomites containing some shale. The basal sandstones range in thickness from 50-350 ft. In the Hunton Anticline area, the basal sandstones of the McLish and Oil Creek Formations consist of high-quality quartz sands that are mined for the manufacture of glass. Water in the Simpson Group is obtained primarily from pore spaces between the sand grains in the sandstones. Wells completed in the Simpson can yield as much as 100-200 gallons per minute (gpm).

Table 3. Stratigraphic section associated with the Arbuckle-Simpson aquifer

<table>
<tr><th>System</th><th colspan="2">Geologic Unit</th><th>Hydrogeologic Unit</th></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></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">Lower Ordovician</td><td rowspan="6">Arbuckle Group</td><td>West Spring Creek Formation</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">Upper 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></tr>
<tr><td>Precambrian</td><td colspan="2">Tishomingo Granite, Troy Granite, Granodiorite, and Granitic Gneiss</td></tr>
</table>

The Arbuckle Group comprises the major portion of the aquifer in terms of thickness, outcrop extent, and volume of usable water. The Arbuckle Group consists of a thick sequence of carbonate rocks (limestone and dolomite), with minor layers of sandstone and shale. Six primary formations comprise the Arbuckle Group in the study area: Fort Sill Limestone and the Signal Mountain, McKenzie Hill, Cool Creek, Kindblade, and West Spring Creek Formations. In addition, two thick dolomite zones (Royer and Butterly) are recognized. In the Arbuckle Anticline area, the Arbuckle Group is as thick as 6,700 ft and consists primarily of limestone ($CaCO_3$). In the Hunton and Tishomingo Anticline areas, the unit is less than 4,000 ft thick and consists primarily of dolomite ($CaMg(CO_3)_2$). Water is obtained from cavities, solution channels, fractures, and intercrystalline porosity present in the limestone and dolomite rocks. Wells completed in the Arbuckle Group commonly yield 200 to 500 gpm. Some deeper wells (800- 2,000 ft) are reported to yield as much as 2,500 gpm, while shallow wells can yield less than one gpm.

Underlying the Arbuckle Group is the Timbered Hills Group. The Timbered Hill Group crops out in small areas within the study area, and consists of up to 700 ft of limestone, dolomite, and sandstone. Little is known about the water-bearing properties of the Timbered Hills Group in the study area. However, rocks in this geologic unit comprise part of the Arbuckle-Timbered Hills aquifer in western Oklahoma. Because the Timbered Hills Group is believed to be in hydrologic connection with the Arbuckle Group, it is considered part of the Arbuckle-Simpson aquifer for the purposes of the Study.

About two-thirds of the aquifer consists of carbonate rocks (limestones and dolomites), which are soluble. Infiltrating water slowly dissolves the rock, leading to the formation of solution channels and cavities along bedding planes, fractures, and faults. Karst (solution) features, such as sinkholes and caverns have developed in some areas of the aquifer.

The complex geologic features of the aquifer affect how water moves through the aquifer. Features such as folds, faults, bedding planes, and solution channels may influence groundwater flow paths and flow rates. The numerous faults affect the movement of water through the aquifer because they can act as barriers to groundwater flow or as conduits through which water travels. Water moves slowly through fine fractures and pores and rapidly through solution-enlarged fractures and conduits.

The Arbuckle-Simpson aquifer receives water primarily from infiltration of precipitation on the outcrop area. Most of the water discharges naturally to streams, rivers, and springs. Presently, only a small portion discharges artificially through pumping and flowing wells. Generally, groundwater flows from topographically high areas to low areas, where it discharges to springs and streams. Groundwater flow in the Arbuckle Anticline region appears to radiate from the crest of the anticline. Regional groundwater flow in the Hunton Anticline area is southeast, but a small component is southwest toward Sulphur. 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 of these wells is Vendome Well in the CNRA.

Surface Water

Major streams emanating from the aquifer are within four watersheds: Honey and Hickory Creeks are in the Middle Washita watershed; Mill, Pennington, and Oil Creeks are in the Lower

Washita; Blue River is in the Blue watershed; and Byrds Mill and Delaware Creeks are in the Clear Boggy watershed (Figure 3). These streams are sustained throughout the year by groundwater discharge to springs and seeps.

At least 100 springs are known to discharge water from the aquifer to streams that drain the outcrop area. The largest is Byrds Mill Spring, which flows an average 20 cubic feet per second (cfs) or 9,000 gpm. The City of Ada, located about 12 miles north of Byrds Mill Spring, relies on the spring for its primary source of water.

Also of importance are the freshwater and mineralized springs in the CNRA. The two principal freshwater springs are Antelope and Buffalo Springs, the primary source of flow in Travertine Creek, a popular recreation spot. Recharge to the springs is most likely from the outcrop of Arbuckle-Simpson rocks to the east. Several springs in the park and Vendome Well produce mineralized water, once valued for its medicinal qualities. Some of the waters have a strong sulfur odor, which is characteristic of hydrogen sulfide. The mineralized water, with large concentrations of sodium and chloride, appears to be a mix of fresh water from the Arbuckle-Simpson aquifer and saline water derived from a regional and/or deeper source.

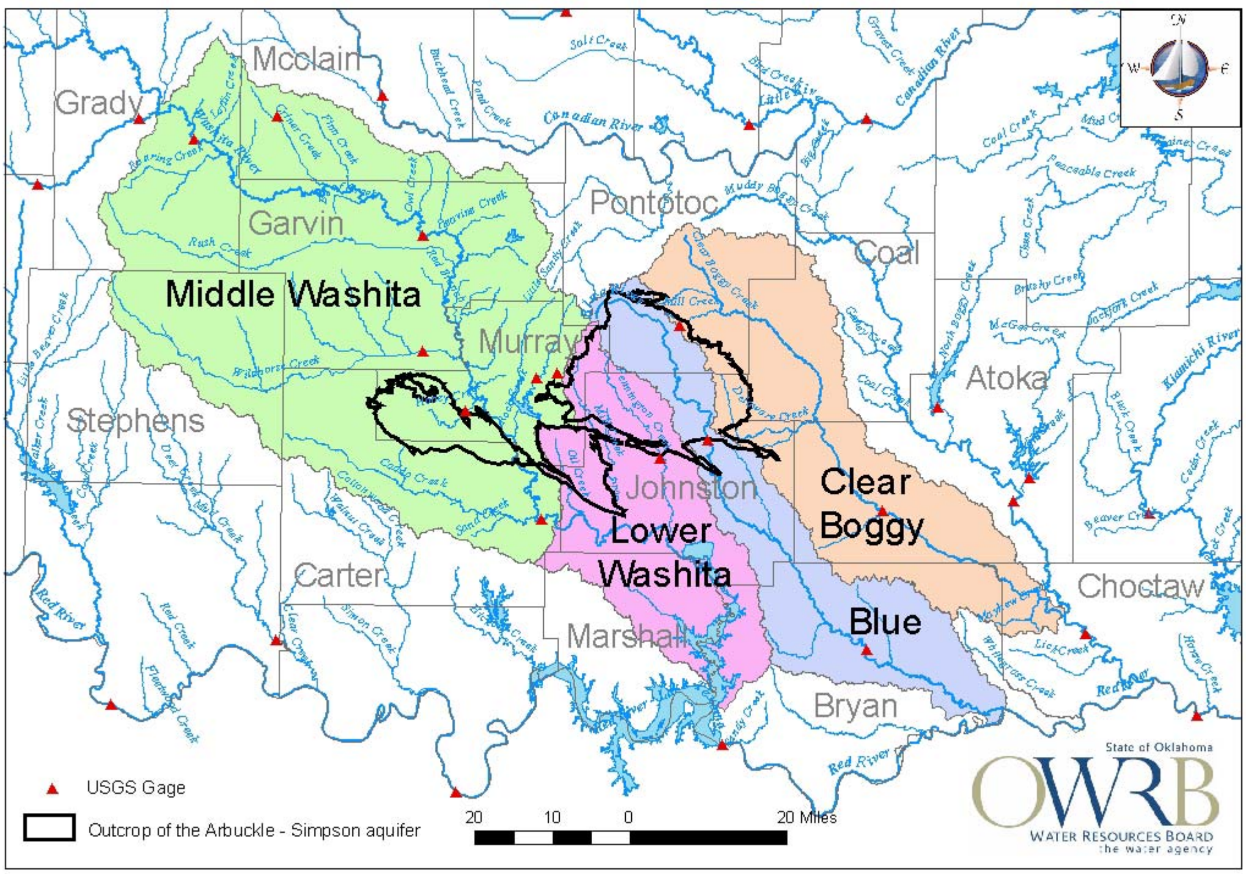

Figure 3. Watersheds in the area of investigation for the Arbuckle-Simpson Hydrology Study.

APPROACH

Scope

The Study is designed as a regional assessment of water resources for the allocation of water rights, and is not designed to address site-specific issues. This is 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".

For a number of hydrologic and practical reasons, the primary focus of the investigation is on the Hunton Anticline area. The Hunton Anticline area contains the most hydrologic data (such as wells, stream gages, and data collected for previous investigations), and is more accessible than the other areas. It is also comprises the largest area of the aquifer, and has more water use demands. On the other hand, the complex geology, paucity of wells, lack of hydrologic data, and poor access to much of the land make an in-depth investigation of the Arbuckle Anticline area impractical. For these reasons, most of the data collection and modeling efforts have been focused on the Hunton Anticline area. The Arbuckle and Tishomingo Anticline areas will be addressed using methods that are more general.

Data and Information Needs

A variety of data and information is necessary to understand and manage the water resources of the region. Understanding the hydrology of the Arbuckle-Simpson aquifer requires information on the hydrologic budget, aquifer characteristics, streamflow, and geologic framework of the aquifer.

Quantifying the hydrologic budget is key to proper management of the ground and surface water resources of the aquifer. The hydrologic budget accounts for all the inflows, outflows, and changes in storage of the aquifer system. Inflow to the aquifer is primarily from recharge from precipitation, which is one of the more difficult parameters to quantify. Outflow occurs naturally as discharge to springs and streams and artificially as withdrawal from wells. Hydrologic factors such as precipitation, recharge, and discharge vary in space as well in time. The recent drought provides a reminder for the importance of understanding climatic variability. In planning for water availability, a wide range of climatic scenarios, including droughts of different lengths, magnitudes, and intensities, should be considered.

