Oklahoma Water Resources Research Institute Annual Technical Report FY 2009

Introduction

The Institute for Sustainable Environments (ISE) at Oklahoma State University promotes interdisciplinary environmental research, graduate education, and public outreach leading to better understanding, protection, and sustainable development of the natural environment. The Oklahoma Water Resources Research Institute (OWRRI) is located within the ISE and is responsible for developing and coordinating water research funding to address the needs of Oklahoma.

This report summarizes some of our accomplishments in 2009. Highlights are presented below.

1. We awarded three research grants, $75,000 each, to researchers at both OSU and the University of Oklahoma to conduct studies of alternative water conservation policy tools, modeling of stream depletion from groundwater pumping, and remote sensing of evapotranspiration. In addition, we worked with an OSU research team to win a USGS 104G grant. This research investigates the effects of Eastern Red Cedar on the water cycle in a tallgrass prairie ecosystem.

2. We co-hosted the 7th annual Water Research Symposium and 30th annual Governor's Water Conference in Oklahoma City, which was attended by more than 400.

3. We co-sponsored a three-day water research conference with the River Systems Institute at Texas State University in San Marcos, Texas, which attracted more than 600 attendees.

4. We concluded the third year of our 4.5-year project to update the Oklahoma Comprehensive Water Plan. We held 30 planning workshops over six months that addressed ten watershed management themes. We believe that our stakeholder participation process is the most robust ever employed in the U.S. to comprehensively manage water resources.

5. We partnered with student and community organizations to sponsor a film series entitled, Is Our Glass Half Empty? and facilitated discussions afterward. Films included Blue Gold: World Water Wars, Liquid Assets, The Unforeseen, FLOW, and Oklahoma Water.

6. Our director served as President of the National Institutes for Water Resources (NIWR).

Research Program Introduction

In 2009, proposals were solicited from all comprehensive universities in Oklahoma. Proposals were received from Oklahoma State University and the University of Oklahoma. Thirteen proposals were submitted, and from these, three projects were selected for funding for one year each.

- Quantification of Water Fluxes and Irrigation Use Through Remote Sensing (Dr. Baxter Vieux, OU) is the continuation of a 2008 project that evaluated and improved remote sensing ET estimation methods and adapted them for use in Oklahoma.

- Stream Depletion by Ground Water Pumping: A Stream Depletion Factor for the State of Oklahoma (Dr. Garey Fox, OSU) will quantify the relationship between groundwater pumping and depletion of adjacent stream water on two Oklahoma streams. This project experienced delays and is not complete. An interim report is included here and the final report will be submitted with next year's annual report.

- Alternative Water Conservation Policy Tools for Oklahoma Water Systems (Dr. Damian Adams, OSU) will increase stakeholders' awareness of water conservation policy tools that are appropriate and feasible for Oklahoma and the associated costs and water savings. This project experienced delays and is not complete. An interim report is included here and the final report will be submitted with next year's annual report.

In 2009, a research team headed by Dr. Chris Zou was awarded a 104G grant entitled Eastern Redcedar Encroachment and Water Cycle in Tallgrass Prairie. This three-year project focuses on developing a water balance for six watersheds on the OSU Range Research Station, located about eight miles west of Stillwater, OK. Two of the watersheds have minimal redcedar encroachment, two have moderate encroachment, and two have significant encroachment. Instrumenting the sites with over 20 stations designed to measure precipitation and soil moisture at several depths is nearly complete. Each watershed has also been fitted with a flume to measure the amount of surface water leaving the basin.

Also, included in this report is the final technical report for two projects funded in 2008. The research teams were granted extensions into the 2009 project year and so the reports are included here.

- Decision Support Model for Evaluating Alternative Water Supply Infrastructure Scenarios (Dr. Brian Whitacre, OSU) developed a step-by-step procedure that rural water systems can follow to assess their water supply infrastructure needs and to plan and locate funding for needed improvements. This project experienced delays and was granted an extension but is now complete. An interim report on this project was included with last year's annual report.

- An Assessment of Environmental Flows for Oklahoma (Dr. Don Turton, OSU) began the six-step Hydroecological Integrity Assessment Process (HIP) to the flow rate necessary to maintain the ecological process in the state s streams and rivers. The project used flow information from 88 streams across Oklahoma to classify the streams into four groups (southeastern plains, temperate prairies, forested hills and semi-arid prairies).

Decision Support Model for Evaluating Alternative Water Supply Infrastructure Scenarios

Basic Information

Title:	Decision Support Model for Evaluating Alternative Water Supply Infrastructure Scenarios
Project Number:	2008OK105B
Start Date:	3/1/2008
End Date:	12/31/2009
Funding Source:	104B
Congressional District:	3
Research Category:	Social Sciences
Focus Category:	Management and Planning, Water Supply, Water Quantity
Descriptors:	
Principal Investigators:	Brian Whitacre, Dee Ann Sanders, Arthur Stoecker

Publications

There are no publications.

Final Report

Oklahoma Water Resources Research Institute

Title: Decision Support Model for Evaluating Alternative Water Supply Infrastructure Scenarios

Principal Investigators: -Brian Whitacre, Assistant Professor of Agricultural Economics, Oklahoma State University
-Art Stoecker, Associate Professor of Agricultural Economics, Oklahoma State University
-Dee Ann Sanders, Associate Professor of Civil Engineering, Oklahoma State University

Section 1: Problem and Research Objectives

Rural water systems often struggle to make decisions regarding their future, particularly when those decisions involve upgrading their infrastructure or consolidating / cooperating with other systems. This study demonstrates the development of a step-by-step methodology that provides assistance to rural water systems for planning and updating their water supply infrastructure. The objective of this study is to create a process that allows a rural water system to assess their own infrastructure and consider different avenues for funding potential enhancements. Specific steps involved in this process are discussed in depth in the report that follows, but a high-level overview includes the ability for a rural water system to perform the following:

1) Develop a list and sources of data required for modeling possible infrastructure upgrades (including maps / information on the infrastructure itself)
2) Create a hydraulic simulation model for the water system, using free or low-cost software
3) Determine problem areas and potential solutions to these problems
4) Estimate capital and operating costs for alternative solutions; gather information on potential funding sources and consider grant or loan-writing options

The methodology described in this project is generalizable to any number of rural water systems, including those using either surface or groundwater. While we initially hoped the tools and methods used under this methodology would be able to be performed by non-specialists, such as local water district managers, our experience indicates that some specialist oversight is likely necessary. This system of evaluation should still dramatically enhance the capability of rural water districts to understand the limitations of their current system and give updates to the local community well in advance of any infrastructure crisis.

Section 2: Background and Methodology

The 2007 Environmental Protection Agency (EPA) report of Drinking Water Infrastructure Needs Survey and Assessment stated that the United States would need an investment of about 335 billion dollars to upgrade its water infrastructure in the coming 20 years. The report said that out of this entire revenue, 60% would be required for just upgrading the distribution systems. The state-by-state classification of the report said that Oklahoma would need about 2.6 billion dollars, out of which 1.4 billion dollars would be required to upgrade the systems serving populations fewer than 3300 people (EPA, 2007). The Oklahoma Water Resources Board (OWRB) set a new water plan to project water demands and the required inventory to meet these demands up to the year 2060. The preliminary goals of this project were as follows: (OWRB, 2009)

- Identify those regions having problems related to water supply
- Collect data, maps and other vital information regarding their water infrastructure
- Evaluate the performance of their systems on the basis of existing demands
- Identify the necessary changes in the system to meet future water demands

OWRB identified 1717 active public water systems, out of which 1240 systems were community water systems, either municipal or rural water districts. Partners in this planning process were the Oklahoma Water Resources Research Institute, the Oklahoma Association of Regional Councils (COG's), Oklahoma Department of Environmental Quality (ODEQ) and federal partners. Based on the water plan for Oklahoma, a project goal was set to develop a cost efficient methodology, which would assist rural water districts in Oklahoma to manage and upgrade their drinking water distribution systems. Four rural water systems were chosen, representing systems with above ground storage, below ground storage, groundwater sources, and surface water sources. The four systems chosen were Beggs, Oklahoma, Braggs, Oklahoma, Kaw City, and Oilton, Oklahoma. These systems represented a variety of infrastructure issues, including insufficient storage, old pipes, and low pressure areas. In addition to the options in the systems selected, two different water distribution models were used during the project. The locations of the towns are shown in Figure 1 while the population, source of water, and general problems for these towns is given in Table 1.

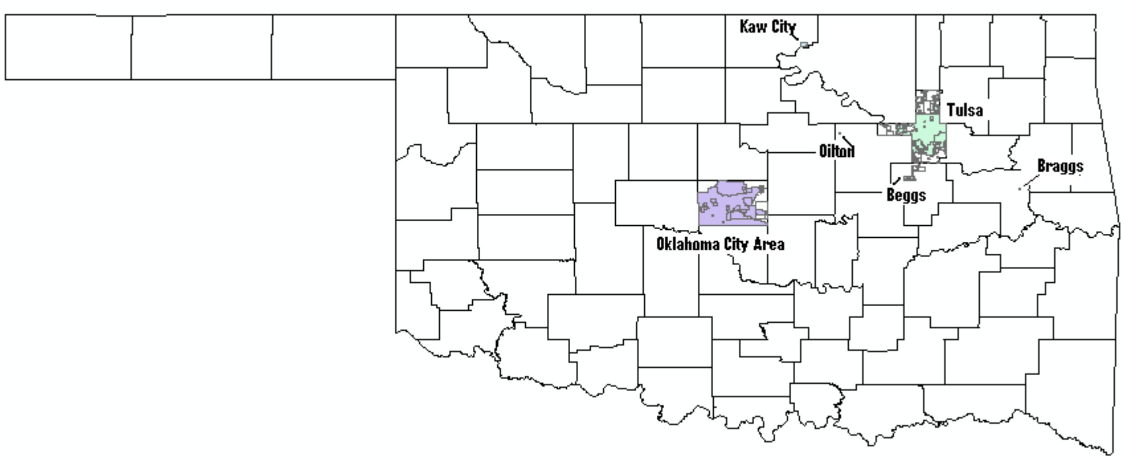

Figure 1. Location of Study Site Towns of Beggs, Braggs, Kaw City, and Oilton in Oklahoma

Table 1. Small Towns in Oklahoma Participating in Study of Water System Planning.

Item	Beggs	Braggs	Kaw City	Oilton
Population	1,364	1,030	400	1,200
Water Source [a]	S.W.	G.W.	G.W.	G.W.

Gallons/Day (thos)	161	75.6	80	118
Treatment	Conventional.	NR	NR	NR
Storage (thos. gal.)	175[b]	200	200	950
Issues: Old pipes	Yes	Yes	Yes	Yes
Insufficient storage	Yes	No	Yes[c]	No
Low Pressure Areas	Yes	Yes	No	Yes
Sufficient Fire Flow	No	Yes	Yes	No
Primary Standards	ok	ok	ok	ok
Secondary Standards	ok	ok	Mn	ok
Water Age	Some[d]	Some[d]	Some[d]	Some[d]

[a] Abbreviations used; S.W. = surface water, G.W. = ground water, NR = not required.
[b] 50,000 elevated plus 125,000 in ground tank.
[c] During summer tourist weekends.
[d] Generally in areas served by long un-looped pipes

Only one of the four towns had a digital pipeline data set. In some cases, the hand drawn pipeline maps were incomplete. The approach in this study was to develop a hydrological simulation model for the town and then use that model to address the problems shown above in Table 1. The following approach was followed.

1) Contact and meet with appropriate local officials such as the mayor, manager, and/or city engineer.
2) Obtain copies of pipe line maps noting length, diameter, age, material, and condition, if possible. Alternatively sketch pipeline maps onto Google or Tiger line drawings of the city. Handheld GPS units were used to verify the location of critical infrastructure such as wells, treatment plants, and water storage units.
3) Obtain available technical information about the pumps, (size, power, model, age, power consumption, and hours of operation) and other system components.
4) Develop and validate an EPANET or WaterCAD simulation model for the water system.
5) Use the EPANET or WaterCAD models to evaluate the ability of the system to meet time of day demands by spatial location. The EPANET hydrological simulation program was developed by EPA and is available at no cost. WaterCAD is a commercial system distributed by Bentley Systems.
6) Determine the ability of the water distribution system to meet fire flow demands at each hydrant (minimum 20 psi after two hours of 250 gpm flow).
7) Evaluate the type, amount, and time of infrastructure needs to meet projected population growth.

The above general steps were refined as discussed below for the four systems evaluated.

<u>Simulation Model Development</u>

The Oklahoma Water Resources Board (OWRB) has developed a set of GIS pipeline drawings for some 800 rural water systems in Oklahoma; however, these drawings typically do not include small towns such as the ones included in this project. The first step was to develop the geographical information system (GIS) drawings of the major pipelines serving the city.

Zonum Systems (2009) has developed several freeware interfaces to EPANET. One program, (EPANETZ) allows the user to digitize pipelines onto a Google Map of the town. Comparison of the Google map of the town with engineering drawings permits development of a digital infrastructure map with approximate (though not exact) location of pipelines. The program automatically creates the necessary linkages between nodes. The user must enter the pipe diameters and the node elevations. The GIS will provide estimates of the length of pipes, but actual lengths should be used when these are available. Two or more pipes are considered joined if they share the same node. One problem in getting EPANET to operate, is that slight differences in placement of pipe lines may generate multiple nodes which appear as a single node on one location. More expensive simulation programs link such nodes automatically. Excel macros were written to check the differences in latitude and longitude between nodes and ask the user if pipes having separate ending nodes within a specified radius should be connected, essentially requiring user verification for each unconnected node.

A second problem encountered was how to determine the elevation of each node, which is a required input for determining water flow. This is difficult for inexperienced users to accomplish in ARCVIEW or ARCMAP. However, a second relatively inexpensive GIS program, Global Mapper, was available that creates XYZ files (which include elevation) by simply overlaying the line drawing of the pipes on a USGS elevation file. Visual Basic macros were then used to add the elevations to the pipeline nodes. (Zonum Solutions (2009) now offers an online program to add elevations to nodes). The values relating to the depth of wells, height and volume of storage facilities, pump curves, rules for pump operation, and diurnal water use patterns must be added to the data set. The effect of corrosion in reducing pipe flows was also approximated after discussions with the city engineer.

The following three sections (sections 2.1 – 2.3) discuss the steps taken to evaluate the distribution systems in Beggs, Oilton, and Braggs, respectively. As indicated, free EPANET software was used in both Beggs and Braggs, while Oilton incorporated the for-fee WaterCAD software typically used by professional engineers. A discussion of the issues faced during each simulation is included. Additionally, the analysis of Beggs (which was completed prior to Oilton and Braggs) incorporates a methodology for assessing the cost of potential upgrades to the existing infrastructure. Finally, a fourth section (section 2.4) describes of the investigation for Kaw City. This analysis differs from the previous three projects in that it deals with the assessment of several options to improve the city's water supply (comparing costs of various new treatment plants) while also providing water to at least one other entity. The Kaw City analysis focuses more on the cost of construction and operation alternatives rather than simulation of the existing infrastructure.

Section 2.1: Simulation Model to Evaluate the Beggs Water Distribution System

The EPANET model developed for the City of Beggs will be used to illustrate the capabilities of the water simulation software to analyze problems and possible solutions for a small town (Lea, 2009).

Figure 2 shows the digitized pipeline for the City of Beggs overlaid on photo map of the city. The low pressure areas indicated by circles along with the areas where the age of water in the pipes was problematic in Figure 2 were confirmed by the city engineer. One area with pressure problems and inadequate fire flow was on the west end where the primary and secondary schools were located. A similar problem was encountered with the "Hilltop" area on the east. Both of these areas represent city expansions made after the initial water system was developed. The dead ends associated with several long pipes also failed the fire-flow test.

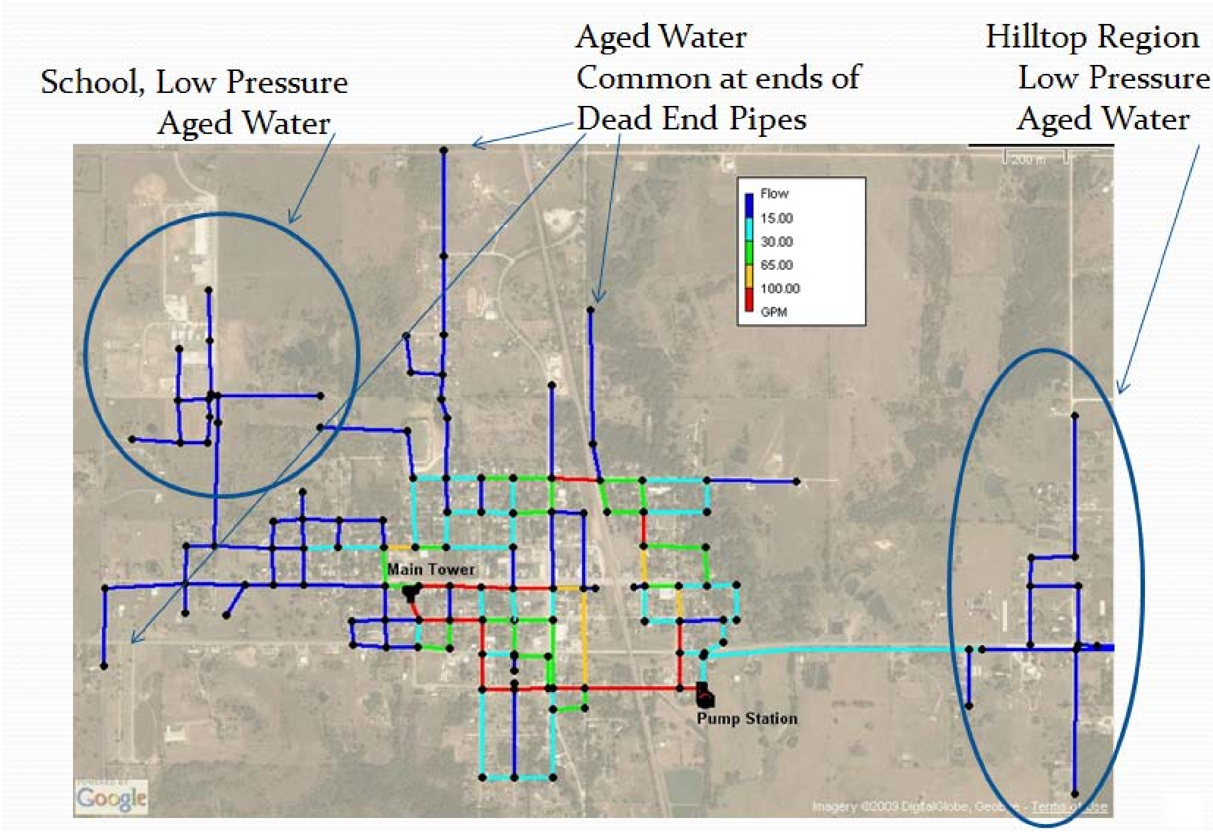

Figure 2. Digitized EPANET Model of the Water System for Beggs, Oklahoma Showing Pipeline Flow and Indications of Areas with Low Pressure and Areas Where Age of Water in the Pipes was Problematic.

The alternatives simulated to correct the problems shown in Figure 2 included installing new or modified pumps, a new water tower on the east end of town, replacing old pipes that had corrosive deposits, and / or adding new pipes to eliminate dead ends and create new water paths.

A set of simulations involving the addition of new pipes to convert the long single pipes shown in Figure 2 into loops indicated the problem of water age could be remedied most of the pressure and fire flow problems could be resolved. The pipes and water tower added during the simulations are shown in Figure 3.

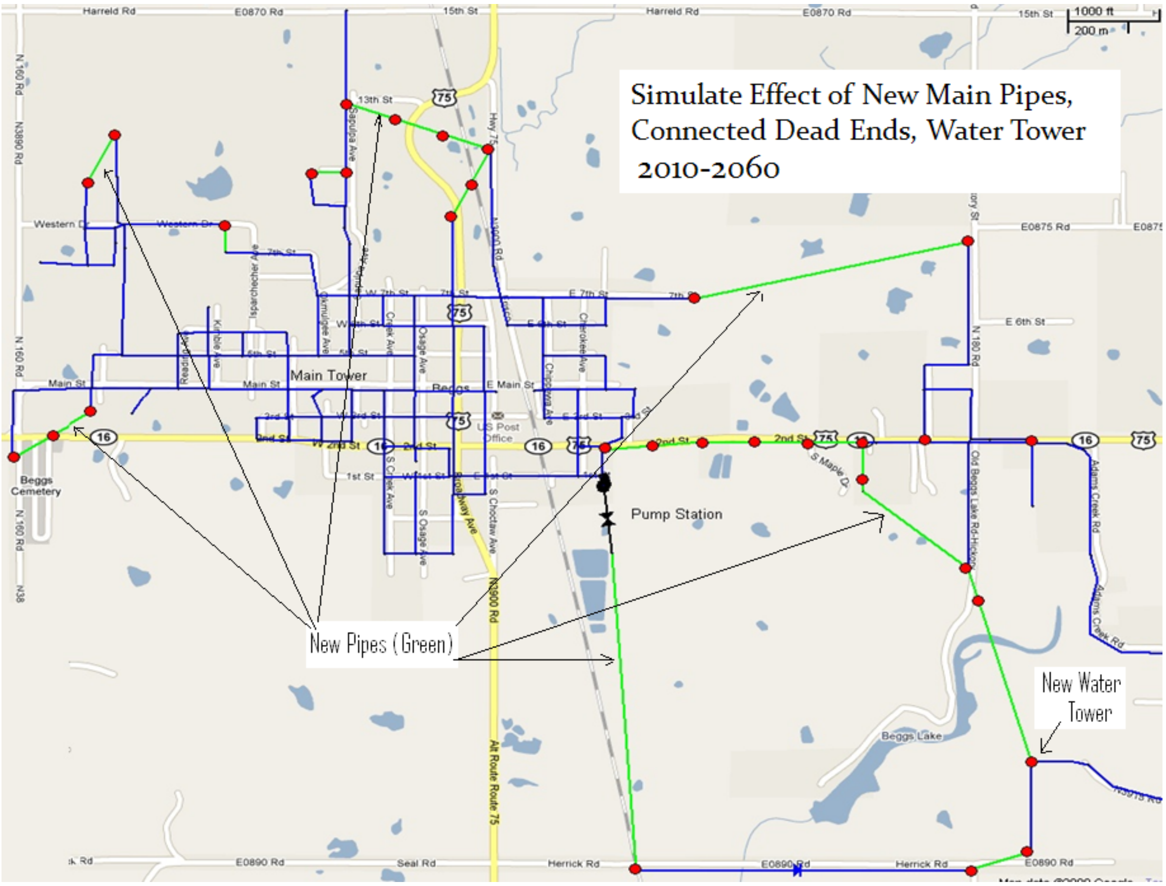

Figure 3. EPANET Model of the Water System for Beggs with Pipes added to Eliminate Dead Ends and the Location of a New Water Tower.

An important issue for a small town like Beggs, which is currently facing sewer upgrade problems, is the cost and the best order in which make modifications.

Cost estimates for pipe, pumps, and storage tanks were obtained from Means (2009) and adjusted were necessary to account for price changes since publication. Table 2 shows the prices used to the cost of installing PVC pipe of alternative diameters. A spreadsheet was used to develop the cost for the purchase and installation cost of alternative sizes of PVC pipe from 2 through 8 inches, using data on the cost of pipe, excavation, and backfilling used estimates from Means (2009).

Table 2. Costs Used for AWWA 160 SDR-18 PVC[a] Pipe, Trenching, and Backfilling

Diameter	Pipe	Trenching[b] and Backfill	Total Cost
Inches	$/LF	$/LF	$/LF
2	2.24	3.47	5.72
3	5.01	3.55	8.56
4	6.12	3.62	9.75
6	8.62	3.77	12.40
8	12.17	3.92	16.10

[a] Polyvinyl Chloride pipe.

[b] Assuming the pipe is placed in a two foot wide trench so the top of the pipe is 36 inches below the surface.

The problem of choosing the most economical diameter for single pipe to deliver a given volume with a designated head or pressure at the delivery can be determined by enumeration. For each diameter, add the annualized installation cost of the pipe to the annual cost of energy required to force the water through the pipe. Choose the diameter with the smallest annual total cost. Suppose it is necessary to purchase pipe that will deliver 100 gpm over a mile and up into an 80 foot tank. The amount of brake horsepower required is calculated as

$$bhp = \frac{\text{Head ft} * \text{GPM}}{(3960*pe*me)},$$

where

pe is the pump efficiency, for example 0.7, and
me is the motor efficiency, for example 0.91.

If an electric motor is used, the amount of electricity used per year is 0.746 * bhp *8760 hours. The total feet of head required is equal to the 80 feet of lift into the tank plus the head (pressure) necessary to force 100 gpm of water through one mile of pipe of a given diameter. According to the Hazen-Williams formula, the head loss is,

$$\text{Hloss (ft)} = \frac{10.51\ (GPM/C)^{1.85}\ \text{Length}}{D^{4.87}}$$

Where

C is a Hazen-Williams friction coefficient, assumed to be 140 for PVC pipe
D is the inside diameter of the pipe in inches
Length is the length of the pipe.

The minimum annual cost involves a tradeoff between pipe size and energy cost. As the diameter of the pipe increases, the total cost of the pipe increases, but the energy required to force the water through the pipe decreases. A standard capital recovery factor was used to annualize the cost of the pipe. The annual capital cost for one mile of pipe (Table 2) and the annual pumping costs are added together in Figure 4. The least cost alternative is the four-inch diameter pipe that would cost $7,000 per year.

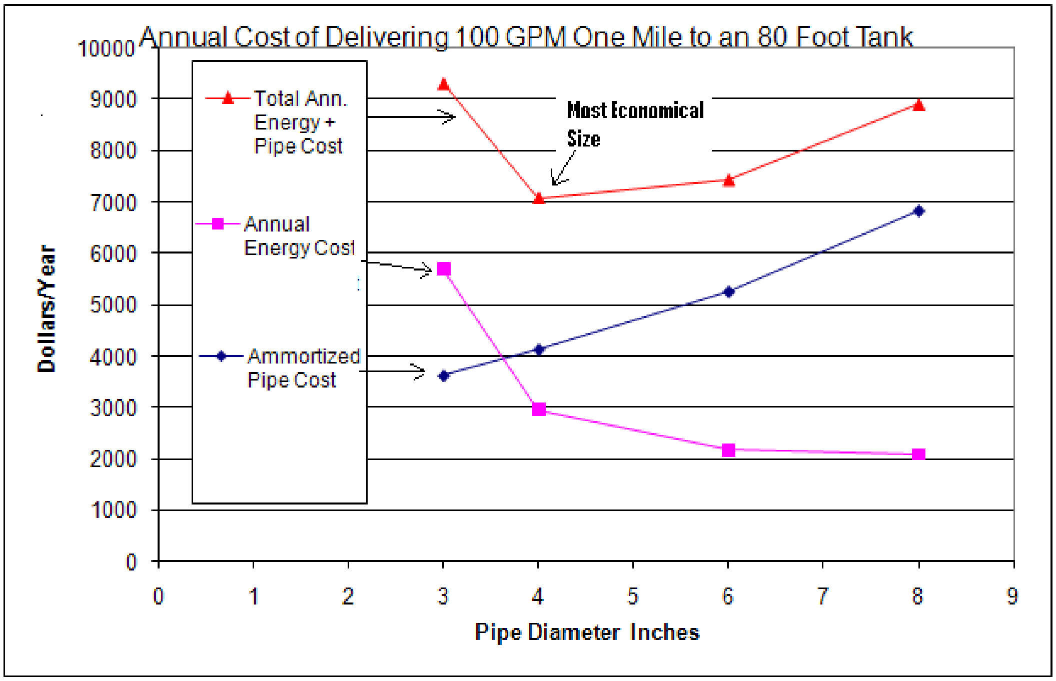

Figure 4. Comparison of Annual Total, Capital, and Energy Cost to Install One Mile of PVC Pipe with a 20-year Life to Deliver 100 GPM to an 80 Foot Tank when Electricity Costs are $0.10 per kwh and the Interest Rate is Five Percent.

However, in a water system the problem is more complicated since a new pipe will be used in a net work with other pipes. Also, Oklahoma mandates require that if a fire hydrant is attached to the pipe, the minimum diameter would have to be six inches. Alternative simulation runs were used to compare the system performance in terms of pressures and energy cost before and after each change in the distribution system infrastructure. The capital costs associated with different solutions were calculated outside the simulation.

The ability to meet fire flow requirements at each fire hydrant node was tested by adding a 250 gpm demand to each node in turn and testing the pressure after a two hour simulation. The full set of fire node tests were repeated after each set of infrastructure changes. Excel macros were again used to write out the simulation input data, run the simulation, retrieve the results of each simulation, and determine the number of fire flow and other failures in the system. A set of incremental infrastructure investments was developed that maximized the number of new fire hydrant nodes meeting the fire flow test per dollar spent. The results are shown in Table 3. In Table 3, the greatest initial improvement per investment dollar came from adding the two major pipes in the eastern part of Beggs. At the bottom of Table 3, the additional water tower in eastern Beggs, added onto the previous changes, had the fewest improvements per dollar spent.

Table 3. Order of Changes in Beggs Water Distribution System to Maximize Fire-Flow Compliance per Dollar Invested.

Order	Description of Changes	Cost
1	Install two major pipes in East Beggs	$69,000
2	Add three additional pipes in East Beggs to finish addressing Hilltop pressure problems	$60,000
3	Add remaining pipes to eliminate targeted dead ends	$57,000
4	Add Additional Fire Hydrants	$60,500
5	Add 50,000 gallon water tower in East Beggs	$167,000
	Total All Changes	$415,000

For a detailed analysis of each step of the Beggs analysis (including all data sources, software modeling inputs, and cost estimation methodology), see Lea (2009).

Section 2.2: Simulation Model to Evaluate the Oilton Water Distribution System

The City of Oilton is located in Creek County and is approximately 54.6 miles to the west of Tulsa. Located close to the Cimarron River, the city of Oilton houses a small community having a population of about 1200 people. The approximate area of the city is 0.65 square miles, which is about 416 acres. The City of Oilton receives its water supply through groundwater. The system has two wells that are located five miles to the south of the city. The storage facilities used by the town are two standpipe tanks. One tank is located outside the city and the other tank is located in the city. The exact age of the pipelines is not known. The main pipeline that brings water to the city is an eight-inch asbestos cement pipeline. There are two main distribution pipes in the town, one of which is an eight-inch PVC pipeline while the other is an 8 inch asbestos cement pipeline. All other mains and sub-mains are in the range of 1 to 6 inches. A summary of the statistics of the Oilton water distribution system is shown below in Table 4. Figure 5 shows the map of the town. Figure 6 shows a schematic of the distribution system.

Table 4: Oilton System Statistics

- Source: 2 deep (approx. 500 ft) wells
- Pumps: Single submersible pump per well
- Total Storage: 950,000 gal
- Pumping Rate: 118,000 gal/day (81 gpm)
- Population Served: 1200

Selection of hydraulic simulation software for Oilton, Oklahoma

The hydraulic simulation software used for this part of the study was WaterCAD V8i distributed by Bentley Systems. The aim of this project was to provide an economic tool which would be affordable to rural water districts. However, after completion of the previous study carried out for the Beggs water system, it was evident that the free hydraulic simulation software used (EPANET) was too sophisticated to be handled and updated by the rural water districts' staff.

Thus this project has a demonstration approach. WaterCAD V8i was selected due to ease of model building and operation and its greater programming capabilities as compared to EPANET. Although rural water system personnel are not likely to be able to use WaterCAD, most professional civil engineers do have knowledge of the software and a demonstration of its applicability to rural systems can potentially aid future efforts to assist these communities.

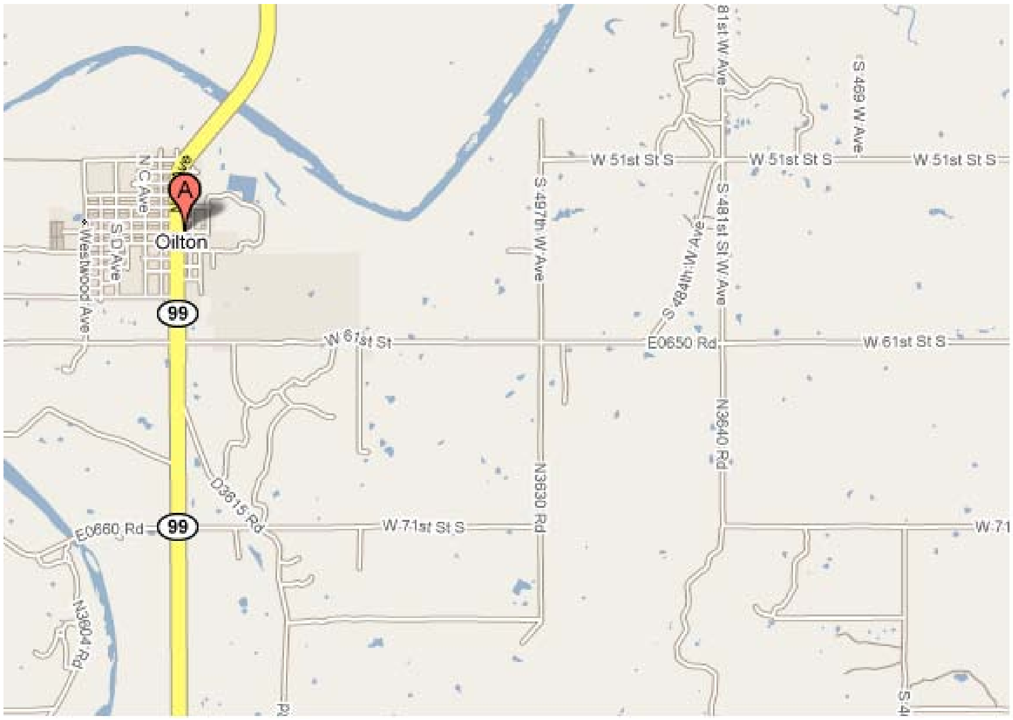

Figure 5: Map of Oilton, Oklahoma, Area (Google Maps, 2009)

To use the simulation software, the following steps were followed:

1. Pipelines were digitized, from information gathered on location (x-y coordinates), length, and diameter.
2. Facilities were located, including treatment plants, wells, pumps, and towers/standpipes.
3. Unknowns at this point included
    - Elevation Changes along pipeline
    - Location of Users along pipeline
    - Demand allocation along pipeline
    - Age, Condition, Materials

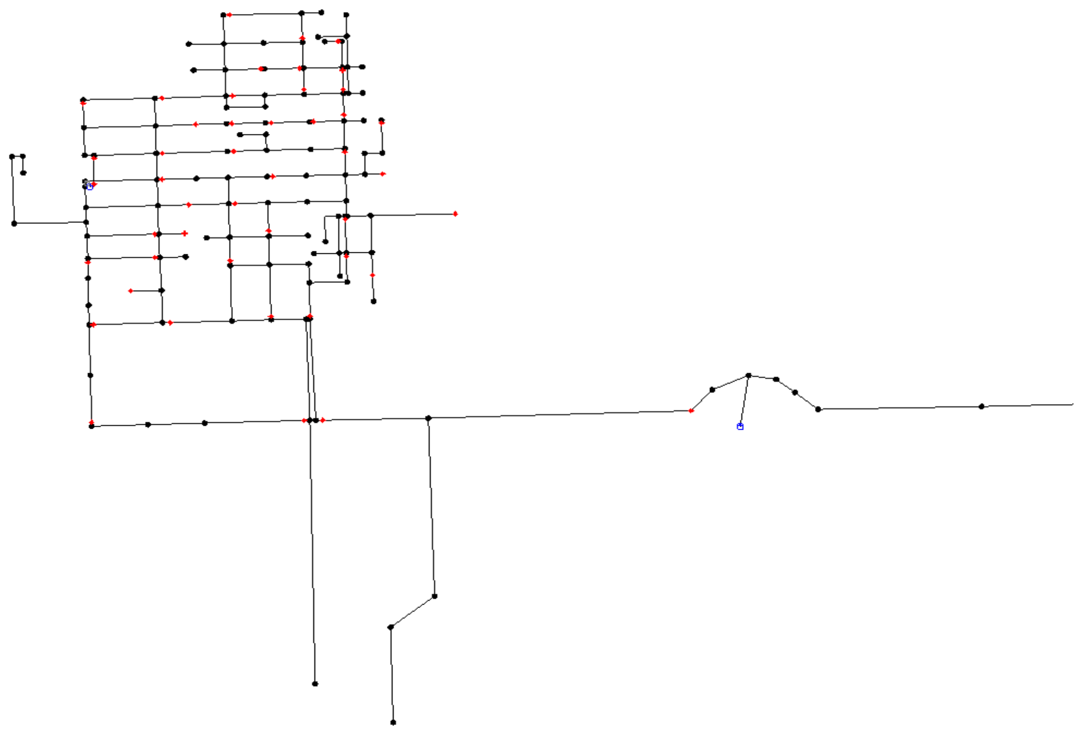

Figure 6: Schematic of Oilton, Oklahoma, Water Distribution System (Bhadbhade, 2009)

Apart from the preliminary information, additional inputs were required for the simulation of the model. The most important was the elevation dataset. Without the elevations, it is not possible to run the hydraulic simulation. The elevation dataset was obtained from the United States Department of Agriculture (USDA) website called the “Geospatial Data Gateway” (USDA, 2009). Note that this elevation data source is different than that used for the Beggs simulation. The second important dataset necessary was the information regarding houses in each census block. This information is required to assign base water demands to each node. The census block data was obtained from the US Census Bureau website called the “2008 TIGER/Line Shapefiles”. The user can select the respective state and county, and the Census 2000 Block data was used to match households to potential nodes. Again, the USDA Geospatial data Gateway website was used to download the ortho-images of Oilton for identification of the houses in each census block.

<u>Oilton Simulation Results</u>

- Very large storage results in long water age and excessively long (several days) pump cycles to fill the tanks.
- However, most storage volume is unusable due to low pressures that result when water in standpipes is dropped more than 30 ft from the top of the tanks.
- Excessively long, low-demand lines result in high water age and low disinfectant residuals at dead ends.

For a detailed analysis of the Oilton simulation using WaterCAD, see Bhadbhade (2009).

Section 2.3: Simulation Model to Evaluate the Braggs Water Distribution System

Braggs is located in eastern Oklahoma, 56 miles south east of Tulsa (Figure 7). The population of the city is 308. The largest section of the existing water distribution system was installed in 1982 and has been serving the local population and 650 people in surrounding areas for the last 27 years.

BRAGGS, OKLAHOMA

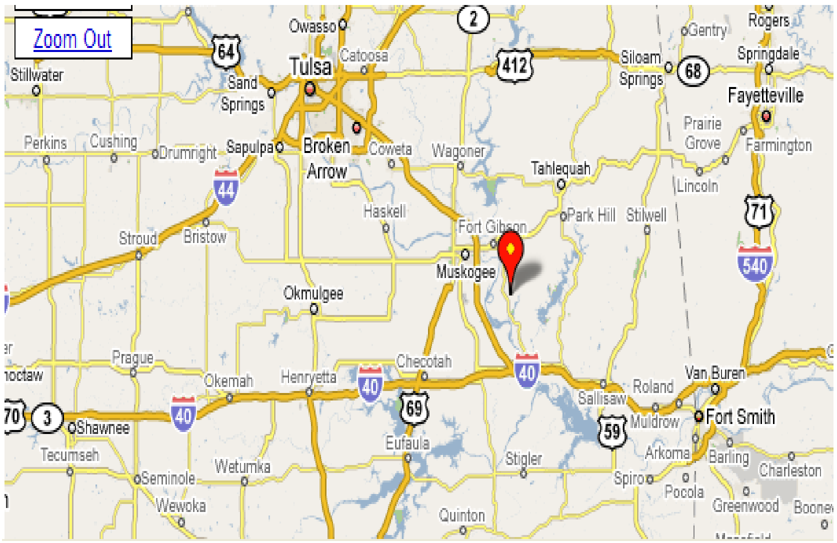

Figure 7: Map of the Braggs, Oklahoma, area (Google Maps, 2009)

Currently the system has 416 service connections and serves 1030 people from its primary water source which is ground water artesian wells. The distribution system network consists of three water towers; one located in the center, one at the north end and one on the south end of the city, giving a total storage capacity of 200,000 gallons. A summary of the statistics for the Bragg distribution system is shown in Table 5.

Table 5: Braggs System Statistics
• Source: Artesian Wells • Pumps: 3 identical working in parallel • Total Storage: 200,000 gal • Pumping Rate: 75,600 gal/day (52.5 gpm) • Service Connections: 416 • Population Served: 1030

The piping consists mainly of long two inch branch pipes which are interconnected by a few four and six inch supply mains.

The map of the Braggs water distribution system was obtained from the Water Information Mapping System (WIMS) on the Oklahoma Water Resources Board (OWRB) website at http://www.owrb.ok.gov/maps/server/wims.php. WIMS is an Internet-based map server that requires a supported web browser. The Braggs system is shown in Figure 8.

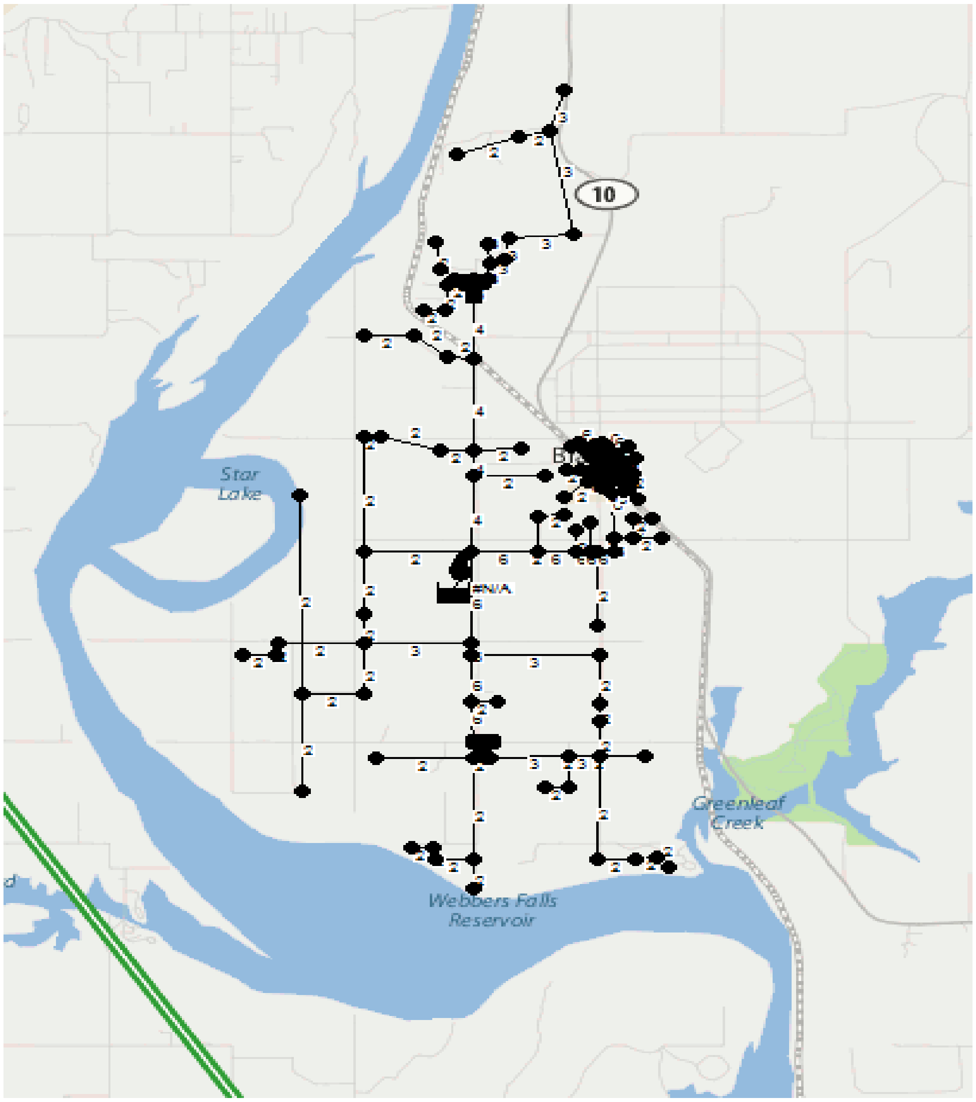

Figure 8: Schematic of Water Distribution Pipelines in Braggs, Oklahoma, Service Area from EPANETZ

Information regarding the age of the system, problems related to inadequate flows, low water pressure, leakages and bursts water usage patterns and equipment information for pumps was obtained from interviews with the plant operator at Braggs, Oklahoma. Water usage data were obtained from the Oklahoma Department of Environmental Quality (ODEQ) records. The records included information regarding the total water pumped daily from the treatment plant, the pH and the doses of the different chemicals added to the water prior to distribution over an eight year period from January 2001 to April 2009.

Hydraulic modeling using EPANET for Braggs, Oklahoma

The process of modeling a network using EPANET involves input of the parameters or variables that most closely describe the operation of the actual system. These parameters include the shape of the tanks, the pump curve which describes the operation of the pump and an infinite reservoir. Other input parameters required for the model to run include the maximum and minimum water levels and an initial water level in the tank. The three water tanks at Braggs are all cylindrical in shape.

There are three identical pumps at Braggs, each delivering 150gpm at 208ft of head. The pumps operate in parallel delivering the same head and are set to sequentially come on line in order to meet increasing flow requirements for the system. The pumps were modeled according to the information received from the system operator. Usually a single pump is switched on when the pressure drops below 65 psi and is switched off when the pressure exceeds 80psi. Therefore, rule based controls were set within the EPANET model to ensure that the first pump was switched on when the pressure dropped below 65psi and switched off when the pressure increased to 80psi. Pump 2 was modeled to switch on if the pressure dropped further as would be the case in the event of a fire. Pump 3 was treated as a standby for the system in case pumps 1 or 2 failed to operate and was not included in the hydraulic modeling process.

The greatest percentage of the pipes at Braggs were installed in 1982 when the currently existing PVC pipes were installed to replace deteriorated cast iron pipes that had been previously installed in the 1940's. Therefore, most of the pipes are almost 30 years old. The operator noted that they had not replaced any pipes recently.

Braggs Simulation Results

- Technical work necessary to use the EPANET software took several months. The software is not user friendly and technical support is non-existent.
- Relatively good records from the operator resulted in good match between simulation and the limited physical system measures (flows and pressures).
- Water age was high and disinfectant residual was predicted to be low in the long dead ends. Looping did not help, since it merely increased the flow paths and further lowered velocities.

For a detailed analysis of the Braggs simulation using EPANET, see Senyondo (2009).

Section 2.4: Cost comparison of alternative treatment plant facilities in Kaw City

Kaw City (located in Kay County has had water problems since the 1990's because of the collapse of one of its wells and from the poor taste of the groundwater. The poor taste is attributed to high levels of minerals such as manganese and iron in groundwater. Chapman (2003) found that the levels of Barium were 0.265 mg/l, iron was 0.071 mg/l and manganese was 0.121mg/l. These chemicals are above the Oklahoma Environmental Secondary Standard. Chapman (2003) also notes the importance of constructing a water treatment plant with capacity of 125 gpm and to use alternative treatment systems to treat the water in order to achieve the quality of the water below secondary standard. Table 6 shows the analysis of the untreated water and the levels that EPA and the State require after water treatment.

Table 6: Organic Compound level in groundwater before and after treatment

Chemicals/Organic compound	Test from the well on the bridge no. 3 (2000).	EPA and State Standard/ primary required level in (units)
Total dissolved solids	637 mg/l	500 mg/l
Turbidity	0.76 NTU	Surface water standard 95% must be < 0.5
iron	0.071 mg/l	0.3 mg/l
manganese	0.121 mg/l	0.05 mg/l
Barium	0.265 mg/l	2 mg/l
Hardness	514 mg/l	Existing hardness is only 152 mg/l

Source: Chapman & Associates (2003)

Another problem with Kaw City's water is its taste and odor. Kaw City officials have specified that they would like to solve the problem of the poor condition and taste of their water while also considering the possibility of selling water to nearby communities (including the city of Shidler). Accordingly, the city requested assistance in estimating the cost of establishing a new well, new water treatment plant, and the necessary extension of pipelines. The presence of Kaw Lake creates an additional tourist demand for water, especially during summer weekends.

To increase the quality of water to solve both the high demand problem and to provide quality drinking water for domestic and other uses (necessary to meet U.S. EPA and Safe Drinking Water Standards), there is a need to develop a comprehensive solution by building a water treatment plant and to use appropriate water treatment systems to treat the water for drinking. The purpose of water treatment is to condition, change and remove the contaminants, to supply safe and good tasting drinking water acceptable to consumers or users (Spellman, 2003). The base water demand for Kaw City and Shidler is 150 gpm. The building of the plant will provide a volume of 216,000 (150*60*24) gpd for the two cities. It will serve customers with its own water and provide portable water to the people of Shidler. Residents hypothesize that this will boost the economic activities of the city, particularly tourism. Because construction costs can be large and vary dramatically by plant type, the city wants to examine both the benefits and costs of the treatment plant and its operations.

This portion of the study estimates the cost of building an alternative treatment plant facility for a reliable supply of drinking water to the people of Kaw City. The focus is on choosing the best (least cost) treatment system while improving quality of the water from the well to the city and other potential buyers. Due to the nature of the chemical compounds in the groundwater, two main treatment systems that is nanofiltration (reverse osmosis) and Aeralator® would be considered because it is the most effective systems of treating water.

Economies of scale dictate that the capacity of the treatment plant needs to increase in order to supply both Kaw City and Shidler. Increasing the capacity of the treatment plant and supply to serve these cities is economically viable and better than building small capacity to serve only Kaw City. Moreover, the expansion of the size and supply will reduce the cost of building treatment plant, the cost of treatment of the water and the distribution of water.

The general of objective of this portion of the study is to determine and compare the cost of building alternative treatment plant facilities in Kaw City. Specific objectives of this research include:

1. To determine the total discounted investment capital cost and annual capital cost of the two possible sizes and types of water treatment plants.
2. To determine the annual operating cost of the two possible sizes and types of water treatment plants.
3. To determine the cost of a new well and the cost of the transmission line from monitoring well to the treatment plant (at the "greenhouse" site) and from the treatment plant to the existing pipeline at Washunga bay.
4. To compare the discounted amortized capital cost and plus the amortized operating cost for two sizes and two types of treatment plant.
5. Determine the cost of replacing the entire Kaw City distribution pipeline.

<u>Estimation of Cost</u>

The best systems among the various water alternative treatments may be selected on the basis of cost of construction, other capital, operating and cost associated with capital and plant maintenance cost over a designated planning area.

Capital Cost

Capital costs are the costs for the physical assets of the project. Capital costs are part of the fixed component of the total cost. They are normally incurred at one time but also include cost of rehabilitation or replacement of equipment during the life of the system. Capital costs are typically estimated for equipment, materials, construction, and other assets. Capital costs can be estimated using a recently developed model (Sethi, 1997; Sethi and Wiesner, 2000) that divides water system costs into major capital cost components. These categories include pipes and valves, membranes, pumps, electrical and instrumentation, tanks, frames, and miscellaneous items (including buildings, electrical supply, treated water storage and pumping, etc.). Total construction cost includes all costs related to construction contract, overhead and profit of the contractor (Kawamura, 2000).

Generally, there are economies of size so as the capacity of the system increases the unit cost of capital declines. Therefore, the per gallon capital cost of water treatment for only Kaw city with capacity of 86,000 gpd may higher would a combined system for Kaw City and Shidler with capacity of 216,000 gpd. Some of existing low-pressure membrane water treatment plants are indeed small, with capacities of less than 3,800 m^3/d (1-mgd). As plant capacity increases, per capital costs typically decrease, due to economies of size associated with manufactured equipment and other facilities. Therefore, for large treatment plants, the annualized capital costs may become similar to the operating costs.

Operation Cost

Operation costs are the variable cost components in the project cost. They include costs incurred in running the day-to-day business or project. For a water treatment plant, operating costs include costs for chemicals, maintenance, energy, taxes, and insurance. Generally, the costs for maintenance, taxes, and insurance are estimated merely as a percentage of the total capital cost. Labor costs are based on the manpower needed and the average salary. The manpower requirements for each design are can be calculated according to EPA documentation (USEPA, 1971).

According to Sethi and Wiesner (2000), operating costs can be systematically calculated for the energy utilized by pumps, for membrane replacement, and for chemicals. Costs related to other components, like concentrate disposal and labor, are highly dependent on factors such as geography, scale, and application of the membrane process. Operation and maintenance costs of water treatment plant normally consist of labor, supervision and administration, power, chemicals, maintenance, repairs, and miscellaneous supplies and services. Other factors that can influence the maintenance and operation cost include the policy of the owners, the complexity of the system, the local environment, and weather. Operating cost can also be increased due to continuing inflationary trends of labor, power, and equipment (Kawamura, 2000).

Distribution Cost

Water is delivered to consumers through transmission pipelines and distribution mains. Trunk lines are the major pipelines that represent the major trunk lines used to deliver water. They connect the treatment plant to the pumping station and to the distribution system. Pumping stations, pipelines, and labor energy comprise the major costs of distribution. The distribution works include the meters, pipelines, and storage facilities (water tanks or reservoir) necessary to convey the water from the transmission system to the consumer (Clark, 1981). As a result, the cost of distribution depends upon the quantity consumed by individuals at various distances from the plant. Clark (1964) noted the energy cost depended upon the flow and distance pumped.

Anticipated Contribution

The result of this portion of the study will assist the Kaw tribe and Kaw City in planning for their water treatment plant and for the distribution of the water to the customers in the city or the area and the cities around it. The results will also give the insight of the power needed to supply certain amount (in gallons) of water a day and a minute (gallons per day or gallons per minute). It will enable city to project the number of water (gallons per day) for future increase in population, cost of equipment like pipes, installation cost and maintenance cost. Moreover, the study will help the city to choose the best (and more cost effective) treatment system.

In addition, the study will help Kaw City and Shidler to solve their long term water problems resulting from poor taste and high amount of minerals in the water, and water shortage in the city (especially during weekends) due to tourism activities in the area.

