Oklahoma Water Resources Research Institute Annual Technical Report FY 2010

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 year, 2010, marked our 45th year of serving Oklahoma through research, education, and outreach.

This report summarizes some of our accomplishments in 2010. Highlights are presented below.

- We awarded three research grants of $50,000 each to researchers at both OSU and the University of Oklahoma to conduct studies of the use of an Acoustic Doppler Current Profiler to measure sediment transport in shallow streams, on the water conservation and irrigation habits of Oklahomans, and the development of a novel approach to predicting drought severity by measuring plant available moisture in the soil via the Oklahoma Mesonet. These projects began on March 1 and lasted one year.

- We are pleased that Oklahoma research teams have now been awarded prestigious USGS 104G grants in two consecutive years. In 2010 an OSU and University of Arkansas research team won a $200,000, two-year grant to investigate the subsurface flow of phosphorus through preferential flow channels in the alluvium of streams in eastern Oklahoma and western Arkansas. In 2009, a team based at OSU and OU, received a $225,000, three-year grant to investigate the impact of eastern red cedar encroachment on groundwater.

- We co-sponsored and co-hosted the 8th annual Water Research Symposium and 31th annual Governor's Water Conference in Norman, which was attended by more than 500. The keynote address was delivered by Scott Huler, the author of On the Grid.

- We concluded the fourth year of our 4.5-year project to update the Oklahoma Comprehensive Water Plan. We worked with the Oklahoma Academy for State Goals to hold a 3-day Town Hall meeting in Norman, Oklahoma. This Town Hall meeting resulted in 56 policy recommendations which were presented to the Oklahoma Water Resources Board for inclusion in the revised Water Plan.

- OWRRI director, Dr. Will Focht, served as Past-President of the National Institutes for Water Resources (NIWR). In this capacity he oversaw the creation of a new web-based system for water institutes to report their annual activities and a revision of the bylaws of NIWR.

Research Program Introduction

2010

In 2010, proposals were solicited from all comprehensive universities in Oklahoma. Proposals were received from Oklahoma State University and the University of Oklahoma. Ten proposals were submitted, and from these, three projects were selected for funding for one year each.

- *A Fluvial Geomorphic and Sediment Transport Study of the Little River Upstream of Lake Thunderbird Using an Acoustic Doppler Current Profiler (ADCP)* (Dr. Randall Kolar, OU) is an investigation into the efficacy of ADCP for measuring sediment load in Oklahoma streams under both low and high discharge conditions.

- *Drought monitoring: a system for tracking plant available soil moisture based on the Oklahoma Mesonet* (Dr. Tyson Ochsner, OSU) completed the first phase of this project to develop a near-real-time online map of plant available moisture using soil moisture measurements form the Oklahoma Mesonet.

- *Water conservation in Oklahoma urban and suburban watersheds through modification of irrigation practices.* (Dr. Justin Moss, OSU) assessed homeowners water use and the water needs of bermudagrass lawns in Oklahoma. This information was used to develop education programs to encourage home irrigators to optimize their landscape watering and thus, reduce water consumption.

2009

Also, included in this report are the final technical reports for two projects funded in 2009. These projects experienced delays and were extended but are now complete. Interim reports for these projects were included with last year's annual report.

- *Alternative Water Conservation Policy Tools for Oklahoma Water Systems* (Dr. Damian Adams, OSU) investigated water conservation policy tools that are appropriate and feasible for Oklahoma including associated costs and water savings.

Stream Depletion by Ground Water Pumping: A Stream Depletion Factor for the State of Oklahoma (Dr. Garey Fox, OSU) quantified the relationship between groundwater pumping and depletion of adjacent stream water on two Oklahoma streams.

Alternative Water Conservation Policy Tools for Oklahoma Water Systems

Basic Information

Title:	Alternative Water Conservation Policy Tools for Oklahoma Water Systems
Project Number:	2009OK114B
Start Date:	3/1/2009
End Date:	10/1/2010
Funding Source:	104B
Congressional District:	3
Research Category:	Social Sciences
Focus Category:	Conservation, Law, Institutions, and Policy, Water Quality
Descriptors:	
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.
4. Boyer, C.N., D.C. Adams, and J. Lucero, Rural Coverage Bias in Online Surveys?: Evidence from Oklahoma Water Managers. Journal of Extension [online] 48(3)(2010):3TOT5. Available at: http://www.joe.org/joe/2010june/tt5.php.
5. Adams, D.C., C.N. Boyer, T. Borisova, and M.D. Smolen, Water conservation strategies by rural and municipal water systems. Proceedings of the USDA/NIFA National Water Program. Hilton Head, SC, February 20, 2010.
6. 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.
7. Adams, D.C. and M.D. Smolen, Water Policy & Economics: Issues of Interest in the Southern Region. Proceedings of the Southern Region Water Policy & Economics Conference. Gainesville, FL, October 14, 2009.

Alternative Water Conservation Policy Tools for Oklahoma Water Systems

Final Report

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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:

- <u>Objective 1</u>: 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.**

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

- <u>Objective 3</u>: Synthesize the results from Objectives 1 & 2 into a framework document for use in expert panel sessions (Objective 4 below). Alternative method used, but status is **Completed**.

- 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). **Completed.**

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

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.

Literature Review of Water Conservation Mechanisms

I. Background

Until recently, *the* solution to water shortage was expanding supplies. Severe droughts, climate change, and the desire for sustainability has shifted the focus (somewhat) to increase efficiency of water use and reducing water use (e.g., Renwick and Archibald 1998; Michelson et al. 1999; Howarth and Butler 2004; Olmstead and Stavins 2008).

The Federal Energy Policy Act of 1992 established and mandated new plumbing efficiency standards for new household fixtures, such as maximum flow rates for showerheads and toilets, and standards for faucet aerators. As part of the act, the US Department of Energy was required to issue recommendations that encourage state and local governments to establish incentive programs for water conservation (Dunham et al. 1995). To facilitate information-sharing, the American Water Works Association and the US Environmental Protection Agency were commissioned to establish the *WaterWiser* clearinghouse on water efficiency (www.waterwiser.org). The 1996 amendments to the Safe Drinking Water Act increased the focus on water conservation by establishing voluntary guidelines (basic, intermediate and advanced) for water systems (EPA 2009). These efforts grew out of the 1970s energy crisis as an effort to decrease hot water usage (Dunham et al. 1995). In the 1970s and 1980s, several water utilities successfully demonstrated the effectiveness of water conservation at reducing energy use. For example, the Osage Municipal Utilities energy saving program included the distribution of low-flow showerheads and faucet aerators, and reduced annual energy growth to 3% from 7.2% (Dunham et al. 1995). By the late 1980s, water districts were beginning to deploy water conservation as a substitute for expanding supplies (e.g., Goleta, CA). Connecticut was the first state to require water conservation measures as a way to reduce the impact of population growth on strained water supplies. In 1989, Connecticut adopted a law that mandated residential retrofit for more efficient plumbing fixtures and formal water conservation planning (Dunham et al. 1995).

More recently, there has been a large amount of research and application of water conservation mechanisms. For example, in 2002 the US EPA published a review of case studies on water conservation in 17 states, cities, and regional water districts. These included Arizona, California, Florida, Kansas, Massachusetts, New Mexico, North Carolina, New York, Pennsylvania, Oregon, Ontario (Canada), and Texas (EPA 2002). Today, most water districts view water conservation mechanisms as complements and in some cases partial substitutes for additional storage and conveyance infrastructure (Kennedy and Goemans 2008).

Nationwide, water use per person is 160 gallons per day (Dickinson et al. 2003). Although the agricultural sector is the largest water user in these states, it is unrealistic to expect large-scale transfers of water rights from agricultural to urban areas (e.g., Brewer et al. 2007). As constraints on water supplies are reached, it is likely that urban and suburban areas will need to reduce water demand through a combination of price and non-price conservation mechanisms.

Severe droughts are typical precursors to water conservation programs, particularly non-price programs that limit or require particular instruments, appliances or behaviors (Syme 2000). This usually accompanies a shift in planning focus from short- to long-term (Syme 2000). Initially, it was mainly states in the Western US that implemented such programs, but today drought-stricken southern states are also turning to water conservation as a means to ensure adequate and safe water supplies (Olmstead and Stavins 2008).

Water districts and utilities that have studied water conservation as part of a broad collection of potential supply-enhancing alternatives typically find a strong role for conservation:

"Conservation effectively provides an additional resource by freeing up water that was previously consumed inefficiently or wasted. In this sense, it is the most cost-effective source of water available to the community. It is also a resource over which the local community has a great deal of autonomy to implement, since it depends on our own efforts and less on influences outside the community." – Southern Nevada Water Authority (2004).

These studies demonstrate the effectiveness of water conservation: "Many utilities throughout the region reduced per capita demand by up to 30% in response to the drought, and reductions of 15% to 20% were fairly typical." – Western Water Advocates (2003) from "Smart Water: A Comparative Study of Urban Water Use Efficiency across the Southwest." Boulder, CO. Effective water conservation can even eliminate the need for new supply (Cooley et al. 2007).

Water conservation programs usually involve several co-integrated measures that fall into one of five categories: financial (pricing, rebate, incentive), technological (mandatory specifications), educational (awareness, etc), maintenance (leak detection) and operational (reducing water pressure). Governments and utilities have employed a wide variety of mechanisms to conserve scarce water resources. Below, we summarize the use of water conservation mechanisms in the US, including information on relative cost, effectiveness, participation rates, and factors that impacted program success.

II. Price Mechanisms

The price of publicly-supplied water is typically not based on market transactions. Instead, utilities and municipalities set both water rates and rate structures. In most cases, households face a fixed fee for service, with an additional volumetric charge per unit of water they consume that may step up or down according to "blocks" of water use. The block rate structure is typically either uniform (unit price does not vary by quantity), decreasing (price per unit falls as consumption quantity increases), or increasing (price per unit rises as quantity increases) (Klein et al. 2006). Rates can be adjusted during specific months or seasons of high water demand, or during the drought times. Rate structures with high fixed rates, but low variable (volumetric) rates do not promote conservation (Cooley et al. 2007).

Studies have generally reported an inelastic relationship between water demand and price (Inman and Jeffrey 2006), and water demand generally does not respond to price rises above a certain point (e.g., Dalhuisen et al. 2003). Dalhuisen et al. (2003) conducted a meta-analysis of 64 regions in the US and Europe and generated 314 separate price elasticities for water. They found that elasticities varied greatly by region. European elasticities averaged -0.28. In the US, elasticities averaged -0.17 in western states and only -0.005 in eastern states. Lower income households have more elastic water demand (UKWIR 1996; Renwick and Green 2000). Renwick and Green (2000) found that households earning less than $20,000 per year had elasticities five times larger than households earning $100,000 or more. However, this does not hold below some minimum amount of water needed for absolute necessities (Howarth and Butler 2004).

Outdoor water use studies report much more elastic demand (e.g., UKWIR 1996; Renwick and Archibald 1998). Perhaps this is expected, since indoor water use is linked to the necessities of bathing, eating, etc while outdoor use is linked to aesthetics or recreation. Also, there is a discussion in the literature about whether customers are able to interpret their water bills and hence, understand and respond to water rate signals (e.g., Shin 1985, Whitcomb 2004).

Irrigation accounts for the bulk of water use. Elasticity studies show that during the summer months, elasticity of demand is 5-10% larger compare to winter months (e.g., Klein et al. 2006). Nieswiadomy (1992) found that elasticities can differ greatly by region, with water users in the southern and western states having more than twice the demand elasticity of the rest of the US. In California, the demand elasticity in Santa Barbera was almost three times larger than in nearby Goleta (Renwick and Green 2000).

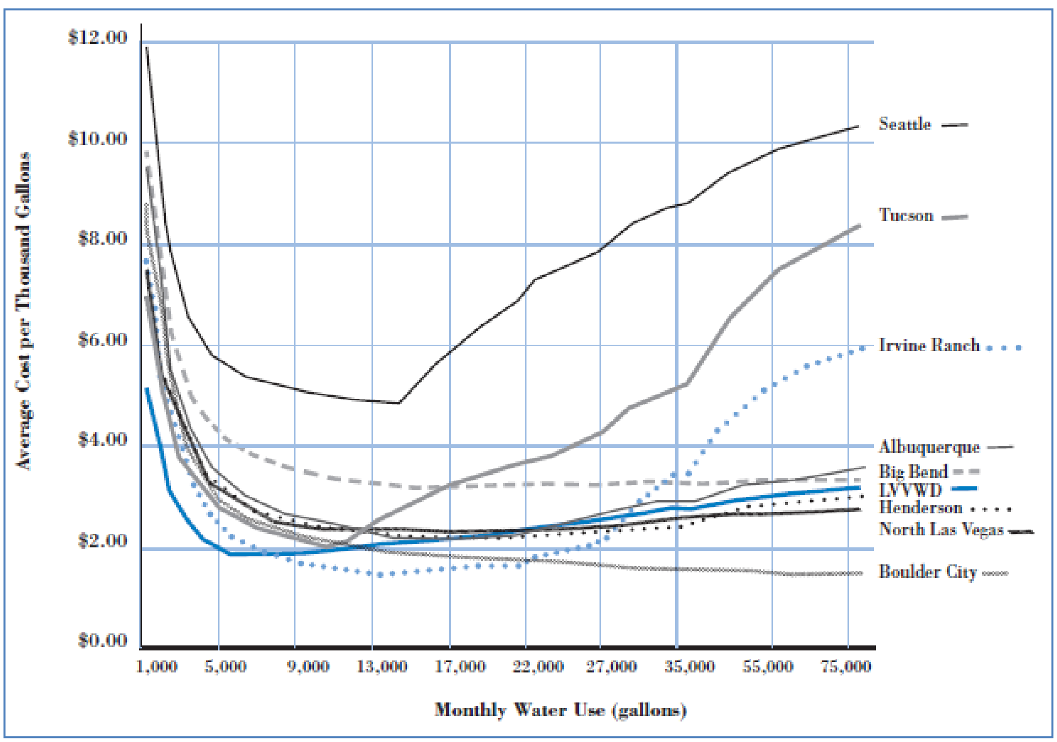
Block structure impacts elasticity, for example with households in a two-tier inclining block structure having five times larger elasticity than those in a uniform block (Cavanaugh et al. 2002). Despite evidence that users may respond more to average than marginal costs of water (Nieswiandony 1992), from an economic efficiency perspective, the price of water should be set equal to its long-run marginal costs of supply (Olmstead and Stavins 2008). This price would reflect water's full economic cost, including related costs of pumping, storage, treatment, infrastructure maintenance, and related expenses.

Water prices are typically set below the LRMC (e.g., Timmins 2003). There are political, geo-physical, informational and other factors that preclude setting the price of water equal to its long-run marginal cost. Criteria used by water utilities in designing water rates include revenue level and stability; fairness and impacts on low-income customers; ease of understanding by customers and ease of implementation; water use efficiency and conservation; and adequate long-run water supply. While these objectives are not mutually exclusive, they sometimes can conflict with each other, the most common example being the potential tradeoff between water conservation and utility revenue objectives.

The use of water rates to achieve water use efficiency and conservation objectives has its pros and cons. The benefits of conservation water rates include: (a) communication of general water conservation need, rewarding efficient users, and penalizing non-efficient water use; (b) reduces operating costs, and delays the need for system expansion and acquiring additional water supplies and storage capabilities; (c) drought preparedness by public utilities and customers; (d) environmental benefits associated with water conservation (e.g., Wang et al. 2005, Alliance for Water Efficiency 2008). The two main pitfalls of conservation rate are: (a) the tradeoff between water conservation and utility revenue requirement objectives; and (b) increased volatility and difficulty of predicting utility revenues (Wang et al. 2005). Approaches used to address the issues of revenue variability and uncertainty include revenue stabilization funds, bond issuing or retiring, tax and/or water rate adjustments, and spending excess revenues on conservation and public education programs.

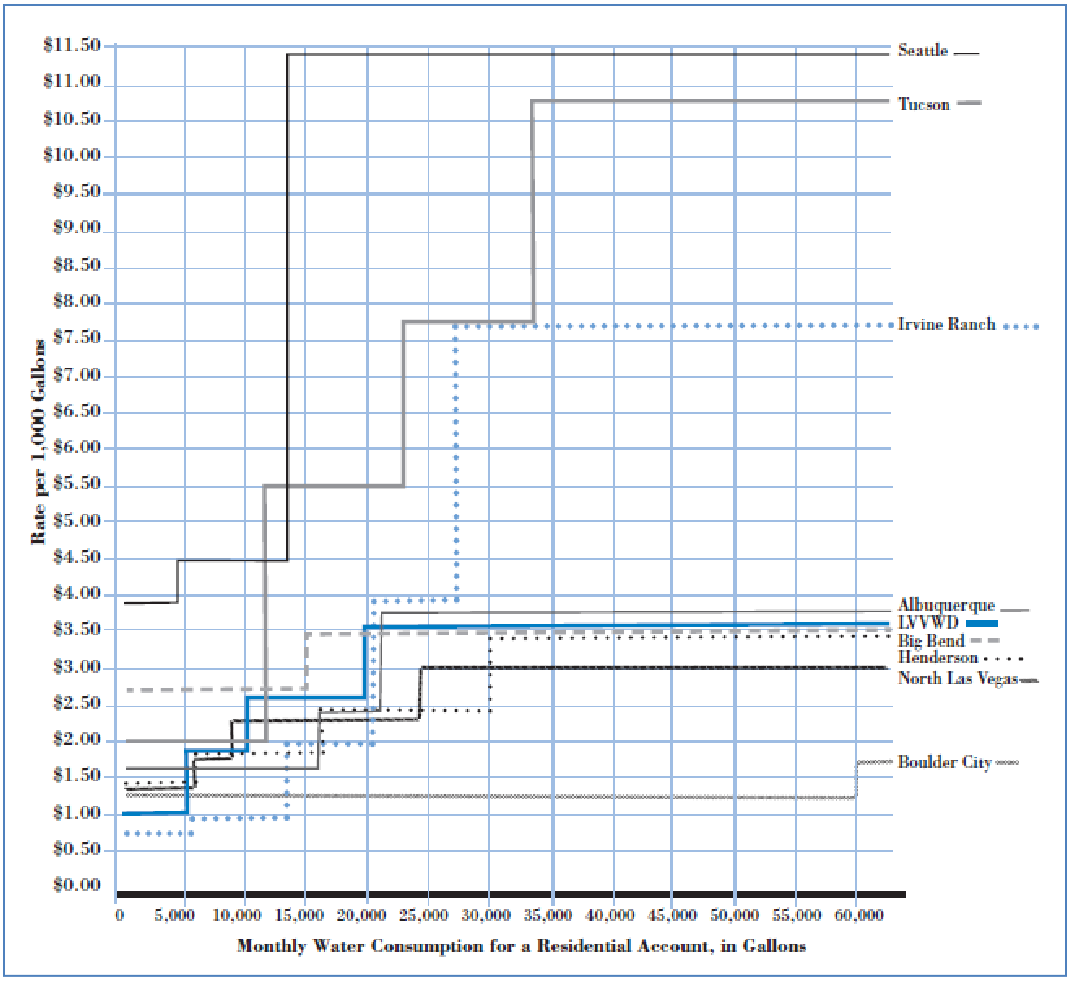
Examples of rate structures and average cost functions for several communities are shown below (Figures 1 and 2).

Figure 1. Example of Average Water Cost Functions



Cooley et al. (2007).

Figure 2. Example of Block Rate Structures for Several Communities



Source: Cooley *et al*. (2007).

III. Non-Price Mechanisms

Price mechanisms, while effective, are inherently limited. Public resistance to rate increases and increasing price inelasticity necessitate the use of non-price mechanisms. Also, integrating price and non-price mechanisms may improve the overall effectiveness (both in economic and water savings terms). Several studies support the notion of synergy between price and non-price mechanisms (e.g., Moncur, 1987; Campbell et al., 2004), and that the effectiveness of price changes is significantly impacted by non-price mechanisms (Howe and Geomans, 2002). Below, we describe a host of non-price mechanisms that have been successfully applied in the United States.

A. Education and Awareness

As Howarth and Butler (2004) note, gaining public support for water conservation may be crucial to programmatic success. As a result, awareness and education campaigns are usually accompany other water conservation mechanisms. For example, the effectiveness of pricing mechanisms can be strongly influenced by the billing process (Stevens et al. 1992; Kulshreshtha 1996). In fact, significant decreases in water use might only accompany a large price hike if the public is highly aware of the price increases and the new price schedule (Nieswiadomy 1992). Carter and Milon (2005) used survey and household water use data from three Florida utilities. Only 6% of their respondents knew the price they paid for water. They also found that households with increasing block rates were *less* likely to know what they paid for water, but that those who said they knew the price of their water had 2-5 times larger elasticities (they also used more water on average).

A few studies have measured the disaggregated impact of education and awareness on water use. Renwick and Green (2000) report an average 8% water savings in eight urban California areas due to education/information. US EPA (1998) estimates that an education program in Austin was responsible for 2-5% annual water savings. Wang et al. (1999) estimated a 4.8% reduction in summer water use between 1992 and 1997 due to bill inserts and pamphlets in New Castle County, Delaware. Nieswiadomy (1992) used a survey of 430 US water utilities to estimate the impact of public education campaigns in the West, South, North Central and Northeast United States. The results indicated that these campaigns are only effective in the West, perhaps due to their experiences with droughts. Renwick and Green (2000)'s panel data regression analysis of eight urban California water agencies found an average 8% water savings associated with public awareness campaigns, while Howarth and Butler (2004) report zero impact on demand in Swindon, England. Shaw et al. (1992) found that San Diego's intensive education and advertising campaign achieved a 22% reduction in water use. Syme et al. (2000) reviewed the literature on the impact of public awareness campaigns on voluntary water conservation. They estimate that up to 25% of short-term water savings can be attributed to such campaigns, but long-run impacts have not be measured. On the other hand, Wang et al. (1999) found public awareness campaigns to have no statistically-significant effective when used in conjunction with price and device retrofit in New Castle County, Delaware. They used panel data on 500 households to estimate water use changes from 1992 to 1997. The information program appeared to have a very slight and short-term impact (only 1 year), but the number of households changing water use was perhaps too small for the model to adequately estimate the impacts of the campaign.

Decisions to curb water demand have been influenced by the degree to which towns have experienced a perceptible limit to their supply. A crisis brings the focus to water and allows water managers to redefine the problem, thus allowing conservation as a possible solution. 'Regional' water systems may impact perceptions of water vulnerability (Brown 2006).

Outreach efforts can also improve retrofit kit installation rates (Dunham et al. 1995). Dunham et al. (1995) report that Seattle's retrofit kit program achieved a 34% installation rate without and 68% with a campaign that included advertising, newspapers, and 'organizers.'

The state of Colorado used a xeriscaping DVD to help promote efficient lawn landscapes (CFWE 2007). From April to June 2007, 97,900 DVDs were mailed to residents in Douglas and Arapahoe counties. A random mail survey to 3000 DVD recipients followed (n=208). Only 48% of respondents had viewed the video. The DVD promoted awareness of water issues (92% of viewers). However, the effectiveness of the DVD is suspect. While 76% reported already using water conservation measures, only 78% said they would pursue water conservation after watching the video.

Awareness programs can be particularly cost-effective. For example, a recent innovation in billing includes conservation 'report cards' that use smiley faces to indicate how energy efficient customers are compared to their neighbors (NY Times 2009). This approach is being used in 10 major metropolitan areas. In Sacramento, after 6 months, customers receiving the report cards reduced their energy use by an average of 2% compared to those not receiving report cards. A similar program by the Owatonna Public Utility in Minnesota cost $654,532 for about 11,300 electric, 10,000 natural gas and 9,400 water customers – about $58/household (People's Press 2008). In studies using social norms to motivate environmental conservation, it has been found that among three types of messages – conserving to save the earth for future generations, personal financial savings, and a majority of neighbors had already taken steps to curb their energy use – only the message regarding neighbors' behavior had significant effect (Goldstein et al. 2008).

B. Restrictions and Household Rationing

Voluntary and mandatory measures are effective water conservation mechanisms. Voluntary measures publicize suggested water use behaviors, such as off-peak or every-other-day lawn irrigation. Mandatory measures impose penalties for violating use mandates.

Mandatory measures seem to provide positive results. Los Angeles achieved a 36% drop in demand due to mandatory restrictions over the same period (Shaw et al. 1992). Also, new plumbing codes (EPA 1998) have resulted in overall 5-10% water savings since 1996. In Goleta, California, restrictions on certain uses, such as washing cars and irrigating lawns during peak hours, reduced water use by 29% (Renwick and Archibald 1998). The city of Tampa's Sensible Sprinkling landscape evaluatations program achieved a 25% reduction in water use (EPA 2002). The program includes irrigation and plumbing codes, fines for violations, and water use restrictions. Outdoor irrigation is limited to one day/week and prohibited between 8am and 6pm, and irrigation systems must incorporate rain sensors. Free rain sensors are distributed along with education materials. The landscape code limits irrigated turfgrass to 50% in new developments. Also, drought-tolerant, native plants are encouraged. Renwick and Green (2000) estimate that rationing led to a 19% drop in demand in eight California communities.

There is very little evidence supporting the effectiveness of voluntary measures. One noted exception is Shaw et al. (1992), who estimated that San Diego's water use fell by 27% due to voluntary restrictions during a 1990-1991 drought. Kenney et al. (2004) examined voluntary and mandatory restrictions on lawn irrigation in eight Denver areas. They found that voluntary restrictions produced between 4-12% drops in water use, while mandatory restrictions led to much larger drops of 18-56%. Lee and Warren (1981) also found that mandatory measures were much more effective than voluntary ones. They examined 12 Iowa districts that adopted voluntary measures in 1977, four of which later imposed mandatory measures. Predicted and actual water use was compared. Narayanan et al. (1985)'s study of 33 Utah communities from 1976-1977 found evidence that voluntary restrictions may lead to increased water use, perhaps because users expect stronger restrictions to follow.

Mandatory measures returned the highest water use reduction, but voluntary measures were also very effective in towns that were located near other towns with severe water shortages. Renwick and Green (2000) found that mandatory restrictions on peak-hour lawn irrigation and washing impervious surfaces led to a 29% drop in use. Their study involved eight California utilities between 1989 and 1996, while California was in a drought.

C. Retrofits, Rebates, and Improved Devices (low flow toilets, showers, washers, etc)

Retrofit programs involve modifying existing appliances, etc with devices that improve efficiency. This includes faucet aerators, toilet displacement dams, low-flow showerheads and the like. Related programs would also include replacing inefficient appliances, for example with low volume toilets, front-loading clothes washers, and certain dishwashers.

Retrofit programs can be fairly effective – reducing water use by about 10% on average (Inman and Jeffrey 2006; Wang et al. 1999; Mayer et al. 2003; Maddaus 1984; Turner et al. 2004). Given the typically low cost of such programs, retrofit measures are very effective on a water-saved-per-dollar-spent basis. Tables 1 - 6 reports a comparison of cost, water saved and participation rates for various water conservation measures.

While much more expensive, replacement of household appliances with newer, more efficient versions can significantly reduce water demand by 35-50% on average (Inman and Jeffrey 2006). The most exhaustive studies of retrofits and replacements were conducted by Mayer et al. (2000), Mayer et al. (2003), and Mayer et al. (2004b) with over 100 homes in Seattle, San Francisco, and Tampa. In each case, homes were retrofitted with faucet aerators, low-flow showerheads, and high efficiency toilets and clothes washers. These studies identified leakage –

primarily from faulty toilet valves – as being responsible for a large amount of water loss. Reduction of water waste from leaks accounted for the majority of retrofit savings in San Francisco and Tampa Bay. Toilet replacement accounted for the highest savings for Seattle, and second-most for San Francisco and Tampa Bay. In San Francisco, total demand reduction was 39.4% with leakage and 27.9% without (Mayer et al. 2003). Hot water use dropped by 21.8% - a potentially significant savings in energy as well.

Conservation kits that include several devices (e.g., faucet aerators and low-flow showerheads) as well as information/education materials are also effective. Renwick and Green (2000) found that free retrofit kits that included toilet displacement dams, dye tablets to detect toilet leaks, and a low-flow showerhead reduced average water use by 9%. An econometric model by Renwick and Archibald (1998) found that the presence of an additional low-flow toilet in each household reduced water use by 10%, and for each low-flow showerhead, water used fell by 8%. Mayer et al. (1998) found similar results – almost 20% water savings from low-flow toilets and 9% savings from low-flow showerheads. In some cases, low-flow fixtures and appliances produced no statistically-significant water savings. Ultra low-flush toilets in Santa Barbera, California (Renwick and Green 2000) is one such example. The city of Tampa replaced 27,239 toilets, savings 254.9 million gallons/year (EPA 2002). Although population has increased by 20% from 1989 – 2001, per capita water use has fallen by 26%.

Campbell et al. (1999) used regression analysis of 1200 water bills from 1990-1996 in Phoenix, Arizona. Among the tools analyzed were water price increases, low-flow retrofits and kits, and a local ordinance mandating water saving devices for new and replacement fixtures. While estimated to conserve 1,000 times less water than a 10% price increase, the ordinance was most effective of the non-price measures.

The US GAO (2000) provides a description of program costs, savings, and duration of six toilet retrofit/replacement programs (Table 1). These occurred primarily during the 1990s in Austin (Texas), Los Angeles (California), New York (New York), Phoenix (Arizona), Tampa (Florida), and Hillsborough County (Florida). For the six programs, 2,330,939 toilets were distributed free or through rebate programs. Estimated water savings ranged from 23.4 to 53.8 gallons per day, and total water savings were 102,018,864 gallons per day. The total cost of the programs was $409.6 million, or $0.25 per gallon saved per day. Average costs per toilet were $175.72. Dunham et al. (1995) reviewed case studies of five successful water conservation programs. These were primarily rebate/bill credit programs (New York, Los Angeles, San Antonio, Austin, and Seattle), threat of regulation (Los Angeles), and showerhead kits (Seattle).

Table 1. Rebate and Retrofit Case Studies

	Total cost	# of measures	Cost of measure	Water savings
Program				
New York toilet rebate	$270mn	1-1.25mn	$150(each addl)-$240(first)/toilet	29-68 gpcd
Los Angeles toilet rebate	$6.56mn	65,167	$110/toilet + $25 for install/promo	58.6 gpcd +/- 14 gpcd
San Antonio toilet rebate	$315,000	4,200	$75/toilet	79,000 gpd
Austin toilet rebate	$155,000	7148	$40 (residential) -$75 (commercial) credit	172,000 gpd
Seattle retrofit kit (showerhead)	$3,877,500	330,000	$11.75/kit	Not available
Seattle toilet rebate	Not available	Not available	$100-$150/facility	30%

Source: Dunham et al. (1995).

Conservation programs typically enjoy high returns to investment (see Tables 2 – 4). For example, the Houston, TX retrofit program projects a 3.7 to 1 benefit-cost ratio, and a predicated total savings of $262 million (EPA 2002). The program included a combination of conservation kits (showerheads and aerators), school-age education, and low-flow toilet replacement. One study used undergraduate students with self-administered water audits. Apartment users had higher water use, but when correcting for direct payment of the water bill, this effect disappeared. Residence managers can save over $45/person/year by installing standard low-flow water use devices: $39.53 in residence halls, $54.86 in apartments, and $40.65 in single family homes (Buckley 2004). Davis (2008) estimated net savings from efficient, front-loading washer installation. In the Bern, Kansas program, 98 households were provided with free replacement washing machines. 83% of households saved money on energy in present value terms. The cost of washing clothes fell by 65% (from $.11/lb to $.04/lb). The washers use 44% less energy and 41% less water. Present-value cost savings from energy were $524 at a 5% discount rate. Efficient washers cost, on average, $239 more. Total cost per cycle were $.30 less for the efficient machines. Water use per cycle fell from 10.4 gallons for hot and

27.8 gallons for cold to 4.3 gallons for hot and 19.4 gallons for cold. Dickinson et al. (2003) conducted a nationwide survey of 1,200 households to estimate the impact of plumbing standards (efficient showerheads, toilets and faucets) on water use. On average, efficient toilets use 52% less water, showerheads 21% less water, and faucets use 2% less water. The total drop in water use from these fixtures was 32%. For each household that installed all three, utilities saved $26/person; communities saved $127 on average. A total of $7.5 billion on infrastructure was saved. Including hot water savings, the total savings could be $35 billion in the US.

Table 2. Conservation Results (Expected) for Cary, NC Programs

Program	Water savings/yr 2009 (mgd)	Water savings/yr 2019	Unit cost of water saved	First 5 yrs cost	Benefit/cost ratio
Residential water audits	0.053	0.077	546.85	71,335	1.13
Public education	0.3	0.41	400.59	314,280	1.53
Toilet flapper rebate	0.005	0	828.04	11,762	1.03
Water reclamation facility	0.27	0.3	n/a	n/a	n/a
Landscape water budgets	0.013	0.023	754.33	64,175	0.88
New home points program	0.5	0.77	38.18	100,000	16.2
Landscape/irrigation codes	0.02	0.04	276.07	128,350	2.6
Inverted-block rate structure	0.14	0.42	49.4	54,000	14.26
Combined results	1.17	2	137.5	655,552	4.44

Source: EPA (2002).

Table 3. Residential Indoor End Uses of Water

End Use	Without Conservation		With Conservation		Water Savings	
	Percent (%)	Gcd*	Percent (%)	Gcd*	Percent (%)	Gcd*
Toilets	27.7	20.1	19.3	9.6	52	10.5
Showers	17.3	12.6	20.1	10.0	21	2.6
Faucets	15.3	11.1	21.7	10.8	2	0.3
Baths	1.6	1.2	2.4	1.2	0	0
Clothes Washers	20.9	15.1	21.3	10.6	30	4.5
Dishwashers	1.3	1	2	1	0	0
Other Domestic	2.1	1.5	3.1	1.5	0	0
Leaks	13.8	10	10.1	5	50	5
Total Indoor Use	100	72.6	100	49.7	32	22.9

Source: Dickinson et al. (2003); *Gcd = gallons per capita per day.

Table 4. Estimates of Indoor Water Use with and without Conservation

End Use	Without Conservation		With Conservation		Water Savings
	Percent of total (%)	Amount gpcd	Percent of total (%)	Amount gpcd	Percent (%)
Toilets	28.4%	18.3	23.2%	10.4	44%
Clothes washers	23.1%	14.9	23.4%	10.5	30%
Showers	18.8%	12.2	22.4%	10.0	18%
Faucets	16.0%	10.3	22.5%	10.0	2%
Leaks	10.2%	6.6	3.4%	1.5	77%
Baths	1.9%	1.2	2.7%	1.2	0%

Dishwashers	1.6%	1.1	2.4%	1.1	0%
Total Indoor Use	100%	64.6	100%	44.7	31%
Toilets	28.4%	18.3	23.2%	10.4	44%

Source: AWWA Water Wiser 1997, cited by EPA 2009.

D. Offsetting Behavior, Demand Hardness, and Persistent Impacts

Offsetting behavior can sometimes result in *increases* in water use after retrofits and replacements (Campbell et al. 2004; Geller et al. 1983). The installation of low-flow showerheads may lead to longer showers (Mayer et al. 1999). For example, a study of 129 households in Blacksburg, Virginia found evidence of this behavior following the installation of toilets dams, aerators, and two other plumbing devices (flow control device and shut-off shower control) in an experiment that also included information feedback and education. Davis (2008) conducted a field trial involving front-loading clothes washers, and found a 5.6% increase in washing after the replacement. Geller et al. (1983) also found offsetting behavior in their study of 129 residences for 70 days. They used a 2x2x2 design involving education, daily consumption feedback, and retrofit. The retrofit group yielded less water savings than expected, which they attributed to offsetting. They noted other studies where the water users were not informed of expected savings associated with the retrofits. In those studies, water savings were substantially more. They also suggest that low water prices can render education programs ineffective. Campbell et al. (2004)'s study of a 6-year program in Phoenix, Arizona discovered strong offsetting behavior that was significantly counteracted by moral suasion (the idea that the whole community is working toward a common goal). Indeed, the authors caution against simply relying on retrofit/replacement programs without complementary education and awareness programs and/or rules. Offsetting behavior may occur when households know that conservation devices are causing conservation, but communication in the form of moral suasion (person-to-person communication about cooperation toward a common goal) can overcome this effect (Campbell et al. 2004). Davis (2008) found that, after receiving a highly efficient washing machine, washer use increased by 5.6%. On average, the washers use 48% less energy and 41% less water per use, so savings were still overwhelmingly positive.

Demand hardening can occur as water conservation measures are implemented, and as systemic inefficiencies are reduced, additional water conservation measures are less-and-less effective (Cooley et al. 2007). Cooley et al. (2007), however, found that demand no evidence of demand hardening from indoor or outdoor efficiency measures in Las Vegas, Nevada. The authors noted that households that adopted low-flow faucets and efficient appliances can still reduce their water use during shortages by adjusting their behavior. Given the benefits of water conservation over the long-run (e.g., reduced vulnerability to drought), they argue, communities should not forego water conservation for fear of demand hardening.

Water conservation programs can lead to persistent behaviors that outlast the need for water use reductions (Gilbert et al. 1990; Shaw et al. 1992; Shaw and Maidment 1988). Shaw et al. (1992) examined San Diego's voluntary water restrictions, and found that they persisted for several months although weather conditions normalized. Shaw and Maidment (1988) found that the effects of a mandatory restriction lasted at least a year after the program was discontinued. The authors suggest that this might be the result of homeowners adjusting their habits to decrease consumption.

E. Lawn Irrigation (sprinkle, drip, restrictions, ordinances, etc.) and Xeriscape Landscaping

Several factors impact the level of outdoor water use. Households with more expensive and technologically-sophisticated irrigation systems use more water than those with manual systems (Syme et al. 2004). Water use tends to increase with the sophistication of lawn irrigation equipment (Lyman 1992; Mayer et al. 1999; Renwick and Archibald 1998; Cavanagh et al. 2002). Households with sprinkler systems use 9% more water on average than those without (Renwick and Archibald 1998). Those with in-ground sprinkler systems use 35% more outdoor water; if the system has an automatic time, they use 47% more (Mayer et al. 1999). By comparison, those with drip irrigation systems use 16% less, and those with hand-held irrigation use 33% less. Chestnut and McSpadden (1991) estimated that users in Los Angeles, California with automatic irrigation systems use 11.2% more water on average. Renwick and Archibald (1998) found that adoption of efficient irrigation systems reduce average household use by 11%. The effects were much more pronounced for large lots (average 31% drop) than small landscapes (average 10% drop). Technologies that incorporate evapo-transpiration and soil moisture sensors are likely to significantly reduce water use.

F. Leak Control and Water Metering

Leaks can account for a tremendous percentage of water use; fixing leaks can sometimes achieve more water savings than other conservation tools (Inman and Jeffrey 2006).

Metering allows utilities to determine water use on a per unit basis. If used in conjunction with pricing and other financial incentives, metering can be particularly effective at reducing systemic water demand. On average, metering reduces water demand by 20% (Inman and Jeffrey 2006). The effects tend to be much stronger for outdoor than indoor demand (e.g., Maddaus 2001). Metering also tends to have a large initial impact that is eroded over time. Maddaus (2001) reported an 18.9% reduction in water use from 1997-1998 in Davis, CA following metering. From 1997-1999, the average reduction only measured 8.7%. Metering also shows significant reductions for multi-family buildings. Mayer et al. (2004b) found that a combination of sub-metering and a price increase led to a 15.6% reduction in per capita demand.

IV. Limitations of studies

We note that water use and conservation policies often lack clear purpose (Renwick &Green 2000), which can lead to poor data collection on policy impacts. Also, the implementation of multiple policies at once (e.g., retrofits and inclining block rates at the same time) muddle the analysis.

Further, data limitations are a serious barrier to evaluating the effectiveness of water use and conservation policies. For example, data that are both cross sectional and time series (panel data) are usually unavailable. Fewer than half the studies reviewed by Hewitt and Hanemann (1995) used disaggregated, household-level data needed for an individual demand model. As a result, many studies rely on aggregate data that cannot reflect individual heterogeneity (income, race, etc); and elasticity calculations are prone to large error (Martinez-Espineira 2006). Also, in most studies involving water pricing, prices have not varied a great deal, which means that the relevant range for elasticity calculations is necessarily very limited. One noted exception is Pint (1999), who estimated the impact of large price increases (and increasing block rates) – over 400% increase for the highest block.

Michelson et al. (1999) point out that simple pre/post analysis fails to take into account other factors that might impact water use, for example droughts. Length of study can influence results. Mechanism effectiveness is not uniform over time (Michelson et al. 1999). For example, water use fell by 18.9% in the first year of a metering program in Davis, California, but leveled-out at only an 8.7% decrease over the first two years (Maddaus 2001).

Many studies may suffer from omitted variables. Some studies that include a weather variable find it statistically-significant (e.g., Kenney et al. 2004; Hewitt and Hannemann 1995; Nieswiadomy 1992), but many have not (e.g., Gegax et al. 1998; Michelson et al. 1999). Other factors, such as household characteristics, are well known to influence demand. Income elasticity estimates are positive and inelastic (Piper 2003), generally between 0.2 and 0.6 (Cavanagh et al. 2002). For example, Cochran and Cotton (1985) estimate income elasticity to be 0.58 for Oklahoma City. Size of household is also a factor (e.g., Nieswiadomy 1992; Renwick and Archibald 1998; Cavanaugh et al. 2002; Piper 2003). For example, Cavanagh et al. (2002) examined data from 1,082 households and found that for each additional person in the household, water use increases by 22%. On the other hand, Nieswiadomy (1992) found that household size was only significant in the south region for a marginal price model, for the northeast and west for an average price model of demand, and for the west using a price perception model. However use depends on age as well. For example, highest per-capita water users in Moscow, Idaho are children under 10 and the lowest are teens (Lyman 1992). In their study, they found that children used 2.5 times more water than teens, and 1.4 more than an adult. Dwelling characteristics can also impact demand. For example, Cochran and Cotton (1985) found that number of households (i.e., more multi-family versus single family) per thousand population was a statistically-significant predictor of demand; however, the variable was insignificant when water price and per capita income entered the model. Home age also impacts use, as newer homes tend to be more efficient (e.g., Mayer et al. 1999; Cavanagh et al. 2002). However, Cavanagh et al. (2002) caution that homes built in the 1960-70s are relatively heavy water users because they do not have the smaller connections and fewer water fixtures of much older homes, or the efficient fixtures that are required of homes built after the 1980s. Mayer et al. (1999) suggest that the retrofit and replacement programs are perhaps most effective for homes built in the 1970s and 1980s. Number of bathrooms tends to increase water use (Hewitt and Hanemann 1995). For example, Cavanagh et al. (2002) estimate that each additional bathroom increases water use by 6%. However, Lyman (1992) found a negative correlation. House size, generally, is also linked to water use. Cavanagh et al. (2002) estimate a 13-15% increase in water demand for each additional 1000 square feet. Lot size is also positively correlated with water use (Lyman 1992; Renwick and Green 2000; Cavanagh et al. 2002). For example, Renwick and Green (2000) report a 2.7% increase in water demand for each 10% increase in lot size.