Hydraulic properties, such as transmissivity, hydraulic conductivity, and storage coefficient, help define the flow characteristics of the aquifer. Water levels are necessary to evaluate groundwater flow directions, rates, and changes in storage. Stream information includes measurements of gaining and losing sections of streams, volume attributed to base flow from groundwater and to runoff, surface-water diversions and return flows, stream quality, and habitat. Geologic information is necessary to evaluate groundwater flow through the highly faulted, structurally complex, carbonate aquifer. Information on the deeper portion of the aquifer, the depth generally ranging from 1,000 to 4,000 feet, is needed to understand the full extent of the freshwater zone and the volume of water in storage in the aquifer. Although information from petroleum wells is abundant on the flanks of the aquifer, it is sparse over the aquifer.

Methods

Several methods are being used to obtain these data, including 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.

Groundwater Flow Model
A key component of the study is the development of a digital groundwater flow model of the aquifer, which will be used as a tool to improve understanding of the aquifer, to evaluate the allocation of water rights, and to simulate management options. A digital groundwater flow model represents the operation of a real aquifer with mathematical equations solved by a computer program. Digital groundwater models have been widely used in the United States since the 1970's to analyze groundwater-flow systems and predict the effects of water development. Models have been used for over 20 years in Oklahoma to set the maximum annual yield in accordance with Oklahoma water law.

The model that will be used to simulate the Arbuckle-Simpson aquifer is known as MODFLOW, which was developed by the U.S. Geological Survey. MODFLOW was selected because it has been applied to a wide variety of real-world conditions, it has been extensively tested, and MODFLOW has been accepted in many court cases in the United States as a legitimate approach to analyze groundwater systems.

Because models are simplifications of real systems, they cannot simulate every aspect of the real system. The MODFLOW model of the Arbuckle-Simpson aquifer is designed 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. The maximum annual yield is based the premise that *all* groundwater users are permitted to withdraw an equal share of water proportional to the amount of land overlying the aquifer owned by each individual user. Thus, the model is designed to work at the aquifer scale, not at the scale of individual wells.

Most of the data about the hydrology of the Arbuckle-Simpson aquifer is available only for the Hunton Anticline area. Thus, the MODFLOW model of the Arbuckle-Simpson aquifer will cover only this part of the Arbuckle-Simpson aquifer.

Minimum Instream Flow
Senate Bill 288 dictates the OWRB to conduct a comprehensive study to determine the maximum annual yield that will not reduce the natural flow of water from springs or streams emanating from the aquifer. If we assume that some amount of pumping is allowable, then some small amount of reduction to spring and streamflow would also be allowable. To help evaluate acceptable streamflow reduction, a couple of methods will be used to assess minimum instream flows.

One method, a river basin network flow model, will be developed to evaluate the impact of groundwater withdrawals on downstream water rights for the Clear Boggy, Blue, and Lower Washita watersheds. River basin network flow models simulate large-scale, complex water resource systems so that water is allocated according to physical, hydrological, and institutional aspects of river basin management, including stream water-aquifer interactions. The network flow optimization accounts for lagged return flows, stream depletions, channel losses, and stream water rights.

The Indicators of Hydrologic Alteration (IHA) and Range of Variability Approach (RVA) methods will be used to evaluate the natural flow regime of Blue River, Pennington Creek, Honey Creek, Travertine Creek, and Byrds Mill Creek. The IHA is a computer program that allows hydrologists and ecologists to create a statistical description of a daily record of stream flow and to measure changes in this description over time. The program calculates a suite of more than 60 ecologically-relevant statistics from a daily hydrologic data series. For example, it calculates the timing and maximum flow of each year's largest flood, then calculates the mean and variance of these values over some decades. If these statistics were changed significantly by, for instance, increased consumptive withdrawals, ecologists and water managers could then consider and evaluate whether or not the observed change are of significance to the downstream ecosystem.

The IHA also includes the Range of Variability Approach (RVA) to support ecologically based management of hydrological systems. This method helps with the design of adaptive management programs that use the quantified natural variation of a hydrological system as an interim management target. Using the RVA, one can propose a range of variability for each IHA parameter as a management target and quickly calculate how frequently the system has met these goals during the data period.

The Instream Flow Incremental Methodology (IFIM) will be used to assess instream flow requirements of selected fishes. The IFIM is the most comprehensive instream flow assessment technique used by state and federal agencies. The method provides an organizational framework for evaluating and formulating alternative water management options when managing stream flows. The IFIM quantifies aquatic habitats beneficial to fish and other aquatic organisms a function of stream discharge. Instream habitat of selected fishes, such as the least darter, the red spot chub, will be modeled in the Blue River near Connerville and Pennington Creek near Reagan.

Climatic Variability

The earliest instrumental hydroclimatic measurements in the Arbuckle-Simpson study area begin after 1900 and are too short to capture the full range of climate variability the region has experienced in the past. From a climatic perspective, such records are not long enough to provide information about the occurrence of low frequency mega droughts or extreme floods, so proxy indicators are needed to gain insights into the long-term patterns of climatic variability.

Tree rings offer the primary means for evaluating decal scale precipitation variability. A hydroclimatic reconstruction of the Arbuckle-Simpson aquifer using tree-ring chronology will be used to gain insight into the long-term pattern of climatic variability predating instrumental records. The chronology will be used to reconstruct the precipitation, temperature, streamflow, and Palmer Drought Severity Index (PDSI) for the Arbuckle-Simpson aquifer for the same length as the chronology (200-300 years). This information can then be used to investigate the occurrence and frequency of periods of rainfall deficit or surfeits and to place climatic variability during the instrumental period in a long-term climatic perspective.

Data Management

Many types of data and information are being collected for the Study. Types of data and information include documents (publications, theses, and unpublished reports), environmental data (measured or collected data) spatial data (such as topographic maps, geologic maps, or a coverage of water wells), and model inputs and outputs. Information themes include physical setting (physiography, climate, topography, soil), cultural setting (population, land use), geology (regional setting, tectonic history, structure, stratigraphy), hydrology (stream and spring discharge, hydraulic properties, groundwater flow, water-level fluctuations, groundwater recharge), groundwater and surface water quality, and water use. These data and information will be used to support hydrologic models and provide information necessary to evaluate water management options.

Because researchers from several organizations are collecting, using, and interpreting various types of information and data, a system for sharing and managing these data is essential. In June 2004, 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.

Integral to the plan is a geographic information system (GIS) to store, analyze, and display spatial data. The Study is using ESRI ArcGIS as a spatial database. OWRB serves as the clearinghouse and repository for the GIS layers, and ensures that the GIS layers have adequate metadata and meet agreed upon standards.

Public Involvement

The OWRB is committed to keep various cooperators and stakeholders informed of the Study’s progress. With the Bureau’s assistance, a public involvement plan was developed in 2003. This plan outlines a course of action for informing and involving interested stakeholders in the Arbuckle-Simpson Hydrology Study and subsequent management plan. Specific goals of the plan are 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.

During Phase I (field investigation) of the Study, the primary emphasis has been on keeping stakeholders informed. Information has been distributed through a variety of media including a project web site, newsletters, press releases, videos, field trips, and presentations.

PROGRESS AND SIGNIFICANT RESULTS

Accomplishments for the third year of the study include expanding the geochemical investigation, conducting various geophysical surveys, rainfall-runoff modeling, and developing a three-dimensional geologic model. An observation well was drilled at the Fittstown Mesonet site to monitor groundwater level. In addition, the network of wells equipped with continuously recording water-level records was expanded. Considerable effort was devoted to drilling a deep observation well to collect information on the lower portion of the aquifer. Although tests on the 1,820-foot well yielded extremely beneficial information about the aquifer, funds were exhausted before the well reached its intended 2,000 - 3,000-foot goal. Finally, a surface water committee was convened to determine surface water needs and impacts to flows in the study area. Progress and activities of the first three years of the Study are summarized below.

Literature Review and Data Compilation

Early in the Study, OSU was contracted to compile, describe, and assess existing literature and data pertaining to the hydrology of the Arbuckle-Simpson aquifer and related surface waters. OSU conducted a literature search and compiled a bibliography of journal articles, theses, dissertations, and books. Additionally, OSU scanned pertinent documents that are not copyrighted. Bibliographic data are compiled in an Endnotes database, and scanned documents are provided as Adobe PDF files. OSU continues to update the bibliographic database and to scan documents. The database, which contains more than 340 references, provides researchers and Study participants with ready access to pertinent information.

Shayne Cole (OSU) compiled existing groundwater and surface water chemistry data from USGS, the EPA STORET database, Oklahoma Department of Environmental Quality (ODEQ), Oklahoma Department of Environmental Health (OEH), and various publications. The database, consisting of more than 70,000 analyses from 515 stations, is available in EnviroData database files or as Excel spreadsheets.

A dataset of almost 15,000 records of oil and gas wells was obtained for the study area. Oil-Law Records Corporation of Oklahoma City provided the dataset 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.

In collaboration with the geologic modeling effort, Dr. Jim Puckette (OSU) analyzed various well databases and created a master dataset of more than 850 wells drilled for oil and gas production in the study area. The dataset was configured to allow importing data into EarthVision software, and will be used to provide the information needed to construct maps of key marker beds and hydro-stratigraphic units.

Joseph Zume and Mike Sughru (OWRB) are compiling well location and historic pumping data into a geodatabase for use in the groundwater flow model. They are also compiling and reviewing reported water use and diversion points for surface water permits.

OWRB contracted with Mark Gregory (OSU) to digitize and create GIS layers of the USGS 1:24,000-scale hydrography and hypsography for the study area. This task is near completion.

Monitoring

The monitoring program encompasses climatic, stream, and groundwater variables. Active monitoring stations for the past year include 1 Mesonet weather station, 3 USGS stream gages, 12 OWRB periodic stream stations, 1 OWRB continuous station, and 15 OWRB wells for monitoring water levels (Figure 4). In addition to the measurements collected at these stations, discharge from streams and water levels in wells were measured during quarterly synoptic events.