<u>Data Collection</u>

The data used to estimate costs for distribution of water, the capital and operation costs for water treatment plants, and the pattern of water demand in Kaw City were collected from various sources. The data on costs of water treatment systems were obtained from manufacturers. The costs for pipeline materials and installation were obtained from Means Construction Cost Estimates (RSMeans, 2009).

The data on the layout of the city pipelines including the diameter, the length of the pipe and the materials like fire hydrant collected from drawings provided by the city engineer, which provided an in-depth layout of the existing pipelines in the city and the one connecting Shidler. The treatment plant and monitoring well design are also obtained from the City Engineer through the Department of Environment, Kaw Nation.

The estimated current and projected population of the city were obtained from the website, http://www.census.gov, and Oklahoma Department of Commerce (USCS 2008; ODOC 2008).

<u>Data Details</u>

The study requires detailed information on cost for trenches, pipes, and energy. The study also requires knowledge of the effect of specific variables such as diameter of the pipe, width and depth of the trench, horsepower, distance of the pipeline and overall capital and operating costs. The mains areas of the estimation include the well and pipelines to the treatment plant, the treatment plant, and the distribution system. In each area, costs are divided into fixed (or capital) and operating (or variable) costs.

<u>Estimation of Cost of Water Treatment Systems</u>

Two different sizes of each alternative treatment system will be. For example, one size of the estimated nanofiltration (reverse osmosis) treatment plant system will serve a population of four hundred (400), (Kaw City only); while the other size will serve approximately one thousand people (1,000) (both Kaw City and Shidler). Because of economics of scale, a plant that serves both Kaw city and Shildler is more likely to be economically viable. The cost estimates in this study will be summarized in three main categories: (1) capital cost, (2) operating cost and (3) distribution cost.

Capital Cost

Capital costs are mainly for construction cost and cost of treatment equipment. Once installed these become the fixed component of cost. Capital costs are expected to be incurred mostly at the beginning of the planning process and in future years when the equipment is replaced or renovated. Capital cost can be calculated as the sum of material cost and equipment cost, trench cost, fixed pipe cost and contingency cost. Contingency is a proportion of construction cost estimated as a lump sum cost. The proportion of the contingency depends on the contractor or the estimator of the project but usually ranges from 2% to 5% (Roberts, 2008).

The cost of equipment is a major part of the total capital cost for a water treatment system. The estimation of equipment cost is based on the size, type and quantity of equipment needed to complete the project. The cost of equipment is estimated by multiplying the quantity of equipment by its current price. Some of the equipment can be rented or leased (Roberts, 2008). The materials needed for water treatment include pipes, fire hydrants and others. This category also includes membranes, pumps, pipes and valves, electrical and instrumentation, tanks and frames, and miscellaneous items such as buildings, electrical supply, and treated water storage. Some data are adjusted using the Engineering News Record's Construction Cost Index (ENR CCI) ratio. The ENR CCI value is determined by averaging index values for various equipment. For example, to update a representative cost of 2002 (ENR CCI value $6,538), the cost of 2002 would be multiplied by the ratio of $7,872 over $6,538. The ENR CCI values are based on material and labor construction costs of all major cities across the US. The index measures the amount of money it would cost to purchase a theoretical quantity of services and goods in one year, as opposed to another. The approach of accounts for the individual economies of scale related to different equipment and facilities, and thereby considered an overall economy of scale for the entire membrane system (Sethi, 2000).

Estimation of Pipe Cost

The pipe cost is part of fixed component of cost. Pipe cost is a function of its diameter. Mathematically,

FPC = IP*Dia*MF………… (1)

where FPC = the Fixed Pipe cost, Dia =Diameter of the pipeline and MF = Mortgage factor, IP= Investment Cost of pipe

Trench Cost

Trench cost is the cost of excavating the trench to lay pipes. The trench cost is a function of width and an exponential of depth of the trench. The larger the size of the pipe, greater the width of the trench will be. The depth of the trench varies associated with the size of the diameter of the pipe. T_i is Trench Cost, Di= the depth, $D^\wedge 2_i$ = square depth and δ_i= the coefficients. The model is:

$$T_i = a + bD_i + ce^D \text{ ………………… (2)}$$

T_i is the cost of trenching

D_i is the depth of the trenching which varies with the cost of pipe.

e is natural logarithms

a, b and c are the parameters of the model and are estimated using regression. Budgets are first constructed based on different trench depths. Then, as equation (2) indicates, regression was used to estimate trenching cost as a function of depth. Since the width of the trench was held constant, it did not have effect on the ordinary least squares (OLS) estimation of the trench cost. R^2 will be calculated to show the goodness of fit of the depth in relation to unit cost of the pipe.

In addition, the total cost of excavation and backfill includes the cost of the trench, packing, and backfill. Trenching cost can expressed as the sum of the cost for backfill, packing, and trench cost.

$$ExB_f = T_i + P_i + B_i + OC_i \text{ ……………………………………..(3)}$$

where ExB_f is the Total cost of Excavation and backfill

T_i is the trench cost, P_i the cost of packing on the sides of the pipe in the trench, B_i is cost backfill and OP_i is other cost such as bedding, surveying or blasing..

Estimation of Operation Cost

The operation cost represents the variable part of the cost of the treatment plant, and represents the cost incurred in running the day-to-day activities of the plant. It comprises of chemical cost, energy cost, staff, maintenance, monitoring and labor cost. Total operation cost can be calculated as the sum of the above stated costs. Labor cost can be calculated base on the number of hour per work. It will be estimated base on the current wage of the labor per hour. In estimating operation cost, there general assumptions include:

a. The number of operation hours in a year, usually 8760 hours. (365*24=8760 hours).

b. The unit cost of electricity use during the operations. This has significant effects on the cost of operations. The unit cost electricity consumed in this study is $0.108.

c. The capacity of the well. In this study the capacity is the 150 gpm for Kaw City and Shidler.

d. The unit cost of potassium permanganate use to control odor, and taste in the water is $1.60.

e. The unit cost of chlorine use to kill bacteria in the water is $0.50 per lb.

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Chemical Cost

Chemical costs are the cost for those chemicals used in the water treatment plant. However, this cost depends on the quantity of the chemical use during treatment process and the price of the chemical per pound. When the price per pound of the chemical used for treatment increase, the cost will also increase. In the estimation of chemical cost, there are some baseline assumptions that should be followed:

a). The unit cost of chlorine (in $) should be clearly stated. The unit cost of chlorine is $0.50/lb. This cost will give the cost of the chlorine that will be use in treatment of water base on the quantity of the chlorine use. The chlorine is the most important chemical as far as treatment of water is concern which is use to kill bacteria in water.

b). Another assumption is the cost of the potassium permanganate ($KMnO_4$) use during the treatment. Potassium permanganate ($KMnO_4$) is used primarily to control taste and odors, remove color, control biological growth in treatment plants, and remove iron and manganese.

c). The third assumption to be considered is the unit cost of the scale inhabitor. The unit cost is $1.15lb. The scale inhibitors specifically develop to manage the problems associated with hard water, specifically hardness salts and the formation of scale in a wide range of commercial and industrial process environments.

The chemical cost is estimated base on P_i= price of $KnMnO_4$, (Potassium permanganate), Q_i= quantity of $KnMnO_4$, δi = Scale inhibitor, S_i=cost of inhibitor, α_i=cost of chlorine and C_i is Chlorine. Chemical cost (C_N) is calculated as

$$C_N=P*Q + \delta_i * S_i + \alpha_i * C_i \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Energy Cost

The Energy cost is the cost of energy needed to run the pumps or treatment plant and other facilities. The energy cost can be estimated with the use of both water horsepower and the Brake Horse power method. In estimating energy cost, the following assumptions should be considered:

a. Pump efficiency should be range from 50-85% efficiency. Pumping efficiency is water horsepower divided by brake horsepower. Mathematically, *Pump efficiency = Whp/Bhp*

b. The efficiency of the electric motor efficiency is also ranging from 80-95%. Motor efficiency is the quotient of Bhp to Mhp where Mhp is Motor horsepower. Algebraically, *Motor efficiency = Bhp/Mhp.* (Spellman, 2000).

Water Horsepower *(Whp=GPM*Head/3960)* is the theoretical power required to pump a given volume of water from a well and through a pipe. The amount of head (pressure) that must be supplied by a pump is equal to the sum of the pumping lift and head loss in the pipeline. The headloss in the pipeline may be calculated by the Hazen-Williams formula as, (Spellman, 2000),

$$\text{Head Loss} = \frac{10.51*(GPM/C)^{2}*Dist}{(Dia)^{4.87}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

where *Dia* is the diameter of the pipe in inches, *Dist*= distance of the pipe in feet, *C*= coefficient of roughness for type of pipe.

Horsepower (Bhp) is defined as the horsepower supplied to the pump from the motor. It depends on the water horsepower. It can be calculated as

$$Bhp = \frac{GPM*Head\ (pr)}{3960*Peff*Meff} \ldots\ldots\ldots\ldots\ldots\ldots\ (6)$$

where *GPM* is gallon per minute, *Peff* is Pumping efficiency, *Meff* is Motor efficiency and Head (pr) is the pressure flow.

EC is Energy Cost, *GPM* is gallons per minute, *Hd* is head loss, Pe is Pump efficiency, Me is motor efficiency, *KwBhp* is kilowatt per brake horse power, *hpy* is hour per year, and *pelec* electricity cost

$$EC= \frac{\{(GPM*Hd)*Kwbhp*hpy*pelec\}}{3990*Pe*Me} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (7)$$

Estimation of Cost of Drilling the Well

The necessary depth of drilling a well for Kaw City can be estimated based on a previous monitoring well drilled by CRC & Associates, Inc of Tulsa, OK. The monitoring well is located in the north of Kaw Lake near Washunga Bay. The cost of the drilling of the well is part of construction cost or capital cost. Therefore, the costs of the materials and the equipment which were used in the process of the drilling will be the main focus.

In this estimation, certain features of drilling of the well such as the depth of the hole and diameter (size) of the hole taken into consideration. Previous estimates suggest that typical hole diameter is 8", the length of the hole from the casing to the bottom cap level is 120' and the casing diameter is 4" (CRC & Associates, Inc). Therefore, it is assumed that the length of the pipe (specifically PVC 4") will be 120 feet (120'). To estimate the cost of drilling the well accurately, the quantity of each equipment and material will be multiply by the current prices from the Construction cost data (RSMeans, 2009).

Description and Method of Treatment System

The Aeralater® water treatment process is designed to remove high levels of iron and/or manganese from water. The Aeralator® treatment system is divided into three main sections: aeration, detention and filtration (four filter cells) (Figure 9). The system has been described as three in one system because it performs three functions in a single unit. The type II AERALATER® is considered as a modified conventional treatment system for Kaw City.

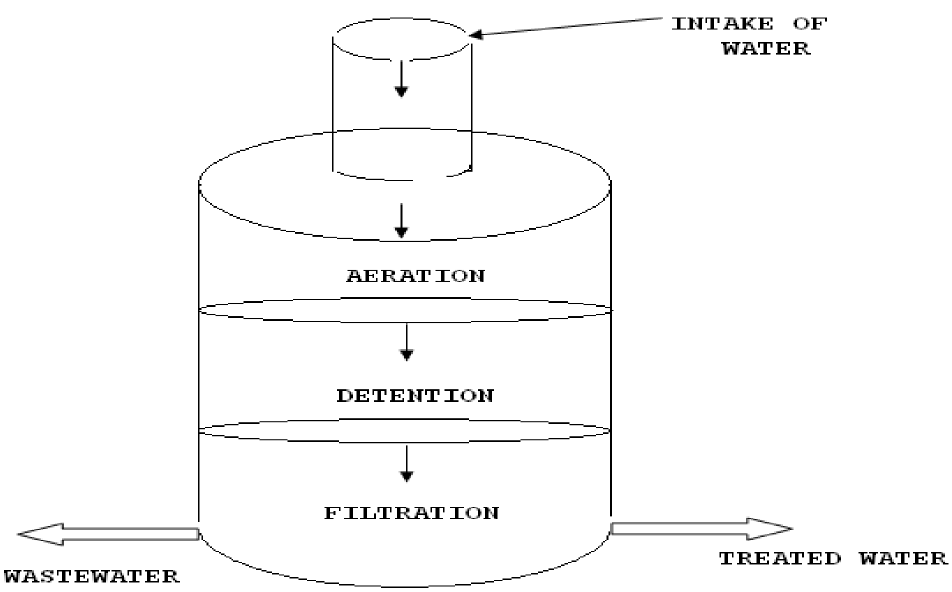

Figure 9. The Flow System of Aeralator ® Treatment Process

The Aeralater® is a complete self-contained filter plant for treating water. It combines aeration, detention, and filtration functions. The treatment processes involves aeration, iron manganese oxidation (with the oxidant added at inlet piping to the Aeralator® system), detention and gravity filtration (with four filter cells). Water from the well (groundwater) enters the top of the Aeralater® and pass through inlet hole (PVC pipe) to the aeration section. After aeration water moves to detention area where oxidation and flocculation of iron and manganese occurs.

The static mixer is mounted in between aeration and detention in order to speedup oxidation process. The probes in the detention tank are used to control the operation of pumps and chemical feeders to control the reaction.

The oxidized iron and manganese water is distributed to the four filter cells through simple piping arrangement. The filtered water later passes through low pressure rate. These filters contain Anthra/sand to remove the manganese., The media is advertized as an alternative to greensand. After the raw water has passed through these processes, multiplates with low headloss are used to collect the filtered water. A similar process is used to automatically backwash the filters and remove the wastewater. The filtered water is then pumped to the elevated storage tank.

Description of Nanofiltration Water Treatment System

As an alternative to the Aeralator®, the nanofiltration system under consideration has a two-stage array system (Figure 10). The system was constructed by Fluid Processes Inc. and the spiral-wound membranes supplied by Hydranautics. The first stage consisted of two parallel pressure vessels, each consist of three membrane elements.

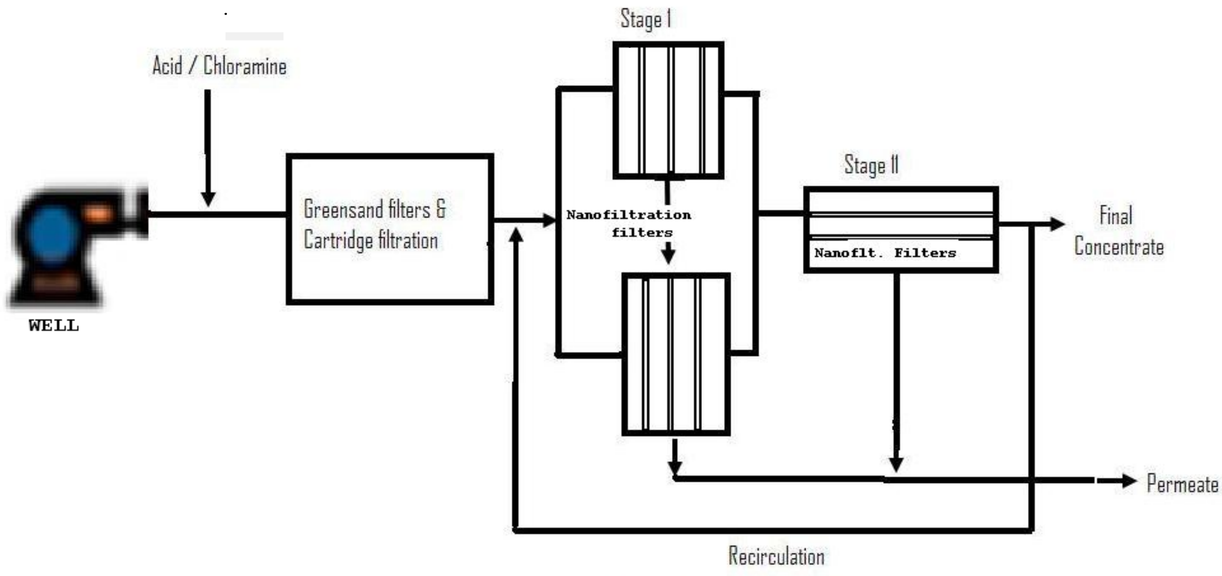

Figure 10. Nanofiltration Treatment Design Process

The second stage consisted of one pressure vessel containing three membrane elements (Hem, 2008). The system was assumed to run at 75 percent recovery. This means that 75 percent of the intake water enters the distribution system while 25 percent enters the wastewater system. Before the nanofiltration, the water would be filtered through a cartridge filter or greensand filters, to oxides manganese and to prevent the plugging of the membrane module with particles. Acid will be introduced into the nanofiltration feed line to keep the pH between 5.6 and 5.8 to enable solubility of carbonates to minimize inorganic scaling. Chloramines would be injected at a set rate and concentration to prevent biofouling (formation of a biological slime or biofilm that can be avoided by feeding chlorine into the feed water). Because the nanofilter membranes do not tolerate free chlorine, chloramines would be used. Chloramines are defined as chlorine that exists in a chemical combination with ammonia in water. Chloramines were made by mixing sodium hypochlorite with ammonium sulfate. Chloramines controlled such that no more than 0.1 mg/l of free chlorine applied to the membranes. The goal residual in the permeate stream will be one mg/l of chloramines.

Creating of pipeline distance and elevations using EPANET Software model

EPANET software was used to create a digital pipeline map for Kaw City. A modified version EPANET called EPANET-Z (Zonium Solutions) was used which has Google and Yahoo maps as the background. Parameters such as length of the pipeline, elevation of the nodes and equipment like pumps added into the model of the distribution system. The distribution system of the Kaw City receives its water from the existing city water tower (Figure 12).

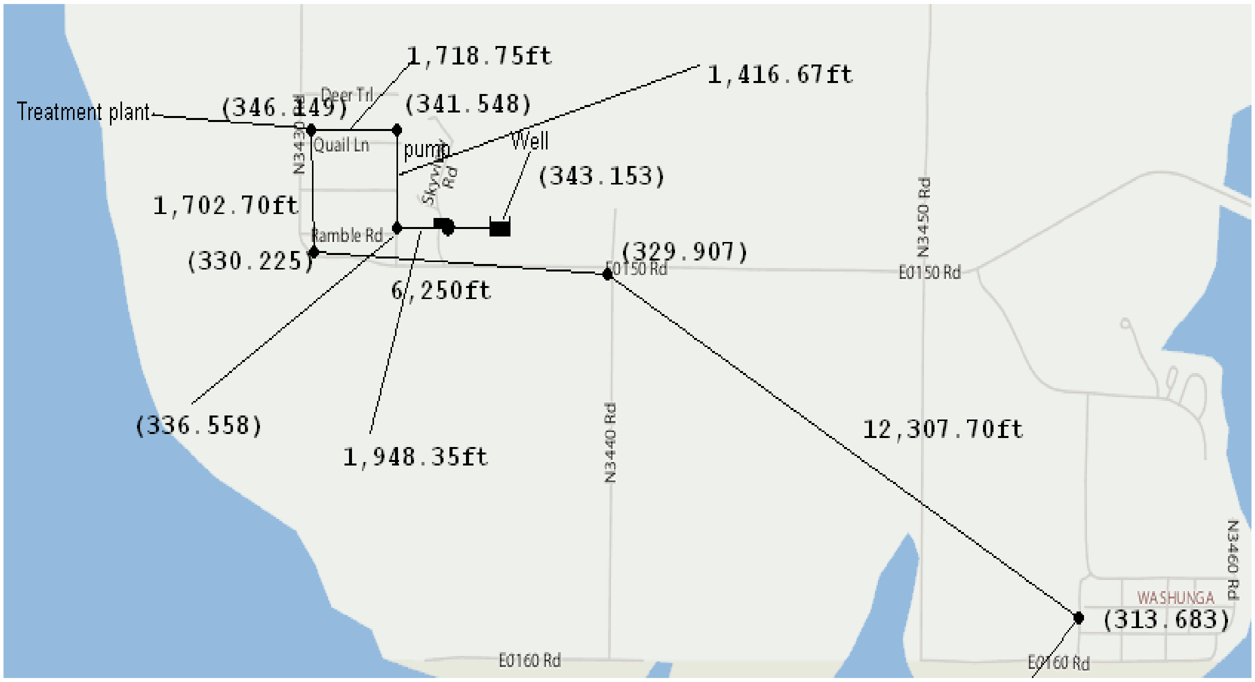

Figure 11: Kaw City Network System with Elevations

In EPANET–Z's toolbar, the pipe and link icons used to create link and endpoint (junction) of the pipe. Precisely, the node formed the endpoint of the pipeline and the link formed the pipeline (Figure 12).

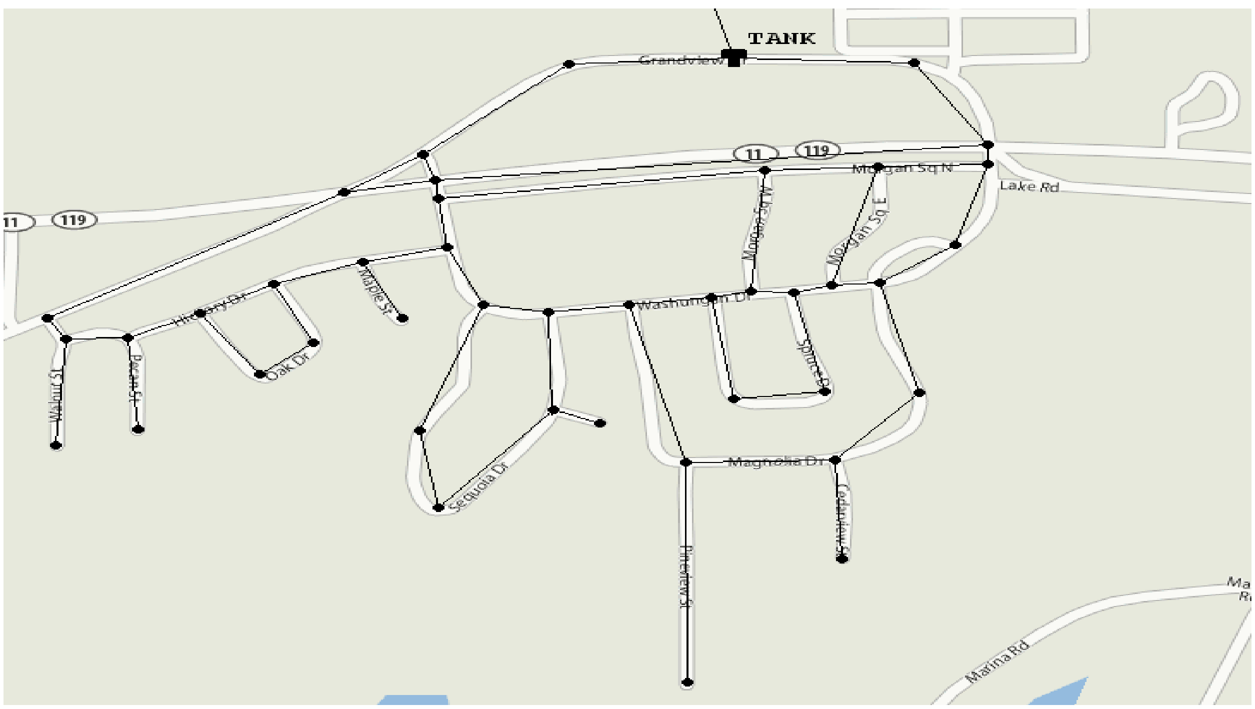

Figure 12: Kaw City's Pipeline Layout

The main tower (tank) and the pump are located in the model in addition to the pipelines and the nodes. Then EPANET-Z will save the data in an *.inp file by exporting the network (pipeline layout).

The elevation of each node was estimated by overlaying the pipeline file on a USGS 1/3 second elevation map in the GIS software program Global Mapper©. An xyz file is exported from Globalmapper. The elevations from this file are added to the node identification section of the EPANET input (.inp) file using a text editor such as WordPad or Notepad.

The elevations values were in meters but were converted to feet. In GlobalMapper, the measure icon can be used to calculate the distance (length) of the pipelines. This procedure was used repeatedly until all the measurements finished. In areas where there were large elevation changes between nodes, it was necessary to use Pythagoras's theorem to estimate the length of the pipeline between nodes. Alternatively, a tread measurement method can be applied. GlobalMapper was used to create a cross section from one node to another. The tread was used to measure the undulating cross section and multiple by the scale to get the exact distance.

For detailed estimates on the cost of constructing and operating various versions of the two systems (modified conventional and reverse osmosis), see Atta-Asiamah (2010). This includes estimates of smaller (Kaw City only - 60 gpm) and larger (Kaw City plus Shidler - 150 gpm) systems. Shown below in Table 7 is a comparison for the two systems for supplying Kaw City only (60 gpm). Because of the location of the treatment plant relative to the Kaw City, a large part of the cost is for the necessary pipe to connect well, treatment, and Kaw City. The cost of the modified conventional system is estimated to be about $3.00 per 1,000 gallons while the cost of the reverse osmosis system is about $4.00 per 1,000 gallons.

Table 7. Comparison of Capital and Annual Costs for Modified Conventional and Reverse Osmosis Plants to Supply 86,000 GPD to Kaw City (60 gpm)

Item	Unit	Modified Conventional				Reverse Osmosis			
Capital Cost		Years Life	Units	Unit Price	Initial Cost	Years Life	Units	Unit Price	Initial Cost
Well	depth	50	120	na	$ 4,020	50	120	na	$ 4,020
Pump and motor	gpm	3	60	na	$ 8,400	3	80		$ 9,080
Pipe, trench to WTP, 4" dia.	ft	50	5082	$17.5	$ 88,935	50	5082	$17.5	$ 89,087
Water Treatment Plant (wtp)	sqft	50	750	$125	$ 93,750	50	1000	$120	$ 120,000
Treatment equipment	tgpd	20	86		$ 81,000	20	86		$ 209,000
Pump: WTP to W.Tower	hp	10	6	na	$ 4,000	10	6	na	$ 4,000
Pipe,trench: WTP to W.Tower	ft	50	20262	$17.5	$ 354,585	50	20262	$17.5	$ 354,990
Engineering Cost	10% Cost	50	na	na	$ 4,000	50			$ 79,018
Total Initial Cost					$ 638,690				$ 869,195
Annual Operating Cost									
Pumping Well to WTP	Kwh		32.8	$10	$ 3,285		48	$10	$ 4,842
Energy within WTP	Kwh		46	$10	$ 4,599		100.3	$10	$ 10,356
Pumping: WTP to WT	Kwh		33.9	$10	$ 3,393			$10	$ 3,393
Chemical and supplies	cost/yr		-	-	$ 4,201		-	-	$ 4,621
Labor	hrs		730	$35	$ 25,550		913	$35	$ 31,938
Maintenance	1.5% Investment				$ 9,580				$ 13,038
Office expense	Cost/mo		12	$300	$ 3,600		12	$300	$ 3,600
Total Variable Cost					$ 54,208				$ 71,787
Annual Capital Cost					$ 39,971				$ 56,070
Total Annual Cost					$ 94,180				$ 127,857
Average Cost per 1000 gallons					$ 2.99				$ 4.05

Section 3: Principal Findings and Significance

The primary findings from the first three projects (Beggs, Oilton, and Braggs) suggest that it is possible to develop GIS-based water system simulations for small towns and rural communities at reasonable cost. This can be accomplished with a combination of public domain software, relatively low cost web-based systems such as Google Earth® , GIS software, and macro driven spreadsheets. Examples of the data requirements and steps necessary to run these simulations can be found in Lea (2009), Bhadbhade (2009), and Senyondo (2009).

The EPANET freeware program is capable of providing useful simulations of piping layouts, pumping demands, spatial analysis of water pressures and water ages in pipeline systems, and calculating operational costs (electricity for pumps) for small towns and rural areas. This software developed by EPA is free and reasonably sophisticated. Base systems can be developed and initially calibrated with minimal effort from the communities involved. The models can then be further refined and used to address specific water system planning needs such as excessive water ages, high pumping cost, low and high-pressure zones, and fire fighting capacities.

The most time consuming process is the development and validation of the current water supply system. The problems and their associated solutions differ between small towns and rural water districts. The findings or methods developed for rural water districts are reviewed first, followed by a discussion of small towns.

<u>Rural Water Districts</u>. In Oklahoma, the Oklahoma Water Resources Board (OWRB) has developed GIS files of pipelines for rural water districts. Supporting files provide information (generally from the year 1995) on the source of water, type of treatment, number of people served, number of meters, average use, and peak use. The GIS files contain estimates of pipeline location, length and diameter. The files do not contain elevation levels of system elements. The ORWB files show individual pipelines along with the location of their beginning and ending nodes. However, the pipes are not connected in a system that allows modeling using commercial software. Other problems include the presence of numerous duplicate pipes. These problems are solvable. Steps to fill these data gaps and allow modeling of the systems are outlined below.

1. The estimation of elevation at end nodes for individual pipes is accomplished by overlaying the pipelines on USGS elevation data sets. GIS software is used to overlay the pipeline map on a USGS 1/3 arc second elevation map and add the elevations to the nodes. Critical elevation points along the pipeline can be verified with GPS units when site visits are made.
2. Spreadsheet macros are developed to eliminate duplicate pipes and to join pipes at the appropriate nodes. The process of joining two pipes at a common node consists of replacing the node identification on one of the pipes with the identification of the joining pipe, so that both pipes have the same ending node. The process of joining pipes in the middle (creating a "T") is accomplished by dividing the initial pipe into two shorter ones, and adding the identification of the ending node of the second pipe to the newly created nodes on the pipe which was just divided. This process creates one new pipe whose identification code (along with the identification of its nodes) must be added to the original list of pipes.
3. Initial estimates of rural water demands tied to specific spatial locations are accomplished by overlaying the pipeline maps on annual NRCS one-meter aerial photo files. Census blocks are generally too large geographically to be of use in locating the position of rural households. The initial estimates are used to develop an operating model that will be later revised through site visits, discussions with RWD personnel, and ground-truthing maps. Field GPS units can also be used in this step.
4. An initial analysis of the system under average and peak flow conditions for the current period is modeled, as well as an analysis, without additional major infrastructure additions, for the 2050-2060 time period.
5. Points of high and low pressure, points of constriction along pipelines, problems of pump and water tower cycling, water age in pipes (particularly dead ends) and unacceptable head losses are noted in both evaluations (current and year 2050).
6. From the problem list prepared in step 5, a priority list of problems is developed. Multiple (at least two) specific system changes (such as pipeline replacement, additional pumps, additional above-ground storage) are then modeled and cost data developed based on the required infrastructure changes.

7. The results of the modeling and priority list of infrastructure improvements are presented to the water district personnel.

Small Towns**.** Many small towns lack accurate water system maps and records. Between personnel limitations and non-availability of funding, the system managers cannot focus on long-term problems. Since the OWRB does not provide maps of small town systems, a different set of procedures is used to model and evaluate small towns.

1. Water managers or city engineers are contacted to determine the approximate locations and diameters of pipelines serving the city. Thus, the first step is to develop GIS-based pipeline maps. This is done using the freeware program EPANET-Z developed by Zonum Solutions®. This program allows the user to develop a pipeline map of a town using a street grid map obtained from Google Earth. The pipeline diameters must be provided by local officials. It is necessary to check the pipeline lengths using known measurements of square miles or measured highway miles to verify the distances assigned to the pipelines by the software.
2. Census block data from the 2000 census, along with the pipe line map developed in step 1, are used to determine the residential population served at each of the nodes on the pipe network.

The remaining steps follow the same procedure as for rural water districts, steps 4-7.

Section 3.1: Final Project Conclusions

The project was successful in constructing a methodology to evaluate rural water system infrastructure. The incorporation of different water sources, infrastructure issues, and modeling software indicates that several approaches can be taken to effectively help rural water systems plan and update their water supply infrastructure. The development of a cost estimating methodology was also an essential part of the project, since understanding the costs associated with different upgrades is important for the community to understand. Highlights of the project results include:

- Small systems have common problems of low demand and long, low-velocity lines, which result in high water age and low disinfectant residual.
- The common remedy for high water age, which is to loop the pipes, does not always work for small systems, due to very low demand. A loop will add even more length to an already excessively-long system.
- Elevation differences mean that some areas have high pressures while others have very low (sometimes unacceptable) pressures.
- Technical expertise and experience necessary to use either EPANET or WaterCAD are beyond the staffing capabilities of small systems. It took several months for engineering graduate students to become familiar with the software.
- Small communities need assistance in writing grants to get funding for system improvements. Just getting a grant written is beyond the capability of most system staff members.

To this last point, each of the communities participating in the project expressed anxiety about paying for the upgrades suggested by the simulations. Discussions with OWRB personnel indicate that significant effort has already taken place to educate rural water district personnel about requirements for applying for funding, including a multitude of fact sheets and even a yearly full-day conference sponsored by the Funding Agency Coordinating Team (advertised as "one stop shopping to find the financing you need for your project" (Oklahoma Rural Water Association, 2009)). Our experience suggests the promotion of this type of event is crucial, as is the technical help provided by "Circuit Riders" who travel to small water systems and provide educational sessions for system personnel. Finally, the need for professional engineering help indicates that an extension program (provided by any land-grant university) focused on this area would be in high demand, particularly for states with many rural water systems. Funding a full-time engineer to deal with projects such as those explored in this paper would provide significant benefit for the rural water systems assisted and would likely result in extremely positive publicity for the departments involved.

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Appendix A: Presentation to Southern Agricultural Economics Association February 2010

Decision Support System for Evaluating Rural Water Supply Infrastructure Scenarios

Primary Investigators:
Brian Whitacre, Ag Econ
Art Stoecker, Ag Econ
DeeAnn Sanders, Civil Engineering

EXTENSION

Prepared for SAEA Meetings
February 9, 2010

Introduction / Statement of Need

- Rural water systems have difficulty making decisions about the future of their infrastructure
  - Should they consolidate with other systems?
  - What needs upgrading? Pipe, pump, tower,…
  - How much will it cost?
  - What funding sources are available?
- This project develops a process that assists towns in assessing and managing their water infrastructure needs
  - Including list of priority improvements

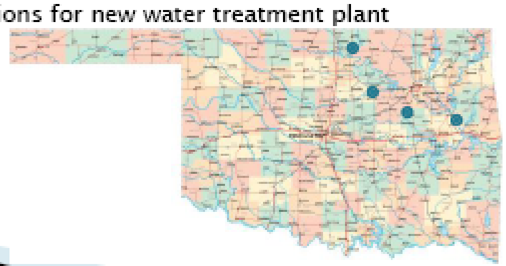
Project Description

- Steps in Decision Support Model
  1) Understand current system layout
  2) Obtain data for modeling infrastructure and possible upgrades (census projections, terrain maps)
  3) Analyze existing distribution system using free software (EPANET) or professional software
  4) Assess problem areas & explore solutions
  5) Estimate procurement and maintenance costs of various options
  6) Summarize available funding options and requirements

Test Systems

City	Population	Water Type
Beggs, OK	1,400	Surface
Braggs, OK	300	Ground
Oilton, OK	1,100	Ground
Kaw City, OK	400	Surface

- Also studying options for new water treatment plant



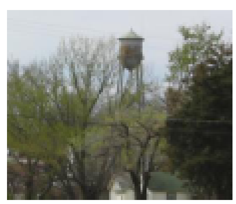
Common Problems

- Lack of funding and personnel
- Aging infrastructure
- Low pressure areas
- Water age in pipes
- Fire protection issues
- Old and/or incomplete pipe line and facilities maps

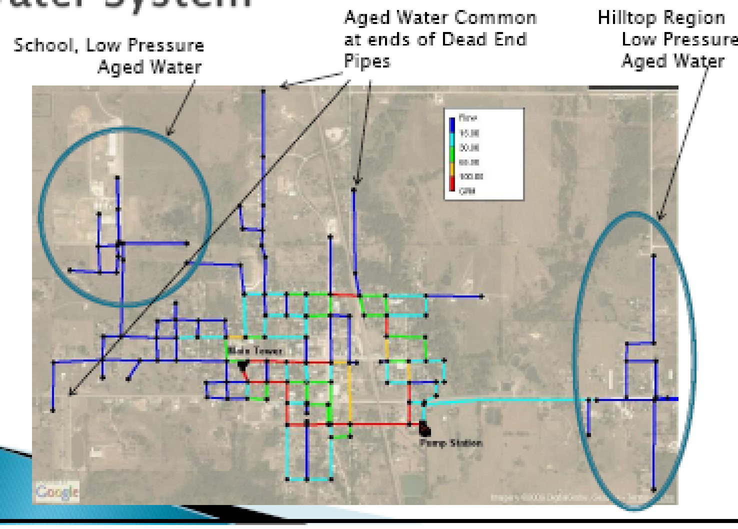
Case Study: Beggs, OK

Location and Stats

- ~ 4.3 square miles, Okmulgee County, south of Tulsa
- Population of 1364
- Water supplied from Beggs Lake
- 1 Pump station (very low elevation)
- 2 Water storage tanks
  - 50,000 gal elevated (highest elevation)
  - 150,000 gal underground
- Pipelines
  - Majority are cast iron and 45+ years old
  - Minority are newer PVC
- 6" mains serve 2"-4" branches

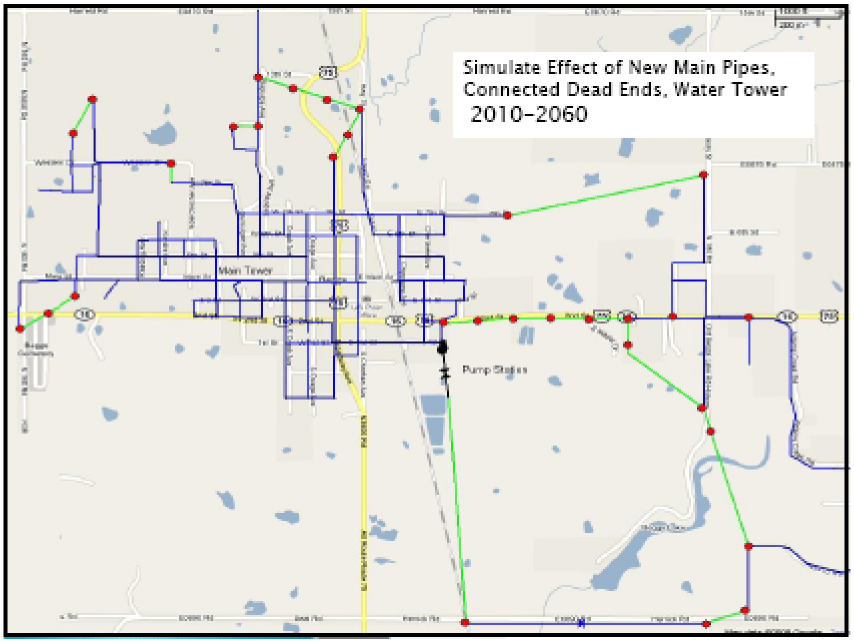


Digitized Pipeline Model of Beggs Water System



Use Model for Present and Future Scenarios

- Deficiencies within the current system
  - Hilltop region and dead ends fail fireflow tests badly
  - School area is also a concern because of its value and somewhat low pressures
- Possible Solutions
  - New or modified pumps
  - New or modified water tower
  - Replacing old pipes (that have inside deposits)
  - New pipes to eliminate dead ends or create new water paths

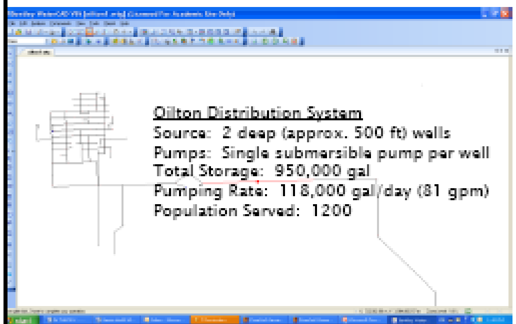


Tested different combinations and timing of improvements
Suggested order for improvements

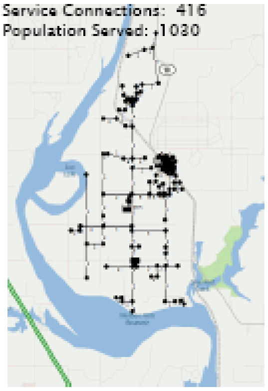
1. Cost: $69,000; Two major pipes in rural East Beggs
2. Cost: $60,000; Three pipes in rural East Beggs to finish addressing the Hilltop pressure problems
3. Cost: $57,000; Then add all the remaining pipes to target selected dead ends
4. Cost: $60,500; Required fire hydrants & pipe fittings
5. (Cost: $167,000; New 50,000 gal water tower)

TOTAL = $415,000

Similar Analysis Performed in Braggs and Oilton

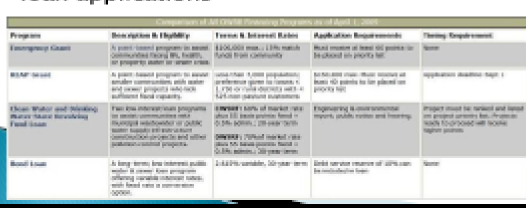


Braggs Distribution System
Source: Artesian Wells
Pumps: 3 in parallel
Total Storage: 200,000 gal
Pumping Rate: 75,600 gal/day (52.5 gpm)
Service Connections: 416
Population Served: 1030



Funding Options

- Once infrastructure improvements have been suggested, most communities ask, "How can we pay for this?"
- OWRB is already providing good resources
  - Financial Assistance Program
  - Loan and Grant Resource Guide
  - Full-day conference by Funding Agency Coordinating Team (FACT) ~250 attendees
- Our role: summarize information into easy-to-use document, provide workable examples of grant / loan applications



Program	Description & Eligibility	Terms & Interest Rates	Application Requirements	Timing Requirement
Emergency Grant	[illegible]	[illegible]	[illegible]	None
REAP Grant	[illegible]	[illegible]	[illegible]	[illegible]
Clean Water and Drinking Water State Revolving Fund Loan	[illegible]	[illegible]	[illegible]	[illegible]
Bond Loan	[illegible]	[illegible]	[illegible]	None

Conclusions

- Small systems have common problems of low demand and long, low-velocity lines, which result in high water age and low disinfectant residual.
- The common remedy for high water age, which is to loop the pipes, does not always work for small systems, due to very low demand. A loop will add even more length to an already excessively-long system.
- Elevation differences mean that some areas have high pressures while others have very low (sometimes unacceptable) pressures.

The Road Ahead

- Tool is not directly usable by most rural water systems (too complex)
- We believe Extension can play a role
  - Example: Rural hospital work
  - 1 full-time, dedicated employee handles 6-7 rural hospital assessments per year
  - Funded externally via HRSA grant
- Future funding?
- OSU Civil Engineering Class Project?

An Assessment of Environmental Flows for Oklahoma

Basic Information

Title:	An Assessment of Environmental Flows for Oklahoma
Project Number:	2008OK107B
Start Date:	3/1/2008
End Date:	6/19/2009
Funding Source:	104B
Congressional District:	3
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Water Quantity, Ecology
Descriptors:	
Principal Investigators:	Don Turton, William Fisher

Publications

There are no publications.

OWRRI Project
Final Report
An Assessment of Environmental Flows for Oklahoma

Start Date: February 29, 2008

End Date: February 28, 2009

Congressional District: 3

Focus Categories: ECL, HYDROL, MET, SW, WQN, WU

Submitted by:

Co-PIs:

Dr. Don Turton
Associate Professor
Oklahoma State University
Department of Natural Resource Ecology and Management

Dr. Bill Fisher
USGS, NY Coop Research Unit
206F Fernow Hall, Cornell Univ
Ithaca, NY 14850

And:

Titus S. Seilheimer, Ph.D.
Postdoctoral Fellow
OK Cooperative Fish and Wildlife Research Unit
404 Life Sciences West
Oklahoma State University

Rachel A. Esralew
Hydrologist
U.S. Geological Survey
Oklahoma Water Science Center
202 NW66th
Oklahoma City 73116

Publications: none to date

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Problem and Research Objectives:

Background:

The state of Oklahoma is in the process of updating the Oklahoma Comprehensive Water Plan. The water plan was last updated in 1995, and water demand projections for the current plan will be for the next 50 years (http://www.owrb.ok.gov/supply/ocwp/ocwp.php, accessed on 27 May 2009). The water plan will focus on development of system-level plans to provide the most water to the majority of Oklahomans. Assessment of current and projected water demands and water supply and availability will be made by 2011 prior to implementation of the water plan. Development of the plan will proceed through three phases. Phase one will focus on developing water demand projections by county and region through year 2060 and a comprehensive inventory and analysis of the state's water supplies. Phase two will identify local and regional problems and opportunities related to the use of water for public supply, agricultural, industrial, recreational, and environmental uses. Phase three will involve implementation of planning initiatives and tools derived from the issues, problems and needs identified in phase two. Technical studies will be needed to identify environmental uses of water, particularly the flows required for fish and other aquatic biota, to aid in planning for Oklahoma's future water needs.

Previous Oklahoma water plans have not recognized environmental flows or made provisions for protecting them. Assessment of current and projected water demands and water supply and availability will be made by 2011 prior to implementation of the water plan. Oklahoma has four fish species and three mussel species that are federally-listed as threatened or endangered and sensitive to alterations in streamflow. It is imperative that environmental flows be assessed and considered in the development of the updated Oklahoma comprehensive water plan to aid in sustaining aquatic life and protecting federally threatened and endangered and state species of greatest conservation concern in Oklahoma.

Alteration of the hydrologic regime of rivers from impoundments and flow diversions modifies the structure and function of river ecosystems (Poff et al. 1997, Rosenberg et al. 2000, Postel and Richter 2003, Poff et al. 2007). Hydrologic alterations such as flow stabilization, prolonged low flows, loss of seasonal flow peaks, rapid changes in river stage, and low or high water temperatures downstream disrupt life cycles of aquatic plants, invertebrates, and fishes resulting in a reduction in species diversity and modifying reproduction and growth rates that oftentimes lead to local extinctions of native species and the invasion and establishment of exotic species (Poff et al. 1997). Large water diversions deplete streamflows, sometimes to damaging levels that affect aquatic and floodplain habitats, aquatic biodiversity, sport and commercial fisheries, natural floodplain fertility, and natural flood control (Postel and Richter 2003). The development of water resources to meet the demands of urban population centers is growing and threatens the ecological integrity of many freshwater ecosystems (Fitzhugh and Richter 2004).

Water management goals in the new millennium have broadened from traditional societal goals of water supply, flood control, channel maintenance, power production and commerce to include maintenance and enhancement of natural aquatic communities and ecosystem services. This has resulted in a paradigm shift from the simple question of “How much water can be taken from streams and lakes for human use?” to the more complex question of “How much water needs to be left in streams and lakes to sustain critical water-dependent natural resources?” (USFWS and USGS 2004). Evaluation of water use and development projects now requires consideration of effects at multiple scales, including consideration of the whole hydrograph and not simply minimum flows, the dynamic river channel rather than the static channel, the linkage between surface and ground water, and ecological communities rather than single species.

Assessment of environmental flows, traditionally referred to as instream flows, for Oklahoma is needed to aid planners, policy makers and the public in developing of the Oklahoma Comprehensive Water Plan. An initial step in assessing environmental flows for Oklahoma is characterizing and classifying streams and rivers based on their flow regimes. There are currently over 200 methods for evaluating environmental flows, which range from those that determine “minimum” flows to those that mimic the “natural flow regime” (Arthington et al. 2006). Scientists and many managers are now in general agreement that a regulated river needs to mimic the five components of the natural flow regime, including the magnitude, timing, frequency, duration, and rate of change and predictability of flow events, plus the sequence of these conditions (Olden and Poff 2003, Arthington et al. 2006). These more complex methods go beyond developing simple hydrological “rules of thumb” to more comprehensive environmental flow assessment. HIP is a tool developed by the USGS that identifies 10 non-redundant hydrologic indices that are ecologically relevant, specific to stream classes, and characterize the five components of the natural flow regime (Figure 1) (http://www.fort.usgs.gov/Resources/Research_Briefs/HIP.asp, accessed on 27 May 2009). The HIP process can be developed for a state (e.g., Massachusetts, Missouri, New Jersey, Pennsylvania, and Texas, are using HIP), but also can be applied at the stream reach level.

Objectives:

We used the Hydroecological Integrity Assessment Process (HIP) approach developed by the U. S. Geological Survey to assess environmental flows in Oklahoma’s perennial streams. The HIP is a modeling tool that identifies 10 non-redundant hydrologic indices that are ecologically relevant, specific to stream classes, and characterize the five components of the natural flow regime. These components are the magnitude, timing, frequency, duration, and rate of change and predictability of flow events, plus the sequence of these conditions. Information derived from the HIP analysis will be used to make environmental flow recommendations for incorporation into the Oklahoma Comprehensive Water Plan and for future water permitting and planning.

The HIP is a process consisting of four development and two application steps (Figure 1). The objectives of this work were to complete the first 3 steps:

1. Obtain baseline data and identify appropriate streams for classification.
2. Calculate 171 hydrologic indices using the Hydrologic Index Tool (HIT).
3. Classify streams and identify the 10 primary flow indices.

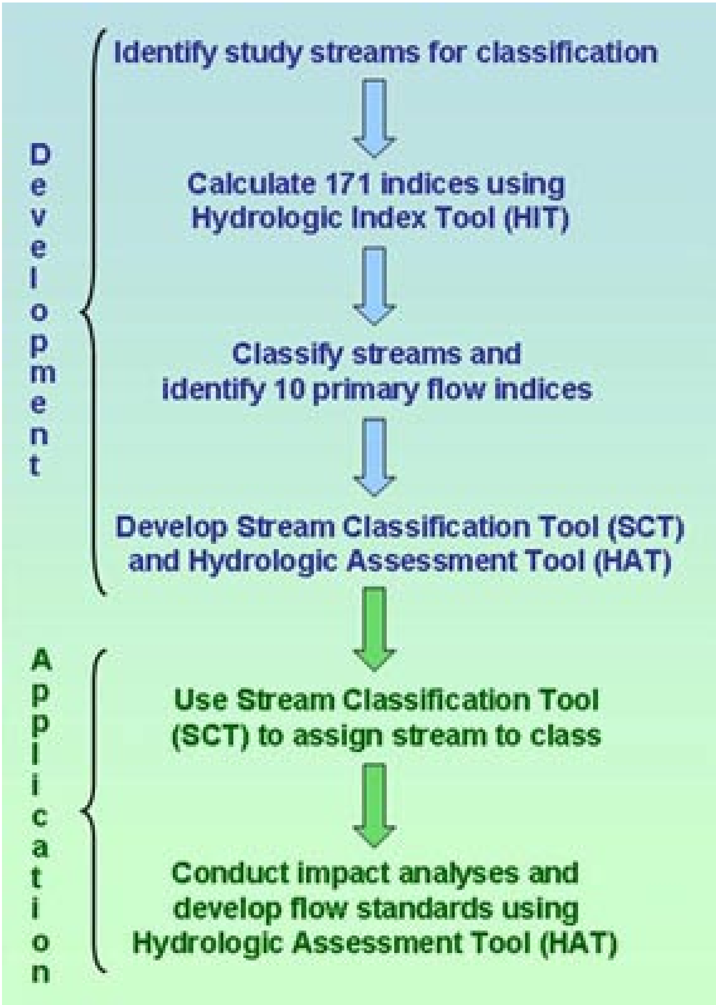


Figure 1. The development and application steps of the Hydroecological Integrity Assessment Process (HIP).

Methods and Results of HIP Development Steps 1,2 and 3

Step 1: Baseline Period of Record and the Identification of Streams for Classification

<u>This section of the report was prepared by the U.S. Geological Survey</u>

Ideally, a HIP classification suite should include long-term continuous streamflow record from the most natural state of streamflow available. This allows for the HIP classification to represent the most "natural" conditions of the basin which can be used as a hydrologic foundation for future assessment of ecological impairment with respect to anthropogenic alteration of the flow regime. Usage of the most natural (or least-altered) streamflow record in the HIP classification also reduces the likelihood that the records will be statistical outliers in the cluster analysis.

In addition to selecting streamflow data from a least-altered period, streamflow records need to be sufficient in length to ensure that typical variations in climate are observed during the selected period. Due to potentially limited gaging record and increasing development of the stream over time, the least-altered period of record for some gages may be relatively short. A sufficient record length would increase the probability that intra-annual variability of the daily hydrograph, which may be affected by recurrent climate cycles, is encompassed by the period chosen for classification. This pre-condition will help to minimize statistical bias and random error in the cluster analysis.

For each USGS streamflow-gaging station with continuous streamflow record selected for use in the HIP classification, a minimum optimal baseline period of record was determined. The baseline period of record can be defined as a period which is both "least altered" by anthropogenic activity and has sufficient record length to represent the extremes of climate variability. By this definition, there is a possibility for streams with continuous streamflow data not to have a period of record that could be considered baseline. For this study, if a streamflow-gaging station had data that either was substantially altered by human activity or did not have a minimum of 10 years of least-altered, then that record was either omitted from use in the HIP classification or downgraded in quality.

In Oklahoma, substantial streamflow alteration can be caused by a variety of human activities. Irrigation with both surface water and groundwater and other consumptive water uses are common throughout Oklahoma and represent the single largest use of water (Tortorelli 2002). Most irrigation water comes from groundwater, primarily from the High Plains aquifer in the panhandle as well as from other parts of western Oklahoma. Surface-water withdrawals, primarily used for consumptive water supply and livestock, are also common throughout the state. Many surface-water diversions in Oklahoma are withdrawn from reservoirs or other impoundments (Tortorelli 2002).

Flood peak reduction, from numerous flood-water retarding structures that serve to decrease main-stem flood peaks and regulate runoff recession of single storm events, also affects streamflow for large areas of Oklahoma (Tortorelli and Bergman 1985; Bergman and Huntzinger 1981).

Few if any streams in or near Oklahoma have been completely free of anthropogenic activity during the last century. Therefore, an allowable amount of anthropogenic alteration must be permitted in order to include sufficiently long-term record in the HIP classification. Long-term record is desired for the classification in order to provide a representative sample of streamflow during variable climate conditions. By accepting some alteration, the goal of the baseline period determination process is to select, for each gage, a sufficiently long period that is "least altered". The selection of a least-altered period of record includes eliminating the period of streamflow data where the degree of alteration is substantially high and that the streamflow record is unacceptable for use in the HIP classification. The degree of anthropogenic alteration varies over time and over a spatial extent. Determining if a period is "natural" or "altered" may require some subjective judgement. In addition, the effects of anthropogenic activity in a stream basin may not occur over the course of one year, but may take many years. Examples would be increasing irrigation development over a period of time, construction of numerous small flood retarding structures in the stream basin, or gradual urban development in a watershed.