Attitudes about conservation and water use can impact water demand, but Syme et al. (2000) point out the consensus in the literature of a weak correlation between conservation attitudes and conservation behavior.

Savings of 35% - 70% are possible from changes in residential landscaping and improved management of outside watering, which often accounts for more than 50% of total residential water use. Hurd (2006) examines landscapes in three New Mexico cities to identify and measure behavioral factors affecting water conservation. Using survey data, landscape choices are analyzed with a mixed logit model that assesses the effects of landscape and homeowner characteristics on choice probabilities. Water cost, education, and regional culture are significant determinants of landscape choice. Moral suasion can also have a positive influence (Hurd 2006).

Some studies involve intrusive monitoring that may influence the results.

Residential water use reductions are linked to a number of concrete benefits that may not be fully captured by economic evaluations. Water conservation programs can lead to reductions in costs faced by water suppliers, such as for maintaining, operating, expanding or acquiring water-related infrastructure (Maddaus 1999). Australian water policy is based on the concept that a drop of water saved equals a drop of water supplied (Fane et al. 2004).

Although price and non-price mechanisms are usually co-implemented, the vast majority of studies do not explicitly measure the impact of interactions between price and non-price mechanisms (e.g., Nieswiadony 1992; Renwick and Archibald 1998). A noted exception is Michelson et al. (1999). Their study of panel data over 11 years from seven western cities (2 in California, 3 in New Mexico, and 2 in Colorado) included a price/non-price interaction variable; however the term was statistically insignificant (although they did not differentiate between different kinds of non-price programs). Individual program effectiveness is also influenced by the number of other programs implemented. There is evidence that a combination of price and non-price programs improves the overall effectiveness of both (e.g., Moncur 1987); however, marginal returns to the number of programs are apparent (Michelson et al. 1999). Michelson et al. (1999) found that cities employing fewer water conservation mechanisms experienced slightly larger per-mechanisms effects. On the other hand, Gegax et al. (1998) argue for a critical mass of programs below which conservation is negligible; and Wang et al. (1999) found no statistically-significant impact of an education campaign when used in conjunction with price and retrofit programs in Delaware.

A. Current Institutional and Political Barriers

Concerns about revenue streams are important barriers to the use of water conservation tools. Public utilities may not have sufficient incentives to support water conservation programs, particularly because conservation practices are expensive to implement and investments are not quickly recovered (Wang et al. 1994). Municipalities receive revenue by selling water (Kennedy & Geomans 2008). Price-based mechanisms could lead to short-run profits that exceed statutory maximums (Mansur and Olmstead 2007). Water conservation absent rate increases can lead to financial shortfalls (Anderson 1996). For example, voluntary water restrictions in Los Angeles, California during a 1991 drought led to a more than 20% drop in the utility’s revenues (Hall 2000). Rate increases soon followed to make up the shortfall. Establishment of a contingency fund, in conjunction with long-run demand forecasting, can alleviate some of these concerns (Chesnutt et al. 1996).

Politics also govern the use of conservation. In the late 1970s, Tucson, Arizona was the first American city to set water rates equal to marginal cost. This resulted in a large price increase, and a year later the entire city council was ejected from office (Hall 2000). During droughts conservation policies are politically acceptable (Syme et al. 2000), (Kennedy & Geomans 2008), (Brown 2006). But generally, lawn watering restrictions are politically “unpalatable” (Brown 2006).

Institutional barriers are also a problem, including: clouded titles, water transfer restrictions, illusory water savings, insecure rights to conserved water, shared carry-over storage, interstate compacts, conservation attitudes, land tenure arrangements, and uncertain duty of water. Price is a major limiting factor. (Ward, Michelson, and DeMouche 2007). Legal limitations hinder municipalities to pricing water during drought situations (Kennedy & Geomans 2008). Since increasing prices are politically dangerous municipalities have little cash to maintain infrastructure (Brown 2006) causing water loss.

Permit structure can also hinder water conservation efforts. For example, in Florida, agricultural water producers receive consumptive use permits from Water Management Districts. These permits allow water withdrawal for "reasonable and beneficial uses such as public supply (drinking water), agricultural and landscape irrigation, and industry and power generation" (FWMD 2009). Water conservation can lead to consumption below the permitted level, which can lead to a reduction in permitted withdrawals. This type of permit system creates a strong disincentive for water conservation, particularly for agricultural producers, and it does not allow temporal or spatial transfer of permitted water amounts.

In the context of water markets, lack of transferability hinders efficiency of water use. Brooker et al. (2005) estimated that future drought damages in the Rio Grande Basin (New Mexico and Texas) could be reduced 20-33% by allowing interstate water markets that allow transfers.

Lack of information and guidance for water utilities, particularly smaller and rural utilities, is a formidable barrier. In Oklahoma, a lack of guidance in the design of conservation rate structures can hinder water conservation. Also, a lack of information about the effectiveness and efficiency of alternative conservation tools available to utilities (specific to their customer base), a lack of monitoring and enforcement of mandatory water use restrictions in some locations, and a reliance of some landowners on un-monitored private wells present hurdles to water conservation (Borisova [personal communication] 2009).

In seemingly wet states, such as Florida, the apparent abundance of water can make it difficult to garner public support for water conservation. This is particularly true in places where groundwater can be accessed close to the surface by private landowners. This view of water does not account for seasonal variation, droughts, or environmental uses. A 2003 study in Georgia found that the biggest reason why residents do not adopt water conservation plans is a lack of feedback about whether their efforts were effective (Duda 2003).

One important barrier to public support for conservation is the potential impacts on low-income users. The impacts of water conservation programs have unequal impacts on some groups. For example, Davis (2008) estimates that 17% of water users would not benefit from water and energy efficient clothes washers. They used data from 98 households in Bern, Kansas that received front-loading, efficient clothes washers free of charge. They constructed a utility model and estimated expected impacts. Costs of installation exceeded water and energy-saving benefits for households that used relatively little water pre-installation.

In Oklahoma, other factors play a serious role as well. For example, cost/benefit analysis is lacking for water conservation programs and projects; agricultural water use is largely unmetered; there is a lack of information about water conservation options for rural areas; older and rural systems with narrow funding options must contend with sunk costs for inefficient systems; local ordinances prevent the use of some conservation tools (e.g., prohibition of rain barrels rules in Tulsa); water is perceived as abundant in many areas, and this has led to a lack of awareness of the value of water; and groundwater is viewed as a property right and not under the purview state interference.

B. Questions Unanswered by the Literature

- Long-run vs short run effectiveness (Kennedy and Goemans 2008); which programs work best under drought conditions?
- Forecasting non-price policy affects (Olmstead and Stavins 2008). What is the lag time? How much water will be conserved?
- When does more knowledge of water use increase/decrease consumption?
- Efficient billing procedure? (bill which is understandable to customers)
- Public involvement into the design of conservation programs?

C. Description of water conservation mechanisms

The US Environmental Protection Agency provides guidance for water systems seeking to implement water conservation measures (EPA 1998; EPA 2009):

Level 1 Measures

Source-water metering: helps account for system losses.

Service-connection metering: needed to supply customers with use information and to more accurately track and bill for water use.

Public-use water metering: Helps with loss control, costing and pricing.

Leak repair: system audits, leak detection and repair; automated sensors; loss-prevention program.

Pricing: metered rates, cost analysis, conservation signals.

Advanced pricing: Allocate costs by customer class and/or type of water use; seasonal variations. Conservation rate structures, marginal cost pricing. Take advantage of different elasticities of demand. Address potential revenue instability with revenue-adjustment mechanisms.

Information/water bill: Clear and understandable, informative, and sometimes educational water bill.

Education programs: School programs, printed/video materials, speakers, etc.

Level 2 Measures

Audits of large-volume and large-landscape users: Identify categories of water use, and opportunities for efficiency.

Selective end-use audits: Residential audits by water-use practices within each customer class (e.g., older housing).

Retrofits, replacements: Efficient toilets, showerheads, faucets.

Pressure management: Pressure-reducing valves, systemwide pressure control.

Landscape efficiency: Promotions, irrigation sub-metering, landscape planning, and irrigation management.

Level 3 Measures

Reuse and recycling: Graywater use (treated wastewater for nonpotable uses) for industrial, agricultural, groundwater recharge, and direct use.

Water use regulation: (SR) Restrictions on nonessential uses (lawn watering, car washing, filling swimming pools, washing sidewalks, and irrigating gold courses); restrictions on commercial car washes, nurseries, hotels and restaurants; standards for water-using fixtures and appliances, bans on decorative fountains, non-recirculating car washes & laundries; bans on other types of water use or practice as needed.

V. Other Cost and Water Savings Data

Tables 5 and 6 report the results of two studies on water savings and conservation program costs in two states – Arizona and Texas. Both provide valuable reference data for evaluating and planning water conservation programs in Oklahoma.

Table 5. Summary of Cost and Savings from Arizona Water Conservation Tools

User Type	Program	Base demand	Water savings	Cost of measure
Residential	Pool cover rebate	-	-	$362/AF
	W.E.T. indoor rebate	-	-	$163/AF
	AZ state water bank	-	-	$461/AF
	Water smart landscape rebate	-	-	$467/AF
	W.E.T. outdoor rebate	-	-	$652/AF
	Efficient appliances/fixtures	78	40%	-
	toilets	21	55%	-
	leaks	14	86%	-
	clothes washers	15	40%	-
	showers/bath	13	12%	-
	dishwashers	1	38%	-
	other domestic	3	0%	-
	faucets	11	0%	-
	Efficient landscapes	-	40%	-
Commercial	Efficient appl./fixtures (hotels & casinos)	80	29%	-
	showers	16.2 per guest	29%	-
	faucets	9	17%	-
	toilets	10.9	54%	-
	laundry	13.7	42%	-
	kitchen	16.7	14%	-
	icemakers	1.1	20%	-
	cooling	12.3	20%	-
Supply Expansion	6-basin groundwater pipeline	-	-	$1,163/AF
	5-basin groundwater pipeline	-	-	$1,320/AF
	River diversion	-	-	$2,039/AF

Source: Cooley et al. (2007)

Table 6. Estimates of Water Conservation Cost and Savings in Texas

	Savings /capita - urban	Savings/ capita - sub urban	Savings/ capita - rural	People/ unit - urban	People/ unit – sub urban	People/ unit - rural	Savings/ unit - urban	Savings/ unit - sub urban	Savings/ unit - rural	Measures/ unit	Savings/ measure (gpd)	Cost/ measure	Cost/AF saved (amort)	Delivery method
Residential														
SF Toilet Retrofit	10.5	10.5	10.5	2.5	2.7	2.2	26.7	28.5	23.0	2.0	13.3	$85	$403.45	free or rebate
SF Showerheads and Aerators	5.5	5.5	5.5	2.5	2.7	2.2	14.0	14.9	12.0	2.0	7.0	$7	$115.77	free
SF Clothes Washer Rebate	5.6	5.6	5.6	2.5	2.7	2.2	14.2	15.2	12.3	1.0	14.2	$120	$801.17	rebate
SF Irrigation Audit-High User	19.7	18.4	22.8	2.5	2.7	2.2	50.0	50.0	50.0	1.0	50.0	$70	$458.95	staff
SF Rainwater Harvesting	15.6	14.6	18.1	2.5	2.7	2.2	39.7	39.7	39.7	1.0	39.7	$250	$541.33	rebate
SF Rain Barrels	1.7	1.6	2.0	2.5	2.7	2.2	4.3	4.3	4.3	1.0	4.3	$45	$900.03	rebate or distrib.
MF Toilet Retrofit	10.5	10.5	10.5	1.6	1.7	1.7	16.9	18.3	17.3	1.2	14.1	$75	$337.80	free or rebate
MF Showerheads and Aerators	5.5	5.5	5.5	1.6	1.7	1.7	8.8	9.6	9.1	1.2	7.4	$4	$62.78	free
MF Clothes Washer Rebate	1.0	1.0	1.0	1.6	1.7	1.7	1.7	1.7	1.7	0.056	30.0	$120	$552.51	rebate
MF Irrigation Audit	1.6	1.4	1.5	1.6	1.7	1.7	2.5	2.5	2.5	n/a	125.0	$150	$393.39	staff
MF Rainwater Harvesting	5.7	5.3	5.6	1.6	1.7	1.7	9.2	9.2	9.2	n/a	461.7	$2050	$381.87	rebate

Commercial														
Toilet Retrofit	-	-	-	-	-	-	-	-	-	-	26.0	$150	$365.44	free or rebate
Coin Clothes Washer Rebate	-	-	-	-	-	-	-	-	-	-	45.0	$170	$521.81	rebate
Irrigation Audit	-	-	-	-	-	-	-	-	-	-	125.0	$150	$393.39	staff
General Rebate	-	-	-	-	-	-	-	-	-	-	1.0	$1.2	$103.21	rebate
Rainwater Harvesting	-	-	-	-	-	-	-	-	-	-	461.7	$2050	$381.87	rebate

Source: GDS Water Associates (2002)

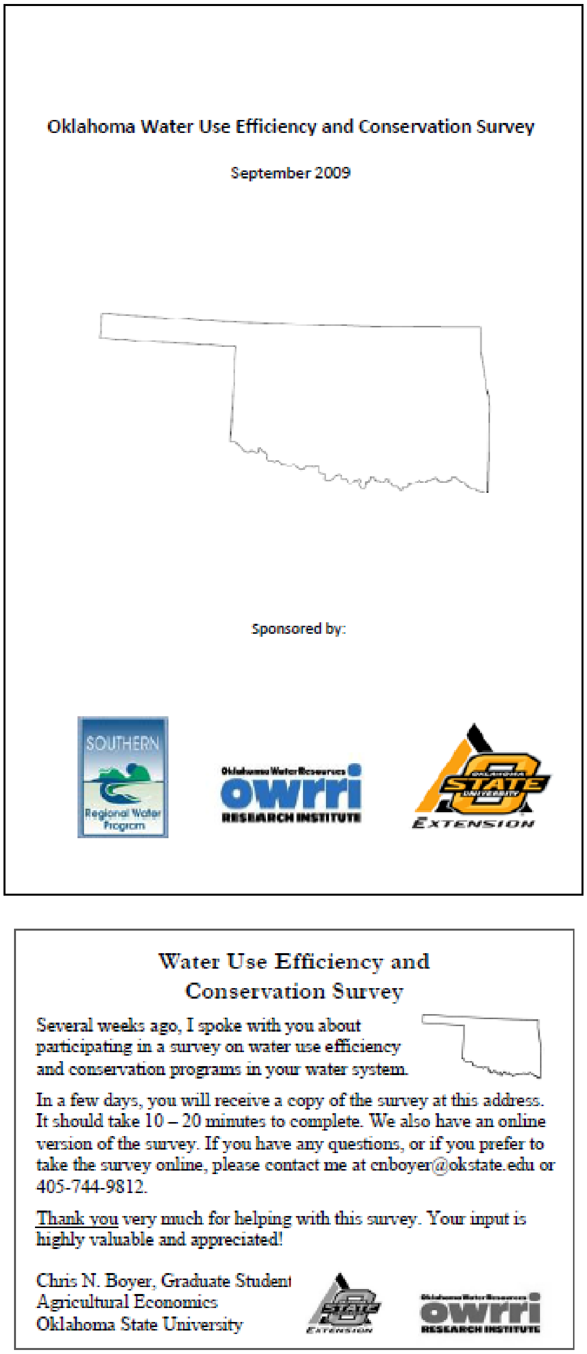
Survey Methods

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. Working with collaborators in three other states (Arkansas, Tennessee, and Florida), we identified, contacted, and ultimately received completed surveys from 695 water managers.

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 Figure 3. The online version can be viewed at http://www.surveymonkey.com/s/5G3ZTHD and the questions are in Appendix A. 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.



Oklahoma Water Use Efficiency and Conservation Survey

September 2009

Sponsored by:

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 3. Example reminder postcard and survey cover

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

$$\Pr = \left[PC = 1, NPC = 1 \mid x\right] = \Phi_2[\beta_{PC}'x, \beta_{NPC}'x, \rho) \tag{1}$$

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:

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

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 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

[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.

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.

We used a multistage survey design process (e.g., Dillman et al. 2007). Based on the literature review and interviews with water system managers, we developed the survey, then pre-tested it on a sub-sample of 88 water utility managers. Comments from the pre-test were used to improve the survey. The final version of the survey contained 33 questions.

Recent research has focused on water conservation policy tools as feasible responses to water crises. Table 7 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 7. 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 and Adams, 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; Dickerson 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 (Boyer and Adams, forthcoming). Table 8 provides a summary of some of the more interesting respondent characteristics.

Table 8. 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.

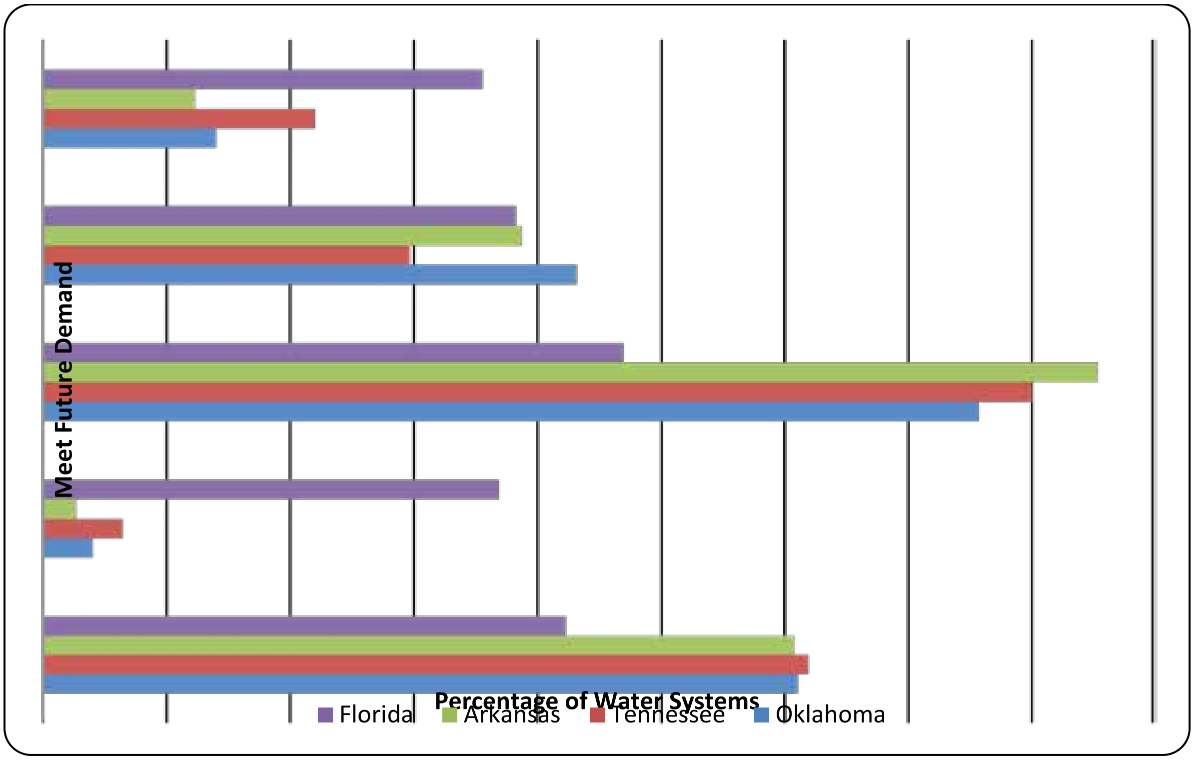


Figure 4. Plans to Meet Future Demand by State.

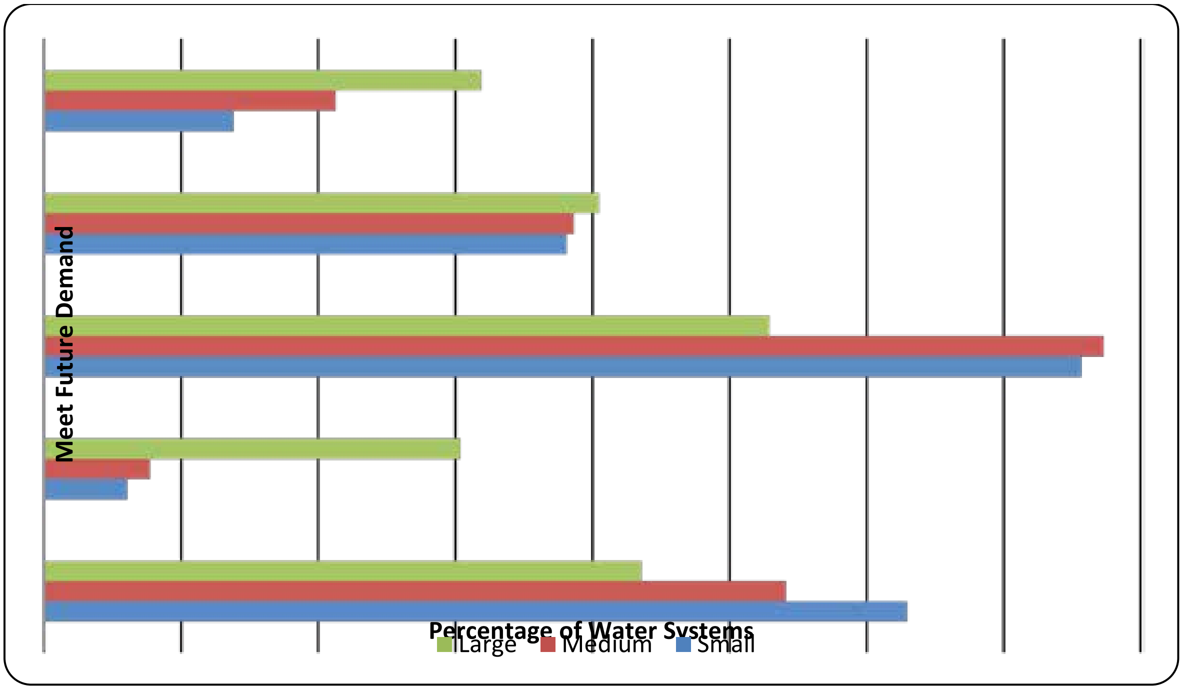


Figure 5. Plans to Meet Future Demand by Utility Size.

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.

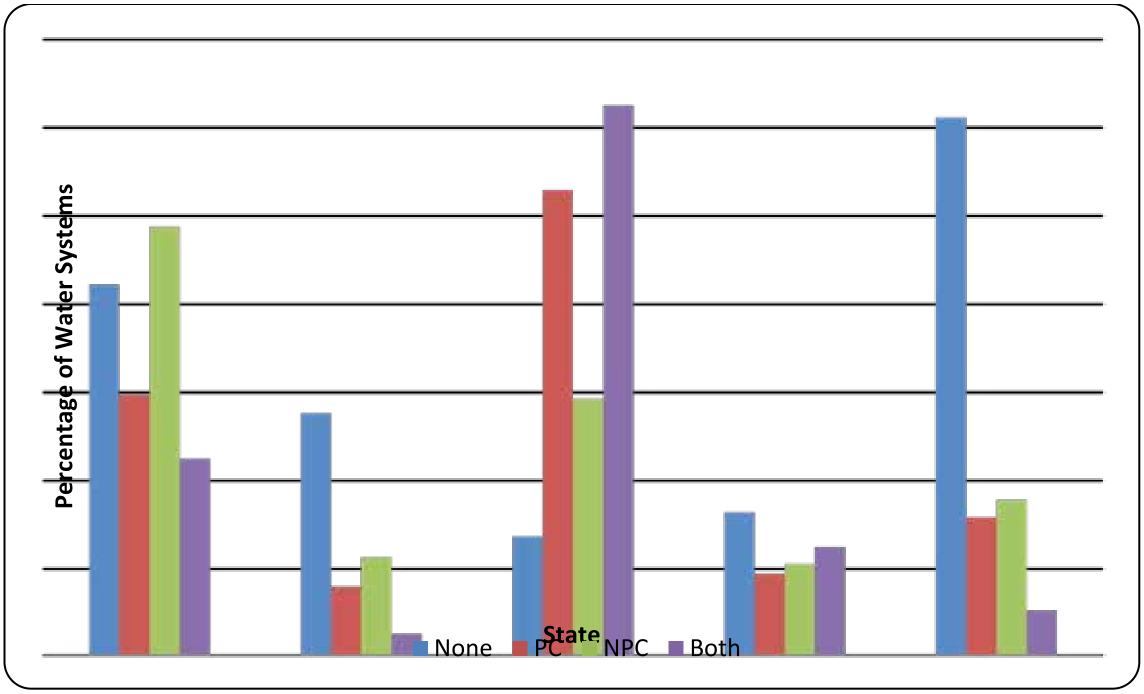


Figure 6. Water Conservation Adoption in the Last Five Years by State.

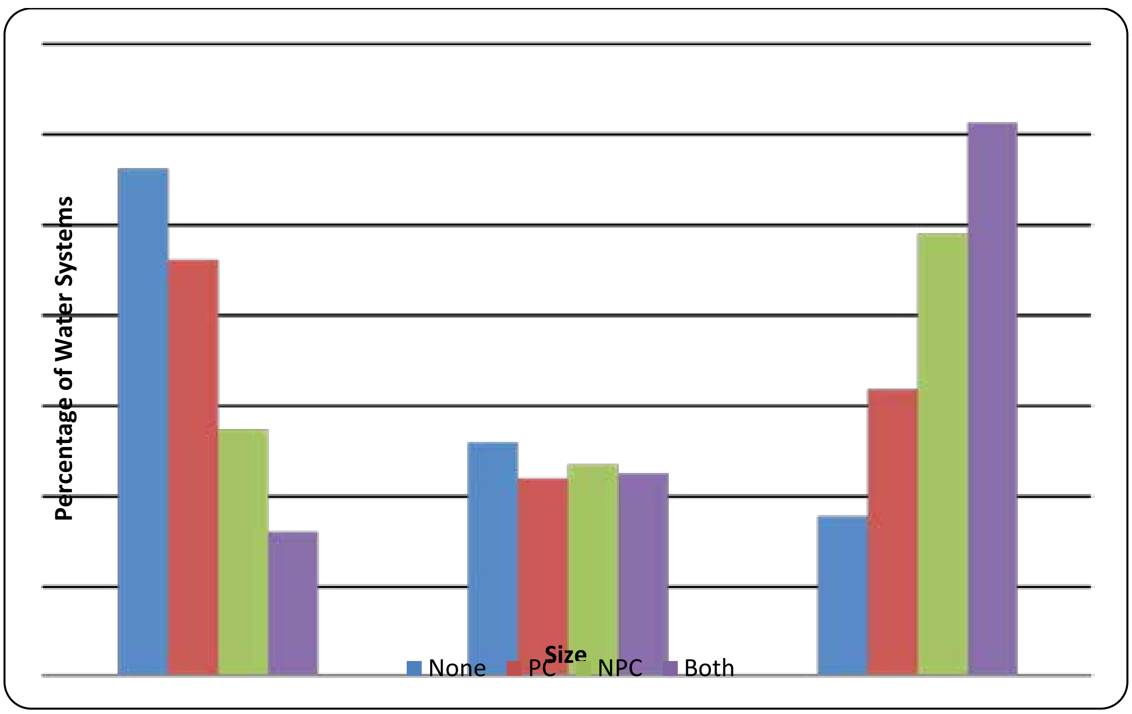


Figure 7. Water Conservation Adoption in the Last Five Years by Utility Size.

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.

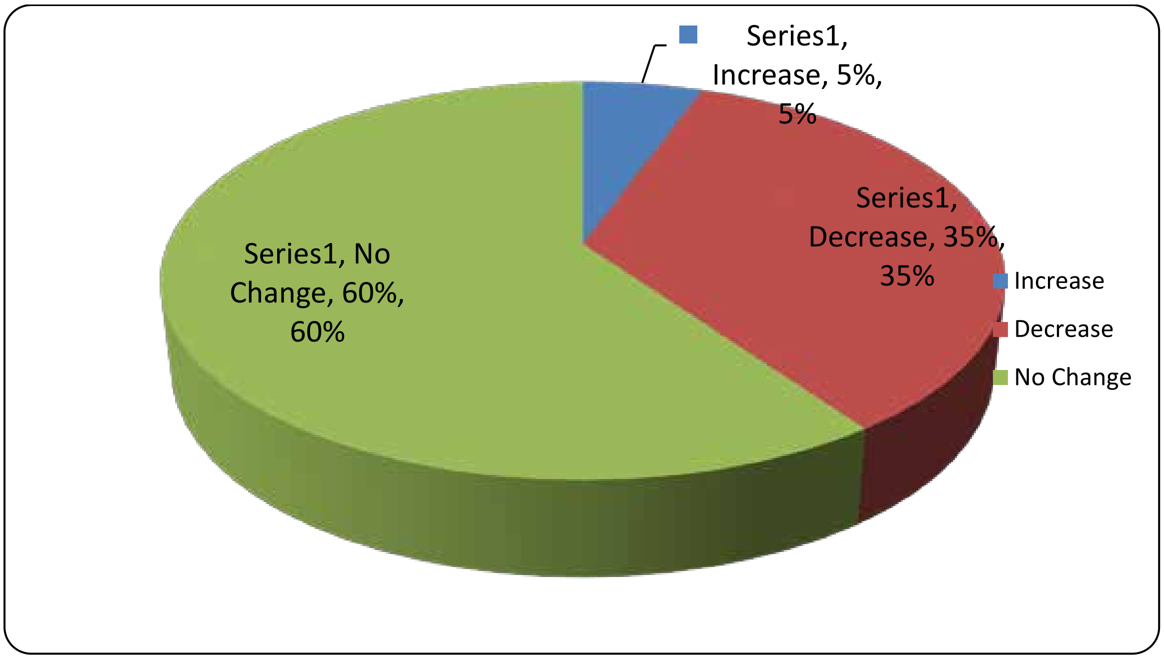


Figure 8. Managers' Perception of Customers Response to a 10% Increase in Price.

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 9). 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 9. Bivariate Probit Model of Factors Influencing Conservation Adoption.

	Dependent Variables

Independent variable§	Price Based Conservation Coefficient	P-value	Non-Price Conservation 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 10). The logit models accurately predicted 91.9% of PC adoption and 86.0% of NPC adoption. Table 11 reports the odds ratio estimates and significance levels for the explanatory variables (nonsignificant 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 10. 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 11. 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.

To achieve **Objective 5 – evaluate the relative feasibility of the alternatives from the water users' perspective**, we conducted a survey of Oklahoma residents. Using the same approach identified for Objective 2, we designed, pre-tested and implemented a statewide survey.

The second survey focused on residential water users' motivations, attitudes, and perceptions about water use and conservation alternatives. This study provides timely and valuable insight on the preferences of water users in Oklahoma and how they use and conserve water. Increased strain is currently being placed on water systems, from population growth and diminishing freshwater supplies, making it crucial to assess all options available to those in charge of managing and developing policies for these systems. Specific objectives of this survey included: (1) determining if receptivity to water conservation mechanisms is affected by the attitudes, perceptions, characteristics and experiences of household water users; (2) determining if adoption of a water conservation behavior or mechanism is associated with the receptivity of household water users; and (3) determining if rural households engage in water conservation behaviors differently than urban households.

Determining the influence of a household's attributes, motivations, attitudes, and perceptions on their water use and adoption of conservation practices can provide a framework for predicting their responsiveness to prospective water policies and conservation programs. We employ a model that measures a respondent's receptivity to adopting water conservation.

Many studies have examined the effects that common household characteristics have on demand for water (Campbell et al. 2004; Inman and Jeffrey 2006; Renwick and Archibald 1998; Renwick and Green 2000). Some of the common attributes that have been examined are: income, density of neighborhood, household occupancy, number of people per household, home ownership status, home lot size, etc.

One important aspect of adopting conservation policies is to know how individual's attitudes and perceptions influence their behavior towards water conservation. Nieswiadomy and Cobb (1993) found that utility managers may be more likely to select conservation rate pricing structures if the individuals in their region are more interested in conservation. Howarth and Butler (2004) discuss the need for utilities to assist individuals in a process of moving from ignorance to awareness to interest to desire to finally adopting a behavior. It is important to understand what factors are influencing the household's decision to move towards practicing conservation behavior.

One model that is helpful in determining if a household will adopt a water conservation mechanism is the 'receptivity' model (Jeffrey and Seaton 2004). The receptivity model has been used in Australia (Brown and Davies 2007; Clarke and Brown 2006) as a way to determine the receptivity of households to implementing water conservation mechanisms. Positive attitudes and awareness about conservation alone is not a good predictor of adopting water conservation behavior. It is important to determine what the barriers to households changing their behavior are and the receptivity model provides a way to model that.

The four main categories of the receptivity model are: awareness (capable of searching for knowledge that is new), association (recognition of the potential benefit of this knowledge by associating it with needs and capabilities), acquisition (the ability to acquire technologies and learn new models), and application (actually apply knowledge to achieve benefit). See Table 12. The categories provide a way of determining how receptive a household will be to a water conservation mechanism. They also reveal what types of barriers are preventing individuals from adopting the behavior.

Table 12. Attributes of household water users influencing adoption of a conservation behavior

Attributes of Households	Category
Willingness to adopt conservation / Application	Conservation intention (dependent variable)
Household Income [a b d]	Demographics
Household Occupancy [a b d]	Household composition
Household Lot Size [a d e]	Dwelling characteristics
Renter Status [d]	Dwelling characteristics
Location	Climate
Number of bedrooms in each household [a]	Dwelling characteristics
Awareness	Awareness/ Cognitive vs. habit behaviors
Access to Technology [b]	Access
Association	Association
Types of water-related technologies in use [a b d]	Past water use behavior / Acquisition
Garden, pool, etc	Outdoor area interest & use
Institutional Trust	Institutional trust & fairness
Fairness	Institutional trust & fairness

Restrictions are too restrictive	Restrictions attitude
Cost is high	Pricing attitude
Average cost of water [a]	Pricing & use regulations
Consumer perception that water shortages are likely in the near future [a]	Perceived risk of shortages
Conservation orientation perceived by customers [a c]	Conservation attitude, generally
Cultural/Social Norms [b]	Subjective norm
Inter-personal Trust (Perceived control)	Perceived behavioral control
Cost of installation vs. Potential savings [b]	Pricing & use regulations (or factors)
Climate Factors [b]	Climate & seasonal factors

[a] Wang et al. 2005; [b] Inman and Jeffrey, 2006; [c] Brown and Davies, 2007; [d] Renwick and Archibald, 1998; [e] Renwick and Green, 2000; [f] Jorgensen et al., 2009; [h] Atwood et al., 2007

Table 13. Direct and indirect drivers of water saving behaviors (from Jorgensen et al., 2009)

Direct drivers	In-direct drivers
• **Climate/seasonal variability** (Berk et al., 1980; Campbell et al., 2004; Klein et al.2006) • **Incentives/disincentives** (e.g., tariff structure and pricing, rebates on water saving technologies, etc.) (Berk et al., 1980; Campbell et al., 2004; Dandy et al.,1997; Lyman, 1992; Martin et al., 1984; Nieswiadomy, 1992; Renwick and Archibald, 1998; Renwick and Green, 2000) • **Regulations and ordinances** (e.g., water restrictions, local government planning regulations) (Klein et al., 2006; Lee, 1981; Renwick and Green, 2000) • **Property characteristics** (e.g., lot size, pool, bore, tank, house size, house age, etc.) (Campbell et al., 2004; Cavanagh et al., 2002; Lyman, 1992; Olmstead et al., 2003; Renwick and Archibald, 1998; Renwick and Green, 2000; Syme et al., 2004) • **Household characteristics** (e.g., household composition, household income, water saving technology, water supply technology) (Campbell et al., 2004; Gilg et al., 2005; Loh and Coghlan, 2003; Mayer et al., 1999; Nancarrow et al., 2004; Renwick and Archibald, 1998; Syme et al.,	• **Personal characteristics** (e.g., subjective norm, behavioral control, attitude toward the behavior) (Beedell and Rehman, 1999; Hines et al., 1986; Leviston et al., 2005) • **Institutional trust** (i.e., trust in the water provider) (Lee, 1981; Lee and Warren, 1981) • **Inter-personal trust** (i.e., trust in other consumers) (Lee, 1981; Lee and Warren, 1981) • **Fairness and equity** (i.e., in decision-making processes, water restrictions, tariffs, new pipelines) • **Environmental values & conservation attitudes** (Corral-Verdugo et al., 2002; De Young, 1996; Syme et al., 1990–1991; Syme et al., 2004) • **Socio-economic factors** (e.g., income, household composition, age, gender, education, etc.) (Agthe and Billings, 1997; Campbell et al., 2004; Loh and Coghlan, 2003; Nancarrow et al., 2004)

2004; Tognacci et al., 1972) • **Personal characteristics** (e.g., intention to conserve water, knowledge of how to conserve water) (Corral-Verdugo et al., 2002; De Young, 1996; St Hilaire et al., 2003; Syme et al., 1990–1991; Syme et al., 2004)	

While research has continued to place an emphasis on water conservation through demand-side management, most of the studies have been performed on urban household water demand (Campbell et al., 2004; Renwick and Archibald, 1998; Renwick and Green, 2000; Michelsen et al., 1999). There is a lack of data available on how rural household water users will respond to water conservation policies. New studies are encouraged for areas that have not been examined because it is difficult to adopt water conservation policies based on previous studies from regions that are have different characteristics (Espey et al., 1997).

Another limitation of the current research is that most of the household attributes that have been studied tend to be general demographic and household characteristics. Information is needed about how a household's attitudes and perceptions influence their willingness to adopt conservation mechanisms. One way to measure that is to use the 'receptivity' model (Brown and Davies, 2007; Jeffrey and Seaton, 2004) as way to evaluate what stage a household is in adopting conservation mechanisms.

Conceptually, the receptivity model explains adoption of water conservation tools along a continuum with adoption of a tool as the ultimate step that is influenced by: (1) awareness of the need for water conservation in the respondent's community; (2) association of specific water conservation tools as a solution to water supply problems; (3) ease of acquisition of specific water conservation tools, which includes affordability, search problems, access, technical difficulty, etc; and (4) application/application of water conservation tools. The receptivity model has been implemented in Australia, but it has not yet been applied in the U.S.

Using this model, we test the following hypotheses: (1) the receptivity (as defined by awareness, association, acquisition, and application) of households to water conservation will be associated with their attitudes, perceptions and experiences; (2) water conservation choices and behavior will be associated with the receptivity of households to water conservation; (3) receptivity to water conservation will be different between rural and urban household water users; and (4) water conservation choices and behaviors will be different between rural and urban household water users. This model may also provide a way to determine if off-setting behavior can be expected based on what component of the model is most influencing each household.

Methods

In 2010, we design, pre-tested and implemented a survey of Oklahoma residents to determine their views on specific water conservation tools. Based on a review of the literature, we designed a survey on water use and conservation. The survey was reviewed by survey experts (n=4) and pre-tested on Oklahoma State University students (n=27) and residents of Stillwater, Oklahoma (n=33). The final survey contained 32 questions on various water-related attitudes and behaviors. A copy of the survey is found in Appendix B.

Using a marketing firm, we identified potential respondents with equal numbers of males/females and otherwise balanced according to the 2000 US Census for Oklahoma. We employed the Dillman (2007) survey method for online surveys as described above (see Objective 2).

The hypotheses were tested using a multinomial logit model (e.g., Greene, 2000). Receptivity to water conservation *j* is described by the characteristics X_j of the household *i*. To get the coefficients used in the likelihood function, I will run the following logit model (1):

$$(1)\ U_{receptivity} = \alpha_j + \beta_{attitudes} X_{ij} + \beta_{perceptions} X_{ij} + \beta_{characteristics} X_{ij} + \beta_{experiences} X_{ij}$$

To determine the likelihood of household *i* being receptive to water conservation *j*, I will use the log-likelihood function (2):

$$(2)\ \text{Logit} = \sum_{i=1}^{N} \sum_{j=1}^{J} d_{ij} \log\left[\frac{1}{1+\sum_{j=2}^{J} e^{\alpha_j+\beta_{ij1}x_1+\beta_{ij2}x_2+\ldots+\beta_{ijn}x_n}}\right]$$

where β_{ijn} denotes the n^{th} attribute of household *i* for receptivity category *j*, and X_n represents the n^{th} characteristic for attitudes, perceptions, and experiences. D_{ij} represents a dummy variable that takes the value of 1 if Y_i=1 and 0 otherwise.

To compare the effects of different attitudes, perceptions, and experiences on receptivity to water conservation *j,* by household *i*, we determine their marginal effects as estimated by equation (3):

$$(3)\ \frac{\partial P_j}{\partial x_i} = P_j\left(\beta_j - \sum_{k=1}^{J} P_k B_k\right)$$

The relative influence of each receptivity category *j* is evaluated with attitudes and perceptions X_n, where *n* represents the number different household attitudes or perceptions. If the p-value for the coefficient β_{jn} estimated is less than or equal to 0.05, then the likelihood of being receptive to water conservation *j* is influenced by the attitude or perception X_n of household *i*. A similar approach is taken to test each hypothesis.

Results and Interpretation

We implemented the survey online in January 2011. Respondents were recruited by a marketing firm (Market Tools, Inc.) who provided a balanced sampling frame according to the 2000 US Census for Oklahoma. The survey was completed by n=841 Oklahoma residents, for a response rate of 43.6% and a 3.4% margin of error. Analysis is ongoing, and here we present preliminary analytic results.

Recall that the purpose of this study is to match Oklahoma water managers' perceptions of water conservation tools (discussed above) with those of Oklahoma water users, and identify feasible water conservation tools. We employ the receptivity model (Brown and Davies, 2007; Jeffrey and Seaton, 2004) to explore water users' views of water conservation tools, and identify potential key barriers to their use in Oklahoma communities. We empirically measure receptivity as a composite measure that includes questions regarding awareness (of a need for water conservation in the respondent's community), association (of specific water conservation tools as a solution to water supply problems), acquisition (of specific water conservation tools, in terms of difficulty of finding, affording, and installing the tools) and application (of water conservation tools).

Application/adoption of water conservation tools is defined as having installed, used or otherwise having applied the tool. Awareness was comprised of questions related to whether the respondent's community was adequately meeting current water needs, whether climate change was expected to have negative impacts on their community, and whether the community was adequately prepared to meet its near-future water needs. Assocation was comprised of views on effectiveness of specific tools. Acquisition was comprised of views on cost, difficulty of finding, and difficulty of installing/maintaining specific tools.

Application

Oklahomans report engaging in several water conservation efforts (see Table 14). Chief among these is repairing leaks (55%), followed changing behaviors or daily routines (42% for outdoor use, 40% for indoor use), installing new indoor devices (32% for faucets/showerheads, 23% for toilets, and 18% for appliances), installing outdoor devices (4% for rain barrels), changes in outdoor plants (4%), and "other" (3%). Nearly one-in-eight (15%) engage in none of these conservation activities.