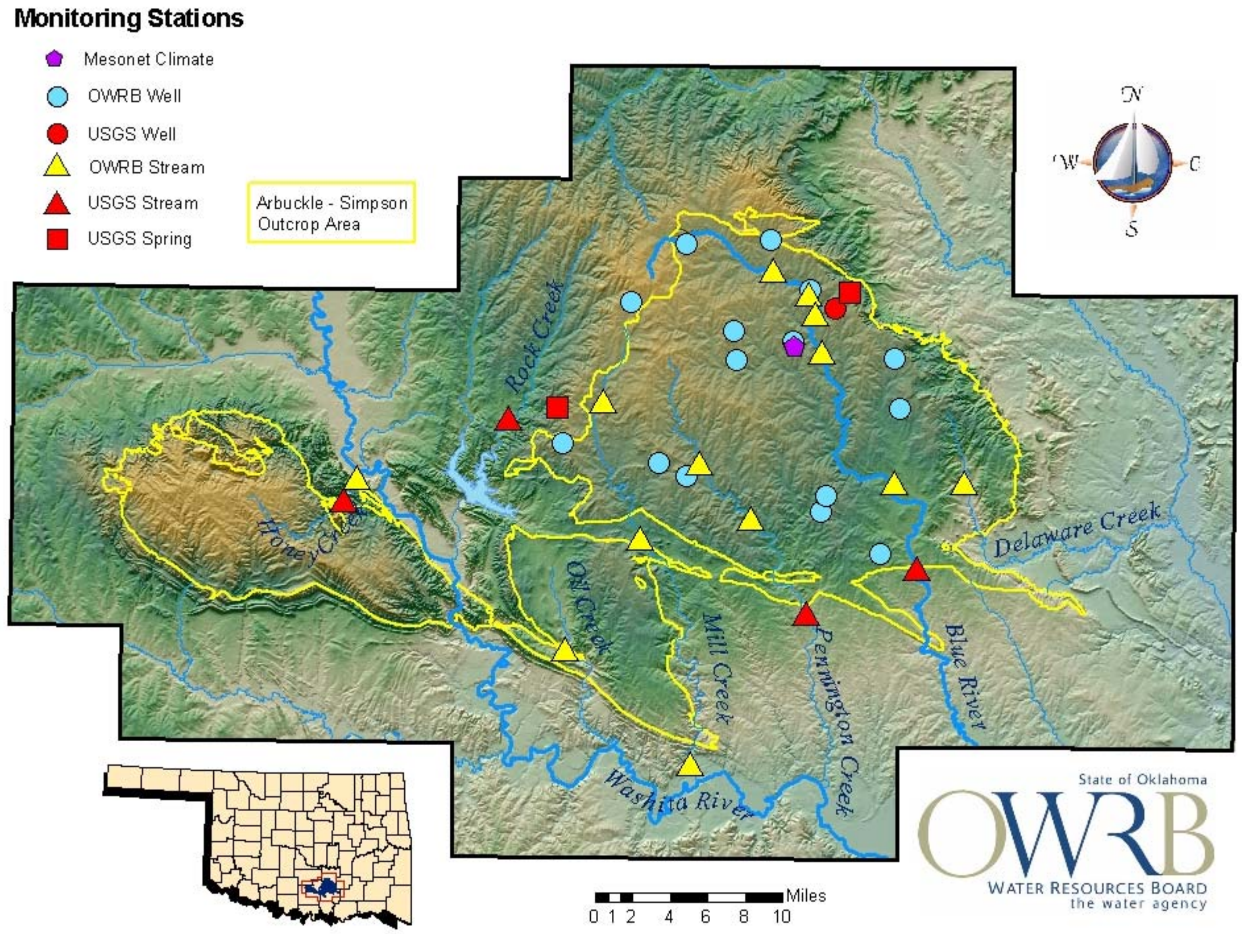

Figure 4. Monitoring stations for the Arbuckle-Simpson Hydrology Study as of September 30, 2006.

Climate
Climatic data are necessary in evaluating the hydrologic budget. Climatic factors such as precipitation, evaporation, temperature, wind speed, and soil temperature, and soil moisture affect groundwater recharge. Regionally, these parameters are monitored by the Oklahoma Mesonet. To provide additional precipitation data for the Study, USGS installed rain gages at the Pennington Creek, Honey Creek, Byrds Mill Spring, and Blue River gage stations.

The Oklahoma Mesonet, established in 1994, is a network of over 110 automated measuring stations covering Oklahoma. The system is designed to measure the environment at the size and duration of mesoscale weather events, which range in size from a few kilometers to a few hundred kilometers, and last from several minutes to several hours. At each site, the environment is monitored by a set of instruments located on or near a 10-meter-tall tower. Measurements include precipitation, temperature, barometric pressure, relative humidity, wind speed and direction, solar radiation, soil temperature, and soil moisture. Mesonet stations in the study area are Fittstown, Sulphur, and Tishomingo.

As part of the Study, OCS commissioned the Fittstown Mesonet weather station on May 12, 2005. Located about six miles southwest of the town of Fittstown, it is the only Mesonet station on the outcrop area of the Arbuckle-Simpson aquifer. Data are transmitted to a central facility every 15 minutes and 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.

Streamflow
USGS has installed three stream gages specifically for the Study. Pennington Creek near Reagan and Blue River near Connerville were installed in September 2003, and Honey Creek below Turner Falls was installed in October 2004. These are in addition to other USGS gages at Byrds Mill Spring, Antelope Spring, and Rock Creek at Sulphur. All USGS gage data are available in real time through the USGS NWIS web site: http://waterdata.usgs.gov/nwis.

OWRB staff continued 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.

Groundwater

Continuous groundwater-level measurements provide information on how the aquifer responds to various stresses, such as precipitation and pumping. These measurements are recorded with pressure transducers and data loggers installed in unused and abandoned wells. OWRB staff installed recorders in three additional wells this last year, bringing the total number of recorders in the OWRB network to 15. Unfortunately, due to current drought conditions, landowners re-installed pumps in four of the wells, and the units in these wells were consequently taken out of service. Currently, OWRB is maintaining water-level recorders in 11 wells. The data loggers, which are programmed to record hourly water levels, are downloaded monthly. All OWRB water-level data are available through the OWRB Water Well Record Search: http://www.owrb.state.ok.us/wd/search/search.php.

One of the new additions to the continuous water-level monitoring network is the observation well at the Fittstown Mesonet weather station. Drilled in October 2005 by Layne-Western to 255 ft, the well encountered only small amounts of water. Static water level at the time of drilling was about 105 ft below land surface. OWRB staff installed a pressure transducer and data logger in the observation well in January 2006. Daily water level measurements and hydrographs became available April 27, 2006 on the Mesonet web site (www.mesonet.org). To view graphs of the water-level elevation and precipitation, download the free WxScope plug-in, then go to *Interactive Products*. Select *Graphs (Ground Water)* for the Fittstown station and the desired time period.

Figure 5 shows a graph, obtained from the Mesonet web site, of the water-level elevation and precipitation recorded at the Fittstown Mesonet station. Between April 28 and May 12, 2006, the water level rose 19 feet after 5.84 inches of rain fell. Water level in the well declined 24 feet until October 15-16, when 5.06 inches of rain fell. However, due to extremely dry soil conditions, water level in the well rose only two feet in response to the rain. Following one of the warmest and driest summers on record, the October rain had little effect on groundwater levels.

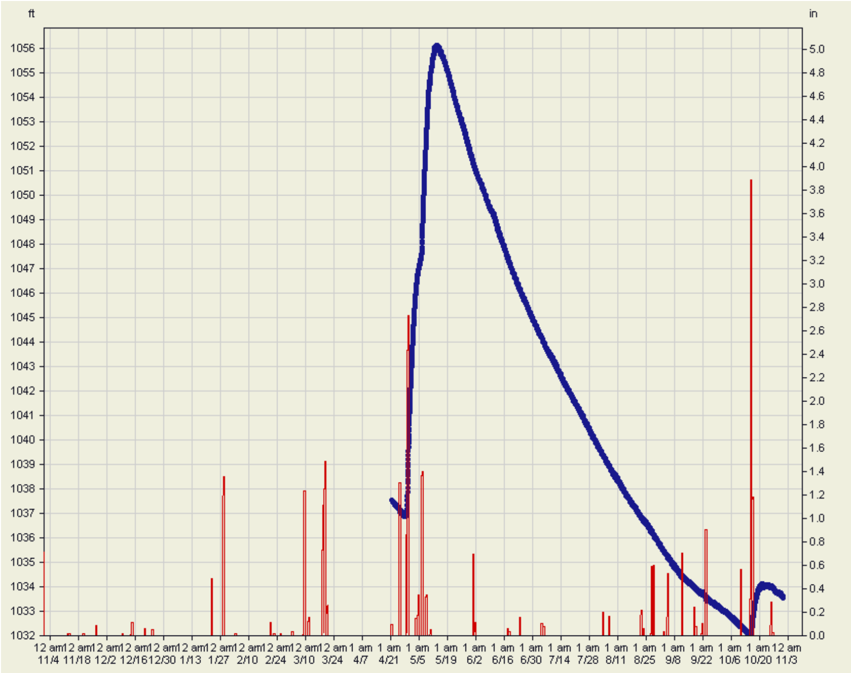

Figure 5. Water-level hydrograph and precipitation at the Fittstown Mesonet weather station (from Oklahoma Mesonet website).

Monitored since 1959, the USGS Fittstown groundwater-observation well holds the longest record of continuous water level measurements in the study area. Real-time and historic data are available on the USGS web site: http://waterdata.usgs.gov/ok/nwis/current/?type=gw. Neither the Fittstown Mesonet well nor the USGS Fittstown groundwater well is located in Fittstown: the

Mesonet well is located 6.5 miles southwest of the town, and the USGS well is 3.4 miles southwest of town.

Locations of wells equipped with continuous recorders are shown in Figure 6, and hydrographs showing average daily water levels are displayed in Figure 7.

Synoptics

In addition to the continuous and periodic measurements, OWRB staff conducted synoptic measurements of water levels and stream discharge. The synoptics are conducted over short time periods during base-flow conditions, when there is no surface runoff. Data obtained from the synoptics provide a "snapshot" of the water table and streamflow for a specific time, and will be used for constructing potentiometric maps, determining change in aquifer storage, determining recharge rates, and calibrating the groundwater-flow model. Table 4 lists the synoptic events to date.