Streamflow data have been collected for streams in and near Oklahoma over periods ranging from a few years to nearly a century (U.S. Geological Survey National Water Information System, http://waterdata.usgs.gov/nwis, accessed June, 2008). Shorter periods of record may coincide with aberrant climate conditions and streamflow patterns that are not representative of typical conditions. Longer periods of record are more likely to provide a representative sample of central tendencies and variability of streamflow. However, as population increases and agricultural, industrial, and urban development increase in Oklahoma over the course of a century, longer periods of record and more recent periods of record are likely to contain streamflow data that are affected by human activity in the basin.

Based on the potential sources of subjectivity involved with selection of baseline periods for gages as described above, baseline periods of some gages may be more complete than others. Quality assurance and examination of outliers in the HIP classifications may require a qualitative assessment of the data used to develop the model. In order to reduce the subjectivity of selecting a baseline period and enable comparison of the baseline periods from one gage to another, a quality ranking was assigned to each baseline period. The terms in the quality ranking of the baseline period are "excellent"," good", "fair", "poor", or "unusable" and are based on the relative degree of anthropogenic activity, severity of climatic bias for the period with the least anthropogenic activity, and length of the record. The goal of the baseline analysis was to select a period for each stream that had the most favorable quality ranking based on these criteria. Streams where the period of record was determined to be "poor" or "unusable" were entirely omitted from use in the HIP classification.

Methods for Determining the Baseline Period of Record

Streamflow data from gaging stations with a minimum of 10 years of daily streamflow record, and a drainage area that is greater than 1 square mile but less than 2,600 square miles were considered for use in the HIP classification. A minimum period of record of 10 years was assumed to be an adequate minimum record length for determination of the least-altered period. This assumption was based on the use of 10 years of record for the New Jersey statewide HIP classification (Eraslew and Baker 2008 and Kennen et al. 2007). Drainage areas of streams selected for analysis were greater than 1 square mile and less than 2,600 square miles based on drainage area criteria used in previous statistical analysis studies (Tortorelli and Bergman 1985; Tortorelli 1997). Streamgages selected for analysis and contributing drainage area upstream from the streamgage were located within 8-digit hydrologic unit boundaries (based on the 8-digit hydrologic unit codes, or HUC) that were located at least partly in Oklahoma. There were 168 streamgages that met the criteria for analysis. Figure 2 shows the locations of gages that meet these criteria, and were initially included in baseline period determination process.

Streamflow data from substantially altered streams, or periods of streamflow record that were determined to be affected by human alteration, were removed from consideration from the HIP classification after a series of analysis procedures (Figure 1). After this elimination, if the gage did not have at least 10 years of remaining continuous period of record, the streamgage was eliminated from consideration for use in the HIP classification. The methods used to determine a baseline period of record were incorporated from visual and statistical procedures as well as professional judgment.

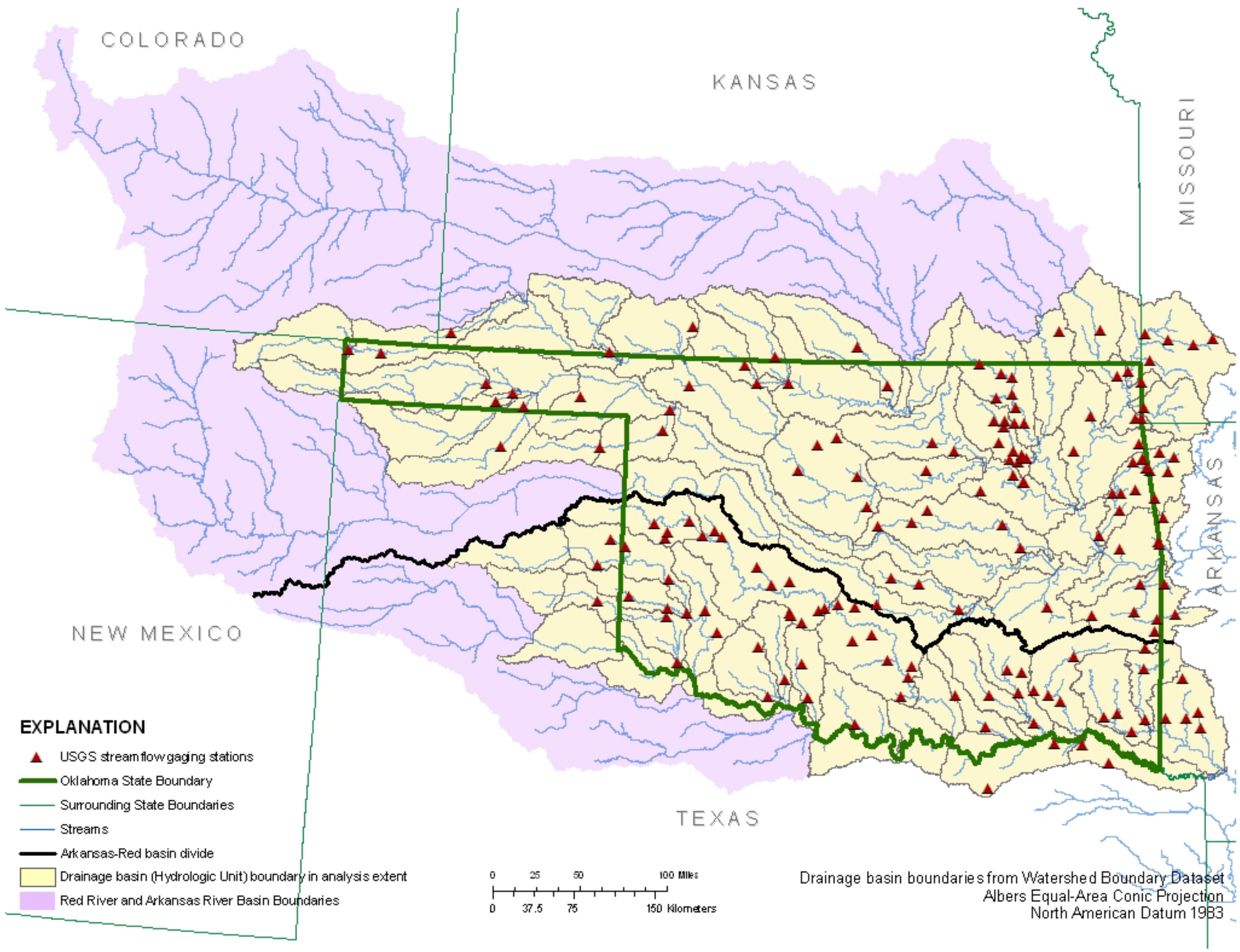


Figure 2. USGS streamflow gaging stations, within a selected analysis extent, having 10 or more years of continuous daily streamflow record and a drainage area of less than 2,600 square miles.

Determination of the Least-Altered Period of Record

Determination of a baseline period was conducted in two phases. In the first phase, least-altered periods were selected for gages that had a minimum record length of 10 years. In the second phase, an optimum minimum period of record was determined for gages in each Climate Division (National Oceanic and Atmospheric Administration, 2008) to determine if 10 years of record sufficiently represented long-term climate variability.

In the first step of the process to determine the least-altered period of record, streamgage information was evaluated using previous publications, historical gage record notes, and information gathered from oral and written communication with data-collection staff familiar with selected gages. Known anthropogenic events in the basin were used to reduce the record to a least-altered period with a minimum of 10 years. If the least-altered period of record included streamflow that was affected by anthropogenic alteration, then the quality ranking was reduced accordingly.

In the second step of the determination of the least altered period, gages that had substantial effects from upstream impoundment were identified by evaluating the location and extent of dams in the drainage basin. Impounded areas were delineated using geographic information system (GIS) software in order to estimate the percent of impoundment in the basin, and how much that percentage changed over time. The percentage of the basin that was impounded was used to determine a preliminary quality ranking for the baseline period. If 20 percent or more of the drainage basin was affected by impoundment, it was eliminated from consideration.

In the third step of the determination of the least-altered period, statistical trend analysis was performed for selected streamgages with 20 or more years of record to detect statistically significant changes in baseflow, runoff, total flow, and baseflow index for selected gages where visual trends in the annual hydrograph were observed. Significant trends in streamflow were compared with trends in precipitation, using visual trend observation and analysis of covariance of double-mass curves, in order to determine if the trend was attributable to climate or possible anthropogenic affects. If trends were suspected to be due to anthropogenic affects and not trends in precipitation, an additional Kendall's tau test was performed for selected datasets to determine if statistically significant trends existed for each of the annual flow parameters (Kendall and Gibbons 1990). If the preliminary baseline period determined from previous steps had a statistically significant trend in the annual hydrograph that was not attributable to climate changes, then the quality ranking was reduced to "poor".

Determination of an Optimum Minimum Period of Record to Encompass Climate Variability

In the second phase, an optimum minimum period of record was determined for each of the least-altered periods to ensure that the selected period had a sufficient record length to provide a representative sample of the extremes of climate variability. An assumption was made in the previous phase that no less than 10 years should be considered for the baseline period. For each climate division that contained gages that were to be used in the HIP classification, an optimum minimum period of 10 years or more were evaluated by using a Wilcoxon rank-sum test. This test was used to analyze the variability of annual precipitation for selected 5-, 10-, 15-, 25-, and 35-year periods. The results from the test were used to determine how many years of annual precipitation were needed for the distribution of annual precipitation for the selected period to be statistically similar to the distribution of annual precipitation for a longer period, 1925-2007. This period was selected because it encompasses all of the years of streamflow record considered in the baseline analysis. In addition, this longer period was compared to the annual precipitation for the least-altered period to determine if the least-altered period was statistically representative of long-term climate variability. Results of the record-length analysis for each gage are listed in Table A.

For purposes of this study, the baseline period was the same as the least-altered period determined from previous steps because least-altered periods were not eliminated from use in the HIP classification if it did not contain an optimal minimum number of years as a result of the second phase of the analysis process. Instead, the quality ranking was reduced for these periods. If the preliminary baseline period determined from previous steps did not have an optimum minimum period of record or was statistically different from the period 1925-2007, the quality ranking was reduced accordingly. Eliminating gages from the HIP classification where the least-altered period of record was less than the optimum minimum period would substantially reduce the number of stations. Instead of eliminating gages from consideration where the least-altered period of record did not meet these criteria, the quality ranking was lowered by one level (for example a “fair” baseline period would be reduced to a “poor” baseline period). Therefore the difference between the baseline period and least-altered period are only due to the quality ranking and not the number of years.

Final Baseline Period of Record

A final baseline period was determined for each gaging station considered for use in the HIP classification. The baseline period for each station was rated as “excellent”, “good”, “fair”, “poor”, or “unusable” by combining the quality rankings determined for the degree of alteration in the basin for the least-altered period of record, and whether or not the least-altered period was long enough to likely be representative of long-term climate variability. The baseline period of record determined for each gage considered for use in the HIP classification, and the associated quality ranking of the baseline period, are presented in Table A and are shown in Figure 3. Gages that were removed from the list because they did not have an adequate baseline period (the baseline period was rated as “unusable”) are not listed in Table A or Figure 3.

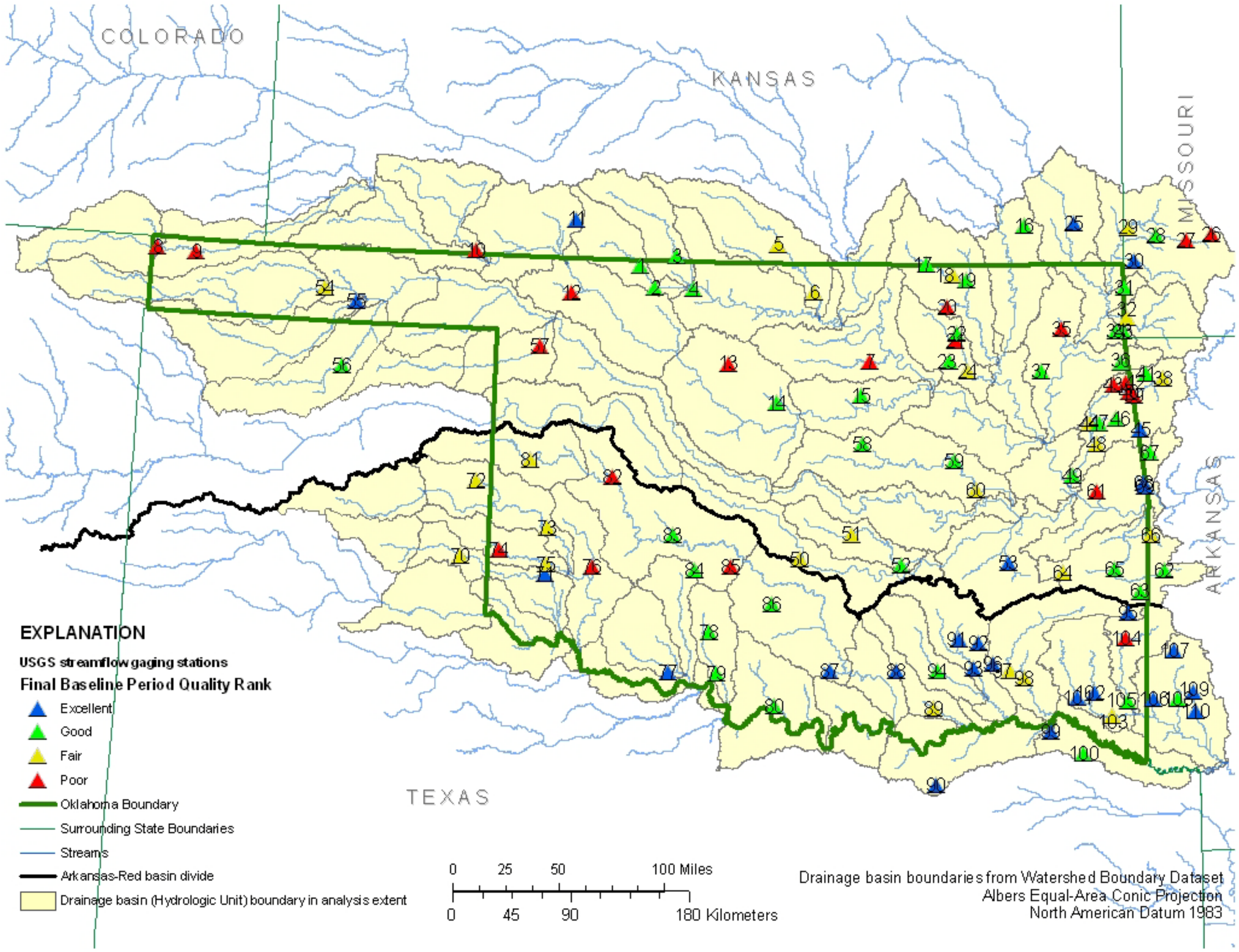


Figure 3. USGS streamflow gaging stations with a baseline period of record of 10 or more years, and the quality ranking of the baseline period for each gage.

Step 2: Calculation of 171 hydrologic indices using the Hydrologic Index Tool (HIT).

We used multivariate statistical analysis on streamflow statistics to describe the variability in the flow regime for reference conditions of Oklahoma rivers (Henriksen et al. 2006; Kennen et al. 2007; Olden and Poff 2003). Classification was completed using data from 88 USGS streamflow stations (Table 1) obtained from the baseline analysis described in the previous section (Table A). The stations were primarily located in Oklahoma (59), along with stations located in bordering states with flows that were relevant to Oklahoma: Kansas (6), Texas (6), Missouri (6), and Arkansas (11).

Flow Regime

Factors such as the quantity of water, the time of the year that high and low flows occur, and how often flow events happen are collectively referred to as the natural flow regime. This set of unique conditions is determined by many factors, such as geology, climate, and vegetation cover (Poff et al. 1997), and can be used to identify groups of streams with similar hydrologic behaviors. In addition to being useful for classification of streams, flow regime is important to biological organisms and the health of aquatic ecosystems, which have adapted over time to those conditions. Impacts to aquatic organisms from flow regime alteration can include the disruption of their life cycle (Scheidegger and Bain 1995), loss of connection and access to wetlands or backwaters (Junk et al. 1989), and change in plant cover types (Auble et al. 1994). Thus to protect ecosystems, the flow regime should be maintained or mimicked to support the natural cycles that species rely on.

The natural flow regime can be described with five categories that cover the natural hydrologic variation that is present in a stream (Poff et al. 1997). Magnitude is a measure of the quantity of water moving past a point per unit time. This category is divided into magnitudes of average (MA), low (ML), and high (MH) flows. Frequency describes how often specified low (FL) and high (FH) flow events occur. Duration describes the length of time that low (DL) and high (DH) flow events occur. Both the frequency and duration categories deal with low (e.g. no flow days) and flood flow events. Timing describes the dates that average (TA), low (TL), and high (TH) flow events occur. The rate of change (RA) describes the rise or fall in streamflow. Streams with high or rapid rate of change can indicate they are “flashy,” while low rates may indicate that a stream has “stable” streamflow.

Software

We used the Hydrologic Index Tool (HIT, Version 1.48; USGS, Fort Collins, CO; http://www.fort.usgs.gov/Products/Software/NATHAT/hitinst.exe) software to calculate indices from all five classes of streamflow. The HIT software calculates a total of 171 indices (Henriksen et al. 2006; Olden and Poff 2003) with 94 describing magnitude, 14 describing frequency, 44 describing duration, 10 describing timing, and 9 describing rate

Table 1: Site code, station ID, and station name of 88 USGS streamflow stations used to classify Oklahoma streams.

Site Code	Station ID	Station Name
CAVC	07157900	Cavalry Creek at Coldwater, KS
LGHT	07184000	Lightning Creek near McCune, KS
SHOL	07187000	Shoal Creek above Joplin, MO
BRND	07196900	Baron Fork at Dutch Mills, AR
GAIN	07232000	Gaines Creek near Krebs, OK
COLD	07233000	Coldwater Creek near Hardesty, OK
LEES	07249985	Lee Creek near Short, OK
LEEV	07250000	Lee Creek near Van Buren, AR
STRM	07300500	Salt Fork Red River at Mangum, OK
DFCK	07311500	Deep Red Creek near Randlett, OK
CADO	07330500	Caddo Creek near Ardmore, OK
BLUM	07332400	Blue River at Milburn, OK
BDRC	07332600	Bois D'Arc Creek near Randolph, TX
CHCS	07333500	Chickasaw Creek near Stringtown, OK
MCGE	07333800	McGee Creek near Stringtown, OK
MBOG	07334000	Muddy Boggy Creek near Farris, OK
KIAC	07335700	Kiamichi River near Big Cedar, OK
TENM	07336000	Tenmile Creek near Miller, OK
LPIN	07336750	Little Pine Creek near Kanawha, TX
LTRW	07337500	Little River near Wright City, OK
GLOV	07337900	Glover River near Glover, OK
ROLL	07339500	Rolling Fork near DeQueen, AR
COSV	07340300	Cossatot River near Vandervoort, AR
SALD	07341000	Saline River near Dierks, AR
SALL	07341200	Saline River near Lockesburg, AR
SLTW	07148350	Salt Fork Arkansas River near Winchester, OK
SLTA	07148400	Salt Fork Arkansas River near Alva, OK
MEDL	07149000	Medicine Lodge River near Kiowa, KS
SLTC	07149500	Salt Fork Arkansas River near Cherokee, OK
SKEL	07160500	Skeleton Creek near Lovell, OK
CNCL	07163000	Council Creek near Stillwater, OK
BHIL	07170700	Big Hill Creek near Cherryvale, KS
CNYE	07172000	Caney River near Elgin, KS
LCAN	07174200	Little Caney River below Cotton Creek, near Copan, OK
CNDY	07176800	Candy Creek near Wolco, OK
HMNY	07177000	Hominy Creek near Skiatook, OK

Table 1, continued.

Site Code	Station ID	Station Name
SPRC	07185765	Spring River at Carthage, MO
LOST	07188500	Lost Creek at Seneca, MO
CVSP	07189540	Cave Springs Branch near South West City, MO
HONY	07189542	Honey Creek near South West City, MO
SPAV	07191220	Spavinaw Creek near Sycamore, OK
PRYR	07192000	Pryor Creek near Pryor, OK
FLTS	07195800	Flint Creek at Springtown, AR
PECH	07196973	Peacheater Creek at Christie, OK
BRNE	07197000	Baron Fork at Eldon, OK
ILRG	07198000	Illinois River near Gore, OK
LTRS	07231000	Little River near Sasakwa, OK
PALO	07233500	Palo Duro Creek near Spearman, TX
DRYC	07243000	Dry Creek near Kendrick, OK
DFKB	07243500	Deep Fork near Beggs, OK
POTC	07247000	Poteau River at Cauthron, AR
BLFK	07247250	Black Fork below Big Creek near Page, OK
POTW	07248500	Poteau River near Wister, OK
COVE	07249500	Cove Creek near Lee Creek, AR
LBEA	07313000	Little Beaver Creek near Duncan, OK
BVCK	07313500	Beaver Creek near Waurika, OK
MUDC	07315700	Mud Creek near Courtney, OK
COBB	07326000	Cobb Creek near Fort Cobb, OK
LWSC	073274406	Little Washita River above SCS Pond No 26 near Cyril,OK
RUSH	07329000	Rush Creek at Purdy, OK
CBOG	07335000	Clear Boggy Creek near Caney, OK
PCAN	07336800	Pecan Bayou near Clarksville, TX
MTNE	07339000	Mountain Fork near Eagletown, OK
COSD	07340500	Cossatot River near DeQueen, AR
CHCC	07151500	Chickaskia River near Corbin, KS
CHCB	07152000	Chickaskia River near Blackwell, OK
CNYH	07173000	Caney River near Hulah, OK
BRDS	07177500	Bird Creek near Sperry, OK
SPRW	07186000	Spring River near Waco, MO
ELKR	07189000	Elk River near Tiff City, MO
OSAG	07195000	Osage Creek near Elm Springs, AR
ILRT	07196500	Illinois River near Tahlequah, OK
CNYC	07197360	Caney Creek near Barber, OK

Table 1, continued.

Site Code	Station ID	Station Name
WNUT	07229300	Walnut Creek at Purcell, OK
BVRV	07232500	Beaver River near Guymon, OK
DFKD	07244000	Deep Fork near Dewar, OK
FOMA	07247500	Fourche Maline near Red Oak, OK
JMSF	07249400	James Fork near Hackett, AR
STRW	07300000	Salt Fork Red River near Wellington, TX
SWET	07301410	Sweetwater Creek near Kelton, TX
NFRR	07301500	North Fork Red River near Carter, OK
ELMM	07303500	Elm Fork of North Fork Red River near Mangum, OK
WASC	07316500	Washita River near Cheyenne, OK
BLUB	07332500	Blue River near Blue, OK
KIAA	07336200	Kiamichi River near Antlers, OK
KIAB	07336500	Kiamichi River near Belzoni, OK
LTRI	07338500	Little River below Lukfata Creek, near Idabel, OK

of change of streamflow. Categories with many indices, such as magnitude, had sets indices that were calculated for individual months (e.g. January mean flow, May mean minimum flow), and this resulted in many indices in those categories.

We used data from a reference period recorded at USGS streamflow stations. The analysis used two types of data: daily average flows (mean flow in 24 hours in ft^3/second), and peak flow (instantaneous ft3/sec) data for each gage, which were required for the calculation of six indices. The length of reference period used in the analysis for all stations had a median length of 22 years and ranged from a minimum of 10 to a maximum of 83 years. A set of eleven indices were not able to be calculated for all 88 stations. This was a result of an error in calculation of indices for some sites due to a zero in denominator of the index equation. Ten of the indices had too many zero flow days in their record (MA6, MA7, MA8, ML18, ML21, FL2, DL6, DL7, DL8, DL17), while one had no zero flow days (DL19). After exclusion of the indices, the available dataset was reduced from 171 to 160, but all five components of flow regime were still represented.

Step 3: Classification of streams and identification the 10 primary flow indices

Data Screening and Standardization

We used the two step process called the Hydroecological Integrity Assessment Process (HIP) for classification of streams based on flow regime from hydrological indices (Henriksen et al. 2006; Kennen et al. 2007; Olden and Poff 2003). The first step uses principal component analysis (PCA) to reduce redundancy in the 171 indices and select hydrologic indices that explain the most variation. The selected indices were then used in the second step in a cluster analysis to classify and group streamflow-gage stations based on similarity between flow regime.

Data standardization was required because the indices used different units (e.g. ft^3/second, percent), which can affect the results from the cluster analysis (McGarigal et al. 2000). The standardization procedure we selected was the z-score method, which normalized each column (i.e. hydrologic indices) to have a mean of zero and a standard deviation of one (McCune and Grace 2002). An outlier analysis was also conducted using PC-ORD to remove the confounding influence of multivariate outliers on the principal components analysis and cluster analysis (McCune and Grace 2002). Outliers were defined as indices more than two standard deviations from the mean. The analysis found three indices that were classified as outliers (ML20, FL01, RA08), although they were only slightly over the two standard deviation threshold (2.1, 2.0, and 2.1 respectively). Outliers were flagged and excluded from later analyses. The outliers were not identified as high information variables in the principal components analysis, so no unique information was lost with their exclusion.

Principal Components Analysis

We used principal components analysis (PCA) to identify the hydrologic indices that contained the most information about the flow regime across the region. PCA is an eigenvector method of ordination that is used to reduce a large datasets into a smaller number of synthetic variables that describe the maximum amount of variation in the dataset (McGarigal et al. 2000). The reduced dataset of high information variables can then be used to characterize the flow regime of the selected streams. Variables with high eigenvector values on a principal component (i.e. have high score) contribute more information about the variation in the data than variables with near zero scores. This allows for the heaviest loading variable to be used to explain the ordination of the sites (McGarigal et al. 2000).

We used a PCA on a correlation matrix (PC-ORD) to ordinate 88 stations and 160 hydrologic indices. The first two principal components explain over 50% of the total variation in the dataset. A site's location on the PCA plot represents the centroid of all the hydrologic variables for that site on each plotted principal component (PC; Figure 4a). Stations like SPRC and BRNE both are found on the far left negative end of the first axis, but they do not have high scores on the second axis. The opposite is true for stations like GLOV and MBOG, which have low scores on the first axis but high scores on the second axis. The PCA also produced eigenvectors for the hydrologic indices for each principal component (Figure 4b). Indices with high loadings on an axis indicate that the index is explaining a larger amount of variation (e.g. high positive on PC1 MA3 in Figure 4b) in the dataset than index scores that are near zero (e.g. DH23 in Figure4b). Both the lower left and lower right quadrants of the graph have large groups of indices with high loadings on one or both of the first two principal components.

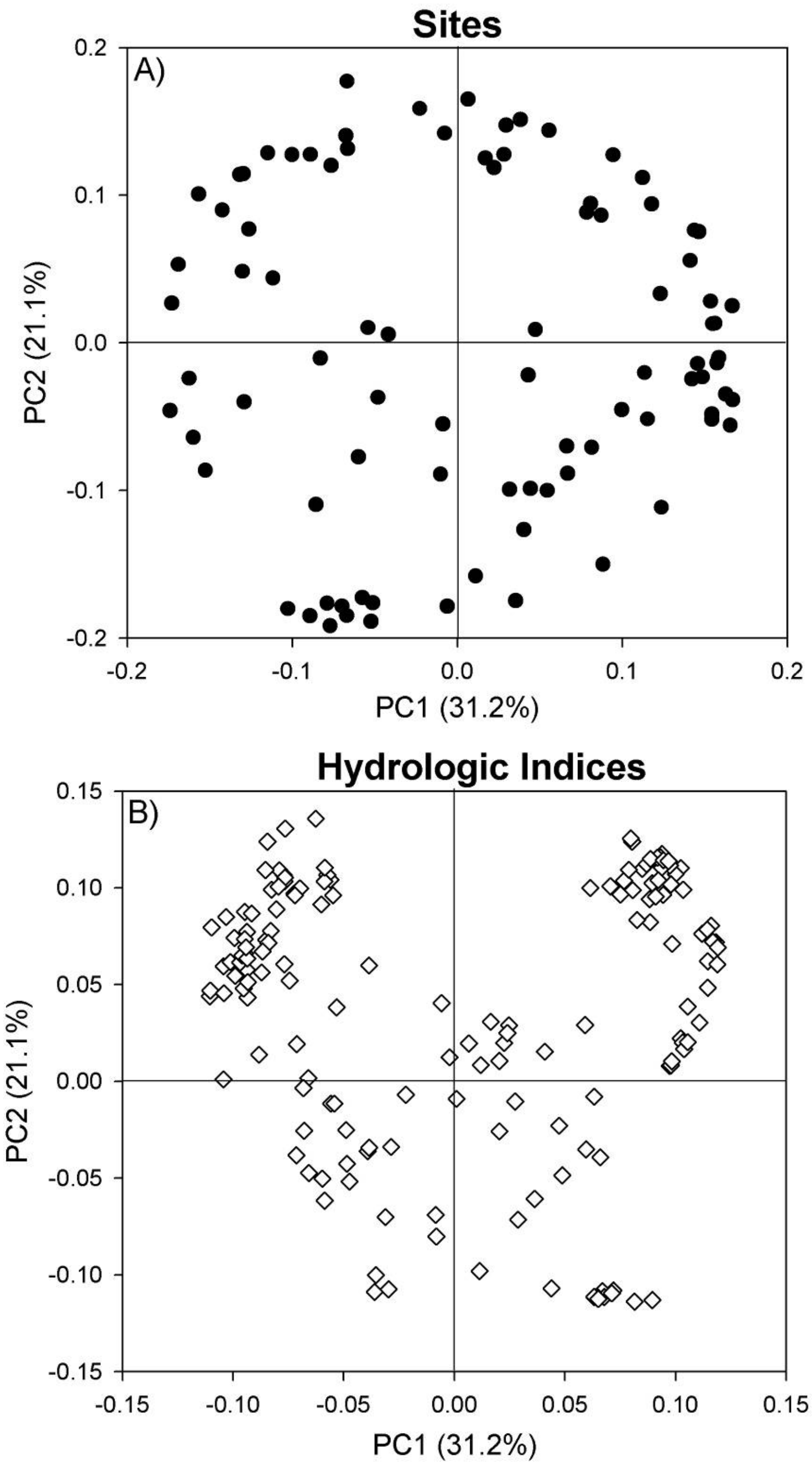
We used the first six principal components as the source for the selection of high information indices. The first two axes explain 52.2% of the variation in the dataset (Table 2). The total variation explained by the first six principal components was 77% (Table 2). We identified the first six principal components as important axes using the brokenstick eigenvalues. Brokenstick eigenvalues are an estimation of the eigenvalues that would be expected from the PCA by chance alone (Jolliffe 1972; King and Jackson 1999). Thus, when the actual eigenvalues are higher than brokenstick eigenvalues, then the patterns observed in the PCA are not random. The first six PC had higher real eigenvalues than brokenstick values and could be used in the selection of the most important hydrologic indices for describing Oklahoma streams (Table 2).

Table 2: Eigenvalues, percent variance explained, cumulative percent variance, and broken-stick eigenvalues for the first six principal components from the principal components analysis of 160 hydrologic indices and 88 stream gages.

Axis	Eigenvalue	Percent Variance	Cumulative Percent Variance	Broken-stick Eigenvalue
1	49.9	31.2	31.2	5.7
2	33.7	21.1	52.2	4.7
3	15.4	9.6	61.8	4.2
4	12.6	7.9	69.7	3.8
5	6.8	4.3	74.0	3.6
6	4.9	3.0	77.0	3.4

The process of index selection seeks to identify indices that contain the maximum amount of information about the flow regime, while removing redundant indices that are highly correlated with each other. One target in the reduction of the number of variables to maintain a 3:1 ratio of sites to indices for the cluster analysis (McGarigal et al. 2000). Based on the number of sites in the dataset (88), we used the target number of 29 hydrologic indices for selection into the cluster analysis. Another guideline was that the selected variables would include each of the ten components of the flow category, in order to include a picture of the entire flow regime in the classification process.

Figure 4: Principal components analysis plots. (A) site scores of streamflow stations and (B) eigenvectors of hydrologic indices for the first and second principal components. Percentages indicate proportion of total variation in dataset that is explained by each principal component.



We selected indices on the first six principal components that were within 15% of the highest absolute loading on each axis. This criterion reduced the total number of variables from 160 to 55. The 55 remaining indices were considered to contain a high amount of information that would be useful for classification of the stations (Table 3). In order to reduce the redundancy between the selected indices, we used a nonparametric correlation analysis (Spearman rho) for indices within each flow category. Indices that were highly correlated (e.g. May and June mean flows) were identified and the least correlated (i.e. most non-redundant) hydrologic indices were selected to be included in the classification portion of the analysis. The subset of 55 variables was further reduced to 27 indices, which was near our target of 29 variables for the 3:1 ratio (Table 4). The five flow components are represented in this set of variables with 8 describing magnitude (3 average magnitude, 2 low magnitude, and 3 high magnitude), 4 describing frequency (1 low flow frequency and 3 high flow frequency), 9 describing duration (3 low flow duration and 6 high flow duration), 3 describing timing (1 in timing of average, low, and high flows), and 3 describing rate of change (Table 4). With this set of variables, we can represent the natural flow regime at the stations and group them based on similarities in streamflow patterns.

Table 3: Eigenvector loading on the first six principal components for the 27 hydrologic indices used to classify Oklahoma streams. Bold indicate the principal component was selected from.

	Eigenvector on Principal Component					
	1	**2**	**3**	**4**	**5**	**6**
MA01	**-0.1023**	-0.1104	-0.0178	-0.0466	0.0104	0.0437
MA04	0.0845	**-0.1239**	-0.0105	-0.0053	-0.0052	0.0342
MA28	**0.1043**	-0.0596	0.0291	-0.0770	-0.0979	-0.1007
ML01	**-0.1119**	-0.0764	-0.0392	-0.0151	-0.0169	-0.0798
ML09	**-0.1039**	-0.0167	-0.1226	0.0055	-0.0532	-0.1487
MH04	-0.0918	**-0.1157**	-0.0025	-0.0454	0.0169	0.0504
MH14	**0.1012**	-0.0617	-0.0895	0.0043	-0.0853	0.0208
MH20	-0.0224	-0.0199	-0.0096	0.0838	-0.0275	**-0.1808**
FL03	**0.1032**	-0.0850	0.0084	-0.0914	-0.0105	-0.0116
FH01	0.0533	-0.0383	0.1126	-0.1385	**-0.1875**	-0.0603
FH04	0.0764	**-0.1307**	-0.0117	0.0472	0.0066	0.0590
FH05	0.0392	0.0360	0.0457	**-0.1871**	-0.2018	0.0487
DL03	-0.0984	-0.0104	-0.1276	0.0129	-0.0666	**-0.1606**
DL05	**-0.1191**	-0.0693	-0.0655	-0.0258	-0.0312	-0.0612
DL18	**0.1041**	-0.0456	-0.0698	0.0023	0.0275	-0.1287
DH02	-0.0937	**-0.1175**	-0.0175	-0.0634	0.0092	0.0581
DH07	0.0474	0.0517	**-0.1512**	-0.1307	0.0636	-0.0131
DH10	0.0678	0.0254	-0.1121	**-0.1646**	0.0997	-0.0216
DH15	-0.0632	0.0079	-0.0566	**0.1627**	0.1177	0.0524
DH21	-0.0119	-0.0085	-0.0777	0.1016	**0.2081**	0.0192
DH23	-0.0164	-0.0309	-0.0516	-0.0595	0.1116	**0.1778**
TA01	-0.0661	0.0391	**-0.1504**	0.0121	-0.1354	-0.0533
TL01	-0.0247	-0.0290	**-0.1030**	0.0737	0.0331	0.0289
TH01	0.0385	0.0342	-0.1024	**-0.1718**	0.0862	0.0494
RA03	-0.0797	**-0.1256**	0.0215	-0.0657	0.0128	0.0725
RA05	-0.0488	0.0485	0.0130	-0.1388	-0.1305	**0.1567**
RA07	**0.1097**	-0.0797	-0.0244	-0.0403	-0.0630	-0.0568

Table 4: Names and definitions of the 27 hydrologic indices used to classify Oklahoma streamflows grouped primarily by flow category.

Code	Hydrologic Index	Units	Definition
	Magnitude		
MA01	Mean daily flows	ft^3/second	Mean daily flows
MA04	Variability in daily flows 2	Percent	Coefficient of variation of the logs in daily flows corresponding to the {5th, 10th, 15th, . . . , 85th, 90th 95th} percentiles
MA28	Variability in May flows	Percent	Coefficient of variation in monthly flows for May
ML01	Mean minimum January flows	ft^3/second	Mean minimum monthly flow for January
ML09	Mean minimum September flows	ft^3/second	Mean minimum monthly flow for September
MH04	Mean maximum April flows	ft^3/second	Mean of the maximum monthly flows for April
MH14	Median of annual maximum flows	Dimensionless	Median of the highest annual daily flow divided by the median annual daily flow averaged across all years
MH20	Specific mean annual maximum flows	ft^3/second /$mile^2$	Mean annual maximum flows divided by catchment area
	Frequency		
FL03	Frequency of low flow spells	Events per year	Total number of low flow spells (threshold equal to 5% of mean daily flow) divided by the record length in years
FH01	High flood pulse count 1	Events per year	Mean number of high pulse events, where the 75th percentile is the high pulse threshold
FH04	High flood pulse count 2	Days per year	Mean number of days per year above the upper threshold (defined as 7 times median daily flow), and the value is represented as an average instead of a tabulated count
FH05	Flood frequency 1	Events per year	Mean number of high flow events per year using an upper threshold of 1 times median flow over all years
	Duration		
DL03	Annual minima of 7-day means of daily discharge	ft^3/second	Magnitude of minimum annual flow of 7-day mean daily discharge
DL05	Annual minima of 90-day means of daily discharge	ft^3/second	Magnitude of minimum annual flow of 90-day mean daily discharge

Table 4, continued.

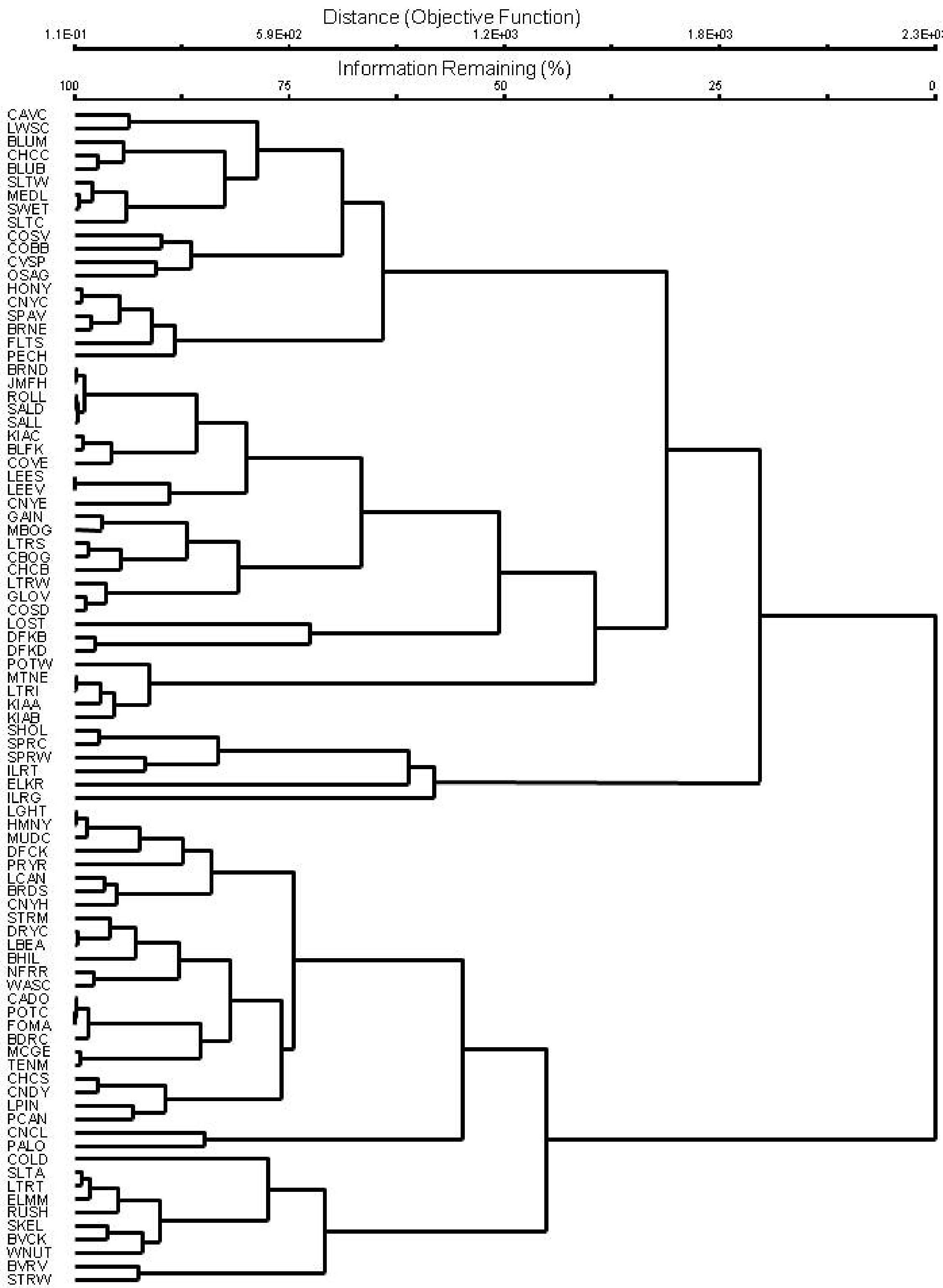
Code	Hydrologic Index	Units	Definition
DL18	Number of zero-flow days	Days per year	Mean annual number of days having zero daily flow
DH07	Variability in annual maxima of 3-day means of daily discharge	Percent	Coefficient of variation in the 3-day moving average flows
DH10	Variability in annual maxima of 90-day means of daily discharge	Percent	Coefficient of variation in the 90-day moving average flows
DH15	High flow pulse duration	Days per year	Mean duration of FH1 (high flood pulse count 1)
DH21	High flow duration 2	Days	Average duration of flow events with flows above a threshold equal to the 25th percentile value for the entire set of flows
DH23	Flood duration 2	Days	Mean annual number of days that flows remain above the flood threshold averaged across all years
	Timing		
TA01	Constancy	Dimensionless	See Colwell (1974)
TL01	Julian date of annual minimum	Julian day	The mean Julian date of the 1-day annual minimum flow over all years
TH01	Julian date of annual maximum	Julian day	The mean Julian date of the 1-day annual maximum flow over all years
	Rate of Change		
RA03	Fall rate	ft^3/second /day	Mean rate of negative changes in flow from one day to the next
RA05	No day rises	Dimensionless	Ratio of days where the flow is higher than the previous day
RA07	Change of flow	ft^3/second /day	Median of difference between natural logarithm of flows between two consecutive days with decreasing flow

Cluster Analysis (CLA)

Cluster analysis is a multivariate statistical method that can be used to identify patterns between many sites using many variables. This study uses a polythetic agglomerative hierarchical clustering that first calculates a dissimilarity matrix with sites and indices. Then, a clustering algorithm is used to group the most similar sites together. In this study, we used Euclidean distance as the measure of dissimilarity and Ward's method (Ward 1963) for the clustering algorithm. This method produced clusters that we were able to classify the stations in a useful and interpretable fashion. The length of the lines on the dendrogram that connect any two stations or groups of stations, indicate the relative similarity of the streamflow, where shorter lines are more similar (CAVC to LWSC) and longer lines are less similar (CAVC to STRW; Figure 5). The selection of clusters was done at levels of information remaining that were the most interpretable for the study. We can divide the cluster dendrogram (Figure 5) in different places to create many combinations of group numbers. The distance function on the top of the graph is measure of the amount of information remaining while the clustering process is being complete (Figure 5; McCune and Grace 2002). The most useful groups produced two clusters at 20% of information remaining, four clusters at 45% of information remaining, and six clusters at 54% of information remaining. These three classification schemes are discussed in the following sections.

We used two nonparametric tests to determine significant differences between the groups identified by the cluster analysis. The Mann-Whitney test was used to compare pairs of groups (i.e. 2 cluster group) and the Kruskal-Wallis with a post-hoc test was used for multiple groups (i.e. 4 cluster group). The Kruskal-Wallis test is similar to the commonly used analysis of variance (ANOVA), but is nonparametric and compares the rank of data in a group rather than actual values (Conover 1999). While the Kruskal-Wallis test can be used to determine if any significant differences were present between the groups. The post-hoc test was used to find the groups that differed between each other, which is similar to the Tukey-Kramer post-hoc test (Conover 1999). The small size of some groups in the 6 cluster classification made statistical analysis not as powerful to compare all the groups, but we did use the Mann-Whitney test to differences in pairs of interest.

Figure 5: Cluster analysis dendrogram made by using Euclidian distance measure and Ward's method for classification of 88 streams in Oklahoma. Station codes are shown in Table 1.



Two-Cluster Classification

The two cluster classification (Figure 6) has a larger cluster (21) with 52 stations and a smaller cluster (22) with 36 stations. The distribution of the sites from both groups are mixed together throughout the region and there is not a clear geographic pattern (Figure 7), although there does appear to be more stations from group 21 in the eastern part of the area. The only stations in the panhandles of Oklahoma and Texas are from group 22, and this area is not well represented in the number of available stations in the analysis.

Statistical analyses with the Mann-Whitney test found that all but 5 indices (MH20, DH21, DH23, TL01, and RA03) were significantly different between groups (Table 5). The stations in group 21 had higher mean flow (MA01) with higher flow during low flow periods (ML01, ML09; Figure 8). The stations in group 22 had more flood events (FH01, FH04, FH05), more days with zero flow (DL18), and more variable flows (TA01; Figure 8).

The cluster analysis shows that 21 had higher flows that were more stable (i.e. perennial streams). The stations in group 22 had lower low flows that stay low for longer and even long periods of zero flows (i.e. intermittent streams). Group 22 also had a greater number of high flow pulses compared to group 21. In general, the streams of group 21 are perennial streams with stable flow, while the streams of group 22 are more intermittent and flashy (Figure 8).

Table 5: Mean and standard deviation for two cluster classification using 27 hydrologic indices. Significant differences (α = 0.05) between groups was tested with the Mann-Whitney test and are indicated by different letters.

Index	**Unit**	**21**			**22**		
		Mean	**SD**		**Mean**	**SD**	
MA01	ft^3/second	482.7	507.2	a	115.6	98.9	b
MA04	Percent	140.0	44.7	a	206.0	45.5	b
MA28	Percent	119.2	34.9	a	209.8	34.2	b
ML01	ft^3/second	109.9	133.0	a	10.4	8.6	b
ML09	ft^3/second	26.9	42.5	a	2.2	2.6	b
MH04	ft^3/second	4671.0	4870.3	a	1604.6	1733.6	b
MH14	Dimensionless	93.5	65.6	a	489.3	333.0	b
MH20	ft^3/second/mile^2	34.0	58.3		24.6	17.3	
FL03	Events per year	3.4	2.6	a	8.3	2.1	b
FH01	Events per year	2.5	10.2	a	1.8	12.6	b
FH04	Days per year	36.6	21.4	a	62.7	25.8	b
FH05	Events per year	8.4	2.3	a	10.2	3.0	b
DL03	ft^3/second	18.3	34.4	a	0.9	1.4	b
DL05	ft^3/second	73.6	76.2	a	12.1	10.2	b
DL18	Days per year	8.5	12.5	a	57.4	39.7	b
DH02	ft^3/second	8315.0	8491.9	a	3289.0	2570.6	b
DH07	Percent	67.9	17.6	a	84.5	27.4	b
DH10	Percent	57.3	15.5	a	79.2	19.4	b
DH15	Days per year	8.4	2.3	a	6.2	1.4	b
DH21	Days	85.0	28.0		80.3	25.4	
DH23	Days	2.3	1.3		2.3	0.8	
TA01	Dimensionless	0.35	0.11	a	0.28	0.06	b
TL01	Julian day	257.9	11.8		253.8	15.2	
TH01	Julian day	114.5	47.2	a	147.8	36.1	b
RA03	ft^3/second /day	168.1	156.4		92.1	61.8	
RA05	Dimensionless	0.23	0.04	a	0.22	0.04	b
RA07	ft^3/second/day	0.12	0.05	a	0.24	0.08	b

Figure 6: Cluster analysis dendrogram (Euclidean distance and Ward's method) showing two cluster classification of 88 Oklahoma streamflow stations. Station codes are shown in Table 1.

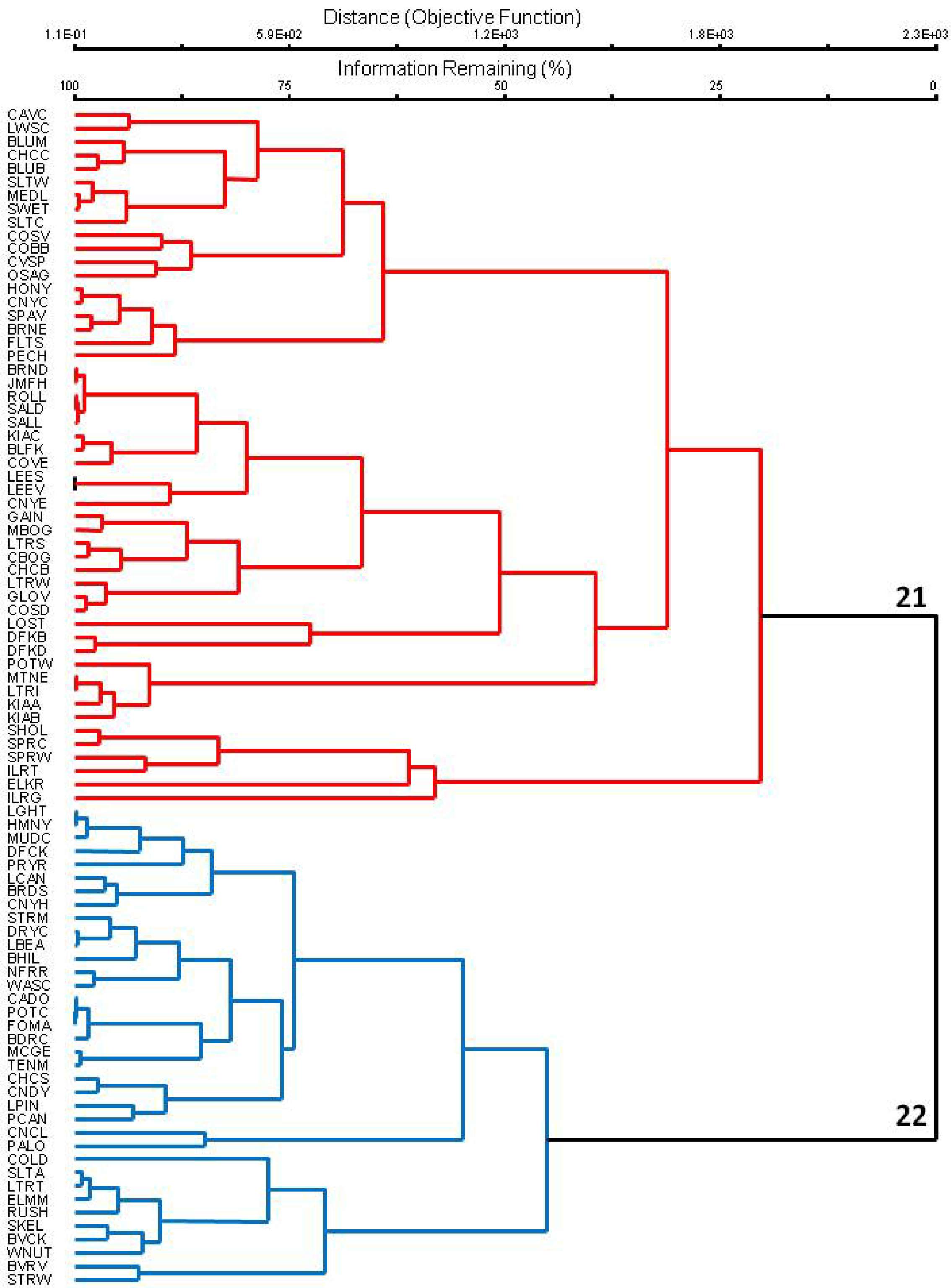


Figure 7: Map of 88 streamflow station in Oklahoma classified by two group cluster analysis. Red triangles are members of group 21 and blue circles are members of group 22.

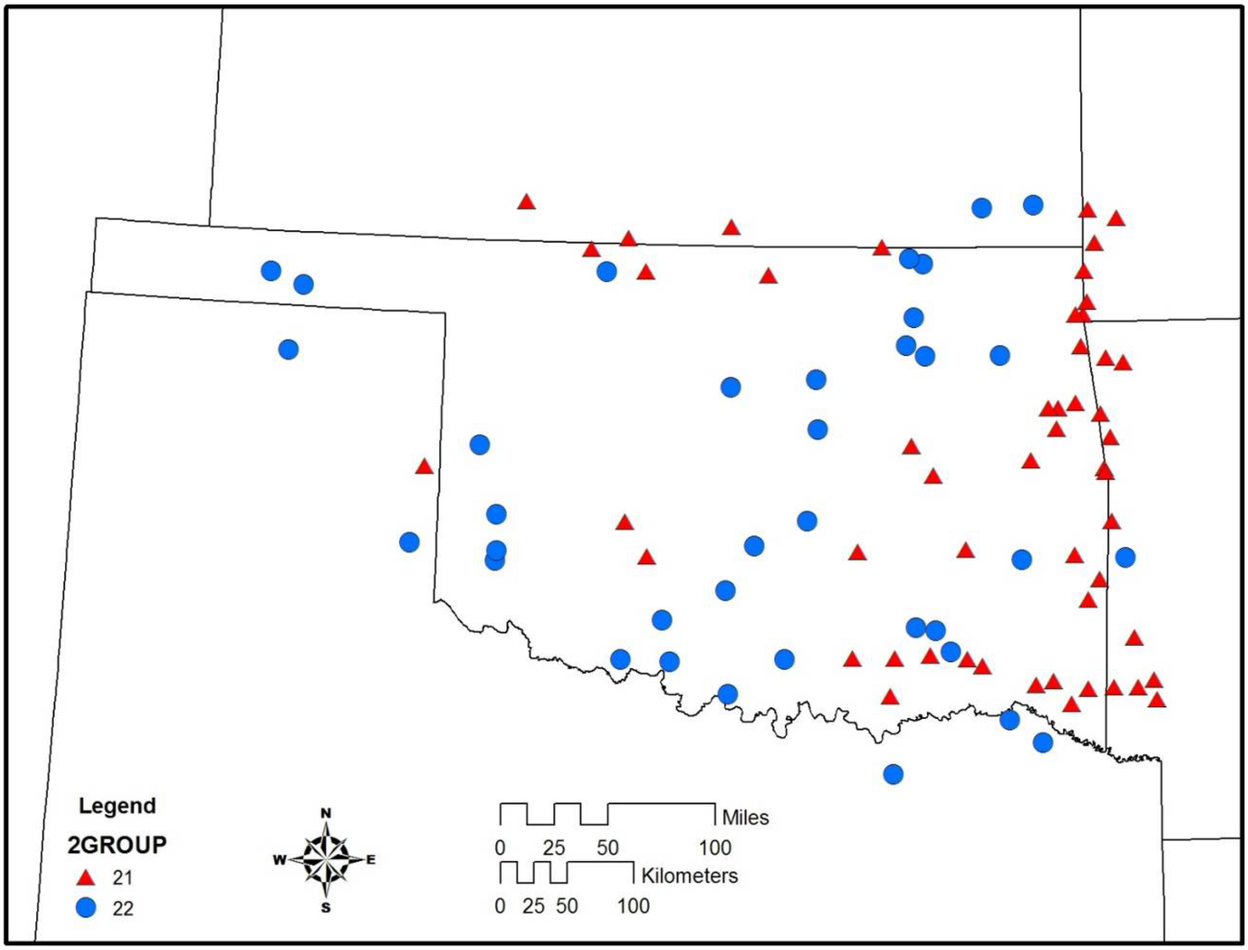


Figure 8: Boxplots of hydrologic indices for the two cluster classification of streamflow-gaging stations in Oklahoma. See Table 4 for hydrologic index names and Figure 6 for groups.