Table 14. Summary of Current Conservation Tool Use

Conservation Alternative	Adoption Rate	No Barrier Identified
Repaired a leaky faucet, showerhead, or toilet	55.4%	67.1%
Changed behavior and daily routines for outdoor use	42.1%	56.5%
Changed behavior and daily routines for indoor use	39.8%	42.4%
Installed new low-flow faucets and/or showerheads	31.7%	34.3%

Installed ultra low-flush toilets	22.7%	23.7%
Installed a water-conserving dishwasher and/or washer	17.5%	24.3%
Installed a rain barrel for outdoor water use	4.04%	8.3%
Replaced lawn or other water-consuming plants	3.57%	19.1%
Other	3.21%	-
None of the above	15.1%	-

Awareness, Association and Acquisition

We asked respondents to identify primary barriers to their use of water conservation tools for both indoor and outdoor use. Responses differed significantly by type of tool (Tables 15 and 16). Note that we allowed respondents to pick more than one "primary barrier". Nearly two-thirds of respondents indicated that repairing leaks had no barriers (67.1%), which may explain the very high use of this conservation tool (55.4%). Over half of respondents (56.5%) indicated this was the case for changing outdoor water use behaviors. This was also indicated for a large percentage of respondents regarding installation of low-flow faucets and/or showerheads (34.3%), installing water-conserving appliances (24.3%), installing ultra low-flush toilets (23.7%), and replacing lawn or other water-consuming plants (19.1%). Only 8.3% of respondents indicated that there were no barriers to installing a rain barrel.

A significant percent (15.3% - 38.4%) of respondents indicated that the primary barrier to water conservation tool use is a lack of water shortage. This was lowest for installing indoor water conserving devices (15.3% for faucets and showerheads, 18.4% for appliances, and 18.5% for toilets) and repairing leaks (15.5%). Nearly one-quarter (28.3%) said this was the primary barrier for changes in behaviors. Lack of a current water shortage was a much larger driver for outdoor conservation. Nearly one-quarter identified this as the primary barrier for changes to behavior (22.9%) and installing a rain barrel (26.4%), and over one-third said this was the case for replacing lawn/plants (38.4%). These summary results suggest that information regarding water shortages may have a large influence on the use of conservation tools, especially for outdoor water use.

Effectiveness of water conservation tools appears to be a barrier to adoption, but not many respondents indicated it was the primary barrier to repairing leaks (3.4%) and appliances (3.8%). Roughly 6 – 8% of respondents indicated this was the primary barrier to adopting changes in outdoor behaviors (5.7%), installing low-flow faucets and showerheads (6.8%), replacing lawn/plants (7.8%), installing ultra low-flush toilets (8.6%), and changing indoor water behaviors (8.7%). Notably, the effectiveness of rain barrels was viewed as a primary barrier by one-in-ten respondents (10.0%).

Cost did appear to be a large driver of some conservation tools: appliances (54.6%), toilets (49.4%), lawn/plants (31.3%), faucets/showerheads (21.9%), and rain barrels (18.5%). Few respondents indicated cost as a primary barrier to changes in water behaviors (3.5% for indoor, 3.7% for outdoor) or repairing leaks (6.2%). These results indicate areas where economic incentives may help improve conservation tool use.

The level of difficulty with installing and/or adopting conservation tools was also a primary barrier for many respondents. Nearly one-third indicated this was the case for toilets (29.9%). Replacing lawn/plants and installing a rain barrel were also seen by many as difficult (18.9% and 15.7%, respectively). This was also a primary barrier to installing low-flow faucets and showerheads (9.7%), changing indoor water use behaviors (9.1%), repairing leaks (8.4%), installing water-conserving appliances (8.0%), and changing outdoor water use behaviors (5.2%). This indicates that technical support for installing both indoor and outdoor devices might provide substantial improvement in the use of these conservation tools.

Lack of information about water conservation tools is a major barrier for replacing lawn or other water-consuming plants, with nearly half of all respondents indicating this was the primary barrier to their use (46.1%). Over one-third also said this was the case for rain barrels (36.0%). These results indicate that extension and other information sources need to be further supported if these tools are viewed as a high priority for water managers. Lack of information is also a large problem for other tools: for toilets (13.0%), appliances (12.4%), faucets/showerheads (12.1%), changes in indoor behavior (8.1%), repairing leaks (6.9%), and changes in outdoor behavior (6.0%).

Table 15. Perceived Barriers to Adoption of Indoor Conservation Practices

Conservation Practice	No Barrier	Not Enough Savings	Cost Is Too High	Difficult to Install /Adopt	Not Enough Info.	Currently No Water Shortage
Changes in behavior and daily routines	42.4%	8.7%	3.5%	9.1%	8.1%	28.3%
Installing low-flow faucets and/or showerheads	34.3%	6.8%	21.9%	9.7%	12.1%	15.3%
Installing ultra low-flush toilets	23.7%	8.6%	49.4%	29.9%	13.0%	18.5%
Installing water-conserving appliances	24.3%	3.8%	54.6%	8.0%	12.4%	18.4%

Repairing leaks	67.1%	3.4%	6.2%	8.4%	6.9%	15.5%

Table 16. Perceived Barriers to Adoption of Outdoor Conservation Practices

Conservation Practice	No Barrier	Not Enough Savings	Cost Is Too High	Difficult to Install/ Adopt	Not Enough Info.	Currently No Water Shortage
Changes in behavior and daily routines (e.g. water lawn less)	56.5%	5.7%	3.7%	5.2%	6.0%	22.9%
Replacing lawn or other water-consuming plants	19.1%	7.8%	31.3%	18.9%	46.1%	38.4%
Installing a rain barrel	8.3%	10.0%	18.5%	15.7%	36.0%	26.4%

Tables 15 and 16 describe perceived barriers to non-price conservation tools that the typical water user can adopt; but water managers and other community decision-makers may be considering the use of: (1) conservation pricing to promote water use efficiency; (2) raising average water rates; and (3) restrictions of outdoor water use. Indeed, as the price of water increases, we expect that concerns about cost of water conservation tools, their water savings, and a lack of water shortage would be overcome. We also expect that other tools would see increased use due to higher water prices and outdoor water use restrictions.

We asked respondents to indicate how likely they would be to support outdoor watering restrictions and conservation pricing – for just high-volume users and for all water users (Table 17). We found highest support for the use of mandatory water restrictions (which would be enforced in conjunction with fines for those violating the restrictions) – an overwhelming 34.0% definitely would support this tool being used in their community, while 42.4% probably would support its use. In total, over three-fourths (76.4%) of respondents would likely support this tool being used in their community. Only 8.8% indicated opposition to its use.

Conservation pricing, or tiered water rate schedules, also was broadly supported by the respondents. Six-in-ten indicated support for this conservation tool, with 21.6% definitely supporting and 38.4% probably supporting its use. Only 17.5% indicated opposition to its use, and nearly one-quarter (22.6%) was unsure. Interestingly, we found strong opposition to the use of higher average water prices for all users. Only 19.6% indicated support for higher average water prices: 5.7% definitely would, and 13.9% probably would support its use. A majority (54.8%) oppose its use: 23.3% definitely would not support, and 31.5% probably would not support using this approach to promoting conservation. Over one-quarter (25.6%) were unsure.

Table 17. Preferences on Watering Restrictions and Price Increases

Conservation Alternative	Definitely would NOT support	Probably would NOT support	Unsure	Probably would support	Definitely would support
Mandatory Water Restrictions	3.3%	5.5%	14.8%	42.4%	34.0%
Increased water prices for high-volume users (Conservation Pricing)	7.0%	10.5%	22.6%	38.4%	21.6%
Increased water prices for all users	23.3%	31.5%	25.6%	13.9%	5.7%

In an effort to gauge how sensitive water users are to prices, we asked respondents to indicate the smallest increase in water prices that would be needed for them to adopt additional conservation tools (Table 18). Our findings are consistent with the literature on the price elasticity of demand, which shows that a 5% - 10% increase in water prices results in a 1% drop in water use (e.g., Klein et al., 2006; Nieswiadomy, 1992; Renwick and Green, 2000). We found that over one-third of respondents would seek to adopt water conservation tools if water prices rise by 10%. Indeed, nearly two-thirds (65.1%) would adopt additional water conservation tools if prices rose 20%, and almost nine-in-ten (85.6%) would adopt conservation tools if prices rose 30%. A price rise of 40% would bring an additional 5.7% of water users to adopt conservation tools, and a 50% rise would yield 94.4% of respondents' using additional water conservation tools. Only 5.6% would need water prices to rise by more than 50% on average to adopt any water conservation tools. These results indicate that water users are rather sensitive to water prices, and that water price increases may be a strong motivator for the adoption of water conservation tools.

Table 18. Smallest Increase in Water Prices Needed for Adoption of Conservation Tools

Increase in water prices	Percent Frequency	Cumulative Percent Frequency
0-10%	35.90%	35.90%

10-20%	29.19%	65.09%
20-30%	20.50%	85.59%
30-40%	5.71%	91.30%
40-50%	3.11%	94.41%
More than 50%	5.59%	100.00%

The use of water conservation tools depends not just on price, cost, water savings, and other barriers discussed above; they also depend on the efforts of others in the community and pressure to support the community (i.e., "moral suasion"). We asked respondents to gauge the efforts of their neighbors and their water utility regarding water conservation (Table 19). We found a large percentage of respondents who were unsure (40.6% for their neighbors' efforts, and 35.0% for their utility's efforts). Roughly one-quarter hold pessimistic views about their neighbors' efforts (26.0%) and their utility's efforts (25.8%). Nearly one-third hold optimistic views about their neighbors' efforts and their utility's efforts on water conservation (33.5% and 36.5%, respectively). Only 2.8% of our respondents do not get water from a water utility, and could not answer the utility-related question. These results indicate that respondent are generally uncertain about conservation efforts, but are slightly more likely to view their utilities and neighbors as making efforts to support and promote conservation than not making efforts.

Table 19. Views about Others' Conservation Efforts

Views on Others' Conservation Efforts	Definitely NO	Probably NO	Unsure	Probably Yes	Definitely Yes	Not applic-able
Do your neighbors make an effort to conserve water?	7.7%	18.3%	40.6%	28.7%	4.8%	-
Does your local water utility promote water conservation?	8.7%	17.1%	35.0%	25.9%	10.6%	2.8%

We empirically evaluated the receptivity model using a series of econometric models that explain the adoption of water conservation tools as a function of the factors discussed above. Several models were evaluated using various factors as explanatory variables. Recall that we define receptivity as a composite of four factors: Awareness, Association, Acquisition, and Application.

In our econometric models, **Awareness** is comprised of (1) views on whether there is currently enough water to meet the needs of your community ("Current Need", question 2), views on whether the respondent's community will need to increase water supply or reduce water use in the next 20 years ("Future Need", q. 3), and whether climate change will reduce water supply in their area ("Climate Change", q. 20). **Association** is captured by views on effectiveness of each water conservation tool ("Effectiveness", q. 5, 11 and 12). **Acquisition** is comprised of the smallest price change that would lead to water conservation tool adoption (q. 17), whether the respondent's household would use less water if the cost increased by 20% (question 18), and how much the respondent's households water has changed in the last 5 years (q. 15).

In Tables 20 and 21, we report the parameter estimates for our econometric model (Table 20), and the calculated marginal effects based on the parameter estimates (Table 21). The logit model parameter estimates indicate the change in log odds with each one level change in the explanatory variable, which is not very intuitive. The marginal effects, however, are interpreted as the change in probability of an average respondent adopting a particular water conservation tool for each one-level increase in a particular explanatory variable. We discuss only the marginal effects here.

Table 20. Receptivity Model Effects

	Inter-cept	Current Need	Future Need	Climate Change	Effective-ness	Price Change	Use-change20	Use Changed
Indoor	-3.5229	-0.1919**	0.1930**	0.1209*	0.7968***	-0.0802	0.1325*	-0.2465***
Low-flow	-3.6406	-0.1516*	0.2214**	0.1086	0.6395***	0.0302	-0.0201	-0.0813
Low-flush	-4.5333	0.00433	0.2757**	0.0318	0.6693***	-0.00242	-0.00363	-0.1605**
Applian-ces	-5.1519	0.0851	0.0887	0.00142	0.8563	-0.00673	-0.1499	-0.000584
Leaks	-2.8139	-0.0138	0.2840***	-0.0623	0.6061***	-0.0597	-0.0855	0.0443
Outdoor	-3.7736	-0.1624*	0.3433***	0.1300*	0.7234***	-0.0885	0.0491	-0.2105**
Plants	-5.9764	-0.3319*	0.3221	0.1564	0.6464**	0.0727	-0.0135	-0.1615
Rain Barrels	-6.5180	-0.3194*	0.2093	0.0878	1.0637***	-0.3142*	0.0303	-0.0596
None	0.5331	0.1266	-0.5006**	-0.0393	-	0.0249	-0.2044	-0.0618**

*** = 1% Significance, ** = 5% Significance, * = 10% Significance

Table 21. Receptivity Model Marginal Effects

	Current Need	Future Need	Climate Change	Effective-ness	Price Change	Usechange -20	Use Changed
Indoor	-0.0451**	0.0454**	0.0284*	0.1875***	-0.0189	0.0312*	-0.0580***
Low-flow	-0.0323*	0.0472**	0.0232	0.1364***	0.0064	-0.0043	-0.0173
Low-flush	0.0007	0.0448**	0.0052	0.1087***	-0.0004	-0.0006	-0.0261**
Appliances	0.0115	0.0120	0.0002	0.1154	-0.0009	-0.0202	-0.0001
Leaks	-0.0034	0.0690***	-0.0151	0.1472***	-0.0145	-0.0208	0.0108
Outdoor	-0.0393*	0.0831***	0.0315*	0.1752***	-0.0214	0.0119	-0.0510**
Plants	-0.0083*	0.0080	0.0039	0.0161**	0.0018	-0.0003	-0.0040
Rain Barrels	-0.0066*	0.0043	0.0018	0.0219***	-0.0065*	0.0006	-0.0012
None	0.0154	-0.0608**	-0.0048	-	0.0030	-0.0248	-0.0075**

*** = 1% Significance, ** = 5% Significance, * = 10% Significance

We found that the receptivity model is useful for explaining the likelihood of Oklahoma water users adopting water conservation tools. Variables comprising awareness were statistically significant for several of the conservation tools, but these varied somewhat depending on the tool. Indoor behavior changes are negatively influenced by current need, and positively influenced by future need and climate change; low-flow faucets and showerhead use is negatively influenced by current need, and positively influenced by future need; low-flush toilet installation is positively influenced by future need; appliance installation was not statistically significantly influenced by any awareness variables; leaks were positively in

As expected, current need – views that the respondent's community has enough water to meet current needs – negatively influences adoption of conservation tools; future need – beliefs that the community will need to increase water supply – positively influences adoption; and climate change – beliefs that climate change will reduce water supply in the respondent's area – positively influence adoption of conservation tools. However, these variables were not all statistically significant, and their relative influence varied by conservation tool.

We measured beliefs about current water needs on a 5-point Likert-like scale, where 1 indicated that the respondent answered "Definitely No" and 5 indicates that the respondent answered "Definitely Yes" to the question "In your opinion, is there currently enough water in your area to meet the needs of your community?" We found that for every 1-level increase in this scale, the probability of adopting indoor behavior changes falls by 4.5%; installing low-flow toilet falls by 3.2%, adopting outdoor water use behavior changes falls by 3.9%, installation of new lawn/plants falls by 0.8%, and installation of rain barrels falls by 0.6%. This variable was not statistically significant for other conservation tools.

We asked a similar question related to future water needs, where a 1 indicates “Definitely No” and 5 indicates “Definitely Yes” to the question “In your opinion, will your community need to increase its water supply or reduce water use within the next 20 years?” For every 1-level increase in this scale, the probability of adopting indoor behavior changes increases by 4.5%, installing low-flow toilets increases by 4.7%, installing low-flush toilets increases by 4.5%, fixing leaks increases by 6.9%, adopting outdoor water use behavior changes increases by 8.3%, and the likelihood of adopting no water conservation tools falls by 6.1%.

Views on climate change also have the expected impact, but were not highly significant; only indoor behavior changes and outdoor behavior changes have statistically significant influences form climate change views. For every 1-level increase in the belief that climate change will reduce water supply, there is a 2.8% increase in the use of indoor water conservation behaviors, and a 3.2% increase in the use of outdoor water conservation behaviors. This may indicate that education about climate change may be needed to boost changes in water use behaviors.

Association, as captured by views on effectiveness of water conservation tools, was highly influential. For every 1-level increase in the perception of a conservation tool as effective in reducing water use, there was an 18.8% increase in the use of indoor water behavior changes, a 13.6% increase in the installation of low-flow faucets/showerheads, a 10.9% increase in the installation of low-flush toilets, a 14.7% increase in repairing leaks, a 17.5% increase in the use of outdoor conservation behavior, a 1.6% increase in the use of water conserving lawn/plants, and a 2.2% increase in the use of rain barrels. Again, indoor and outdoor behavior changes are most heaving influenced.

Acquisition, as measured by the minimum water price change (as %) needed to adopt water conservation tools, the likelihood of reducing household water use for a 20% increase in water prices, and whether the respondent’s household had changed in the last five years, provided weak results. As expected, the less sensitive a respondent is to price change, the less likely they are to adopt conservation. More every 10% increase in minimum change in water prices needed to adopt conservation, the chance of adopting rain barrels decreases by 0.7%. Also, for every 1-level increase in the chance that a respondent’s household would use less water if prices rose by 20%, there was a 3.1% increase in the adoption of indoor water conservation behaviors. We also found that reported changes in water use over the past five years has a clear influence on the likelihood of adopting water conservation tools. We asked respondents to respond to the question “Over the last five years, how has your household's water use changed?" where 1 – Large Decrease, and 5 – Large Increase. For every 1-level change (increase in water use), we find a 5.8% decrease in the adoption of indoor water conservation behaviors, a 2.6% fall in the installation of low-flush toilets, a 5.1% drop in the adoption of outdoor conservation behaviors, and a 0.8% drop in the installation of rain barrels.

For comparison, we also tested a conceptual model with only awareness and association variables (Table 22). We still found that association (effectiveness) dominated the model results.

Table 22. Impact of Attitudes on Adoption of Conservation Tools

	Attitude Questions			
	Intercept	**Current Need**	**Future Need**	**Effectiveness**
Indoor	-3.5732	-0.2138***	0.1763**	0.8545***
Low-flow	-3.4757	-0.1674**	0.2283***	0.6395***
Low-flush	-4.8275	-0.00336	0.2700***	0.6733***
Appliances	-5.5613	0.0778	0.0847	0.8349***
Leaks	-3.2899	-0.0101	0.2724***	0.6028***
Outdoor	-3.8369	-0.1907**	0.3268***	0.7404***
Plants	-5.7853	-0.3599**	0.3368	0.6667***
Rain Barrels	-6.9760	-0.3514**	0.1710	1.1538***
None	-0.4833	0.1258	-0.4834***	-

*** = 1% Significance, ** = 5% Significance, * = 10% Significance

We also tested other conceptual models, including one that evaluated perceived barriers and the use of conservation tools (Tables 23 and 24); and the influence of views on community and neighbor efforts on conservation tool use (Table 24).

Stated barriers to adoption are good indicators of self-reported adoption of water conservation tools. For every 1-level increase in the view that water conservation tools provide not enough water savings, we find a 17.3% drop in the use of indoor behaviors, a 11.6% drop in the use of low-flow faucets/showerheads, a 9.8% drop in the installation of low-flush toilets, a 5.1% decline in the installation of water conserving appliances, and a 3.0% drop in leak repairs. For a 1-level increase in the view that cost is too high, we find a 14.6% drop in the use of low-flow faucets/showerheads, a 15.7% drop in low-flush toilet use, a 6.8% reduction in the installation of water conserving appliances, a 1.6% decline in outdoor water behavior changes, a 2.0% fall in the installation of water conserving lawn/plants, and a very negligible 0.006% fall in the use of rain barrels. Difficulty of installation was also a factor, with increased perceptions of difficulty negatively influencing adoption – by 9.7% for indoor behaviors, 17.2% for low-flow faucet/showerheads, 8.6% for low-flush toilets, 16.1% for leak repairs, and 14.2% for outdoor behavior changes. Insufficient information was also a major barrier that influences water conservation tool adoption, and negatively influences indoor water behavior changes by 14.9%, low-flow faucets/showerheads by 14.9%, low-flush toilets by 12.5%, water conserving appliances by 3.0%, outdoor behavior changes by 14.5%, and water conserving lawn/plants by 1.8%.

Table 23. Logit Model Comparing Barriers to Water Conservation Adoption

	Barriers to Adoption (Relative to 'No Barriers')					
	Intercept	Not Enough Water Savings	Cost is too High	Difficult to Install or Adopt	Not Enough Information	Currently No Water Shortage
Indoor	-0.5761	-1.1035***	-0.5225	-0.5408*	-0.9093***	-1.0333***
Low-flow	-0.7438	-0.8876**	-1.1020***	-1.5724***	-1.2139***	-1.3916***
Low-flush	-1.0645	-1.1973**	-1.7275***	-0.9504***	-1.7081***	-0.7479***
Appliances	-1.3909	-1.7002*	-1.4896***	-14.7530	-0.6633*	-1.0070***
Leaks	-0.2733	-1.8043*	-0.4888	-0.7383**	-0.3881	-0.4630**
Outdoor	-0.6415	-0.4000	-0.9680*	-0.8054**	-0.8249**	-0.5767***
Plants	-3.0890	-0.8230	-1.4436*	-1.2548	-1.2418*	-1.3997*
Rain Barrels	-2.7132	-1.5773	-1.3895*	-13.8307	-13.8307	-0.8869*

*** = 1% Significance, ** = 5% Significance, * = 10% Significance

Table 24. Logit Model Comparing Barriers to Water Conservation Adoption, Marginal Effects

Barriers to Adoption Marginal Effects (Relative to 'No Barriers')

	Not Enough Water Savings	Cost is too High	Difficult to Install or Adopt	Not Enough Information	Currently No Water Shortage
Indoor	-0.1725***	-0.0932	-0.0971*	-0.1489***	-0.1778***
Low-flow	-0.1158**	-0.1461***	-0.1722***	-0.1485***	-0.1661***
Low-flush	-0.0984**	-0.1572***	-0.0863***	-0.1247***	-0.0732***
Appliances	-0.0509*	-0.0678***	-0.1200	-0.0300*	-0.0417***
Leaks	-0.3037*	-0.1105	-0.1607**	-0.0891	-0.1058**
Outdoor	-0.0778	-0.1631*	-0.1422**	-0.1452**	-0.1113***
Plants	-0.0123	-0.0203*	-0.0164	-0.0177*	-0.0197*
Rain Barrels	-0.0006	-0.0006*	-0.0018	-0.0159	-0.0004*

*** = 1% Significance, ** = 5% Significance, * = 10% Significance

Views about water conservation efforts by neighbors and utilities had little influence with a few important exceptions (Table 25). For every one-level increase the belief that neighbors are making efforts to conserve water, there is an expected 13.8% increase in the use of indoor water conservation behaviors, and a 20.1% increase in the installation of water conserving appliances; and for utility's effort, a 1-level change in perceived effort increases leak repair by 12.8%. Also, importantly, increased perceived effort by utilities significantly reduces the likelihood of adopting none of the water conservation tools – by a substantial 14.2%.

Table 25. Influence of Other-Regarding Behavior on Water Conservation Adoption

	Other-Regarding Behavior Questions		
	Intercept	Neighbor Conserve	Utility Conserve
Indoor	-0.9181	0.1384*	0.0408
Low-flow	-0.9133	0.0558	0.00484
Low-flush	-0.9856	-0.00291	-0.0654
Appliances	-2.1828	0.2018**	0.0112
Leaks	0.1179	-0.0754	0.1276**
Outdoor	-0.3747	-0.0330	0.0657
Plants	-3.2096	-0.1176	0.0947
Rain Barrels	-2.7039	0.0508	-0.2029

None	-1.1992	-0.0252	-0.1420*

*** = 1% Significance, ** = 5% Significance, * = 10% Significance

Conclusion

We conducted a survey of Oklahoma water users to identify major barriers to and primary drivers of water conservation tool use. Water conservation tool use varied significantly by tool, with repairing leaks most likely to be used, and replacing lawn/plants least likely. In every case, the adoption rate of these tools approximated the percent indicating no barriers to their use.

The results indicate that approaches to implementing water conservation tools would do best to tailor programs to water users' specific perceptions. For example, programs that ease the economic burden of installing appliances, low-flow faucets/showerheads, and ultra low-flush toilets would address cost concerns, which drive decisions regarding these tools. Replacing lawn and other water consuming plants, and installing rain barrels are both seriously limited by insufficient information. Also, in general, fundamental beliefs about needs for water conservation drive the use of these tools. For example, believing that there is currently no water shortage is a major barrier that could be overcome with an effective public awareness and information campaign. The same is true of climate change, although this issue has perhaps been too politicized to gain traction with many water users.

Using econometric models, we predicted the likelihood that an Oklahoma resident would adopt water conservation tools. We examined receptivity factors including awareness, association, and acquisition, and found that association is a major influential driver of adoption. Awareness and acquisition were also somewhat determinative, but much less so. We also examined stated barriers and perceptions on community and neighbor efforts on conservation. Stated barriers were highly influential, but perceptions were less influential. We note, however, that respondents' perceptions about their water utility's efforts on water conservation have a significant influence over whether the respondent adopts any water conservation tools or not.

The results from the study showed that high costs and lack of information were major barriers to households adopting new conservation alternatives. Association between a conservation mechanism's effectiveness and a future water demand problem increased the likeliness of a household to adopt the mechanism. The findings of this research will be useful for water policy educators and decision makers in developing water programs to meet the demands of their population in the future. This survey and model could be replicated in other areas to further test the validity of the findings and assist other regions that will need to make tough decisions about how to manage the precious resource of water in the future.

Objective 6, is achieved by writing this report and extending our results through the research and extension publication channels.

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:

This project evaluated water conservation policy tools that have been used or proposed in Oklahoma and other parts of the United States, and looked for conservation tools that are feasible in Oklahoma given water managers' and water users' views. The analysis is ongoing, but initial results show that efforts by many water utilities are asynchronous with water users' preferences. While only 6% of Oklahoma water utilities have adopted programs that promote non-price based conservation tools, this category was the most popular with water users. On average, water users were much more supportive of non-price water conservation tools, with 76.4% likely to support these conservation tools being in their community; only 8.8% registered opposition to their use.

Likewise, 22% of Oklahoma utilities have raised average water rates to promote conservation, but this was viewed as least popular by water users. They were decidedly opposed to water utilities raising average water rates on all users as a means of conserving water, with 54.8% opposing its use, and only 19.6% in support. Although there was less support for price-based tools, water users were generally supportive of conservation pricing, which charges higher per-unit water rates to high volume users. A clear majority (60.0%) were supportive of this approach to conserving water. These results stand in stark contrast to the approach typically taken by most Oklahoma water utilities, and suggest an area where decision-making by utilities may need additional support.

Our literature review provides estimates on average costs of implementing various price-based an non-price based water conservation programs. When coupled with the results of major drivers of both price and non-price conservation programs by utilities, and specific preferences and drivers of water conservation adoption by water users, preferred conservation strategies could be identified. Additional work will identify these, and this information will be shared with appropriate stakeholders in Oklahoma in due time.

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Appendix A. Oklahoma Water Managers Survey

Oklahoma Water Use Efficiency and Conservation Survey

August 2009

Sponsored by:

"Conservation" has been defined many different ways. Some studies have defined water conservation to be similar to water efficiency (i.e., reducing wasteful use). For example, a utility provides its customers with low flow shower heads to reduce the amount of water being used per shower, resulting in higher efficiency. Other studies have defined water conservation to mean a decrease in total water use. For example, a utility mandates that its customers are not allowed to water their yards, resulting in a total reduction in water use.

Our desire is to determine which programs are best at increasing efficiency as well as reducing water use. For the purposes of this survey, please consider "conservation" to mean both increased efficiency and reduction in total water use.

In some cases, more than one water system is run by the same person or group. If this describes your situation, please answer the following questions according to the system with the MOST METERED CONNECTIONS.

1. What region of the state is your utility in? *(circle one answer)*
    a. Northwest (NW)
    b. Northeast (NE)
    c. Central (C)
    d. Southwest (SW)
    e. Southeast (SE)

2. How is your utility's ownership structured? *(circle one answer)*
    a. Municipal, county, or state owned
    b. Private investor owned
    c. Customer owned nonprofit or cooperative
    d. Other – public *(please describe)* ____________________
    e. Other – private *(please describe)* ____________________

3. In a typical year, what are primary and secondary sources of water for your utility? *(circle the source that applies)*

	Primary	Secondary	Not Applicable
Surface water, self supply	P	S	n/a
Surface water, purchased from other utility	P	S	n/a
Ground water, self supply	P	S	n/a
Ground water, purchased from other utility	P	S	n/a

4. Roughly what percent of your utility's water is delivered to the following? (*provide estimates that adds to 100%)*
   _____ % Residential
   _____ % Industrial
   _____ % Commercial and institutional
   _____ % Oil & Gas
   _____ % Agricultural
   _____ % Wholesale and sale to other systems
   _____ % Unaccounted water loss
   _____ % Other *(please specify)*_______

5. During a non-drought period, how many gallons of metered water does your system deliver? *(provide an estimate in the blank)*

6. Over the last five years, how has the amount of water that your system delivers changed*? (circle one answer for (6a) Total Delivery and (6b) Per Capita Delivery)*

6a) Total Delivery	6b) Per Capita Delivery
a. Decreased by more than 10%	a. Decreased by more than 10%

b. Decreased by 5% to 10%	b. Decreased by 5% to 10%
c. Stayed about the same	c. Stayed about the same
d. Increased by 5% to 10%	d. Increased by 5% to 10%
e. Increased by more than 10%	e. Increased by more than 10%

7. In your opinion, what is the primary cause for the change in demand?

8. Who in your system determines RATE changes? *(check all that apply)*

	Recommends changes	Has final approval	Not applicable
Utility/District manager	☐	☐	☐
Utility's board of directors	☐	☐	☐
City/county/state government	☐	☐	☐
Utility's customers (by direct vote)	☐	☐	☐
Corporate decision	☐	☐	☐
Other *(please specify)*___________	☐	☐	☐

9. Who in your system determines CONSERVATION programs? *(check all that apply)*

	Recommends changes	Has final approval	Not applicable

Utility/District manager	☐	☐	☐
Utility's board of directors	☐	☐	☐
City/county/state government	☐	☐	☐
Utility's customers (by direct vote)	☐	☐	☐
Corporate decision	☐	☐	☐
Other *(please specify)*___________	☐	☐	☐

10. How does your utility notify its customers about changes to water rates and conservation programs? *(select all that apply)*

☐ Special mail out

☐ Attachment in water bill

☐ Local TV and radio stations

☐ Posting on utility's web-page

☐ Notice in local newspaper(s)

☐ Public meeting

☐ Other *(please specify)* _______________

11. Where can your customers learn about your utility's current water rates and rate structure? *(select all that apply)*

☐ Contact the utility

☐ Visit the utility's website

☐ Water bill

☐ Utility newsletter

☐ Contact the municipality

☐ Visit the municipal website

☐ Annual report available to public

☐ Utility's website *(please provide website address)* ____________________

12. How does your utility plan on meeting future water demand? *(select all that apply)*

    ☐ Secure new water supply from traditional ground and surface water sources

    ☐ Secure new water supply from alternative sources such as reclaimed water, desalination, etc

    ☐ Replace or improve infrastructure, including water loss control

    ☐ Increase water or sewer rates

    ☐ Demand-side programs to promote water use efficiency and conservation

    ☐ Other *(please specify)* ____________________

13. What factors will significantly impact your utility's ability to meet future water demand? *(select all that apply)*

    ☐ Leakage/loss in old infrastructure

    ☐ Inefficient use or waste by customers

    ☐ Increasing population

    ☐ Increasing cost to treat water

    ☐ Increasing cost to meet testing and other regulatory requirements

    ☐ Inability to maintain access to supply

    ☐ Inability to maintain withdrawal levels

    ☐ Other *(please specify)* ____________________

14. Do you believe that long-run changes in weather patterns (including regional climate change) will seriously and negatively impact your utility's available water supply?
    a. Yes
    b. Not sure
    c. No

    What plan does your utility have to adapt to these long-run changes?

15. Does your utility plan on increasing its delivery capacity in the next five years?
    a. Yes
    b. No (skip to question 17)

16. Please describe the projects to increase capacity over the next five years

    Type of Project

    Total Cost $ ($/gallon if known)

    Total increase in capacity (gallons/day if known)

17. Please include a copy of your rate schedule with the survey or provide a link to a website where the rates are available.

    Website address_______________________________

18. How important are the following components when determining your utility's water rate (1-lowest, 4-highest)? *(please circle one rank per row)*

Issue	**Lowest**			**Highest**	**Not Applicable**
Consumer expectations & attitudes	1	2	3	4	n/a
Cost of delivery (other than regulatory requirements)	1	2	3	4	n/a
Future capital and infrastructure re-investment	1	2	3	4	n/a
Reduce wasteful water use	1	2	3	4	n/a

Regulatory requirements	1	2	3	4	n/a
Repair and maintenance of infrastructure	1	2	3	4	n/a
Revenue or profit requirements	1	2	3	4	n/a
Subsidies for non-water util. operations	1	2	3	4	n/a
Other *(please specify)*______________	1	2	3	4	n/a

19. Has your utility changed its water rate structure in the last five years? *(for example, declining block to inclining block)*
    a. Yes
    b. No (skip to question 22)

20. How has your water rate structure changed in the last five years? (for example, declining block to inclining block)

21. What were the major reasons for changing the rate structure?

22. Has your utility's AVERAGE rate changed in the last five years?
    a. Yes
    b. No (skip to question 25)

23. How has your utility's AVERAGE water rate changed in the last five years?

24. What were the major reasons for changing the rate?

25. Has your utility estimated how a change in water rates will impact water use?
    a. No
    b. Not sure
    c. Yes (please indicate source of information or process used)

26. If residential water rates increased by 10%, what change in total gallons delivered would you expect? *(select one answer for (26a) Total Delivery and (26b) Per Capita Delivery)*

26a) Total Delivery	26b) Per Capita Delivery
a. Increase	a. No change
b. Decrease	b. Less than 5%
c. Stayed about the same	c. 5-10%
	d. 10-15%
	e. 15-20%
	f. More than 20%

27. Has your utility ever used non-price programs such as rebates, water restrictions, low flow devices, etc to manage water demand or promote conservation?
    a. Yes
    b. No (skip to question 33)

28. Please indicate which water conservation programs your utility has used or is currently using. *(select all that apply)*

	Currently using	Have used in the past
Rebates & Retrofit	☐	☐
Efficient irrigation systems	☐	☐
Voluntary watering restriction	☐	☐
Mandatory watering restrictions	☐	☐
Education/awareness programs	☐	☐
Xeriscaping and/or turf buyback	☐	☐
Leak detection at homes	☐	☐
Water budgets and/or audits	☐	☐
New water meter (e.g., smart meters)	☐	☐
Other *(please specify)* ____________________	☐	☐

29. Please describe the water conservation program (or group of programs) that saved MOST water per dollar spent.

Program name or description

[ ]

Program cost $ ($/gallons if known)

[ ]

Reduction in water use (gallons/day if known)

[ ]

Process used to estimate these (study, internal estimate, etc)

30. Please describe the water conservation program (or group of programs) that saved LEAST water per dollar spent

Program name or description

Program cost $ ($/gallons if known)

Reduction in water use (gallons/day if known)

Process used to estimate these (study, internal estimate, etc)

31. How does conservation PRICING impact your utility's revenue? *(select one answer per column)*

Revenue	Revenue Variability	Budget
a. Increase	a. More variable	a. creates a Deficit
b. Decreases	b. Less variable	b. create a Surplus
c. No effect	c. No effect	c. No effect

32. How do conservation PROGRAMS impact your utility's revenue? *(please select one answer per column)*

Revenue	Revenue Variability	Budget
a. Increase	a. More variable	a. creates a Deficit
b. Decreases	b. Less variable	b. creates a Surplus
c. No effect	c. No effect	c. No effect

33. What are the primary barriers to your utility using conservation pricing or conservation programs? *(select all that apply)*

☐ Currently no water shortage

☐ Conservation rates impact low-income customers

☐ Decision makers have little awareness of the policies effectiveness

☐ Cost-effectiveness of programs

☐ Not enough funding for programs

☐ Limited staff

☐ Revenue requirements

☐ Regulatory requirements

☐ Not enough politically support

☐ Other *(please specify)* ________________________

Thank You

If you would like to receive a report summarizing our results, please provide your contact information below. Your information will be kept confidential, and will not be used to identify your survey responses.

Name ________________________________

Address ________________________________

____

____

Phone ________________________________

Email ________________________________

Thank you very much for completing this survey. Your insight will play an important role in determining which water conservation programs work best in Oklahoma. Our contact information is below; please feel free to contact us if you have any questions or comments about the survey.

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Appendix B. Oklahoma Water Users Survey

zoomerang

Oklahoma Water Use and Conservation Survey_V7

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Oklahoma Water Use and Conservation Survey

Page 1 - Image

The Oklahoma Water Resources Research Institute and Oklahoma Cooperative Extension Service are concerned with water use and conservation and how they might affect our daily lives and businesses.
Your views and the views of other Oklahoma residents about water use and conservation as provided in the following survey are very important to guide research and educational efforts in our state.
Your response to this survey is important - you are one of only 800 Oklahomans being asked their views on water use and conservation. Your responses will represent the residents of our state.
Would you please complete this questionnaire? It should only take about 7-10 minutes to complete. Also, your response will remain completely confidential, and no personally identifying information is requested.

Page 1 - Question 1 - Yes or No [Mandatory]

Are you an Oklahoma resident, or have you lived in Oklahoma within the last 5 years?

- ○ Yes [Skip to 2]
- ○ No [Screen Out]

Page 2 - Heading

Water Use and Conservation in Your Community

Page 2 - Question 2 - Rating Scale - One Answer (Horizontal) [Mandatory]

In your opinion, is there currently enough water in your area to meet the needs of your community?

Definitely No	Somewhat No	Neutral/Not Sure	Somewhat Yes	Definitely Yes
○	○	○	○	○

Page 2 - Question 3 - Rating Scale - One Answer (Horizontal) [Mandatory]

In your opinion, will your community need to increase its water supply or reduce water use within the next 20 years?

Definitely No	Somewhat No	Neutral/Not sure	Somewhat Yes	Definitely Yes
❍	❍	❍	❍	❍

Page 2 - Question 4 - Choice - Multiple Answers (Bullets) [Mandatory]

Which of the following water conservation tools or programs has your community used within the last 5 years? (check all that apply)

- ❑ Mandatory watering restrictions
- ❑ Voluntary watering restrictions
- ❑ Helping homeowners install low-flow fixtures and appliances
- ❑ Helping homeowners install rain barrels
- ❑ Paying homeowners to remove turf-grass or plant drought-tolerant plants
- ❑ Increasing water prices for all water users
- ❑ Using conservation pricing so high-volume users pay more for excess water
- ❑ Education and awareness campaigns on water use and conservation
- ❑ None/Don't know

Page 2 - Question 5 - Rating Scale - Matrix [Mandatory]

In your opinion, how effective are the following water conservation tools or programs?

	Very Ineffective	Somewhat Ineffective	Don't Kn
Mandatory watering restrictions	❍	❍	❍
Voluntary watering restrictions	❍	❍	❍
Helping homeowners install low-flow fixtures and appliances	❍	❍	❍
Helping homeowners install rain barrels	❍	❍	❍
Paying homeowners to remove turf-grass or plant drought-tolerant plants	❍	❍	❍
Increasing water prices for all water users	❍	❍	❍
Using conservation pricing so high-volume users pay more for excess water	❍	❍	❍
Water budgets/audits for high-volume users	❍	❍	❍
Education and awareness campaigns on water use and conservation	❍	❍	❍

Page 2 - Question 6 - Rating Scale - One Answer (Horizontal) [Mandatory]

In your opinion, do your neighbors make an effort to conserve water?

Definitely No	Somewhat No	Unsure	Somewhat Yes	Definitely Yes
❍	❍	❍	❍	❍

Page 2 - Question 7 - Rating Scale - One Answer (Horizontal) [Mandatory]

In your opinion, does your local water utility promote water conservation?

Definitely No	Somewhat No	Unsure	Somewhat Yes	Definitely Yes	Do not get water from a local water utility
❍	❍	❍	❍	❍	❍

Page 2 - Question 8 - Rating Scale - Matrix [Mandatory]

Please rate your support for the following practices to conserve water during a drought?

	Definitely Would NOT Support	Probably Would NOT Suppor
Mandatory water restrictions	❍	❍
Increased water prices for high-volume users (conservation pricing)	❍	❍
Increased water prices for all users	❍	❍

Page 2 - Question 9 - Choice - Multiple Answers (Bullets) [Mandatory]

What information sources have you used to learn about your water prices? (Please check all that apply)

- ❑ Visited the utility's website
- ❑ From a water bill
- ❑ From a utility newsletter
- ❑ Contacted the municipality
- ❑ Visited the municipal website
- ❑ Read an annual report
- ❑ From traditional media (e.g., TV, newspaper, radio)
- ❑ Do not know my water price
- ❑ Do not buy water (e.g., have private well)
- ❑ Other, please specify

Page 3 - Heading

Household Water Use and Conservation

Page 3 - Question 10 - Choice - Multiple Answers (Bullets) [Mandatory]

Which of the following has your household adopted?

- ❑ Changed behavior and daily routines for indoor use (e.g., shorter showers)
- ❑ Installed new low-flow faucets and/or showerheads
- ❑ Installed ultra low-flush toilets
- ❑ Installed a water-conserving dishwasher and/or washer
- ❑ Repaired a leaky faucet, showerhead, or toilet
- ❑ Changed behavior and daily routines for outdoor use (e.g., watering lawn less often)
- ❑ Replaced lawn or other water-consuming plants
- ❑ Installed a rain barrel for outdoor water use
- ❑ None of the above
- ❑ Other, please specify

Page 3 - Question 11 - Rating Scale - Matrix [Mandatory]

In your opinion, how effective are each of the following for reducing household indoor water use?

	Very Ineffective	Somewhat Ineffective	Unsure	Somew
Changes in behavior and daily routines (e.g., taking shorter showers)	❍	❍	❍	
Installing low-flow faucets and/or showerheads	❍	❍	❍	
Installing ultra low-flush toilets	❍	❍	❍	
Installing water-conserving appliances (e.g., dishwasher)	❍	❍	❍	
Repairing a leaky faucet, showerhead, or toilet	❍	❍	❍	

Page 3 - Question 12 - Rating Scale - Matrix [Mandatory]

In your opinion, how effective are each of the following for reducing household outdoor water use?