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

Date	Area	Type
January 15-16, 2004	Hunton Anticline	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	Hunton Anticline	Groundwater
March 28-30, 2005	Blue River	Stream
June 22-23, 2005	Hunton Anticline	Groundwater
September 21-25, 2005	Hunton Anticline	Stream
September 22-24, 2005	Hunton Anticline	Groundwater
December 11-17, 2005	Aquifer-Wide	Stream
December 12-13, 2005	Hunton Anticline	Groundwater
March 24-29, 2006	Hunton Anticline	Groundwater
March 28-30, 2006	Hunton Anticline	Stream
June 21-22, 2006	Hunton Anticline	Groundwater
June 19-21, 2006	Hunton Anticline	Stream
September 5-7, 2006	Hunton Anticline	Stream
September 7-8, 2006	Hunton Anticline	Groundwater

Quarterly synoptics, consisting of both water level and stream discharge measurements, were conducted during the last year. The winter synoptic, conducted in December 2005, was aquifer-wide for stream measurements. Discharge and water quality measurements were collected from 90 sites on streams emanating from the Arbuckle, Tishomingo, and Hunton anticlines. Quarterly synoptics conducted during the spring, summer, and fall of 2006 focused on about 50 stream sites in the Hunton Anticline area. The NPS measured stream and spring flows in CNRA to supplement the OWRB measurements. Water levels for all quarterly synoptics were measured only in the Hunton Anticline area from a network consisting of about 100 used and unused wells.

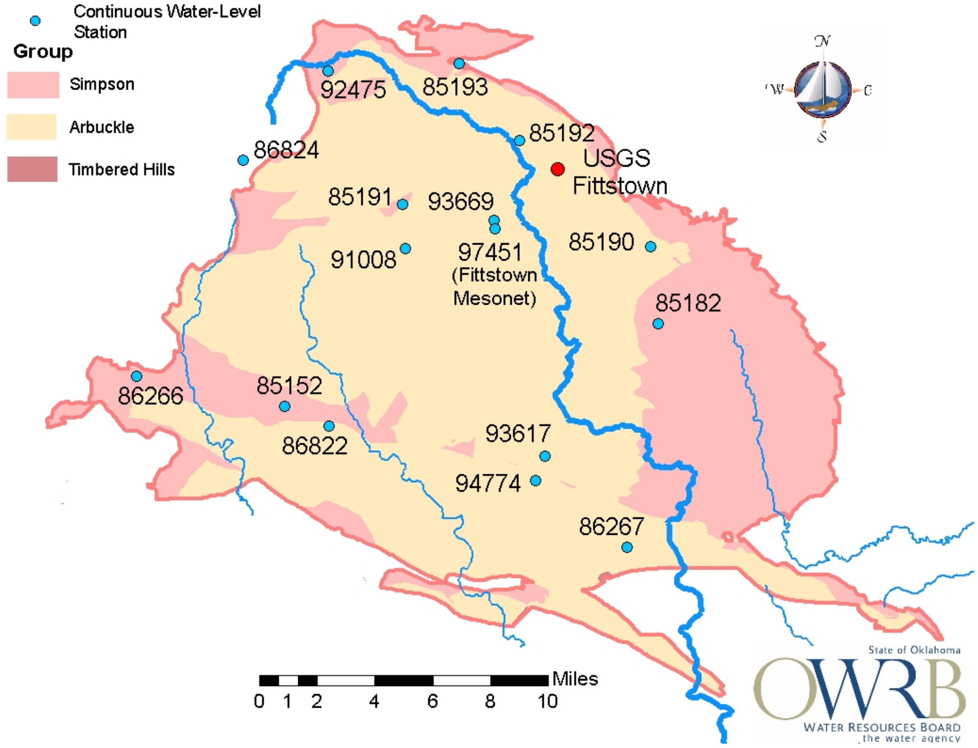

Figure 6. Map of the Hunton Anticline area showing location and OWRB well IDs of continuous water-level stations.

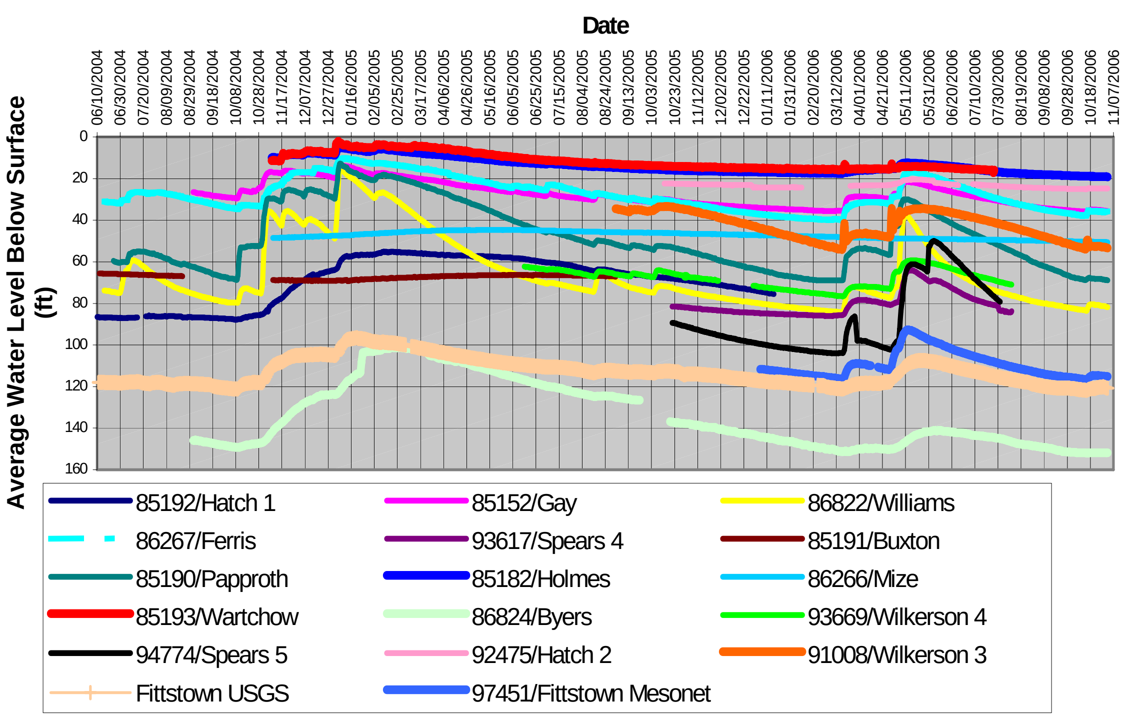

Figure 7. Hydrographs of wells with continuous water-level recorders.

Test Wells

Background

A deep well was needed to collect information on the lower portion of the Arbuckle-Simpson aquifer, for which information is sparse. 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. The drilling site is located on the Spears Ranch in section 23-01S-06EI, Johnston County, and is approximately 1,300 feet from Blue River. The West Spring Creek Formation of the Arbuckle Group is exposed at the surface.

Drilling Summary

USGS began drilling the Spears Test Well #1 on September 14, 2005. The well was drilled with air rotary to 80 ft, where $6^{5/8}$-in surface casing was set and cemented. A 6-in diameter hole was then drilled through the casing using a 5-in percussion hammer. A fractured zone at 364-366 ft made approximately 300-350 gpm of water, which created substantial backpressure against the hammer and greatly decreased its efficiency. Drilling continued using a new 6-in pneumatic hammer. The tight clearance between the hammer body and the drill bit did not allow larger cuttings to be adequately removed from the hole which, in turn, began to cause the bit to bind and torque in the hole. After struggling with this problem, the driller recommended abandoning the 628-ft hole, and starting over with a new, larger-diameter well.

On September 25, drilling commenced on the Spears Test Well #2, located about 200 ft east of the initial test hole. A 12¼ -in hole was drilled to 35 ft, where $8^{5/8}$-in surface casing was set and cemented. An 8-in diameter hole was drilled below the casing using the 6-in pneumatic hammer. The well steadily gained water (>300 gpm), until about 645-700 ft, where a heavily fractured zone was encountered and the well made an estimated 600-700 gpm of water. Drilling with the air hammer continued to a depth of 875 ft, where excessive backpressure again decreased the hammer efficiency to the point where bit penetration virtually stopped. Drilling continued using standard air rotary methods with a $6^{3/4}$-in carbide-tipped rollercone bit. Drilling foam was injected to bring up golf-ball sized rock fragments from a particularly fractured or brecciated zone at 1,335-1,341 ft. On October 26, the drill rig engine overheated, resulting in shutting down the rig for major repair work.

Drilling resumed on November 16. At a depth of 1,540 ft, as a test, the drilling crew attempted to drill with hydraulic rotary using the rig's 200-gpm duplex mudpump and a portable shaker tank. However, due to the large number of fractures in the well, water was lost into the formation and circulation of fluid to the surface could not be achieved. They concluded that with lost circulation, drilling with water was not feasible, and drilling with mud and lost circulation material would be cost and time-prohibitive. The crew resumed drilling with air, and continued until November 30, when budgeted funds were exhausted. Total depth was 1,820 ft. Water produced with air was estimated to be greater than 1,000 gpm at this depth.

Drilling of the two test holes 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 are being conducted on the wells, including examination of rock cuttings, geochemical sampling, and geophysical logging. Information gained from these tests is providing researchers with a greater understanding of the geologic and hydrologic characteristics of the aquifer.

Henry Badra (OWRB) examined and described the rock cuttings from Spears Test Well #2, which were collected at 10-ft intervals. The cuttings are primarily massive, finely crystalline dolomite with sporadic chert beds and oolitic grainstones. Major water-producing zones occur widely spaced between zones of non-porous dolomites. The major water zones are characterized by an increase in vugs (small holes) and fractures. These voids are commonly filled by large, rhombic dolomite crystals. Fine-grained dolomite crystals often appear coating rhombohedra, and may represent more recent fluid movement through the rock. Chert and oolitic grainstones are abundant in the deeper portions of the well, suggesting a transition into the Kindblade or Cool Creek Formations.