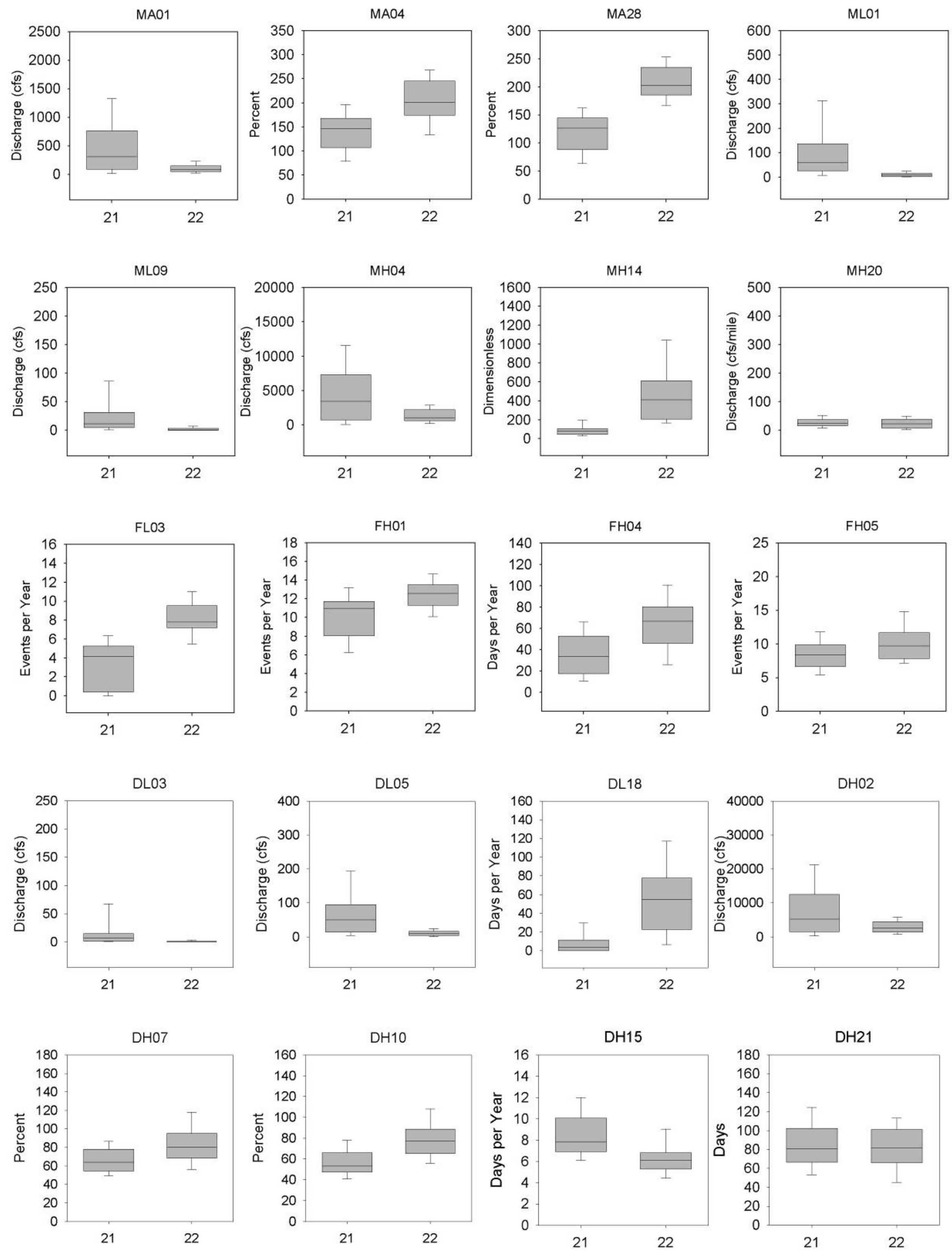
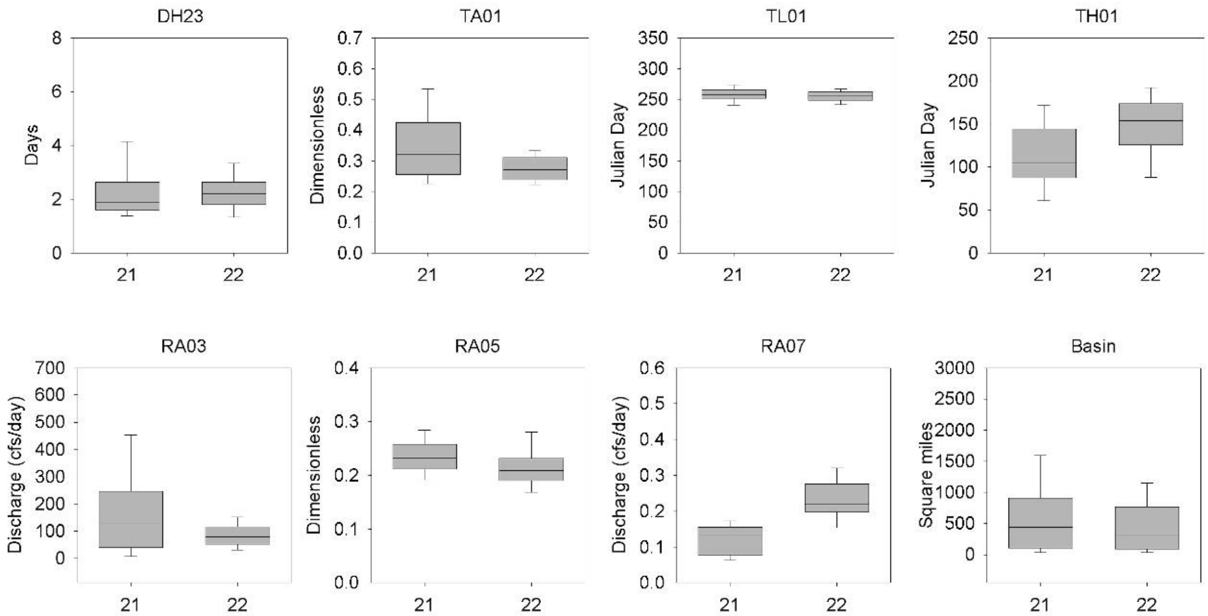


Figure 8, cont.



Four-Cluster Classification

The 4 group dendrogram (Figure 9) is divided with 45% of the information remaining and divided the two cluster classification group 21into three groups, numbered 41,42 and 43. Group 41 had 19 stations, group 42 had 27 stations, and group 43 had 6 stations. Group 44 contained 36 stations and is the same as group 22. Group 43 was more dissimilar (longer distance away on the dendrogram) from groups 41 and 42 than the differences between groups 41 and 42. There was a more regional distribution of the sites in the four group classification (Figure 10) than in the two group classification. The group 41 stations were found throughout the study area. Group 42 stations are concentrated in the southeastern part of the region but it also has some stations in the northeast. Group 43 has the fewest number of stations, which are located only in the northeastern part of the region (i.e. Ozark Highlands). The stations in group 44 were the same as group 22 and were located throughout the region.

A statistical comparison of the stations in the four group classifications with the Kruskal-Wallis test and post test show that there were significant differences between groups for all the hydrologic indices (Table 6). Group 41 stations had lower mean flows (MA01) with relatively stable flows (MA04, TA01; Figure 11). Group 42 stations had more frequent (FH01, FH04) and less variable (DH07) high flow events (Figure 11). Group 43 had the highest stability of flows (TA01) with high baseflows (ML01, DL03, DL05), and no zero flow days in the entire record (DL18). There were also similarities for the stations in groups 42 and 43, which had significantly higher mean flows (MA01) with a higher magnitude of maximum flows in April (MH04) than the other groups. When high flow events did occur at these stations, the flows fell quickly (RA03; Figure 11). The stations of group 44 are the same as group 22, so similar patterns are present with a high number of flood events (FH01) and a high number of zero flow days (DL18; Figure 11).

Based on the trends observed between the four groups, we can classify group 41 as perennial run-off streams, while group 42 stations are perennial flashy streams. The stations in group 43 are stable groundwater streams. Group 44 has streams that have many zero flow days and can be classified as intermittent.

Table 6: Mean and standard deviation for the four cluster classification using 27 hydrologic indices. Significant differences (α = 0.05) between groups was tested with the Kruskal-Wallis test with post-hoc test to differentiate between groups. Significant differences between groups is indicated by different letters.

		41			42			43			44		
		Mean	**SD**		**Mean**	**SD**		**Mean**	**SD**		**Mean**	**SD**	
MA01	ft^3/second	122.2	119.5	a	643.3	519.6	b	901.1	570.4	b	115.6	98.9	a
MA04	Percent	101.8	30.2	a	173.1	29.0	b	112.0	18.8	a	206.0	45.5	c
MA28	Percent	98.7	28.5	a	142.4	23.4	b	79.9	17.4	a	209.8	34.2	c
ML01	ft^3/second	38.2	31.9	a	118.5	135.4	b	298.6	136.9	c	10.4	8.6	d
ML09	ft^3/second	16.4	15.5	a	11.9	10.5	a	127.4	57.0	b	2.2	2.6	c
MH04	ft^3/second	1098.6	1250.1	a	6562.0	4811.6	b	7473.8	6220.6	b	1604.6	1733.6	a
MH14	Dimensionless	57.1	22.8	a	131.6	69.6	b	36.8	12.1	a	489.3	333.0	c
MH20	ft^3/second/$mile^2$	18.7	13.5	a	32.6	15.2	b	88.6	168.3	ab	24.6	17.3	ac
FL03	Events per year	1.5	1.7	a	5.3	1.7	b	0.6	0.9	a	8.3	2.1	c
FH01	Events per year	9.7	3.0	a	11.1	1.8	b	7.9	1.7	a	12.6	1.8	c
FH04	Days per year	17.3	8.8	a	53.5	14.4	b	21.1	8.3	a	62.7	25.8	b
FH05	Events per year	9.3	2.9	ab	8.3	1.5	a	6.0	0.9	c	10.2	3.0	b
DL03	ft^3/second	11.2	12.3	a	5.3	5.5	a	99.6	48.6	b	0.9	1.4	c
DL05	ft^3/second	32.1	27.6	a	70.9	59.7	b	216.8	81.9	c	12.1	10.2	d
DL18	Days per year	6.7	11.1	ab	11.6	13.8	a	0.0	0.0	b	57.4	39.7	c
DH02	ft^3/second	2185.4	2282.5	a	11245.0	8162.3	b	14540.8	11605.9	b	3289.0	2570.6	a
DH07	Percent	75.0	20.1	ab	61.0	14.3	d	76.7	9.4	ac	84.5	27.4	bc
DH10	Percent	59.8	19.7	a	55.4	13.8	a	58.2	3.7	a	79.2	19.4	b
DH15	Days per year	8.1	2.7	a	8.1	1.8	ab	10.2	2.1	b	6.2	1.4	c
DH21	Days	75.1	26.5	ab	87.5	28.8	ac	105.3	16.8	d	80.3	25.4	bc
DH23	Days	1.8	0.5	ac	2.6	1.7	ab	2.7	0.8	bd	2.3	0.8	cd
TA01	Dimensionless	0.40	0.11	a	0.28	0.05	b	0.54	0.03	c	0.28	0.06	b
TL01	Julian day	253.0	11.8	a	258.7	10.9	a	269.7	6.5	b	253.8	15.2	a
TH01	Julian day	128.8	55.9	ab	104.5	43.4	a	114.4	19.3	ab	147.8	36.1	b
RA03	ft^3/second /day	51.3	53.4	a	238.3	161.7	b	222.6	146.4	b	92.1	61.8	c
RA05	Dimensionless	0.24	0.04	a	0.23	0.03	ab	0.24	0.02	ab	0.22	0.04	b
RA07	ft^3/second/day	0.09	0.03	a	0.16	0.03	b	0.06	0.01	a	0.24	0.08	c

Figure 9: Cluster analysis dendrogram (Euclidean distance and Ward's method) showing four cluster classification of 88 Oklahoma streamflow stations. Station codes are shown in Table 1.

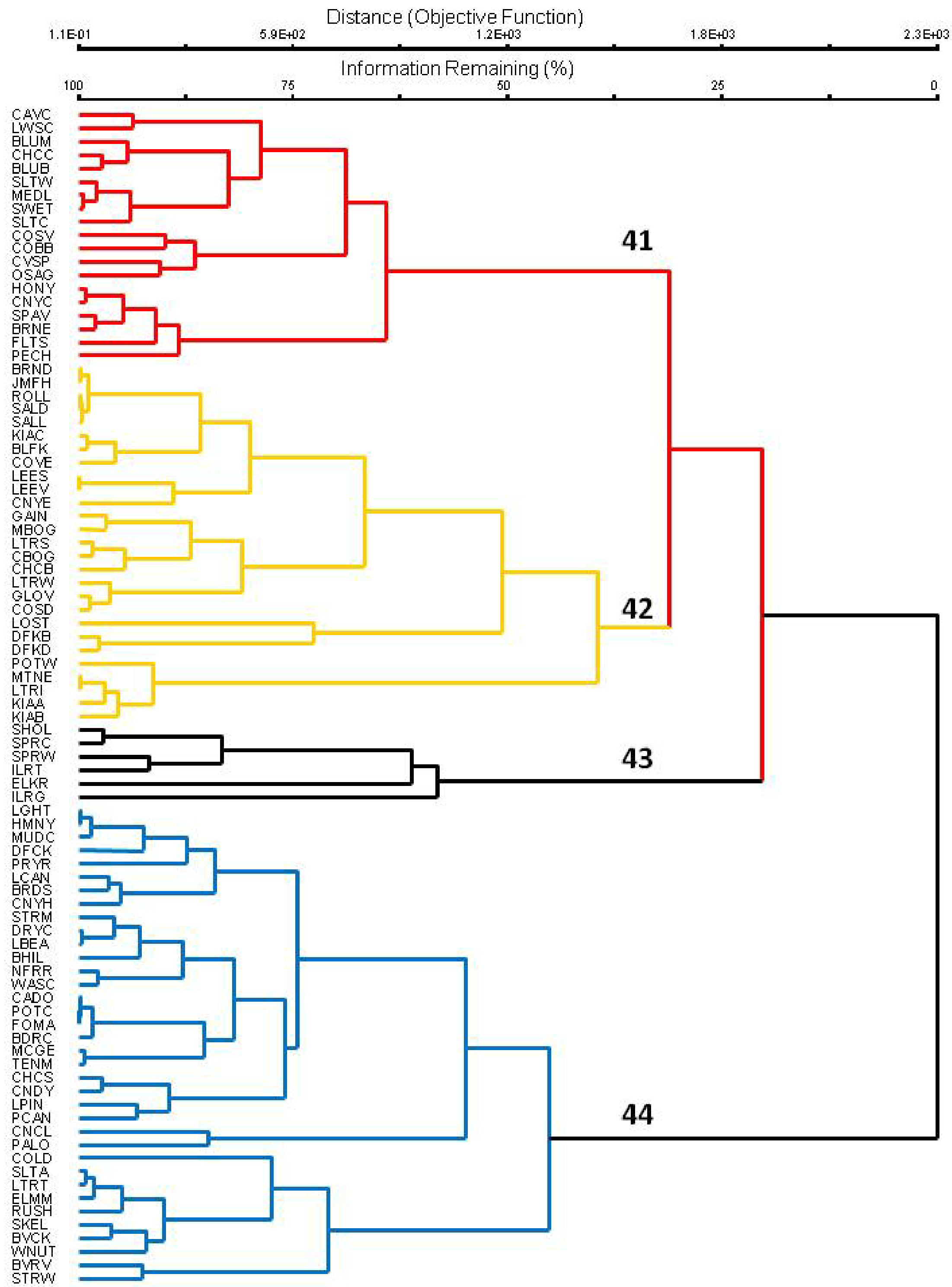


Figure 10: Map of 88 streamflow stations in Oklahoma classified by four group cluster analysis. Red triangles are members of group 41, yellow pentagons are members of group 42, black diamonds are members of group 43, and blue circles are members of group 44.

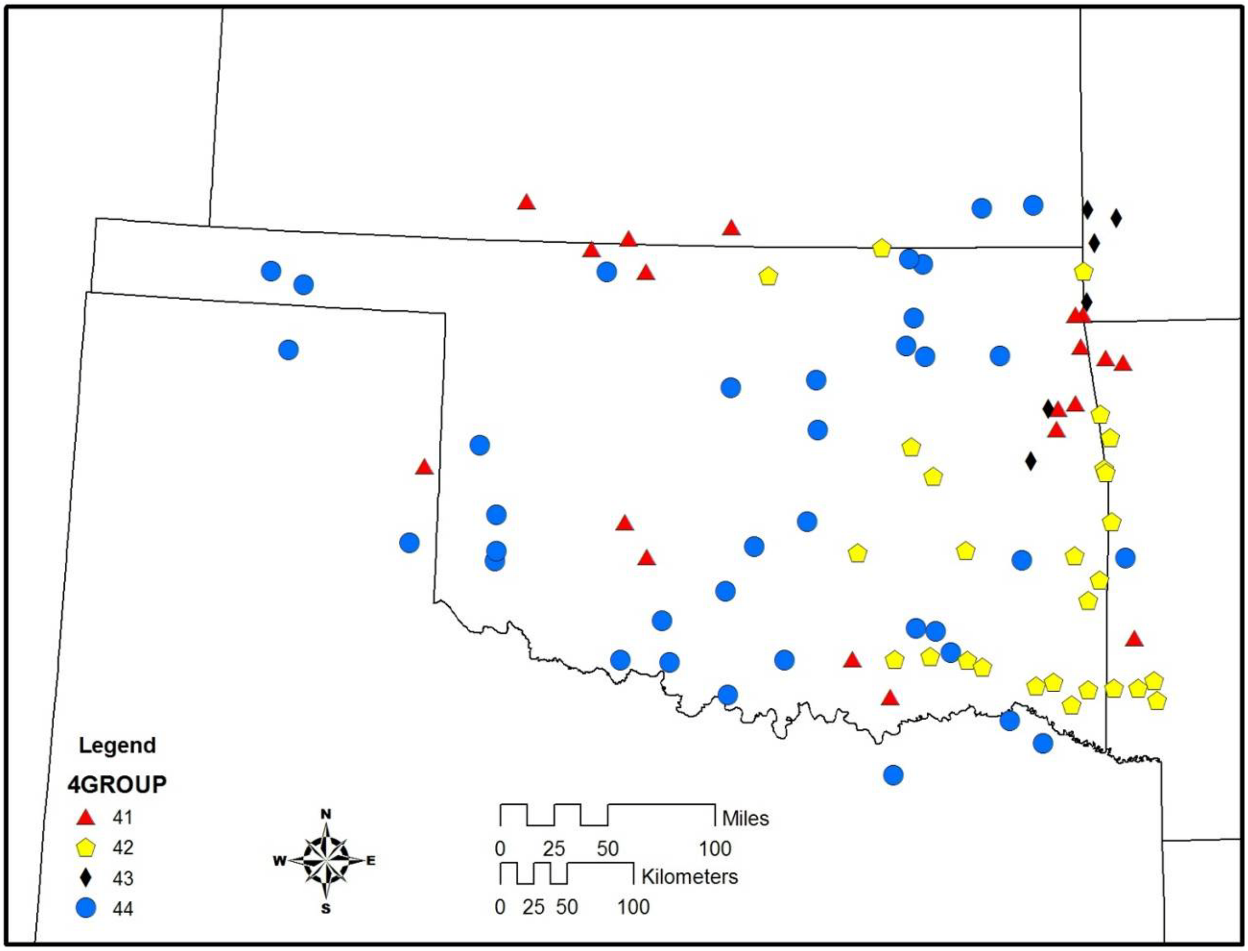


Figure 11: Boxplots of hydrologic indices for the four cluster classification of streamflow-gaging stations in Oklahoma. See Table 4 for hydrologic index names and Figure 9 for groups.

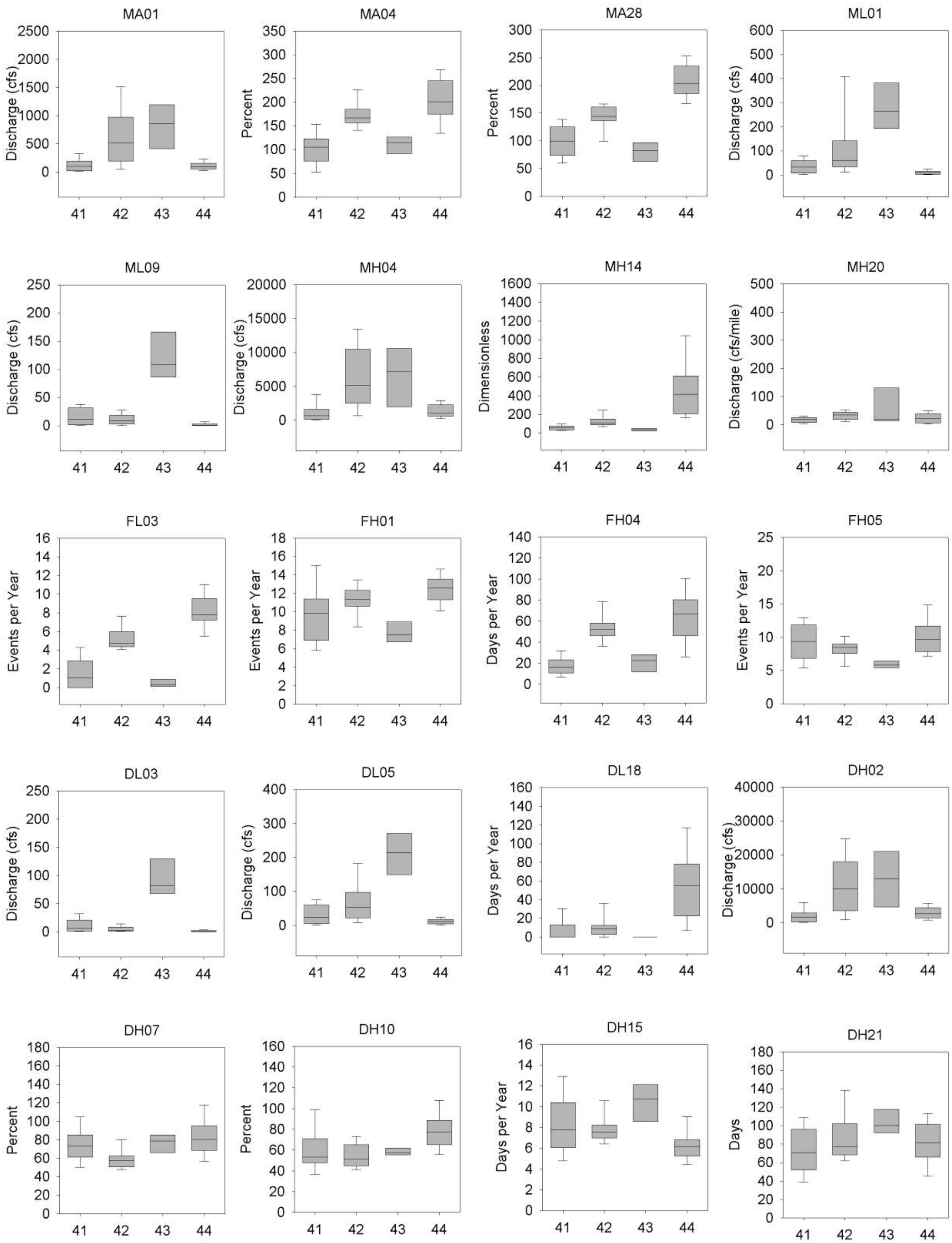
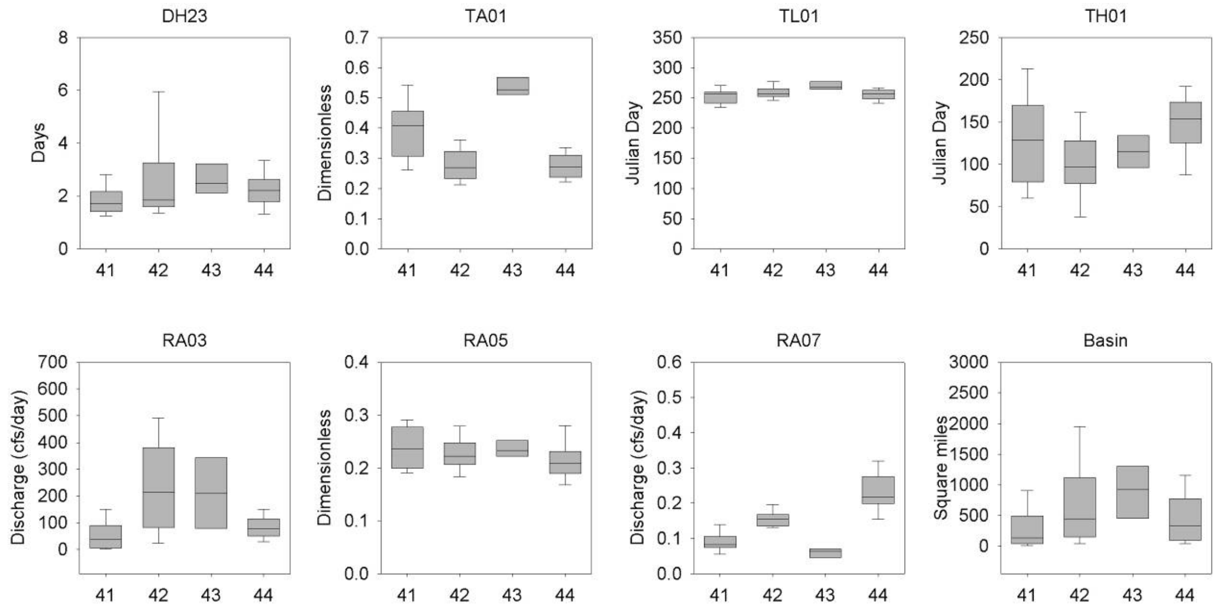


Figure 11, cont.



Six-Cluster Classification

The dendrogram divided at 54% of the information remaining had several smaller clusters compared to the four cluster classification (Figure 12). The group numbers and the number of stations in each group were: 61 (19 stations), 62 (22 stations), 63 (5 stations), 64 (6 stations), 65 (26 stations), and 66 (10 stations). The two changes from the four cluster classification are that group 42 was divided into two groups (62 and 63), and group 44 was divided into two groups as well (65 and 66; Figure 12). We will focus on the differences within groups 62/63 and 65/66 that only occur in the six cluster classification because groups 61 and 64 were discussed in the previous section as 41 and 43, respectively. Group 62 is located primarily in the eastern part of the region, while the five stations of Group 63 are found only in southeastern Oklahoma (Figure 13). The stations of groups 65 and 66 are mixed together around the region (Figure 13). Group 66 stations are mostly in the western part of the region, while stations in group 65 are scattered among the other stations, with a concentration of eight stations in the northeastern part of the region (Figure 13).

Only 10 of the 27 hydrologic indices were significantly different between the groups 62 and 63 when tested with the Mann-Whitney test (Table 7). Group 63 had higher magnitude flows for average (MA01), low (ML01, ML09), and high (MH04) magnitude flows (Table 7). The stations of group 63 had more stable flows (TA01) and a higher fall rate (RA03). There was also a significant difference in basin size (608 miles^2 in group 62 and 1142 miles^2 in group 63), which would be linked to the values of the magnitude and other indices. The stations in groups 65 and 66 have been clustered together in both the two cluster classification as 22 (Figure 6) and the four cluster classification as 44 (Figure 9). There were 17 indices that were significantly different between groups 65 and 66 (Table 7). Group 65 stations had more variable daily flow (MA04) and higher mean annual maximum flows (MH14) than group 66. The group also had more low flow spells (FL03) and twice as many zero flow days per year (DL18). Group 66 stations had more frequent (FH05) and longer floods (DH15). The timing of flows for group 66 stations were earlier in the year for low flows (TL01) and later in the year for high flows (TH01) than station in group 66 (Table 7). The group 66 stations also had more days with no rise (RA05) and a lower rate of change between days (RA07) than group 65.

The analysis of the differences between the groups in the six cluster classification indicate that group 62 are perennial streams with smaller watersheds, while group 63 are stations are perennial streams with larger watersheds. The stations in groups 65 and 66 are both intermittent streams. Group 65 appears to be more intermittent flashy streams and group 66 streams are intermittent run-off streams.

Table 7: Mean and standard deviation for the six cluster classification using 27 hydrologic indices. Letters separate significant differences (α = 0.05) between groups tested with the Mann-Whitney test for groups 62/63 (a/b) and 65/66 (y/z).

		61		**62**			**63**			**64**		**65**			**66**		
		Mean	**SD**	**Mean**	**SD**		**Mean**	**SD**		**Mean**	**SD**	**Mean**	**SD**		**Mean**	**SD**	
MA01	ft^3/second	122.2	119.5	451.7	347.2	a	*1486.4*	176.9	b	901.1	570.4	124.8	112.2		91.6	46.7	
MA04	Percent	101.8	30.2	173.2	31.9		172.9	11.4		112.0	18.8	*225.0*	35.6	y	156.6	27.7	z
MA28	Percent	98.7	28.5	144.2	25.3		134.5	10.4		79.9	17.4	214.0	36.4		198.9	26.3	
ML01	ft^3/second	38.2	31.9	63.1	44.9	a	*362.0*	132.9	b	298.6	136.9	9.2	8.8		13.4	7.5	
ML09	ft^3/second	16.4	15.5	10.0	10.0	a	*20.6*	9.3	b	127.4	57.0	1.3	1.6	y	*4.7*	3.3	z
MH04	ft^3/second	1098.6	1250.1	4885.3	3342.4	a	*13939.3*	2888.4	b	7473.8	6220.6	1828.2	1963.9		1023.2	673.6	
MH14	Dimensionless	57.1	22.8	*142.7*	72.2	a	82.8	20.5	b	36.8	12.1	*592.7*	337.6	y	220.6	59.2	z
MH20	ft^3/second/$mile^2$	18.7	13.5	33.6	16.5		28.5	6.7		88.6	168.3	*29.4*	17.2	y	12.1	9.8	z
FL03	Events per year	1.5	1.7	5.4	1.8		5.1	1.0		0.6	0.9	*8.9*	2.1	y	7.0	1.7	z
FH01	Events per year	9.7	3.0	10.9	1.9		12.1	1.0		7.9	1.7	12.1	1.5	y	*13.9*	1.7	z
FH04	Days per year	17.3	8.8	53.8	15.9		52.5	4.4		21.1	8.3	*74.0*	20.0	y	33.4	12.2	z
FH05	Events per year	9.3	2.9	8.2	1.7		8.7	0.9		6.0	0.9	9.1	2.2	y	*13.3*	2.8	z
DL03	ft^3/second	11.2	12.3	4.6	5.6		8.3	4.1		99.6	48.6	0.4	0.8	y	*2.4*	1.7	z
DL05	ft^3/second	32.1	27.6	50.2	39.2	a	*162.3*	47.5	b	216.8	81.9	10.8	10.9	y	*15.7*	7.5	z
DL18	Days per year	6.7	11.1	12.2	15.2		9.0	4.6		0.0	0.0	*68.7*	35.3	y	27.8	36.2	z
DH02	ft^3/second	2185.4	2282.5	8368.3	5773.0	a	*23902.4*	3508.2	b	14540.8	11605.9	3478.3	2925.7		2796.7	1244.3	
DH07	Percent	75.0	20.1	*63.6*	14.3	a	49.4	6.7	b	76.7	9.4	79.2	25.3		98.3	29.2	
DH10	Percent	59.8	19.7	56.6	14.7		50.0	6.8		58.2	3.7	74.7	16.8		90.9	21.7	
DH15	Days per year	8.1	2.7	8.3	2.0		7.3	0.7		10.2	2.1	*6.7*	1.2	y	4.9	0.8	z
DH21	Days	75.1	26.5	91.0	30.8		72.0	7.1		105.3	16.8	83.0	23.1		73.2	30.9	
DH23	Days	1.8	0.5	2.6	1.9		2.5	0.7		2.7	0.8	2.3	0.8		2.4	0.8	
TA01	Dimensionless	0.40	0.11	0.27	0.05	a	*0.32*	0.02	b	0.54	0.03	0.28	0.07		0.29	0.03	
TL01	Julian day	253.0	11.8	258.7	11.8		258.5	6.8		269.7	6.5	*258.3*	8.0	y	242.0	22.5	z
TH01	Julian day	128.8	55.9	106.3	48.0		96.7	7.6		114.4	19.3	138.3	37.1	y	*172.5*	17.0	z
RA03	ft^3/second/day	51.3	53.4	178.7	108.6	a	*500.5*	50.3	b	222.6	146.4	97.2	70.2		78.9	30.1	
RA05	Dimensionless	0.24	0.04	0.23	0.04		0.23	0.02		0.24	0.02	0.20	0.02	y	*0.26*	0.04	z
RA07	ft^3/second/day	0.09	0.03	0.16	0.03		0.15	0.02		0.06	0.01	*0.26*	0.08	y	0.18	0.04	z

Figure 12: Cluster analysis dendrogram (Euclidean distance and Ward's method) showing six cluster classification of 88 Oklahoma streamflow stations. Station codes are shown in Table 1.

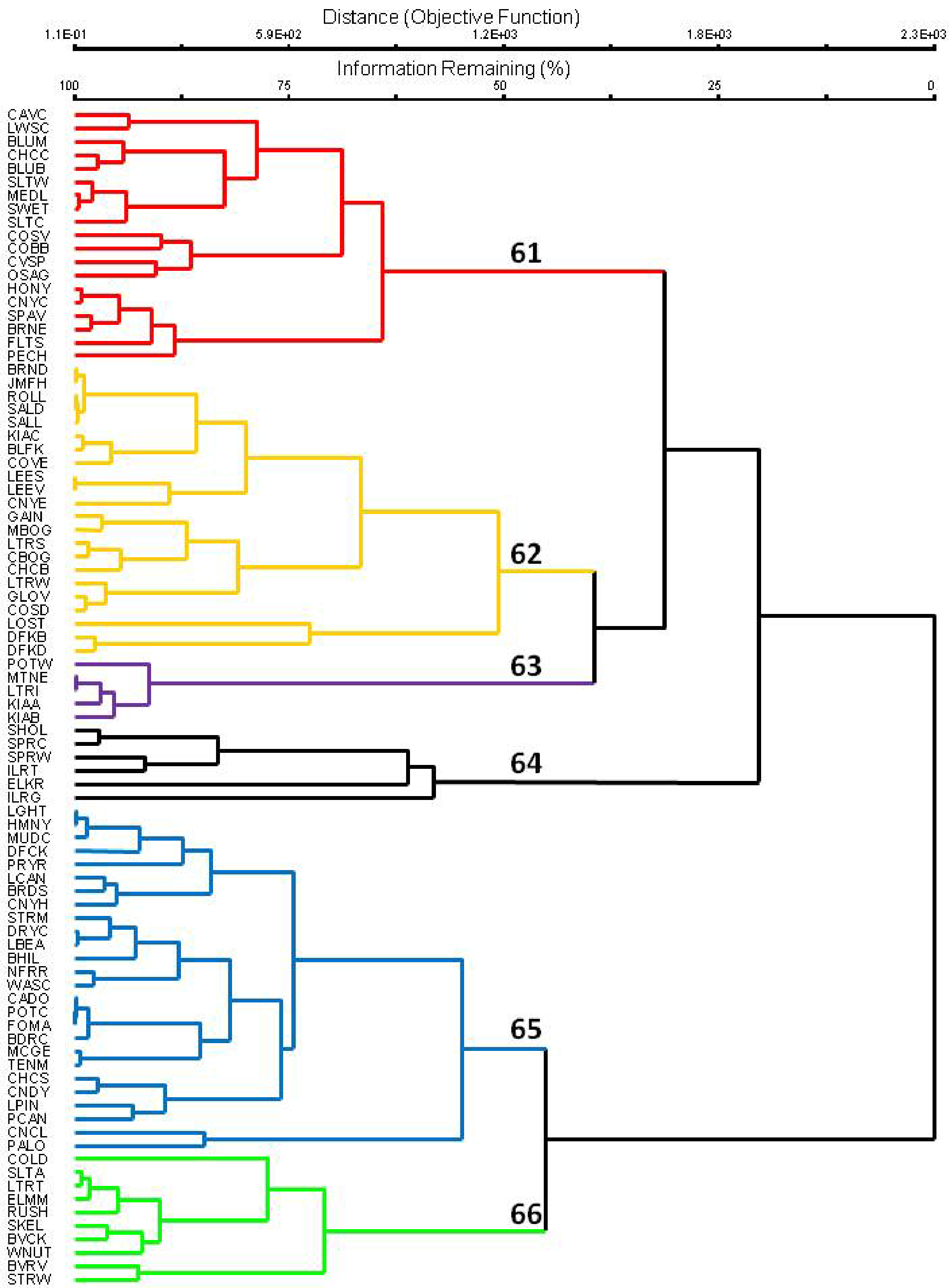
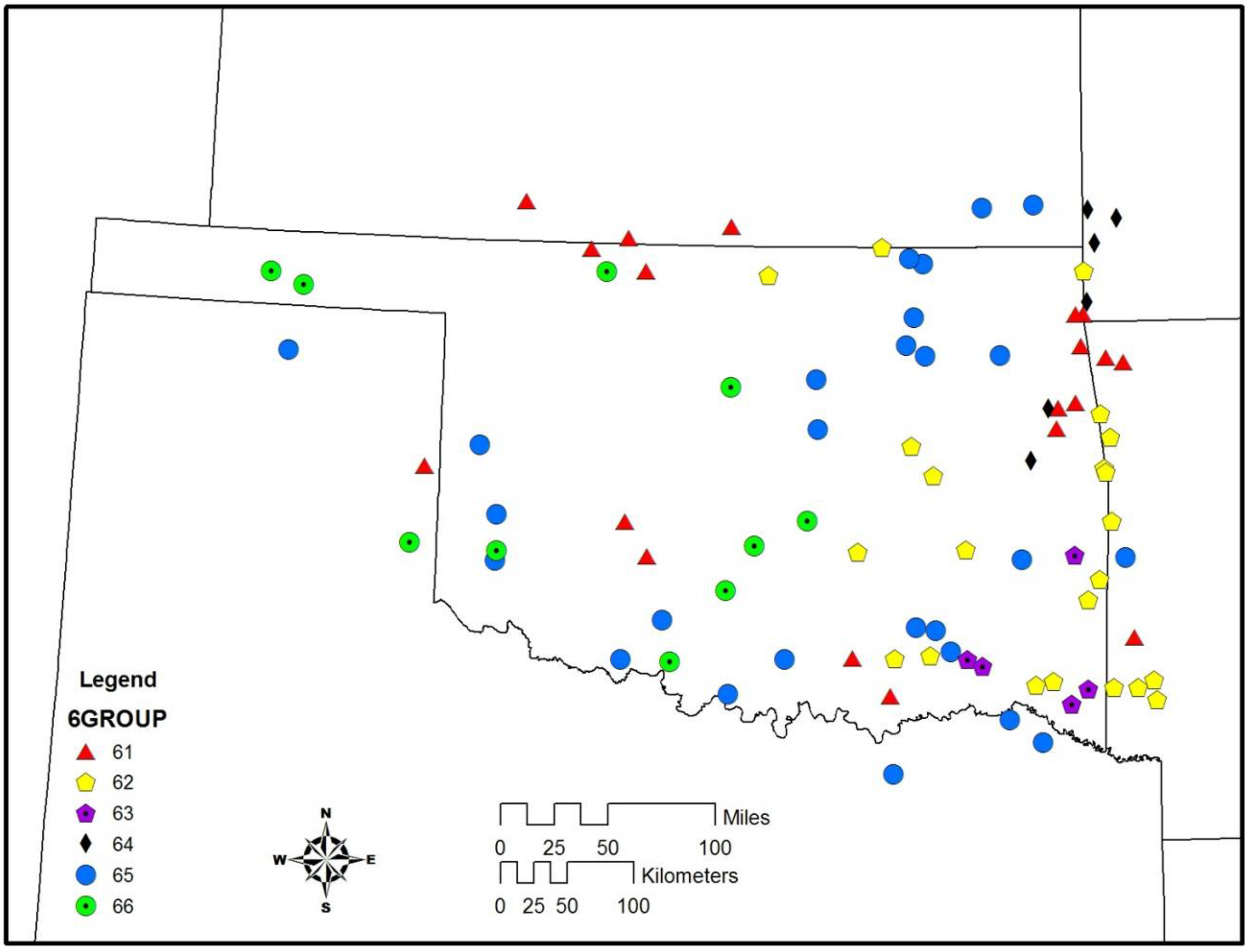


Figure 13: Map of 88 streamflow stations in Oklahoma classified by six group cluster analysis. Red triangles are members of group 61, yellow pentagons are members of group 62, purple pentagons with a dot are members of group 63, black diamonds are members of group 64, blue circles are members of group 65, and green circles with a dot are members of group 66.



Stability of Clusters

We tested how reliable the clusters were using a jackknife method in order to determine if the clusters were dependent on a specific combination of sites and variables (Armstrong et al. 2008; McGarigal et al 2000). Cluster stability was tested by removing individual indices and stations and then running the cluster analysis again. The number of sites that changed cluster membership were then counted. This process was repeated 115 times for each of the 88 sites and 27 indices. The analysis showed that the clusters represent unique groups of stations. The mean stability across all indices and sites was 91% and 94%, respectively. The stability of the clusters from site removal ranged from 73% (with removal of MA04, MA28) to 100%, while the stability of clusters from hydrologic indices ranged from 75% (with removal of SALD, KIAB) to 100%.

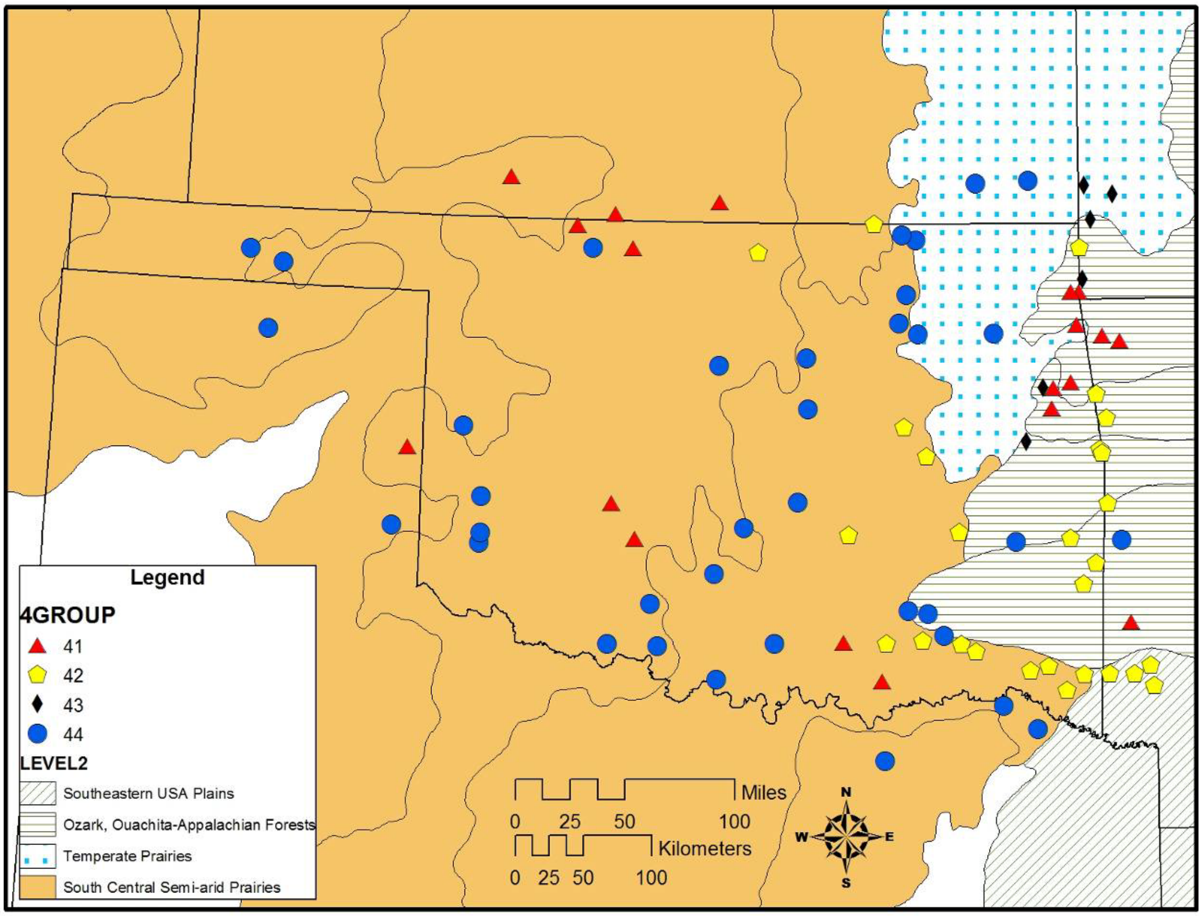
Principal Findings and Significance

This report documents the hydroecological classification of Oklahoma streams based on natural flow regime that incorporates natural flow variability. The classification completes the first 3 development steps of the Hydroecological Integrity Assessment Process (HIP). Completion of the remaining steps of the HIP process will provide tools to water resource managers to include environmental flows to support aquatic life in specific streams as part of Oklahoma's Comprehensive Water Plan.

We calculated 171 ecologically-relevant hydrologic indices for 88 streams across Oklahoma, which described the magnitude, frequency, duration, timing, and rate of change of stream flows. The 27 most non-redundent, high information indices representing all five components of a flow regime were selected for use in the classification of 88 streamflow stations. Cluster analysis was then used to group streamflow stations with similar flow characteristics in two cluster, four cluster, and six cluster groups.

We found that the groupings of streams fell roughly within specific ecoregions of Oklahoma. For example, most of the Group 42 streams (4 cluster analysis) were located in (or the majority of the watershed drained) the Ozark, Ouachita-Appalacian Forests Level II ecoregions (Figure 14). Group 44 streams were located predominately in the Temperate Prairies and South-Central Semi-arid Prairies ecoregions (Figure 14). Ecoregions are based on differences in the inter-related characteristics of climate, geology, soils, and vegetation of a particular location. The hydrologic characteristics of a particular stream (or watershed) are also based on the same characteristics. Therefore we can conclude that the stream groupings generated by the HIT procedure and identification of the primary flow indicies represent "real world" differences in the hydrologic characteristics of the watersheds. From a water resources management perspective, this information is vital to develop environmental flow prescriptions that are stream and organism specific.

Figure 14. A comparison of the four-group cluster analysis stream classifications and Level II Ecoregions of Oklahoma. Note that the symbols represent the location of a gaging station at the watershed outlet. The majority of the watershed drained by the stream may lie in a different ecoregion.



Future Needs

In order to gain the maximum amount of usefulness from this work, the remaining steps of the Hydroecological Integrity Assessment Process (HIP) should be completed. The next development step in the HIP is the development of the Stream Classification Tool (SCT) and the Hydrologic Assessment Tool (HAT) for Oklahoma streams. The SCT development further refines the stream classification and provides water resource managers tools to classify streams that were not included in the baseline analysis performed in this project. The HAT is based on the initial classifications created in this report and the SCT procedure. It is used to provide options for setting environmental flow standards and evaluating past and proposed hydrologic modifications for a specific stream reach.

The baseline stream classification developed in this report and further development of the SCT and HAT will also serve to increase our understanding of the link between natural climate variability, or a changed climate under different climate change scenarios and the variability of the hydrologic characteristics of a stream and populations of various aquatic species. This could include state and federally listed species as well as sportfishes.

Overall, the HIP represents an evolution from simple “rules of thumb” minimum flows to a complex system of hydroecologic flow parameters that support aquatic life throughout the life cycle. The HIP will provide water resource managers with better information with which they can better balance water allocation between human and ecological uses.

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Appendix

Table A: Final baseline period of record for selected streamflow gaging stations in and near Oklahoma that were considered for use in the HIP Classification. *This data was prepared by the US Geological Survey*

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
1	07148350	Salt Fk Arkansas River near Winchester, OK	OK2	848.7	1960-1993	34	Minor Irrigation	Yes	Good
2	07148400	Salt Fork Arkansas River near Alva, OK	OK2	1007.5	1939-1951	13	Minor Irrigation	Yes	Good
3	07149000	Medicine Lodge River near Kiowa, KS	KS8	908	1939-1950, 1960-1968	21	None to note	Yes	Good
4	07149500	Salt Fk Arkansas River near Cherokee, OK	OK2	2420	1941-1950	10	None to note	Yes	Good
5	07151500	Chikaskia River near Corbin, KS	KS8	833.6	1951-1965, 1976-2007	47	Withdrawal, diversion, and irrigation	Yes	Fair
6	07152000	Chikaskia River near Blackwell, OK	OK2	1921.6	1937-1949	13	Withdrawal, diversion, and irrigation	Yes	Fair
7	07153000	Black Bear Creek at Pawnee, OK	OK3	552.3	1945-1960	16	Minor Regulation	No	Poor
8	07154500	Cimarron River near Kenton, OK	OK1	1140.4	1951-1966	16	Irrigation	Yes	Poor
9	07155000	Cimarron River above Ute Creek near Boise City, OK	OK1	2017.6	1943-1954	12	Irrigation, Diversion	No	Poor

Table A, continued.

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
10	07157500	Crooked Creek near Englewood, KS	KS7	843.3	1943-1963	21	Irrigation	Yes	Poor
11	07157900	Cavalry Creek near Coldwater, KS	KS8	42.6	1967-1980	14	None to note	Yes	Excellent
12	07157960	Buffalo Creek near Lovedale, OK	OK1	411.7	1967-1993	27	Minor Regulation	Yes	Poor
13	07159000	Turkey Creek near Drummond, OK	OK2	261.4	1948-1970	23	Diversion	Yes	Poor
14	07160500	Skeleton Creek near Lovell, OK	OK5	422.7	1950-1993, 2002-2007	58	None to note	Yes	Good
15	07163000	Council Creek near Stillwater, OK	OK5	30.8	1935-1960	26	None to note	Yes	Good
16	07170700	Big Hill Creek near Cherryvale, KS	KS9	37.8	1958-1980	23	None to note	Yes	Good
17	07172000	Caney River near Elgin, KS	KS9	439.6	1940-1964	25	None to note	Yes	Good
18	07173000	Caney River near Hulah, OK	OK3	729.2	1938-1949	12	None to note	No	Fair

Table A, continued

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
19	07174200	Little Caney River below Cotton Cr, near Copan, OK	OK3	516.4	1939-1963	24	None to note	No	Good
20	07174600	Sand Creek at Okesa, OK	OK3	141.4	1960-1993	34	Regulation	Yes	Poor
21	07176500	Bird Creek at Avant, OK	OK3	378.1	1946-1967	22	Regulation	No	Poor
22	07176800	Candy Creek near Wolco, OK	OK3	32.2	1970-1980	11	None to note	No	Good
23	07177000	Hominy Creek near Skiatook, OK	OK3	348.9	1945-1980	36	None to note	Yes	Good
24	07177500	Bird Creek near Sperry, OK	OK3	930.5	1939-1957	20	Diversion	No	Fair
25	07184000	Lightning Creek near McCune, KS	KS9	201	1939-1946, 1960-2007	56	None to note	Yes	Excellent
26	07185500	Stahl Creek near Miller, MO	MO4	4.1	1951-1976	26	None to note	No	Poor
27	07185700	Spring River at LaRussell, MO	MO4	313.5	1958-1973, 1976-1980	21	None to note	No	Poor
28	07185765	Spring River at Carthage, MO	MO4	459.4	1967-1980, 2002-2007	20	None to note	No	Good

Table A, continued

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
29	07186000	Spring River near Waco, MO	MO4	1188.1	1925-2007	83	Minor regulation	Yes	Fair
30	07187000	Shoal Creek above Joplin, MO	MO4	438.5	1942-2007	66	None to note	Yes	Excellent
31	07188500	Lost Creek at Seneca, MO	MO4	41.8	1949-1959	11	None to note	No	Good
32	07189000	Elk River near Tiff City, Mo	MO4	872.7	1940-2007	68	Backwater from Regulation	Yes	Fair
33	07189540	Cave Springs Branch near South West City, MO	MO4	8.2	1997-2007	11	None to note	No	Good
34	07189542	Honey Creek near South West City, MO	OK3	49.9	1997-2007	11	None to note	No	Good
35	07191000	Big Cabin Creek near Big Cabin, OK	OK3	462	1948-2007	60	Effluent, Irrigation	Yes	Poor
36	07191220	Spavinaw Creek near Sycamore, OK	OK3	135	1962-2007	46	None to note	Yes	Good
37	07192000	Pryor Creek near Pryor, OK	OK3	233.3	1948-1963	16	None to note	No	Good
38	07195000	Osage Creek near Elm Springs, AR	AR1	133.3	1966-1975, 1996-2007	22	Effluent, Minor Regulation	Yes	Fair

Table A, continued.