	Very Ineffective	Somewhat Ineffective	Unsure
Changes in behavior and daily routines (e.g., watering grass lawn less often)	❍	❍	❍
Replacing lawn or other water-consuming plants	❍	❍	❍
Installing a rain barrel	❍	❍	❍

Page 3 - Question 13 - Rating Scale - Matrix [Mandatory]

What barriers prevent your household from adopting each of the following for indoor water conservation?

	No Barriers (Have already adopted)	Not Enough Water Sav
Changes in behavior and daily routines (e.g., taking shorter showers)	❍	❍
Installing low-flow faucets and/or showerheads	❍	❍
Installing ultra low-flush toilets	❍	❍
Installing water-conserving appliances (e.g., dishwasher)	❍	❍
Repairing a leaky faucet, showerhead, or toilet	❍	❍

Page 3 - Question 14 - Rating Scale - Matrix [Mandatory]

What barriers prevent your household from adopting each of the following for outdoor water conservation?

	No Barriers (Have already adopted)	Not Enough
Changes in behavior and daily routines (e.g., watering grass lawn less often)	❍	
Replacing lawn or other water-consuming plants	❍	
Installing a rain barrel (costing about $50 to $100)	❍	

Page 3 - Question 15 - Rating Scale - One Answer (Horizontal) [Mandatory]

Over the last five years, how has your household's water use changed?

Large Decrease	Small Decrease	Stayed About the Same	Small Increase	Large Increase	Unsure
❍	❍	❍	❍	❍	❍

Page 3 - Question 16 - Choice - One Answer (Bullets) [Mandatory]

About how much does your water cost (per 1,000 gallons)? Note: the typical household uses about 5,000 gallons per month.

- ❍ Less than $1.00
- ❍ $1.00 - $2.00
- ❍ $2.00 - $3.00
- ❍ $3.00 - $4.00
- ❍ More than $4.00
- ❍ Do not know

Page 3 - Question 17 - Choice - One Answer (Bullets) [Mandatory]

What is the smallest rise in water prices needed for your household to adopt new conservation tools or behaviors?

- ❍ 0 - 10%
- ❍ 10 - 20%
- ❍ 20 - 30%
- ❍ 30 - 40%
- ❍ 40 - 50%
- ❍ More than 50%

Page 3 - Question 18 - Rating Scale - One Answer (Horizontal) [Mandatory]

Would your household use less water if the cost increased by 20%?

Definitely No	Probably No	Neutral/Unsure	Probably Yes	Definitely Yes
❍	❍	❍	❍	❍

Page 3 - Question 19 - Rating Scale - One Answer (Horizontal) [Mandatory]

Based on this scale, please indicate your attitude about the use of water and other natural resources:

Total natural resource use	More use than protection	Equal Balance	More proection than use	Total environmental protection
❍	❍	❍	❍	❍

Page 3 - Question 20 - Rating Scale - One Answer (Horizontal) [Mandatory]

Do you believe that climate change will reduce water supply in your area?

Definitely No	Somewhat No	Unsure	Somewhat Yes	Definitely Yes
❍	❍	❍	❍	❍

Page 4 - Heading

Tell Us About Yourself

Page 4 - Question 21 - Choice - One Answer (Bullets) [Mandatory]

What is your household's drinking water source?

- ❍ Private Supply (Private well, etc)
- ❍ Public Supply (City water utility)
- ❍ Public Supply (Rural water district)
- ❍ Bottled Water
- ❍ Unsure

Page 4 - Question 22 - Choice - One Answer (Bullets) [Mandatory]

Approximately how large is your community size?

- ❍ Less than 3,500 people
- ❍ 3,500 to 7,000 people
- ❍ 7,000 to 25,000 people
- ❍ 25,000 to 100,000 people
- ❍ More than 100,000 people
- ❍ Unsure

Page 4 - Question 23 - Open Ended - One Line

What is your zip code?

Page 4 - Question 24 - Choice - One Answer (Bullets) [Mandatory]

Do you rent or own your home?

- ❍ Rent
- ❍ Own
- ❍ Other (e.g. live with family)

Page 4 - Question 25 - Choice - Multiple Answers (Bullets) [Mandatory]

Does your home have any of the following? (Check all that apply)

- ☐ Lawn
- ☐ Irrigation system
- ☐ Pool

- ☐ Garden
- ☐ None of the above

Page 4 - Question 26 - Choice - One Answer (Bullets) [Mandatory]

Including yourself, how many people live in your household?

- ○ 1
- ○ 2
- ○ 3
- ○ 4
- ○ 5
- ○ More than 5

Page 4 - Question 27 - Choice - One Answer (Bullets) [Mandatory]

How many bathrooms does your home have?

- ○ 1
- ○ 1.5 or 2
- ○ 2.5 or 3
- ○ 3.5 or 4
- ○ More than 4

Page 4 - Question 28 - Open Ended - One Line

What is your age?

Page 4 - Question 29 - Choice - One Answer (Bullets) [Mandatory]

What is your education level?

- ○ Some High School
- ○ High School Graduate
- ○ Some College or Vocational Training
- ○ Bachelors Degree
- ○ Graduate Degree

Page 4 - Question 30 - Choice - One Answer (Drop Down) [Mandatory]

What is your household's annual income?

- ○ Less than $20,000
- ○ $20,000 - $40,000
- ○ $40,000 - $60,000
- ○ $60,000 - $80,000
- ○ $80,000 - $100,000
- ○ More than $100,000
- ○ Prefer not to answer

Page 4 - Question 31 - Choice - One Answer (Bullets)

Approximately how much time did it take you to complete this survey?

- ○ Less than 5 minutes

- ❍ 5 - 10 minutes
- ❍ 10 - 15 minutes
- ❍ More than 15 minutes

Page 4 - Question 32 - Open Ended - Comments Box

Thank you for your time! Please provide any comments about the survey in the space below.

Thank You Page

Screen Out Page

Over Quota Page

Survey Closed Page

Standard

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

Basic Information

Title:	Stream Depletion by Ground Water Pumping: A Stream Depletion Factor for the State of Oklahoma
Project Number:	2009OK119B
Start Date:	3/1/2009
End Date:	8/15/2010
Funding Source:	104B
Congressional District:	3
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Surface Water, Agriculture
Descriptors:	
Principal Investigators:	Garey Fox, Mike Kizer

Publications

1. Fox, G.A., D.M. Heeren, and M.A. Kizer. 2010. Evaluation of alluvial well depletion analytical solutions from a stream-aquifer analysis test along the North Canadian River in Oklahoma. In Proceedings of the American Society of Civil Engineers, Environmental Water Resources Institute Annual Meeting, Reston, VA, 10 pages (CD-ROM).
2. Fox, G.A., D.M. Heeren, and M.A. Kizer. Evaluation of a stream-aquifer analysis test for deriving reach-scale streambed conductance. Transactions of the ASABE 54(2): 473-479.

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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, 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. While the water policy within the state of Oklahoma fails to consider streamflow depletion by groundwater extraction within alluvial systems, a methodology can be developed to assess the importance of this policy limitation. Significant research in the last several years has improved the capability of hydrologists to analyze stream/aquifer interaction during alluvial well depletion through the development of analytical solutions; however, these solutions become mathematically complex. Evaluation of these solutions using field data from multiple regions is needed to assess existing and recently proposed solutions' applicability and predictive capability.

The objective of this research was to develop an Oklahoma stream depletion factor for analyzing the impact of stream depletion of surface water by ground water pumping. Tasks included the following: (1) measuring streambed conductivity in specific stream reaches of two major alluvial river systems in the state of Oklahoma (i.e., North Canadian River and Washita River) using grain size analyses and/or falling head permeameter tests; (2) developing a database of geologic characterization (i.e., depth and extent of the alluvial aquifer) and aquifer parameters for the North Canadian and Washita River alluvial aquifers; (3) long-term monitoring of stream and ground water levels during both recharge and pumping conditions in order to conduct stream/aquifer analysis tests, to evaluate existing analytical solutions, and to determine applicability of the solutions at one field site within each alluvial aquifer; and (4) developing a stream depletion worksheet based on improved analytical solutions for estimating stream depletion by ground water pumping.

In-situ streambed hydraulic conductivity (at both the site of interest and along a several mile reach upstream and downstream of the site) and stream-aquifer analysis tests conducted on the North Canadian River and Washita River in central Oklahoma 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 both rivers behaved similar to streams with little to no hydraulic resistance provided by a streambed layer. It is suggested to use the Hunt (1999) solution for estimating stream depletion in these alluvial aquifers with a large streambed conductance unless measurements of the streambed conductance suggest otherwise. An appropriate method for estimating reach-scale streambed conductance is to conduct stream-aquifer analysis tests. Stream depletion estimates due to the ground water pumping wells were approximately 40-70% of the pumping rate after five days. Both the hydrogeologic and streambed conditions were more heterogeneous at the Washita River site compared to the North Canadian site; therefore, more care needs to be taken in determining characteristic parameters for the Washita alluvial river system along this reach. An Oklahoma Stream Depletion Factor (OSDF) worksheet was developed to allow water managers to determine the impact of a single pumping well discharging at a constant rate on the streamflow in the adjacent river.

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

I. PROBLEM AND RESEARCH OBJECTIVES

Quantifying surface water and ground water interaction in stream/aquifer systems has become an increasingly critical issue for water quantity and quality management. Extracting ground water from pumping wells located adjacent to streams can reduce stream flow, known as alluvial well depletion. The depletive effects on a stream caused by irrigation wells must be estimated in order to administer water rights in many of the states in the western United States (Fox, 2007). In addition, new water management strategies, such as managed recharge projects, are being utilized throughout the United States to manage stream and ground water supplies. The two primary factors influencing stream/aquifer interaction are the hydrologic properties of the aquifer and a streambed layer with a hydraulic conductivity different than the conductivity in the aquifer (Fox, 2007).

When a stream and aquifer are hydraulically connected, the stream and ground water intimately interchange water. When the water level in the stream is above the water level in the aquifer, water is discharged from the stream and into the aquifer. In this situation, the stream is classified as a losing stream. If the water level in the aquifer is above the water level in the stream, water is discharged from the aquifer into the stream. The stream is then classified as a gaining stream. However, if the water level in the aquifer is below the bottom of the streambed, an unsaturated layer can form underneath the stream. The stream is said to hydraulically disconnect from the aquifer. When ground water pumping occurs, recharge from the stream satisfies the applied stress created by the pumping well causing water to flow from the stream into the aquifer. While the water policy within the state of Oklahoma fails to consider stream/ground water interactions within alluvial systems, a methodology can be developed to assess the importance of this policy limitation.

Methodologies based on 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 was defined as the time [d] when the volume of stream depletion reaches 28% of the total volume pumped. Mathematically, SDF was expressed as

$$SDF = \frac{L^2 S}{T} \qquad (1)$$

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

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) solution assumed an infinitely long, straight, completely penetrating stream in a homogeneous aquifer, as shown in Figure 1. Changes in water table elevations were assumed small compared to the saturated thickness of the aquifer, leading to the Dupuit flow assumption. No parameters accounted for a semipervious streambed layer. Applying the principle of superposition, image wells were used to simulate a constant head boundary condition at the stream, and drawdown was given by:

$$s_w(u) = \frac{Q}{4\pi T}\left[E_1(u) - E_1(u_i)\right] \tag{2}$$

where s_w is the drawdown in the semi-infinite domain [m], Q is the pumping rate [m^3 d^{-1}], T is the transmissivity of the aquifer [m^2 d^{-1}], u is the Boltzmann variable, and $E_1(u)$ and $E_1(u_i)$ are the well functions for the real and image well, respectively.

In addressing limitations of the Theis (1941) equation, Hantush (1965) developed an analytical model that considered 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 conductivity 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 equal to the ratio between the hydraulic conductivity of the aquifer, K [m d^{-1}], and the streambed conductivity, K_{sb} [m d^{-1}], divided by the streambed thickness, M [m]. As noted by Sophocleous et al. (1995) and Conrad and Beljin (1996), the Theis (1941) and Hantush (1965) analytical models failed to adequately represent the physical conditions representative of alluvial aquifer systems (e.g., streams that do not fully penetrate the aquifer).

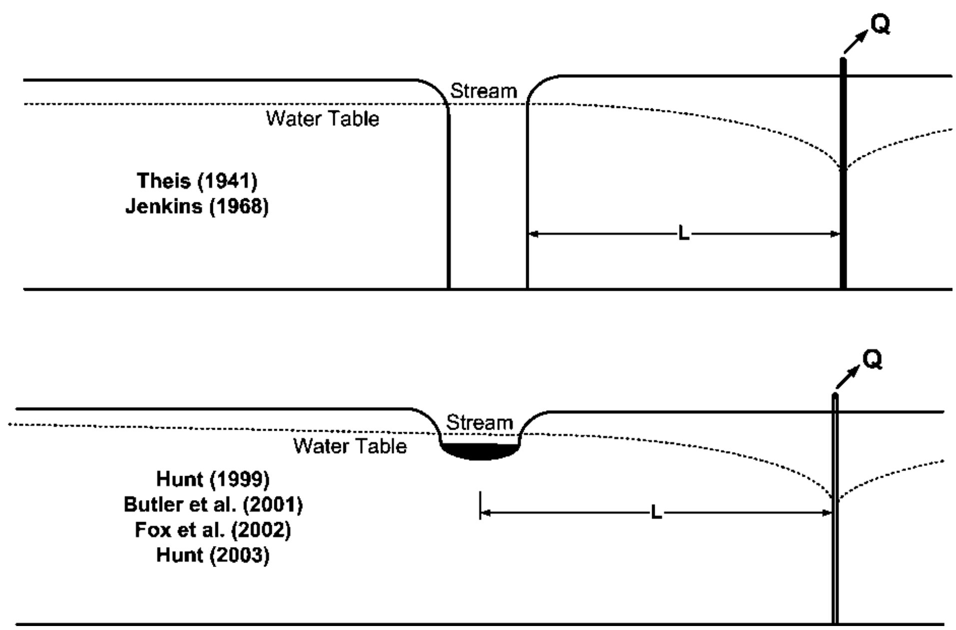


Figure 1. Hydrologic conditions modeled by numerous analytical solutions. Q is the constant discharge rate of the pumping well and L is the distance between the pumping well and stream.

Hunt (1999) developed an analytical model that incorporated streambed conductance and stream partial penetration in the simulation of a groundwater pumping well located near a stream, as shown in Figure 1. Hunt's (1999) 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 were 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 the streambed conductance, λ [m d^{-1}]:

$$\lambda = \frac{K_{sb} W}{M} \tag{3}$$

where W is the width of the river (m). The product of λ and the head gradient between the aquifer and river gave the stream leakage per unit length of river. Hunt (1999) derived both a streamflow depletion equation and drawdown equation:

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

$$s_w(x,y,t) = \frac{Q}{4\pi T}\left\{E_1\left[\frac{(L-x)^2 + y^2}{4Tt/S}\right] - \int_0^\infty e^{-\theta} E_1\left[\frac{(L+|x|+2T\theta/\lambda)^2 + y^2}{4Tt/S}\right] d\theta\right\} \tag{5}$$

where Q_s is the stream depletion rate [m^3 d^{-1}], E_1 is the well function, S is the aquifer storage coefficient, t is the time since the start of pumping [d], 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 [m]. 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 these analytical solutions is that tests can be conducted to simultaneously estimate aquifer and reach-scale streambed parameters in what has been termed a stream-aquifer analysis (SAA) 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, with numerous parameters that must be inversely estimated from potentially limited groundwater data.

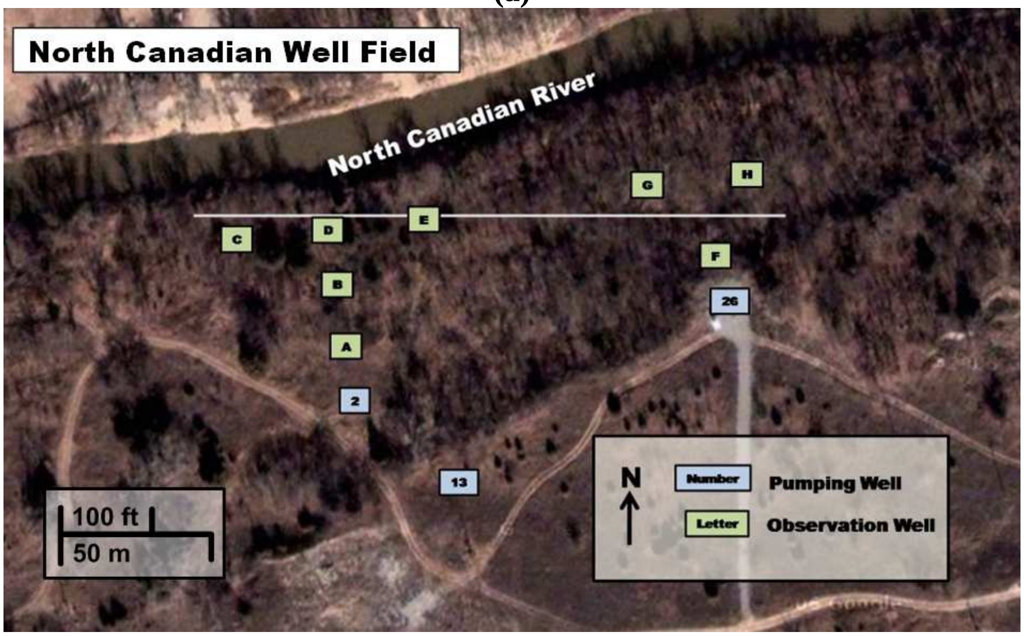
Predicted K_{sb} from SAA tests has been hypothesized to better represent the spatially variable, reach-scale K_{sb} as opposed to point, in-situ measurements, which can vary significantly for different measurement techniques and across a stream cross-section (Landon et al., 2001; Fox, 2004). However, only a few SAA tests have been documented in the literature and compared to field-measured K_{sb} or λ (e.g., Hunt et al. (2001) in New Zealand, Nyholm et al. (2002) in Denmark, and Fox (2004) in eastern Colorado). Field data from multiple regions are needed to assess the applicability and predictive capability of these analytical solutions.

II. METHODOLOGY

2.1 Field Sites

The North Canadian River and Washita River alluvial aquifers were selected for this project due to the magnitude of ground water extractions. 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 is primarily 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. The specific field site along the North Canadian River for the long-term monitoring and stream-aquifer analysis test was located just north of El Reno, OK (Figure 2).

(a)



(b)

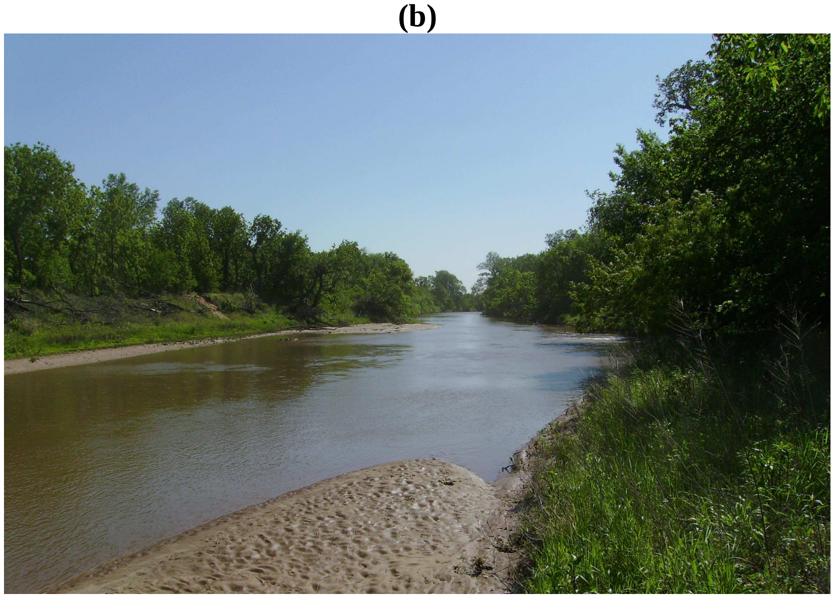
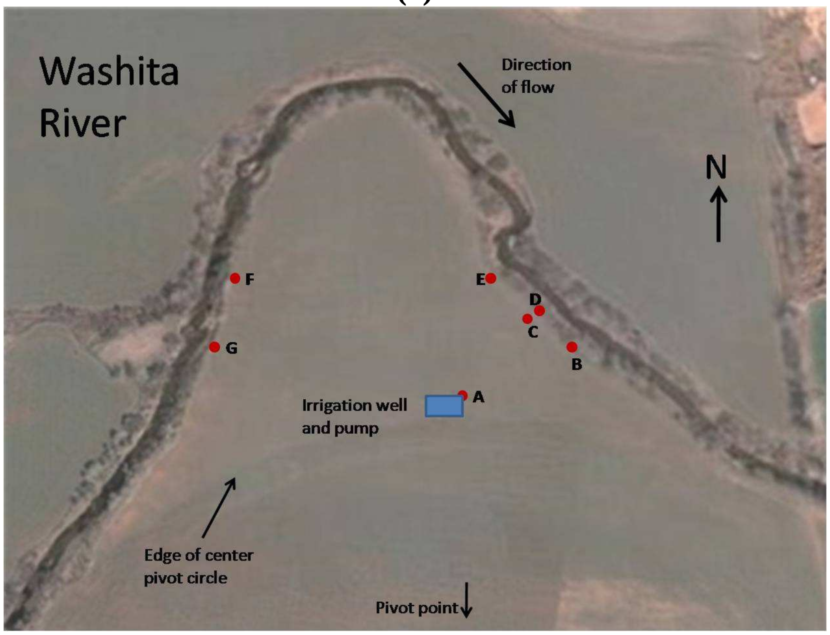


Figure 2. North Canadian River well field site. Observation wells (letters) were installed around two active pumping wells (#2 and #26). Pumping well #26 was utilized for the stream-aquifer analysis test.

Water from the Washita River alluvium and terraces are used for municipal, irrigation, and industrial uses (Hart, 1965). As discussed by Ryder (1996) and Hart (1965), the alluvium was approximately 64 ft (20 m) thick, consisting of primarily fine-grained sand and clay, and lesser amounts of coarser material. The specific field site along the Washita River for the long-term monitoring and stream-aquifer analysis test was located just north of Clinton, OK (Figure 3).

(a)



(b)

Figure 3. Washita River well field site. Observation wells (letters) were located near the irrigation well and also adjacent to the river to prevent interference with farming operations in the adjacent field.

At both sites, observation wells were installed to a depth of approximately 8 m, constructed of Schedule 40 PVC, and included a 5 m screened section at the base. The observation wells were installed using a Geoprobe (Kejr, Inc., Salina, KS) drilling machine. 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 each river to monitor stream stage and temperature.

2.2 Measuring Streambed Conductivity

Streambed sediment samples were acquired from the upper 5 to 10 cm of the streambed and vertical K_{sb} was measured using falling-head permeameter tests near each specific well field and also along a several mile reach upstream and downstream of each site (Figure 4). For the North Canadian site, streambed sediment samples and conductivity measurements at the well field site consisted of three points in the thalweg of the river and two points in sand beds closer to the south bank. At the Washita River well site, streambed sediment samples were obtained at four sampling points: near bank and in the thalweg near observation wells F and G and near observation wells D and E. Falling-head permeameter tests were conducted in the thalweg and near the banks (i.e., in sand bars) of the Washita River at five sampling points. Because of the variability in streambed sediment at the Washita River, falling-head permeameter tests were focused on sampling points that were predominately sand. All reach-scale streambed samples were obtained from near the thalweg of both rivers (Figure 4). Because of the fewer number of sampling sites for the reach-scale Washita River samples, two samples were acquired per sampling site.

Sediment samples were sieved, and the soil texture was determined using ASTM Standard D422-63. The K_{sb} was estimated based on the d_{10} (the effective grain diameter, mm) and d_{50} (the median grain diameter, mm) using the Alyamani and Sen (1993) equation:

$$K_{sb} = 1300[I_o + 0.025(d_{50} - d_{10})]^2 \tag{6}$$

where I_o is the intercept (mm) of the line formed by d_{50} and d_{10} with the grain-size axis. Permeameter tests were performed by pushing a pipe partially into the streambed (10 to 20 cm) and adding water to induce a hydraulic gradient on the sediments inside the pipe (Figure 5). The water level inside the pipe was allowed to fall while the water level was measured over time. Vertical K_{sb} was calculated using an application of Darcy's equation (Landon et al., 2001; Fox, 2004):

$$K_{sb} = \frac{d}{(t - t_0)} \ln\left(\frac{H_0}{H(t)}\right) \tag{7}$$

where $H(t)$ is the water level elevation above the stream level at various times during the experiment, t_0 is the initial time, H_0 is the initial water level elevation in the pipe above the stream water level, d is the sediment interval being tested (10 to 20 cm), and t-t_0 is the elapsed time. Each test was performed for at least 5 minutes with measurements of the head inside the pipe approximately every 30 s. Equation (7) was solved for K_{sb} using the t versus $H(t)$ data by minimizing the sum of squared errors (SSE) between measured and predicted $H(t)$.

(a)

(b)

Figure 4. Locations of reach-scale measurements of streambed hydraulic conductivity at the (a) North Canadian River site and (b) Washita River site.

2.3 Hydrogeologic Cross-Sections and Aquifer Parameters

Information was compiled to create generalized hydrogeologic cross sections and the critical alluvial aquifer parameters within the specific stream reaches of interest along the North Canadian River and Washita River. These parameters included the aquifer transmissitivity (hydraulic conductivity and saturated thickness) and the storage coefficient or specific yield. Well logs reported through the Oklahoma Water Resources Board's Water Information Mapping System (WIMS, http://www.owrb.ok.gov/maps/server/wims.php) were used to determine variability in hydrogeologic cross-sections in wells near the selected field sites.

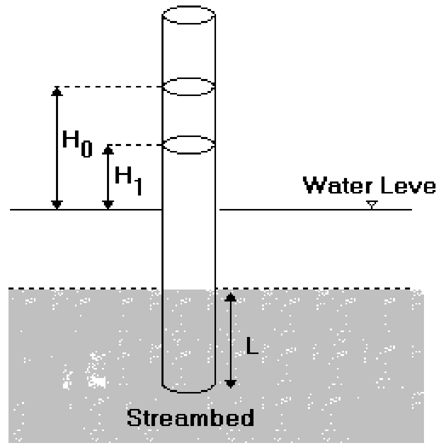


Figure 5. Schematic diagram of falling head permeameter used to measure vertical streambed hydraulic conductivity.

2.4 Long-Term Monitoring and Stream-Aquifer Analysis Tests

For several months prior to the stream-aquifer analysis tests at each site, water levels were monitored in the observation wells every 5 to 15 minutes. This data assisted in determining the most optimal time for the stream-aquifer analysis test and to determine the most suitable observation wells for the test.

At the North Canadian River site (Figure 2), 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.

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

Site	Well Identification (Figure 2)	*x* (m)	*y* (m)	*Q* (m^3/d)
North Canadian River	26	85	0	2180
	F	70	0	---
	G	41	-15	---
	H	50	19	---
Washita River	Irrigation Well	200	0	2728
	F	35	50	---
	G	25	-100	---

At the Washita River site, hydrologic conditions were complicated by numerous factors: (1) greater hydrogeologic variability, (2) the site was within a meander bend, and (3) the irrigation well did not pump at a steady, constant rate. The hydraulic gradient was typically directed from observation well A to observations wells B, C, D, and E, even during pumping, which violates the assumption of existing, transient stream depletion models. Future work must be devoted to developing analytical solutions for the condition of base flow reduction through reducing the ground water gradient. Therefore, the stream-aquifer analysis test focused on observation wells G and F, during a time period of August 8-9, 2010 and a pumping rate of 500 gpm (2728 m^3/d) for the irrigation well located approximately 200 m from the stream. Spatial locations for this site are also provided in Table 1.

Predicted drawdown using the Hunt (1999) solution was fit to the observed drawdown measured in the observation wells for each test site. The Hunt (1999) solution required estimates of T, S_y, and λ. Parameter estimates 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 minimizing the NOF.

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.

2.5 Development of a Stream Depletion Worksheet

The final task of this project was to develop an Oklahoma Stream Depletion Factor (OSDF) worksheet based on the results of the earlier tasks. The OSDF is an automated solution tool that solves for stream depletion by a pumping well based on Hunt's (1999) solution shown in equation (4). The OSDF is based in Excel, allowing the user to easily input the streambed conductance (λ), aquifer parameters (T, S_y), the pumping rate (Q), and the location of the pumping well relative to the stream (L). The program will then estimate the stream depletion in terms of stream infiltration into the alluvial aquifer.

III. PRINCIPLE FINDINGS AND SIGNIFICANCE

3.1 Measuring Streambed Conductivity

3.1.1 North Canadian River

All streambed sediment samples in the North Canadian River were classified as coarse sand. Approximately 99% of each of the five streambed samples was sediment with particle sizes greater than 0.075 mm (Figure 6). The Alyamani and Sen (1993) equation estimated K_{sb} as approximately 30 m/d based on d_{50} = 0.37 mm and d_{10} = 0.19 mm. Streambed K_{sb} estimates from the falling-head permeameters had low variability (i.e., coefficient of variation of 0.2) for this reach of the North Canadian River (Figure 7), especially compared to previous data sets reported in the literature (Landon et al., 2001; Fox, 2004). Only small differences were estimated in thalweg versus edge of channel (i.e., sand bar) measurements. The three thalweg permeameter tests estimated K_{sb} in the range of 13.9 to 20.6 m/d, with the K_{sb} estimated for the sand bars within this range (i.e., 14.6 and 19.0 m/d).

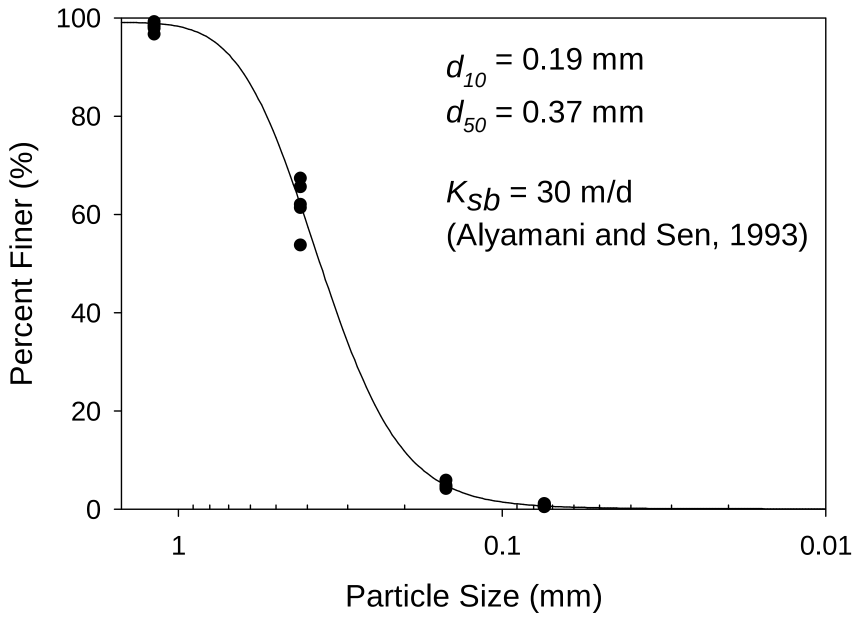


Figure 6. Grain-size distribution measured from five streambed sediment samples in the North Canadian River. The best-fit trend line was used to derive the representative grain size diameters (d_{10}, and d_{50}).

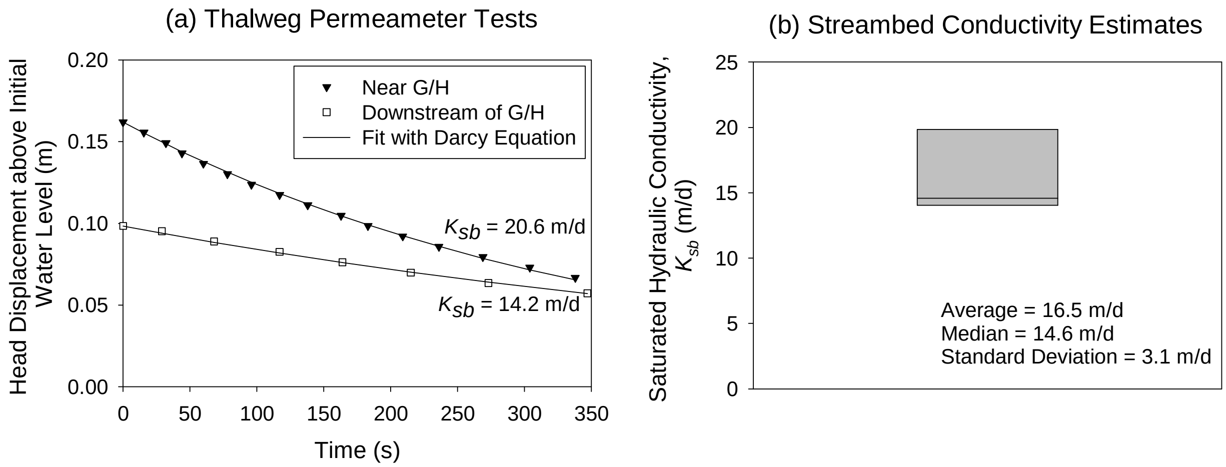


Figure 7. (a) Data from the streambed hydraulic conductivity, K_{sb}, measurements using falling-head permeameter tests in the North Canadian River including the resulting fit of the data with the Darcy equation. (b) Box plot of K_{sb} measurements for both thalweg and sand bar measurements.

Reach-scale K_{sb} estimates were similar to those measured at the specific North Canadian field site. The grain-size distributions from the streambed samples were relatively uniform within the study reach with approximately equivalent d_{10} and d_{50} to the samples at the field site (Figure 8). One exception was an exposed shale/clay layer upstream of the site, with samples from this location not included in the analysis (Figure 4). Falling-head permeameter tests along this reach of the North Canadian River suggested even higher K_{sb} than previous tests (Figure 9).

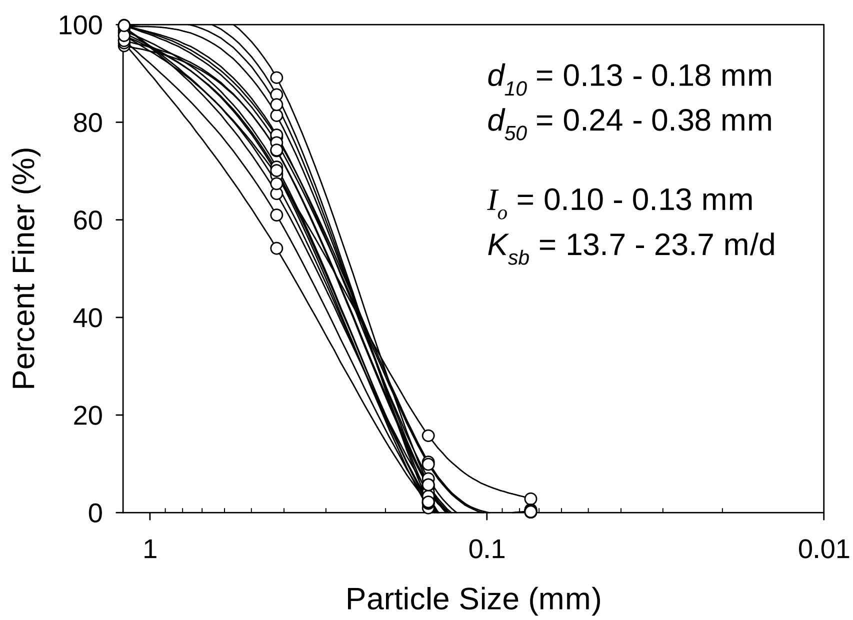


Figure 8. Particle size distribution curves for reach-scale streambed samples along the North Canadian River. Sampling sites are shown in Figure 4(a). The saturated hydraulic conductivity (K_{sb}) was estimated using equation (6).

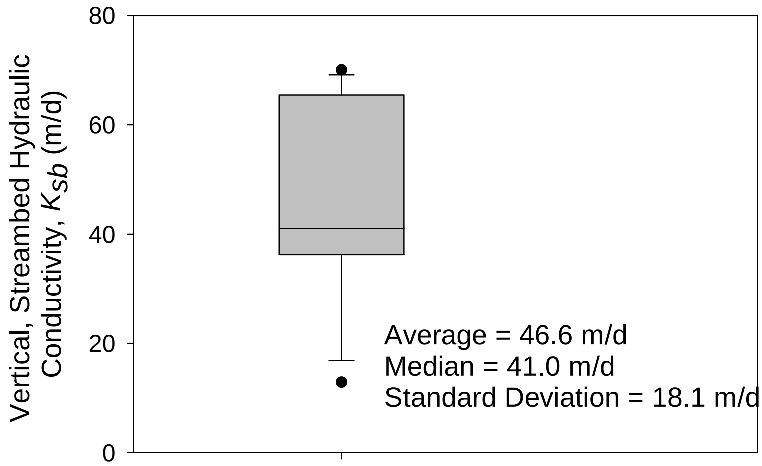


Figure 9. Streambed hydraulic conductivity (K_{sb}) from falling-head permeameter tests measured along the North Canadian River near the El Reno field site. Measurement sites are shown in Figure 4(a).

In general, the North Canadian River K_{sb} measurements were on the same order of magnitude of K for the aquifer material suggesting minimal hydraulic restriction at the streambed. With such high K_{sb}, it was difficult to identify any streambed restriction layer and therefore challenging to estimate M. The W of the North Canadian River was typically between 20 and 25 m. Based on equation (3), the estimated λ was on the order of 10^3 to 10^4 m/d.

3.1.2 Washita River

Streambed samples in the Washita River were more variable than corresponding samples in the North Canadian River. This variability was not surprising considering pictures of the stream at the site (Figure 3b). Samples collected in the thalweg were classified as sand with a d_{50} near 0.4 mm; samples near the banks were classified as sandy loam with a d_{50} near 0.1 mm. The K_{sb} estimated from grain size distribution curves reflected the differences in the streambed samples (Figure 10), with an approximate four-order magnitude difference in estimated K_{sb}. The falling-head permeameter tests also suggested a considerable variability (i.e., 0.3-27.4 m/d), even when trying to measure the K_{sb} of sand dominated locations (Figure 11).

Rach-scale estimates of K_{sb} from the falling-head permeameter tests and particle size distributions were even higher than K_{sb} measured at the site (Figure 12). Falling-head permeameter tests estimated K_{sb} ranging from 8.5 to 185.0 m/d. These estimates support the idea that the Washita River's K_{sb} are on the same order of magnitude of K for the aquifer material, suggesting minimal hydraulic restriction at the streambed.

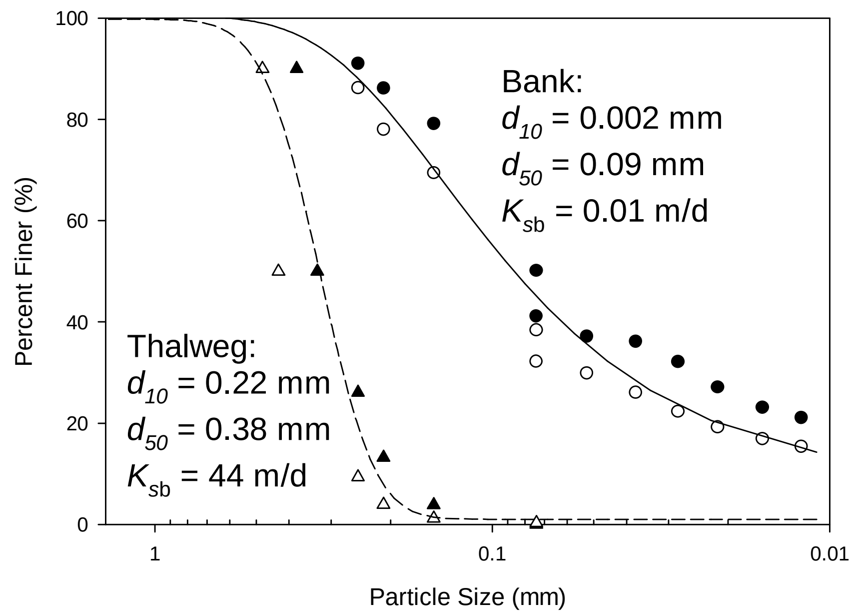


Figure 10. Grain-size distributions measured from four sampling points (two in the thalweg and two in near-bank sediment) in the Washita River. The best-fit trend line was used to derive representative grain size diameters (d_{10} and d_{50}).

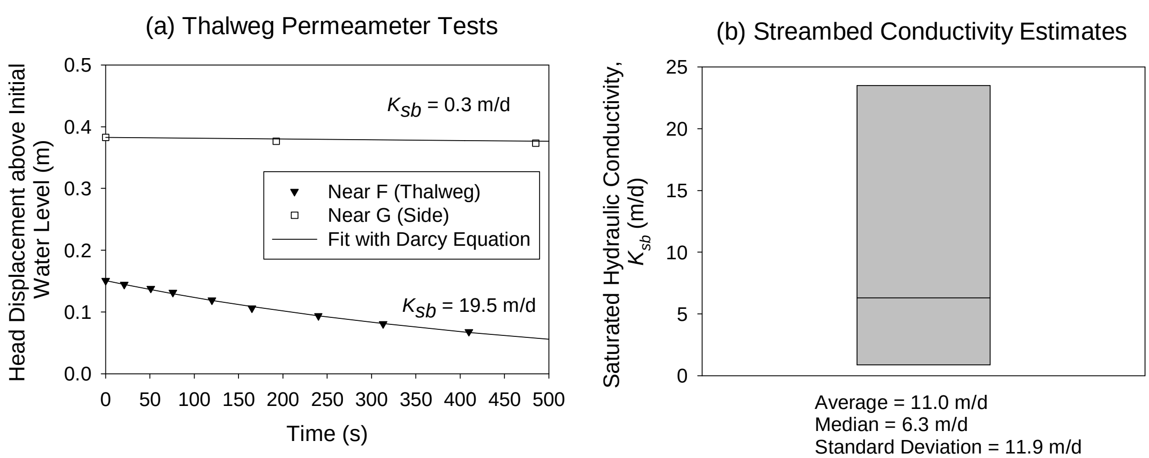


Figure 11. (a) Data from the streambed hydraulic conductivity, K_{sb}, measurements using the falling-head permeameter tests in the Washita River including the resulting fit of the data with the Darcy equation. (b) Box plot of K_{sb} measurements for both thalweg and side channel measurements.