Scott Christenson had planned to collect geochemical samples as the wells were drilled. The initial plan was to sample 5-6 zones 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 hole. Testing consisted of measuring the hydraulic head and collecting water-quality samples. The USGS sampled three zones in this manner. However, after pumping the well 9-10 hours prior to collecting the a sample from 1,282-1,320 ft in the Spears #2 well, drilling foam was still present in the water. Concerned that injected air or fluids may be contaminating the samples, Scott decided to return later to adequately purge the hole and complete the sampling.

USGS returned to the site in July 2006, to complete the sampling of the Spears Test Well #2. Single and straddle packer tests were used to sample five discreet zones at various depths in the well. Chemical 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.

In June 2006, Dr. Ross (EPA) ran geophysical logs of the two test wells. In addition to borehole testing, several geophysical surveys have been conducted at the drilling site.

Test Well Summary

In summary, two wells were drilled in an attempt to test the deeper portion of the aquifer. The Spears Test Well #1 was drilled to a depth of 628 ft, and the Spears Test Well #2 to a depth of 1,820 ft (Table 5). Although neither well reached the 2,000-3,000-ft goal, the wells have provided much information on the aquifer. In both wells, the first water zone encountered, between 100-200 ft, produced marginal amounts of water. However, several major water-producing zones were encountered deeper in the wells. The productive zones correlate with dolomites that have high intercrystalline porosity and are faulted and/or brecciated (broke up).

Fresh water, remarkably similar to shallow Arbuckle-Simpson water, is circulating at a depth of 1,800 ft in the aquifer.

Table 5. Summary of Spears Test Wells

	Test Well #1	Test Well #2
OWRB Well ID	101246	101247
Well Depth	628 ft	1,820 ft
Depth to First Water	110 ft	200 ft
Static Water Level, time of drilling	24.8 ft	38.9 ft

Geologic Interpretation

Petroleum Information

Dr. Puckette is evaluating information collected during the exploration for petroleum to augment the limited aquifer data provided by water supply wells. The well data acquired for petroleum exploration are essential to determining the thickness, type and spatial distribution of flow units within aquifer-bearing intervals, establishing the structural grain and predicting paths of potentiometric flow, delineating the distribution of fresh, brackish and saline waters within flow units, and quantifying flow unit porosity and thickness for numerical modeling. Types of data include lithologic and geophysical logs to determine interval and flow unit thicknesses, 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.

During the last year, Dr. Puckette compiled thickness data for the Basal McLish and Basal Oil Creek sandstones; examined cores from wells drilled in the proximity of the study area that are available at the Oklahoma Geological Survey Oklahoma Petroleum Information Center Core Repository and Library; and examined bit cuttings from wells drilled through the Arbuckle Group in the Hunton Anticline area. Core examination confirmed that karstic processes controlled porosity in the Arbuckle aquifer. Porosity types include matrix-influenced intercrystalline and moldic types and matrix-independent vuggy, cavernous and fracture types.

Fracture Property Analysis

Dr. Halihan is evaluating fault properties across the aquifer. He investigated several sites, including the area surrounding Byrds Mill Spring, for fracture analysis and data collection.

Sassan Mouri (OSU) analyzed stream orientation as a means to determine fracture characteristics. The creek data in the Arbuckle-Simpson GIS dataset were converted into more than 60,000 stream segments. Results indicate that two dominant orientations exist for the fractures in the Arbuckle-Simpson aquifer on a regional basis, and significant local variability is present on a smaller scale. Sassan also collected outcrop fracture data to ground truth the larger scale results.

Geophysics
Several efforts using geophysical techniques are underway to characterize the geologic framework and hydrogeology of the aquifer. In December 2005, OSU hosted a planning meeting at the newly constructed Devon Visualization Facility, where researchers discussed how to integrate the various geologic and geophysical efforts for the Study. Scott Christenson discussed geologic information needs for the groundwater flow model; Dr. Dan Scheirer (USGS) presented initial results from the CNRA gravity survey; and Dr. Charles Blome (USGS) described progress and issues with the 3-D geologic model. Dr. Roger Young (OU), Dr. Surinder Sahai (OSU), and Dr. Halihan discussed some of their geophysical work.

Drs. Daniel and Allegra Scheirer, with the USGS Western Region Geophysical Investigations, completed a study for the NPS. The goal of this study was to understand better the geological configuration beneath CNRA, where geological units play a governing role in the distribution of fresh and mineral springs within the park and in the existence of artesian wells in and around the park. Gravity surveys were used to define the buried extensions of major faults, which are exposed at the land-surface east of CNRA where rainwater recharges the Arbuckle-Simpson aquifer. The results of this investigation are presented in USGS Open-File Report 2006-1803: *Gravity investigations of Chickasaw National Recreation Area, south-central Oklahoma*, available on the USGS publications web site http://pubs.usgs.gov/of/2006/1083/.

Dr. Sahai evaluated five existing seismic lines over the Hunton Anticline. One of the lines was available as digital (legacy 2-D) data of poor quality. However, Western Geophysical reprocessed the line with modern processing techniques, resulting in much improved quality. The reprocessed line shows strong reflectors between 0.3 and 0.4 seconds (about 3,800 feet below surface) corresponding to the basement granite. The line shows highly faulted basement and overlying carbonate units, and indicates a possible collapse feature near the eastern end of the line (near Blue River, west of Byrds Mill Spring). The very shallow section (less than 0.1 sec) is not imaged well and is difficult to interpret. Drs. Sahai and Puckette will be evaluating the data to determine the depth to bedrock and the location of faults and collapse features that are present in the dataset.

In January, Dr. Young and Carlos Russian (OU) conducted Ground Penetrating Radar (GPR) imaging at the Spears Ranch drilling site. They presented preliminary results at the GSA field trip and as a poster entitled *Fracture characterization by the correspondence between geologic mapping and Ground Penetrating Radar imaging* at the GSA, South-Central Section annual meeting March 6-7.

Dr. Young, with the assistance of Dr. Halihan and his students, collected reflection seismic data at two sites to establish if he could obtain a basement reflection using a Betsy gun as a source. Dr. Young is evaluating this method as well as other potential methods to determine depth to basement.

Mathew Riley (OSU) conducted electrical resistivity imaging over major faults at three sites. As part of his Masters thesis, Mathew evaluated the dip of faults and hydraulically active features. The data demonstrate that the larger faults are nearly vertical. Other vertical faults and fractures are evident in the images. Significant conductive features exist near the fault plane, indicating possible flow paths along the fault zones.

Dr. Ross, with the U.S. EPA Robert S. Kerr Laboratory in Ada, ran geophysical logs of selected wells in the aquifer. In October 2005, he logged the observation well at the Fittstown Mesonet weather station. In June 2006, he logged the test wells on the Spears Ranch and Ada's well #3, from which the pump was temporarily pulled. The borehole tools include 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.

Geochemistry

Shayne Cole (OSU) compiled and evaluated existing water quality data for her Masters thesis, "Evaluation of the Geochemistry in the Arbuckle-Simpson Aquifer: Finding Flow Paths". The majority of the samples did not have complete analyses. Of the 2927 samples, 359 had analysis of both calcium and magnesium concentration, and all but two of these samples had chloride concentration. Shayne used calcium-magnesium ratios to evaluate the flow system, and chloride concentrations to determine brine mixing.

In 2004, USGS conducted a reconnaissance sampling of the geochemistry of the Arbuckle-Simpson aquifer. Samples from 5 springs and 24 wells were analyzed for major cations and anions, trace metals, nutrients, oxygen and hydrogen isotopes, noble gases, tritium, and carbon-14. The purpose of the sampling was to determine the general water quality of the aquifer, identify possible water quality problems, gain insight into the aquifer's flow system, and provide data for more detailed geochemical studies.

The geochemical reconnaissance showed that the quality of groundwater in the Arbuckle-Simpson aquifer is generally good, with most samples suitable for domestic and municipal uses. Two samples had nitrate concentrations that exceeded the U.S. Environmental Protection Agency's 10 mg/L Maximum Contaminant Level (MCL). No other MCLs were exceeded.

Water quality was very consistent in water samples from wells and springs in the outcrop areas. For all water samples, dissolved solids concentrations ranged from 222 to 1,250 milligrams per liter (mg/L) with a median concentration of 351 mg/L. However, for samples from the outcrop area, the inter-quartile range (50 percent of the data centered on the median) of dissolved solids was 332 to 384 mg/L.

Most of the water samples from wells and springs producing water from the outcrop area were of a calcium bicarbonate or calcium magnesium bicarbonate water type. Water from the Hunton Anticline area tends to have higher magnesium concentration than water from the Arbuckle Anticline area, which is consistent with the geology. The Arbuckle Anticline tends to have more limestone, which consists mostly of calcium carbonate, and the Hunton Anticline tends to have more dolomite, a form of carbonate rocks similar to limestone but with a substantial amount of magnesium.

Preliminary analyses by Dr. Andrew Hunt (USGS Noble Gas Laboratory, Denver) of helium-3/tritium data indicate water from most springs and wells (with depths less than 500 ft) is considered modern water that has circulated through the aquifer in less than 60 years. However, water from two artesian wells, with depths greater than 700 ft, is considered fossil water. David Parkhurst (USGS) used the NETPATH geochemical model to correct the carbon-14 groundwater ages for exchange of carbon with the aquifer solid phase. Vendome Well, in the CNRA, has a corrected carbon-14 groundwater age of 13,000 years, and a well on the eastern Hunton Anticline has an age of about 33,000 years. These wells are considered to be producing water from the edge of the freshwater flow system in the Arbuckle-Simpson aquifer.

During the last year, three additional sites were sampled as part of the geochemical investigation. In November 2005, Scott Christenson sampled Byrds Mill Spring. Additionally, Scott collected a brine sample from an oil well, located west of Sulphur. Analysis of the brine sample will provide an end member of aquifer water, representing saline water that may be mixing with water from the flow path near the CNRA.