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
39	07195430	Illinois River South of Siloam Springs, AR	AR1	582.5	1996-2006	11	Minor Regulation	No	Poor
40	07195500	Illinois River near Watts, OK	OK6	646.1	1991-2007	18	Diversion	No	Poor
41	07195800	Flint Creek at Springtown, AR	AR1	15.1	1962-1963, 1965-1979, 1981-2007	44	None to note	Yes	Good
42	07195865	Sager Cr near West Siloam Springs, OK	OK3	19.6	1997-2007	11	Effluent	No	Poor
43	07196000	Flint Creek near Kansas, OK	OK3	118.6	1956-1977	22	Irrigation	No	Poor
44	07196500	Illinois River near Tahlequah, OK	OK6	974.9	1936-1977	42	Minor Regulation	Yes	Fair
45	07196900	Baron Fork at Dutch Mills, AR	AR1	42.2	1959-2007	49	None to note	Yes	Excellent
46	07196973	Peacheater Creek at Christie, OK	OK6	25.5	1993-2003	11	None to note	No	Good
47	07197000	Baron Fork at Eldon, OK	OK6	319.7	1949-2007	59	None to note	Yes	Good
48	07197360	Caney Creek near Barber, OK	OK6	92.5	1998-2007	10	None to note	No	Fair
49	07198000	Illinois River near Gore, OK	OK6	1656.8	1940-1951	12	None to note	No	Good

Table A, continued.

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
50	07229300	Walnut Creek at Purcell, OK	OK5	207.4	1966-1993	28	Backwater from Regulated Stream	Yes	Fair
51	07230500	Little River near Tecumseh, OK	OK5	474.5	1944-1964	21	Irrigation	Yes	Fair
52	07231000	Little River near Sasakwa, OK	OK5	911.4	1943-1961	19	None to note	Yes	Good
53	07232000	Gaines Creek near Krebs, OK	OK6	600.2	1943-1963	21	None to note	Yes	Excellent
54	07232500	Beaver River near Guymon, OK	OK1	1653.5	1938-1960	23	Minor Regulation	Yes	Fair
55	07233000	Coldwater Creek near Hardesty, OK	OK1	1055.5	1940-1964	25	None to note	Yes	Excellent
56	07233500	Palo Duro Creek near Spearman, TX	TX1	640.9	1946-1969	24	Diversion	Yes	Good
57	07236000	Wolf Creek near Fargo, OK	OK1	1511.1	1943-1956	16	Impoundment	Yes	Poor
58	07243000	Dry Creek near Kendrick, OK	OK5	70.1	1956-1994	39	None to note	Yes	Good
59	07243500	Deep Fork near Beggs, OK	OK6	2056.2	1939-1960	22	Minor Regulation	Yes	Good
60	07244000	Deep Fork near Dewar, OK	OK6	2355.5	1938-1950	13	Minor Regulation	No	Fair

Table A, continued.

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
61	07245500	Sallisaw Creek near Sallisaw, OK	OK6	185.8	1943-1962	20	Diversion	Yes	Poor
62	07247000	Poteau River at Cauthron, AR	AR4	208.8	1940-1963	29	Minor Regulation	Yes	Good
63	07247250	Black Fork below Big Creek near Page, OK	OK9	96.8	1992-2007	16	None to note	Yes	Good
64	07247500	Fourche Maline near Red Oak, OK	OK9	123.5	1939-1963	25	Impoundment	Yes	Fair
65	07248500	Poteau River near Wister, OK	OK9	1019.4	1939-1948	10	None to note	Yes	Good
66	07249400	James Fork near Hackett, AR	AR4	150.5	1959-2007	19	Diversion/Withd rawal	Yes	Fair
67	07249500	Cove Creek near Lee Creek, AR	AR4	35.7	1950-1970	21	None to note	Yes	Good
68	07249985	Lee Creek near Short, OK	OK6	445.3	1931-1936, 1950-1991, 1993-2007	63	None to note	Yes	Excellent
69	07250000	Lee Creek near Van Buren, AR	OK6	449.3	1931-1936, 1951-1992	48	None to note	Yes	Excellent

Table A, continued.

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
70	07300000	Salt Fk Red Rv near Wellington, TX	TX2	1029.4	1953-1966	14	Irrigation	Yes	Fair
71	07300500	Salt Fork Red River at Mangum, OK	OK7	1380.4	1938-1966	29	None to note	Yes	Excellent
72	07301410	Sweetwater Creek near Kelton, TX	TX2	305	1963-1978	15	Diversion	Yes	Fair
73	07301500	North Fork Red River near Carter, OK	OK4	2155	1938-1961	25	None to note	Yes	Fair
74	07303400	Elm Fk of N Fk Red River near Carl, OK	OK7	449.3	1960-1979, 1995-2007	33	Diversion/Withdrawal	Yes	Poor
75	07303500	Elm Fk of N Fk Red River near Mangum, OK	OK7	868.3	1938-1976	39	Minor Regulation	Yes	Fair
76	07304500	Elk Creek near Hobart, OK	OK7	563.5	1950-1966	17	Irrigation	No	Poor
77	07311500	Deep Red Creek near Randlett, OK	OK7	619.7	1950-1963,1970-1973	18	None to note	No	Excellent
78	07313000	Little Beaver Creek near Duncan, OK	OK8	160.6	1949-1963	15	None to note	Yes	Good

Table A, continued.

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
79	07313500	Beaver Creek near Waurika, OK	OK8	579	1954-1976	23	None to note	Yes	Good
80	07315700	Mud Creek near Courtney, OK	OK8	589.3	1961-2007	47	Minor Regulation	Yes	Good
81	07316500	Washita River near Cheyenne, OK	OK4	782.3	1938-1957	18	Irrigation	Yes	Fair
82	07325000	Washita River near Clinton, OK	OK4	1998.8	1936-1955	20	Irrigation, Minor Regulation	Yes	Poor
83	07326000	Cobb Creek near Fort Cobb, OK	OK7	318.8	1940-1950	11	Minor Regulation	No	Good
84	073274406	Little Washita River above SCS Pnd 26 near Cyril, OK	OK7	3.7	1995-2007	13	None to note	No	Good
85	07327490	Little Washita River near Ninnekah, OK	OK5	213.3	1952-1969	18	Irrigation, Minor Regulation	Yes	Poor
86	07329000	Rush Creek at Purdy, OK	OK8	143.3	1940-1953	13	None to note	Yes	Good
87	07330500	Caddo Creek near Ardmore, OK	OK8	304	1937-1950	14	None to note	Yes	Excellent
88	07332400	Blue River at Milburn, OK	OK8	208.5	1966-1986	21	None to note	Yes	Excellent
89	07332500	Blue River near Blue, OK	OK8	489.8	1937-1980	44	Minor Regulation	Yes	Fair

Table A, continued.

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
90	07332600	Bois D'Arc Creek near Randolph, TX	TX3	74	1964-1985	22	None to note	Yes	Excellent
91	07333500	Chickasaw Creek near Stringtown, OK	OK8	33.5	1956-1968	13	None to note	Yes	Excellent
92	07333800	McGee Creek near Stringtown, OK	OK8	91.1	1956-1968	13	None to note	Yes	Excellent
93	07334000	Muddy Boggy Creek near Farris, OK	OK8	1117.1	1938-1958	21	None to note	Yes	Excellent
94	07335000	Clear Boggy Creek near Caney, OK	OK8	731.8	1943-1960	18	None to note	Yes	Good
95	07335700	Kiamichi River near Big Cedar, OK	OK9	40.7	1966-2007	42	None to note	Yes	Excellent
96	07336000	Tenmile Creek near Miller, OK	OK9	70.1	1956-1970	15	None to note	Yes	Excellent
97	07336200	Kiamichi River near Antlers, OK	OK9	1158.3	1973-1982	10	Diversion	Yes	Fair
98	07336500	Kiamichi River near Belzoni, OK	OK9	1452.6	1926-1972	47	Diversion	Yes	Fair
99	07336750	Little Pine Creek near Kanawha, TX	TX4	77.2	1970-1980	11	None to note	Yes	Excellent
100	07336800	Pecan Bayou near Clarksville, TX	TX4	101.5	1963-1977	15	None to note	Yes	Good
101	07337500	Little River near Wright City, OK	OK9	665	1945-1966	22	None to note	Yes	Excellent

Table A, continued.

Map Number	USGS Station Identifier	Station Name	Climate Division	Drainage Area (Miles^2)	Baseline Period of Record*	Baseline Years	Human Activities	Climate Variability in Baseline?†	Baseline Quality Ranking
102	07337900	Glover River near Glover, OK	OK9	328.6	1962-2007	46	None to note	Yes	Excellent
103	07338500	Little River blw Lukfata Ck, near Idabel, OK	OK9	1260	1930-1968	39	Diversion/Withdrawal	Yes	Fair
104	07338750	Mountain Fork at Smithville, OK	OK9	330.7	1992-2007	16	None to note	No	Poor
105	07339000	Mountain Fork near Eagletown, OK	OK9	820.5	1930-1968	39	None to note	Yes	Good
106	07339500	Rolling Fork near DeQueen, AR	AR7	188.1	1949-1976	28	None to note	Yes	Excellent
107	07340300	Cossatot River near Vandervoort, AR	AR4	91.4	1967-2007	29	None to note	Yes	Excellent
108	07340500	Cossatot River near DeQueen, AR	AR7	370.6	1939-1974	36	None to note	Yes	Good
109	07341000	Saline River near Dierks, AR	AR7	123.3	1939-1974	36	None to note	Yes	Excellent
110	07341200	Saline River near Lockesburg, AR	AR7	259.3	1964-1974	11	None to note	Yes	Excellent

*A water year is the 12-month period beginning October 1 and ending September 30 and is named for the year in which it ends; %, percent; --, did not exceed indicated percentage; "no change" indicates that the baseline period of record did not change as a result of the assessment of impoundment.
†An optimum minimum period of record to encompass climate variability was determined by analyzing variability in annual precipitation for each climate division and determining the minimum number of years where the distribution of annual precipitation in the climate division was similar to the distribution of annual precipitation for a longer period, 1925-2007. If the gage has fewer baseline years than the minimum number of years determined for the climate division that the gage is located in, the quality ranking was reduced.

Alternative Water Conservation Policy Tools for Oklahoma Water Systems

Basic Information

Title:	Alternative Water Conservation Policy Tools for Oklahoma Water Systems
Project Number:	2009OK114B
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End Date:	10/1/2010
Funding Source:	104B
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Research Category:	Social Sciences
Focus Category:	Conservation, Law, Institutions, and Policy, Water Supply
Descriptors:	Water Conservation, Policy Tools, Willingness-to-Adopt, Water Use
Principal Investigators:	Damian Adams, Larry Sanders, Michael Smolen

Publications

1. Boyer, C.N., D.C. Adams, and J. Lucero. Rural Coverage Bias in Online Surveys?: Evidence from Oklahoma Water Managers. Journal of Extension, forthcoming.
2. Adams, D.C., C.N. Boyer, and M.D. Smolen. 2009. Water Rate Structure: a Tool for Water Conservation in Oklahoma. Oklahoma Cooperative Extension Service, AGEC-1017.
3. Adams, D.C., C.N. Boyer, and T. Borisova. 2009. Barriers to Water Conservation by Rural and Municipal Water Systems. Proceedings of the Southern Region Water Policy & Economics Conference, Gainesville, FL, October 13, 2009. Pp. 36-41.

Midterm Technical Report

Title: Alternative Water Conservation Policy Tools for Oklahoma Water Systems

Authors' Names and Affiliations

Damian C. Adams, Asst. Professor, Department of Agricultural Economics, Oklahoma State University, damian.adams@okstate.edu, (405) 744-6172

Larry D. Sanders, Professor, Department of Agricultural Economics, Oklahoma State University, larry.sanders@okstate.edu, (405) 744-9834

Michael D. Smolen, Professor and Water Quality Coordinator, Department of Biosystems & Agricultural Engineering, Oklahoma State University, smolen@okstate.edu, (405) 744-8414

Problem and Research Objectives:

As the Comprehensive State Water Plan moves toward making recommendations, an evaluation of viable, practical, and politically acceptable water conservation policy tools is needed. Experts agree that the pressure on Oklahoma's water supply may increase due to population growth, environmental regulations, climate change, and several other factors. With continuing competition among water consuming municipalities to secure their water supplies, and pressure from the rapidly growing urban complex in North Texas, every option will be needed to conserve Oklahoma's water resource. Although there is increasing experience around the U. S. with crisis-oriented drought response tools, most of this experience has not been shared, or evaluated, or packaged as conservation policy tools. The research will evaluate such tools and bring them out for consideration and evaluation as part of the Water Plan.

Despite the demonstrated vulnerability to drought in Oklahoma, few water managers have formal contingency plans for crises. Lack of awareness of feasible water conservation policy alternatives presents a significant barrier to development and adoption of contingency plans. The primary goal of this project is to increase water managers' and other stakeholders' awareness of: (1) available alternative water conservation policy tools, (2) their feasibility for local conditions, and (3) their relative costs and water savings. Our specific objectives are:

- Objective 1: Catalogue and analyze alternative water conservation policy tools that are potentially applicable to water supply managers in Oklahoma (e.g., pricing schemes, quantity controls [voluntary or involuntary], subsidies, and education/awareness or information feedback programs). **Completed.**

- Objective 2: Determine which water conservation policy tools are currently being applied in Oklahoma. **Completed.**

- Objective 3: Synthesize the results from Objectives 1 & 2 into a framework document for use in expert panel sessions (Objective 4 below). **Not completed (chose alternate data collection method).**

- Objective 4: Evaluate the relative feasibility of the alternatives from the water managers' perspective. **Completed.**

- Objective 5: Evaluate the relative feasibility of the alternatives from the water users' perspective (survey of willingness to adopt). **In progress – nearly completed.**

- Objective 6: Analyze, synthesize, report and extend the results. **In progress.**

Using a literature review and surveys, we identify and evaluate water conservation policy tools that are suitable for local conditions in Oklahoma. First, we conducted a literature review that includes the gray literature (e.g., technical reports) with the help of collaborators at universities in other states (Florida, Tennessee, Arkansas, Texas, and New Mexico). Second, we designed and conducted a survey of water supply managers in Oklahoma and other Southern states to identify which water conservation policy tools are currently being used. Third, we created a framework literature review document and identified potentially feasible conservation policy tools. Fourth, we are designing and will soon conduct a region-wide survey of water users to identify willingness to support potential alternative policy mechanisms. Finally, we will synthesize the results and report the findings to stakeholders as appropriate. This project is expected to generate valuable information that can be used to support the efforts of the Comprehensive State Water Plan process.

Methodology:

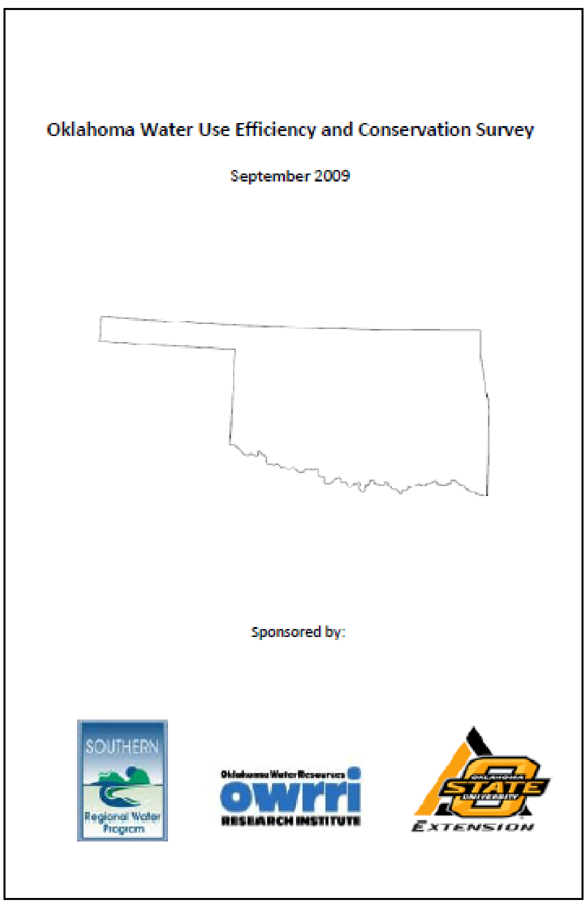
To complete **Objective 1**, we conducted an extensive review of the water conservation literature. The review included both peer-reviewed publications as well as the gray literature (e.g., technical reports and circulars). Collaborators at peer institutions (University of Florida, University of Tennessee, University of Arkansas, Texas A&M University, and New Mexico State University) helped with the literature review for water-related publications within their respective states. In addition to determining what water conservation policy tools are currently being used in the Southern states, we determined the relative effectiveness and cost of each, where possible.

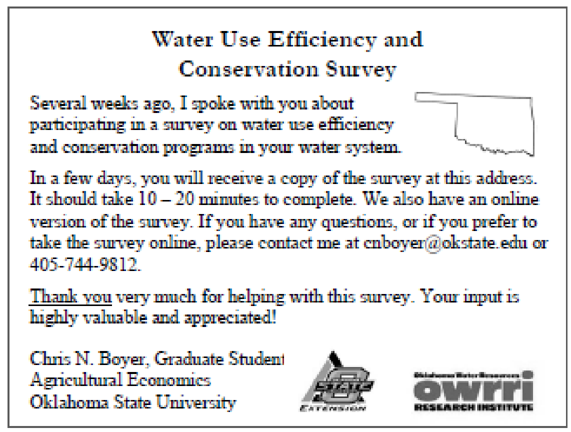
We conducted a survey of Oklahoma water supply managers to achieve **Objective 2 – determine which water conservation policy tools are currently being applied in Oklahoma**. The survey was designed to elicit responses that adequately determine: (1) to what degree water supply managers consider adequate water quantity to be a problem, (2) what water conservation policy tools they are currently applying, (3) what other tools they may have tried in the past, (4) whether they are willing to adopt water conservation tools, and (5) what additional types of information they would need to determine whether to apply these tools.

To reduce unforeseen issues with survey content or communication, we recruited former water district members to provide feedback on the survey. We also pre-tested the survey using water supply managers to ensure a valid instrument and adjusted as necessary.

Surveys were implemented following Dillman's (2006) Tailored Design Method for surveys from July – November 2009. We identified 821 potential respondents using the Oklahoma Rural Water Association and Oklahoma Municipal League directories. Water supply managers were contacted via a pre-survey request to participate (by telephone, email or mail as needed). The survey instrument was delivered by email and/or mail. Example survey materials for the hardcopy version are shown in Figures 1 and 2. The online version can be viewed at http://www.surveymonkey.com/s/5G3ZTHD. Surveys were coded and reminders will be sent to non-respondents with additional questionnaires as necessary to improve the response rate. Survey results are reviewed in the Results section.

Figure 1. Example survey booklet.





Water Use Efficiency and Conservation Survey

Several weeks ago, I spoke with you about participating in a survey on water use efficiency and conservation programs in your water system.

In a few days, you will receive a copy of the survey at this address. It should take 10 – 20 minutes to complete. We also have an online version of the survey. If you have any questions, or if you prefer to take the survey online, please contact me at cnboyer@okstate.edu or 405-744-9812.

Thank you very much for helping with this survey. Your input is highly valuable and appreciated!

Chris N. Boyer, Graduate Student
Agricultural Economics
Oklahoma State University

Figure 2. Example reminder postcard.

We specified predictive models of price-based and non-price conservation programs by water utilities to determine the influence of various factors on adoption. We specified a bivariate probit model to evaluate the impact of demographics, attitudes and perceptions of conservation, and future planning activities.[1] The dependent variable in this model was categorized into three choices: (1) no conservation adoption; (2) PC adoption; and (3) NPC adoption. An advantage of this model is it tests if PC and NPC decisions are correlated or made *jointly* (Greene, 2000); that is, they are considered as substitutes by water utilities. Renwick and Archibald (1998) and Kenny et al. (2008) both state that there needs to be a better understanding of the relationship between PC and NPC use. This model is expressed as

$$\Pr = [PC = 1, NPC = 1 \mid x] = \Phi_2[\beta_{PC}'x, \beta_{NPC}'x, \rho) \qquad (1)$$

where Φ_2 is the bivariate standard normal cumulative distribution function; x is a matrix of independent variables; β_{PC} *and* β_{NPC} are vectors of coefficients; and ρ is the correlation between the equations for PC and NPC. PC was defined as using an inclining block rate structure, and NPC was defined as the used of any programs such as mandatory water restrictions, awareness/education, low flow devices, etc.

Results of the bivariate probit model (discussed below) indicated that there is no statistically-significant relationship between PC and NPC; as such, we chose to specify logit models to estimate the influence of various factors on the adoption of PC and NPC, individually. The first logit model considers the choice between no conservation use and PC adoption, and the other logit model considers the choice between no conservation use and NPC adoption. Logit models provide more direct interpretation and allow the calculation of marginal effects, unlike the bivariate probit. The coefficients from the two logit models did not significantly differ from the coefficients in the bivariate probit model (model results are provided in the Principal Findings and Significance section below).

The NPC and PC logit models are expressed as:

$$\log \frac{P_i}{1 - P_i} = \alpha + \sum_{j=1}^{n} \beta_j x_{ij} + u_i \qquad (2)$$

where P_i is the probability of the i th dependent variable is one Prob(y_i = 1); α is the intercept; x is a matrix of the i th observation and the j th explanatory variable; u_i is the error term that follows the

[1] A multi-nominal logit was also used to evaluate the impact of explanatory variables. The dependent variable in this model was categorized into four choices: (1) no conservation adoption; (2) PC adoption; (3) NPC adoption; and (4) both PC and NPC adoption. However, the survey data did not contain enough respondents that adopted both PC and NPC, and therefore, the model did not prefer well.

logistic distribution; and β_j is the vector of coefficients for the explanatory variable. The left hand side of the equation is the odds ratio of adopting conservation, and is a linear function of the explanatory variables. The odds ratio estimates tell the odds that of each explanatory variable has on PC and/or NPC adoption, while holding the other parameter estimates constant.

Based on initial conversations with water supply managers, pre-test results, and full survey results, **Objective 3 – create a framework document for expert panel members** was deemed unnecessary. We were able to collect the necessary information using an extended version of the water managers survey. To achieve **Objective 4 – evaluate the relative feasibility of the alternatives from the water managers' perspective**, we included directly relevant questions in the full survey. Responses to these questions helped identify potential barriers to a range of alternatives. We discuss the findings on barriers to conservation adoption below.

To achieve **Objective 5 – evaluate the relative feasibility of the alternatives from the water users' perspective**, we will conduct a willingness-to-adopt survey. Using the same approach identified for Objective 2, we will design, pre-test and implement a survey of water users using referenda-type questions (Haab and McConnell, 2002; List, 2006; McConnell, 1990).

Referenda-type questions allow respondents to consider alternative policy choices, tradeoffs, etc. This approach is appropriate when evaluating policy choices that may involve a public vote (Hoban and Clifford, 1999). Using this method, we can determine under what circumstances Oklahoma residents would support the implementation of various water conservation policy tools. Below is an example of a referenda-type question (Figure 3).

Figure 3. Example of a Referenda-type Question.

	Choice A	Choice B
Initial Cost	$0	$10
Water Savings	5%	8%
Increased Water Costs	1%	2%
Vote yes?	☐	☐

The survey will include background information to help respondents that may be less knowledgeable about water. Using a marketing firm, we will identify 1000 potential respondents with equal numbers of males/females and otherwise balanced according to the 2000 US Census for Oklahoma. We will employ the Dillman (2006) survey method as described above (see Objective 2). The water user survey is currently being designed, and an initial pre-test has been completed. We expect this objective to be completed in July 2010.

To achieve **Objective 6**, we will analyze the results in total and write a final report. The report will include a list of feasible alternatives to consider in the Comprehensive Water Plan process. We will present the results to the Oklahoma Water Resources Board and to other interested stakeholders as appropriate. These are likely to include the Oklahoma Rural Water Association, the Oklahoma Municipal League, and Oklahoma Cooperate Extension Service professionals.

Principal Findings and Significance:

Few Oklahoma municipal or rural water managers have contingency plans for crises, despite demonstrated vulnerabilities to drought, flood, and other disasters. The project will evaluate water conservation policy tools that have been used or proposed in Oklahoma and other parts of the United States. Results will include: (1) a list of water conservation policy tools that are feasible given local conditions in Oklahoma, (2) cost and efficiency evaluations of each of the policy tools, and (3) materials (e.g., final report, framework document) that can support the Comprehensive Water Plan process. Over the short-run, this project should increase water managers' and other stakeholders' awareness of the feasibility and effectiveness of alternative water conservation policy tools. Over the long-run, this project may result in an increase in the number of water districts (particularly rural water districts) that implement water conservation policies as part of a comprehensive drought management plan.

Recent research has focused on water conservation policy tools as feasible responses to water crises. Table 1 provides a brief overview of the major studies. Water prices in the US are typically below their long-run marginal cost (Hanemann, 1997; Timmins, 2003). Water suppliers seem to price water at the short-run average cost of supplying water (transportation, storage, etc.) (Olmstead and Stavins, 2007). Given low and often no price signals regarding water use, studies suggest that water conservation does not happen absent regulation or some general environmental awareness that leads to less use (Howe, 1997).

During the last severe water shortage in Oklahoma, several water districts reluctantly increased prices to reduce water demand. There is anecdotal evidence that this was effective. Studies in other states suggest that similar price increases have significant impacts on water use (e.g., Pint, 1999). Olmstead and Stavins (2007) found a wide range of water conservation policy tools that have been applied throughout the United States, noting that price-based approaches have been most effective. Stevens et al. (1992) found that water pricing changes have significant impact on residential water demand, with an elasticity of demand between -0.1 and -0.69. Other studies have found similar estimates (e.g., Male et al., 1979). Some communities use different pricing mechanisms. For example, about 46% of Massachusetts municipalities use increasing block pricing for water, and only 5% apply flat fees (Tighe and Bond, 2004).

Table 1. Past Studies that Examined Price and Non-Price Conservation.

Conservation Program	Study	Effectiveness
Price – Price Elasticity of Demand	Campbell et al. 2004; Hurd 2006; Kenney et al. 2008; Renwick and Archibald 1998; Wang et al. 1999; Olmstead et al. 2007; Brookshire et al. 2002; Espey et al. 1997; Dalhuisen et al. 2003; Gaudin 2006	Average of 5% reduction in water demand with a 10% in price
Non-Price - Education/Awareness	Howarth and Bulter 2004; Geller et al. 1983; Michelson et al. 1999; Syme et al. 2000; Campbell et al. 2004; Wang et al. 1999; Inman and Jeffery 2006; Miri 1998	0-25% reduction in water demand
Non-Price - Retrofit Devices	Geller et al. 1983; Michelson et al. 1999; Renwick and Archibald 1998; Renwick and Green 2000; Timmins 2003; Turner et al. 2004; Wang et al. 1999; Campbell et al. 2004; Buckley 2004; Maddaus 1984; Campbell et al. 1999; White and Fane 2002; Baer 2001	8-32% reduction in water demand
Non-Price - Rebates	Michelson et al. 1999; Renwick and Archibald 1998; Renwick and Green 2000; White and Fane 2002; Howe and White 1999	0-10% reduction in water demand
Non-Price – Outdoor Watering Restrictions	Mansur and Olmstead 2007; Michelson et al. 1999; Olmstead and Stavins 2008; Renwick and Green 2000; Renwick and Archibald 1998; Campbell et al. 2004; Howe and White 1999; Shaw and Maidment 1988	19-29% reduction in water demand
Non-Price- Efficient Lawn Irrigation Systems	Hurd 2006; Kenney et al. 2004; Kenny et al. 2008; Renwick and Archibald 1998; Schuck and Profit 2004; White and Fane 2002; Mansur and Olmstead 2007; Miri 1998	7-53% reduction in water demand

[a] Most studies include multiple NPC in the analysis, and some include both price and non-price conservation.

Other water conservation policy tools may yield superior results for certain regions of Oklahoma. For example, although controversial, adding water meters can result in significant savings (OECD, 1999). One national study found an average 20% reduction in water use (Maddaus, 1984). Water use restrictions have found mixed conservation results (e.g., Schultz et al., 1997; Renwick and Green, 2000). Policies with education components may further improve conservation success (e.g., Corral, 1997).

There is evidence that community preferences for water policy are not identical across Oklahoma. Every two years, the Oklahoma Municipal League conducts a survey of municipal utility rates (OML, 2007). These indicate a great deal of variability in water pricing schemes across communities of different sizes. In other states, some communities have even charged variable rates based on non-use – for example by head of livestock or number of barber shop chairs on premises (Baumann et al., 1997, pp. 137 – 138).

There is surprisingly little cost-benefit analysis on water conservation (Timmins, 2003). The cost-per-gallon-saved is very rarely calculated for water conservation programs. The costs of applying alternative policy instruments can differ greatly by community attributes. For example, initial costs of water conservation technology adoption can be relatively high. For example, one study estimates that the cost of retrofitting toilets is between $81.56 and $223.07 for two US cities (Olmstead and Stavins, 2007).

In addition of efficiency concerns, distributional impacts of water policy changes may also be significant (Mansur and Olmstead, 2006). Water policy changes are unlikely to change water use behavior uniformly. Studies have surveyed water users during times of drought (e.g., Schultz et al., 1997), and find that some user groups reduce their water use considerably. Some water pricing policies may actually increase water use among higher-income users, while poor households are left worse-off.

If policies are chosen without regard to local preferences, water policy changes can generate political discontent. For example, when Tucson, Arizona adopted a variable rate water pricing scheme following a 2-year drought, the entire city commission was voted out of office the following year (Hall, 2000). Recently, more emphasis has been placed on directly involving the public in the policy decision-making process. A necessary preliminary step to engaging the public in policy design is education on the issues and alternatives. Awareness campaigns have been particularly effective at improving public knowledge. For example, a recent unpublished study in Florida evaluated the impact of a public awareness campaign in the St. John's River Water Management District (SJRWMD, 2007).

More research is needed to determine what water conservation policy tools are appropriate for local conditions in Oklahoma.

Results

Survey responses

We anticipated having 200 water managers as potential respondents, but were able to achieve a much higher response rate: 292 responses for 59% response rate. For this size pool, this response rate provides statistically-valid results and a small margin of error. We are aware that Camp, Dresser & McKee are conducting several surveys involving water managers. We expected that this might increase respondent fatigue and lead to a relatively lower response rate. Given past experience with surveys of water managers in Oklahoma, as well as the increased chance of respondent fatigue, we did not expect a high (over 40%) response rate, particularly from smaller, rural water districts. We were prepared to address this issue by over-sampling small and/or rural water managers as needed, but we found that rural coverage bias was not an issue (Boyer et al., forthcoming).

We received a total of 695 responses from surveys conducted in four states for a 41% response rate, considered high for mixed-mode surveys (Dillman et al., 2007; Dickinson et al., 2000). 594 of these were by web-based survey and 101 responses by hard copy survey. Across the four states, we received 292 surveys responses from Oklahoma utilities (59% response rate), 155 from Florida (48%), 149 from Arkansas (41%), and 99 from Tennessee (20%). These responses provide a sampling error less than ±2.85% at a 95% confidence level. We tested for non-response bias (e.g., Armstrong and Overton, 1977) and coverage bias (e.g., Boyer et al., forthcoming), but found no serious problems. Table 2 provides a summary of some of the more interesting respondent characteristics.

Table 2. Summary Statistics of Water Utilities.

Size	OK	FL	TN	AR
Small	67%	24%	24%	63%
Medium	20%	23%	44%	22%
Large	12%	53%	32%	15%
Water Source				
Ground water	42%	87%	36%	48%
Surface water	58%	13%	64%	52%
Secondary source	18%	19%	23%	17%
No Secondary source	82%	81%	77%	83%
Changes in Per-Capita Demand				
Decreased > 10%	1%	12%	4%	4%
Decreased 5-10%	3%	35%	7%	7%

No Change	58%	44%	58%	57%
Increased 5-10%	32%	7%	27%	24%
Increased > 10%	5%	3%	4%	8%
Plans to Meet Future Demand				
Non-price conservation	6%	18%	10%	6%
Increase rates	22%	19%	15%	19%
Repair & Maintenance	38%	23%	40%	43%
Alternative sources	2%	18%	3%	1%
New Supply	31%	21%	31%	30%

Utilities were classified as small (delivers less than 0.5 million gallon water per day (MGD)), medium (0.5 MGD to 2.0 MGD), and large (more than 2.0 MGD). Approximately 50% of the respondents were small sized utilities, 25% were medium sized utilities, and 25% were large sized utilities. As expected, the majority of the Oklahoma and Arkansas respondents were small sized utilities, and the majority of the Florida respondents were large sized utilities. Tennessee had more large utilities than small utilities, but most respondents were medium sized.

The primary water source for the utilities differs significantly across the four states. Florida utilities depend heavily on groundwater (82%) as their primary source of water, and Oklahoma, Arkansas, and Tennessee rely more on surface water than groundwater. The majority of the utilities in each state did not have a secondary source of water. A secondary source was defined to include both sources owned by the utility and those available through agreement with other systems.

Utility managers were asked to estimate how they perceive their customers' per-capita water demand has changed in the last five years. The majority of the utilities in each state responded that per-capita water demand has not changed. However, Florida water managers believe more of their customers' per-capita water use has decreased than increased, suggesting they believe customers have become more efficient water users in the last five years. While Arkansas, Tennessee, and Oklahoma water managers believe more of their customers have increased their per-capita water use than decreased, suggesting they believe their customers have become less efficient water users.

To ensure the utilities have enough water to meet its future demand, the majority of small utilities plan on repairing old infrastructure or securing a new water supply (Figures 4 and 5). Large utilities responses were more equally distributed across non-price programs, increase rates, repair and maintenance, alternative source, and new supplies. Oklahoma, Arkansas, and Tennessee plan on repairing old infrastructure or securing new water supplies, while Florida is more evenly distributed across the answer choices. Oklahoma utilities plan on adopting more PC than the other states, and nearly 20% of the Florida utilities plan on using an alternative water source such as rainwater harvesting or desalinations.

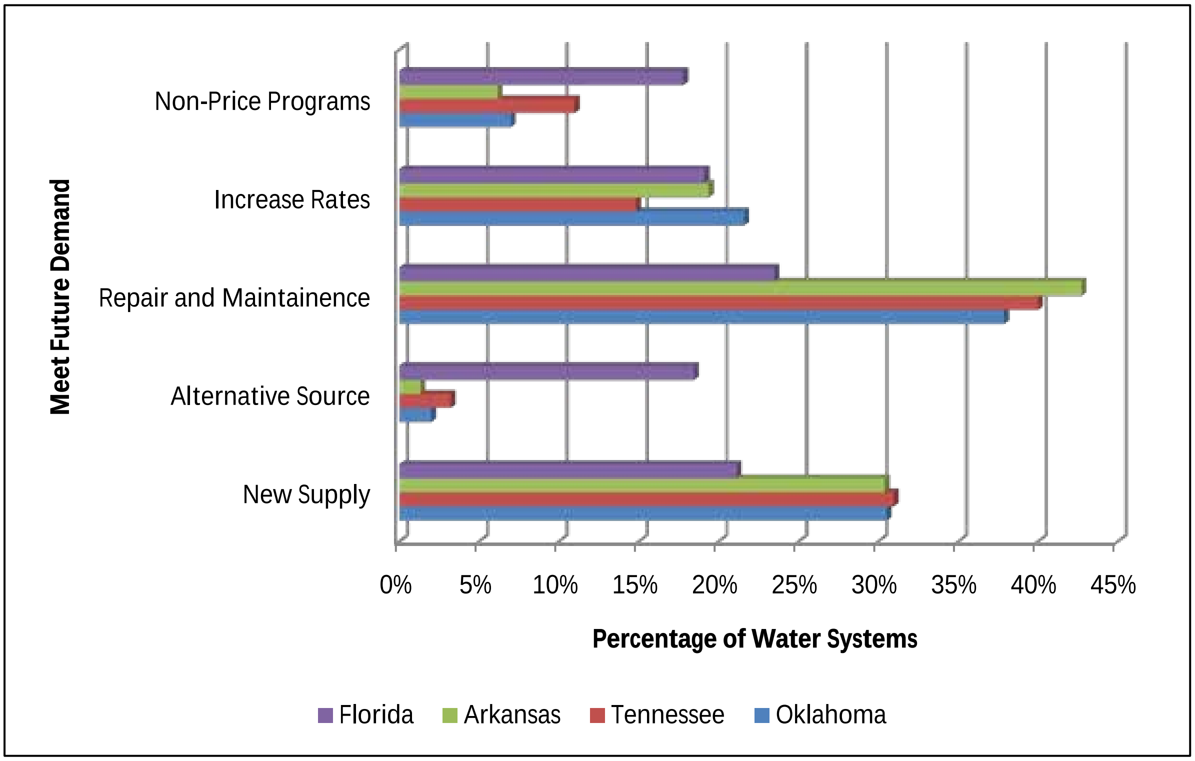


Figure 4. Plans to Meet Future Demand by State.

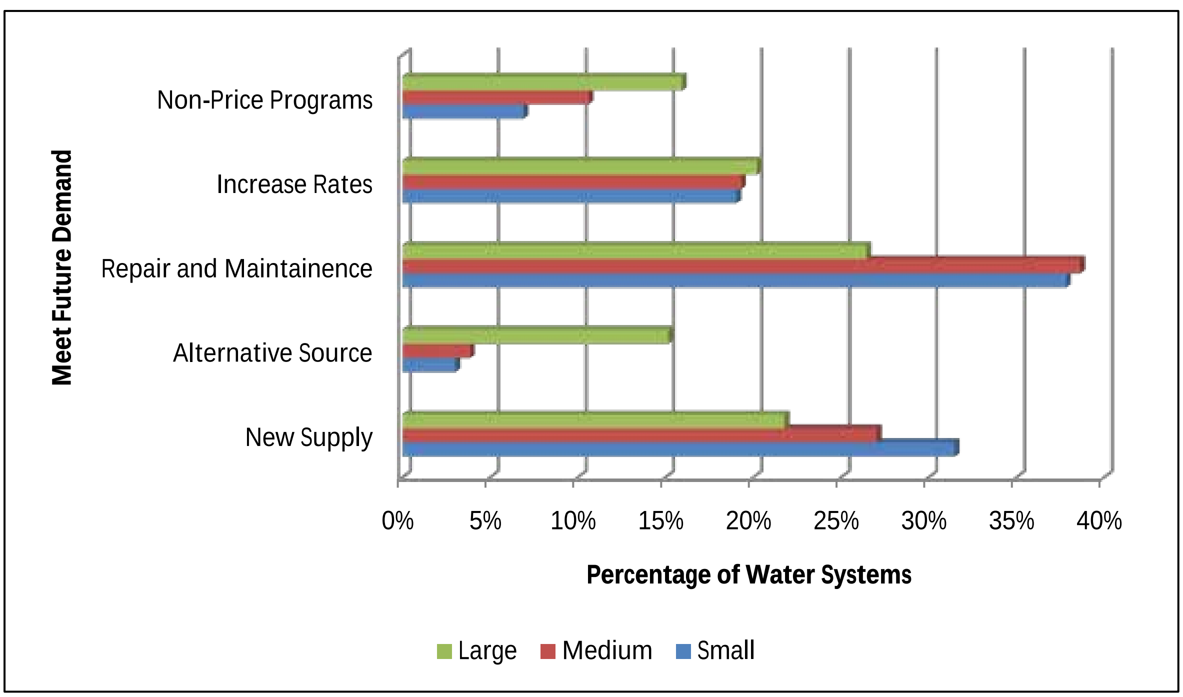


Figure 5. Plans to Meet Future Demand by Utility Size.

Over half of the utilities had not used any PC or NPC programs in the last five year (Figure 6 and 7). The use of NPC and PC programs was fairly equal, and a small percentage had adopted both PC and NPC. Florida adopted PC and both PC and NPC the most, and Oklahoma used NPC the most. Arkansas and Tennessee utilities had adopted the least amount of conservation. Large utilities adopted NPC and both PC and NPC more the small and medium sized utilities. NPC programs can be expense (e.g., rebates on low-flow devices) and sometimes require several man hours (e.g., awareness/education), making it hard for small utilities to adopt the NPC programs. Small utilities adopted PC more than medium and large utilities. Several comments received from rural utilities said that raising treatment costs and regulatory costs are heavy financial burden on their utility, and switching to an inclining block rate helps cover raising costs better than the uniform or declining block rate.

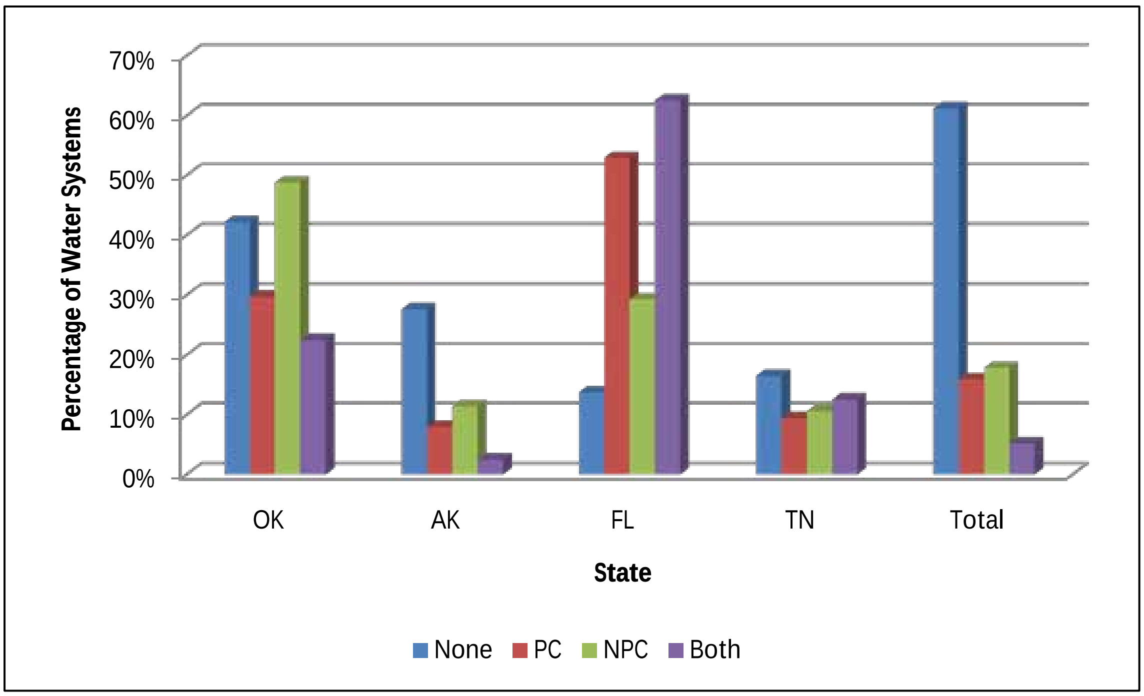


Figure 6. Water Conservation Adoption in the Last Five Years by State.

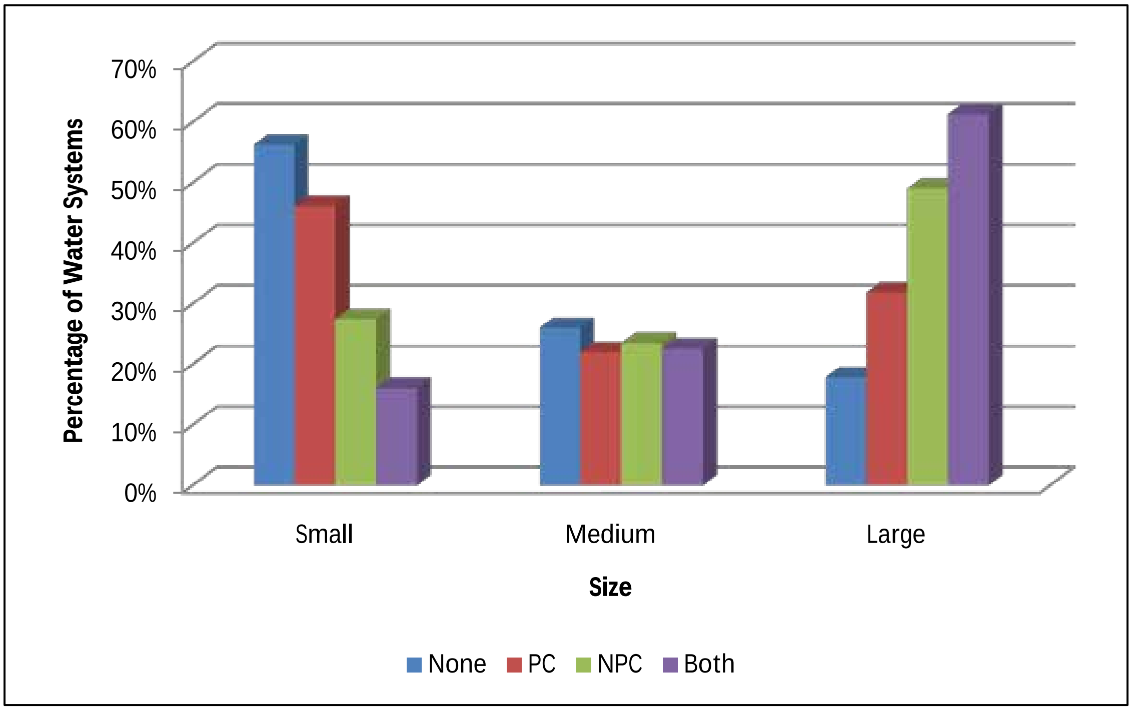


Figure 7. Water Conservation Adoption in the Last Five Years by Utility Size.

We asked utility managers their perception of customers' price elasticity of water demand. The question asked to state how the utility believe their customers would respond to a 10% increase water prices. The majority believe a price increase would not change their customers water use, 35% of the utilities believe their customers water use would decrease, and a small group believed water users would increase water use. Economic theory and previous research finds price elasticity of water demand to be inelastic (i.e., customers respond slightly to price changes), but not perfectly inelastic (i.e., customers are unresponsive to price changes) as most the utilities believe. Water demand becomes more elastic as rates increase (Olmstead and Stavins, 2008), and what utilities in these states might be indicating that their rates are low enough on the demand curve that the price elasticity is close to zero.

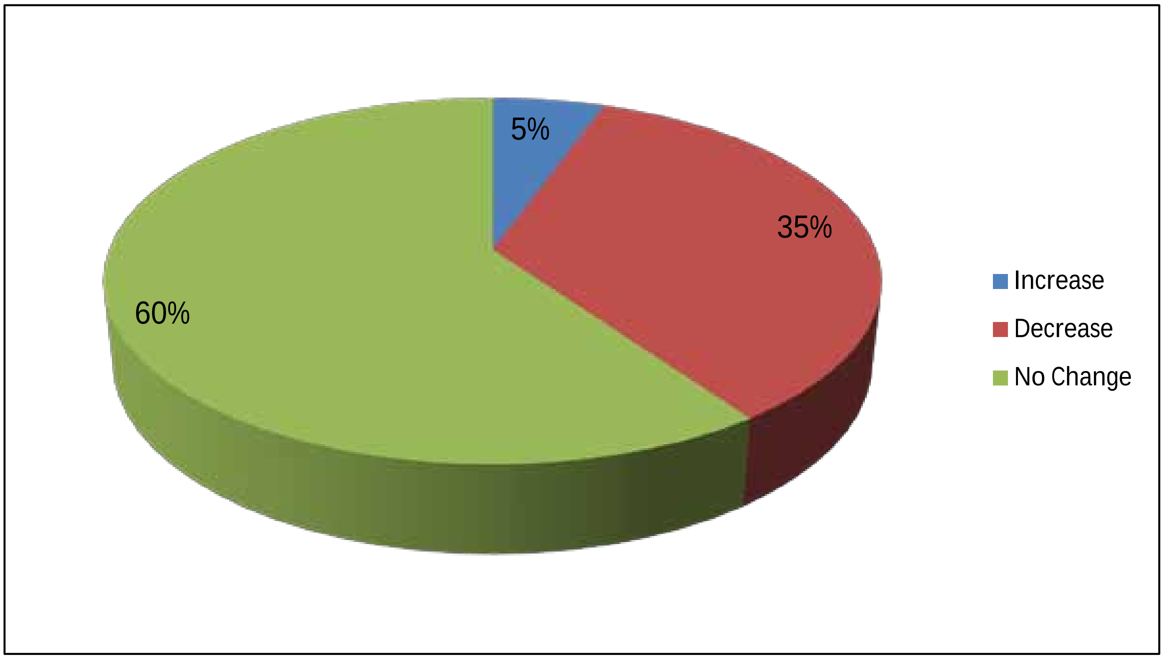


Figure 8. Managers' Perception of Customers Response to a 10% Increase in Price.

Predictive Models of Conservation Adoption

The bivariate probit model produced good overall results with a large number of statistically-significant explanatory variables for both PC and NPC equations. The ρ statistic indicates the relationship between the PC and NPC choices, and a likelihood ratio test of ρ=0 was not statistically significant ($\chi 2$ (1 d.f.)=0.05, p=0.9323) (Table 3). This suggests the utilities in our sample do not jointly consider using PC and NPC adoption together. A positive correlation would suggest utilities are adopting PC and NPC, and a negative correlation suggests that utilities are adopting PC or NPC, but no correlation means there is no relationship between adopting PC and NPC.

Table 3. Bivariate Probit Model of Factors Influencing Conservation Adoption.

	Dependent Variables			
	Price Based Conservation		Non-Price Conservation	
Independent variable§	Coefficient	P-value	Coefficient	P-value
Demographics				
Florida	0.808**	0.0360	1.069***	0.0001
Oklahoma	0.926***	0.0039	0.550**	0.0242
Arkansas	0.163	0.6319	0.145	0.5991
Municipal Organization	0.561**	0.0412	0.413*	0.0583
Small size (< 0.5 million gallons/day)	0.407**	0.0254	0.007	0.9641
Purchase primary water source	0.584***	0.0056	0.339*	0.0513
Groundwater primary water source	0.507**	0.0213	-0.088	0.6275
Has secondary source	-0.682*	0.0649	-0.182	0.5001
Management recommends cons. adoption	-1.123**	0.0277	0.113	0.7202

Had a per-capita water use increase, last 5 yrs	0.414*	0.0886	-0.056	0.7900
Notify customers of rate changes - website	0.036	0.9064	0.512**	0.0139
Notify customers of rate changes - meeting	-0.095	0.5806	0.080	0.5806
Notify customers of rate changes – special mail out	0.335**	0.0495	0.159	0.2829
Attitudes and Perceptions				
Determining rate schedule - cost of delivery	0.224**	0.0418	0.122	0.1890
Determining rate schedule - consumer waste	0.073	0.4221	-0.128*	0.0975
Reason for past rate increase - treatment costs	0.425**	0.0131	0.133	0.4532
Reason for past rate increase - utility maintenance	0.619**	0.0323	0.496*	0.0799
Reason for past rate increase - conservation	1.609***	0.0001	1.061***	0.0001
Internally studied demand elasticity	0.692**	0.0219	0.022	0.9366
Climate change will not impact water supplies	-0.136	0.4676	-0.324**	0.0476
Future Planning				
Meet future demand - alternative source	0.592**	0.0488	0.591***	0.0090
Meet future demand - infrastructure expansion/replacement	0.428**	0.0142	-0.069	0.6357
Meet future demand - manage demand	0.902***	0.0001	0.172	0.3661
Barrier to meeting demand - treatment costs	0.276	0.1042	0.053	0.7093
Barrier to meeting demand - inability to increase withdrawals from source	-0.517*	0.0579	0.594***	0.0035
Correlation of Price and Non-Price Conservation				
Rho (ρ)	0.0100	0.9323		

* Significant at the 10% level; ** Significant at the 5% level; *** Significant at the 1% level.
§ Excludes insignificant variables, except Arkansas.

Similar to the bivariate probit, the logit models have a large number of significant explanatory variables. Logit model results were statistically significant and were theoretically correct. The likelihood ratio test implies the overall PC and NPC models were highly statistically significant (Table 4). The logit models accurately predicted 91.9% of PC adoption and 86.0% of NPC adoption. Table 5 reports the odds ratio estimates and significance levels for the explanatory variables (non-significant parameter estimates are not shown). Odds ratio of the significant variables are used to explain the probability an explanatory variable has on PC and NPC adoption, while holding all other explanatory variables constant.

Table 4. Logit Model Goodness of Fit for Price and Non-Price Conservation.

	Price Conservation		Non-Price Conservation	
Model test statistics	Statistic	P-value	Statistic	P-value
-2 Log Likelihood	-648.825	-	-692.778	-
Likelihood ratio: χ^2 (48 d.f.)	287.769	0.0001	226.368	0.0001
Model fit (Percent correctly predicted)	91.9%	-	86.0%	-

Table 5. Odds Ratio Estimates for Factors Influencing Price and Non-Price Conservation Adoption.