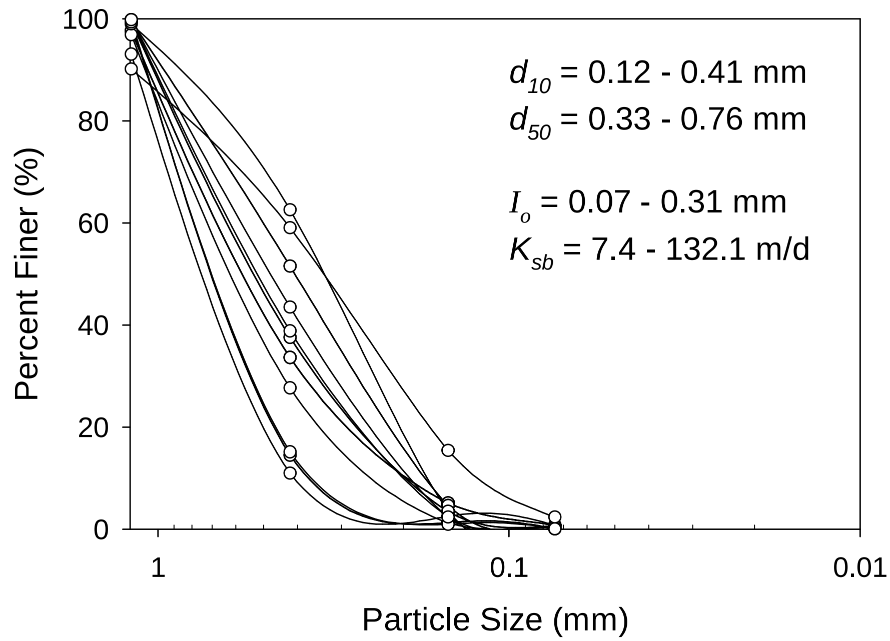


Figure 12. Particle size distribution curves for reach-scale streambed samples along the Washita River. Sampling sites are shown in Figure 4(b). The saturated hydraulic conductivity (K_{sb}) was estimated using equation (6).

3.2 Hydrogeologic Cross-Sections and Aquifer Parameters

Limited data was available on typical parameters for characterizing the alluvial aquifers at both sites. For the North Canadian site, driller's logs reported mostly fine sand with interdispersed clay (ACOG, 2009). Schoff and Reed (1951) reported an aquifer transmissivity, T = 870 m^2/d near in the alluvium near Oklahoma City and El Reno. Ryder (1996) reported specific yield and hydraulic conductivity estimates of 0.29 and 48 m/d.

For the Washita River alluvium, Ryder (1996) and Hart (1965) both mention that the alluvium in the area downstream of the field site was approximately 64 ft (20 m) thick, consisting of primarily fine-grained sand and clay, and lesser amounts of coarser material. Kent (1978) reported depths to bedrock of 12 to 30 m, T of 100 to 400 m^2/d, and S_y of 0.30 for the alluvium between Anadarko and Alex, OK.

Hydrogeologic cross-sections were investigated from well logs from the Oklahoma Water Resources Board's Water Information Mapping System and located adjacent to both field sites (Figures 13 and 14). The well logs demonstrated similar results to the streambed samples in that the Washita River alluvium was much more complex and variable compared to the North Canadian River alluvium at the field sites. The North Canadian alluvium at this location consisted of a large component of fine and coarse sand with interdispersed clay. However, many of the Washita River wells possessed considerable depths of clay and shale with interdispersed sand and coarse gravel (Figure 14).

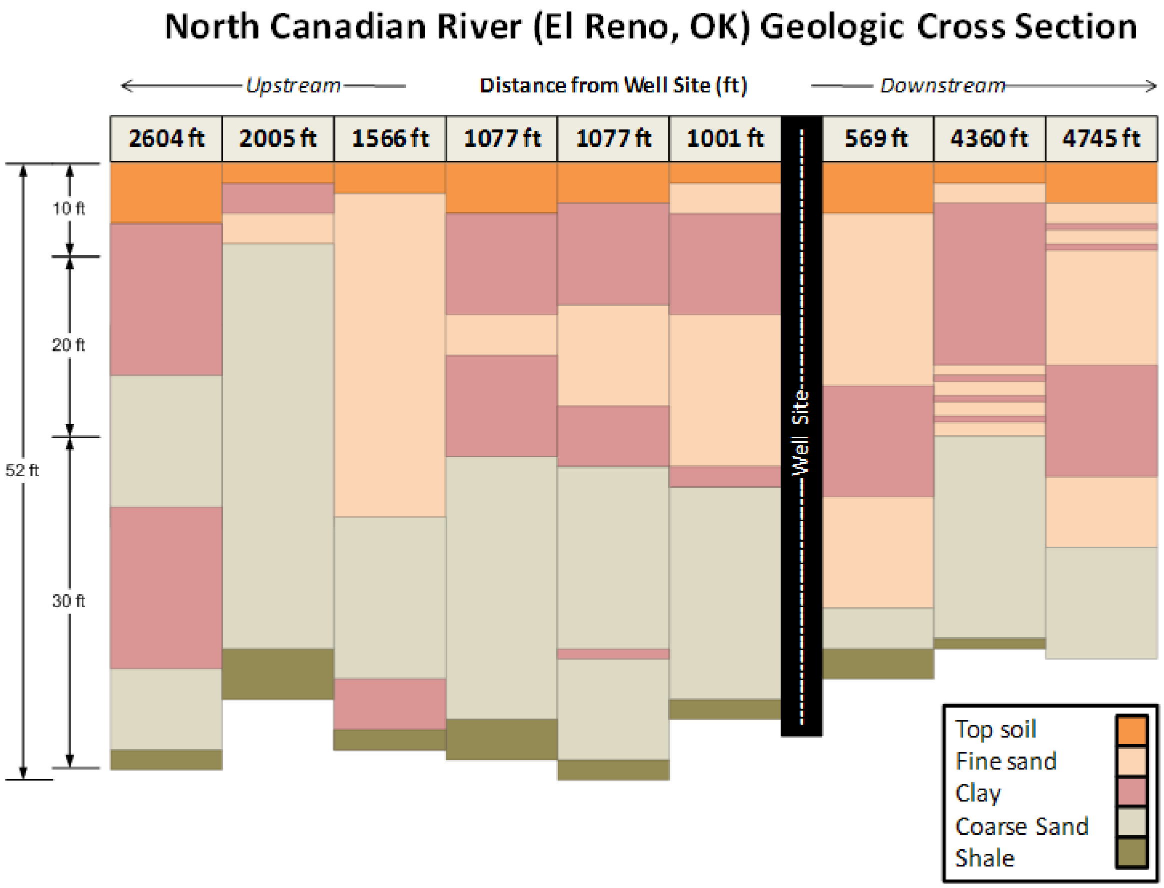


Figure 13. Hydrogeological cross-sections for wells near the North Canadian River field site. Data used to generate the graph is from the Oklahoma Water Resources Board's Water Information Mapping System.

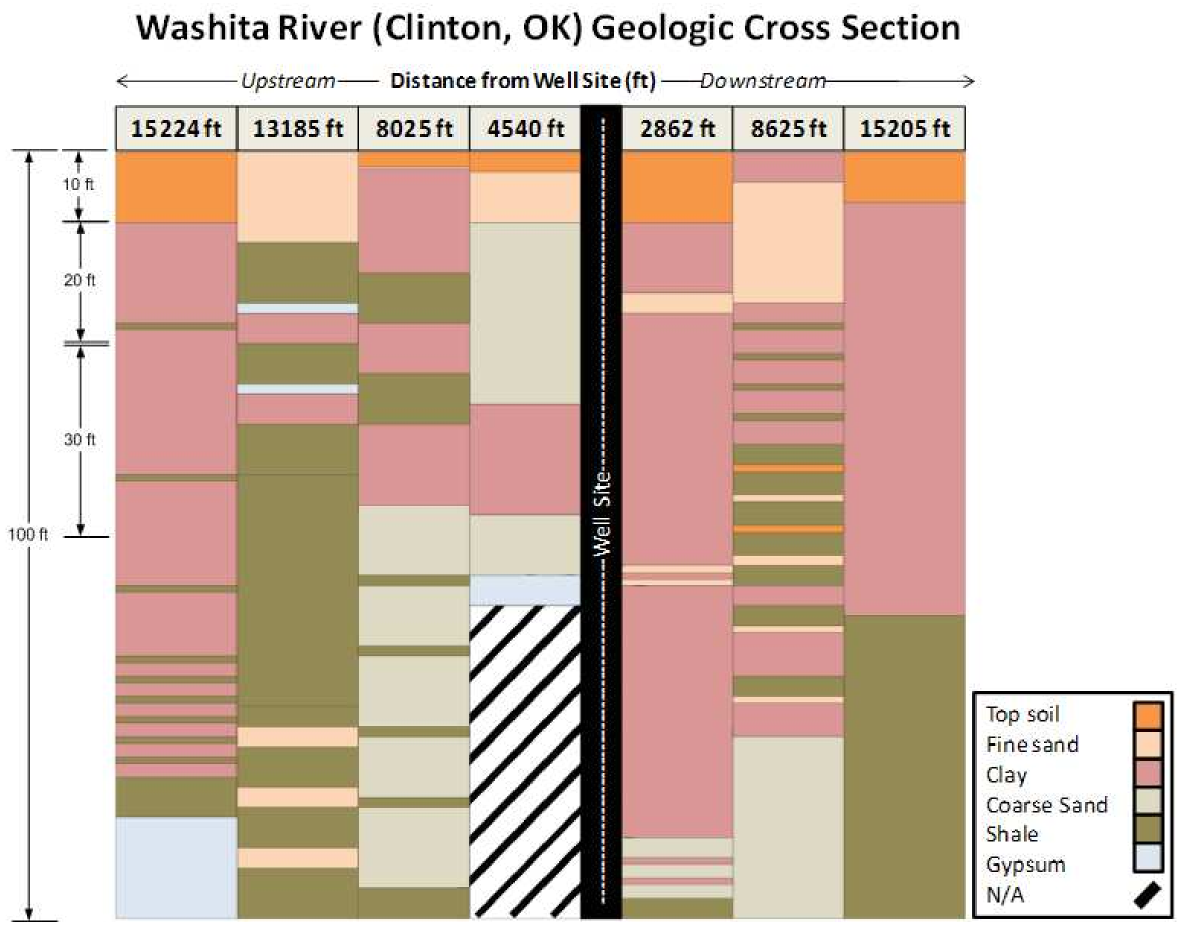


Figure 14. Hydrogeological cross-sections for wells near the Washita River field site. Data used to generate the graph is from the Oklahoma Water Resources Board's Water Information Mapping System.

3.3 Stream/Aquifer Analysis Tests

3.3.1 North Canadian River

For the stream-aquifer analysis (SAA) test period at the North Canadian River site, the initial gradient was directed from the stream and into the alluvial aquifer (i.e., a stream depletion condition), as shown in Figure 15. The initial hydraulic gradient was 0.017 m/m based on a transect from the stream through observation wells G and F.

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 from 790 to 950 m^2/d and 0.19 to 0.28, respectively (Figure 16). 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.

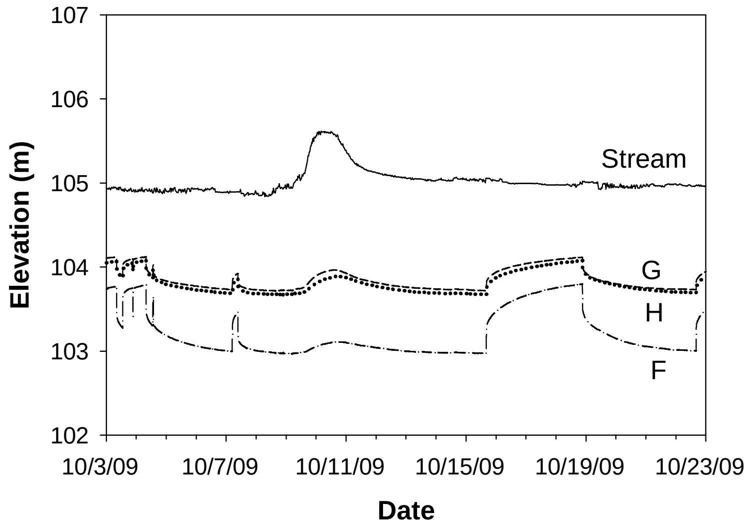


Figure 15. Water levels in the North Canadian River and observation wells during October 2009. The stream-aquifer analysis test was performed from October 18-22, 2009.

Estimates for λ suggested that the North Canadian River at this site was equivalent to a fully penetrating stream with little to 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 (5) converged to the Theis (1941) solution for a fully penetrating stream with no streambed resistance. 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 16a. 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.

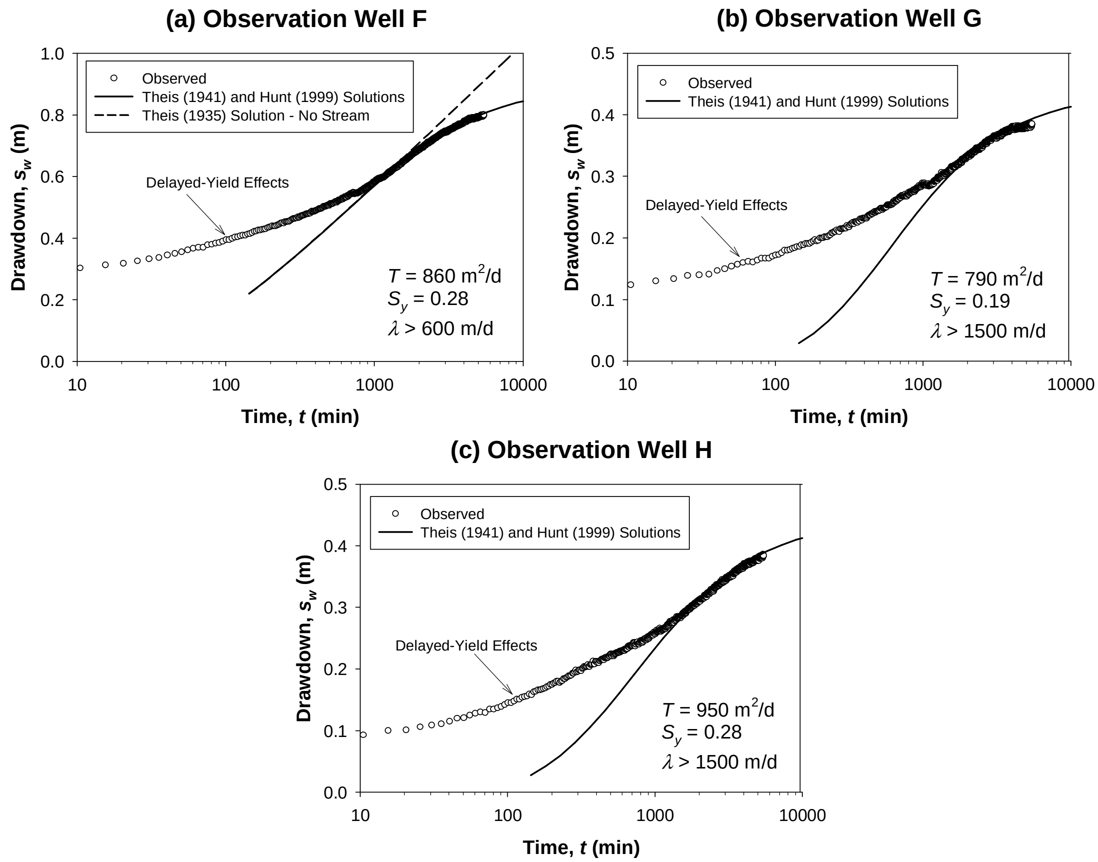


Figure 16. Inversely estimated aquifer transmissivity (*T*), specific yield (S_y), and streambed conductance (λ) derived from fitting the Hunt (1999) analytical solution to the observed drawdown during the stream-aquifer analysis test at the North Canadian River.

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 (4), 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 17). Since λ was relatively large, equation (4) simplified to equation (8), which is the equation obtained when analyzing stream depletion from a fully penetrating stream with no streambed resistance:

$$\frac{Q_s}{Q} = erfc\left(\sqrt{\frac{SL^2}{4Tt}}\right) \quad (8)$$

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 (4), should be used.

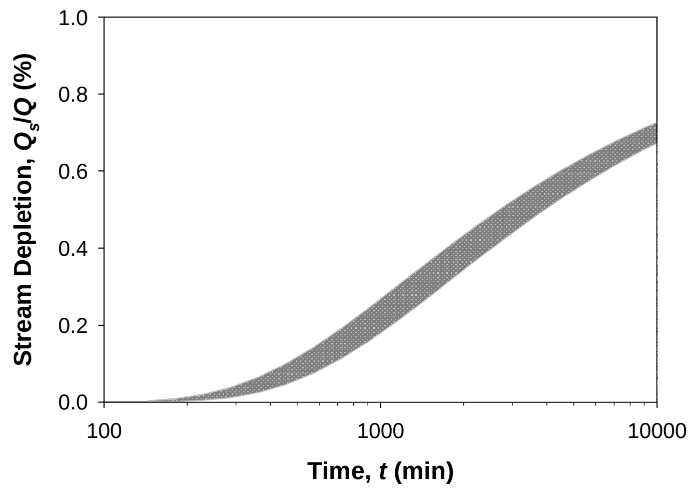


Figure 17. Estimated stream depletion due to pumping well 26 during the stream-aquifer analysis test. Stream depletion was estimated using the Hunt (1999) solution with inversely estimated aquifer and streambed parameters from observation wells F, G, and H (gray area).

3.3.2 Washita River

Long-term monitoring from the Washita River site indicated a greater degree of heterogeneity within this system; i.e., even during times of irrigation well discharge, water levels in observation well A were consistently higher than water levels in some observation wells closer to the stream (Figure 18). This condition suggested preferential flow through coarse material near the irrigation well at the field site. Such conditions created a non-ideal situation for using stream-aquifer analysis tests to estimate aquifer parameters and the streambed conductance. First, observation wells B, C, and D could not be used due to the fact that the water table gradient was directed from A to B, C, and D throughout the test (Figure 18). In other words, the irrigation well did not have enough influence on the ground water system to create a stream depletion scenario, but rather a capture of return base flow. While this condition may be common in many ground water systems, the analytical models utilized in this research are not capable of simulating transient dynamics for this condition. Therefore, the stream-aquifer analysis test focused on observation wells G and F, during a time period of August 8-9, 2010 and assuming a pumping rate of 500 gpm (2728 m^3/d) for the irrigation well located approximately 200 m from the stream.

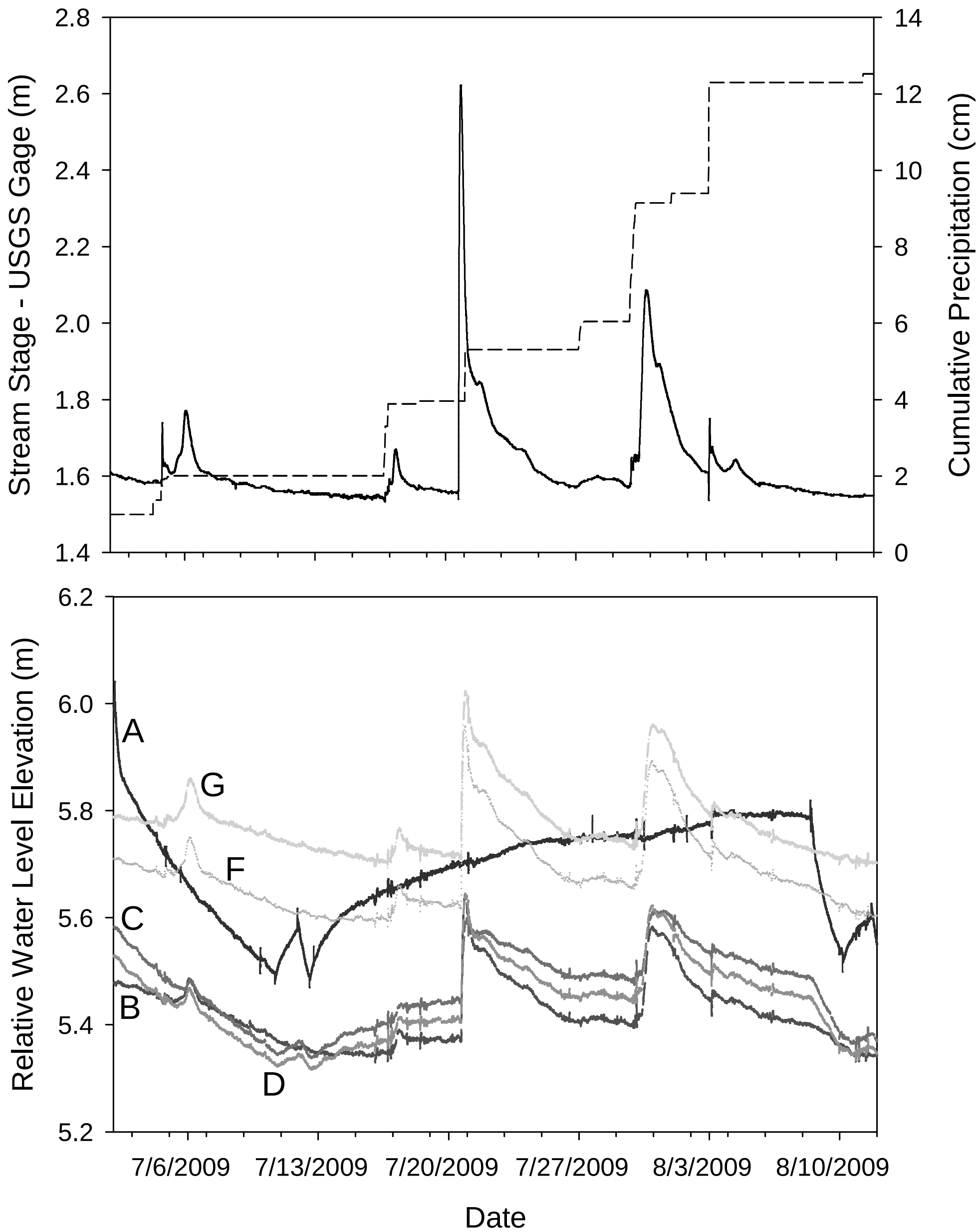


Figure 18. Stream stage as measured at the USGS gage on the Washita River in Clinton, OK, cumulative precipitation, and water level elevations in observation wells at the Washita River site.

Since only observation wells F and G were used in the analysis, drawdown was only observed in these observation wells during late-time data. Inversely estimated T and S_y ranged between 400 to 450 m^2/d and 0.07 to 0.08, respectively (Figure 19), and these values were consistent with limited literature values for the Washita River alluvium. The NOF for both observation wells was approximately 0.30. The larger NOF for the Washita compared to the North Canadian River was due to the dependence of the metric on the average of the observed data; the average of observed drawdown for these two observation wells were small compared to the drawdown observed at the North Canadian River field site. Further attempts at calibrating parameters for the model were not successful in significantly reducing the NOF while at the same time maintaining reasonable parameter values. More complex analytical solutions may be warranted for the Washita River due to the heterogeneity within the system, but these complex solutions required a user to inversely estimate a multitude of other parameters for which reasonable parameter values were unknown.

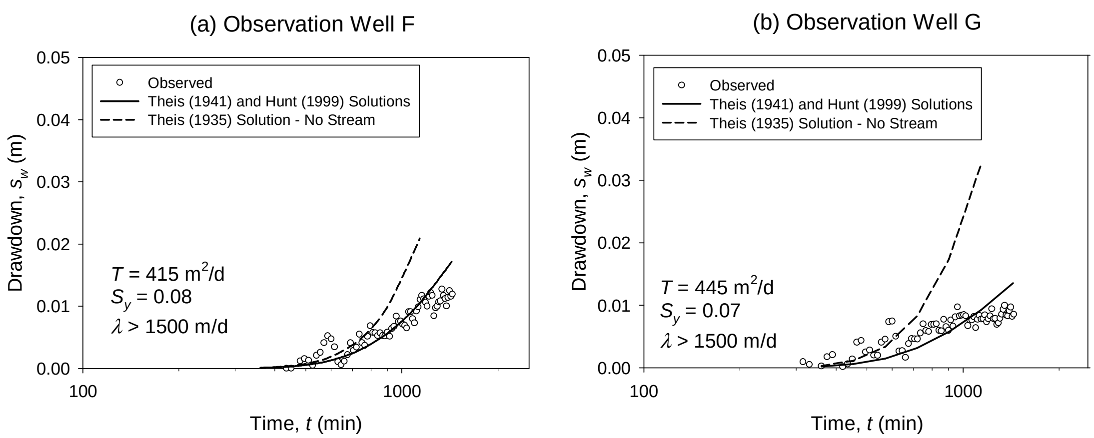


Figure 19. Inversely estimated aquifer transmissivity (*T*), specific yield (S_y), and streambed conductance (λ) derived from fitting the Hunt (1999) analytical solution to the drawdown during the stream-aquifer analysis test at the Washita River.

Estimates for λ suggested that the Washita River at this site, similar to the North Canadian River site, was equivalent to a fully penetrating stream with little streambed conductivity resistance. Estimates of λ from both observation wells were approximately 1500 m/d, with greater λ resulting in approximately equivalent drawdown profiles. As shown in Figure 19, the Hunt (1999) solution mimicked data from the Theis (1941) solution for a fully penetrating stream and no streambed resistance. Also, as shown in Figure 19, the predicted drawdown response due to pumping the well without consideration for the stream (i.e., the Theis (1935) solution) was significantly different, serving as another indicator of the importance of intense stream-aquifer interaction on the drawdown profiles.

Estimated stream depletion based on the Hunt (1999) solution, i.e., equation (4), using the inversely estimated parameters from observation wells F and G were approximately 10% of Q after one day of pumping and approximately 50% of Q after one week of pumping (Figure 20). It can be noted that these numbers are smaller than the corresponding stream depletions estimated using data from the North Canadian River site. The primary reason was the location of the pumping well relative to the stream; the pumping well at the Washita River site was 115 m further from the river than the pumping well at the North Canadian River. Similar to the North Canadian River site, it is suggested that equation (8) can be used as a first estimate of stream depletion unless site-specific conditions (i.e., measurements of λ being small) suggest otherwise.

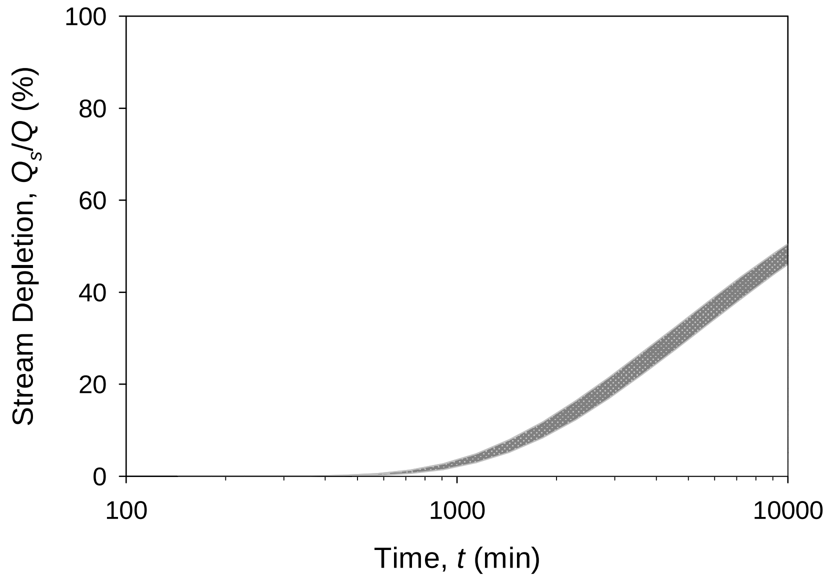


Figure 20. Estimated stream depletion due to the irrigation well at the Washita River site during the stream-aquifer analysis test. Stream depletion was estimated using the Hunt (1999) solution with inversely estimated aquifer and streambed parameters from observation wells F and G (gray area).

3.4 Oklahoma Stream Depletion Factor (OSDF) Worksheet

Stream-aquifer analysis test results have indicated that both the North Canadian River and Washita River sites have intense stream-aquifer interaction during alluvial well depletion. To assist water managers with estimating stream depletion using equations (4) or (8), the stream depletion factor worksheet can be used. The interface of the worksheet is shown in Figure 21. Technical information is provided in a tab in the worksheet. Users can also access the values used to generate the figures for cumulative stream depletion (in ft^3/s) or the stream depletion factor (Q_s/Q) shown on the main page through a calculations tab. This spreadsheet is intended to serve as an initial tool for determining the impact of a single alluvial pumping well discharging at a constant rate on the adjacent streamflow. This spreadsheet tool can be obtained free of charge by contacting Dr. Garey Fox at garey.fox@okstate.edu or by downloading the program at http://biosystems.okstate.edu/Home/gareyf/OSDF.htm.

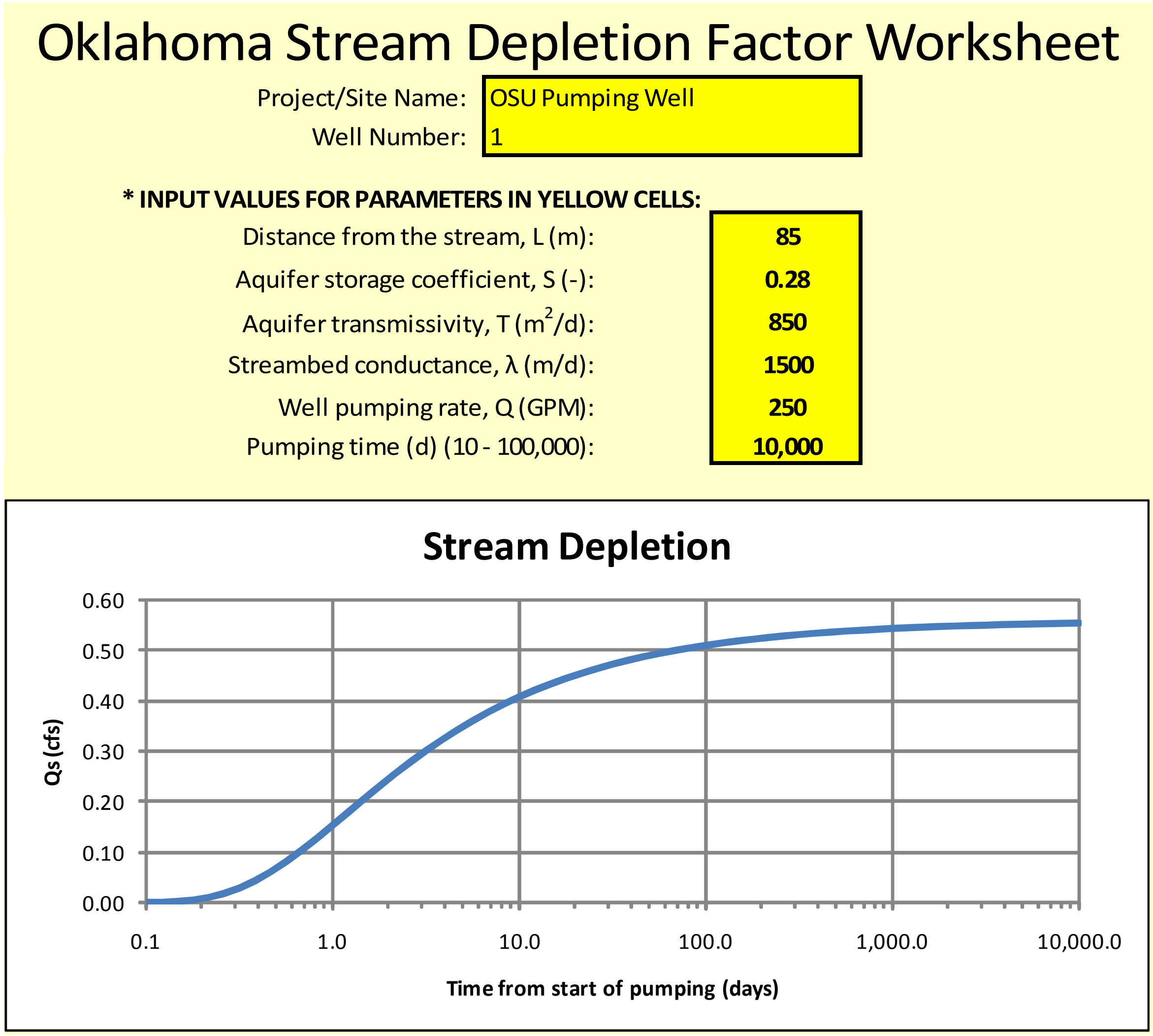


Figure 21. Oklahoma Stream Depletion Factor Worksheet main page. Users can enter the aquifer and streambed parameters, location of the pumping well from the stream, and pumping rate. The worksheet solves for the stream depletion over time. The program can be downloaded from http://biosystems.okstate.edu/ Home/gareyf/OSDF.htm.

IV. Conclusions and Future Work

The stream-aquifer analysis tests conducted on the North Canadian River and Washita River in central Oklahoma 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 both rivers behaved similar to fully penetrating streams with little to no hydraulic resistance provided by a streambed layer. Estimates of streambed hydraulic conductivity from grain-size analyses and falling-head permeameter tests indicated that at both sites the conductivity of the streambed was on the same order of magnitude as the conductivity in the aquifer. The Washita River streambed hydraulic conductivity was much more variable, potentially due to the variability in the geological system through which the river is flowing.

Because of the large values of field measured and inversely estimated streambed conductance, simpler analytical solutions proposed by Theis (1941), Jenkins (1968) and Hunt (1999) were appropriate for the rivers at the site locations. Even though the streams only physically partially penetrated into the alluvial aquifers, the lack of hydraulic resistance created streams that intensely interacted with their alluvial aquifers. In fact, estimates of stream depletion were as high as 40 to 70% of the pumping rate after only five days of pumping. Predicted streambed hydraulic conductivity from stream-aquifer analysis tests were similar to streambed hydraulic conductivity measured in situ using falling-head permeameter tests and grain-size distribution empirical equations. The advantage of the stream-aquifer analysis tests is that they provide a reach-scale integrated estimate of the streambed conductivity, less influenced by local-scale spatial heterogeneity within the river.

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 in 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. These simpler solutions were used to develop an Oklahoma Stream Depletion Factor (OSDF) worksheet to allow water managers to determine the impact of a single pumping well discharging at a constant rate on the streamflow in the adjacent river.

V. ACKNOWLEDGEMENTS

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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:	9/30/2012
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.
4. Zou Chris, Don Turton, Rod Will, Sam Fuhlendorf, David Engle, Jenny Hung. 2010. Estimating watershed level evapotranspiration using water budget method. ESA 95th Annual Meeting.
5. 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.
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7. 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.
8. Zou Chris, Don Turton, Rod Will, Sam Fuhlendorf, David Engle, Jenny Hung. 2010. Estimating watershed level evapotranspiration using water budget method. ESA 95th Annual Meeting.
9. Zou, CB, Turton D, Engle D. 2010. How eastern redcedar encroachment affects the water cycle of Oklahoma rangelands. NREM-2888. Oklahoma Coop. Ext. Serv. Oklahoma State University, Stillwater.
10. Stebler E, Turton D, Zou C. 2011. Impact of eastern redcedar (Juniperus virginiana) encroachment on streamflow in Oklahoma grassland watersheds. Poster presentation at Oklahoma Clean Lakes and Watershed Association Conference, Edmond OK, April 7 8, 2011. (Poster, Abstract)

11. Stebler E, Turton D, Zou C. 2010. Rainfall interception by eastern redcedar (Juniperus virginiana) and its implications for water balance in Oklahoma grassland watersheds. Governor's Water Conference and OWRRI Water Research Symposium. 2010. Norman, Oklahoma. (Poster, Abstract)
12. Hung J, Zou CB, Engle D, Turton, Will R, Fuhlendorf S, Winton K. 2010. Temporal dynamics of soil-water content and soil-water depth in mesic tallgrass prairie and eastern redcedar woodland. Governor's Water Conference and OWRRI Water Research Symposium. 2010. Norman, Oklahoma (Poster, Abstract)
13. Zou CB. Climatic change and ecohydrology. Special session. 2010. The 95th ESA Annual Meeting, Pittsburgh, PA. (Oral presentation, Abstract)
14. Zou CB, Turton D, Will R, Fuhlendorf S, Engle D, Hung J. 2010. Estimating watershed level evapotranspiration using water budget method. The 95th ESA Annual Meeting, Pittsburgh, PA (Poster, Abstract).

Interim Report 2011

Title: Eastern redcedar encroachment and water cycle in tallgrass prairie

Start Date: 09/01/09

End Date: 08/31/12

Congressional District: Oklahoma Congressional District 3

Focus Category: ECL, FL, GW, HYDROL, INV, SW, WS, WU

Descriptors: baseflow, evapotranspiration, grassland, precipitation interception, sapflow, soil water dynamic, streamflow, water budget and water cycle

Principal Investigators:

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

Supported Students:

Student Status	Number	Disciplines
Undergraduate		
M.S.	1	Natural Resource Ecology and Management
Ph.D.	1	Natural Resource Ecology and Management
Post Doc	0	
Total	2	

Publications

Since the 2010 report, we published one Factsheet, six presentation/abstracts in regional and national meetings and one more presentation has been accepted for 2011 ESA annual meeting. We are working on two manuscripts towards peer-reviewed journal publication.

ü Zou, CB, Turton D, Engle D. 2010. How eastern redcedar encroachment affects the water cycle of Oklahoma rangelands. NREM-2888. Oklahoma Coop. Ext. Serv. Oklahoma State University, Stillwater.

ü Stebler E, Turton D, Zou C. 2011. Impact of eastern redcedar (*Juniperus virginiana*) encroachment on streamflow in Oklahoma grassland watersheds. Poster presentation at Oklahoma Clean Lakes and Watershed Association Conference, Edmond OK, April 7 – 8, 2011. (Poster, Abstract)

ü Stebler E, Turton D, Zou C. 2010. Rainfall interception by eastern redcedar (*Juniperus virginiana*) and its implications for water balance in Oklahoma grassland watersheds. Governor's Water Conference and OWRRI Water Research Symposium. 2010. Norman, Oklahoma. (Poster, Abstract)

- Hung J, Zou CB, Engle D, Turton, Will R, Fuhlendorf S, Winton K. 2010. Temporal dynamics of soil-water content and soil-water depth in mesic tallgrass prairie and eastern redcedar woodland. Governor's Water Conference and OWRRI Water Research Symposium. 2010. Norman, Oklahoma (Poster, Abstract)

- Zou CB. Climatic change and ecohydrology. Special session. 2010. The 95th ESA Annual Meeting, Pittsburgh, PA. (Oral presentation, Abstract)

- Zou CB, Turton D, Will R, Fuhlendorf S, Engle D, Hung J. 2010. Estimating watershed level evapotranspiration using water budget method. The 95th ESA Annual Meeting, Pittsburgh, PA (Poster, Abstract).

Problem and Research Objectives:

The overall objectives are to develop an improved understanding of the effects of eastern redcedar encroachment in tallgrass prairie on ecohydrological processes and potential effect on water supplies.

The specific objectives for year 2 included:

1. Construction and instrumentation of 4 watersheds to quantify streamflows of the grassland watersheds and grassland heavily encroached by redcedar;

2. Installation of three Dynamax sapflow systems to continuously record sapflow of redcedar trees representative of a range of size classes to estimate watershed level transpiration dynamics;

3. Calibration of ET chamber and deployment of it in the field to directly measure ET;

4. Construction and installation of canopy interception equipment to estimate precipitation loss directly to canopy of both grass and trees;

Methodology:

1. **Streamflow** - All 4 watersheds were constructed with the help of Oklahoma State University Kiamichi Forestry Research Station field crew (as reported last year) and instrumentation was completed in late summer 2010.

Fig.1 One of the redcedar encroached watersheds equipped with H flume, stage recorder, datalogger, rain gage, solar radiation, wind speed, wind direction, soil temperature, air temperature, and RH sensors.

2. Sap flow Measurement- Installation of Dynamax sap flow systems was completed 20 December 2010 with 44 total probes inserted in 22 redcedar trees. The trees were selected based on diameter distribution and canopy openness to represent the range of tree sizes and conditions throughout the encroached watersheds. Data are downloaded and processed weekly. The systems are working as expected. Transpiration was very low during the coldest part of winter, but has increased with warming and rainfall this spring.

Fig 2: The probes and insulation installed at the closed-grown site (upper pictures) and the data being downloaded from the system at the open-grown site (lower pictures). Power is supplied to each system from two marine batteries that are kept charged by solar panels.

3. **ET Chamber** – We worked with USGS Oklahoma Water Science Center personnel to build and calibrate the ET chamber during 2010. The chamber was deployed for field

measurement in late 2010 and we have conducted multiple full-day ET measurements in 2011.

Fig. 3. ET chamber measuring ET from a sapling redcedar during an early spring field run while grass was still dormant

4. **Canopy interception –** Instrumentation for grassland sites was completed by August 2010. By the end of November, 25 redcedar trees were equipped with stemflow collectors and each tree had 8 throughfall collectors installed under the tree canopy. The trees were selected nearby and similar to the trees used for sap flow measurements.

Fig. 4. Throughfall and stemflow collectors installed under redcedar trees and grass.

5. Soil Water Content – Soil moisture measurements were continued for the three stations located within each watershed.

The entire project has been proceeding mostly according to the research plan. However, construction of the watershed flumes was delayed for several months due to weather and the field ET measurements were delayed due to a technical glitch when the extension tube was added to the chamber design to accommodate tall grass and redcedar seedlings.

Principal Findings and Significance:

Our first set of sapflow data revealed minimum sap flow activities during both winter and early spring, suggesting low redcedar transpiration rates during this cold time of year. This is in contrast to our general assumption that the evergreen redcedar trees are actively transpiring year around. It is unclear to us whether this was controlled or triggered by temperature or soil moisture (which was very low) or whether those initial low transpiration values were a result of the tree healing due to probe installation.

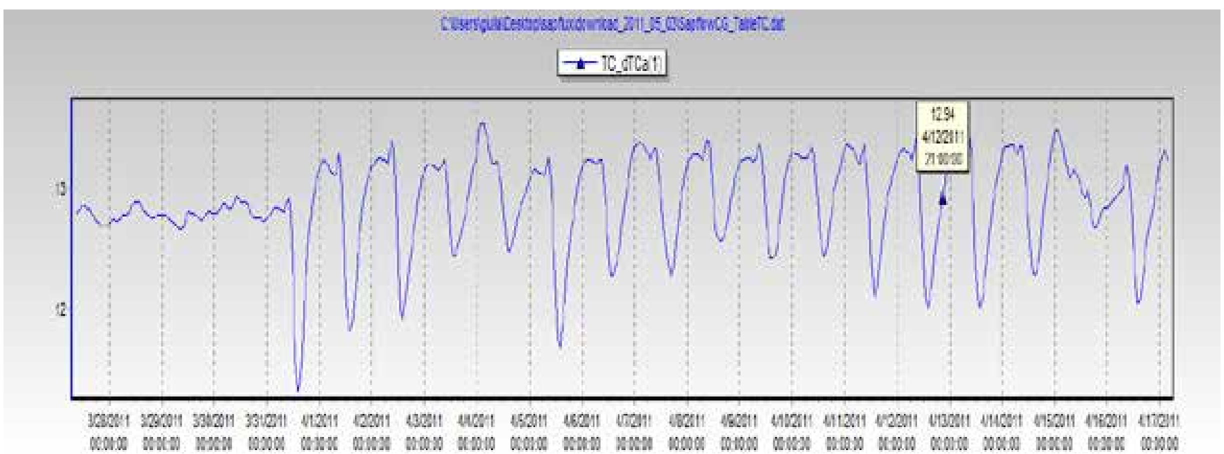

Fig. 5: Representative data from one probe between 28 March 2011 and 17 April 2011. Magnitude of the cyclical diurnal pattern is proportional to transpiration.