In July 2006, USGS sampled the Spears Test Well #2. The well was not sampled during drilling, because of fear that the water samples were contaminated with drilling fluid and air. The USGS Central Region Research Drilling Project installed single and straddle packers in order to obtain depth-stratified samples. Scott Christenson and Carol Becker (USGS) collected water samples from five depths for a comprehensive suite of analytes. Sample results will be used to construct a water chemistry profile with depth at this location. Age dating of deep groundwater can determine how lower regions of the aquifer function, recharge rates, and better define the direction and velocity of groundwater flow.

USGS is conducting data management and analysis of the water-quality data collected during the geochemical study. A USGS Scientific Investigations Report describing the geochemistry of the aquifer is planned for early 2007. Preliminary results are described in *A brief overview of the geochemistry of the Arbuckle-Simpson aquifer*, which was prepared by Scott Christenson for a Geological Society of America field trip. The report is available on the OWRB Arbuckle-Simpson Hydrology Study web site:
http://www.owrb.state.ok.us/studies/groundwater/arbuckle_simpson/pdf/USGS_arbuckle_geochem.pdf.

Groundwater Use

Joseph Zume (OWRB) compiled, reviewed, and verified reported withdrawals from historic water use records for all groundwater permits in the aquifer. In addition, he conducted site visits to permitted water wells to verify well locations and pumping schedules.

An evaluation of water use reports from 1964-2004 for permitted groundwater users indicates that the average annual withdrawal from the aquifer for this period was 4,356 acre-feet. As shown in Figure 8, the largest use was for public water supply (PWS). Cities, including Sulphur and Ada, and some rural districts pump water from the aquifer. Other uses included power, mining, and irrigation. However, since the closure of the OG&E power plant in 1987, water is no longer withdrawn from the aquifer for power supply purposes. It should be noted that the water-use data do not account for water withdrawals for which permitting is not required, including withdrawals for domestic purposes (household, stock, and windmills), flows from artesian wells, and dewatering of quarries.

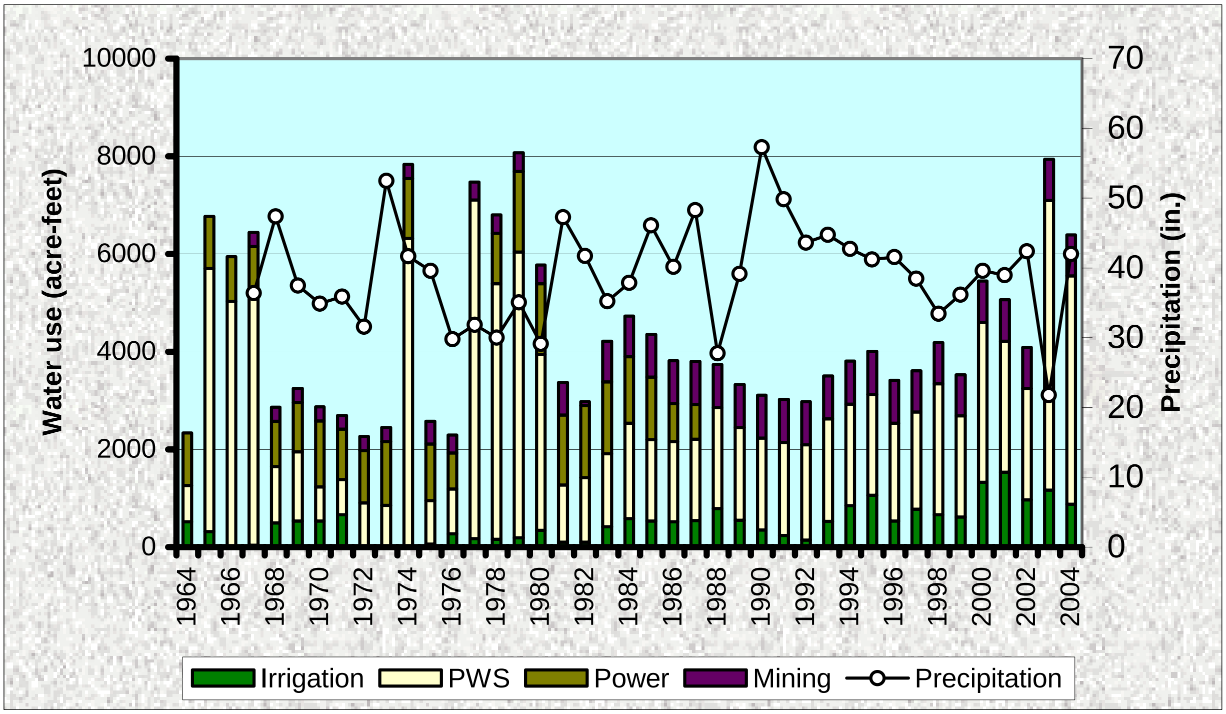

Figure 8. Average annual groundwater use from the Arbuckle-Simpson aquifer for the years 1964-2004.

Reported PWS withdrawals are unusually high some years. These high values are attributed to the City of Ada, which uses groundwater from the Arbuckle-Simpson aquifer and surface water from Byrds Mill Spring conjunctively to meet its water supply needs. For example, when flow from Byrds Mill Spring falls below 7 million gallons per day, Ada pumps water from the aquifer in order to preserve some spring flow for downstream landowners. (Spring water use is reported as surface water.)

Figure 9 shows a ranked breakdown of aquifer withdrawal per site based on the average reported annual use from 1995 to 2004. As shown on the map, most water withdrawals are in the Hunton Anticline area.

Artesian Well Inventory

OWRB staff conducted an inventory of flowing artesian wells in the Sulphur area. Staff reviewed historical records and documented existing sites by obtaining 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.

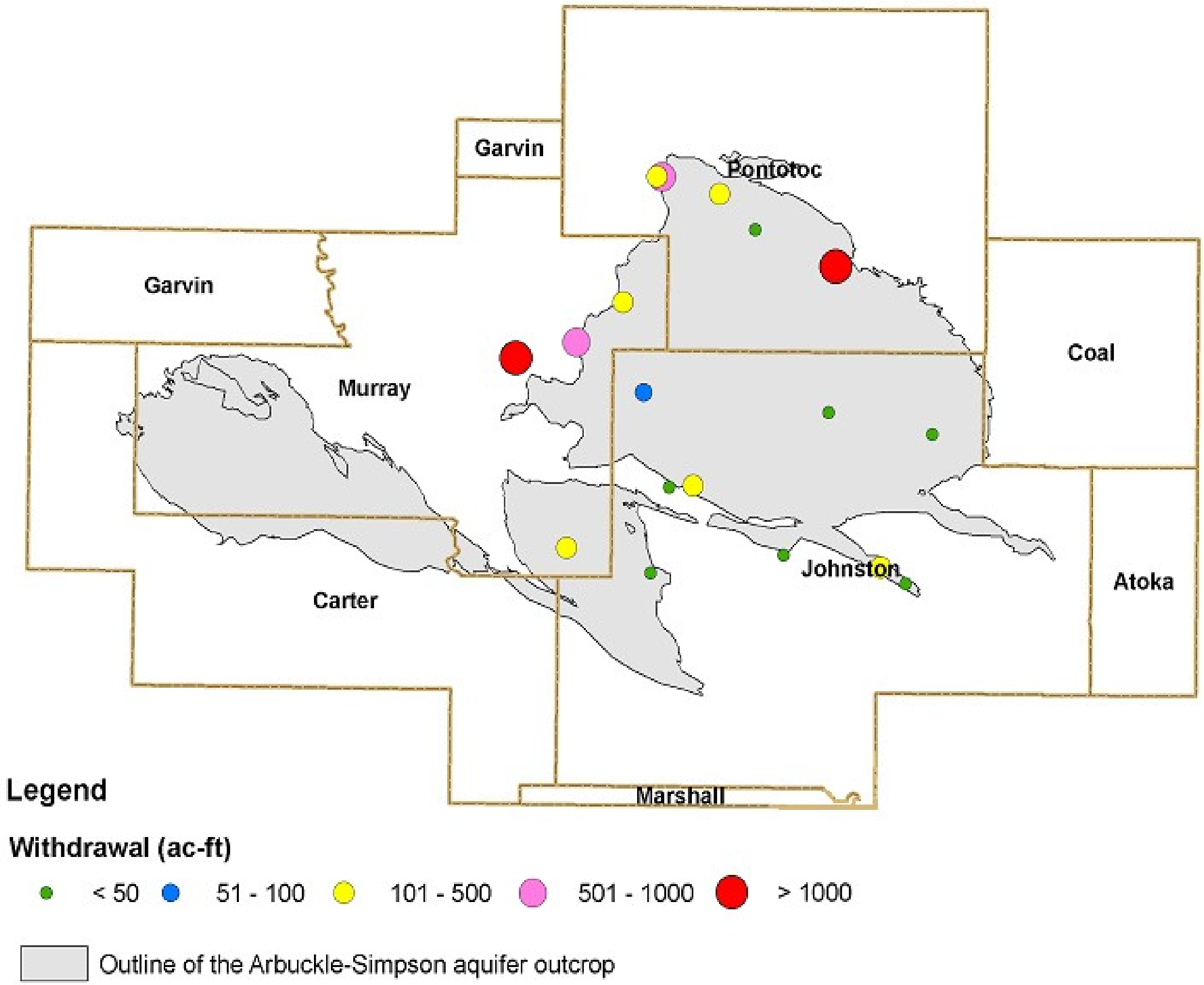

Figure 9. Average annual groundwater use by permit for years 1995-2004.

Aquifer Properties

Hydraulic properties, such as transmissivity, hydraulic conductivity, storativity, and specific yield, help define the flow characteristics of the aquifer. Both site-specific and regional methods are used to determine these properties. Aquifer tests are site-specific, and usually involve pumping a well and observing the change in hydraulic head in the aquifer.

Aquifer Tests

In 2005, Carol Becker compiled historical aquifer-test data and re-evaluated data from 13 recovery tests using AQTESOLVE computer program. Also in 2005, Scott Christenson conducted an aquifer test at the City of Ada well field.

In June 2006, OWRB staff and Scott Christenson conducted an aquifer test using two Murray County Rural Water District wells. A production well, located two miles east of Sulphur, was pumped for 24 hours at an average rate of 518 gpm. An observation well, located 63 ft from the production well, was equipped with a pressure transducer and data logger that recorded the water level every minute. Scott Christenson will evaluate the data to determine if they are sufficient for determining aquifer hydraulic properties.