	Dependent Variables			
	Price Based Conservation		Non-Price Conservation	
Independent variable§	Coefficient	P-value	Coefficient	P-value
Demographics				
Florida	4.213**	0.0399	6.695***	0.0001
Oklahoma	5.040***	0.0026	1.084**	0.0325
Arkansas	1.326	0.6529	0.400	0.7381
Municipal Organization	2.513*	0.0554	1.992*	0.0893
Small size (< 0.5 million gallons/day)	2.114**	0.0221	0.848	0.8952
Purchase primary water source	2.863***	0.0045	1.829*	0.0778
Groundwater primary water source	2.458**	0.0311	0.821	0.5661
Has secondary source	0.030*	0.0754	0.626	0.3776
Management recommends cons. adoption	0.147**	0.0270	1.196	0.7632
Had a per-capita water use increase, last 5 yrs	2.119*	0.0929	0.858	0.7412
Notify customers of rate changes - website	1.078	0.8810	2.537**	0.0155
Notify customers of rate changes - meeting	0.865	0.6653	1.156	0.6394
Notify customers of rate changes – special mail out	1.762*	0.0856	1.237	0.4751
Attitudes and Perceptions				
Determining rate schedule - cost of delivery	1.492*	0.0855	1.264	0.1801
Determining rate schedule - consumer waste	1.117	0.4927	0.776*	0.0825
Reason for past rate increase - treatment costs	2.155**	0.0179	1.313	0.4768
Reason for past rate increase - utility maintenance	2.829*	0.0652	2.478	0.1444
Reason for past rate increase - conservation	16.968***	0.0001	6.528**	0.0002
Internally studied demand elasticity	3.389*	0.0630	1.101	0.8130
Climate change will not impact water supplies	0.792	0.4824	0.529**	0.0447
Future Planning				
Meet future demand - alternative source	2.702*	0.0613	2.825**	0.0158
Meet future demand - infrastructure expansion/replacement	2.152**	0.0257	0.842	0.5479
Meet future demand - manage demand	5.297***	0.0001	1.279	0.4993
Barrier to meeting demand - treatment costs	1.602	0.1196	1.066	0.8204
Barrier to meeting demand - inability to increase withdrawals from source	0.357*	0.0963	2.929**	0.0058

* Significant at the 10% level; ** Significant at the 5% level; *** Significant at the 1% level.
§ Excludes insignificant variables, except Arkansas.

The results of our models identify several factors that influence the adoption of NPC and PC, including utility system demographics, water managers' attitudes and perceptions, and utilities' approach to planning for future water needs.

Several demographic factors influence NPC and PC adoption. For PC, municipally-owned utilities are 2.5 times more likely to adopt conservation than private, cooperative, and other ownership types. For NPC, municipally-owned utilities were 2.0 times more likely to adopt conservation. This indicates that non-municipal ownership is a potential barrier to conservation adoption. For PC only, utility size is a strong determinant of conservation adoption, with small utilities (<0.5 MGD) 2.1 times more likely to adopt conservation.

Water source also appears to drive conservation adoption. For PC, utilities that use groundwater as their primary source are 2.5 times more likely to adopt conservation, while those whose primary source is purchased are 2.9 times more likely to conserve. For NPC, having purchased water as a primary source increased the likelihood of adopting conservation by 1.8 times. These results may indicate that utilities with primary sources that are potentially more insecure (particularly during droughts) or costly are more likely to conserve. For PC, having a secondary source of any kind very slightly increases the use of conservation. This may be because utilities that seek secondary sources perceive their primary sources as less secure or more costly than utilities that do not.

Management decision-making, mode of notifying customers of rate changes, and recent per-capita water use changes also influence conservation. For NPC, utilities that rely on management to recommend conservation (as opposed to city or state officials, customers, etc) are 0.15 times more likely to conserve, and those that notify customers of rate changes with special mail-outs are 1.8 times more likely to conserve. For NPC, utilities that notify via website are 2.5 times more likely to conserve. Also, utilities that have experienced a per-capita water use increase in the last five years are nearly 2.1 times more likely to adopt PC. Such increases may put a strain on existing infrastructure, and necessitate demand management through price signals.

Finally, in both PC and NPC models, Oklahoma and Florida utilities were significantly more likely to adoption conservation as compared to Tennessee (our baseline) or Arkansas. For PC, Oklahoma utilities were 5.0 times more likely and Florida utilities were 4.2 times more likely to adopt conservation; for NPC, Oklahoma utilities were 1.1 times more likely and Florida utilities were 6.7 times more likely. The dummy variable indicating a utility was from Arkansas was not statistically significant in either model. These results indicate that there may be inherent differences between states, perhaps due to state-level policy, population growth, or other factors that influence the adoption of PC and NPC, but are not captured by our models.

Water utility managers' attitudes and perceptions also play a large role for both PC and NPC. Managers were asked to indicate the primary factors that influence their rate schedule, and reasons for past rate increases. For PC, managers that indicate cost of delivery was the primary driver of the rate schedule were 1.5 times more likely to adopt conservation. For NPC, conservation adoption was more likely when managers indicated that consumer waste was the primary driver of the rate schedule. For PC, there were several reasons for past rate increases were statistically-significant: treatment costs (2.2 times more likely), utility maintenance (2.8 times more likely), and most notably conservation (17.0 times more likely). This indicates that an inclining block rate might help utilities cover costs of delivery and repair and maintenance costs more effectively than uniform rates or declining block rates. Conservation as a reason for past rate increases also played a large role in the adoption of NPC (6.5 times more likely). This result was not unexpected, since utilities that have considered conservation before should be more likely to adopt PC and NPC in the future.

Awareness of how changes in water pricing would impact water use also strongly influence the adoption of PC. Utilities that have conducted these elasticity studies were 3.4 times more likely to use PC. Knowing their customers price elasticity of water demand allows utilities to better understand the impacts of price changes on water use, and can help design a more effective inclining block rate.

Finally, managers' views on climate change impacts on water supplies have some influence on the adoption of NPC. Utilities are, on average, 0.5 times more likely to adopt NPC when its manager believes that climate change with significantly impact water availability in their area. Many managers specifically commented about the uncertainty of climate change on their water supplies and future planning.

Utilities' approach to future planning also influences PC and NPC. Adoption of PC was significantly influenced by utilities' planning on the following to meet future demand changes: seeking alternative non-traditional sources (i.e., graywater reuse; 2.7 times more likely), infrastructure expansion/replacement (2.2 times more likely), and managing demand (5.3 times more likely). For NPC, only seeking alternative source was significant (2.8 times more likely).

Finally, we asked managers to indicate what factors they viewed as primary barriers to adoption conservation. Only the inability to increase withdrawals from existing sources was a statistically-significant driver of conservation adoption. For PC, it increased adoption by 0.4 times while for NPC it increased adoption by 2.9 times. An explanation for this finding is that water managers believe the price elasticity of water is inelastic and an increase in price will not decrease use enough. Also, population growth was found not to be a primary barrier to meeting future demand. While large cities are growing in population, rural communities are decreasing. The large number of rural utilities in the survey can explain why, on average, population growth was not a statistically-significant barrier to meeting future demand.

Analysis of the results is ongoing, and additional models are being investigated. These may allow additional interpretation of interactions between several of the above variables. However, both the PC and NPC logit models performed well and provide important insight into factors driving the adoption of PC and NPC. For example, using the model results for PC, the type of utility most likely to adopt price-based conservation would be: (1) a small utility located in Oklahoma that purchases its primary source of water from other utilities; (2) a municipal utility in Florida that relies on groundwater as a primary source, and does not have a secondary source of water; (3) one that determines current rates largely based on cost of delivery, and has increased rates in the past primarily due to rising treatment costs and to encourage conservation; (4) utilities that have conducted an internal study to evaluate consumers' price elasticity of demand for water, suggesting that understanding customer demand might be important component in adopting PC; and (5) plans on accessing non-traditional sources, improving infrastructure and managing consumer demand for water to meet future demand.

The logit model for NPC had fewer statistically significant explanatory variables than PC, but still provides useful insight to utilities that were most likely to adopt NPC. Utilities with a high likelihood of adopting NPC would most likely be: (1) a municipality located in Florida and uses a website to notify customers about rates changes; (2) one that has changed the water rate in the past to send a conservation signal; and (3) considering using alternatives sources of water in the future, and is current withdrawing the maximum amount of water from its source, which suggest these utilities have nearly exhausted its primary water source. NPC programs are commonly used to manage short-term droughts, and are not always as straightforward as PC programs to implement. We suspect that utilities' decision makers can be hesitant to use these programs due to the cost, labor requirements, and uncertainty of success for these programs, which might explain the difficulty in predicting utilities adoption of NPC programs.

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Stream Depletion by Ground Water Pumping: A Stream Depletion Factor for the State of Oklahoma

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Title:
Stream Depletion by Ground Water Pumping: A Stream Depletion Factor for the State of Oklahoma

Principal Investigators:
Garey A. Fox, Ph.D., P.E., Department of Biosystems and Agricultural Engineering, Oklahoma State University; Mike Kizer, Ph.D., Department of Biosystems and Agricultural Engineering, Oklahoma State University

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SUMMARY TABLE OF STUDENT SUPPORT

Student Status	Number	Disciplines
Undergraduate	2	Biosystems and Agricultural Engineering
M.S.		
Ph.D.	1	Biosystems and Agricultural Engineering
Post Doc		
Total	3	Biosystems and Agricultural Engineering

ABSTRACT

Extracting ground water from pumping wells located adjacent to streams can reduce streamflow, a result that is known as alluvial well depletion. Primary factors influencing stream-aquifer interaction during alluvial well depletion are the hydrologic properties of the aquifer, the degree of penetration of the stream into the aquifer, and a potential streambed layer with a hydraulic conductivity different than the aquifer conductivity. Research over the past decade has developed analytical solutions for streams that account for more site-specific features but become mathematically complex. Evaluation of these analytical solutions using field data from multiple regions is needed to assess existing and recently proposed solutions' applicability and predictive capability.

At a well site located adjacent to the North Canadian River in central Oklahoma, a stream-aquifer analysis test was performed. Observation wells were installed between the stream and the pumping well and were instrumented with automated water level sensors to measure water levels every 5 minutes. During the stream-aquifer analysis test, a discharge well located approximately 85 m from the North Canadian River was pumped at a constant rate (2180 m^3/d) for 90 hrs. Predicted drawdown from several analytical solutions were fit to the measured drawdown to inversely estimate the aquifer transmissivity, T = 790 to 950 m^2/d, specific yield, S_y = 0.19 to 0.28, and streambed conductance, λ > 1500 m/d, and then to estimate stream depletion caused by the pumping well. The stream-aquifer analysis test suggested that the stream was behaving similar to a fully penetrating stream with streambed conductivity equivalent to the alluvial aquifer conductivity. For this system, simple analytical solutions were adequate to inversely estimate the aquifer and streambed hydrologic parameters, especially since early-time delayed yield effects were ignored. After only one day of pumping, estimated stream depletion ranged between 30 and 35% of the pumping rate. After five days of pumping, the estimated stream depletion was 60 to 70% of the pumping rate. These results highlight the intense degree of stream-aquifer interaction in this system, which should be accounted for in allocating future water rights.

Future work will measure the streambed conductivity, using falling-head permeameter tests and empirical equations based on grain-size distributions, in the North Canadian River at both the pumping well site and also in reaches upstream and downstream of the site. Also, a second pumping well site near Clinton, OK, on the Washita River has been instrumented. Data from stream-aquifer analysis tests are currently being analyzed from this site and streambed conductivity measurements will also be performed in the Washita. Finally, an automated solution tool is currently being developed to solve for stream depletion due to pumping wells relative to aquifer properties, the pumping well's location relative to the stream, and the pumping rate.

STREAM DEPLETION BY GROUND WATER PUMPING: A STREAM DEPLETION FACTOR FOR THE STATE OF OKLAHOMA

I. PROBLEM AND RESEARCH OBJECTIVES

Methodologies based on simple analytical solutions are widely applied in administering tributary groundwater rights (Spalding and Khaleel, 1991). For example, the U.S. Geological Survey standardized a procedure for analyzing the timing of flows between an aquifer and stream called the stream depletion factor (SDF). Jenkins (1968) originally developed the SDF in studying stream depletion by groundwater pumping. The SDF is defined as the time when the volume of stream depletion reaches 28% of the total volume pumped. Mathematically, SDF is expressed as

$$SDF = \frac{L^2 S}{T} \tag{1}$$

where L is the perpendicular distance from the pumped well to the stream [L], S is the storage coefficient or specific yield, and T is the transmissivity of the aquifer [L^2T^{-1}].

The SDF methodology makes several simplifying assumptions about the flow regime and stream-aquifer characteristics and, in general, makes use of the Theis (1941) solution. The Theis (1941) equation assumes an infinitely long, straight, completely penetrating stream in a homogeneous aquifer, as shown in Figure 1. Changes in water table elevations are assumed small compared to the saturated thickness of the aquifer, leading to the Dupuit flow assumption. No parameters account for a semipervious streambed layer. Applying the principle of superposition, image wells are used to simulate a constant head boundary condition at the stream, and drawdown is given by:

$$s_w(u) = \frac{Q}{4\pi T}\left\{W(u) - W(u_i)\right\} \tag{2}$$

where s_w is the drawdown in the semi-infinite domain [L], Q is the pumping rate [L^3T^{-1}], T is the transmissivity of the aquifer [L^2T^{-1}], u is the Boltzmann variable, and $W(u)$ and $W(u_i)$ are the well functions for the real and image well, respectively.

In addressing limitations of the Theis equation, Hantush (1965) developed an analytical model that considers the effects of a semipervious streambed, a common feature in many alluvial systems (Landon et al., 2001). The semipervious streambed was represented as a vertical layer of lower conducting material extending throughout the saturated thickness of the aquifer. The Hantush model was based on the principal of additional seepage resistance due to this semipervious layer. Seepage resistance extended the distance between the well and stream by an ‘effective distance’. Therefore, the streambed layer of lower hydraulic conductivity created a flow resistance, R, equal to the ratio between the hydraulic conductivity of the aquifer, K [LT^{-1}], and the streambed conductivity, K_{sb} [LT^{-1}], divided by the streambed thickness, M [L]. As discussed by Sophocleous et al. (1995) and Conrad and Beljin (1996), the Theis (1941) and Hantush (1965) analytical models fail to adequately represent the physical conditions representative of alluvial aquifer systems.

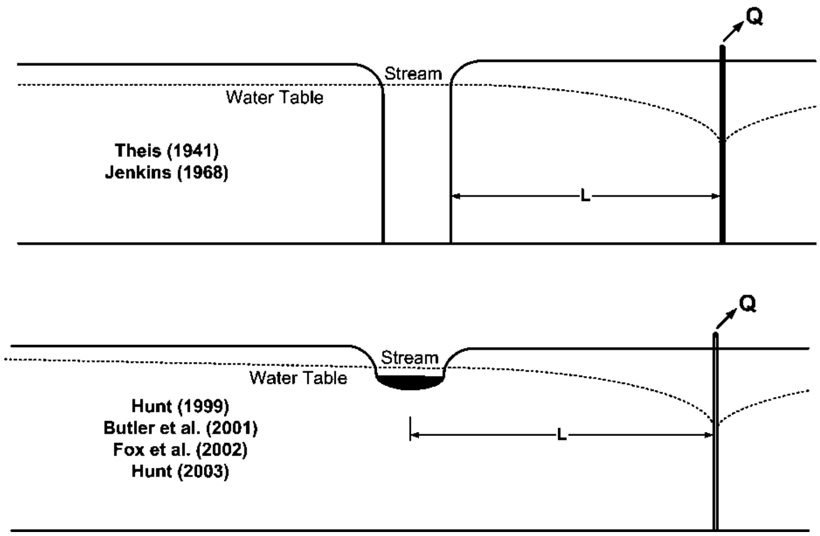

Figure 1. Hydrologic conditions modeled by numerous analytical solutions. Q is the constant discharge rate of the pumping well and L is the distance between the pumping well and stream.

Hunt (1999) developed an analytical model that incorporates streambed conductance and stream partial penetration in the simulation of a pumping well located near a stream, as shown in Figure 1. Hunt's model assumed a homogeneous, isotropic aquifer of infinite extent with Dupuit flow. The model also assumed that changes in water surface elevation due to pumping are small, and vertical and horizontal streambed cross-sections were small compared to the aquifer saturated thickness. Seepage flow rates from the river into the aquifer were assumed linearly proportional to the head gradient between the aquifer and stream dependent upon a streambed conductance parameter, λ [LT^{-1}]. Streambed conductance was a function of the streambed hydraulic conductivity. The product of the streambed conductance and the head gradient between the aquifer and river gave the stream leakage per unit length of river. Hunt derived both a streamflow depletion equation (3) and drawdown equation (4) applicable throughout the infinite domain:

$$\frac{Q_s}{Q} = erfc\left(\sqrt{\frac{SL^2}{4Tt}}\right) - \exp\left(\frac{\lambda^2 t}{4ST} + \frac{\lambda L}{2T}\right) erfc\left(\sqrt{\frac{\lambda^2 t}{4ST}} + \sqrt{\frac{SL^2}{4Tt}}\right) \tag{3}$$

$$s_w(x,y,t) = \frac{Q}{4\pi T}\left\{E_1\left[\frac{(L-x)^2 + y^2}{4Tt/S}\right] - \int_0^\infty e^{-\theta} E_1\left[\frac{(L+|x|+2T\theta/\lambda)^2 + y^2}{4Tt/S}\right] d\theta\right\} \tag{4}$$

where Q_s is the stream depletion rate [L^3T^{-1}], L is the distance between the well and the stream [L], E_1 is the well function, S is the aquifer storage coefficient, t is the time since the start of pumping [T], and x and y are the locations within the infinite domain with respect to a datum at the river on a perpendicular line with the well [L]. Additional solutions that expand in complexity have been proposed by Butler et al. (2001) for finite width streams in an aquifer of limited lateral extent, Fox et al. (2002) for finite width small streams, Hunt (2003) for semiconfined aquifers, and Chen and Yin (2004) for base flow reduction and stream infiltration.

The benefit of all of these analytical solutions is that tests can be conducted for simultaneously estimating aquifer and locally averaged streambed parameters in what has been termed a stream-aquifer analysis test (Hunt, 1999; Fox, 2004; Fox, 2007). The disadvantage of many of the recent solutions is that most are based on differential equations so mathematically complex that they require numerical inversion of Laplace transforms to derive a semi-analytical solution.

Another benefit of stream-aquifer analysis tests is that predicted streambed conductivity may better represent the spatially variable, average streambed conductivity as opposed to point, in-situ measurements. However, only a few stream-aquifer analysis tests have been documented in the literature: Hunt et al. (2001) in New Zealand, Nyholm et al. (2002) in Denmark, and Fox (2004) in eastern Colorado. Field data from multiple regions is needed to assess the applicability and predictive capability of simpler, more general solutions versus the more complex solutions. Therefore, the objective of this research was to perform a stream-aquifer analysis test at a well site along the North Canadian River in central Oklahoma for the purpose of evaluating the need for and applicability of numerous stream depletion equations.

II. METHODOLOGY

The field site was located just north of El Reno, OK, on the North Canadian River (Figure 2). The North Canadian River is a sand bed, partially penetrating (incised) stream that does not extend throughout the entire saturated thickness of the alluvial aquifer. The surface geology of the site is mostly composed of Quaternary alluvial sands and gravels. These deposits are both aeolian and fluvial in origin, usually no more than 15 to 20 m in thickness, and the width extends approximately 1.6 km from the North Canadian River. Driller’s logs in the area have reported mostly fine sand with interdispersed clay (ACOG, 2009). Ryder (1996) reports specific yield and hydraulic conductivity estimates of 0.29 and 48 m/d.

Observation wells were installed to a depth of approximately 8 m, constructed of Schedule 40 PVC, and had a 5 m screened section at the base. The observation wells were installed using a Geoprobe (Kejr, Inc., Salina, KS) drilling machine. Five observation wells were installed between pumping well 2 and the North Canadian River; three observation wells were installed between pumping well 26 and the North Canadian River (Figure 2). Drawdown and temperature were measured every 5 minutes using the automated water level loggers (HoboWare, Onset Computer Corp., Cape Cod, MA) installed in each observation well. One logger was also installed in the North Canadian River to monitor stream stage and temperature.

For several months prior to the stream-aquifer analysis test, pumping well 2 was pumped continuously; therefore, pumping well 26 was used for the stream-aquifer analysis test with the assumption of a constant, minimum interference between the wells. Pumping well 26, located approximately 85 m from the North Canadian River, discharged water at a constant rate of 2180 m^3/d for 90 hrs from October 18 to 22, 2009 after being off for approximately four days. The drawdown response due to this groundwater extraction was measured in observation wells F, G and H as shown in Figure 2. Spatial locations relative to a coordinate origin at the river and on a perpendicular line with the well are provided in Table 1.

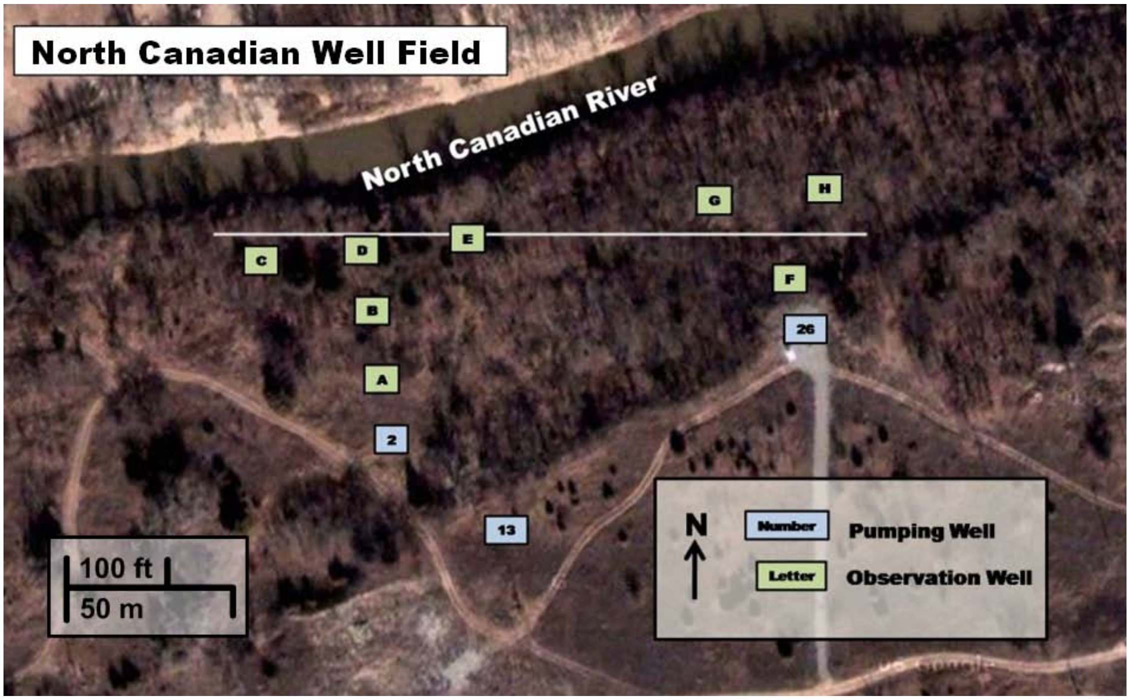

Figure 2. North Canadian River well field site. Observation wells (letters) were installed around two active pumping wells (#2 and #26). Pumping well #26 was utilized for the stream-aquifer analysis test.

Table 1. Coordinate locations of the pumping and observation wells utilized in the stream-aquifer analysis test along the North Canadian River. The origin of the coordinate system is at the river on a perpendicular line with the well.

Well Identification (Figure 2)	***x*** **(m)**	*y* **(m)**	***Q*** **(m^3/d)**
26	85	0	2180
F	70	0	---
G	41	-15	---
H	50	19	---

Predicted drawdown using the Hunt (1999) and Hunt (2003) solutions were fit to the observed drawdown measured in observation wells F, G, and H. The Hunt (1999) solution requires estimates of T, S_y, and λ, defined as the product of the streambed conductivity, K_{sb}, and the ratio between the width of the river, w, and the streambed thickness, M. The Hunt (2003) solution is for a semi-confined aquifer and also requires estimates of the storativity, aquitard permeability, aquitard saturated thickness, aquitard thickness beneath the stream, and the aquitard porosity. Parameter estimates for each case where derived by attempting to minimize the difference between the predicted and observed drawdown. A quantitative index based on an acceptance criterion as quantified by a normalized objective function (*NOF*) (Pennell et al., 1990; Hession et al., 1994) was utilized. The NOF is the ratio of the standard deviation of differences (*STDD*) to the overall mean (X_a) of the observed parameter. The NOF has been used in the past for model evaluation (Pennell et al., 1990; Hession et al., 1994; Fox et al., 2006). In general, 1%, 10%, and 50% deviations from the observed values results in NOF values of 0.01, 0.10, and 0.50, respectively. Inverse estimation was deemed acceptable when NOF approached 0.02 or 2% average deviation from the observed values.

For the Hunt (1999) solution which utilizes partial differential equations for confined flow as estimates for unconfined flow (valid when the drawdown is small compared to the saturated thickness), the fit was confined to the late-time drawdown data as delayed yield effects were neglected. This procedure is reasonable in cases where the goal is to predict aquifer and streambed parameters for long-term water management (Fox, 2004). Using parameter estimates, stream depletion due to ground water pumping during the stream-aquifer analysis test was predicted.

III. PRINCIPLE FINDINGS AND SIGNIFICANCE

For the stream-aquifer analysis test period, the initial gradient was directed from the stream and into the alluvial aquifer (i.e., a stream depletion condition), as shown in Figure 3. The initial hydraulic gradient was 0.017 m/m based on a transect from the stream through observation wells G and F.

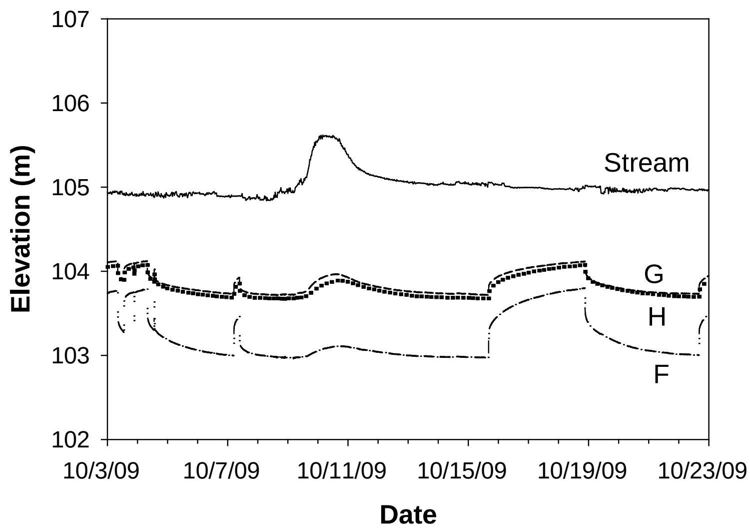

Figure 3. Water levels in the North Canadian River and observation wells during October 2009. The stream-aquifer analysis test was performed from October 18-22, 2009.

The Hunt (2003) solution for semi-confined flow was more difficult than the Hunt (1999) solution to fit to the drawdown data due to the complexity of the analytical solution and the number of variables to be inversely estimated. Since the focus was also on predicting streamflow depletion due to long-term ground-water pumping, the Hunt (1999) solution was fit to the late-time drawdown data, thereby neglecting delayed yield effects (Figure 4). Late-time drawdown data was typically greater than 1000 minutes based on an appropriate fit of the Hunt (1999) solution to the observed data within ranges of T and S_y that matched previous investigations in the ground water system. Inversely estimated T and S_y ranged between 790 and 950 m^2/d and 0.19 to 0.28, respectively (Figure 4). Descriptive statistics of the fit between observed and predicted late-time (i.e., t > 1000 minutes) drawdown data are shown in Table 2. In general, the NOF for all three observation wells were less than 0.02.

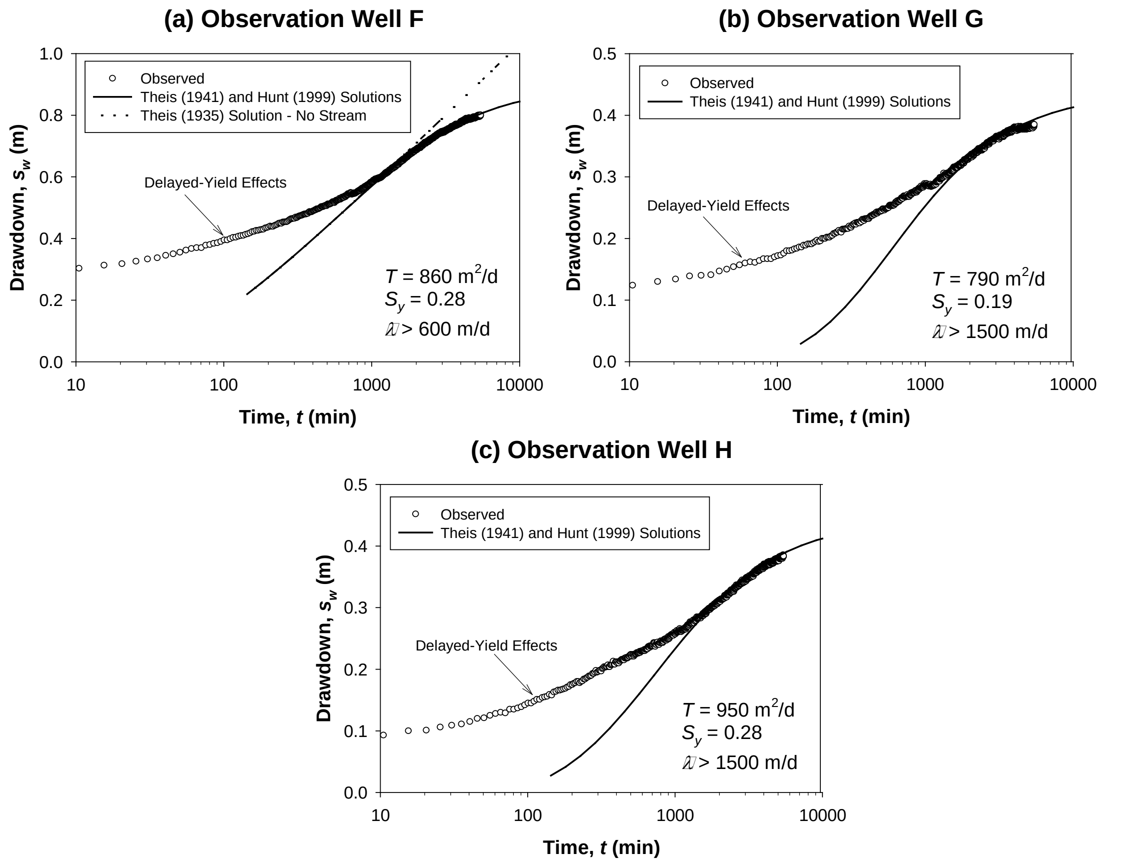

Figure 4. Inversely estimated aquifer transmissivity (T), specific yield (S_y), and streambed conductance (λ) derived from fitting the Hunt (1999) analytical solution to the observed drawdown during the stream-aquifer analysis test.

Estimates for λ suggested that the North Canadian River at this site was equivalent to a fully penetrating stream with no streambed conductivity resistance. Drawdown from observation well F was the first to be utilized and suggested that λ greater than 600 m/d was reasonable. As λ increased in the Hunt (1999) solution, equation (4) converged to the Theis (1941) solution for a fully penetrating stream with no streambed resistance (Figure 1). In fact, predictions by the Theis (1941) solution with image wells using the inversely estimated T and S_y closely matched the predictions by the Hunt (1999) solution with λ greater than 600 m/d, as shown in Figure 4a. Also included in this figure is the predicted drawdown response due to pumping the well without consideration for the stream (i.e., the Theis (1935) solution). It is apparent from this figure that the stream definitively provided a recharge source for the pumping well. Estimates of λ when using observations wells G and H, located closer to the stream, were even higher (i.e., greater than 1500 m/d) than corresponding estimates from observation well F. These observation wells provided data at locations closer to the river where the interaction of the stream and aquifer was more pronounced. This is one reason why Fox (2007) emphasized the use of multiple observation wells, including ones closer to the stream, when performing stream-aquifer analysis tests.

Table 2. Descriptive statistics of the fit between predicted and observed drawdown (late-time data) when using the Hunt (1999) solution. SSE = sum of squared errors; STDD = standard deviation of differences; X_a = average observed drawdown; NOF = normalized objective function.

Well Identification (Figure 1)	SSE	n	STDD	X_a	NOF
F	0.09	891	0.01	0.73	0.01
G	0.07	891	0.01	0.35	0.02
H	0.07	891	0.01	0.34	0.02

Estimated stream depletion based on the Hunt (1999) solution, i.e., equation (3), using the inversely estimated parameters from observation wells F, G, and H were as high as 30% to 35% of Q after one day of pumping and approached 60% to 70% of Q approximately five days after initiation of pumping (Figure 5). Since λ was relatively large, equation (3) simplified to the following:

$$\frac{Q_s}{Q} = erfc\left(\sqrt{\frac{SL^2}{4Tt}}\right) \tag{5}$$

For this reach, it is suggested that this equation should be used as a first estimate of stream depletion unless site-specific conditions (i.e., measurements of λ being small) suggest otherwise. Then, the full depletion solution, i.e., equation (3), should be used.

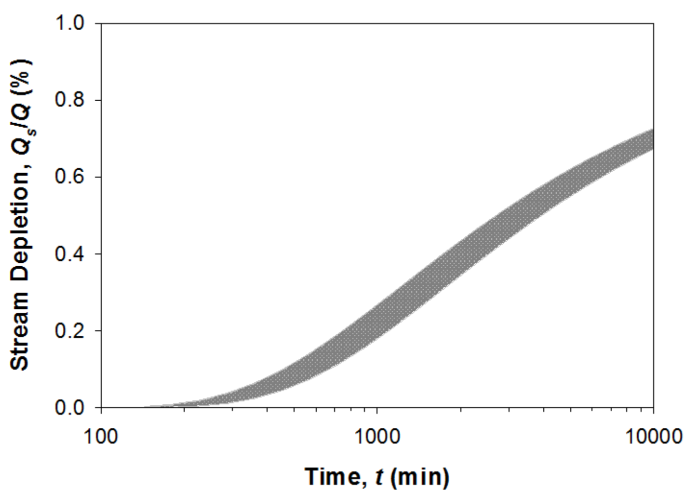

Figure 5. Estimated stream depletion due to pumping well 26 during the stream-aquifer analysis test. Stream depletion was estimated using the Hunt (1999) solution with inversely estimated aquifer and streambed parameters from observation wells F, G, and H (gray area).

IV. Conclusions and Future Work

The stream-aquifer analysis test conducted on the North Canadian River provided field data that supported the use of and the applicability of simpler drawdown and stream depletion analytical solutions. Support for the simpler solutions was largely based on the fact that the North Canadian River behaved similar to a fully penetrating stream with little to no hydraulic resistance provided by a streambed layer. Because of the large values of inversely estimated streambed conductance, simpler analytical solutions proposed by Theis (1941), Jenkins (1968) and Hunt (1999) were appropriate for the North Canadian River at this location. Even though the stream physically only partially penetrated into the alluvial aquifer, the lack of hydraulic resistance created a stream system that intensely interacted with the alluvial system. In fact, estimates of stream depletion were as high as 60 to 70% of the pumping rate after only five days of pumping.

It should be noted that inversely estimated parameters from the observed drawdown were based on only late-time drawdown data, thereby neglecting delayed yield effects of the unconfined aquifer. This was reasonable because of the interest on long-term (i.e., multiple days to months) pumping effects. With this realization, more complex solutions are not warranted for this system, which considerably simplifies the mathematical complexity of analytical solutions to be used and the number of parameters required to be estimated to parameterize the stream-aquifer interaction.

Future work will measure the streambed conductivity, using falling-head permeameter tests and empirical equations based on grain-size distributions, in the North Canadian River at both the pumping well site and also in reaches upstream and downstream of the site. Also, a second pumping well site near Clinton, OK, on the Washita River has been instrumented. Data from stream-aquifer analysis tests are currently being analyzed from this site and streambed conductivity measurements will also be performed in the Washita. Finally, an automated solution tool is currently being developed to solve for stream depletion due to pumping wells relative to aquifer properties, the pumping well's location relative to the stream, and the pumping rate.

V. Acknowledgements

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Quantification of water fluxes and irrigation use through remote sensing

Basic Information

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End Date:	2/28/2010
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Congressional District:	3, 4, 5
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Principal Investigators:	Baxter Vieux, Yang Hong

Publications

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3. M. Sagbohan, B. Vieux, Y. Hong, Sadiq Khan Quantification of Water Fluxes and Irrigation Use Through Remote Sensing. Governor s Water Conference, Oct. 2009, Oklahoma City, OK
4. Vieux, Baxter, Yang Hong, 2009, Quantification of Water Fluxes and Irrigation Use Through Remote Sensing, Oklahoma Water Resources Research Institute, Oklahoma State University, Stillwater, Oklahoma, 53.

QUANTIFICATION OF WATER FLUXES AND IRRIGATION USE THROUGH REMOTE SENSING

FINAL REPORT

Baxter E. Vieux, P.E., Ph.D.[1], Yang Hong, Ph.D[2] Fifame M. Sagbohan, B.S.[3], Sadiq Khan, M.S.[4]
[1]Joseph A. Brandt Professor
Director, International Center for Natural Hazards and Disaster Research
[2]Associate Professor
Associate Director, International Center for Natural Hazards and Disaster Research
[3]Graduate Research Assistant
[4]Ph.D Student
School of Civil Engineering and Environmental Science
120 David L. Boren, Suite 3630
University of Oklahoma
Norman, Oklahoma 73072

Collaborators:
David Dillon and Kyle Arthur, Oklahoma Water Resources Board
Kenneth Crawford, Oklahoma Climate Survey

Problem Statement:

Irrigation accounts for 80% of fresh water use in the U.S. and worldwide, the World Bank estimates 70% of fresh water use is for agriculture. The U.S. irrigates over 50 million acres of agricultural land and 32 million acres of recreational landscapes. In Oklahoma, irrigation is the largest water use accounting for 72% of Oklahoma's groundwater withdrawal (OWRB, 2007). The hydrologic conditions in irrigated areas of Oklahoma dictate that irrigation pumped from aquifers, and to a limited degree, streamflow, must supplement, or entirely satisfy the crop water requirements of cotton, com, wheat, soybeans, or other crops. As the Ogallala aquifer declines and climatic variability affects water supply from reservoir storage, resource conflicts will arise that exacerbate the difficult allocation of insufficient water resources. Evapotranspiration (ET) estimation from agricultural areas is important to water resource management as irrigation consumes the largest share in water use, globally as well as in Oklahoma. Without direct measurement of ET, only indirect computations based on a hydrologic water balance can identify the transport of water to the atmosphere. An additional difficulty arises when ET estimation is computed from atmospheric variables, because such measures represent potential ET and not actual ET. Traditional ET estimation methods typically provide potential or reference ET at points and do not contain information on the geographic variation of ET. Recent advances in satellite remote sensing of ET have opened frontiers in water management at local, regional, and global scales. Integrating satellite data with available ground based measurements by using a Simplified Surface Energy Balance (SSEB) method renders opportunities to utilize remote sensing data products for sustainable water management. This project has integrated MODIS (Moderate Resolution Imaging Spectroradiometer) and ground-based data to estimate actual ET for monitoring water use in agricultural areas and water flux from urban areas and lakes.

Currently, the Oklahoma Climate Survey OCS (Mesonet, 2007) estimates daily grass reference ET at each Mesonet site and interpolates the point values to entire state. Weakness of the ET Model is that it estimates reference ET not actual ET, and that the estimates are sparsely located across the State. The model applied by OCS assumes a uniform crop coefficient of 1.0 that is not representative of the diversity of plant types in an irrigated area or watershed, thus unable to obtain actual ET to account for spatial variability of water deficit/surplus. Second, both crop coefficients and actual *ET* are inherently variable because of crop variety, irrigation methods, weather, soil types, salinity and fertility, and/or field management that can be very different from the field used to derive the reference values. This project advances our understanding over previously established methods for estimating water flux because the ET measurement is distributed spatially and temporally, and is directly attributed to actual rather than potential water flux.

Project Objectives:

The theory and robustness of using of remote sensing for ET estimation has been demonstrated through the combination of SSEB and MODIS data products. Remote sensing ET algorithms mainly solve the Surface Energy Balance (SEB) of the land surface for latent heat flux (LE) at the time of satellite overpass. The central scientific basis of SEB methods is to compute the LE as the residual of the energy balance equation which is the approach taken in the proposed scope that follows. Remote sensing ET algorithms mainly solve the Surface Energy Balance (SEB) of the land surface for latent heat flux (LE) at the time of satellite overpass.

Through quantification of the water fluxes, actual ET and precipitation (P), we will validate the method for the expanded study areas. Once validated with eddy flux measurements, we will develop high resolution maps of water flux, aET - P, and examine the spatial trends and seasonality of water use associated with irrigation in agricultural and urban areas. Towards the goal of extending our study activities, we have planned three phases:

1. Agricultural irrigation evaluation. Evaluation of the ET estimation accuracy will be accomplished in two agricultural counties, Texas and Jackson (Lugert-Altus) where irrigation demand for water resources is high. The two counties represent two distinctly different geographic locations in terms of climate, 10 inches of precipitation in Texas County, and 36 inches annually in Jackson. An improved remote sensing ET algorithm will be calibrated and validated to provide actual ET estimates for monitoring irrigation water usage taking into account the specific study area precipitation, climate and cropping practices.
2. River basin and selected reservoir water flux estimation. We will compute actual ET and water fluxes for purposes of refining our algorithm for the lake and river basin study area.
3. Water fluxes in the urban areas of Oklahoma City and Tulsa.

Students supported by this program

Student Status	Number	Disciplines
Undergraduate	0	
M.S.	1	Civil Engineering/Water Resources Engineering
Ph.D.	1 (partial support)	Geography
Post Doc	0	
Total	2	

Methodology:

Water is taken up by plants and crops and transpired to the atmosphere through evapotranspiration, also called consumptive use. Knowing how much water evaporates from land surfaces to atmosphere can help in estimating water use and availability for water planning purposes. Actual evapotranspiration (aET) can be measured through remote sensing derived from the NASA/MODIS satellite and ground measurements. Traditional evapotranspiration (ET) estimation methods such as pan or atmospheric measurements usually provide potential ET at specific points, but not as spatially distributed ET. Further, these methods only provide potential ET (pET) and not actual ET (aET), which is limited by availability of soil moisture or free water. The robustness of aET estimation using remote sensing is demonstrated with application to irrigation water use in Oklahoma including Texas County, metropolitan areas, and the Altus-Lugert Irrigation District.

Principal Findings and Significance:

Water fluxes for irrigated areas of Texas County and Lugert-Altus Irrigation District, for urban areas of Tulsa City, Oklahoma City and for Lake Thunderbird and Texoma were successfully estimated over a two year period, 2007-2008. Using MODIS data and precipitation data, irrigation water use was computed for Texas County, Lugert-Altus District, Oklahoma City area and the City of Tulsa. In Texas County, it was

found that about 127,892 ac-ft and 49,171 ac-ft were used respectively in 2007 and 2008. The wide variation is due to differences in precipitation for the two years in irrigated areas of the county. In the Lugert Altus District, irrigation water use was estimated to be 37,072 ac-ft and 42,438 ac-ft, respectively for 2007 and 2008. Water flux over urban areas in 2008 was found to be 29.53 inches in Tulsa, and 32.34 inches in Oklahoma City in 2007, and 34.75 inches and 40.94 inches. The validation of the results found that the accuracy of the method produced reasonable amounts of water flux that compared well with pan evaporation and crop water usage.

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1. Introduction

As demand for water increases, water managers need to know how much water is actually consumed in agriculture. This knowledge can help in the reduction in agricultural water use in areas of scarce supplies so that water can be released for other uses. Critical to any irrigation management approach is an accurate estimate of the amount of water applied to a field. Various ways are used for such estimation. Some methods use the water balance approach and others base their approach on the flow rate, the total time of irrigation and the area irrigated. The flow rate, total time of irrigation and the area irrigated approach using Equation (1):

$$Q \times t = d \times A \qquad (1)$$

Where **Q** is the flow rate, in cubic feet per second (cfs), **t** is the set time or total time of irrigation (hours), **d** is the depth of water applied (inches) and **A** is the area irrigated (acres). However, because irrigation water, Q, may not be adequately metered at all farms, indirect methods of estimating water use would be attractive. The approach used in this study, the water balance approach, accounts of the inputs and outputs of water over a specified area, whether it is an agricultural field, watershed, or continent, the water balance can be determined by calculating the input, output, and change in storage of water at the Earth's surface. The general water balance equation is shown as Equation (2) :

$$P - R - E - T - G = \Delta S \qquad (2)$$

Where **P** is the Precipitation, **R** is the Runoff, **E** is the Evaporation, **T** is the Transpiration, **G** is the Groundwater and, **ΔS** is the change in storage. Evaporation and Transpiration can be combined to evapotranspiration (ET). This study uses precipitation and evapotranspiration for the water balance approach to quantify the water fluxes and irrigation use. In fact, the major input of water is from precipitation, and output is evapotranspiration in the study areas. Different methods have been developed to estimate evapotranspiration from remote sensing data. In this study, ET has been calculated using a model that was developed called Mesonet/Modis ET (M/M-ET) described by Khan et al. (in press).

1.1. Statement of Critical Regional and State Water Problem

Throughout the world, irrigation is one of the largest consumers of water. Almost 60 percent of all the world's freshwater withdrawals go towards irrigation uses (USGS, 2010). In many Western States, agriculture accounts for 80 percent of the Nation's consumptive water use and over 90 percent of ground and surface water (ERS/USDA, 2004). In Oklahoma, after public water supply that counts for 41% of total of water use, irrigation accounts for 32%. Groundwater is a predominant source, and accounts for 73 percent of total irrigation water use in Oklahoma (OWRB, 2010). Climatic conditions in irrigated areas of Oklahoma dictate that irrigation water pumped from aquifers and to a limited degree, streamflow, is used to supplement or entirely satisfy the crop water requirements of cotton, corn, wheat, soybeans, and other high value crops. Knowledge of crop water use in high-use areas provides useful planning information for water planning, especially in Texas County supplied by the Ogallala Aquifer (High Plains), and in the Lugert-Altus Irrigation District, and water flux in urban areas. Understanding water use in these areas is critical to understanding where water is consumed in the state, and supports planning efforts.

1.2. Study Background

1.2.1. Remote Sensing: A Good Way To Quantify Water Fluxes and Irrigation

Remote sensing can assist in improving the estimation of the distribution of evapotranspiration. Consequently, it can help in a sustainable water resources management in large cultivated areas for irrigation purposes. Evapotranspiration is one of the main components of the water cycle. However, its estimation is difficult to achieve in practice because actual evapotranspiration cannot be measured directly and varies considerably in time and space. A large number of empirical methods have been developed over the last 50 years worldwide to estimate evapotranspiration from different climatic and meteorological variables (Tsouni et al. 2008).

1.2.2. Previous Study

Actual evapotranspiration can be measured from remotely sensed images from the NASA satellite derived estimates as demonstrated in the current study. Evapotranspiration is among the most important processes in the hydrologic cycle and considered as a critical component in diverse disciplines such as those involved in water resource management, agriculture, ecology, and climate science. Estimation of spatially distributed ET from agricultural areas is important as irrigation consumes the largest share in water use (Glenn et al., 2007; Shiklomanov, 1998). It has been found that in arid and semi arid biomes, around 90% or more of the annual precipitation can be evapotranspired, and thus ET determines the freshwater recharge and discharge from aquifers in these environments (Huxman et al. 2005). Moreover, it is projected that climate change will influence the global water cycle and intensify ET globally (Meehl et al., 2007; Huntington et al., 2006), consequently impacting the scarce water resources.

Similarly, reliable ET estimates are crucial for efficient use of water resources, especially in agricultural areas for water management (Gowda et al., 2008; Bouwer et al., 2007). Methods of ET estimation provide potential or reference ET. Sometimes crop ET is derived as a product of weather based reference ET and crop coefficient (Kc) at points, rather than spatiotemporal information about actual ET (Allen et al. 2005).

Satellite remote sensing for ET estimation has become a pragmatic approach, due to the availability of remote sensing data and development of various modeling techniques. Because remotely sensed data have the advantage of a large area coverage, frequent updates and consistent quality, remote sensing based ET estimation has been a subject of many studies (Jackson, 1986; Kuittinen, 1992; Kite and Pietroniro, 1996; Stewart et al. 1999; Rango and Shalaby, 1998; Mu et al. 2007; Sobrino et al., 2007; Santanello et al., 2007; Wang et al., 2007). Although several recent ET models only use remote sensing data for ET estimation (Jiang et al., 2004; Nishida et al., 2003; Norman et al., 2003), integrating meteorological field observations and remote sensing data with optimum spatial and temporal resolution can overcome many of the shortcomings associated with low spatial coverage of field scale models and low temporal resolution of satellite data products. Cost effectiveness and easy implementation can be an added advantage. Thus, over the years various ET models have been developed that use the remote sensing and ancillary surface and ground-based observations (Choudhury, 1994; Seguin, 1994; Jiang and Islam, 2001; Senay et al., 2007). Surface Energy Balance Algorithm for Land (SEBAL) is described in Bastiaanssen et al.1998, 2005 and later METRIC (Mapping EvapoTranspiration with high Resolution and Internalized Calibration) is an ET estimation model developed and applied by the University of Idaho, USA (Allen et al. 2007). Subsequent applications in ET estimation have opened frontiers in agricultural water use and groundwater resources management at different scales and in diverse climates.

These developments in remote sensing of ET have been applied in the western U.S. and many other parts of the world (Allen et al., 2007). However, most of previous applications have been retrospective in nature (Tang et al., 2009) in part because of the lack of the timely availability of satellite images in relatively frequent revisit frequency, e.g. Landsat 16-day. Furthermore, many in-situ ground observations do not provide data in real-time or with sufficient update frequency. Although the retrospective ET estimates can be useful in modeling studies, they cannot aid operational water management decision-making in real-time.

With the availability of MODIS products twice-daily and well-distributed environmental monitoring stations from the Oklahoma Mesonet that has a 5-minute acquisition frequency, Oklahoma provides a unique setting to develop and application of satellite-based ET estimation. For the past decades, the primary method for estimating ET relied on site-based weather station measurements, which are inadequate to monitor the spatial variability of ET over large regions and only focus on potential rather than actual ET. Therefore, we focus on estimation of daily actual ET on a large scale in Oklahoma and apply it to understanding water use and fluxes from urban areas, and lakes.

1.3. Study Area

There are six areas in Oklahoma considered in this study. They are 1) Texas County, 2) Altus-Lugert Irrigation District, 3) City of Tulsa, 4) Oklahoma City, 5) Lake Thunderbird, and 6) Lake Texoma. The location of these study areas are shown in Figure 1. A range of climatic conditions are represented among the study areas with Texas County and the Lugert-Altus Irrigation District located in arid conditions where potential ET greatly exceeds actual ET making irrigation necessary for most crops. While Tulsa is the farthest east with a subhumid climate, potential ET still exceeds actual ET.

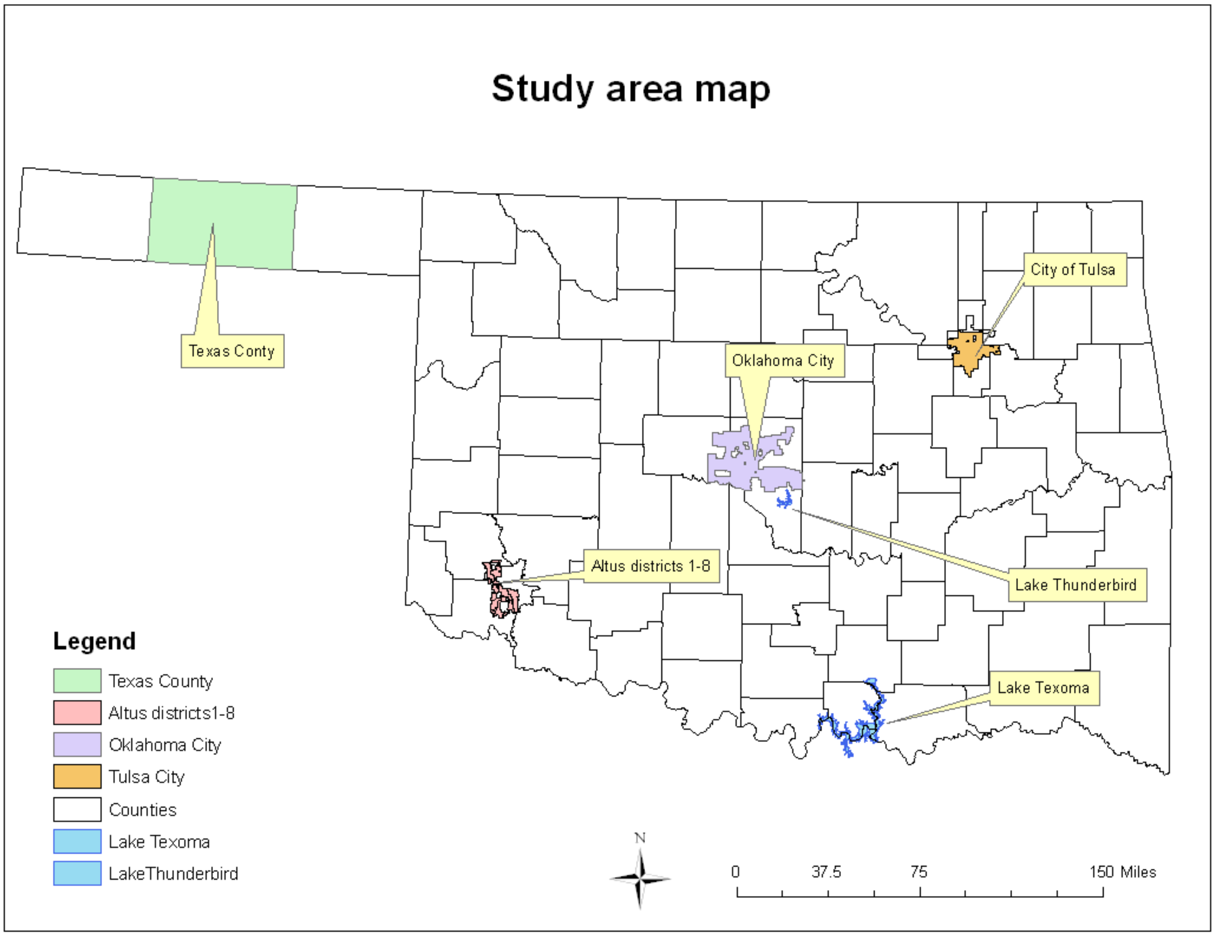

Figure 1: Map of Oklahoma showing study areas

1.3.1. Texas County

Agriculture in Texas County is largely supported by irrigation from the Ogallala Aquifer. The average farm size is 1179 acres. About 23.43% of the land in these farms is harvested cropland with 55.02% as irrigated harvested cropland of land in farms. The majority of the farms, 84.93%, are operated by a family or individual. The National Agricultural Statistics Service (NASS) estimates that there were 81,633 acres of corn harvested for grain, 179,027 acres of wheat harvested for grain, and 45,244 acres of sorghum harvested for grain, in 2007 in Texas County. (USDA/NASS, 2009)

1.3.2. Altus-Lugert District

The Lugert-Altus Irrigation District, also known as W. C. Austin Project, was completed in 1946 by the Bureau of Reclamation (BOR) for irrigation, flood control, municipal water storage, fish and wildlife conservation and recreational benefits. Altus Lake, which serves as the source of water to the District, has a contributing drainage area of 2,515 sq. miles. It receives its waters from the North Fork of the Red River and its tributaries. Three principal canals – the West canal, the Ozark canal, and the Altus canal along with their laterals, distribute water from the Altus Lake to approximately 500 diversions points. Water released through these canals is tabulated and was used in this analysis. Water flows throughout the District by gravitational flow, crossing the North Fork of the Red River and several state highways through siphons. The District is subdivided into eight sub-districts, called ditchrider-districts. The OWRB (2001a) study focused on districts 1 to 8 and estimates the canal losses and other hydrologic quantities. The irrigated area of the District is approximately 26 miles long by 14 miles wide (OWRB, 2001a). The irrigated area varies from year to year depending crops planted; however, the geographic area used in this study for computation of irrigation water use is estimated to be 89,817acres (OWRB, 2001a).