Our ET chamber measurements captured the substantial evapotranspiration difference between redcedar seedlings, grasses and grasses that had been clipped to 1inch height (Fig. 6). We anticipate that this relative difference will likely change during the summer and fall seasons. This plot level ET information, in conjunction with sapflow and streamflow data, will provide insights in terms of the intertwined relationship between plant ecophysiology, landscape level water flux dynamics and watershed runoff processes.

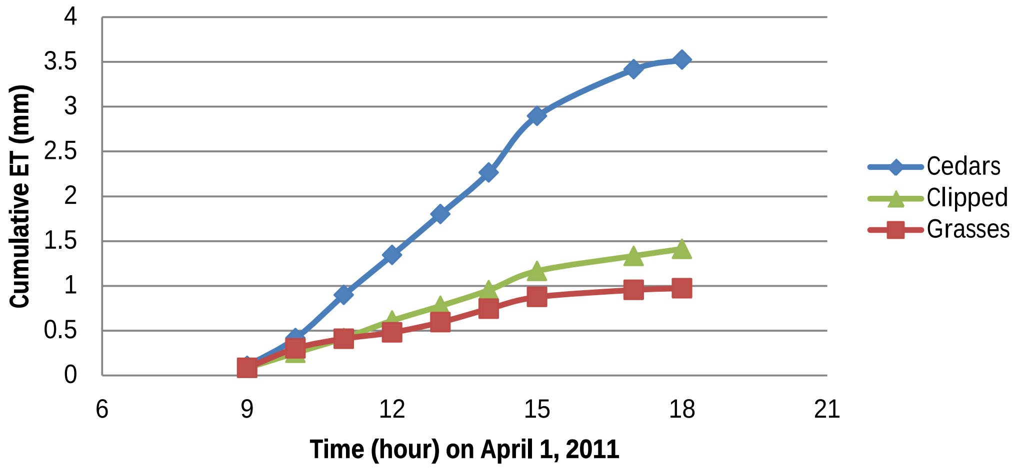

Fig. 6. Evapotranspiration rates (mm day^{-1}) of redcedar seedling, grass and clipped grass (clipped to 1 inch from ground) directly measured using a USGS designed ET chamber.

Due to the extreme drought condition we experienced from 2010 fall to 2011 spring in central Oklahoma, there were few rainfall events and precipitation input on our sites was extremely low. Limited data precludes us from making any conclusion statements regarding the interception data and streamflow data during this report period.

Water conservation in Oklahoma urban and suburban watersheds through modification of irrigation practices.

Basic Information

Title:	Water conservation in Oklahoma urban and suburban watersheds through modification of irrigation practices.
Project Number:	2010OK180B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	3
Research Category:	Biological Sciences
Focus Category:	Conservation, Drought, Climatological Processes
Descriptors:	None
Principal Investigators:	Justin Quetone Moss, Damian Adams, Tracy Boyer, Dennis Martin, Michael Smolen, Kemin Su

Publications

1. Martin, Dennis, Santanu Thapa, Steve Batten, Justin Moss, Greg Bell, Jeff Anderson, Yanqi Wu, and Kemin Su. 2010. Evapotranspiration rates of Riviera and U-3 bermudagrasses under non-limiting soil moisture conditions. In: 2010 Agronomy abstracts. ASA, Madison, WI.
2. Moss, Justin, Dennis Martin, Yanqi Wu, Kemin Su, and Bishow Poudel. 2010. Development and selection of bermudagrasses for water conservation in urban landscapes. In: Proceedings of the 2010 USDA National Water Conference, Hilton Head, SC.
3. Reilley, Michael, Tracy Boyer, Damian Adams. 2010. Using best-worst scaling to understand public perception of municipal water conservation tools. Poster presentation. 2010 Oklahoma Governor s Water Conference, Norman, OK.

Water conservation in Oklahoma urban and suburban watersheds through modification of irrigation practices.

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Start Date: March 1, 2010

End Date: February 28, 2011

Congressional District: 3rd

Focus Category: Conservation, Drought, Irrigation

Number of Students Supported:

Student Status	Number	Disciplines
Undergraduate	3	Horticulture, Agricultural Economics
M.S.	3	Horticulture, Agricultural Economics
Ph.D.	0	NA
Post Doc	1	Horticulture
Total	7	

Publications:

1. Articles in Refereed Scientific Journals

None

2. Book Chapter

None

3. Dissertations & Theses

Haase, John. 2011. Simple Irrigation Audits for Homeowners. “MS Thesis”. Department of Horticulture and Landscape Architecture, Environmental Science Graduate Program, College of Agricultural Sciences and Natural Resources, Oklahoma State University, Stillwater, OK. (in preparation/to be submitted Summer 2011).

Schmidt, JoDee. 2011. Economics and Perception of Turfgrass and Landscape Water Use and Conservation. “MS Thesis”. Department of Agricultural Economics, College of Agricultural Sciences and Natural Resources, Oklahoma State University, Stillwater, OK. (in preparation/to be submitted Summer 2011).

Sidwell, Courtney. 2012. Landscape Irrigation in Oklahoma: Perceptions, Practices, and Best Management Practices. “MS Thesis”. Department of Horticulture and Landscape Architecture, College of Agricultural Sciences and Natural Resources, Oklahoma State University, Stillwater, OK. (in preparation/to be submitted Spring 2012).

4. Water Resources Research Institute Reports

Moss, Justin, Tracy Boyer, Dennis Martin, Kemin Su, Michael Smolen, and Damian Adams. 2011. Oklahoma Water Resources Research Institute Final Technical Report. Oklahoma State University, Stillwater, OK.

5. Conference Proceedings

Martin, Dennis, Santanu Thapa, Steve Batten, Justin Moss, Greg Bell, Jeff Anderson, Yanqi Wu, and Kemin Su. 2010. Evapotranspiration rates of Riviera and U-3 bermudagrasses under non-limiting soil moisture conditions. In: 2010 Agronomy abstracts. ASA, Madison, WI.

Moss, Justin, Dennis Martin, Yanqi Wu, Kemin Su, and Bishow Poudel. 2010. Development and selection of bermudagrasses for water conservation in urban landscapes. In: Proceedings of the 2010 USDA National Water Conference, Hilton Head, SC.

6. Other Publications

Reilley, Michael, Tracy Boyer, Damian Adams. 2010. Using best-worst scaling to understand public perception of municipal water conservation tools. Poster presentation. 2010 Oklahoma Governor's Water Conference, Norman, OK.

Water Conservation in Oklahoma Urban and Suburban Watersheds Through Modification of Irrigation Practices

Problem and Research Objectives:

Water conservation is important for municipalities throughout Oklahoma. As urban and suburban sprawl increases in Oklahoma, large areas of previously non-irrigated pasture and/or croplands are being converted to irrigated homeowner and commercial landscapes. The consequential increase in irrigated turfgrass areas across Oklahoma will result in increased landscape water use. There is a need to assess current landscape irrigation watering practices in Oklahoma. Furthermore, there is a need to assess the willingness to adopt and pay for irrigation systems and management practices that conserve Oklahoma's water resources.

The <u>goal</u> of this project is to understand and promote more conservation oriented landscape water use in Oklahoma.

The following objectives are proposed for the first year of a potential two-year project.

The <u>objectives</u> of this project are as follows:

1. Assess current landscape water use and irrigation practices in Oklahoma urban and suburban areas through conjoint choice surveys.
    a. Survey homeowners and lawn care companies about perceptions and preferences concerning landscape/turfgrass aesthetics and accompanying irrigation practices, how they make landscape irrigation decisions, and economic factors including willingness to pay for water based on plant health and aesthetics versus associated economic water factors.

2. Determine the accuracy and reliability of remote sensing reference evapotranspiration (ET) data with established crop coefficients compared to actual landscape plant water use in Oklahoma.
    a. Calculate historical growing season reference ET from 1993 to present day using Oklahoma Mesonet remote sensing climate data using the Penman-Monteith method.
    b. Estimate actual plant water use by conducting field lysimeter and atmometer studies and measuring actual weekly water applied to adequately maintain bermudagrass over the growing season compared to Penman-Monteith reference ET.

3. Educate Oklahoma stakeholders and citizens of landscape irrigation practices to conserve Oklahoma water resources.
    a. Hands-on irrigation training and demonstration workshops conducted through the OSU Cooperative Extension Service.
    b. Fact sheets and interactive Oklahoma landscape irrigation website.

This project addressed the following two OWRRI high priority research areas:

- Assess the economic value of current and potential future agricultural water conservation methods in Oklahoma (Objective 1).
- Develop/improve methods for accurately estimating evapotranspiration using remote sensing data that are of practical value to local resource managers (Objective 2).

This work allowed us to gather important and current data to determine the present situation of landscape irrigation in Oklahoma. Critical future work would allow us to collect post-survey and post-implementation data to assess the effectiveness of our water conservation research and extension efforts.

OBJECTIVE 1 – Assess current landscape water use and irrigation practices in Oklahoma urban and suburban areas through conjoint choice surveys.

Objective 1 was split between two separate studies. For easier reading, each study will be discussed separately below.

Study 1: Using best worst scaling to understand public perception of municipal water conservation tools.

Methodology:

Best worst scaling was first introduced by Finn and Louviere in 1992. The concept is widely used in marketing, medical, and more recently food research. Best Worst Scaling is a relatively simple concept whereby respondents are shown a set of characteristics and asked to choose one as being most important and one as being least important. Consumers are shown a set of choices, varied in the number of choices, and asked to rank one of the choices as most preferred (best) and least preferred (worst). An example of a choice set is provided in Figure 1.

Figure 1. Example of Best - Worst Scaling Question

Please check your most preferred and least preferred water conservation tool out of the following choices.

Most Preferred	*(Check only **one** that is most preferred and **one** that is least preferred)*	Least Preferred
☐	**Smart Meter** (Meter that allows homeowners to monitor real time water use)	☐
☐	**Public Information** (Information about water use, and appeals by city officials to voluntarily reduce water use during drought)	☐
☐	**Rebates for Drought Tolerant Landscapes** (Financial assistance for homeowners to install drought tolerant plants)	☐

After making repeated choices among sets, the responses give a relative position of that attribute to each other attribute, i.e., a ranking. Finn and Louviere stated that “Best Worst scaling models the cognitive process by which respondents repeatedly choose the two objects in varying sets of three or more objects they feel exhibit the largest perceptual difference on an underlying continuum of interest.” According to Louviere the advantages of this method is that it attributes and levels are not confounded as in a traditional discrete choice experiment since the utility of just the attribute is calculated.

Unlike ranking, forcing tradeoffs in best worst scaling means avoids the issue of perception of what a particular number represents across individuals. Table 1 shows the 7 policy tools of interest.

Table 1. Water Conservation Methods and Descriptions

Method	Descriptions
Smart Meter	Meter that allows homeowners to monitor real time water use
Restricted Watering	Ordinances to restrict outdoor watering days and/or times
Increasing Block Rates	Increased charge per gallon for water use above the needs of the average household
Public Information	Information about water use, and appeals by city officials to voluntarily reduces water use during drought
Rebates for Drought Tolerant Landscapes	Financial Assistance for homeowners to install drought tolerant plants
Rebates for Low Flow Appliances	Rebates for low-flow faucets, toilets, appliances, etc.
Home Audits	Help for homeowners to evaluate waste of water and/or set individualized water rates

A 2^8 design was used to assign each of the 7 values to an orthogonal experimental design. The final design was made up of 8 choice sets, 7 contained 3 values, and 1 contained all 7 values. Each survey respondent saw the same choice sets in random order to eliminate any bias from the order in which they were presented. Household members were asked to choose which of the tools was least important/least effective or most important/most effective depending on the design treatment they were shown by random assignment.

The choice of the best and worst (most and least preferred) option in a choice set may be conceptualized as choosing the items that maximize the difference in utility. A choice set has J items, then the result is *J* (*J*-1) tools or possible combinations. Following the techniques of Lusk and Briggeman, let λ_j be the location of the value j on the underlying scale of importance and the true level of importance be $\mathrm{I_{ij}} = \lambda_j + \varepsilon_{ij}$; where ε_{ij} is an error term with an extreme value distribution. The probability that consumer chooses to maximize the distance between item *i* and *k*, that is as the best and worst out of J tools is the probability that the difference in $\mathrm{I_{ij}}$ and $\mathrm{I_{ik}}$ is greater than all other *J* (*J*-1)-1 possible differences in that choice set. Thus the conditional logit may be used:

$$(1) = \text{Prob (j is most preferred and k is least preferred)} = \frac{e^{\lambda_j - \lambda_k}}{\sum_{l=1}^{J}\sum_{m=1}^{J} e^{\lambda_l - \lambda_m}} - J$$

Where l, m are the policy tools seen, but not chosen as the maximizing pair. Each best-worst possible pair is coded in SAS as a 1 if chosen. One value, drought tolerant landscapes is dropped to avoid the dummy variable trap, thus other values are interpreted relative to it and each other.

Participation in an internet survey was solicited via an insert in the City of Stillwater, OK utility bill statements from June-July, 2010, one billing cycle. A total of 310 responses were received by our survey instrument programmed in Survey Monkey from 19,608 mailed utility bills for a response rate of 1.6%.[1] Respondents were randomly assigned one of three survey versions to test for social desirability bias, i.e. whether participants would answer to save their own costs and whether they understood which tools were most effective at reducing water demand. One third of the sample was asked which water conservation technique they most prefer and least prefer. One third of the sample was asked which water conservation technique the average homeowner would most prefer and least prefer (Table 2).

Table 2. Version, Description and Sample Size

Version	Description	Sample Size
SHH	What you most/least prefer	101 Respondents
AHH	What would the average homeowner most/least prefer	105 Respondents
EHH	What is most/least effective	104 Respondents

Lastly, one third of the sample was asked which water conservation technique would be most effective and which technique would be least effective. A total of 310 people provided usable survey responses of which 101 answered the survey soliciting the homeowners preferences for his or her household, 105 answered the survey asking "What would the average homeowner most/least prefer?", and 104 answered the version which asked which techniques the homeowner felt would be the most/least effective.

[1] While survey response will suffer from bias toward citizens with greater internet access and civic participation, an option to complete a mail survey was also included. This survey vehicle was chosen because of its extremely low cost, the willingness of city utility directors to participate, and the ability to reach all customers of the municipality.

Descriptive statistics for the survey respondents are given in Table 3.

Table 3. Characteristics of Survey Respondents (n=310)

Variable	Definition	Mean	Std. Deviation
Gender	1 if male, 0 if female	0.528	0.5
Age	Age in years	51.232	16.297
Ownership	1 if own dwelling, 0 if rent dwelling	0.846	0.362
House	1 if resides in house; 0 otherwise	0.885	0.362
Apartment	1 if resides in apartment, 0 otherwise	0.0553	0.229
Mobile Home	1 if resides in mobile home; 0 otherwise	0.019	0.139
Duplex	1 if resides in duplex; 0 otherwise	0.039	0.195
Child (1)	1 if child under age 2 living in household; 0 otherwise	0.069	0.254
Child (2)	1 if child between ages 2 and 18 living in household; 0 otherwise	0.295	0.733
Environmental Organization	1 if active member of environmental organization; 0 otherwise	0.094	0.362
Maintenance	1 if primarily responsible for lawn maintenance; 0 otherwise	0.764	0.425
Connection	1 if city water connection; 0 otherwise	0.984	0.125

Slightly over half of the respondents were male (52%) and the average age was 51 years. As expected, the 85% of the respondents owned their residence, 88% were single family residences, and 98% used city water. The majority of homeowners (76%) did not use a lawn service and only 9% were active members of an environmental organization. All respondents saw the same choices of drought policy tools and the same information about their average efficacy in reducing demand (Table 4).

Table 4. Efficacy data shown to respondents.

CONSERVATION TOOL	Average Gallons Water Saved per Month per Household	Total Monthly Cost Savings per Household
Smart Meter	700	$4.19
Rebates for Drought-Tolerant Landscapes	600	$3.59
Increasing Block Rates[1]	450	$2.69
Rebates for water efficient items		
Indoor Faucet	413	$2.47
Toilets	400	$2.39
Clothes washers	426	$2.55
Audits/budgets	1,500	$8.97
Public Information	210	$1.26
Restricted Watering[2]	300	$1.79

[1] Projected 30% drop in water use, [2] Projected 30% drop in water use.

Principal Findings and Significance:

The results are depicted graphically in Figure 2 and coefficient estimates for the three scenarios are shown in Table 5. In Figure 2, the parameter estimate within each scenario (vertical colored bar) gives a relative ranking of the preference for a policy tool. The policy tools are grouped from left to right in terms of their efficacy. For example, although increasing block rates are the second most effective tool for reducing water demand, households ranked them last when choosing for themselves or the average neighbor. However, when asked to rank efficacy, respondents understood that the technique was in the top three most effective tools. A likelihood ratio test confirmed statistically significant differences between the three versions of the survey at the (5% confidence level).

Figure 2. Best-Worst Scaling Ranking Results

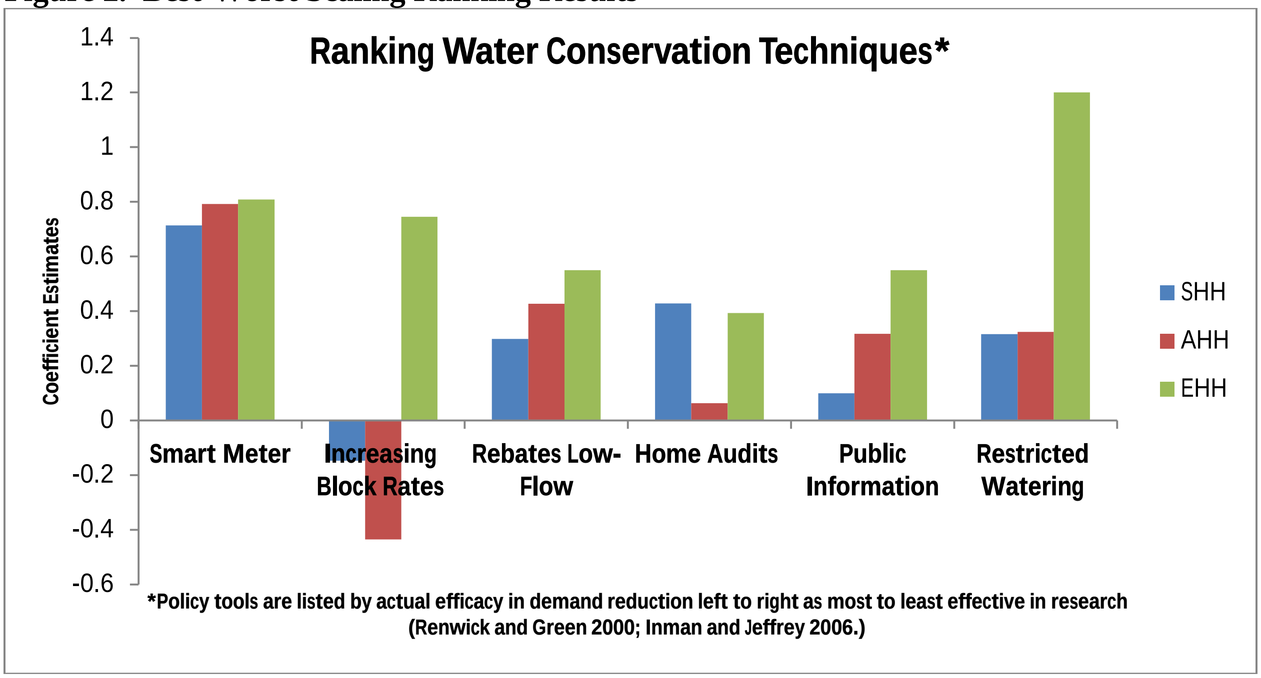


Table 5. Relative Preferences for Water Conservation Tools

	Coefficient Estimate (Standard Error)		
Value	**SHH**	**AHH**	**EHH**
Smart Meter	0.7132*	0.7916*	0.8089*
	(0.102)	(0.1053)	(0.107)
Increasing Block Rates	-0.1479	-0.4347	0.7449*
	(0.1001)	(0.1044)	(0.1012)
Rebates Low-Flow	0.298*	0.4275*	0.5494*
	(0.0984)	0.1013	0.1024
Home Audits	0.428*	0.0637	0.3933*
	(0.0986)	(0.1003)	(0.0996)
Public Information	0.1	0.3176*	0.5494
	(0.0977)	(0.101)	(0.1006)
Restricted Watering	0.316*	0.324*	1.200*
	(0.0986)	(0.1007)	(0.1014)
N individuals	101	105	104
Log Likelihood	101.14	165.20	218.01

*Indicates significance at 99% confidence level

Smart Meters were most popular with homeowners (AHH and SHH), and correctly ranked as highly effective (EHH) suggesting they might be least controversial. Although consumers understood increasing block rate pricing to be effective, households would not choose to levy higher prices on themselves to conserve water. Restrictive Watering, Smart Meter and Increasing Block Rates were ranked as most effective among Oklahomans. Respondents favored Smart Meters, Home Audits and Restricted Watering Schedules as water conservation tools in their own homes. Differences between SHH and AHH results from social desirability bias therefore, AHH may be more accurate than SHH. Although restricted watering is believed (EHH) to be most effective, research has shown it least effective in reducing demand. This result may indicate users did not understand the efficacy chart given or the numbers were too many to remember as they continued through the survey. Results show that policy makers and utility managers should clearly outline efficacy of drought conservation tools and their costs and benefits when seeking to respond to drought. Homeowners will be opposed to tools that will raise costs.

Increasing attention on the efficacy of water conservation tools and the associated household specific data showing the effects on demand for municipal water are direly needed in areas of shortage. In the meantime, however, much of the debate over which tools to adopt to meet seasonal and sustained droughts remain political decisions. Based on the literature on likely tools for reducing demand for water under short term conditions was compiled and the relative preference and understanding of the efficacy of these tools was measured.

We found that people were more likely to say they would adopt voluntary restrictions although these were not presented as the most effective. Household consumers were less likely to adopt methods such as increasing block rates that imposed higher costs on the household. Furthermore, the results between the consumer's statement of his or her own household's preferences were significantly different from the results when reporting preferences believed to be of the "average" household, suggesting that preference surveys do suffer from social desirability bias. Using the results from this study may aide utility managers in designing conservation programs, soliciting support for conservation, and avoiding conflict over the implementation.

Study Two: Determinants of water conservation among Oklahoma golf and recreational turfgrass managers.

Methodology:

On November 16 and 17, 2010, willing participants of the 65th Annual Turf Conference Trade Show held in Stillwater, Oklahoma completed a survey entitled, “Survey of Water Use in Recreational Turfgrass Management.” The survey was designed to determine what current water conservation practices are being utilized in turfgrass management practices on Oklahoma’s golf courses, recreational fields, and parks and how individual characteristics of the facility and the facility’s management influence their adoption. Participants were given two opportunities to complete our survey, one while in attendance at the conference and another a couple weeks later via either online at Surveymonkey.com or through the U.S. mail. In an attempt to increase the response rate, a financial incentive was presented in the form of 6 random drawings for $100. Of the 219 attendees on the conference’s participant list, 72 completed the survey. Five of these 219 attendees were excluded due to their employment affiliation with Oklahoma State University, giving us a response rate of 33.64 %. Additional conference guests provided 52 more completed surveys. In the second opportunity, 119 emails and 37 mailers were sent out using a mailing list of turfgrass managers provided by conference leaders out of which 21 surveys were completed via Surveymonkey.com and 4 completed surveys were returned via the mail. The final response rate for the second contact was 17.6% for Surveymonkey.com and 10.8% for the U.S. mail. Including all attempts to contact Oklahoma professional turfgrass managers, a total of 149 responses were collected.

The survey consisted of several questions relating to not only a facility’s turfgrass management, but also characteristics of the facility’s workers and managers. The survey inquired about: the type of facility, facility location, the annual budget for maintenance, watering methods currently being utilized, type of water source used for irrigation water, motivation and barriers to adopting water conservation methods, education, certifications, age, and the water conservation practices which have been adopted. Ranking was utilized to determine the most important motivations and barriers to adopting water conservation methods. Respondents were asked to rank five motivations for adopting water conservation strategies in order of importance. These motivations included: lowering costs of water used, environmental conservation, reducing labor costs in irrigation, response to price increases by municipal water supply, and reducing mowing or weeding costs. In a separate question, respondents were asked to rank three barriers to adopting water conservation strategies in order of importance. Barriers included: need for knowledge of strategies to reduce water use, concern over performance and appearance of turf for users, and funding for implementing strategies.

After collecting the data from the completed 149 surveys, general statistics were generated and included: the percentages of how many respondents chose a multiple choice answer in a particular question, means, modes, and standard deviations.

Cross tabulations were developed for all completed surveys to demonstrate which of a respondent's/facility's characteristics were mostly associated with either choosing to adopt a particular water conservation practice or choosing not to adopt. These characteristics included: facility type, watering methods currently being used, education level of the respondent, type of college degree held by the respondent, respondent's certifications, number of acres of turfgrass at the facility, ZIP code of the facility, and age of the respondent. For the top 5 most used conservation practices, every characteristic selected by a respondent was categorized as either "conservation method adopted" or "conservation method not adopted," depending on whether or not the individual had adopted the water conservation practice. After all chosen characteristics were categorized, they were then summed or averaged across all responses for each group.

Since our dependent variables have a discrete outcome, either have adopted or have not adopted, the probit procedure was chosen for the regression analysis of the data to predict the likelihood of adoption of users on average, given the facility and individual's characteristics. The probit model is as follows:

$\text{Prob}(Y=1) = F(\beta' x)$ => have adopted
$\text{Prob}(Y=0) = 1 - F(\beta x)$ => have not adopted

The set of parameters (β) reflect the impact changes in x on the probability (Greene, 1992).

Probit models were generated using the SAS 9.2 Program (2011 SAS Institute Inc) to analyze the effects of certain respondent/facility characteristics, such as facility type, current watering methods, education and certifications, and facility location, on the adoption of a certain water conservation technique. Five probit models were estimated, one for each of the top 5 most used conservation practices. In these models, the probability that a respondent/facility will accept a certain water conservation technique is dependent on certain characteristics of the respondent or facility. The water conservation techniques chosen to be analyzed in this study include: reduced watering, reduced percentage of area irrigated, limited irrigation, zoned irrigation, irrigation scheduling, reuse water, irrigation audit, improved cultivars, greens modified, higher mowing heights, switch to alternative, adoption of xeriscaping, and adoption of conservation indoors.

For this study, the following conceptual model was created:

(1) Probability of adopting water conservation technique = ¦ (type of facility, current watering methods, current source for irrigation water, respondent's education level, certification of respondent, acres of turfgrass at facility, age of respondent, regional location of facility)

A linear probability model would not be efficient in analyzing the data because of the discrete nature of the dependent variables. Since $\beta x + \varepsilon$ must equal either zero or one, the variance of the errors depends on β which would result in a problem with heteroscedasticity. Therefore, the empirical model for this study is:

(2) $Y^* = \beta' x + \varepsilon$

Where: $Y^* = 1$ if the practice is chosen, 0 if not chosen, $\varepsilon \sim N(0,1)$, a random error term

For this model all estimated β coefficients are for the x variables. All x variables are dummy variables (1 => characteristic chosen, 0 => characteristic not chosen), except turfgrass acres and age. Y* is the dependent variable or conservation technique, which is either one if adopted or zero if not. Regional information was not directly asked in the survey. Instead, respondents were asked to indicate the ZIP code in which their facility is located. Using GSI software, these ZIP codes were plotted in four Oklahoma regions in which Interstate 35 and Interstate 40 served as boundary lines dividing the state into Southeast, Northwest, Southwest, and Northeast regions. The model in less formal terms is as follows:

The model in less formal terms is as follows:

(3) $Y^* = \beta_1 + \beta_2 Golf + \beta_3 Rec + \beta_4 Sports + \beta_5 Sod + \beta_6 OF + \beta_7 MS + \beta_8 AS + \beta_9 ZS + \beta_{10} MCS + \beta_{11} DI + \beta_{12} SH + \beta_{13} SBH + \beta_{14} OWM + \beta_{15} NoIrr + \beta_{16} City + \beta_{17} Private + \beta_{18} Reten + \beta_{19} OWS + \beta_{20} College + \beta_{21} BS + \beta_{22} Cert + \beta_{23} Acres + \beta_{24} Age + \beta_{25} SE + \beta_{26} NW + \beta_{27} SW + \beta_{28} OS + \varepsilon$

Table 6 provides variable definitions and Table 7, below, provides explanations of the dependent variables used for the different models.

Table 6

Probit Model Independent Variables					
Golf	Golf Course	**DI**	Drip Irrigation	**College**	Some College
Rec	Recreational Park	**SH**	Soaker Hose	**BS**	B.S./B.A.
Sports	Sports Field	**SBH**	Spray by Hand	**Cert**	Certified
Sod	Sod Farm	**OWM**	Other Watering Method	**Acres**	Turfgrass Acres
OF	Other Facility	**NoIrr**	Do Not Irrigate	**Age**	Age
MS	Manual Sprinkler	**City**	City Water Connection	**SE**	Southeast
AS	Automated Sprinkler	**Private**	Private Well Water	**NW**	Northwest
ZS	Zoned Sprinkler	**Reten**	On Site Water Retention	**SW**	Southwest
MCS	Manual Connection Sprinkler	**OWS**	Other Water Source	**NE**	Northeast
		HS	<12th Grade, H.S. Diploma	**OS**	Out of State

Table 7

	Probit Model Dependent Variables
Reduced watering	Reduced watering
Reduced % of area irr	Reduce percentage of area irrigated alone
Limited irr	Limited or nonexistent irrigation
Zoned irr	Zoned irrigation systems
Irrigation scheduling	Irrigation scheduling based on plant water requirements as estimated by site-specific weather data
Reuse water	Reuse or gray water for irrigation
Irr audit	Irrigation audit
Improved cultivars	Selection of improved turfgrass cultivars for drought tolerance
Greens modified	Greens or high use areas modified to improve water percolation and deeper rooting, avoidance of excessive slopes
Higher mowing heights	Higher mowing heights of grass
Switch to alt	Switch to alternative, non-municipal supply
Adopt of xeriscaping	Adoption of xeriscaping or drought tolerant plants where turfgrass is not necessary
Adopt of cons indoors	Adoption of conservation indoors in clubhouse, park structures, etc

Principal Findings and Significance:

Table 8 presents simple statistics of some of the determinants of water conservation adoption. Top responses are highlighted below as follows:

- For facility type, golf courses comprised 47% of responses
- For current watering methods, automated above ground automatic sprinklers comprised 75% of responses
- For water source, city water connection was used for 58% of respondents
- For education level, B.S./B.A. or higher graduate was the highest degree obtained by 46% of respondents
- For facility location, the Northeast region received 46% of responses

In addition, 87% of respondents indicated being certified in the turfgrass management field. On average respondents were about 43 years old and their facilities had an average of 138 acres in turfgrass.

The following are additional findings by the majority of respondents:

- 63% of respondents indicated being lead managers
- 60% of facilities were designated as public, while 40% were private
- Average annual operating budget for maintenance was $469,000
- 80% of respondents apply pesticides to facility turfgrass acres and 82% of respondents apply fertilizers
- 97% were male
- 91% indicated Caucasian decent, 1% African American, and 7% Native American
- 39% ranked “lowering cost of water used” as the most important motivation for adopting water conservation strategies, while 39% ranked “response to price

increase by municipal water supply" as having the least affect on their motivation for adopting water conservation strategies

52% ranked "concern over performance and appearance of turf for users" as the pinnacle barrier to adopting water conservation strategies, while 43% ranked "the need for knowledge of strategies to reduce water use" as having the least effect on prohibiting the adoption of water conservation strategies.

Table 8

Determinants of Conservation Adoption - Simple Statistics

Variable	N	Mean	Std Dev	Sum	Minimum	Maximum
Golf	149	0.46980	0.50077	70.00000	0	1.00000
Rec	149	0.14765	0.35595	22.00000	0	1.00000
Sports	149	0.14094	0.34913	21.00000	0	1.00000
Sod	149	0.02013	0.14093	3.00000	0	1.00000
OF	149	0.31544	0.46626	47.00000	0	1.00000
MS	149	0.23490	0.42537	35.00000	0	1.00000
AS	149	0.75168	0.43350	112.00000	0	1.00000
ZS	149	0.38926	0.48923	58.00000	0	1.00000
MCS	149	0.25503	0.43735	38.00000	0	1.00000
DI	149	0.25503	0.43735	38.00000	0	1.00000
SH	149	0.12752	0.33468	19.00000	0	1.00000
SBH	149	0.50336	0.50168	75.00000	0	1.00000
OWM	149	0.07383	0.26237	11.00000	0	1.00000
NoIrr	149	0.05369	0.22617	8.00000	0	1.00000
City	149	0.58389	0.49457	87.00000	0	1.00000
Private	149	0.26174	0.44107	39.00000	0	1.00000
Reten	149	0.19463	0.39725	29.00000	0	1.00000
OWS	149	0.15436	0.36251	23.00000	0	1.00000
College	149	0.38255	0.48765	57.00000	0	1.00000
BS	149	0.46309	0.50032	69.00000	0	1.00000
Cert	149	0.86577	0.34205	129.00000	0	1.00000
Acres	149	138.27692	255.28471	20603	0	3000
Age	149	42.92414	11.54023	6396	20.00000	76.00000
SE	149	0.18121	0.38649	27.00000	0	1.00000
NW	149	0.22819	0.42108	34.00000	0	1.00000
SW	149	0.06040	0.23903	9.00000	0	1.00000
OS	149	0.05369	0.22617	8.00000	0	1.00000

Figure 3 illustrates which water conservation practices have been utilized and what percent of respondents are implementing them. The data collected shows the top five most used water conservation practices to be: reduced watering (64%), higher mowing heights of grass (64%), zoned irrigation systems (54%), selection of improved cultivars for drought tolerance (47%), and irrigation scheduling based on plant water requirements as estimated by site-specific weather data (43%). Options in facility types included: golf course, recreational park, sports field, and sod farm. In Figure 4, we see golf course (47%) was the most common facility type followed by other facility type (32%), recreational park (15%), sports field (14%), and sod farm (2%). A majority of the other facility types specified by respondents included lawn care services and educational institutes. A majority of respondents chose automated above ground automatic sprinkler systems as the facility's current watering method (75%), followed by spraying the turfgrass area by hand as needed (50%). Only 5% indicated not utilizing any irrigation methods at their facility (Figure 5). Figure 6 exhibits the division of water source usage. The large majority obtain water for irrigation from city water connections (58%) and private wells (26%). A majority of other water sources specified by respondents included lakes and rivers. The distribution of regional location can be observed in Figure 7. Most facilities (46%) reside in the Northeast region of Oklahoma. With only 6%, the Southwest has considerably fewer turfgrass facilities than the other three Oklahoma regions. This uneven distribution of turfgrass facilities may be due to differences in the amount of precipitation received or population. Having less rainfall than the other regions, may prohibit the Southwest region's ability to sustain turfgrass acres.

Figure 3

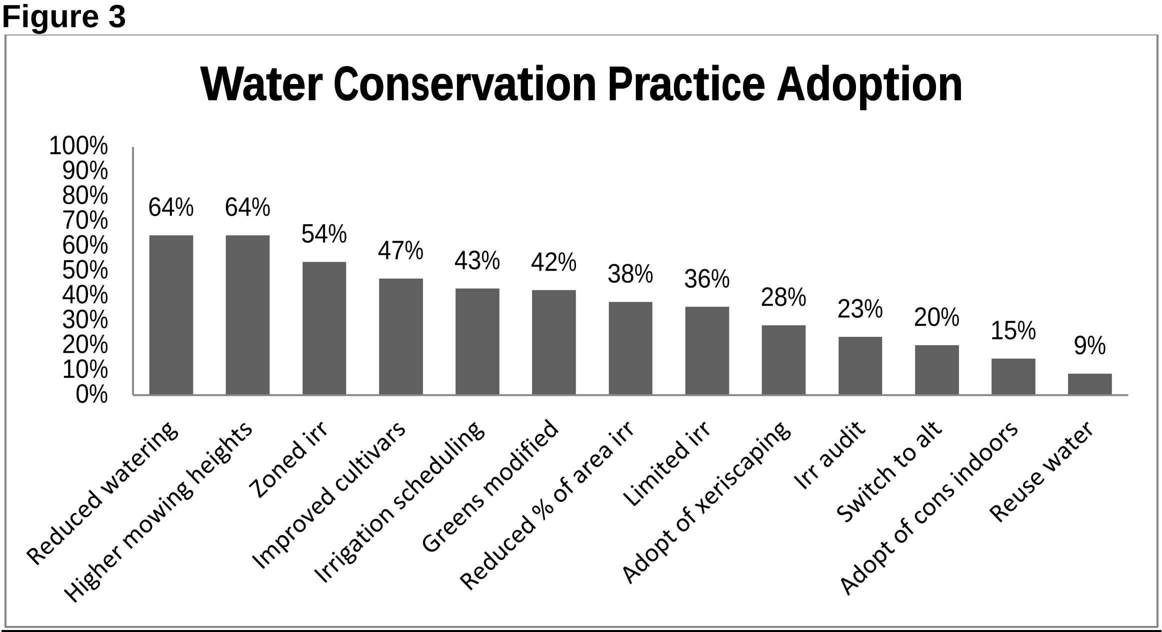


Figure 4

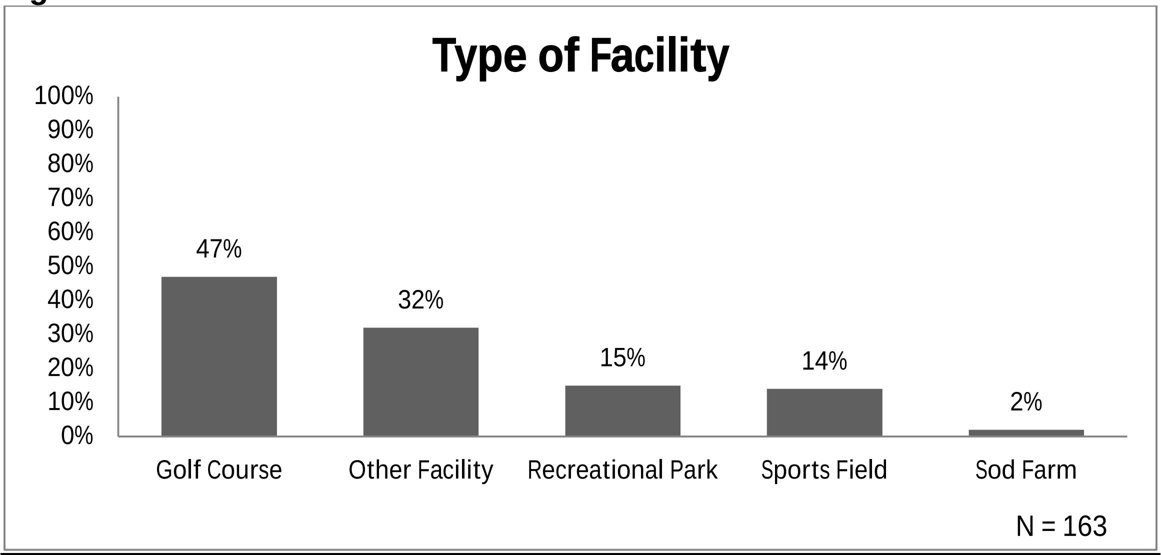


Figure 5

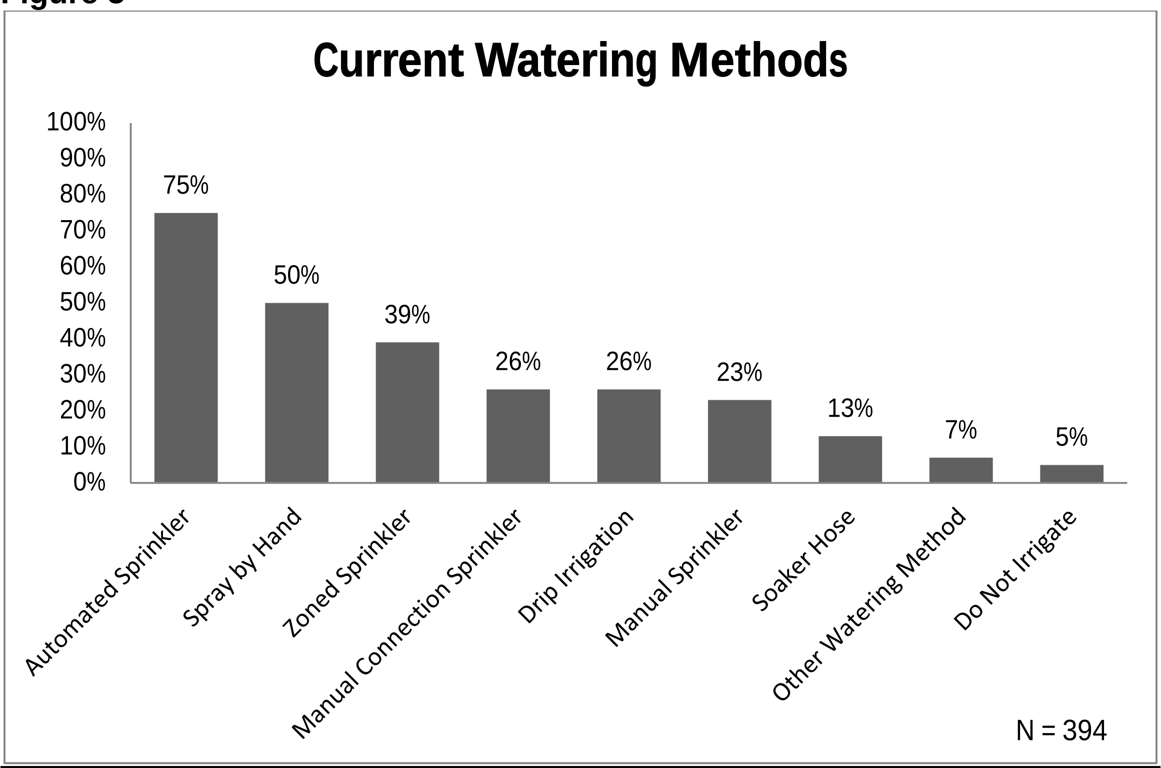


Figure 6

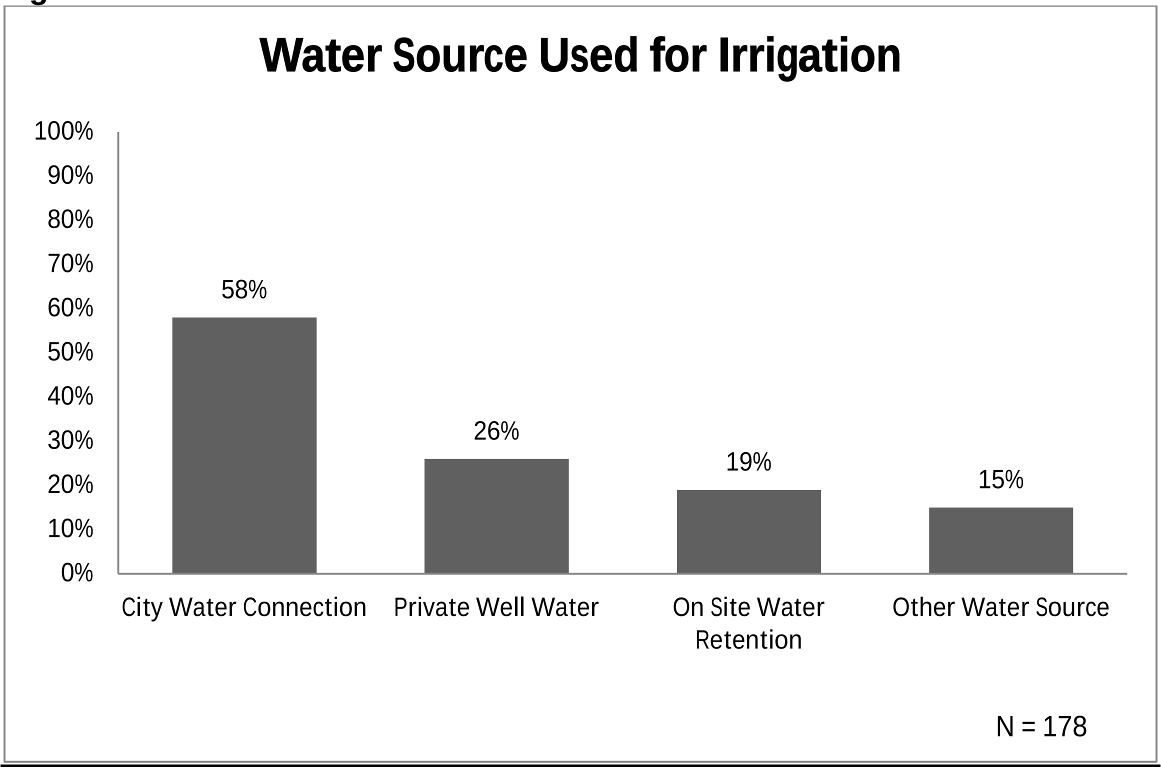
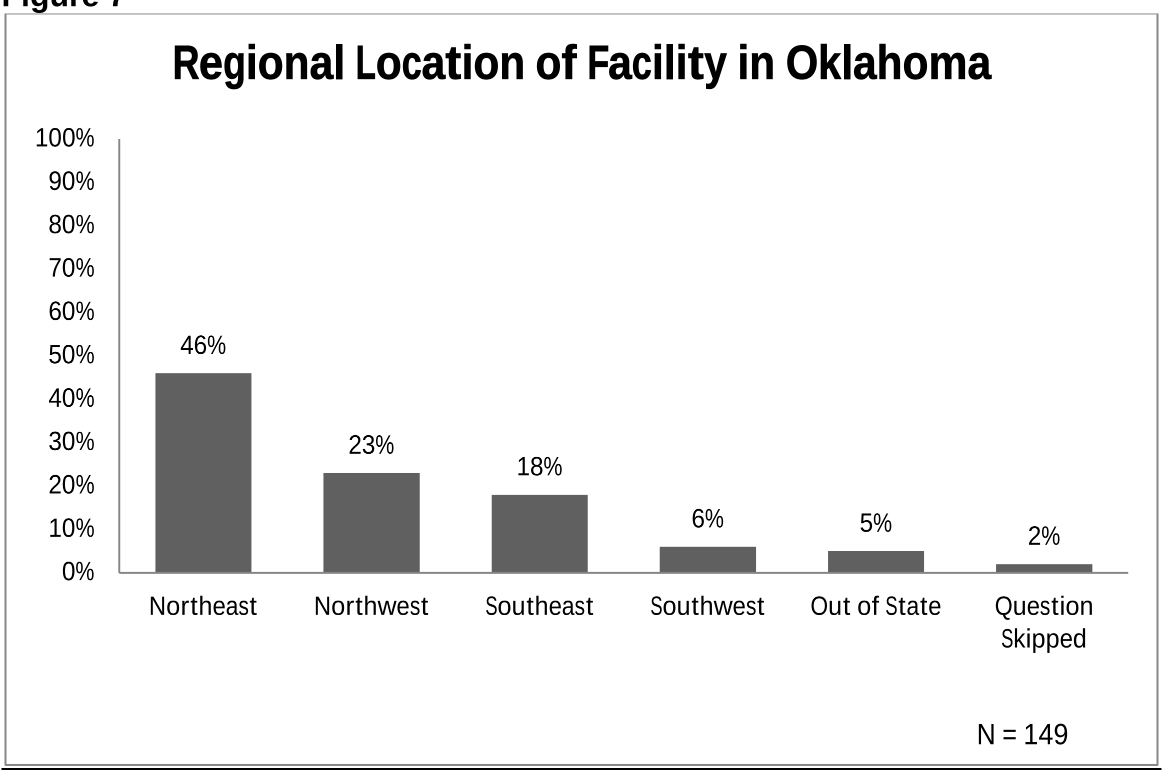


Figure 7



For the most part, survey participants have attained some college education. Approximately 38% have obtained some college education, while 46% have received a college degree, leaving only around 16% that have no college education (Figure 8). As seen in Figure 9, for those who have obtained a college degree, the majority received degrees in Turfgrass Management (32%). Nearly all survey participants (87%) have received certifications relating to turfgrass management. The two prevailing certifications acquired by respondents are the certified pesticide applicator and the licensed pesticide applicator, both state requirements (Figure 10).