Regional Methods
A couple of regional methods are being applied to determine hydraulic characteristics of the aquifer. One method, used by Scott Christenson and Abigail Tomasek (USGS), entailed analyzing regional-scale, continuous stream gage and groundwater-level data to determine recharge, storage, diffusivity, and transmissivity on the scale of surface-water basins.

Researchers from OSU and USGS are investigating the possibility of using water level fluctuations due to Earth tides as a means of determining regional hydraulic characteristics. Earth tides are caused by the gravitational attraction of the sun and moon on the rotating earth. Diurnal water-level fluctuations caused by earth tides are detected in many of the wells in the Arbuckle-Simpson aquifer, and may be used to calculate the specific storage and porosity of the aquifer.

Michael Sample (OSU) is evaluating the epikarst of the Arbuckle-Simpson aquifer to evaluate the storage and conductivity of the system. Near the Hatch well (OWRB Well ID 85192), where soil thickness appears to be negligible with dolomite exposed at the surface, a direct push machine was able to core to depths of 20 feet and obtain grain sizes as large as gravel from the epikarst domain.

Tree-Ring Analysis

Dr. Aondover Tarhule (OU) is using tree-ring chronology to reconstruct hydroclimatic variables for the Arbuckle-Simpson aquifer in order to gain insight into the long-term pattern of climatic variability predating instrumental records. The specific variables of interest are monthly precipitation, temperature, Palmer Drought Severity Index (PDSI) and stream discharge.

Dr. Tarhule developed a 229-year, calendar-dated, tree-ring chronology (1776-2004) based on ring width indices developed from Post Oak (*Quercus stellata*) trees. This chronology, averaged with one developed by Prof. David Stahle (University of Arkansas) from 1700-1995, results in one chronology that spans 1700 – 2004. From this 300-year tree-ring chronology, Dr. Tarhule reconstructed precipitation, temperature, and PDSI for the Arbuckle-Simpson aquifer. He is exploring streamflow reconstruction, which may be complicated by anthropogenic impacts. Dr. Tarhule is finalizing a report documenting the results of his research.

Modeling

Groundwater
Scott Christenson is developing a digital groundwater flow model (MODFLOW), which will be used as a tool to improve understanding of the aquifer and to assist in the water resource decision-making process. Scott is coordinating his groundwater flow modeling efforts with the

geologic and rainfall-runoff modeling efforts. By matching the domain extent and resolution of the models, he hopes to minimize the need to interpolate model results between different grids.

Rainfall-Runoff

Dr. Baxter Vieux and Camilo Calderon (OU) developed a distributed hydrologic model (V*flo*™), which quantifies the hydrologic water balance at gauged locations in terms of surface runoff, aquifer discharge, and other components such as evapotranspiration and precipitation. During the last year, efforts were focused on studying the influence of spatially and temporally variable evapotranspiration (ET) on the water balance of a regional area. In addition, recharge estimates at Pennington, Honey, and Rock Creeks were compared with those estimated at the Blue River near Blue gage station and with analytical results derived from streamflow recession curves. Estimated rates of potential ET are about 28percent less than pan evaporation rates. Preliminary water balance results indicate that for the Blue River basin, approximately 76 percent of the annual rainfall returns to the atmosphere as evaporation or transpiration. The remaining 24 percent discharges from the area as surface runoff, of which 9 percent is base flow and 15 percent is direct runoff from land surface.

Geology

Funded by the USGS Earth Surface Processes Team in Denver as a subtask for the Edwards/Trinity Geohydrology Study, Dr. Blome is developing a three-dimensional geologic model using EarthVision™. This effort would greatly advance our understanding of the structural framework of the Arbuckle-Simpson aquifer. Modeling results will be used to derive boundary layers for the groundwater flow model, to assess flow paths and aquifer properties, and to test our understanding of the structural framework of the Arbuckle-Simpson aquifer.

Dr. Blome and Jason Faith (USGS) are collaborating with Dr. Puckette and other researchers from OSU to compile and interpret petroleum industry data. During the last year, the research team analyzed all digital geologic map and well log data; evaluated all non-digital datasets including available cross-sections, fence diagrams, and structure and isopach maps; identified hydrostratigraphic units; and constructed a preliminary fault tree. Modeling began in October 2006.

Public Involvement

The OWRB is committed to keep various cooperators and stakeholders informed of the Study's progress. Information is distributed through a variety of media including a project web site, newsletters, press releases, videos, and presentations.

News Media

On December 19, 2005, Oklahoma Educational Television Authority (OETA) aired a segment on the OWRB, which included information on the Arbuckle-Simpson Hydrology Study. OWRB published an Arbuckle-Simpson Hydrology Study newsletter in January 2006. In addition, the November-December 2005 issue of *Oklahoma Water News,* the OWRB's bimonthly newsletter, describes groundwater level fluctuations in response to recharge in the article *Arbuckle Water Levels Reflect Unusual Weather*. All OWRB newsletters are available on the OWRB web site: www.owrb.state.ok.us.

Meetings
Noel Osborn gave presentations on the Study to the Citizens for the Protection of the Arbuckle-Simpson Aquifer (CPASA) 2005 annual meeting in Tishomingo, the 2005 Governor's Water Conference, and the Oklahoma Ground Water Association trade show. In August, researchers presented updates to the OWRB at the monthly Board meeting. Noel gave a short update on the time line, budget, and upcoming plans; Derek Smithee discussed plans for an instream flow study; Dr. Caniglia presented some of her findings and observations regarding her interviews with stakeholders; Dr. Tarhule gave an update on the tree-ring analysis; Dr. Vieux discussed his rainfall-runoff modeling; and Scott Christenson discussed principals and limitations of the groundwater flow modeling.

Study participants lead two field trips in February and March 2006. Noel Osborn, with assistance from Dr. Ross, Chris Fiebrich (OCS), Nicole Baylor (OWRB), and Matt Rollins (OWRB), led about 40 participants to Byrds Mill Spring, the Fittstown Mesonet station, Vendome Well, and Turner Falls. Noel Osborn, Scott Christenson, and Dr. Halihan led a field trip entitled *Hydrogeology and Water Management of the Arbuckle-Simpson Aquifer, South-Central Oklahoma* for the Geological Society of America South-Central Section annual meeting. Materials prepared for the field trip are published in Oklahoma OGS Open File report OF 4-2006 (available for $5.00 from Oklahoma Geological Survey).

Other Activities

Meridian Aggregates Monitoring and Management Plan
On July 11, 2006, the OWRB approved a groundwater application for Meridian Aggregates Co. (Meridian) for mining operation of the Martin Marietta North Troy Quarry, located north of the town of Mill Creek. Meridian completed the well in August 2006, at a total depth of 1,066 ft. Concerned about potential impacts that the groundwater withdrawals might have on nearby springs and streams, National Park Service (NPS) and U.S. Fish and Wildlife Service (FWS) negotiated a monitoring and management plan with Meridian. As part of this plan, Meridian is conducting groundwater and surface water monitoring in the vicinity of the quarry.

As stipulated in the monitoring and management plan, water levels in six wells and streamflow at Mill and Pennington Creeks are monitored. The six wells are part of the Study's network of observation wells, three of which are maintained by OWRB for continuous monitoring. Under an agreement with Meridian, USGS, and OWRB, additional continuous water-level recorders were installed in the remaining three wells. USGS maintains two of the wells, located on a private ranch, and Meridian maintains the other well, which is located on the quarry property. As part of the new agreement, USGS installed two new stream gages: one on Mill Creek near the town of Mill Creek, and the other on Pennington Creek east of the town of Mill Creek. Both sites were previously OWRB periodic monitoring stations for the Study.

Although the new gages and water-level recorders are funded by Meridian for the quarry monitoring and management plan, they supply additional information that can be used to further our understanding of the aquifer. OWRB Well and USGS Site IDs are listed in Table 6, and locations are shown in Figure 10. USGS and OWRB data are available on their respective web sites.

Table 6. Monitoring stations for the Meridian Aggregates monitorng and management plan

Site Type	Operator	OWRB Well ID	USGS Site ID
Production Well	Meridian	105146	
Observation Well	Meridian	85145	
Observation Well	OWRB	86266	
Observation Well	OWRB	85152	
Observation Well	OWRB	86822	
Observation Well	USGS	92479	342633096494401
Observation Well	USGS	92477	342527096493301
Stream Gage	USGS		07331295 (Pennington Creek east of Mill Creek)
Stream Gage	USGS		07331200 (Mill Creek near Mill Creek)

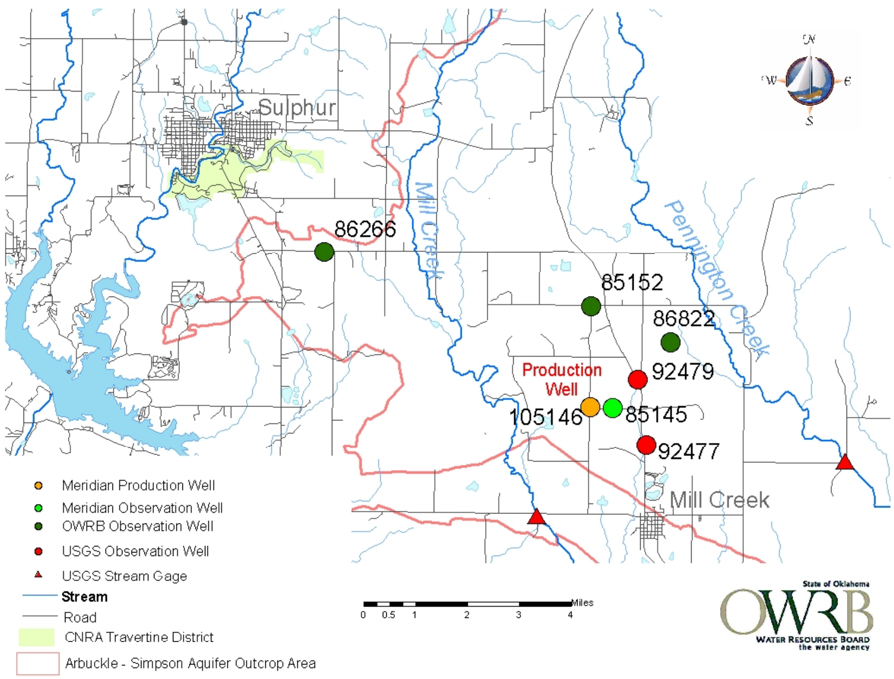

Figure 10. Map showing monitoring stations for the Meridian Aggregates monitoring and management plan.