1.3.3. Urban Areas of Oklahoma City and Tulsa

The metropolitan area of Oklahoma City is a large urban region located in the central part of the state of Oklahoma. It contains the state capital and principal city, Oklahoma City and covers seven counties. The Tulsa Metropolitan Area is located in Northeastern Oklahoma. The area used in this analysis consists of the corporate boundaries for the two metropolitan areas from the Center of Spatial Analyst of the University of Oklahoma (CSA), which were estimated with ArcGis to be 397,908 and 128,782 acres for Oklahoma City and Tulsa, respectively (CSA, 2010).

1.3.4. Lake Texoma

Lake Texoma is one of the largest reservoirs in the United States, the 12th largest Corps of Engineers (USACE) Lake. Lake Texoma is formed by Denison Dam on the Red River in Bryan County, Oklahoma, and Grayson County, Texas, about 726 miles upstream from the mouth of the river. It is located at the confluence of the Red River and Washita Rivers. The dam site is approximately 5 miles northwest of Denison, Texas, and 15 miles southwest of Durant, Oklahoma. The drainage area above the dam of the watershed is 39,719 square miles. While the lake surface area can vary due to inflow and releases from the reservoir, however, the area considered in computation of lake evaporation was estimated with ArcGis as 59,015 acres, corresponding to normal pool elevation for its Oklahoma part (OWRB, 2004).

1.3.5. Lake Thunderbird

Lake Thunderbird, located in Cleveland County in central Oklahoma, serves as a water supply for the City of Norman, Midwest City, and Del City. The Norman Dam was constructed in 1965 and is managed by Central Oklahoma Master Conservancy District. Lake Thunderbird has 76,648 acre feet of capacity assigned to flood control and surcharge capacity of 171,300 acre-feet. The 2001 bathymetric survey conducted by the OWRB determined Lake Thunderbird to have a maximum depth of 58 feet, mean depth of 15.4 feet, surface area of 5,439 acres and volume of 105,838 acre-feet (OWRB, 2001b).

2. Methodology

2.1. Study Dataset

Data required for computation of actual ET include MODIS sensor data, Mesonet measurements of potential ET, and rainfall. The rainfall data is spatially distributed estimates produced from radar and rain gauge and is generated from the ScourCast system operated for the Oklahoma Department of Transportation (Vieux, 2008). Additionally, land cover data, pan evaporation data from COMCD, and study area boundaries were assembled to accomplish the analysis required for this study.

2.1.1. Rainfall Data

The rainfall data was produced by the ScourCast system, which performs continuous distributed watershed model simulation and rainfall monitoring for bridges that are subject to scour. ScourCast provides continuous rainfall at 2x2 km resolution and at 15-minute updates, and made available for this study. A radar mosaic is formed from 13 S-band radars and operational gauge-correction using 120 rain gauges as shown in Figure 2 below.

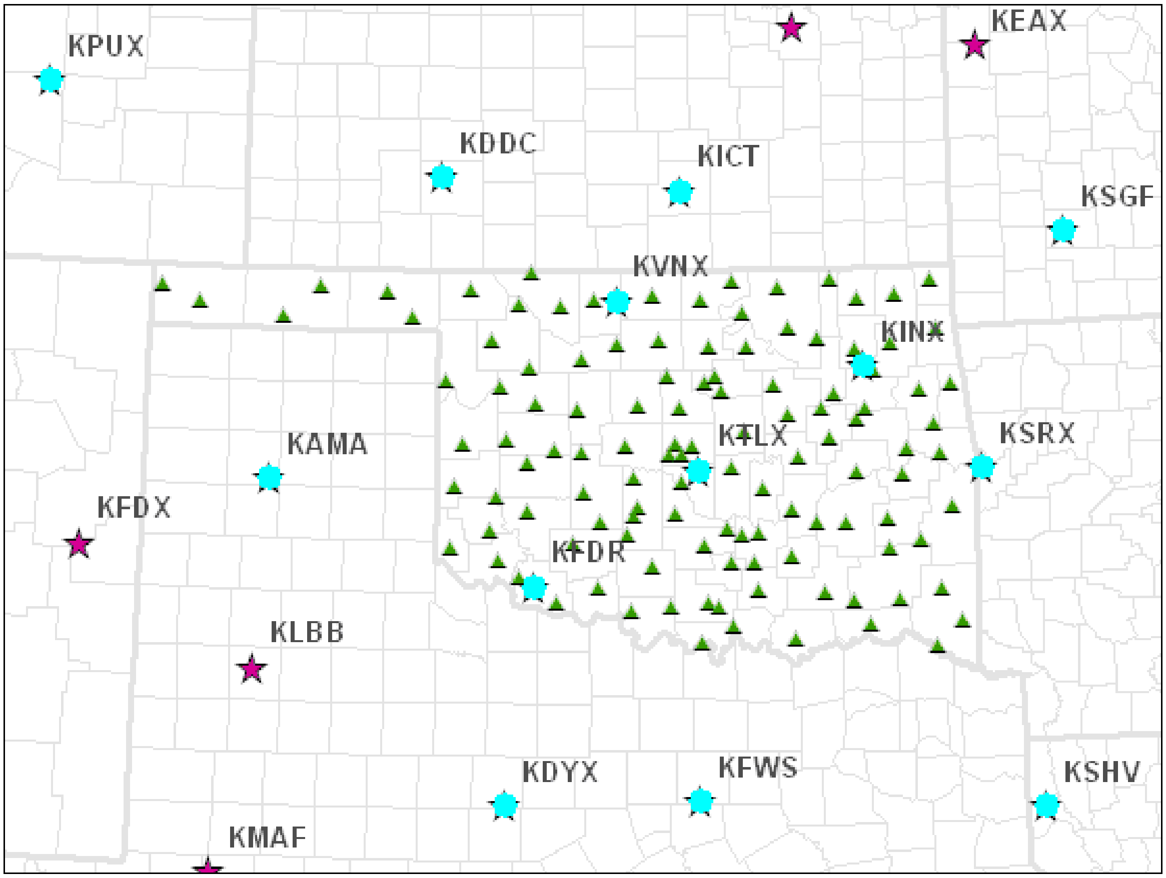

Figure 2: ScourCast observational network composed of 13 NWS Radars and 120 Oklahoma Mesonet Rain Gauges

2.1.2. Land Cover

The land cover data includes the National Land Cover Dataset (NLCD) from USGS Land Cover Institute and Cropland Data Layer (CDL) from National Agricultural Statistics Service (NASS) on USDA data gateway (USDA, 2010). The National Land Cover Database 2001 (NLCD, 2001) was compiled across all 50 states and Puerto Rico as a cooperative mapping effort by USGS. This land cover database has been created using mapping zones and contains standardized land cover components. The NLCD layer has sixteen classes of land cover that were modeled over the conterminous United States at a 30m cell size with a 1 acre minimum mapping unit. This dataset is used in this study to calculate actual evapotranspiration. Figure 3 shows the Anderson Classification scheme for the state of Oklahoma.

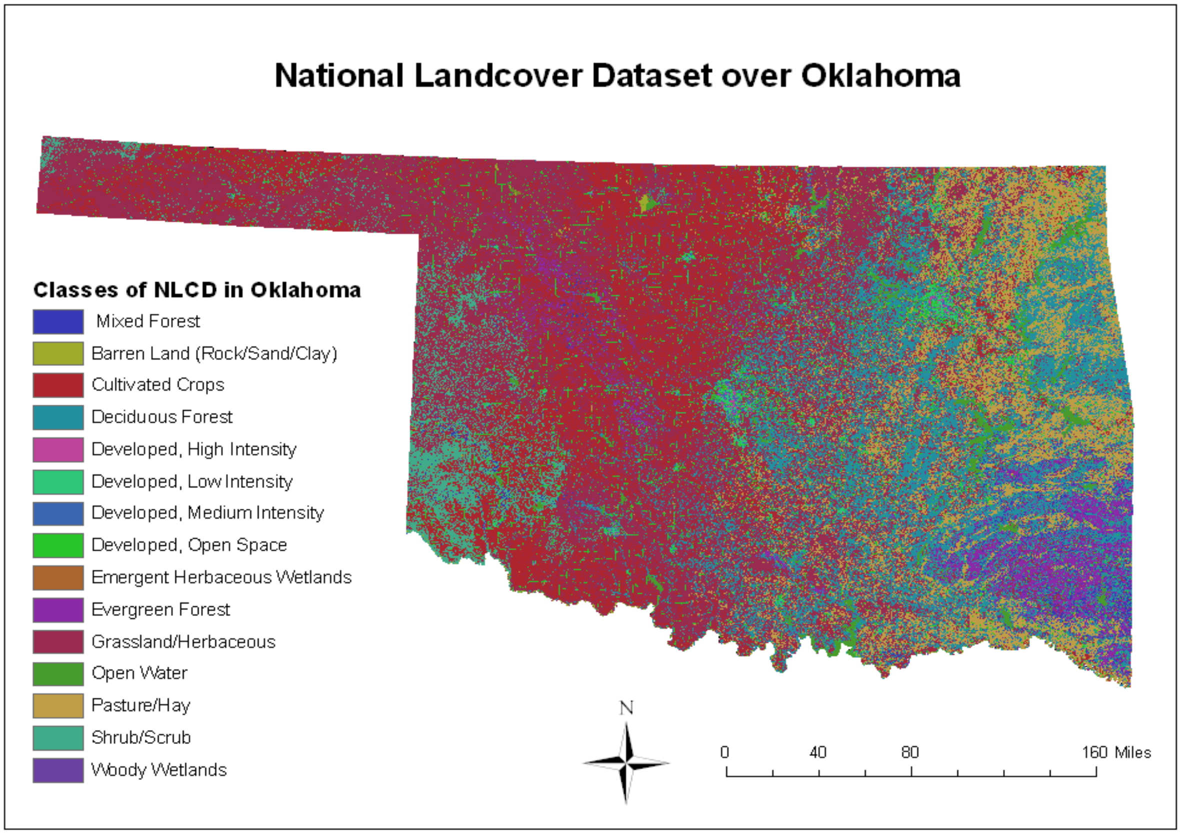

Figure 3: National Land Cover Dataset over Oklahoma

Each year, USDA develops a Cropland Data Layer built upon the NASS traditional crop acreage estimation program, and integrates collected ground survey data with satellite imagery to create an unbiased statistical estimator of crop area at the state and county level. The CDL was used in this study to identify irrigated areas during the study years of 2007 and 2008. The CDL for Oklahoma is shown in Figure 4 for the year 2007.

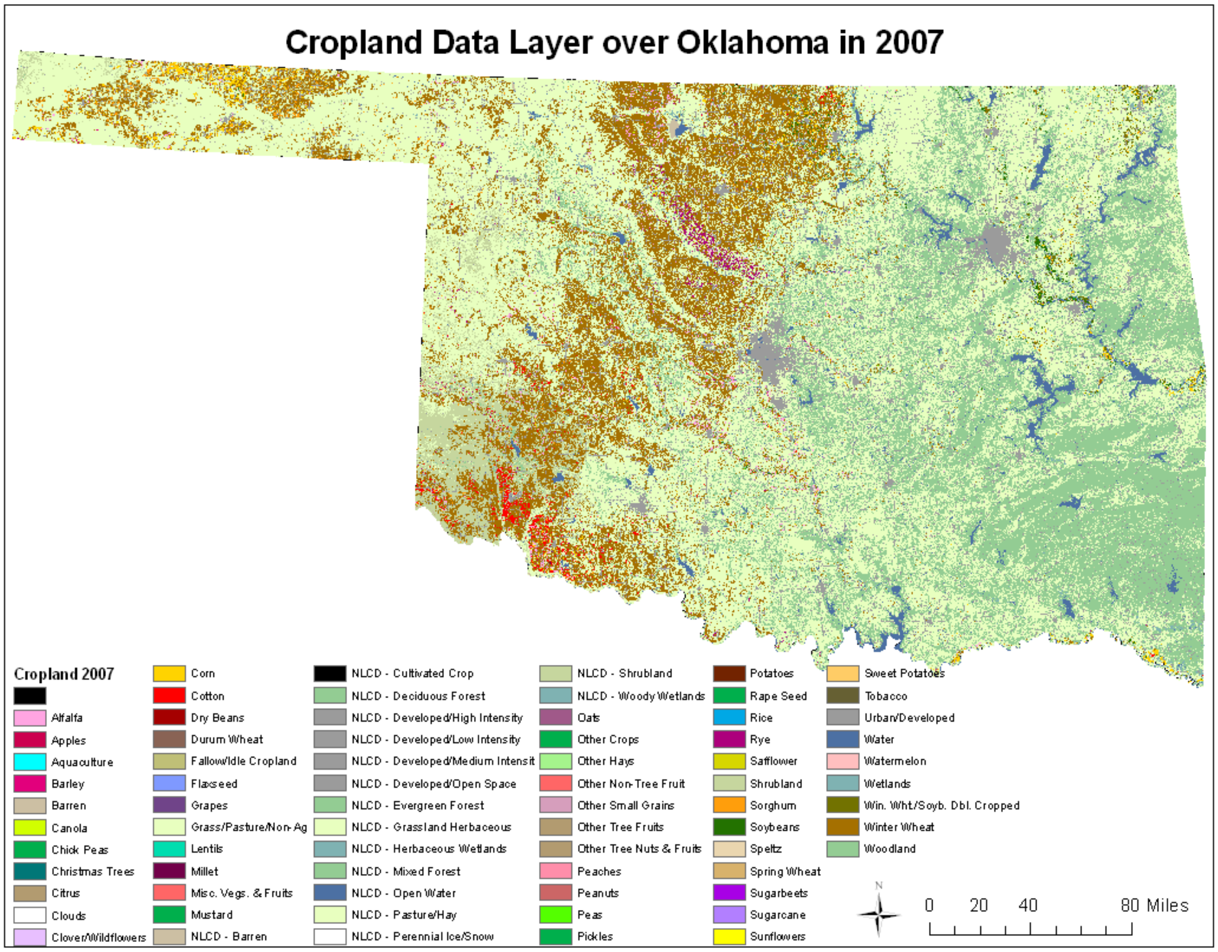

Figure 4: Cropland Data Layer over Oklahoma in 2007

2.1.3. Oklahoma Meteorological Observations: Mesonet

The Oklahoma Mesonet is a network of environmental monitoring stations jointly managed by the University of Oklahoma (OU) and Oklahoma State University (OSU). Established as a multipurpose network, it operates more than 120 automated surface observing stations covering the state of the Oklahoma and measures comprehensive meteorological, hydrological, and agricultural variables since the early 1990's. These monitoring sites have collected over 3,750,000,000 observations since January 1st, 1994 (McPherson et al., 2007). At each site, the environment is measured by a set of instruments located on or near a 10-meter-tall tower. The measurements are packaged into "observations" every 5 minutes; then the observations are transmitted to a central facility every 5 minutes, 24 hours per day year-round. The Oklahoma Climatological Survey (OCS) at OU receives the observations, verifies the quality of the data and provides the data to Mesonet customers. It only takes 5 to 10 minutes from the time the measurements are acquired until they become available to the public.

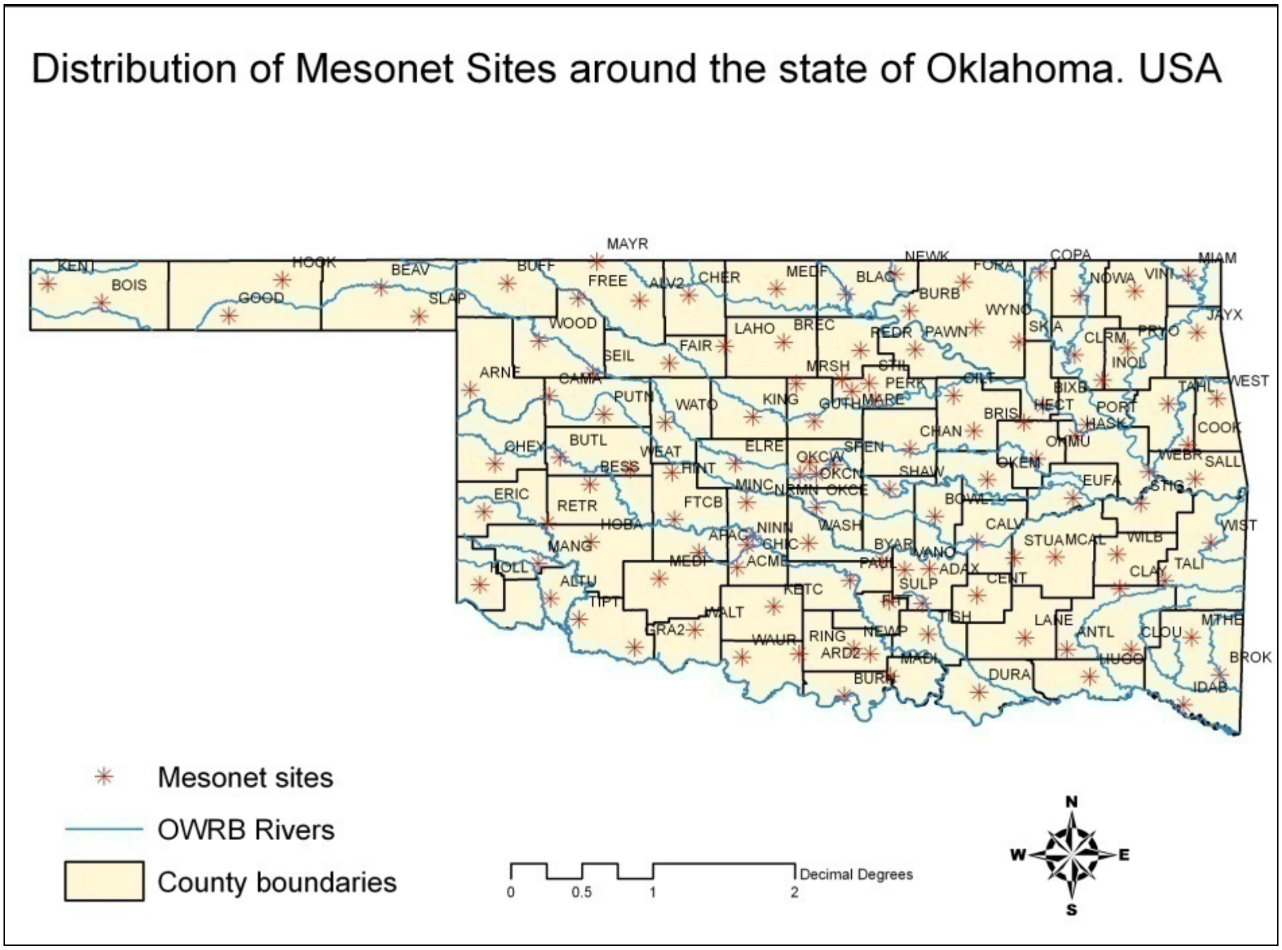

Figure 5: Oklahoma Mesonet monitoring stations (red asterisks) with station ID's.

2.1.4. Satellite Remote Sensing Data

The MODIS sensors, with 36 spectral bands (20 reflective solar and 16 thermal emissive bands), provide information regarding vegetation and surface energy (Justice et al. 2002), which can be used to develop a remotely sensed ET model (Mu et al. 2007). ET-relevant MODIS data used in this study are listed in (Table 2). Wan and Li (1997) described the retrieval of MOD11 land surface temperature (LST) and emissivity from MODIS data. Detailed information about MOD09 surface reflectance products is provided in Vermote et al. (1997) and Xiong et al. (2007). The algorithm for retrieving the Vegetation Index (MOD13) is presented by Huete et al. (2002). The computation of broadband Albedo (MOD43B3) by integrating bi-hemispherical reflectance data modeled over MODIS channels 1-7 (0.3-5.0 um) is explained in Schaaf et al. (2002). All NASA MODIS land products include so called Quality Assessment Science Data Sets (QA-SDS), which considers the atmospheric conditions in term of cloud cover and aerosol content, algorithm choices, processing failure, and error estimates (Colditz et al. 2006). These data products were extracted and processed from the Land Processes Distributed Active Archive Center (LP DAAC) at the USGS EROS Data Center, with the standard Hierarchical Data Format (http://LPDAAC.usgs.gov).

Table 1: ET-Relevant NASA MODIS data products

Product ID	Layer	Spatiotemporal resolution	MODIS QA-SDS[a] Analysis (Quality flags passed)
MOD11A2	Land Surface Temperature (LST) Emissivity View Angle Recording time	1-km[b], overpass 1-km, overpass 1-km, overpass 1-km, overpass	General quality: good
MOD13Q1	Vegetation index NDVI	1-km, 16-day	quality: good ~ perfect mixed clouds: no
MOD43B3	Albedo	1km, 16-day	Quality: good and acceptable Snow: no
MOD09Q1	Red reflectance NIR reflectance	250m, 8-day	Quality: good Clouds: clear Band quality: highest
MOD15A2	Leaf Area Index (LAI)	1km, 8-day	Quality: good Cloud: clear or assumed clear
MOD12Q1	Land Cover Type	250m, annual	Quality: good

[a]*Quality Assessment Science Data Sets*
[b]*The swath products were gridded using the MODIS reprojection tool (MRT)*
[c]*The view angles were analyzed to remove effects from scan geometry caused by increasing IFOV towards the edges of the scan lines*

2.1.5. Study Areas Boundaries

The study area's boundaries were downloaded on the Center for Spatial Analysis of the University of Oklahoma (CSA) website. These boundaries were downloaded as shapefiles that can be added to ArcGis.

2.2. Data Processing

2.2.1. Rainfall Data

The rainfall data have been processed from 15 minutes incremental timesteps and aggregated to daily and monthly using Matlab scripts and mapped with ArcGis. The maps of precipitation are then sampled within the same geographic coordinate system as the aET.

2.2.2. Reference Evapotranspiration and Actual Evapotranspiration

Khan et al., 2009 developed the Mesonet/Modis-ET (M/M-ET) algorithm, which solves the Surface Energy Balance (SEB) of the land surface for latent heat flux (LE) at the time of satellite overpass and extrapolate instantaneous LE to daily ET values. The central scientific basis of SEB methods is to compute the *LE* as the residual of the energy balance equation:

$$LE = R_n - H - G \tag{3}$$

Where the available net radiant energy, Rn (Wm^{-2}), is shared between the soil heat flux G and the atmospheric convective fluxes, sensible heat flux H and latent heat flux LE, which is readily converted to ET. The Rn and other components (H and G) of SEB can be derived through remote sensing information and surface properties such as albedo, leaf area index, vegetation cover, and surface temperature (Ts). The following components of energy balance were solved and are explained here.

2.2.2.1 Net Radiation (Rn)

Rn is computed by subtracting all outgoing radiant fluxes from all incoming radiant fluxes and includes solar and thermal radiation. This is shown as Equation 4.

$$R_n = RS{\downarrow} - \alpha RS{\downarrow} + RL{\downarrow} - RL{\uparrow} - (1 - \varepsilon_o)RL{\downarrow}$$

(4)

Where RS↓=incoming short-wave radiation (Wm^{-2}); α=surface albedo (dimensionless); RL↓=incoming long-wave radiation (Wm^2); RL↑=outgoing long-wave radiation (Wm^2); and εo=broad-band surface thermal emissivity (dimensionless). The (1 −εo) RL↓ term represents the fraction of incoming long-wave radiation reflected from the surface.

2.2.2.2 Soil Heat Flux (G)

Soil Heat Flux (G) is the rate of heat storage in the soil and vegetation due to conduction. General applications compute G as a ratio G/Rn using an empirical equation by Bastiaanssen (2000) representing values near midday as shown in Equation 5.

$$G = (T\text{s} - 273.16)\ (0.0038 + 0.0074\alpha)\ (1 - 0.98\text{NDVI}^4)\ R_\text{n} \quad (5)$$

Where Ts is surface temperature (K), and α is the surface albedo. The Normalized Difference Vegetation Index (NDVI) is used to predict surface roughness and emissivity.

2.2.2.3 Sensible Heat Flux (H)

Sensible Heat Flux (H) is defined by the bulk aerodynamic resistance equation, Equation 6, which uses aerodynamic temperature (T_{aero}) and aerodynamic resistance to heat transfer (r_{ah}):

$$H = \rho_{air}\ Cpa\ (T_{aero} - Ta)\ /\ rah \quad (6)$$

In the bulk aerodynamic resistance equation, ρ_{air} is air density (kg m^{-3}), Cpa is specific heat of dry air (1004 J kg^{-1} K^{-1}), Ta is average air temperature, (K), T_{aero} is average aerodynamic temperature (K), which is defined for a uniform surface as the temperature at the height of the zero plane displacement (d, m) plus the roughness length (Zoh, m) for sensible heat transfer, and rah is aerodynamic resistance (s m^{-1}) to heat transfer from Zoh to Zm [height of wind speed measurement (m).

2.2.2.4 From instantaneous ET_i to daily accumulated ET

At the instant of the satellite image, Latent Heat (LE) is calculated for each pixel from Equation (3-6) and is converted to instantaneous ET (ET_{inst}) in mm h^{-1} by dividing LE by latent heat of vaporization, Equation 7:

$$ET_{inst} = (3600 \times LE) / (\lambda\ \rho_w) \quad (7)$$

Where ρ_w=density of water (~1000 kg m-3); 3,600 converts from seconds to hours; and latent heat of vaporation (J kg^{-1}) representing the heat absorbed when a kilogram of water evaporates and is computed using Equation 8.

$$\lambda = [2.501 - 0.00236 \times (Ts - 273.15)] \times 10^6 \quad (8)$$

Reference ET fraction (ETrF) is the ratio of ET_{inst} to the reference ETr that is defined by the American Society of Civil Engineers and can also be computed using the standard Penman-Monteith alfalfa reference method (ASCE-EWRI, 2005) at overpass time (hourly average). Finally, the computation of daily or 24-h ET (ET_d), for each pixel, is performed with the following, Equation 9.

$$ET_d = ETrF \times ETr \times 24 \tag{9}$$

3. Results

The estimation of water fluxes was based on actual ET and precipitation. This section gives the results for actual ET, precipitation, and actual ET minus precipitation. Details are provided below concerning estimated water fluxes for Texas County, Lugert-Altus Irrigation District, Oklahoma City, City of Tulsa and Lake Texoma.

3.1. Actual Evapotranspiration

Actual evapotranspiration was calculated annually for both years 2007 and 2008 and also monthly. Figure 6 is the map of actual evapotranspiration for 2007 for the entire state of Oklahoma.

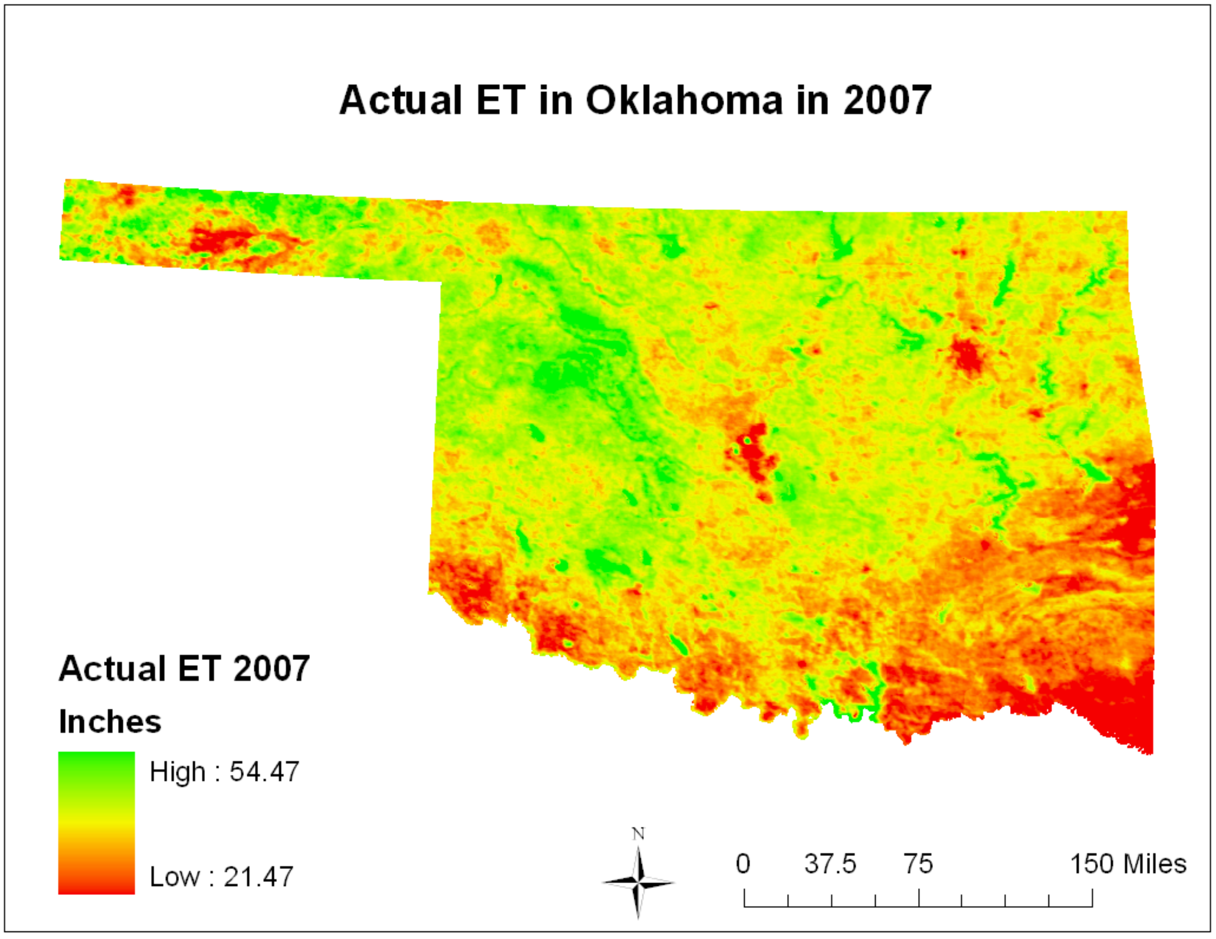

Figure 6: Annual Actual Evapotranspiration map in 2007

3.2. Precipitation

Precipitation was also calculated annually for both years 2007 and 2008 as well as monthly. Figure 7 shows the annual precipitation in Oklahoma for 2007.

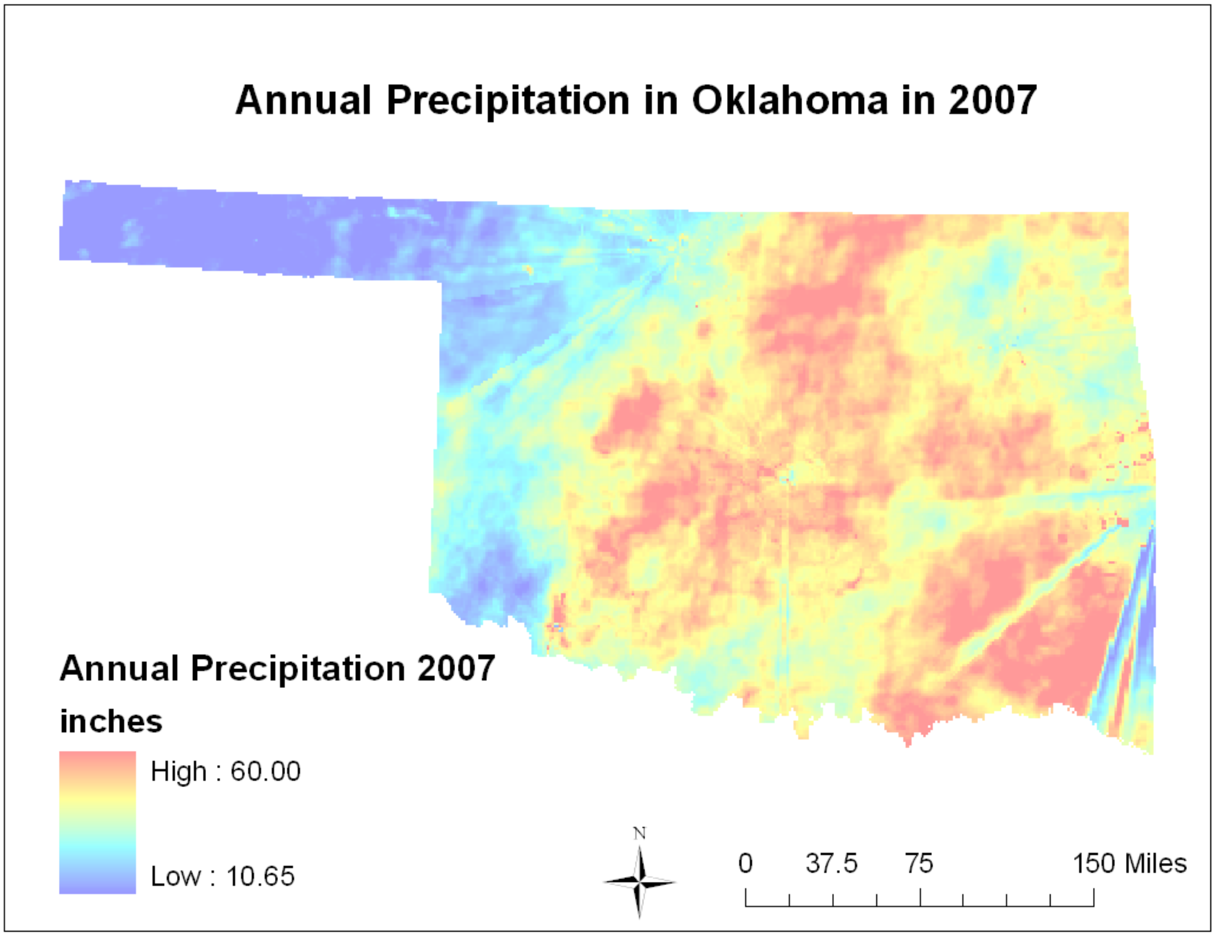

Figure 7: Annual Precipitation map in 2007

3.3. Actual evapotranspiration minus Precipitation

Actual evapotranspiration minus precipitation which is the estimation of water use for irrigation has been calculated annually as well as monthly. Figure 8 shows the annual difference between actual evapotranspiration and precipitation in Oklahoma in 2007.

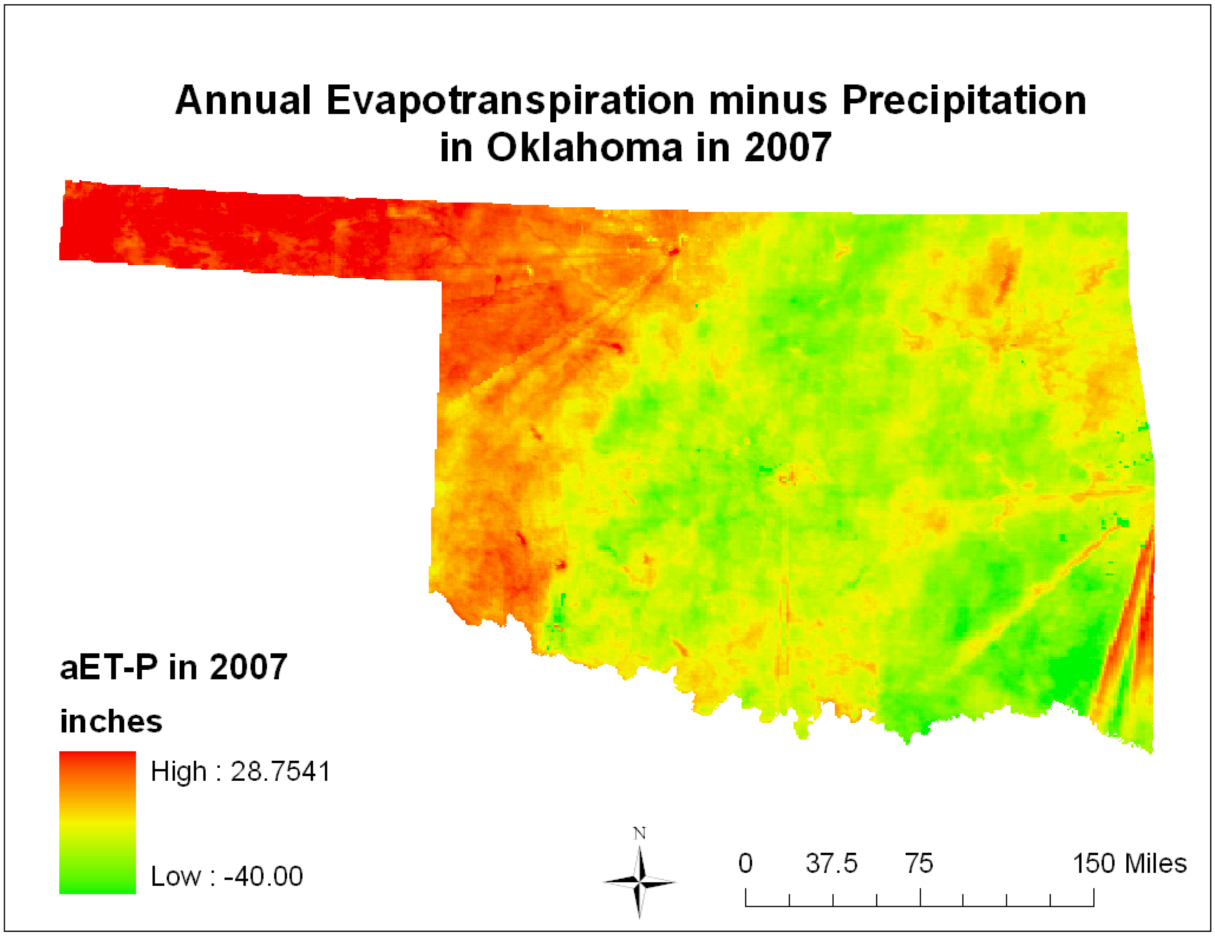

Figure 8 : Annual aET-P in Oklahoma in 2007

3.4. Major Crops

The cropland data layers derived from the NASS (2007 and 2008) geospatial data mentioned above were used for comparison of estimated and expected crop water use. Each year, the type of crop, its geographic extent and location is mapped using remotely sensed information. The difference between actual ET and precipitation (aET-P) is estimated for the crops using NASS data. Because of the arid climate in Texas County no runoff is expected, and therefore, aET-P is considered as crop water use. The aET-P water flux is extracted over each crop type contained in the NASS data for both Texas County and Altus-Lugert District.

The major crops grown in Texas County for 2007 and 2008 were winter wheat, corn and sorghum. While in the Altus-Lugert District, cotton and winter wheat were the major crops for this study period. Table 2 presents the major crop categories listed for the two study areas, Texas County and Altus-Lugert, during

2007 and 2008, along with each crop expressed as a percentage of total irrigated cropland reported by NASS.

Table 2: Major crops and percentage of irrigated areas in Texas County and Altus-Lugert District

	Altus-Lugert		Texas County	
	Crops	% of total irrigated	Crops	% of total irrigated
2007	**Cotton**	**54.40**	**Winter Wheat**	**60.19**
	Winter Wheat	**41.71**	**Corn**	**23.20**
	Sorghum	2.07	**Sorghum**	**14.45**
	Alfalfa	1.59	Alfalfa	1.26
	W. Wheat / Soyb Dbl.	0.10	Soybeans	0.43
	Millet	0.05	Oats	0.30
	Peanuts	0.05	Sunflowers	0.09
	Oats	0.03	Other Small Grains	0.05
			Barley	0.03
			Millet	0.01
2008	**Cotton**	**61.27**	**Winter Wheat**	**66.34**
	Winter Wheat	**37.44**	**Corn**	**19.18**
	Alfalfa	0.50	**Sorghum**	**12.67**
	Sorghum	0.40	Alfalfa	1.54
	W. Wheat/Soy. Dbl. Crop	0.37	Cotton	0.09
	Corn	0.03	Soybeans	0.09
			Sunflowers	0.04
			Rye	0.03
			Other Small Grains	0.02

The growing seasons for these crops are referenced in Appendix A. Table A-1 refers to the growing season of Altus District and Table A-2 to the growing season of Texas County. Only cotton and winter wheat were considered to be irrigated in Altus-Lugert District while winter wheat, corn and sorghum were considered to be irrigated in Texas County.

3.5. Estimation of Water Fluxes and Irrigation Water Use

3.5.1. Texas County

The estimation of irrigation water use based on aET-P is summarized in Table 3 for 2007 and Table 4 for 2008. Figure 9 shows the percentage of water used for irrigation per crop in Texas County in 2007.

Winter Wheat was found to transpire large quantities throughout its growing season from October to May in Texas County. During the year there is water flux from soil moisture and not irrigation water application during the Fall, Winter and Spring seasons. Table 3 presents growing season water use excluding winter wheat in the total water use.

Table 3: Summary of water use, aET-P, for Texas County in 2007

Annual aET-P for Texas County in 2007		
Crops	**Growing Season Acre-ft**	**Growing Season Inches**
Winter Wheat	264,118	14.79
Corn	78,927	11.47
Sorghum	48,965	11.42
Sum major crops (Excluding Winter Wheat)	127,892	22.89

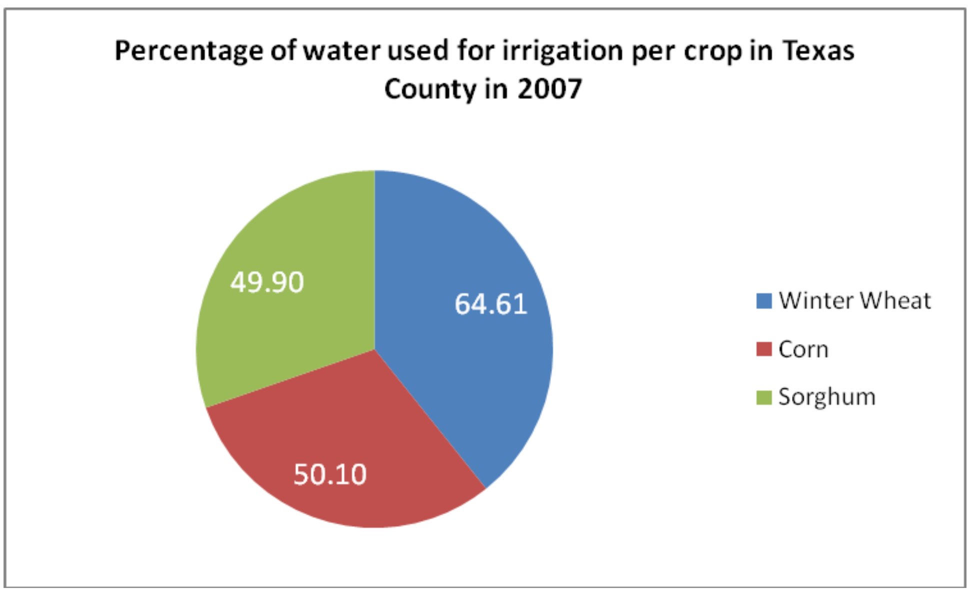

Figure 9: Percentage of water used for irrigation per crop in Texas County in 2007

Table 4: Summary of Results for 2008 for Texas County

Annual aET-P for Texas County in 2008		
Crops	**Growing Season Acre-ft**	**Growing Season Inches**
Winter Wheat	248,713	17.83
Corn	36,858	9.14
Sorghum	12,313	4.62
Sum major crops (Excluding Winter Wheat)	49,171	13.76

Appendix B contains graphs of the variation of aET-P over the entire period of study for Texas County and Altus-Lugert District. Figure B-10 shows aET-P variation in Texas County for the study period while Figure B-11 shows aET-P variation in Altus for the study period. Volume and depth differ because cropland area varies during the season.

3.5.2. Lugert-Altus District

The estimation of irrigation water use (aET-P) in 2007 and 2008 within Lugert-Altus in Districts 1 through 8 is summarized in Table 5. For the Lugert-Altus Irrigation District, only winter wheat and cotton were considered to be irrigated because they are the two major crops in the district. Contrary to Texas County, winter wheat was found to transpire a considerable amount in Lugert-Altus District during the growing season and so is included in the total estimated water use.

Table 5: Summary of Results for 2007 and 2008 for Altus-Lugert District

	Annual aET-P for Altus-Lugert in 2007 and 2008				
	Crops	**Growing Season Acre-ft**	**Growing Season Inches**	**Total Year Acre-ft**	**Total Year Inches**
2007	Winter Wheat	11,893	5.19	27,118	11.84
	Cotton	25,179	8.43	36,626	12.26
	Sum Major Crops	37,072	13.62	63,744	24.11
2008	Winter Wheat	17,071	8.59	27,348	13.76
	Cotton	25,367	7.80	47,843	14.71
	Sum Major Crops	42,438	16.39	75,190	28.47

3.5.3. Oklahoma City

From urban areas, aET is expected to be derived from a variety of sources, i.e. soil moisture, precipitation, groundwater, water bodies and irrigation of lawns. Even though the sources of aET cannot be separated, precipitation and aET are related. Table C-1 and Table C-2 of Appendix C shows monthly totals of these two components of the water balance for 2007 and 2008 respectively while Figure 10 shows the variation of aET, reference ET and precipitation over Oklahoma City (OKC). The values of actual ET, precipitation (precip) and reference ET (ref ET) are also recorded in Appendix C in Table C-3. The aET from OKC does not reach to full potential evapotranspiration represented by the reference ET. There were 1,072,314 ac-ft, or 32.34 inches of measured aET in 2007 and 1,357,565 ac-ft, or 40.94 inches of measured aET in 2008, which is less than reference by 47%, on average over 2007 and 2008. Actual ET for Oklahoma City does not exceed precipitation except for a few months in 2007 and 2008, because there is not sufficient irrigation of lawns to cause aET to exceed P.

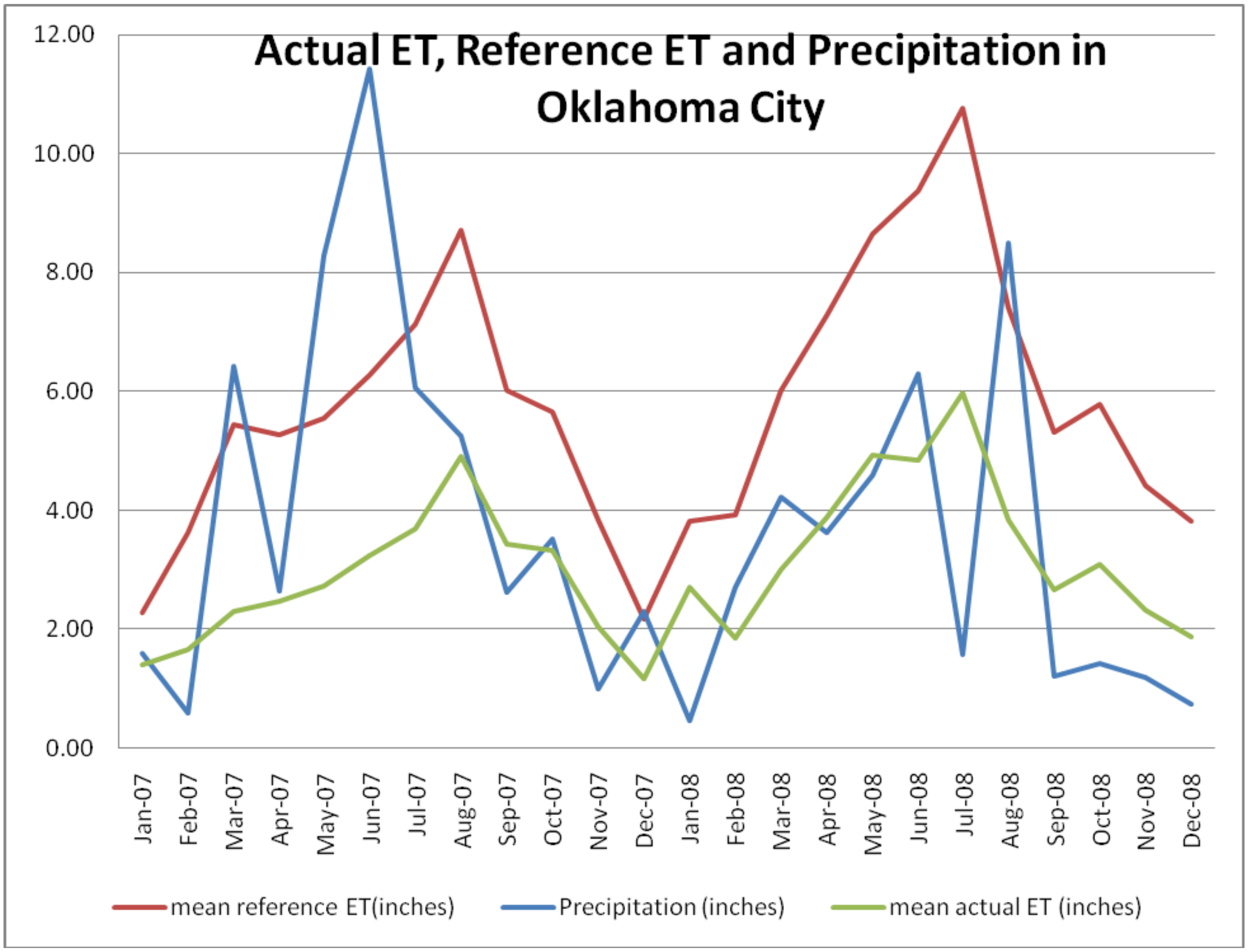

Figure 12: Precipitation, Actual ET, Reference ET in Oklahoma City area

3.5.4. Tulsa

As for Oklahoma City, values of aET were studied for water fluxes in Tulsa. Table D-1 and Table D-2 in Appendix D show monthly totals of these two components of the water balance for 2007 and 2008, respectively. Figure 11 shows the variation of aET, reference ET and precipitation over Tulsa. The values of actual ET, precipitation and reference ET are also recorded in Table D-3 of Appendix D. Similar to Oklahoma City, the aET from Tulsa does not reach to full potential evapotranspiration represented by the reference ET. There were 3,171,391 ac-ft, or 29.53 inches of measured aET in 2007 and 3,731,297 ac-ft, or 34.75 inches of measured aET in 2008, which is less than reference by 46.08%, on average over 2007 and 2008. The water flux from aET for the City of Tulsa does not exceed precipitation on an annual basis. During 2007 and 2008, aET exceeded precipitation in July and August, which may be attributed to lawn irrigation and possibly antecedent moisture from previous rainfall.

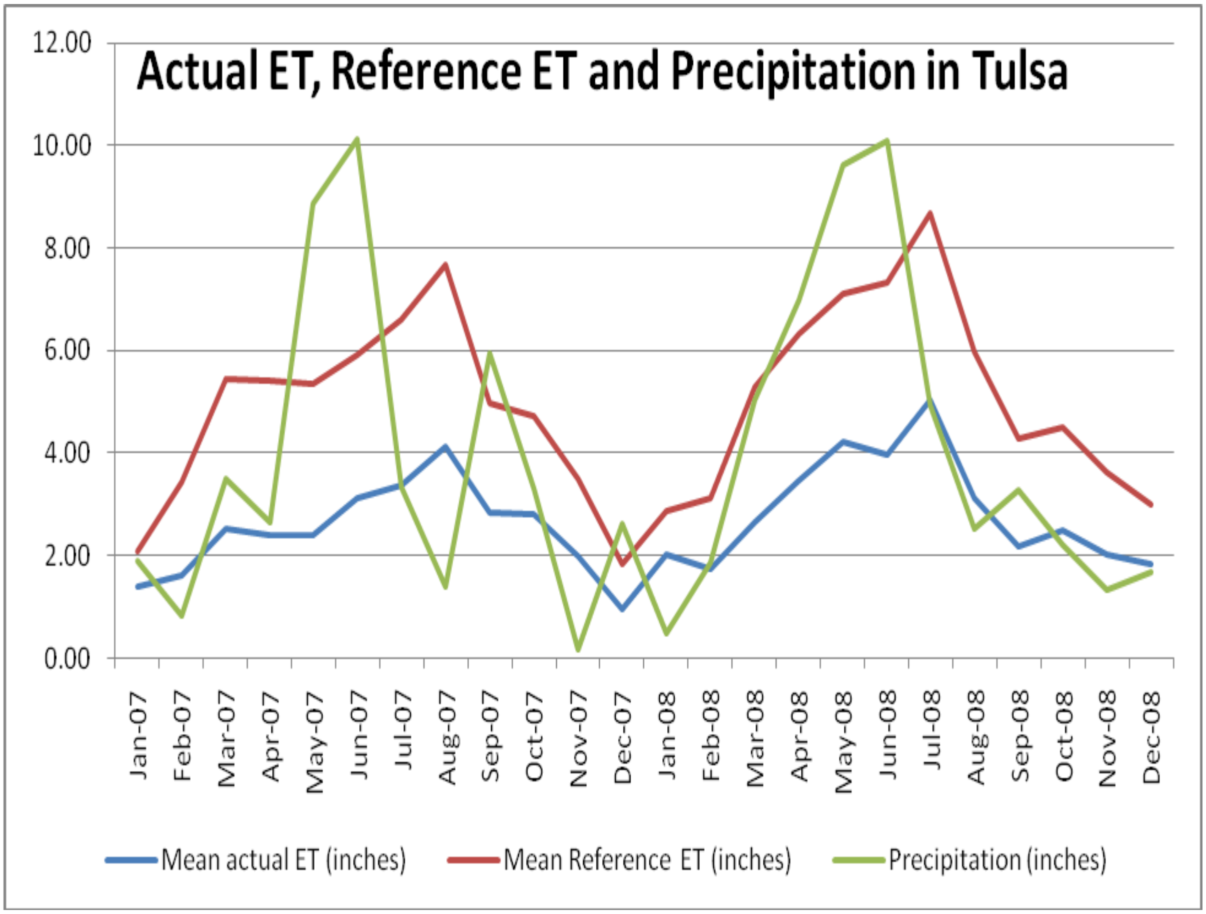

Figure 13: Precipitation, Actual ET, Reference ET in Tulsa area

3.5.5. Lake Texoma

Using the same methods for estimating aET from cropland (M/M-ET), the lake evaporation was estimated. The entire lake area is 84,428 acres, whereas, 58,931 acres are in Oklahoma. In the part of the lake in Oklahoma, the lake evaporation is 39.31 inches for 2007, and 49.43 inches for 2008.