Figure 8

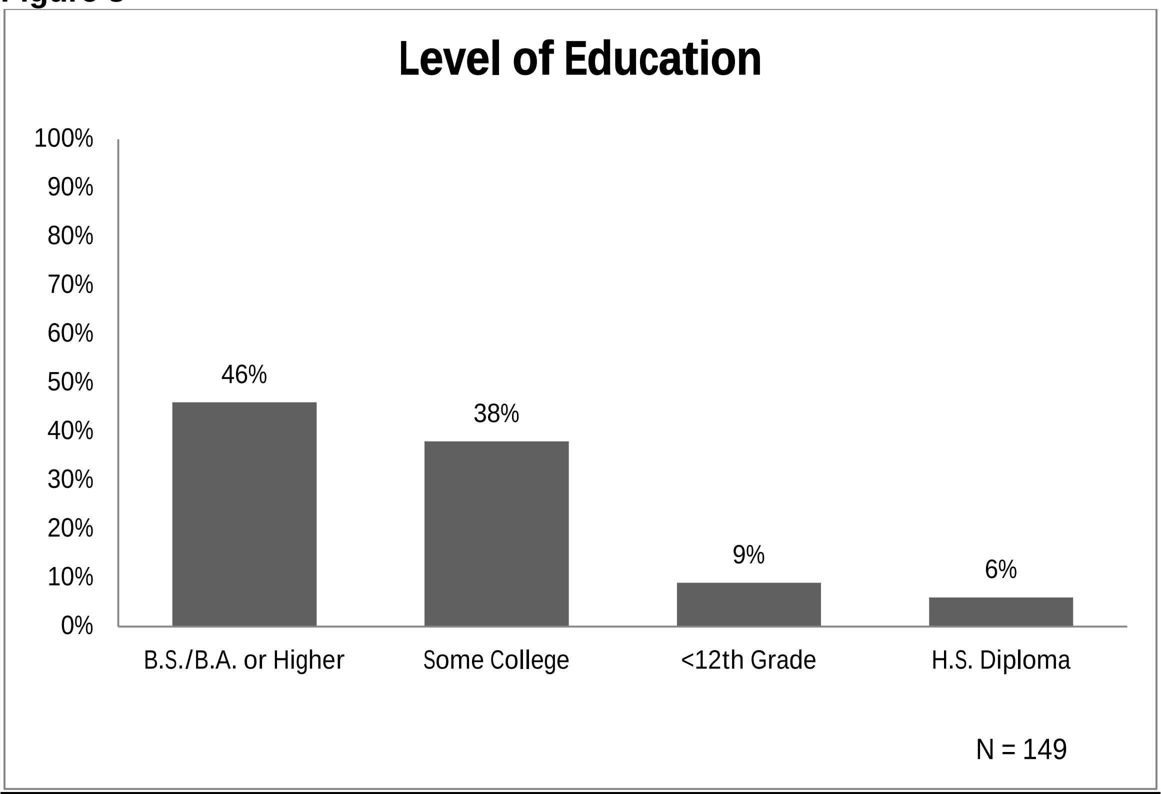


Figure 9

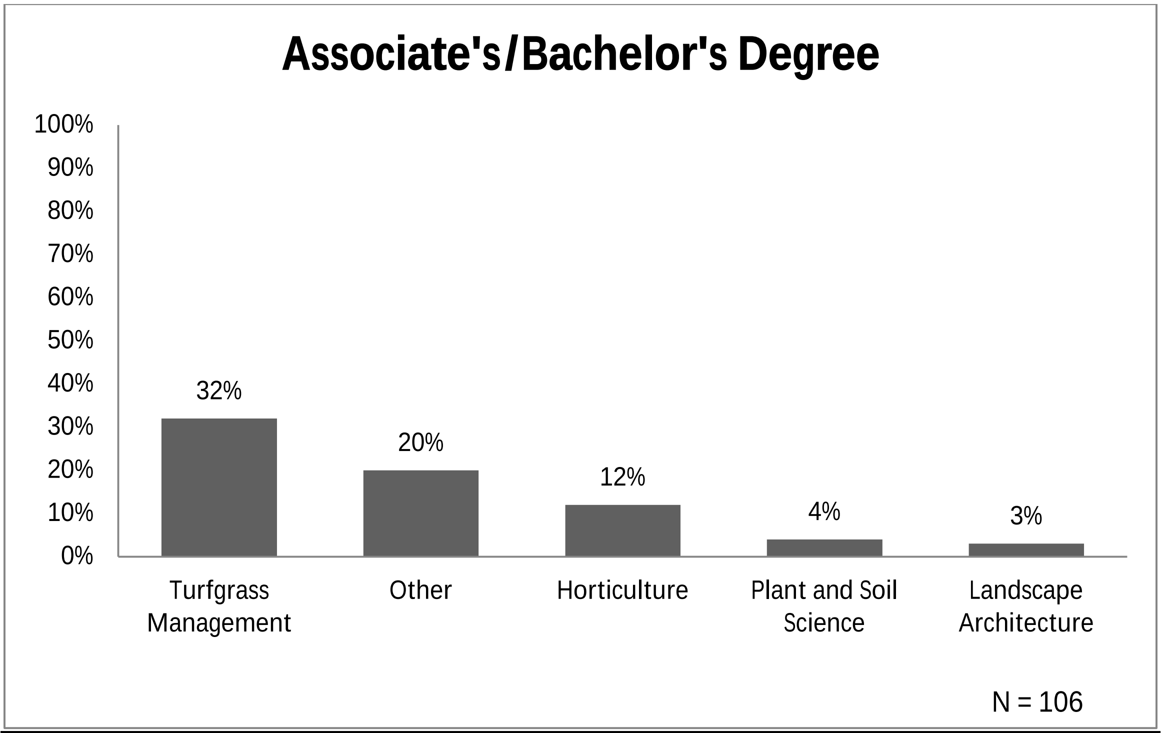
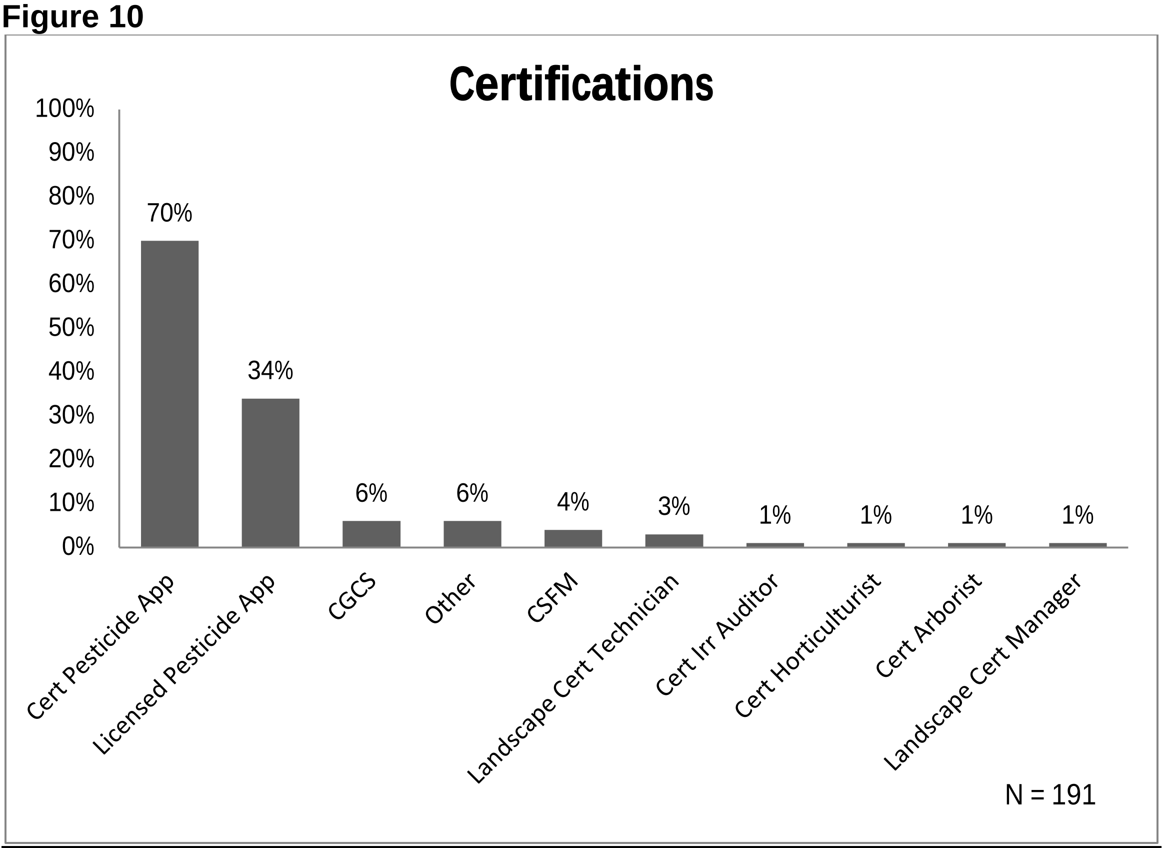


Figure 10



Tables 9 through 13 present the findings of the cross tabulations for the most used water conservation methods. The determinants of water conservation adoption examined in this section of the study are: facility type, watering methods, water source, education, certification, turfgrass acres, facility location, and age. The dominant determinants found upon examination of the data include: golf course, automated above ground automatic sprinkler systems, city water connection, B.S./B.A. or higher graduate, turfgrass management degree, and certified pesticide applicator.

For the reduced watering conservation method (Table 9), all dominant determinants yielded higher percentages of respondents adopting the water conservation strategy than not adopting. Of all the golf course facilities, 74% have adopted reduced watering as a strategy, while 26% have not. For facilities using automated sprinklers as current watering methods, 71% have adopted reduced watering. A majority 62% of respondents who use city water connections for irrigation water have also chosen to utilize this method to conserve water. 67% of college graduates partake in reducing water as do 66% of turfgrass management degree holders. Of the 105 certified pesticide applicators, 69% have reduced watering at their facilities. For respondents using reduced watering, facility size averages 147 acres whereas non-adopters average only 123 acres.

For the higher mowing heights of grass strategy (Table 10), again all dominant determinants produced greater percentages of respondents adopting the water conservation strategy than not adopting. Of golf course facilities, 73% have adopted the strategy. For facilities using automated sprinklers, 69% have adopted higher mowing heights. A majority 66% of respondents who use city water connections for irrigation water have also chosen to utilize this method to conserve water. Approximately 70% of managers who are college graduates partake in higher mowing heights, as do 68% of turfgrass management degree holders. Of the certified pesticide applicators, 70% implement higher mowing heights at their facilities. On average adopters have 144 acres of turfgrass whereas, non-adopters average 127 acres.

For the zoned irrigation strategy (Table 11), all dominant determinants, with the exception of golf course facilities, produced greater percentages of respondents adopting the water conservation strategy than not adopting. Of golf course facilities, only 50% have adopted the strategy. For facilities using automated sprinklers, 57% have adopted zoned irrigation. A majority 64% of respondents who use city water connections for irrigation water have also chosen to utilize this method to conserve water. For zoned irrigation, 55% of college graduates and 55% of turfgrass management degree holders have adopted. Of the 105 certified pesticide applicators, 56% implement zoned irrigation at their facilities. On average adopters have 150 acres of turfgrass whereas, non-adopters average 125 acres.

For the selection of improved cultivars for drought tolerance strategy (Table 12), most of the dominant determinants were associated with producing greater percentages of respondents not adopting the water conservation strategy. Of golf course facilities, only 44% have adopted the strategy, while 56% have not. For facilities using automated sprinklers, 51% have adopted selection of improved cultivars for drought tolerance. A majority 54% of respondents who use city water connections for irrigation water have not chosen to utilize this method to conserve water. Of college graduates, 52% participate in selection of improved cultivars for drought tolerance, but 53% of turfgrass management degree holders do not. Of the 105 certified pesticide applicators, only 45% implement selection of improved cultivars for drought tolerance at their facilities. For respondents using improved cultivars, facility size averages 170 acres whereas non-adopters average only 110 acres.

For the irrigation scheduling strategy (Table 13), all dominant determinants, with the exception of city water connection, produced greater percentages of respondents not adopting the water conservation strategy. Of golf course facilities, 61% have not adopted the strategy while only 39% have. For facilities using automated sprinklers, 54% have not adopted an irrigation scheduling strategy. A majority 53% of respondents who use city water connections for irrigation water have chosen to utilize this method to conserve water. Only 45% of college graduates participate in irrigation scheduling as do only 40% of turfgrass management degree holders. Of the certified pesticide applicators, 58% do not implement irrigation scheduling at their facilities. On average adopters have 174 acres of turfgrass whereas, non-adopters average 111 acres. The cross tabulation results show that with the decrease in the number of facilities who have adopted a particular water conservation practice, the average number of turfgrass acres being managed using the conservation technique generally increase.

Table 9.

Determinants of Conservation Adoption - Cross Tabulations					
Reduced Watering	**Never Used**	**%**	**Used**	**%**	**Total**
Golf Course	18	26%	52	74%	70
Recreational Park	10	45%	12	55%	22
Sports Field	11	52%	10	48%	21
Sod Farm	0	0%	3	100%	3
Other	21	45%	26	55%	47
Manual Sprinkler	11	31%	24	69%	35
Automated Sprinkler	33	29%	79	71%	112
Zoned Sprinkler	20	34%	38	66%	58
Manual Connection Sprinkler	18	47%	20	53%	38
Drip Irrigation	14	37%	24	63%	38
Soaker Hose	7	37%	12	63%	19
Spray by Hand	24	32%	51	68%	75
Other Watering Method	5	45%	6	55%	11
We do not irrigate	8	100%	0	0%	8
City	33	38%	54	62%	87
Private Well	10	26%	29	74%	39
Water Retention	7	24%	22	76%	29
Other	9	39%	14	61%	23
<12th Grade	6	43%	8	57%	14
H.S. Diploma	4	44%	5	56%	9
Some College	20	35%	37	65%	57
B.S./B.A.	23	33%	46	67%	69
Turfgrass Management	16	34%	31	66%	47
Landscape Architecture	3	60%	2	40%	5
Plant & Soil Science	4	67%	2	33%	6
Horticulture	7	39%	11	61%	18
Other	10	33%	20	67%	30
Certified Golf Course Superintendent (CGCS)	3	33%	6	67%	9
Certified Irrigation Auditor	1	50%	1	50%	2
Certified Sports Field Manager (CSFM)	4	67%	2	33%	6
Certified Pesticide Applicator	33	31%	72	69%	105
Licensed Pesticide Applicator	19	37%	32	63%	51
Certified Horticulturist	0	0%	1	100%	1
Certified Arborist	1	50%	1	50%	2
Landscape Industry Certified Manager	0	0%	1	100%	1
Landscape Industry Certified Technician	2	40%	3	60%	5
Other	4	44%	5	56%	9
Turfgrass Acres	123		147		
ZIP	73801		73401		
Age	42		43		

Table 10.

Determinants of Conservation Adoption - Cross Tabulations					
Higher Mowing Heights	**Never Used**	**%**	**Used**	**%**	**Total**
Golf Course	19	27%	51	73%	70
Recreational Park	10	45%	12	55%	22
Sports Field	11	52%	10	48%	21
Sod Farm	2	67%	1	33%	3
Other	18	38%	29	62%	47
Manual Sprinkler	13	37%	22	63%	35
Automated Sprinkler	35	31%	77	69%	112
Zoned Sprinkler	18	31%	40	69%	58
Manual Connection Sprinkler	13	34%	25	66%	38
Drip Irrigation	15	39%	23	61%	38
Soaker Hose	10	53%	9	47%	19
Spray by Hand	23	31%	52	69%	75
Other Watering Method	5	45%	6	55%	11
We do not irrigate	7	88%	1	13%	8
City	30	34%	57	66%	87
Private Well	12	31%	27	69%	39
Water Retention	9	31%	20	69%	29
Other	7	30%	16	70%	23
<12th Grade	8	57%	6	43%	14
H.S. Diploma	4	44%	5	56%	9
Some College	20	35%	37	65%	57
B.S./B.A.	21	30%	48	70%	69
Turfgrass Management	15	32%	32	68%	47
Landscape Architecture	3	60%	2	40%	5
Plant & Soil Science	3	50%	3	50%	6
Horticulture	5	28%	13	72%	18
Other	10	33%	20	67%	30
Certified Golf Course Superintendent (CGCS)	4	44%	5	56%	9
Certified Irrigation Auditor	1	50%	1	50%	2
Certified Sports Field Manager (CSFM)	2	33%	4	67%	6
Certified Pesticide Applicator	32	30%	73	70%	105
Licensed Pesticide Applicator	23	45%	28	55%	51
Certified Horticulturist	0	0%	1	100%	1
Certified Arborist	1	50%	1	50%	2
Landscape Industry Certified Manager	0	0%	1	100%	1
Landscape Industry Certified Technician	2	40%	3	60%	5
Other	4	44%	5	56%	9
Turfgrass Acres	127		144		
ZIP	73801		73401		
Age	43		43		

Table 11.

Determinants of Conservation Adoption - Cross Tabulations					
Zoned Irrigation	**Never Used**	**%**	**Used**	**%**	**Total**
Golf Course	35	50%	35	50%	70
Recreational Park	7	32%	15	68%	22
Sports Field	7	33%	14	67%	21
Sod Farm	2	67%	1	33%	3
Other	22	47%	25	53%	47
Manual Sprinkler	14	40%	21	60%	35
Automated Sprinkler	48	43%	64	57%	112
Zoned Sprinkler	18	31%	40	69%	58
Manual Connection Sprinkler	14	37%	24	63%	38
Drip Irrigation	15	39%	23	61%	38
Soaker Hose	9	47%	10	53%	19
Spray by Hand	32	43%	43	57%	75
Other Watering Method	7	64%	4	36%	11
We do not irrigate	7	88%	1	13%	8
City	31	36%	56	64%	87
Private Well	21	54%	18	46%	39
Water Retention	13	45%	16	55%	29
Other	15	65%	8	35%	23
<12th Grade	7	50%	7	50%	14
H.S. Diploma	3	33%	6	67%	9
Some College	28	49%	29	51%	57
B.S./B.A.	31	45%	38	55%	69
Turfgrass Management	21	45%	26	55%	47
Landscape Architecture	5	100%	0	0%	5
Plant & Soil Science	3	50%	3	50%	6
Horticulture	9	50%	9	50%	18
Other	10	33%	20	67%	30
Certified Golf Course Superintendent (CGCS)	6	67%	3	33%	9
Certified Irrigation Auditor	0	0%	2	100%	2
Certified Sports Field Manager (CSFM)	6	100%	0	0%	6
Certified Pesticide Applicator	46	44%	59	56%	105
Licensed Pesticide Applicator	24	47%	27	53%	51
Certified Horticulturist	1	100%	0	0%	1
Certified Arborist	1	50%	1	50%	2
Landscape Industry Certified Manager	1	100%	0	0%	1
Landscape Industry Certified Technician	1	20%	4	80%	5
Other	4	44%	5	56%	9
Turfgrass Acres	125		150		
ZIP	73801		74012		
Age	43		43		

Table 12.

Determinants of Conservation Adoption - Cross Tabulations					
Improved Cultivars	**Never Used**	**%**	**Used**	**%**	**Total**
Golf Course	39	56%	31	44%	70
Recreational Park	13	59%	9	41%	22
Sports Field	9	43%	12	57%	21
Sod Farm	2	67%	1	33%	3
Other	24	51%	23	49%	47
Manual Sprinkler	20	57%	15	43%	35
Automated Sprinkler	55	49%	57	51%	112
Zoned Sprinkler	31	53%	27	47%	58
Manual Connection Sprinkler	19	50%	19	50%	38
Drip Irrigation	16	42%	22	58%	38
Soaker Hose	9	47%	10	53%	19
Spray by Hand	40	53%	35	47%	75
Other Watering Method	4	36%	7	64%	11
We do not irrigate	7	88%	1	13%	8
City	47	54%	40	46%	87
Private Well	16	41%	23	59%	39
Water Retention	19	66%	10	34%	29
Other	11	48%	12	52%	23
<12th Grade	10	71%	4	29%	14
H.S. Diploma	5	56%	4	44%	9
Some College	31	54%	26	46%	57
B.S./B.A.	33	48%	36	52%	69
Turfgrass Management	25	53%	22	47%	47
Landscape Architecture	4	80%	1	20%	5
Plant & Soil Science	1	17%	5	83%	6
Horticulture	13	72%	5	28%	18
Other	10	33%	20	67%	30
Certified Golf Course Superintendent (CGCS)	5	56%	4	44%	9
Certified Irrigation Auditor	0	0%	2	100%	2
Certified Sports Field Manager (CSFM)	4	67%	2	33%	6
Certified Pesticide Applicator	58	55%	47	45%	105
Licensed Pesticide Applicator	27	53%	24	47%	51
Certified Horticulturist	1	100%	0	0%	1
Certified Arborist	1	50%	1	50%	2
Landscape Industry Certified Manager	0	0%	1	100%	1
Landscape Industry Certified Technician	4	80%	1	20%	5
Other	2	22%	7	78%	9
Turfgrass Acres	110		170		
ZIP	73801		74012		
Age	43		42		

Table 13.

Determinants of Conservation Adoption - Cross Tabulations					
Irrigation Scheduling	**Never Used**	**%**	**Used**	**%**	**Total**
Golf Course	43	61%	27	39%	70
Recreational Park	11	50%	11	50%	22
Sports Field	7	33%	14	67%	21
Sod Farm	2	67%	1	33%	3
Other	28	60%	19	40%	47
Manual Sprinkler	22	63%	13	37%	35
Automated Sprinkler	61	54%	51	46%	112
Zoned Sprinkler	32	55%	26	45%	58
Manual Connection Sprinkler	23	61%	15	39%	38
Drip Irrigation	21	55%	17	45%	38
Soaker Hose	11	58%	8	42%	19
Spray by Hand	47	63%	28	37%	75
Other Watering Method	5	45%	6	55%	11
We do not irrigate	8	100%	0	0%	8
City	41	47%	46	53%	87
Private Well	21	54%	18	46%	39
Water Retention	18	62%	11	38%	29
Other	17	74%	6	26%	23
<12th Grade	10	71%	4	29%	14
H.S. Diploma	6	67%	3	33%	9
Some College	31	54%	26	46%	57
B.S./B.A.	38	55%	31	45%	69
Turfgrass Management	28	60%	19	40%	47
Landscape Architecture	4	80%	1	20%	5
Plant & Soil Science	3	50%	3	50%	6
Horticulture	10	56%	8	44%	18
Other	13	43%	17	57%	30
Certified Golf Course Superintendent (CGCS)	6	67%	3	33%	9
Certified Irrigation Auditor	0	0%	2	100%	2
Certified Sports Field Manager (CSFM)	4	67%	2	33%	6
Certified Pesticide Applicator	61	58%	44	42%	105
Licensed Pesticide Applicator	27	53%	24	47%	51
Certified Horticulturist	1	100%	0	0%	1
Certified Arborist	0	0%	2	100%	2
Landscape Industry Certified Manager	0	0%	1	100%	1
Landscape Industry Certified Technician	2	40%	3	60%	5
Other	5	56%	4	44%	9
Turfgrass Acres	111		174		
ZIP	73801		74008		
Age	43		43		

Table 14 summarizes the probit model information for the five most used water conservation methods: Model 1 - reduced watering, Model 2 - higher mowing heights of grass, Model 3 - zoned irrigation systems, Model 4 - selection of improved cultivars for drought tolerance, and Model 5 - irrigation scheduling based on plant water requirements as estimated by site-specific weather data.

Model 1 produced a log likelihood of -75.7418 and fourteen coefficients significant at a 95% confidence level. Both sports field facilities and other facilities positively affect the probability of adopting reduced watering as a water conservation strategy. Manual sprinklers, automated sprinklers, soaker hose, and spraying by hand as needed are all current watering methods which have a negative impact on the probability of adopting reduced watering. Of these watering methods, use of soaker hoses for irrigation has the greatest negative impact. Manual connection sprinklers however, increase the likelihood of adoption. Three of the water sources have a significantly negative affect on probability of adoption with private well water having the greatest negative affect followed by on site water retention and city water connection. An increase in the number of turfgrass acres at a facility decreases the probability of reducing water. Regionally, facilities in Oklahoma's Northwest are more likely to adopt this conservation method than ones in the Northeast. Having a reverse affect, both out of state and Southwest facilities reduce the likelihood of adopting reduced watering when compared to facilities in the Northeast.

Model 2 produced a log likelihood of -81.10395 and fifteen coefficients significant at a 95% confidence level. Both sports field and sod farm facilities increase the probability of adopting higher mowing heights of grass as a water conservation strategy. All of the watering methods except other watering methods have a significant affect on adoption. Manual sprinklers, drip irrigation, soaker hoses, and having no irrigation practices all increase the likelihood of implementing higher mowing heights of grass while automated sprinklers, zoned sprinklers, manual connection sprinklers, and spraying by hand have the opposite affect and decrease the probability of adoption. Facilities which acquire their irrigation water from city water connections, private wells, and other water sources reduce the probability of using higher mowing heights to conserve water. Individuals who have obtained a college degree are less likely to adopt this water conservation technique than individuals who have no college education. The only region which has a significant impact on the possibility of adoption is the Northwest. Facilities in the Northwest are more likely to utilize higher mowing heights than facilities in the Northeast.

Model 3 produced a log likelihood of -86.0693 and thirteen significant coefficients, including the intercept, at a 95% confidence level. In this model, both recreational park and sod farm facilities have a significant affect on the probability of adopting zoned irrigation. Recreational park facilities reduce the likelihood of adoption while sod farm facilities increase the likelihood of using zoned irrigation systems. Use of manual sprinklers, drip irrigation, soaker hoses, and having no current irrigation practices all increase the likelihood of using zoned irrigation systems. Facilities that use automated sprinklers, zoned sprinklers, and spraying by hand as needed for irrigation are less likely to use this water conservation method. The only water source to have a significant impact on adoption, city water connection, is expected to decrease the probability of using zoned irrigation systems. Having a college degree increases the likelihood of adoption compared to not having any college education. Facilities located in the Southeast are less likely to adopt this water conservation technique than facilities in the Northeast.

Model 4 produced a log likelihood of -83.1073 and seventeen coefficients significant at a 95% confidence level. Golf courses, recreational parks, sod farms, and other facilities all have a positive affect on the probability of adopting the selection of improved turfgrass cultivars for drought tolerance as a water conservation strategy. Of these facilities sod farms have the greatest positive impact while recreational parks have the least. Use of manual sprinklers and having no current irrigation practices both have a positive influence on probability of adoption while the use of automated sprinklers, zoned sprinklers, and other watering methods have a negative influence. Two of the four water sources, city water connection and on site water retention, increase the likelihood of using improved cultivars whereas use of private wells and other watering sources decrease the probability. For every acre increase in turfgrass at a facility the likelihood of adopting selection of improved cultivars is decreased slightly. Facilities located in the Northwest and Southwest regions are more likely to adopt this conservation practice than facilities in the Northeast. Out of state facilities are less likely to conserve water using the selection of improved cultivars than facilities in Northeast Oklahoma.

Model 5 produced a log likelihood of -78.8713 and nineteen significant coefficients, including the intercept, at a 95% confidence level. In this model, four of the five facility types have a significant impact of the probability of adopting irrigation scheduling based on plant water requirements. Golf courses, sod farms, and other facilities increase the probability of adoption while sports fields carry the opposite effect. Use of manual sprinklers, manual connection sprinklers, drip irrigation, and spraying by hand for irrigation all increase the likelihood of adoption whereas probability of adoption of irrigation scheduling is decreased by use of automated sprinklers, soaker hoses, and other watering methods. Facilities which rely on city water connections and private wells for irrigation water are less likely to adopt this water conservation technique. Individuals who either have some college education of received a degree are less likely to adopt irrigation scheduling than individuals who do not have any college education. For every acre increase in turfgrass the probability of utilizing irrigation scheduling decreases slightly. Facilities located in the Northwest region of Oklahoma are more likely to adopt irrigation scheduling than facilities in the Northeast. Out of state facilities are less likely to adopt this conservation measure than facilities located in Northeast Oklahoma.

Table 14

Determinants of Conservation Adoption – Models 1-5 The Probit Procedure	Model 1 - Reduced	Model 2 - Higher Mowing	Model 3 - Zoned Irrigation	Model 4 - Improved Cultivars	Model 5 - Irrigation Scheduling
Log Likelihood	-75.7418	-81.10395	-86.0693	-83.1073	-78.8713
N	149	149	149	149	149
Intercept	0.5140	0.4840	0.7253 *	-0.0994	1.3633 *
	(0.9876)	(0.9326)	(0.9432)	(0.9841)	(1.0329)
Golf	0.0597	0.0759	0.1597	0.9035 *	0.4403 *
	(0.5804)	(0.5372)	(0.5515)	(0.5861)	(0.5901)
Rec	0.1316	0.1264	-0.3603 *	0.4592 *	-0.1326
	(0.4639)	(0.4318)	(0.4685)	(0.4639)	(0.4605)
Sports	0.4880 *	0.5152 *	-0.0264	0.1182	-0.3771 *
	(0.4833)	(0.4614)	(0.4809)	(0.4938)	(0.5002)
Sod	-5.4121	0.9013 *	0.7798 *	1.8283 *	1.4914 *
	(26814.15)	(1.0938)	(1.1148)	(1.1952)	(1.1804)
OF	0.3893 *	0.0067	0.1525	0.5340 *	0.3936 *
	(0.5333)	(0.5037)	(0.5267)	(0.5412)	(0.5482)
MS	-0.2533 *	0.2985 *	0.2735 *	0.5079 *	0.2987 *
	(0.3387)	(0.3287)	(0.3236)	(0.3303)	(0.3430)
AS	-0.3319 *	-0.3598 *	-0.4285 *	-0.5745 *	-0.5997 *
	(0.3524)	(0.3348)	(0.3414)	(0.3553)	(0.3931)
ZS	0.0470	-0.5620 *	-0.9313 *	-0.2416 *	-0.0696
	(0.3292)	(0.3319)	(0.3252)	(0.3243)	(0.3392)
MCS	0.9705 *	-0.3979 *	-0.1853	-0.1975	0.5192 *
	(0.3778)	(0.3743)	(0.3462)	(0.3473)	(0.3645)
DI	0.0350	0.3520 *	0.5000 *	-0.1376	0.4778 *
	(0.3807)	(0.3634)	(0.3640)	(0.3608)	(0.3765)
SH	-0.8402 *	1.0111 *	0.4248 *	-0.0705	-0.6441 *
	(0.5211)	(0.4667)	(0.4535)	(0.4437)	(0.4647)
SBH	-0.4091 *	-0.2170 *	-0.2623 *	0.0036	0.2653 *
	(0.3191)	(0.2977)	(0.2919)	(0.2966)	(0.3081)
OWM	-0.2079	-0.1923	-0.0036	-1.5288 *	-0.9330 *
	(0.5851)	(0.5456)	(0.5454)	(0.6055)	(0.6147)
NoIrr	8.6630	1.6372 *	1.0410 *	1.8633 *	7.9680
	(14094.51)	(0.6923)	(0.7051)	(0.8606)	(14107.63)
City	-0.4148 *	-0.4380 *	-0.5323 *	0.3308 *	-0.9524 *
	(0.4046)	(0.3826)	(0.3629)	(0.3631)	(0.3983)
Private	-0.7406 *	-0.4703 *	-0.0984	-0.5746 *	-0.8147 *
	(0.3949)	(0.3802)	(0.3469)	(0.3633)	(0.3810)
Reten	-0.4285 *	0.0926	0.2156	0.8640 *	-0.0396
	(0.4280)	(0.3978)	(0.3697)	(0.3889)	(0.3840)
OWS	-0.1936	-0.6545 *	0.1659	-0.3302 *	-0.1880
	(0.4619)	(0.4576)	(0.4202)	(0.4189)	(0.4457)
College	-0.1375	-0.1602	0.4102 *	-0.0858	-0.6843 *
	(0.4025)	(0.3813)	(0.3930)	(0.3917)	(0.4112)
BS	0.0941	-0.4448 *	-0.0029	-0.1012	-0.8179 *
	(0.4348)	(0.4104)	(0.4185)	(0.4245)	(0.4474)
Cert	0.0010	-0.0777	-0.1618	-0.2417	0.2134
	(0.4339)	(0.4133)	(0.3979)	(0.4154)	(0.4209)
Acres	-0.0005 *	-0.0000	-0.0003	-0.0012 *	-0.0011 *
	(0.0005)	(0.0005)	(0.0007)	(0.0014)	(0.0007)
Age	-0.0061	-0.0011	0.0001	0.0074	-0.0021
	(0.0114)	(0.0112)	(0.0110)	(0.0110)	(0.0118)
SE	-0.2343	0.1198	-0.3416 *	-0.2268	0.0928
	(0.3731)	(0.3546)	(0.3441)	(0.3417)	(0.3459)
NW	0.4444 *	0.4573 *	0.2138	0.2351 *	0.8006 *
	(0.3521)	(0.3403)	(0.3303)	(0.3327)	(0.3566)
SW	-0.4554 *	0.0972	-0.1934	0.6109 *	0.2233
	(0.6384)	(0.5349)	(0.5030)	(0.6311)	(0.5762)
OS	-0.9047 *	0.0361	-0.3011	-1.6630 *	-0.5080 *
	(0.6976)	(0.6008)	(0.5543)	(0.7384)	(0.6550)

* Denotes significance at a 95% confidence level

Because adoption exceeded 50% of respondents for only three types of water conservation strategies, higher mowing heights, reduced watering, and zoned irrigation systems, there appears to be a lack of motivation or incentive on the part of Oklahoma turfgrass managers to participate in water conservation. Even though respondents consider lowering cost of water used to be an important motivation for adopting water conservation strategies, concern for maintaining performance and appearance of turfgrass for users overshadows those concerns as the most cited barrier to adoption. Thus, no one technique is likely to meet managers' needs given the concerns of appearance and performance.

Dominant determinants which generally increased probability of adoption of the top five most used water conservation strategies included: facilities located in the Northwest region, Sod Farm facilities, and facilities which utilize manual sprinkler systems or do not irrigate at all. Dominant determinants that most often decreased the likelihood of adopting the top five most used water conservation techniques included: utilization of automated and zoned sprinklers for irrigation, facilities which rely on city water connections and private wells for irrigation water, and increases in turfgrass acres at a facility. Quite simply, these conditions of non-adoption are not random, facilities with automated sprinklers are more likely to have invested in them to ensure turf aesthetics, city water connections indicate likelihood of higher returns to use and/or turf managers have already switched to private wells to avoid higher costs of treated water.

Results suggest extension efforts should be directed at aiding managers in the Southern regions first, continuation of sprinkler auditing training programs, and targeting facilities with greater number of acres first and then smaller facilities second. An additional approach, such as that taken in Georgia, would involve aiding golf and parks managers in development of best management plans for water conservation as a long term conservation tool, rather than a short term emergency response to seasonal or prolonged drought.

OBJECTIVE 2 – Determine the accuracy and reliability of remote sensing reference evapotranspiration (ET) data with established crop coefficients compared to actual landscape plant water use in Oklahoma.

Objective 2 was split between two separate studies. For easier reading, each study will be discussed separately below.

Study 1: Calculation of historical growing season reference ET from 1994 to present day using Oklahoma Mesonet data.

Methodology:

The Oklahoma Mesonet ET Model is a weather-based tool for the estimation of daily water loss from a plant canopy through the combined processes of evaporation and transpiration. Using weather data from the Oklahoma Mesonet, the model calculates daily grass reference evapotranspiration (ET_0G) for each Mesonet site, and, based on those values, estimates daily values for alfalfa reference ET, cool-season grass ET (e.g., a fescue lawn), warm-season grass ET (e.g., a bermudagrass lawn), and pan evaporation.