In addition to the monitoring stations, and in accordance with the monitoring and management plan, Meridian conducted an aquifer test in September 2006, prior to withdrawing groundwater for quarry operations. Using the quarry's new production well and the monitoring stations described above, Meridian performed a 24-hour pre-test September 15-16, to develop technical criteria for use in designing the long-term aquifer test. A long-term, constant rate aquifer test was performed September 19-23, when the well pumped for 3.6 days at a rate of 1,013 gpm. This was followed by a 24-hour recovery test September 23-24. Information from the test is being evaluated by NPS and FWS.

Environmental Sociology
Environmental sociologist Dr. Beth Caniglia (OSU) received a grant from the Oklahoma Water Resources Research Institute to help fund a study to evaluate the role of science, politics and values in determining ultimate permitting policy in the Arbuckle-Simpson aquifer. The first phase of the study focused on the controversy over the Arbuckle-Simpson aquifer prior to the passage of Senate Bill 288. Public comment letters, newspapers and newsletters were analyzed and in-depth interviews were conducted to illustrate the diversity of frames being used by members of different sectors that are interested in or affected by Arbuckle-Simpson aquifer policy. The study is beginning the second phase of interviews, which will focus on the impact of OWRB communication with their target stakeholders. The third phase will assess the ultimate impact of the Arbuckle-Simpson Hydrology Study on Oklahoma water policy and will begin after the Study is complete.

PLANS

The fourth year of the Study enters a new phase of investigation. Phases I, which focused on the field investigation, is winding down. Phase II will focus on developing the groundwater and surface water models and evaluating minimum instream flow requirements. The last year of the Study (Phase III) will focus on evaluating various water management options. In addition to ongoing investigations, the following activities are scheduled for Federal FY 2007:

Modeling
The primary focus in 2007 will be the development of a digital groundwater flow model (MODFLOW). Scott Christenson is developing the model, which will be used as a tool to improve understanding of the aquifer and to assist in the water resource decision-making process. Scott will be coordinating his modeling efforts with the geologic (EarthVision™) modeling being developed by Dr. Blome and distributed hydrologic modeling (V*flo*™) by Dr. Vieux.

Minimum Streamflow
Under a cooperative agreement with OSU, Dr. Bill Fisher will conduct a minimum instream flow study. He will use the IHA and RVA methods to evaluate the natural flow regime of Blue River, Pennington Creek, Honey Creek, Travertine Creek, and Byrds Mill Spring; and the IFIM to assess instream flow requirements of selected fishes in the Blue River near Connerville and Pennington Creek near Reagan.

The Bureau is working with OWRB to contract out the development of a river basin network flow model. The model will be developed for the Clear Boggy Creek, Blue River and Lower Washita River stream systems to evaluate the impact of groundwater withdrawals on downstream water rights.

Monitoring
Monitoring of USGS stream gages, the OCS Fittstown Mesonet weather station, and OWRB continuous water-level recorder sites will continue, but periodic and synoptic stream and water-level measurements conducted by OWRB staff will be discontinued.

Helicopter Electromagnetic Survey

Dr. Blome, with the USGS Earth Surface Processes Team in Denver, has received USGS funding to conduct 288 line miles of helicopter electromagnetic and magnetic (HEM) surveys over the Arbuckle-Simpson aquifer. The HEM can be used to delineate geologic features and faults in the shallower portion of the aquifer (to depths of about 200 meters). Plans are to conduct the survey over three areas, of about six square miles each, in the Hunton Anticline area in February 2007.

Drilling

Other methods are under consideration either to deepen the Spears Test Well #2 from 1,820 ft to 3,000-3,500 ft or to drill a different deep well. Noel Osborn and Scott Christenson met with the Oklahoma Ground Water Association (OGWA) board of directors on March 31 to discuss potential methods, such as dual-wall reverse circulation and wireline-core drilling. OWRB plans to submit a request for proposals to evaluate the feasibility of further drilling.

PROJECT FUNDING

The proposed budget for the five-year study was 5.15 million dollars, to be funded through a 50/50 state/federal cost-share agreement with the Bureau. A total of 2.4 million dollars was allocated to the Study through State FY 2006. The Oklahoma legislature appropriated $500,000 for the Arbuckle-Simpson Hydrology Study for State FY 2007. These funds, combined with the $444,000 allocated by the Bureau in Federal FY 2006, will provide $944,000 to start the fourth year of the Study (Figure 11). The Bureau's appropriation for Federal FY 2007, the amount of which is still undetermined, will be applied to the later part of the Study's fourth year and to the fifth year.

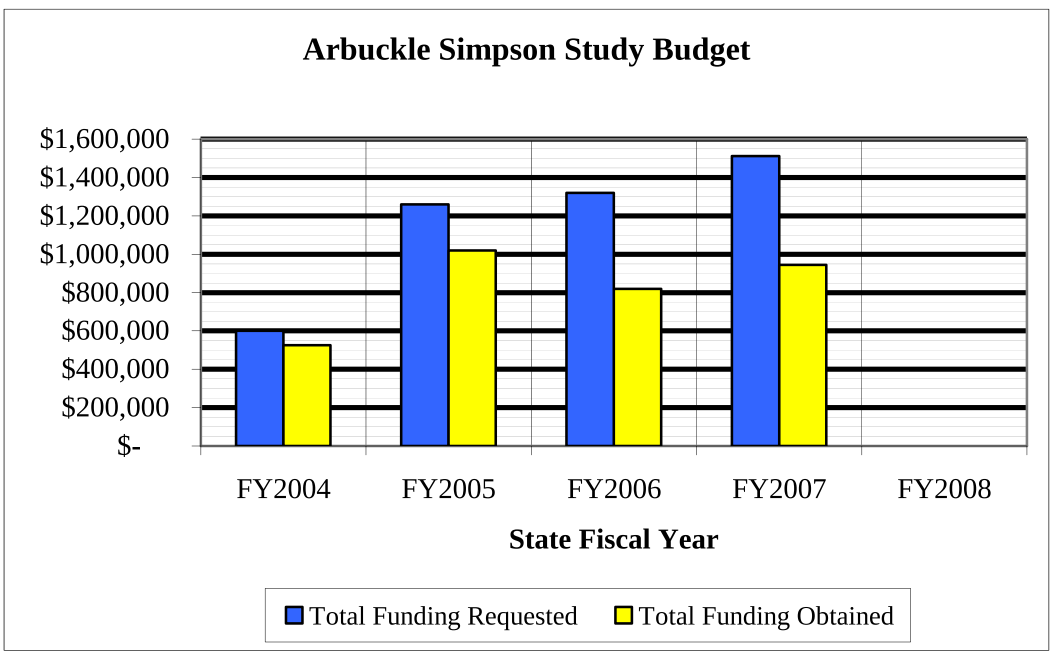

Figure 11. Graph showing project funding through State FY 2007.

Funding obtained through State FY 2007 has been allocated to a wide variety of tasks, which can be grouped into five general categories: *groundwater* (geochemistry, groundwater monitoring, aquifer characterization, groundwater modeling), *surface water* (stream monitoring, rainfall-runoff modeling, instream flow studies, and network modeling), *geology* (fracture characterization, evaluation of petroleum information, geophysics, and well drilling), *climate* (Mesonet station and tree-ring chronology), and *other* (data management, public involvement, and administration). Percent budgeted and spent funding through Federal FY 2007 is shown by category in Figure 12.

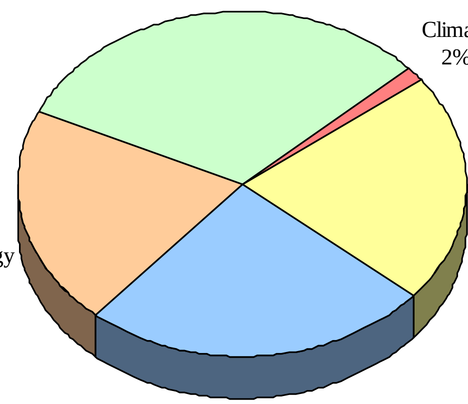

Figure 12. Percent funding by category for the Arbuckle-Simpson Hydrology Study, State FY 2004-2007.

In addition to the allocated monies, the Study has received considerable assistance, both financial and in-kind, from a number of sources. The Chickasaw Nation contributed approximately $27,000 annually to pay for the operation and maintenance costs for three USGS stream gages. USGS contributed a minimum of $45,000 towards the drilling of the deep test well and provided in-kind services for the geochemical work, in that the Study has not been charged for the personnel costs for the geochemist. One significant item is the development of a three-dimensional geologic model by USGS, at no cost to the Study. EPA Kerr Lab donated the use of Dr. Ross and the facility's geophysical logging equipment to log wells. NPS contracted with USGS to conduct a geophysical survey of the CNRA. Additionally, numerous landowners allowed researchers to conduct work on their property, such as drilling the deep test well and installing the Mesonet station, at no cost to the Study.

OWRB has approved cooperative agreements for State FY 2007 with USGS (aquifer characterization, geochemistry, groundwater flow modeling, and stream gaging); OSU (fracture, geologic, and aquifer characterization and in-stream flow study); OU (rainfall-runoff modeling); and OCS (operation and maintenance of the Fittstown Mesonet station). The Bureau will bid the digital stream water resources management model.

PROBLEMS

One of the largest challenges of the Study has been due to funding, which is based on year-to-year allocations from state and federal governments. Making plans, obtaining contracts, and purchasing are 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) adds 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.

Recent activity in the petroleum industry has assisted the gross production tax, making State funds available the last two years. Unfortunately, the current oil boom has resulted in some less desirable affects. For example, the OWRB has had a very high turnover in staff due to the petroleum industry's demand for geologists and other professionals. In addition, there has been a high demand for drilling equipment and oilfield-related services, such as processing seismic lines.

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