Comparing reference ET and lake evaporation, lake evaporation is 0.65 of reference ET, which is consistent with pan coefficients reported by Farnsworth and Thompson (1982) and Bedient et al. (2009, p. 42). Table E-1 of Appendix E summarizes evaporation data in Lake Texoma.

4. VALIDATION OF RESULTS

4.1. Precipitation

The validation of the results includes validation of rainfall and validation of actual ET. To validate rainfall, national service data were used and compared to the processed one from ScourCast. The validation can be done by checking and comparing the precipitation record for the whole study period by ScourCast and NWS. Table F-1 and Table F-2 of Appendix F show the comparisons between recorded rainfall data by ScourCast and NWS in the National Weather Service Oklahoma City gauge, NWS COOP ID 346661 for 2007 and 2008 respectively.. The coordinates of the gauge were entered into GIS and precipitation data from ScourCast were extracted to those points and the values are also recorded in Appendix F. This gauge was not used in bias correction of the radar rainfall mosaic, and therefore represents an independent verification. The difference between the radar-based rainfall from ScourCast and the independent gauge was 6.4% for the two periods (2007-2008). The rainfall data used in this study can therefore considered accurate as they almost perfectly match with the independent NWS data.

4.2. Actual Evapotranspiration

Actual evapotranspiration validation for the current study uses Central Oklahoma Master Conservancy District (COMCD) data over Lake Thunderbird. The comparisons are shown in figure 12 below.

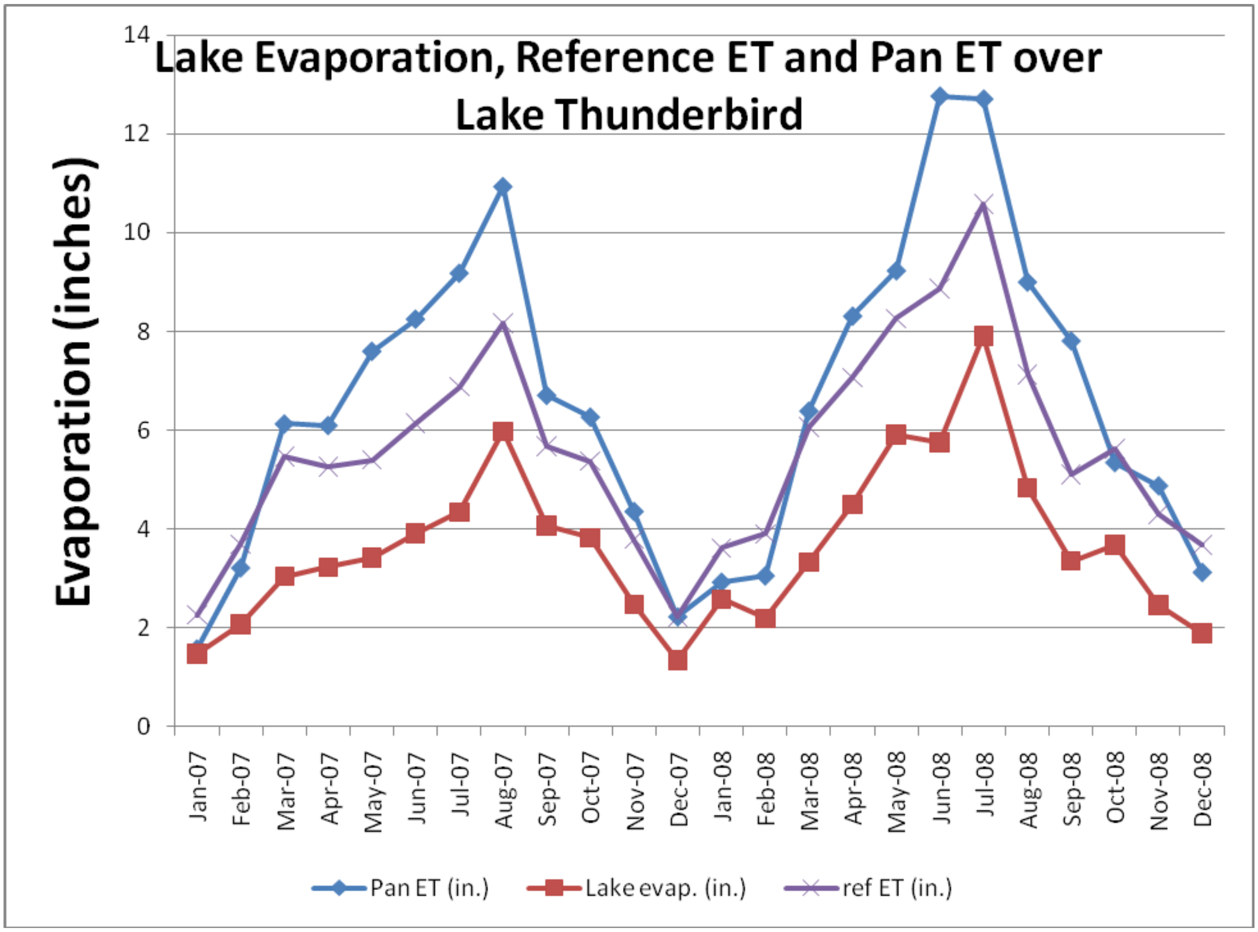

Figure 14: Lake Evaporation validation over Lake Thunderbird

To obtain lake evaporation, the estimates of aET according to the method described by Khan et al., 2009 was used. The average ratio of lake to pan evaporation for the two years of study is 0.59 for Lake Thunderbird. On cloudy days, lake evaporation may be underestimated, and the pan operated by COMCD is located a few miles from the lake. The average coefficient of reference ET taken from the Oklahoma Mesonet station in Cleveland County compared to the pan evaporation for the two study years is 0.92, which indicates that reference ET and pan ET are quite close, but biased by about 8%. The pan coefficient produced using satellite remote sensing of evaporation from the lake surface is close to pan coefficients published by Farnsworth et al. (1982). The closeness of the lake evaporation obtained by satellite methods compared to measured pan evaporation yields confidence in the M/M-ET method. In Table G-1 of Appendix G, the pan evaporation, reference ET, and lake evaporation are presented.

5. Analysis and Discussion

Natural Recourse Conservation Service (NRCS) in the National Engineering Handbook - Part 652 National Irrigation Guide and under Oklahoma Supplements estimate the supplemental water used for irrigation. The monthly consumptive use is described as the evapotranspiration and the net irrigation water use can be compared to aET – P. There is no detail concerning effective rain that was used by NRCS in computation of net irrigiation water requirement. Therefore, it is difficult to make direct comparisons between aET-P and the net irrigation water requirement. Consumptive water use, evaporation and transpiration is more directly related to aET – P. NRCS reports consumptive water use for Altus located near the Lugert-Altus Irrigation District, and in Goodwell located in Texas County. Although the data are given by city, the reported consumptive use is representative of irrigation water use in rural areas of the counties in which they are located. Table 6 presents the comparison between consumptive water use and aET – P.

Table 6: Estimated aET and annual consumptive water use in Texas County and in Lugert-Altus

Crops	Texas County			Lugert-Altus		
	aET 2007 (inches)	Annual Consumptive Use (Inches)	aET 2008 (inches)	aET 2007 (inches)	Annual Consumptive Use (Inches)	aET 2008 (inches)
Cotton	N/A	27.91	23.36	22.03	27.58	24.8
Winter Wheat	28.4	18.94	27.74	16.2	17.01	21.99
Corn	25.32	29.85	25.76	N/A	31.29	24.12
Sorghum	20.34	23.86	18.35	19.15	27.39	21.49

Table 7 below shows the differences observed between the net irrigation requirement by NRCS and the estimated values using the M/M-ET satellite estimation technique. Because 2007 and 2008 precipitation may not represent average conditions, clear comparison is not possible.

Table 7: Differences between net irrigation requirements by NRCS and estimated values of irrigation water use by satellite

	Crop	wheat	cotton	Corn	Sorghum
Texas County	**Net irrigation requirement in normal year (in)**	**6.31**	**18.7**	**17.85**	**13.55**
	Calculated water use in 2007 (inch)	14.79	N/A	11.47	11.42
	Calculated water use in 2008 (inch)	17.83	4.98	9.14	4.62
	Average of calculated water use (inch)	**16.31**	**4.98**	**10.305**	**8.02**
Lugert-Altus	**Net irrigation requirement in normal year (in)**	**3.83**	**14.62**	**17.85**	**15.83**
	Calculated water use in 2007 (inch)	5.19	8.43	N/A	7.25
	Calculated water use in 2008 (inch)	8.59	7.8		
	Average of calculated water use (inch)	**6.89**	**8.115**		

Other crops water requirements are given by USDA Economic Research Service (USDA/ERS, 2010) where it takes 20-22 inches to produce an optimal corn crop, 18-20 inches for a soybean crop, 12-13 inches for small grain, and 24-26 inches for alfalfa. Irrigation can reduce crop stress if rainfall does not provide this amount of moisture during the growing season. The Food and Agriculture Organization (FAO) also suggests crop water requirements, which are presented in Table 8 (FAO, 1986).

Table 8: Average crop water requirements and estimates from M/M-ET

Crop	FAO Water Requirement (in.)	M/M-ET Annual aET Texas County (in.)	M/M-ET Annual aET Lugert-Altus (in.)
Cotton	28-51	23.36	23.42
Corn	20-31	28.07	24.12
Sorghum	18-26	19.35	20.32
Winter Wheat	18-26	28.07	19.10

The values for crop water requirement given by FAO (Table 8 above) compared to the M/M-ET estimates of aET reveals that the satellite-based estimates are within the ranges suggested by FAO.

Based on the difference between aET and precipitation, it is estimated that 127,892 ac-ft in 2007 and 49,171 ac-ft in 2008 is used annually for irrigation of major crops in Texas County. In Lugert-Altus, 37,072 ac-ft was estimated for 2007 and 42,438 ac-ft in 2008. Considering the loss rate of about 36% (OWRB, 2001a), the volume of water used for irrigation in the Lugert-Altus Irrigation District would be 71,823*(1-0.36) or 45,967. Ac-ft which agrees closely with the water flux measured during the growing season as aET-P. Table 9 reports these volumes of estimated water use and reported data from OWRB.

Table 9: Annual irrigation water use and reported data from OWRB

	Texas County		Altus-Lugert	
	M/M-ET (acre-ft)	Irrigation Water Use OWRB (acre-ft)	M/M-ET (acre-ft)	Irrigation Water Use OWRB (acre-ft)
2007	127,892	226	37,072	45,967*
2008	49,171	174.5	42,438	-

*Includes adjustment for canal losses of 36%.

6. Conclusions

A satellite-based remote sensing technique was used to estimate crop water use in Texas County and the Altus-Lugert Irrigation District; water flux from the urban areas of Tulsa and Oklahoma City; and lake evaporation from Lake Thunderbird and Lake Texoma. Validation of these components of the water balance was accomplished by comparing water released from Lake Altus for the Lugert-Altus Irrigation District; published water use requirements for major crops, and by comparison of lake evaporation to pan evaporation. Precipitation was also used in the computation of crop water use, and was taken from radar-based rainfall mosaics, which were validated for the study period and found to be within 6.4%. Lake evaporation expressed as a fraction of pan evaporation was 0.59 and 0.65 for lakes Thunderbird and Texoma, respectively. Crop water use estimated by satellite remote sensing as aET-P was within 0.36% and in Texas County and within 12.89% for the Lugert-Altus compared to published values for the major crops grown.

Irrigation water use, of 127,892 ac-ft in 2007 and 49,171 ac-ft in 2008 in Texas County is under-reported in the OWRB data on permitted water use that is self reported through the OWRB permit requirements.

Whereas in Lugert-Altus, after accounting for canal losses, the volume released from the reservoir is quite close. The satellite-estimated irrigation water use was 37,072 ac-ft in 2007 and 42,438 ac-ft in 2008, which is within 19.4% and 7.7% during those years considering the same irrigation water use estimated by OWRB in 2007 and 2007. Water flux from the urban areas of Tulsa and Oklahoma City, was 29.53 inches, 32.34 inches, respectively in 2007. While in 2008, water flux transported to the atmosphere increased 34.75 inches and 40.94 inches, respectively. This water flux estimated from actual aET is less than potential, but follows closely reference ET. At least some of this aET is expected to derive from lawn irrigation, and other sources such as open water bodies that contribute to water flux transported to the atmosphere. Annual water flux (aET) measured by satellite did not exceed precipitation for Tulsa and Oklahoma City, and actual did not exceed potential ET except for two summer months in 2007 and 2008.

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Appendix A:

Table A-1: Growing season considered in Altus-Lugert Irrigation District

Crop	Growing season considered in Altus
Cotton	May-October
Winter Wheat	October - May
Corn	April-September
Sorghum	May-September

Table A-2: Growing season considered in Texas County

Crop	Growing season considered in Texas County
Cotton	June-October
Winter Wheat	September-June
Corn	May - September
Sorghum	June - October

Appendix B:

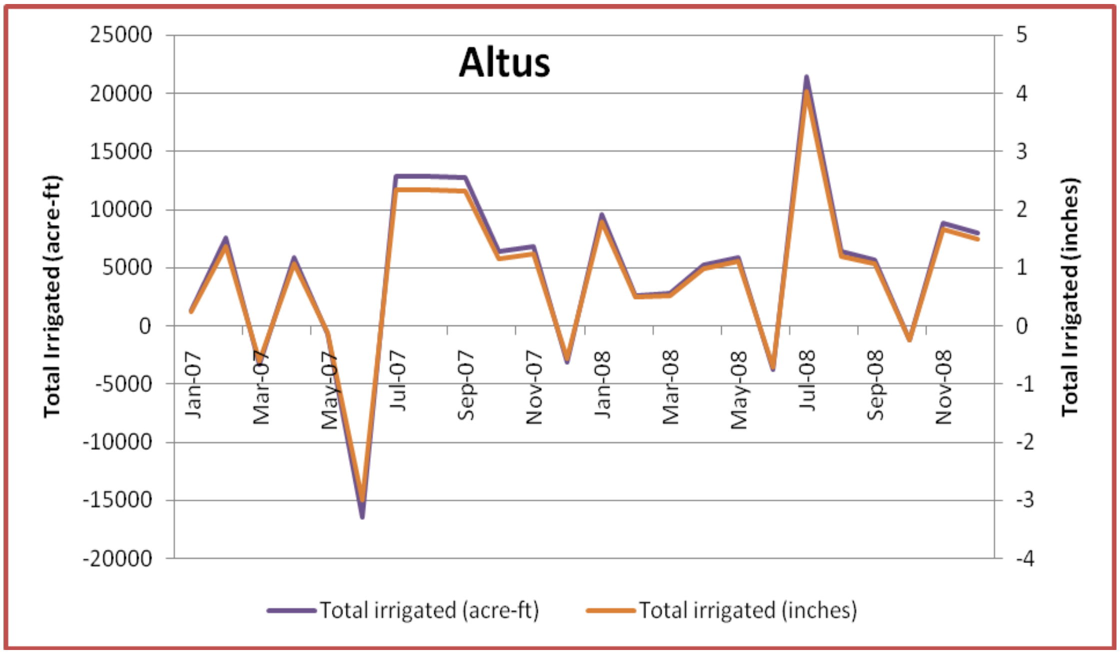

Figure B-13: aET-P variation in Altus for the study period

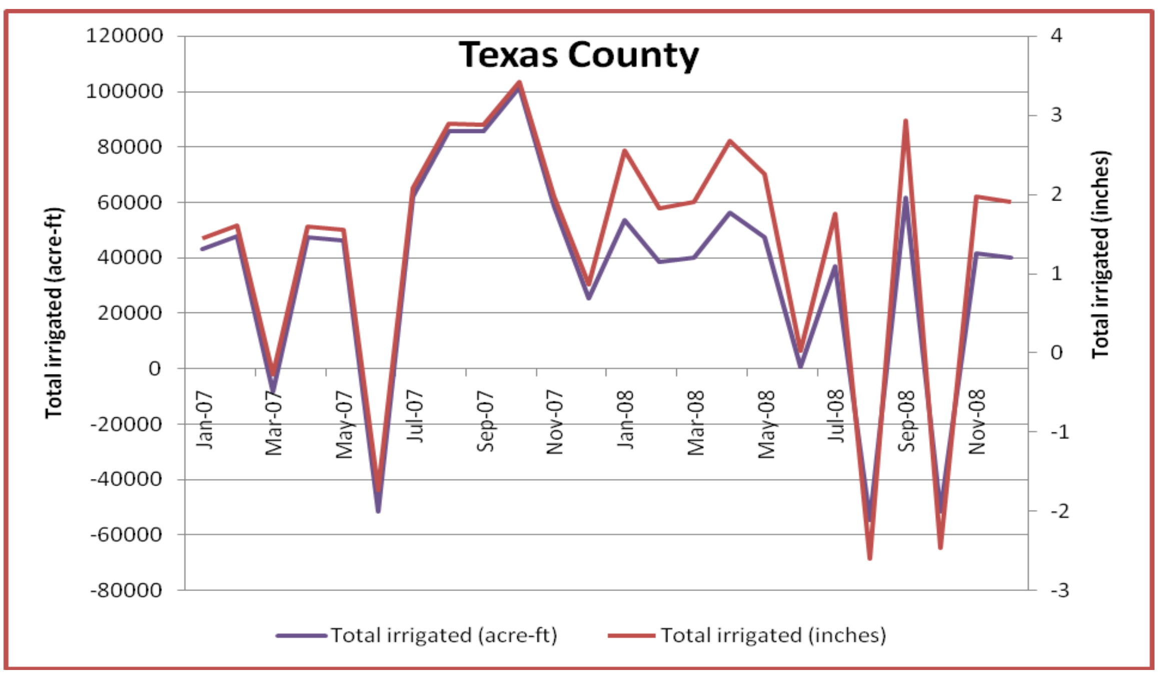

Figure B-14: aET-P variation in Texas County for the study period

Appendix C:

Table C-1: Water Fluxes in Oklahoma City in 2007

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
Mean aET (in.)	1.40	1.65	2.3	2.47	2.73	3.23	3.70	4.09	3.44	3.33	2.03	1.16	32.34
Mean Precip. (in.)	1.59	0.59	6.43	2.64	8.27	11.43	6.07	5.25	2.62	3.53	0.99	2.31	51.72

Table C-2: Water Fluxes in Oklahoma City in 2008

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Mean aET(in.)	2.70	1.84	3.01	3.87	4.92	4.85	5.97	3.84	2.66	3.08	2.32	1.88	40.94
Mean Precip. (in.)	0.46	2.71	4.23	3.63	4.58	6.29	1.56	8.50	1.20	1.42	1.19	0.74	36.52

Table C-3: Actual ET, reference ET and precipitation in Oklahoma City

Date	mean aet	mean ref	bias aet and ref et	Precip(inches)
Jan-07	1.40	2.27	38.16	1.59
Feb-07	1.65	3.63	54.62	0.59
Mar-07	2.30	5.44	57.74	6.43
Apr-07	2.47	5.26	53.13	2.64
May-07	2.73	5.54	50.62	8.27
Jun-07	3.23	6.27	48.44	11.43
Jul-07	3.70	7.13	48.13	6.07
Aug-07	4.90	8.71	43.70	5.25
Sep-07	3.44	6.02	42.96	2.62
Oct-07	3.33	5.64	40.97	3.53
Nov-07	2.03	3.85	47.15	0.99
Dec-07	1.16	2.17	46.78	2.31
Jan-08	2.70	3.82	29.46	0.46
Feb-08	1.84	3.92	52.90	2.71
Mar-08	3.01	6.01	49.92	4.23
Apr-08	3.87	7.27	46.77	3.63
May-08	4.92	8.64	43.07	4.58
Jun-08	4.85	9.38	48.33	6.29
Jul-08	5.97	10.77	44.54	1.56
Aug-08	3.84	7.41	48.14	8.50
Sep-08	2.66	5.30	49.86	1.20
Oct-08	3.08	5.78	46.74	1.42
Nov-08	2.32	4.42	47.50	1.19
Dec-08	1.88	3.83	50.89	0.74
Average bias aet and ref et (%)			**47.15**	

Appendix D:

Table D-1: Water Fluxes in Tulsa in 2007

Date	Jan	Feb	Mar	Apr	May	Jun	Jul-	Aug	Sep	Oct	Nov	Dec	Total
Mean aET (in.)	1.39	1.61	2.54	2.41	2.41	3.11	3.37	4.11	2.82	2.81	1.99	0.97	29.53
Mean Precip (in.)	1.91	0.84	3.50	2.66	8.86	10.11	3.34	1.39	5.95	3.32	0.16	2.61	44.65

Table D-2: Water Fluxes Tulsa in 2008

Date	Jan	Feb	Mar	Apr	May	Jun	Jul-	Aug	Sep	Oct	Nov	Dec	Total
Mean aET (in.)	2.02	1.73	2.66	3.47	4.20	3.97	5.05	3.11	2.19	2.49	2.03	1.82	34.75
Mean Precip (in.)	0.49	1.86	5.04	6.98	9.62	10.10	4.95	2.54	3.29	2.21	1.34	1.68	50.08

Table D-3: Actual ET, reference ET and precipitation over Tulsa area

Date	Mean aET (in.)	Mean Ref ET (in.)	Bias of aET and ref ET (%)	Precipitation(in.)
Jan-07	1.39	2.08	33.40	1.91
Feb-07	1.61	3.43	53.19	0.84
Mar-07	2.54	5.44	53.30	3.50
Apr-07	2.41	5.41	55.43	2.66
May-07	2.41	5.34	54.80	8.86
Jun-07	3.11	5.91	47.47	10.11
Jul-07	3.37	6.59	48.91	3.34
Aug-07	4.11	7.68	46.45	1.39
Sep-07	2.82	4.97	43.26	5.95
Oct-07	2.81	4.72	40.41	3.32
Nov-07	1.99	3.49	42.99	0.16
Dec-07	0.97	1.83	47.19	2.61
Jan-08	2.02	2.88	29.96	0.49
Feb-08	1.73	3.10	44.30	1.86
Mar-08	2.66	5.29	49.73	5.04
Apr-08	3.47	6.32	45.07	6.98
May-08	4.20	7.11	40.87	9.62
Jun-08	3.97	7.34	45.99	10.10
Jul-08	5.05	8.68	41.85	4.95
Aug-08	3.11	5.99	48.09	2.54
Sep-08	2.19	4.28	48.80	3.29
Oct-08	2.49	4.50	44.60	2.21
Nov-08	2.03	3.63	43.92	1.34
Dec-08	1.82	3.00	39.31	1.68
Average	**Bias of aET and ref ET (%)**		**46.08**	

Appendix E:

TableE-1: Lake Texoma variation of evaporation, and reference ET

Date	Reference ET (in.)	Lake evaporation(in.)	Bias (%)	aET/ref ET
Jan-07	2.21	1.22	44.89	0.55
Feb-07	3.94	2.36	40.11	0.6
Mar-07	5.06	3.23	36.24	0.64
Apr-07	5.1	3.57	30.06	0.7
May-07	5.34	3.59	32.78	0.67
Jun-07	6.14	3.88	36.85	0.63
Jul-07	6.29	4.19	33.37	0.67
Aug-07	7.43	5.88	20.89	0.79
Sep-07	5.88	4.08	30.49	0.7
Oct-07	5.41	3.64	32.68	0.67
Nov-07	3.96	2.38	40.08	0.6
Dec-07	2.63	1.39	47.16	0.53
Jan-08	3.22	1.92	40.53	0.59
Feb-08	4.24	2.77	34.73	0.65
Mar-08	6.02	4.21	30.18	0.7
Apr-08	6.7	4.77	28.79	0.71
May-08	7.49	5.77	22.98	0.77
Jun-08	9.22	6.02	34.74	0.65
Jul-08	10.31	7.75	24.89	0.75
Aug-08	7.2	5.13	28.7	0.71
Sep-08	5.29	3.43	35.15	0.65
Oct-08	5.64	3.47	38.4	0.62
Nov-08	4.17	2.34	44.01	0.56
Dec-08	3.48	1.97	43.29	0.57
Average			34.67	0.65

Appendix F:

Station Name: Oklahoma City Will Rogers Airport

Type: LAND SURFACE COOP AB ASOS ASOS-NWS

Call Sign/ICS: OKC / KOKC

WBAN: 13967

COOP ID: 346661

Climate Division: OK-05 - Central

WMO ID: 72353

In Service: 02 Apr 1932 to Present

Elevation: 391.7m (1285') above s/l

Lat/Lon: 35°23'N / 97°36'W

County: Oklahoma

Table F-1: Comparison of recorded precipitation,

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ScourCast	1.19	0.54	7.92	2.61	9.09	10.55	6.06	5.16	4.20	3.72	0.92	2.28
NWS	2.08	0.62	8.02	2.57	8.49	10.06	6.31	5.39	5.73	3.72	0.53	3.43
bias (%)	-42.89	-13.31	-1.30	1.68	7.04	4.91	-3.99	-4.27	-26.73	-0.12	73.48	-33.66

Table F-2: Comparison of recorded precipitation, 2008

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ScourCast	0.66	3.29	4.54	3.82	4.37	7.10	1.60	11.01	0.93	1.34	0.73	0.65
NWS	0.65	2.88	3.29	4.17	4.54	5.83	1.07	9.95	0.59	1.63	0.70	0.52
bias (%)	1.46	14.31	38.06	-8.30	-3.69	21.71	49.76	10.64	57.05	-17.68	4.23	25.14

Appendix G:

Table G-1: Validation of lake evaporation over Lake Thunderbird

Date	Pan ET (in.)	Lake evap (in.)	Reference ET (in.)	Lake evap./pan	ref/pan	Lake evap/ref
Jan-07	1.58	1.48	2.26	0.93	1.43	0.65
Feb-07	3.22	2.07	3.69	0.64	1.15	0.56
Mar-07	6.13	3.04	5.46	0.50	0.89	0.56
Apr-07	6.10	3.23	5.26	0.53	0.86	0.61
May-07	7.60	3.42	5.40	0.45	0.71	0.63
Jun-07	8.25	3.91	6.14	0.47	0.74	0.64
Jul-07	9.18	4.34	6.88	0.47	0.75	0.63
Aug-07	10.93	5.97	8.17	0.55	0.75	0.73
Sep-07	6.71	4.07	5.68	0.61	0.85	0.72
Oct-07	6.27	3.82	5.38	0.61	0.86	0.71
Nov-07	4.36	2.47	3.79	0.57	0.87	0.65
Dec-07	2.23	1.34	2.23	0.60	1.00	0.60
Jan-08	2.93	2.58	3.62	0.88	1.23	0.71
Feb-08	3.06	2.19	3.90	0.72	1.28	0.56
Mar-08	6.39	3.33	6.06	0.52	0.95	0.55
Apr-08	8.31	4.50	7.06	0.54	0.85	0.64
May-08	9.23	5.90	8.26	0.64	0.90	0.71
Jun-08	12.76	5.76	8.87	0.45	0.69	0.65
Jul-08	12.70	7.90	10.58	0.62	0.83	0.75
Aug-08	9.00	4.83	7.13	0.54	0.79	0.68
Sep-08	7.81	3.35	5.11	0.43	0.65	0.66
Oct-08	5.35	3.68	5.62	0.69	1.05	0.65
Nov-08	4.88	2.45	4.31	0.50	0.88	0.57
Dec-08	3.13	1.89	3.68	0.60	1.18	0.51
Average				0.59	0.92	0.64

Appendix H:

Table H-1:

Crops	Average Estimated Annual ET in Texas County (inches)	Annual Consumptive Use in Texas County (Inches)	Difference (%)	Average Estimated Annual ET in Texas County (inches) in Lugert Altus	Annual Consumptive Use in Lugert-Altus (inches)	Difference (%)
Cotton	23.36	27.91	16.30	23.415	27.58	15.10
Winter Wheat	28.07	18.94	-48.20	19.095	17.01	-12.25
Corn	25.54	29.85	14.44	24.12	31.29	22.91
Sorghum	19.345	23.86	18.92	20.32	27.39	25.817
Average			0.36			12.89

Eastern redcedar encroachment and water cycle in tallgrass prairie

Basic Information

Title:	Eastern redcedar encroachment and water cycle in tallgrass prairie
Project Number:	2009OK141G
Start Date:	9/1/2009
End Date:	8/31/2012
Funding Source:	104G
Congressional District:	3
Research Category:	Climate and Hydrologic Processes
Focus Category:	Groundwater, Hydrology, Ecology
Descriptors:	baseflow, evapotranspiration, grassland, precipitation interception, sapflow, soil water dynamic, streamflow, water budget and water cycle
Principal Investigators:	Chris Zou, Dave Engle, Sam Fuhlendorf, Don Turton, Rodney Will, Kim Winton

Publications

1. Zou Chris, Peter Folliott, Michael Wine. 2010. Streamflow responses to vegetation manipulations along a gradient of precipitation in the Colorado River Basin. Forest Ecology and Management 259:1268-1276.
2. Zou Chris, Shujun Chen. 2009. Eastern redcedar encroachment and alternations of ecohydrological properties in tallgrass prairie. IUFRO Forest and Water. Raleigh, NC, USA.
3. Zou Chris, Don Turton, Rod Will, Sam Fuhlendorf, David Engle,Kim Winton. 2009. Eastern Redcedar Encroachment and the Water Cycle in Mesic Great Plains Grasslands.The Oklahoma Water Research Symposium. Oklahoma City.
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Interim Report

Title: Eastern redcedar encroachment and water cycle in tallgrass prairie

Principal Investigators:

Chris Zou, Don Turton, Rod Will, Samuel Fuhlendorf, David Engle at Oklahoma State University and Kim Winton at Oklahoma Water Science Center

Problem and Research Objectives:

Land based water cycle and water supplies to streams and groundwater are heavily influenced by vegetation and vegetation change resulting from management. In the Great Plains, tallgrass prairie is rapidly transforming to woodland largely by the encroachment of eastern redcedar (*Juniperus virginiana*) trees. Of the 17 million acres of rangeland (including prairie) in Oklahoma, eight million acres are currently overgrown with eastern redcedar. Given the magnitude and extent of the observed and projected encroachment, a logical question is: how will increases in eastern redcedar cover modify streamflow and raw water supplies in the Great Plains states where water shortages are increasing? Our understanding of such effects is limited to somewhat inconclusive results from studies on semiarid savanna ecosystems. Therefore, a climate and site-specific investigation focusing on mesic prairies of the Great Plains is urgently needed considering long-term water planning is ongoing for most of these affected states.

Broad Project Objectives:

The proposed project is a field-based, multiple-year collaborative research effort between Oklahoma State University and the USGS Oklahoma Water Science Center. The overall objectives are to develop an improved understanding of the effects of eastern redcedar encroachment in tallgrass prairie on water supply.

Methodology:

We will directly quantify components of the water budget of small watersheds in tallgrass prairie with and without eastern redcedar encroachment. Specifically, we will directly quantify the tallgrass prairie evapotranspiration (E/T) using an USGS-developed portable E/T chamber (Stannard 1988; Garcia *et al*. 2008). We will measure interception by tallgrasses using a method that directly quantifies both throughfall and stemflow (revised from Corbett and Crouse 1968). Transpirational water loss by eastern redcedar trees will be quantified using a sap flow technique (Granier 1985, 1987). Streamflow from each watershed will be measured using appropriately sized flumes. In order to apply our small watershed results to other watersheds in the region, we will apply watershed models such as *R*angeland *H*ydrology and *E*rosion *M*odel (Wei *et al.* 2008). Our results will be used to parameterize, calibrate and validate the models.

Principal Findings and Significance:

This project started in September 2009 and the project has been proceeding according to the research plan. At this phase, effort has been on site survey and information gathering, watershed flume construction, and equipment installation.

Site vegetation survey of redcedar encroached sites was conducted in early spring 2010. This vegetation survey aimed at quantifying the vegetation structure (redcedar density, average diameter and diameter class distributions, and stand basal areas) for the redcedar watershed areas (Figure 1).

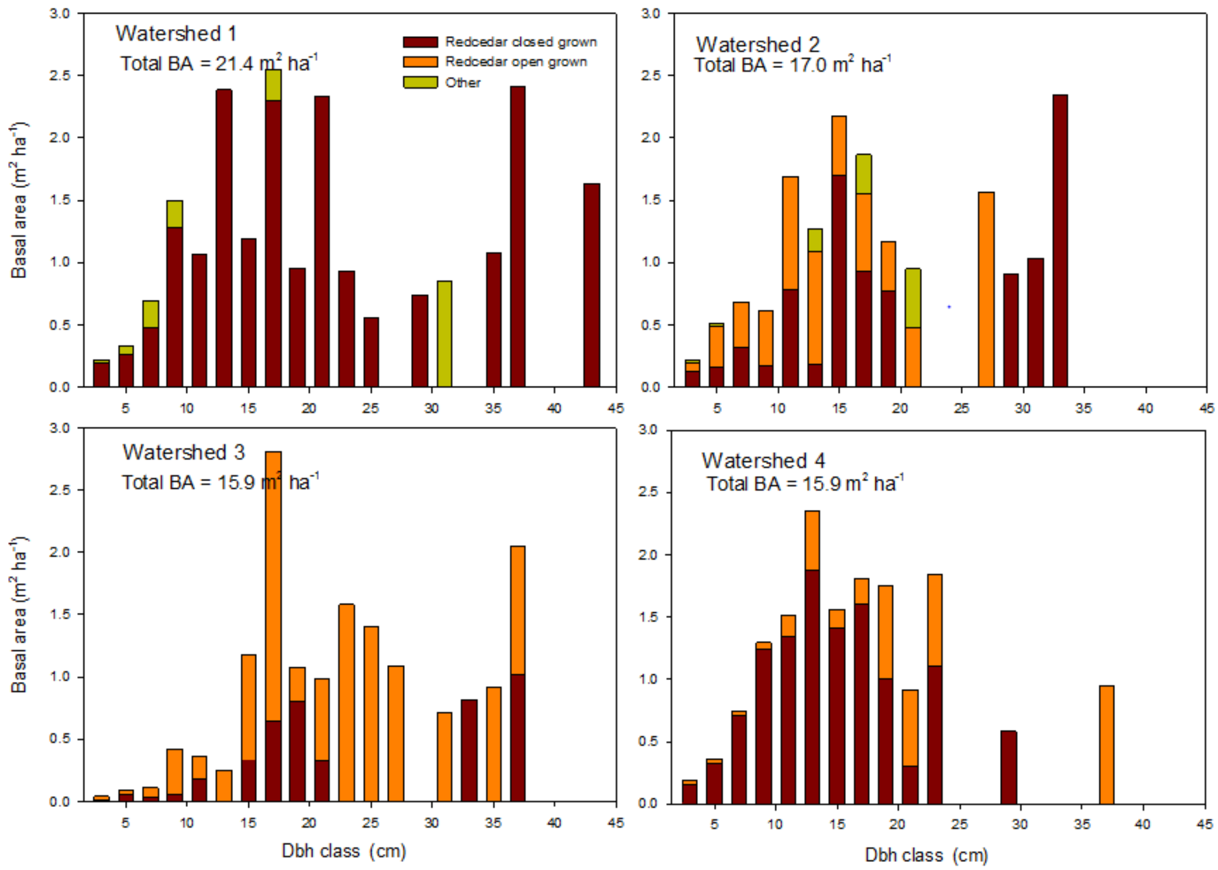

Figure 1. Basal area of woody tree species broken into 2 cm diameter classes measured in four redcedar encroached watersheds. Basal area is a measure of cross sectional area of stems measured at 1.37 m above ground level. Data were collected from a transect run lengthwise through the watershed consisting of 9 to 13 0.9 ha plots. Open grown redcedar are those that had live branches to the ground while closed grown had crown recession due to shading. Basal area is a measure of dominance since it incorporates number of trees per hectare and tree size.

One of the distinguishing characteristics of encroached woodland is the patchiness of overstory canopy. The intercanopy space is grassland with open grown cedar trees and the canopy patch is woodland with closed grown cedar trees. The open grown trees have much longer canopy depth (the length from the lower branch to the canopy top) with live leaves and branches than closed grown ones. Differences in these canopy attributes will affect canopy precipitation, interception and other ecohydrological processes. An experiment designed to study the effect of encroachment on water budget needs to take such difference into consideration. The biophysical attributes of canopy structure such as patchiness and canopy depth were used in our final choice of watershed and flume construction. For example, we initially planned to take advantage of existing watershed infrastructure of watershed 1 and watershed 2. However, site survey indicates that watershed 1 has the highest total basal area (TBA) and almost all trees were closed grown. Therefore watershed 1 represents a condition similar to typical closed canopy forest. In contrast, watershed 2 and watershed 3 have significant percentage of open grown redcedar trees, a typical biophysical structure associated with the patchy canopy cover of encroached woodlands. This is one of the reasons for us to decide to add watershed 4 to fulfill the original project design to have three comparable replicates at the watershed level. In addition, we are using this site specific survey data to refine our sapflow sensors and precipitation interception field deployment strategies.

Soil water held in soil matrix is an important component of water budget. Most importantly, at a given point of time, soil water is the collective effect of other water budget components such as precipitation, evapotranspiration, runoff and deep drainage. Detailed analysis of temporal dynamic (change in soil water) will provide insights in terms of the interactive effects among different hydrologic components. Figure 2 presents some preliminary data collected from a single soil water moisture comparison (one in grassland watershed and the other in redcedar watershed). Even though there was some difference in soil texture among the two sites, some obvious trends associated with each site were emerging. Soil water content at the same soil depth was usually lower at the recedar site and therefore there was generally less water held in the soil matrix under the redcedar woodland. In the grassland, the soil water content at deep soil layer (80 cm) was relatively high and had small range of temporal fluctuation in comparison to that in redcedar encroached site, indicating limited water uptake at this soil depth by roots in grassland and potential higher deep drainage or baseflow opportunity in grassland.

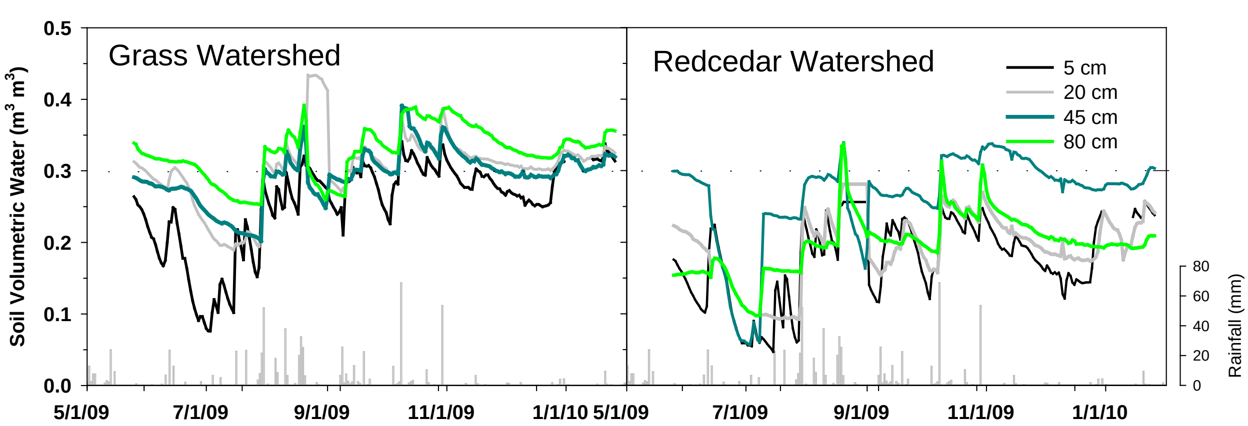

Figure 2. Dynamic of soil water contents along the vertical soil profile for one station in grassland watershed one and other station in redcedar woodland watershed 1. Soil depth is about 100 cm for both sites.

Brief Summary of Other Project Information

Overall Experimental Layout- As proposed, the experiment was carried out in the Oklahoma State University Cross Timber Experimental Range ($36^0$3'27.49", $97^0$11'10.91''). These sites chosen for watersheds had been historically cultivated cropland (Figure 3 upper panel) and sites to the left have been maintained as grassland while some the sties to the right have been encroached by redcedar.

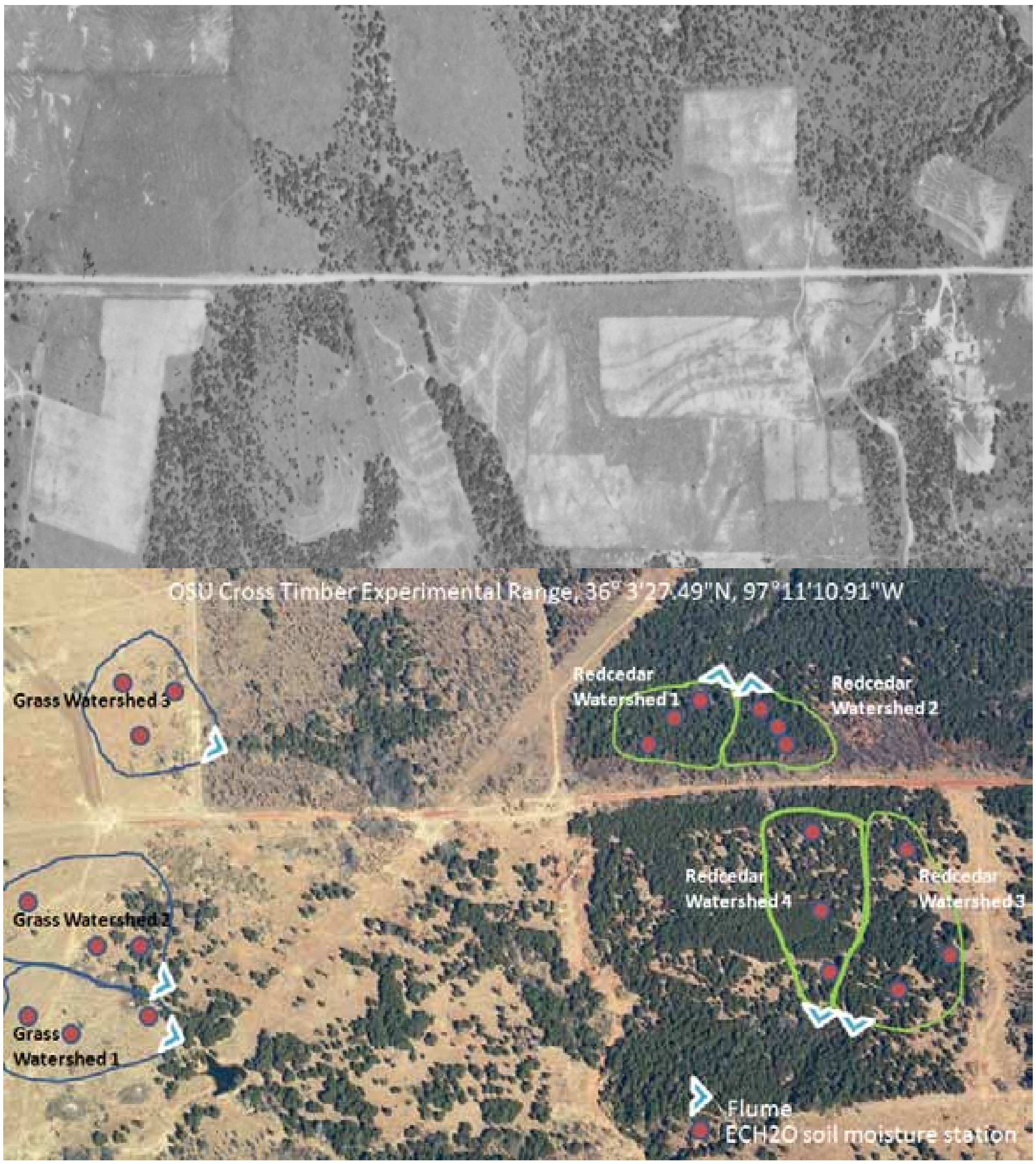

Figure 3 Aerial photo of OSU Cross Timber Experimental Range taken in 1938 (upper panel) showing extensive crop cultivation history. The sites we identify for our watershed study were all cultivated cropland back in 1938. At the present, the grassland watersheds (left) have very little redcedar encroachment and the redcedar watersheds have been largely encroached by redcedar with a canopy cover approximately >70%.

Watershed construction- We proposed to construct three new watersheds and watershed flumes (Grassland watershed 2 and 3; Juniper watershed 3). In addition to these, we built one more flume (Redcedar watershed 4) in the redcedar encroached site by taking advantage of the topography and to increase the representation of soil types. At the time of this report, field construction activities for all four new watersheds and flumes was complete and all four watersheds are undergoing instrumentation. We are able to accomplish this under original budget primarily by support of Oklahoma State University Kiamichi Forestry Research Station field crew. Although the unusual cold temperatures and soil moisture at the end of 09 and the beginning of 2010 postponed the field construction of watershed for 3-4 months, this delay will not affect our research plan.

Grassland Watershed 2	Grassland Watershed 3	Cedar Watershed 3	Cedar Watershed 4

Figure 4 Kiamichi Forestry Research Station field crew were constructing watershed on redcedar watershed 3 and watershed 4 (upper) and all four newly constructed watershed flumes (lower).

Soil Moisture Stations - 21 soil moisture stations have been completed installed with the last array of stations completed in early March 2010 (see Figure 3). All stations have been tested and worked properly since March 2010.

Figure 5. A Decagon ECH2O soil water station installed in watershed 3. There are 4 EC-5 soil water content sensors measuring water content at 5, 20, 45, and 80 cm and 1 precipitation rain gauge. Data were collected every 15 minutes.

Sapflow Measurement – We are in the process to finalize the design of the sapflow sensors and the incoming master student will be working on this project.

ET Chamber and Grass Evapotranspiration – We are actively engaging USGS Oklahoma Water Science Center and the ET chambers are under construction and will be available for use in this summer and a June and an operating training is scheduled in June.

Grass Interception – The grass interception experiment is undergoing the initial phase of field design.

Graduate Students – Based on the research plan, we are going to recruit two graduate students, one at PhD level and the other at master level. The PhD student, Jenny Hung, was recruited and started in the Natural Resource Ecology and Management program at OSU in the 2010 spring semester. One potential master student has been identified and will potentially start in the 2010 fall semester.

Publications - Using this project as a catalyst, we completed a synthesis paper "Streamflow responses to vegetation manipulations along a gradient of precipitation in the Colorado River Basin" with collaborator from University of Arizona. This paper has been published by Forest Ecology and Management recently. This synthesis paper discussed the relevance of precipitation and streamflow response and therefore is critically important for us to explain and interpret our results in the context of our subhumid climate in contrast to many other results from more arid or semiarid regions. Two presentation/abstracts have been presented in regional and national meetings and one more presentation has been accepted for 2010 ESA annual meeting.

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Information Transfer Program Introduction

Activities for the efficient transfer and retrieval of information are an important part of the OWRRI program mandate. The Institute maintains a website (http://environ.okstate.edu/owrri) that provides information on the OWRRI and supported research, grant opportunities, and upcoming events. Abstracts of technical reports and other publications generated by OWRRI projects are updated regularly and are accessible on the website.

Information Transfer Project

Basic Information

Title:	Information Transfer Project
Project Number:	2009OK129B
Start Date:	3/1/2009
End Date:	2/28/2010
Funding Source:	104B
Congressional District:	3
Research Category:	Not Applicable
Focus Category:	Education, Law, Institutions, and Policy, Management and Planning
Descriptors:	
Principal Investigators:	Will J Focht, Kylie Ahern, Jeri Fleming, Jenny Jafek-Jones, Mike Langston

Publications

There are no publications.

Information Transfer Program

An essential part of the mission of the OWRRI is the transfer of knowledge gathered through university research to appropriate research consumers for application to real world problems in a manner that is readily understood. To do this in 2009, OWRRI will engage in six efforts: (1) publication of a newsletter, (2) meetings with state agency personnel, (3) maintenance of an up-to-date website, (4) assisting with water law and policy training seminars, (5) cosponsoring a water film series, and (6) holding of an annual Water Research Symposium.

Newsletter: The OWRRI's quarterly newsletter is the *Aquahoman*. With a distribution list of nearly 1500, the *Aquahoman* not only provides a means of getting information to the general public, but also informs researchers throughout the state about water research activities. In 2009, *The Aquahoman* was produced twice, winter and summer. The *Aquahoman* is distributed to state and federal legislators; to water managers throughout Oklahoma; to state, federal, and tribal agency personnel; to water researchers at every university in the State, to members of our Water Research Advisory Board, and to anyone who requests one.

Water Research Advisory Board: The WRAB consists of 22 water professionals representing state agencies, federal agencies, tribes, and non-governmental organizations. This advisory board was formed in 2006 to assist the OWRRI by setting funding priorities, recommending proposals for funding, and providing general advice on the direction of the Institute. The Board members have found that they also benefit from their involvement in at least two ways. First, they profit from the opportunity to discuss water issues with other professionals. Second, the semiannual meetings afford them the opportunity to stay informed about water research and water resource planning in Oklahoma. This is accomplished, in part, by having the investigators of the previous year's projects return and present their findings to the Board.

Thus, the WRAB is an important part of the OWRRI's efforts to disseminate research findings to state agencies for use in problem solving. In 2009, the WRAB met twice. The July 2009 meeting included an update on the State's water planning effort, presentations on the results of the 2008 OWRRI-funded projects, and selection of the funding priorities for 2010. The funding priorities are distributed as part of the RFP for the annual competition. The January 2010 meeting included presentations by the five finalists in our research grant competition, selection of three of these finalists for funding, and an update on the State's water plan.

Website: The OWRRI continues to maintain an up-to-date website (http://environ.okstate.edu/OWRRI) to convey news and research findings to anyone interested. Site visitors can obtain interim and final reports from any research project sponsored by the OWRRI (reports from 1965-1999 are available via email; reports from 2000-present are available for immediate download). This year OWRRI began a partnership with the Edmon Low Library at OSU to all of our project reports (1965 to present) on their website to make them more readily available to the public and more easily located using web search engines. Also available are newsletters beginning in 2005, information about the annual grants competition including the RFP and guidelines for applying, and details about the OWRRI's effort to gather public input for the state's revision of the State ' s comprehensive water plan. The website is also a major source of information about our annual Research Symposium.

Training Seminars: As part of the statewide water planning effort, OWRRI has an attorney on staff who provides training regarding water issues in Oklahoma to various community groups, such as Rotary Clubs. In 2009, this included speaking at the Oklahoma Water Law Seminar (conducted by CLE International, Inc.).

In another training effort, OWRRI and the Oklahoma Water Resources Board conducted a two-day Basic Water Science Seminar in Oklahoma City. The primary purpose of the seminar was to inform the approximately 250 citizens participating in the water planning effort about water hydrology, the resources in our state, and the research being conducted as part of the water plan. Although the water plan participants were the intended audience, the seminar was open to the general public.

OWRRI co-sponsored a three-day water research conference with the River Systems Institute at Texas State University in San Marcos, Texas. The conference was entitled *Land, Water, People* and attracted more than 600 attendees.

Water Film Series: The OWRRI partnered with student and community organizations to sponsor a film series entitled, *Is Our Glass Half Empty?* The purpose was to facilitate discussion and learning about the state of water resource management in Oklahoma. Five documentaries were presented to the general public free of charge. A facilitated discussion followed each. Films included *Blue Gold: World Water Wars, Liquid Assets, The Unforeseen, FLOW,* and *Oklahoma Water*. Attendance averaged more than 40 each night.

Research Symposium: The OWRRI has held an annual Water Research Symposium since 2002. The purpose of this event is to bring together water researchers and water professionals from across the state to discuss their projects and network with others. Again this year, the Symposium was combined with the Oklahoma Water Resources Board's annual Governor's Water Conference. The keynote address was delivered by Robert Glennon, the author of *Unquenchable: America's Water Crisis and What to Do about It*. The three-day event in Oklahoma City drew over 400 water professionals, agency staff, politicians, members of the press, researchers, participants in the water planning effort, and interested citizens. This combination of events provided a unique opportunity for interchange between those interested in water policy (who traditionally attend the Governor’s Water Conference) and those interested in water research (who traditionally attend the Research Symposium).

The Symposium includes a student poster contest which involves not only staff time, resources, and supplies, but also $1500 used as prize money (provided by gifts from the Cherokee and Chickasaw Nations). In 2009, 24 students from three universities were joined by 13 poster presenters from state agencies and university professors in displaying their posters.

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	3	0	0	0	3
Masters	2	1	0	0	3
Ph.D.	3	1	0	0	4
Post-Doc.	0	0	0	0	0
Total	8	2	0	0	10

Notable Awards and Achievements

In 2009, OWRRI continued its effort to gather public input on policy suggestions for the Oklahoma s update of the comprehensive water plan. The OWRRI is under contract with Oklahoma Water Resources Board (OWRB) for this effort and has designed a novel approach for gathering public input. Utilizing the values of the public as well as the best expertise available, the goal of this four and a half year process is to develop a plan that enjoys broad support and is well informed. The effort includes approximately 85 public meetings across the state to gather, consolidate, and prioritize citizens concerns, and then, develop policy recommendations regarding state water issues.

The first three years have been very successful, consisting of 42 Local Input Meetings in 2007 to identify issues of concern across the state, eleven Regional Input Meetings held across the state in 2008 to identify the high priority issues for the water plan, and thirty half-day workshops in 2009 to develop potential solutions to these issues.

As part of this planning effort, the OWRB has joined the OWRRI in funding research to address the state's water planning needs by providing a match to the money granted by the US Geological Survey.

Publications from Prior Years