The model uses the FAO-recommended Penman-Monteith equation. The ET is calculated for a hypothetical well-watered grass surface of 12 cm height with a bulk surface resistance equal to 70 s/m. Using 5-minute Mesonet data to calculate the various parameters, the model uses the 24-hour calculation approach. Soil heat flux, G, is assumed equal to zero (consistent with the recommendation). The 5-minute average weather variables from Mesonet that are used in the calculation are:

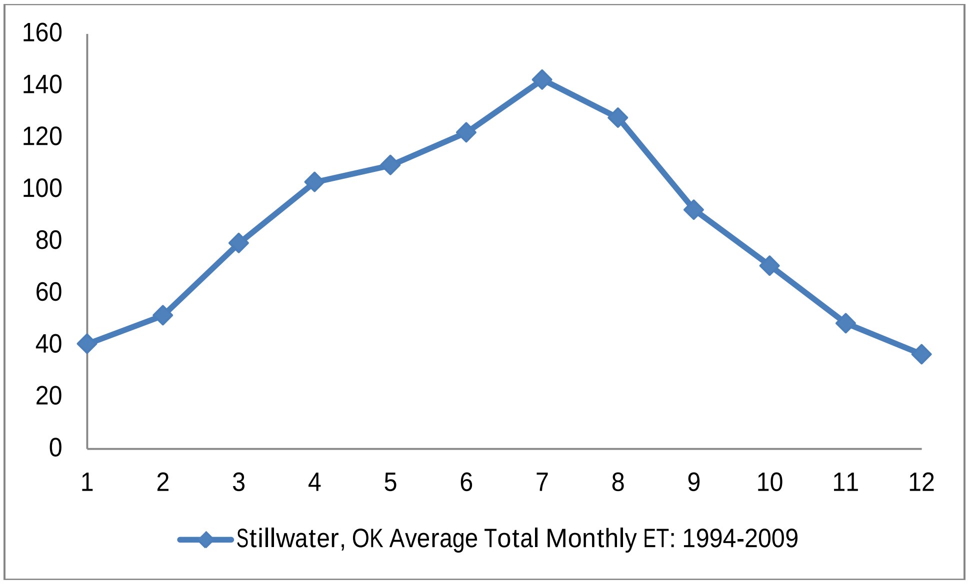
- Solar Radiation (W/m2)
- 2-m Wind Speed (m/s)
- 1.5 m Air Temperature (C)
- 1.5 m Relative Humidity (%)
- Station Pressure (kPa)

Dew point, when needed, is calculated from the air temperature and relative humidity. At station sites not measuring 2-m wind speed, an objective analysis scheme is used to interpolate a value.

Principal Findings and Significance:

Average total monthly ET was calculated from 1994 – 2009 for the Oklahoma Mesonet site at Stillwater, OK (Figure 11). As expected, July and August were the months with the highest total ET at 8.9 and 8.0 inches, respectively. June had the third highest total monthly ET at 7.6 inches.

Figure 11. Average total monthly ET (inches) from 1994-2009 at the Stillwater, OK Mesonet Site.



Study 2: Estimate actual plant water use by conducting field lysimeter and atmometer studies compared to Oklahoma Mesonet ET data.

Methodology:

In addition to the Oklahoma Mesonet reference ET estimates, we also calculated on-site ET at Stillwater, OK using two techniques: 1) modified Bellani plate atmometer (ET Gage, Spectrum Technologies, Plainfield, IL) and 2) weighing micro-lysimeters.

Principal Findings and Significance:

The Bellani plate atmometer method estimated a total monthly ET of 6.5 inches while the Oklahoma Mesonet site recorded a reference ET of 6.8 for August 2010 (Table 11). During September 2010, the atmometer method estimated a total monthly ET of 4.8 inches while the Oklahoma Mesonet site recorded a reference ET of 5.1 (Table 11). Based on the bermudagrass lysimeters during the same two months, total monthly ET of bermudagrass plants was 6.7 inches in August 2010 and was 4.2 in September 2010 (Table 15).

Table 15. Estimated and actual bermudagrass evapotranspiration (ET) in inches during August and September 2010 in Stillwater, OK. Means followed by different letters are different at the 0.05 significance level according to the least significant difference test.

Method	**August 2010**	**September 2010**
	ET (inches)	
Oklahoma Mesonet	6.8 a	5.1 a
Atmometer	6.5 b	4.8 b
Bermudagrass Lysimeter	6.7 ab	4.2 c

Based on these findings, the Oklahoma Mesonet gives a reliable estimate of bermudagrass ET during August 2010, but may overestimate ET during cooler periods such as during September 2010. Similarly, the atmometer data gave a reliable estimate of bermudagrass ET during August 2010, but overestimated bermudagrass ET during September 2010. These results indicate that there is a need to refine crop coefficients for turf areas in Oklahoma, especially during the fall and possibly spring growing periods.

OBJECTIVE 3 – Educate Oklahoma stakeholders and citizens of landscape irrigation practices to conserve Oklahoma water resources.

Methodology:

Three “hands-on”, “train-the-trainer” workshops were conducted during 2010 to educate Oklahomans of proper turf and landscape irrigation practices to conserve water resources. The target audience was Oklahoma Master Gardeners in three Oklahoma counties: Rogers, Tulsa, and Oklahoma. Master Gardeners were chosen as the target audience because each Master Gardener is required to volunteer at least 40 hours per year through their local OSU Cooperative Extension Service county office. Once properly trained, the Master Gardeners have the potential to extend the turf and landscape water conservation information to hundreds of Oklahomans in and near Claremore, Tulsa, and Oklahoma City. The workshops were delivered by Mr. John Haase, OSU CES County Educator in Rogers County, and by PI Justin Moss during 2010.

Principal Findings and Significance:

Seventy-six Master Gardeners attended the training workshops. There were 27 attendees in Rogers County, 27 attendees in Tulsa County, and 22 attendees in Oklahoma County. Each participant completed a pre- and post-survey to assess the effectiveness of the training workshop. In the pre-survey, each participant was asked if they watered their lawns, and if they responded “yes”, they were asked if they knew the quantity of water in inches that they applied to their lawn on a given basis. Of those that responded yes, 83% of participants did not know how many inches they watered their lawn on a given basis. The simple irrigation audit workshop was then delivered to the participants. After participating in the workshop, the participants were asked to conduct a simple irrigation audit at their home and to report the results to Mr. Haase. All participants conducted the simple irrigation audit at their homes and reported their audit results to Mr. Haase. Therefore, 100% of the participants stated in the post-workshop survey that they know how many inches of water were delivered on a given basis for their home irrigation sprinklers. The Master Gardener participants were then instructed to “extend” this information to the general public through their volunteer hours at their local OSU County Extension office. Critical future work should focus on tracking participant outreach and dissemination of simple irrigation audit procedures and practices to conserve water resources to the general public.

As of the writing of this OWRRI report, Mr. Haase is in the process of finishing his M.S. thesis with further results of this project which were not stated as objectives in this OWRRI research grant proposal. Mr. Haase has an expected M.S. thesis completion and graduation date of Summer 2011. Therefore, the research team will orally present further results of this work at the Summer 2011 OWRRI research meeting.

A Fluvial Geomorphic and Sediment Transport Study of the Little River Upstream of Lake Thunderbird Using an Acoustic Doppler Current Profiler (ADCP)

Basic Information

Title:	A Fluvial Geomorphic and Sediment Transport Study of the Little River Upstream of Lake Thunderbird Using an Acoustic Doppler Current Profiler (ADCP)
Project Number:	2010OK181B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	4
Research Category:	Climate and Hydrologic Processes
Focus Category:	Sediments, Geomorphological Processes, Water Quality
Descriptors:	None
Principal Investigators:	Randall L. Kolar, Jason P. Julian, Robert Nairn, Baxter Vieux

Publications

1. Dutnell, Russell, Hollis Henson, Robert Nairn, Randall Kolar, Baxter Vieux, and Jason Julian, 2010, Preliminary Findings of a Fluvial Geomorphic and Sediment Transport Study of the Little River Upstream of Lake Thunderbird Using an Acoustic Doppler Current Profiler (ADCP), in 2010 Governor s Water Conference and Oklahoma Water Research Symposium, Norman, OK. (Poster)
2. Dutnell, Russell, Hollis Henson, Robert Nairn, Randall Kolar, Baxter Vieux, and Jason Julian, 2011, Preliminary Findings of a Fluvial Geomorphic and Sediment Transport Study of the Little River Upstream of Lake Thunderbird Using an Acoustic Doppler Current Profiler (ADCP), in 2011 National Surface Water Conference and Hydroacoustics Workshop, Poster Session, Tampa, FL.

A Fluvial Geomorphic and Sediment Transport Study of the Little River Upstream of Lake Thunderbird Using an Acoustic Doppler Current Profiler (ADCP)

PROJECT REPORT

Oklahoma Water Resources Research Institute
003 Life Sciences East, OSU
Stillwater, Oklahoma 74078-3011

May 2011

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A Fluvial Geomorphic and Sediment Transport Study of the Little River Upstream of Lake Thunderbird Using an Acoustic Doppler Current Profiler (ADCP)

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Start Date: 3/1/2010

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Congressional District: Oklahoma Fourth

Focus Category: GEOMOR, HYDROL, MET, SED, SW & WQN

Descriptors: Fluvial Geomorphology, Sediment Transport, Acoustic Doppler Current Profiler (ADCP)

Principal Investigators: See above

Publications

Dutnell, Russell, Hollis Henson, Robert Nairn, Randall Kolar, Baxter Vieux, and Jason Julian, 2010, Preliminary Findings of a Fluvial Geomorphic and Sediment Transport Study of the Little River Upstream of Lake Thunderbird Using an Acoustic Doppler Current Profiler (ADCP), in 2010 Governor's Water Conference and Oklahoma Water Research Symposium, Student Poster (2nd Place), Norman, OK.

Dutnell, Russell, Hollis Henson, Robert Nairn, Randall Kolar, Baxter Vieux, and Jason Julian, 2011, Preliminary Findings of a Fluvial Geomorphic and Sediment Transport Study of the Little River Upstream of Lake Thunderbird Using an Acoustic Doppler Current Profiler (ADCP), in 2011 National Surface Water Conference and Hydroacoustics Workshop, Poster Session, Tampa, FL.

Students supported by this program

Student Status	Number	Disciplines
Undergraduate	1	Civil Engineering
M.S.	1	Civil Engineering
Ph.D.	1	Civil Engineering
Post Doc		
Total	3	Civil Engineering

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Context of this Technical Report

This report is being prepared as an annual report for OWRRI grant #2010OK181B. Due to delays in the equipment purchase and the lack of significant rain events during the Fall/Winter of 2010/2011, the study is incomplete. Findings to date will be presented in subsequent sections, but the work, which comprises the dissertation topic for the first author on this report, is ongoing. That document (the dissertation), which is now expected to be finished in Spring 2012, will contain more complete findings from this study. An amended report will also be filed with the OWRRI at that time.

Problem

Sediment transport has a profound impact on streams, rivers, lakes, and impoundments. It affects the morphology of streams and rivers, the life span of lakes and impoundments, due to lost capacity, and the water quality in all water bodies, as many nutrients and contaminants (e.g., metals) are bound to the solid particles being transported. Given its importance however, sediment transport is one of the more poorly quantified water quality variables, primarily due to the difficulty in obtaining accurate estimates of both the suspended fraction, that being transported in the water column, and the bed load fraction, the material moving along the bed. The current research project attempts to fill this knowledge gap by developing a cost-effective, yet accurate measurement protocol utilizing an Acoustic Doppler Current Profiler (ADCP) to measure sediment movement in creeks and rivers. The Little River, a tributary of Lake Thunderbird, due to its proximity to the OU campus and the fact that it is representative of many streams in central Oklahoma, is serving as the test bed for the project.

A bathymetric study of the lake conducted by the OWRB (Oklahoma Water Resources Board) in 2001 found that the pool capacity of the lake has been reduced from 119,600 acre-feet in 1966 to 105,644 acre-feet in 2001 for a loss of capacity of 13,956 acre-feet or 11.7% in 35 years (OWRB, 2002). The observed loss rate of 399 acre-feet/year is 14% higher than the 350 acre-feet/year reportedly estimated by the U.S. Bureau of Reclamation (BOR) in correspondence to OWRB back in 1965 (Flaigg, 1965) and is attributed to “larger grained sediment washed in from the watershed” (OWRB, 2002). McHenry (1974) reports an average annual percentage loss of 0.23% per year for reservoirs predominantly from the Midwest, Texas and California with a capacity between 100,000 and 1,000,000 acre-feet. Lake Thunderbird’s loss rate exceeds this value.

Lake Thunderbird, which supplies drinking water to the municipalities of Norman, Midwest City, and Del City, is designated in the Oklahoma Water Quality Standards as a sensitive public and private water supply (SWS) with a nutrient limited watershed. Studies by the Oklahoma Water Resources Board (OWRB, 2005) indicate that the lake is “eutrophic, indicative of high levels of productivity and nutrient rich conditions” due to the fact that the average trophic state index (TSI), using Carlson's TSI (chlorophyll-a), was found to be 58.

The Oklahoma Conservation Commission (OCC) (prepared by Vieux & Associates, 2007) used total phosphorous concentration as a surrogate to estimate the current chlorophyll-a concentration in the lake, finding it to be 30.8 μg/L, three times the State Water Quality Standard of 10 μg/L. Chlorophyll-a concentrations in excess of 20 μg/L result in hyper-eutrophic water conditions with excessive algae growth (OWRB, 2004). OWRB also determined that the turbidity was sufficiently high so that the Fish and Wildlife Propagation, a beneficial use criteria, was deemed to be only partially supported (OWRB, 2005). Data from 2006 indicates that Lake Thunderbird is impaired due to excessive turbidity and low dissolved oxygen.

The OCC study addressed sediment loading to the lake, modeling it as a function of imperviousness, but did not directly measure it. Prior to the current study, there has never been a comprehensive study of the sediment transport characteristics of the Little River and the morphological processes that both drive them and are driven by them. Yet, there is evidence, based upon a preliminary examination, that the Little River is highly unstable and undergoing an evolutionary process of morphological change as a response to increasing urbanization and "channel improvements" made in the past. A reconnaissance study of the river conducted in September 2007 by one of the investigators in the current work revealed clear indications of significant channel incision and widening, including exposed bridge abutments, exposed high pressure gas lines (Fig 1 a), slumping banks, exposed tree roots, fallen trees and tributary head cuts (Fig 1 b). The importance of this cannot be overstated as the ramifications to infrastructure, lost property, and increasing sedimentation rates to the lake are potentially substantial.

Figure 1: Indications of the Little River channel incision and widening including a) an exposed high pressure gas line and b) tributary head cuts.

Lane (1955) described that the morphology of a channel is the result of several factors, including the sediment load and size transported through the channel, the discharge in the channel and the slope of the channel. The size and load of sediment transported through a channel is balanced by the stream slope and discharge. If the balance is altered, the channel morphology adjusts to accommodate the change. Schumm, et al (1984), and later Simon (Simon, 1989, 1994) developed a process-based classification scheme that describes a natural channel's adaptation to straightening. As shown in Figure 2, the Channel Evolution Model describes a complete "cycle" of bank-slope development from the pre-modified conditions through stages of adjustment to the eventual reestablishment of stable bank conditions. The Little River channel bed, in the reach surveyed in the vicinity of 12^{th} Avenue NE, appears to have recently entered Stage IV of the evolutionary cycle, the degradation and widening phase, and appears to have incised at least 6-8 feet thus far.

To fully understand the significance of this process, one needs only to look at Wildhorse Creek, near Hoover, in Garvin County, Oklahoma. Between 1922 and 1933 the channel was "improved" by constructing a straight 10 feet deep trapezoidal channel with a top width of 25 feet and 2:1 side slopes, as may be seen in Figure 3a (Barclay, 1980). In 1999, Dutnell (2000) found the channel to be 193 feet wide and approximately 25 feet deep. The channel has thus incised approximately 15 feet and experienced a 20-fold increase in cross-sectional area (Figure 3b). It appeared to be at Stage V, the aggradation and widening phase, as there was evidence of deposition on inside bends and point bars were beginning to form. As a result of the experienced erosion, the sediment loading to Lake Texoma, since the "channel improvements" were completed, exceeds 50 million cubic yards.

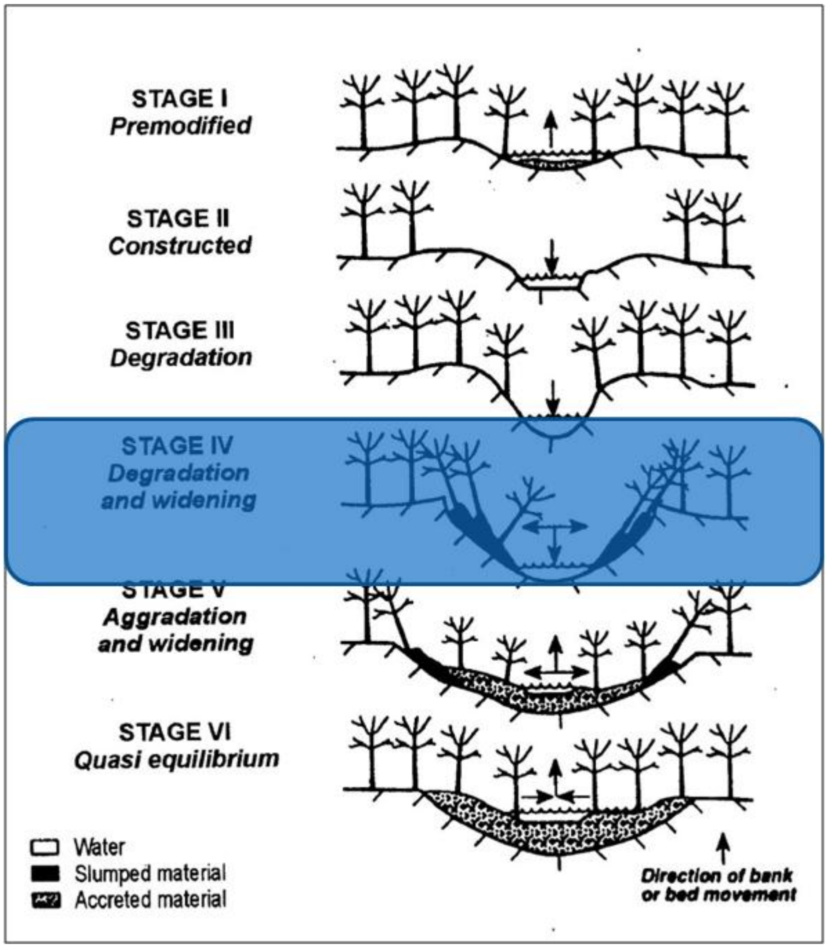

Figure 2: Channel Evolution Model – The Little River is currently at Stage IV, the degradation and widening stage. (Simon (1989))

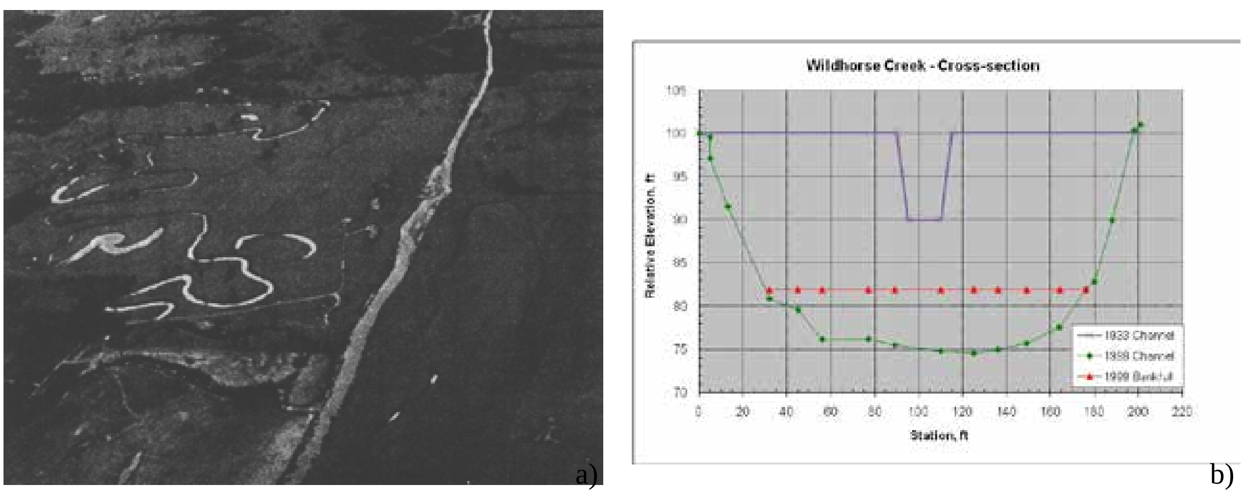

Figure 3: a) Channelized versus natural meandering Wildhorse Creek channel, in Garvin County, Oklahoma (Barclay, 1980); b) Comparison of Wildhorse Creek channel dimensions in 1933 (Barclay, 1980) and 1999 (Dutnell, 2000)

Little River may, or may not experience the same level of degradation and widening as Wildhorse Creek, but the process is certainly ongoing and the degradation and widening occurring in the channel already appears to be significant. Further, the Little River and Wildhorse Creek are not the only streams that are undergoing this process of change. A large number of the creeks and rivers in the State of Oklahoma are undergoing the exact process described here, i.e., they have been straightened and/or are receiving more flow due to urbanization and thus are incising and widening. The current project is attempting to develop a methodology that may be used for assessing and documenting this process in the State's streams.

Research Objectives

The current study is addressing multiple objectives, including the following:
1) Documentation of the Fluvial Geomorphology (FGM) of the Little River from the headwaters to Lake Thunderbird;
2) Development of discharge and sediment rating curves for the Little River watershed;
3) Development of a frequency-duration curve for the Little River watershed;
4) Estimation of the annual and long-term sediment load to Lake Thunderbird;
5) Estimation of the amount of expected channel degradation for the Little River;
6) Potential recommendations for stopping or slowing the expected channel degradation; and
7) Development of a protocol that may be used by other entities, including GRDA, to estimate sediment loading rates to reservoirs and better understand the sediment transport characteristics of streams flowing within their jurisdiction.

Methodology

The methods used to meet the various objectives of the current study are described below. The work centers around the use of a Teledyne RDI Workhorse Rio Grande 600 kHz Acoustic Doppler Current Profiler (ADCP) (see Figure 4) and available off-the-shelf software to estimate stream discharge, suspended sediment concentrations, and at higher flows, the bed load velocities. The equipment and methodology being used in the current project, though relatively new, are becoming more accepted as the use of ADCPs increases. In 2005, the U.S. Geological Survey (USGS), in cooperation with the U.S. Army Corps of Engineers, Detroit District, developed a Quality-Assurance Plan for discharge measurements using ADCPs (Oberg, 2005). More recently, the USGS, recognizing that the use of ADCPs "is now a commonly used method for measuring streamflow," has released guidance on the use of ADCPs for that purpose (Mueller and Wagner, 2009). Similar protocols had previously been developed by the Water Survey of Canada (2004). Both of these publications address all aspects of measuring discharge and bed movement using an ADCP. They do not, however, address measuring suspended sediment concentrations. Software is available on the market that can be used to convert the back-scatter data obtained from the ADCP to sediment concentration using an iterative approach (Aqua Vision, 2009a).

Documentation of the FGM of the Little River from the headwaters to Lake Thunderbird

Documenting the FGM of the Little River requires the surveying of cross-sections and longitudinal bed profiles using traditional surveying methods and a total station. In addition, the project will attempt to measure the elevation of the Little River bed from the lake to the headwaters (or as far up as the channel as possible) using an ADCP in conjunction with a real-time kinematic (RTK) GPS receiver. In this configuration, the RTK determines the elevation of the boat and the ADCP determines the depth from the boat to the bottom of the channel.

Figure 4: Teledyne RDI Workhorse Rio Grande 600 kHz Acoustic Doppler Current Profiler (ADCP) operating from a bridge.

Subtracting the depth from the boat elevation will provide the bed elevation of the channel bottom. An inflatable Saturn “KaBoat” with an electric motor (Figure 5) is to be used to guide the ADCP/RTK down the river. Measurements must be made at intermediate flows so that the water is deep enough for the ADCP to work (>2.5’), but not so swift as to be dangerous. Preferably the work will take place in early fall when the leaves are off of the trees, to allow for better radio reception between the boat GPS and Base GPS, but before the weather gets too cold.

In addition to the surveys, the FGM documentation includes an assessment of stream channel morphology (Rosgen, 1996), evolution (Schumm, et al., 1984; Simon and Hupp, 1986; Simon, 1989; and Simon, 1994), and stability utilizing several different indices, including the Pfankuch Stream Stability Index (Pfankuch 1975), the Bank Erosion Hazard Index (BEHI) (Rosgen, 1996), the Near Bank Stress (NBS) rating (Rosgen,1996), the Channel Stability Index (CSI) as modified by Simon and Klimetz (2008), and the Ozark Streambank Erosion Potential Index (OSEPI) developed by Storm et al. (2010) for streams in the Ozark eco-region. It is not clear if the latter is particularly applicable in the Little River watershed; the data being collected will provide the information needed to determine its applicability in the Little River watershed.

The data from the surveys and the stream channel morphology, evolution and stability assessments are being collected using a TDS Recon Pocket PC. The survey data is being collected using SurveyPro software interfacing with a Sokkia Set 500 Total Station. The stream channel morphology, evolution and stability data is being collected using Excel installed on the Recon. A tabular form was created so that the data required by the various indices could be input into the Recon item by item, line by line. This raw data is then copied and pasted to a "RawData" sheet in a larger, multi-sheet Excel spreadsheet that selects the data needed for each stability index, determines each index and prepares a summary. Indices are being determined at four locations for each reach surveyed. An example of the forms produced by the spreadsheet is shown in Appendix A. The spreadsheets can be made available upon request.

The data from the survey is then combined with the data from the stream channel morphology, evolution and stability assessment to develop a site summary sheet as shown in Appendix B. Photographs of the cross-section and the assessment sites are also included.

Figure 5: The Teledyne RDI Workhorse Rio Grande 600 kHz Acoustic Doppler Current Profiler (ADCP) with Hemisphere RTK-GPS and the inflatable "KaBoat"

Development of discharge and sediment rating curves for the Little River Watershed

Developing discharge and sediment rating curves for the Little River watershed requires measuring the discharge, the concentration of the suspended sediment and bed load movement over a large range of discharges (i.e., at multiple stages), at multiple sites. These sites (shown as triangles in Figure 6) were selected based on being representative of the system being assessed and on site accessibility.

The discharge is being determined using traditional wading methods with a Marsh McBirney Flo-Mate portable velocity meter, and a Teledyne RDI Workhorse Rio Grande 600 kHz Acoustic Doppler Current Profiler (ADCP) mounted to a tethered boat. The Flo-Mate is being used to determine the discharge for lower flows, the ADCP is being used at higher flows, and both are being used at intermediate flows. At higher flows, when most sediment is transported, the Visea Plume Detection Toolbox (PDT) software is being used to convert the back-scatter intensity recorded by the ADCP to suspended sediment concentrations. Visea PDT does this by integrating the back-scatter intensity with information on salinity, temperature and reference measurements of sediment concentrations (Aqua Vision, 2009b). Bed load movement only occurs at high flows, and it is being determined using the ADCP and methods described by the U.S. Geological Survey (Mueller and Wagner, 2009).

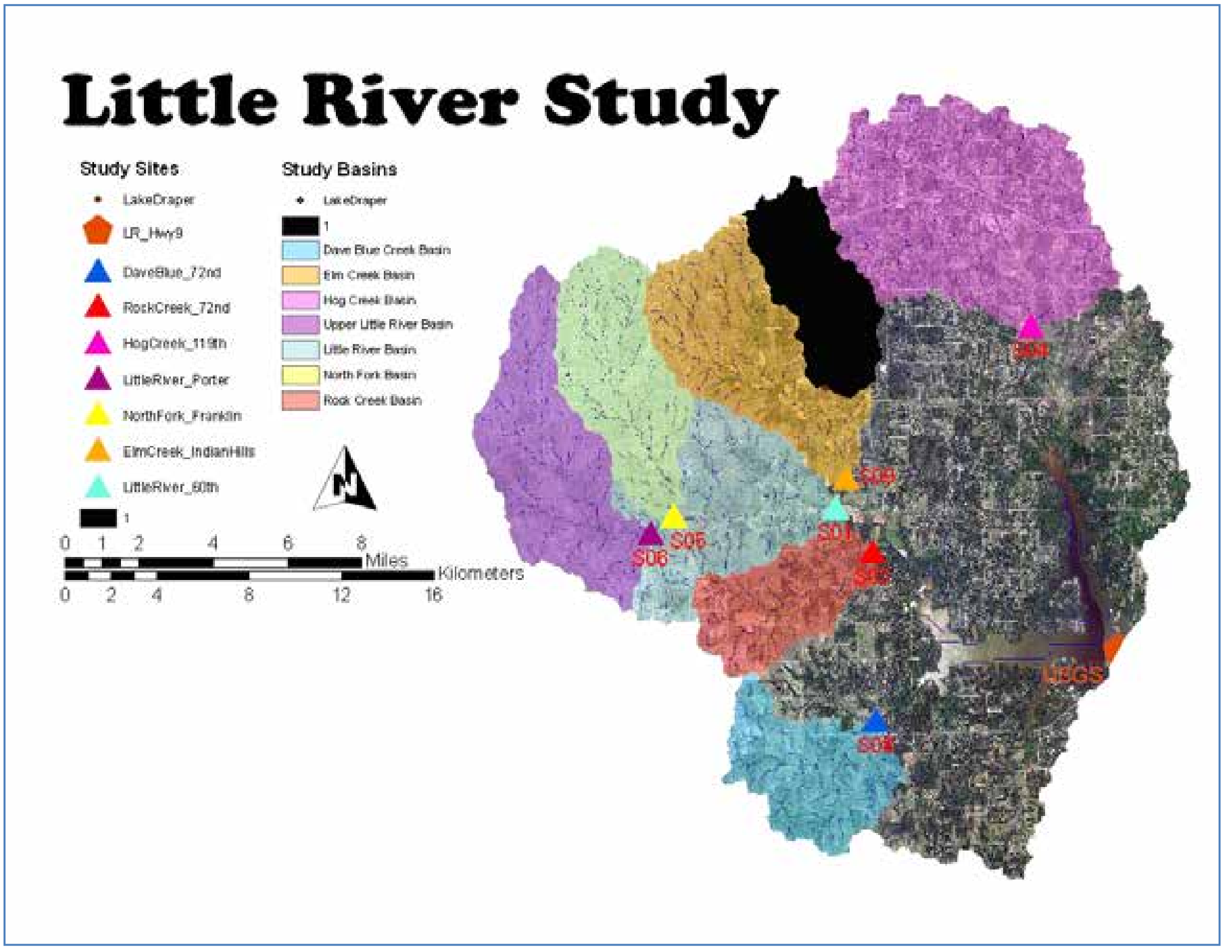

Figure 6: Discharge and Sediment Rating Curve Sites.

The stage, or depth of the water, at the study sites is being measured with HOBO Water Level Data Loggers. HOBOs are pressure transducers that can be set to measure pressure and temperature at varying time steps. For this study the HOBOs are installed in a PVC housing (Figure 7) and mounted to t-posts or re-bar with plastic zip-ties as close to the bottom of the stream as possible. Pressure is being measured every 30 minutes at the seven sites shown in Figure 6. A seventh HOBO is recording atmospheric pressure on the same 30 minute interval. By subtracting the atmospheric pressure from the total pressure of a stream mounted HOBO, the hydrostatic pressure at each HOBO is determined. Knowing the temperature and salinity (assumed to be zero), the density of the water may be determined, and thus the depth of the water above the HOBO may be calculated. Therefore, the HOBOs are essentially providing a record of depth every 30 minutes.

Discharge rating curves that relate stream discharge to channel stage are being developed by measuring discharge at various stages, as provided by the HOBOs. Sediment rating curves that relate sediment discharge to stage are being developed by measuring discharge and sediment concentration at various stages, again as provided by the HOBOs.

Figure 7: HOBO Water Level Logger with PVC housing.

Validation of the data obtained in the Little River watershed is complicated by the fact that there is not a USGS stream gauge on any portion of the river or the creeks upstream of Lake Thunderbird, so there is very little existing flow data for the Little River or its tributaries. Even though several studies have been conducted validating the use of ADCPs for measuring stream discharge (Fulton and Ostrowski, 2008; Everard, 2009; Schinkel, 2009; and Terek, 2009) and sediment movement (Rennie et al., 2002; Kostaschuk et al., 2005; Gaeuman and Jacobson, 2007; and Kim and Voulgaris, 2008) it is still necessary to validate the measurements being taken by the ADCP.

Validation of the use of the ADCP for measuring discharge is being conducted using two approaches. At intermediate flows, when it is still safe to use wading methods, the discharge results are compared to the results from a Marsh McBirney. Validation of higher flows requires measuring discharge at a nearby USGS gauge station and comparing the measured results to the discharge reported by the gauge station. Verification is considered to be achieved if the discharge measurement is within ±5% of the reported gauge discharge. Validation of the suspended sediment is to be accomplished by comparing values obtained using the ADCP to grab samples collected at the time of the measurement.

Unfortunately, there is no reliable means of validating the bedload velocity observed using the ADCP. The quantities of sediment captured in bed-load samplers are highly variable in both space and time. Gaeuman and Jacobson (2007) therefore concluded "conventional physical sampling appears to be the least reliable means for estimating bed-load transport rates in large sand-bed rivers," and therefore should not be used as a means for evaluating the performance of ADCPs. They did note that however that bed-load transport rates estimated from dune migration rates correlated well with ADCP measured bed-load velocities over a wide range of conditions. Obviously, the Little River is not a large sand-bed river, but it is a sand-bed river. It is not completely certain that bed features will be observed sufficient for performing validation in the manner presented, but it is suspected that it might.

Development of frequency-duration curves for the Little River Watershed

Since long-term information on the discharge history of the Little River is not available, the current study is relying on hydrologic modeling to generate the frequency-duration curve for the Little River and its tributaries. The model used in this study is Vflo which is a physics-based distributed hydrologic model developed by Vieux & Associates, Inc (Vieux, 2007). Vflo uses radar rainfall data for hydrologic input to simulate distributed runoff. The model generates distributed runoff maps covering the watershed and hydrographs at selected drainage network grids.

The rainfall data used in this study is produced by the ScourCast system that performs continuous distributed watershed model simulation and rainfall monitoring. ScourCast provides continuous rainfall at 15-minute intervals at a resolution of 2 kilometers. Model parameters, including roughness, saturated hydraulic conductivity, wetting front suction, and effective porosity are derived in ArcGIS at a resolution of 10 meters from maps of land use and soil type.

In order for the program to function properly, the number of cells imported into Vflo must be less than 30,000. Table 1 shows the minimum cell size that may be used to model the various sub-basins and the entire Lake Thunderbird watershed. The minimum allowable cell size for the sub-basins ranges from 35 square meters for the Dave Blue Creek sub-basin to 70 square meters for the Little River sub-basin above 60th Avenue Northeast. Modeling the entire watershed requires a minimum cell size of 150 square meters. Because ultimately, the entire watershed is to be modeled, a cell size of 150 square meters is being used in the current study. All data, however is at a resolution of 10 meters so future modeling of sub-basins could be conducted using finer resolutions as provided in Table1.

By modeling the sub-basins and generating hydrographs at drainage network grids that correspond to the monitoring sites where the HOBOs are installed, we can calibrate the model using the data collected in the current study. The model, thus calibrated is being used to generate frequency-duration curves, showing the percentage of time various flows are exceeded.

Table 1: Cell Size Determination Results

	LR Below Lk Tbird	Little River @ 60th	Little River @ Porter Ave	North Fork	Elm Creek (w/o Draper)	Rock Creek	Hog Creek	Dave Blue Creek
# of cells	6642426	1434356	524887	430349	520333	296330	924852	343092
Cell size (m)	10	10	10	10	10	10	10	10
Cell area (m^2)	100	100	100	100	100	100	100	100
Total area (m^2)	664,242,600	143,435,600	52,488,700	43,034,900	52,033,300	29,633,000	92,485,200	34,309,200
Total area (km^2)	664.2	143.4	52.5	43.0	52.0	29.6	92.5	34.3
Total area (mi^2)	256.5	55.4	20.3	16.6	20.1	11.4	35.7	13.2
Cell size (m)	150	70	45	40	45	35	60	35
# of cells	29522	29273	25920	26897	25695	24190	25690	28008

Estimation of the annual and long-term sediment load to Lake Thunderbird

Utilizing the information from the sediment rating curves, which allow for estimation of sediment loading rates at various flows, together with the frequency-duration curves, which predict how often a given discharge occurs, the annual sediment yield to Lake Thunderbird is being estimated.

Estimation of the amount of expected channel degradation for the Little River

Using the results of the surveys, including the longitudinal profile survey described above, an estimate of how far the Little River channel has degraded is being made. An estimate of how much farther it is anticipated to degrade will also be made.

Potential recommendations for stopping or slowing the expected channel degradation

Using the results of the surveys and the estimation of expected channel degradation, recommendations on potential methods for stopping or slowing the degradation will be prepared.

Development of sediment loading rates estimation protocol

Upon completion of the study, the lessons learned in the study will be used to develop a protocol for other entities to use to determine sediment loadings in other stream systems.

Principal Findings and Significance

Although delays in purchasing equipment and the lack of significant rain events prevented completion of this study in the proposed time period, the time was spent working on preliminary studies and related research tasks, as presented briefly below. In addition, researchers took the opportunity provided by the lack of rain to become more familiar with operating the equipment and software that it interfaces with. Training on the use of the Hemisphere RTK GPS system was provided by the manufacturer in Scottsdale, AZ in April 2010; and training on the use of ADCPs was obtained at a USGS course in Houston, Texas in January 2011, and at the 2011 USGS Surface-Water Conference and Hydroacoustics Workshop in Tampa, Florida in March 2011.

Documentation of the Fluvial Geomorphology (FGM) of the Little River from the headwaters to Lake Thunderbird

Work on documenting the FGM of the Little River has been somewhat slower than anticipated, mainly due to the lack of survey control in the vicinity of the river. Since the objective is to document the morphology of the entire length of the channel, it is desirable to know locations (Easting and Northing) and elevations to a high degree of accuracy. Methods typically used to measure channel morphology (i.e., a level and tape measure) are insufficient for the current study, and accurately using a total station over the length of the study is proving more time consuming than expected. Further, using the total station is particularly difficult when the leaves are on the trees, due to blocked line-of-site, so the only efficient time to conduct these surveys is in the fall and winter. Thus the surveys, including the longitudinal profile, will be completed this fall.

A couple of FGM surveys have been completed and the results are provided in Appendix B. Each summary sheet includes a legal description of the site location; the drainage area; an aerial photograph of the site showing the points surveyed and the location of the assessment sites; locations of the control points in both Oklahoma State Plane (NAD83-South Zone) coordinates and geodetic coordinates (Lat/Long – Decimal Degrees); a summary of the channel morphology including the bankfull width, the mean bankfull depth, the maximum bankfull depth, the flood prone area width, the bankfull area, the entrenchment ratio, the width to depth ratio, the sinuosity, the slope, the bed material, the Rosgen stream type, and the channel evolution stage; the stream channel stability data for the site that includes the scores and ratings of the various erosion indices (CSI, Pfankuch, BEHI, NBS and OEBSI) for each of the four assessment locations at the site; a cross-section of the site showing the ground, the water surface, the bankfull level and the flood prone area level; and a longitudinal profile plot showing the thalweg, the water surface, the location of the cross-section and surveyed points at the bankfull level and on top of the left and right banks.

Photographs of the sites are also taken at the time of the survey. Photographs are taken of both banks and facing upstream and downstream at the cross-section and of the study bank and facing upstream and downstream at the assessment sites. Photographs of the sites surveyed thus far are provided in Appendix C.

The results thus far are not surprising. They show a channel that is entrenched, with a Rosgen classification of F5 and G5c, and getting wider and deeper, with a channel evolution stage of IV. Practically every metric at every site assessed indicates that the channel is unstable or highly unstable with high to extreme near bank stress. Three other sites have been surveyed but the data has not yet been processed for inclusion in this report.

Development of discharge and sediment rating curves for the Little River watershed

The first information required to develop rating curves is a record of stage and discharge. As described above, the stage is being determined every thirty minutes using HOBO water level loggers deployed at seven sites as shown previously in Figure 6. At each of the sites, 18” x ½” iron pins were placed on both sides of the channel and the channel cross-section was surveyed. The elevations of the HOBOs were surveyed relative to the re-bar markers on the left banks.

Plots of the cross-sections, information on the HOBO deployments and aerial photographs of the rating curve sites, are provided in Appendix D. The depth and elevation of the HOBO is based on the elevation of the left pin, which is provided either as a reference elevation or a true elevation, if it has been determined. Two sites, the Little River at 60th and Hog Creek have staff gauges installed and at these sites the datum for the staff gauge was also surveyed relative to the left pin. The aerial photographs show the location of the cross-section and HOBO.

The dates that the HOBOs were deployed at the study sites are provided in Table 2. Plots of the stages recorded for each station, extending from the date of deployment through March 22, 2011 are provided in Appendix E. Perhaps, the most notable feature of the plots is the lack of peaks after September 2010. This is most pronounced at Rock Creek (Figure E-4). Another noteworthy feature is the rise in stage at Elm Creek (Figure E-5) beginning in October 2010. This perplexed the researchers prompting an investigation downstream, which revealed a newly constructed beaver dam that has since seemed to have fallen in disrepair. The last feature of note is the missing data at the Little River at 60th (Figure E-1) in May and August 2010. This occurred due to an error in logging the data. This highlights the necessity of diligence when logging the data and of logging the data at a frequency not to exceed a month.

Table 2: HOBO Deployment Dates

Site	Date
Little River @ 60th	3/6/2010
Hog Creek	3/29/2010
North Fork	3/29/2010
Rock Creek	3/29/2010
Elm Creek	3/26/2010
Dave Blue Creek	4/16/2010
Little River @ Porter	4/16/2010

The discharge has been measured multiple times at each site using the Marsh McBirney Flo-Mate, and multiple times at the Little River at 60th using the ADCP. Unfortunately, discharge has not been measured for larger flow events, due to a lack of precipitation. Plots of Stage versus Discharge for the sites are provided in Appendix F. The coefficient of determination (r^2) is somewhat low for the Little River at 60th, 0.545, fairly good for the Little River at Porter, 0.778, and good at the other sites, ranging from 0.845 to 0.969. The plots are not complete however because of a lack of measurements at higher discharges. This will be remedied in the coming months, provided the weather cooperates.

A few comparisons have been made between discharge measurements taken with the ADCP and measurements taken with the March McBirney. Measurements were taken at Site S01 the Little River at 60th. Table 3 shows the results of those measurements. The comparisons range from very good to very poor. Comparisons were also made between the measurements taken with the ADCP and the reported discharge from an active USGS gauge station. The gauge station used for the comparison was USGS Gauge Number 07240000, the Lake Hefner Canal. The results of those measurements are shown in Table 4.

There are a couple of potential reasons for the inconsistent performance of the ADCP including; operator error, which is very likely, as the investigators are still learning proper field protocol for using the equipment; instrument limitations, another likely reason, as the conditions under which the tests were conducted are near, or at, the limiting conditions in which the instrument will not operate, in that the advertised minimum depth for the 600 kHz Rio Grande is 0.7 meters (2.3 feet). More comparison tests are planned in the upcoming months.

Table 3: Discharge Measurement Comparison between Teledyne RDI Rio Grande 600 and Marsh McBirney Flo-Mate

Date	Mean Depth	ADCP	Marsh McBirney	ADCP % Diff.	Number of Measurements
7/9/2010	2.88	69.80	69.98	-0.3%	10 ADCP; 1 MMB
7/9/2010	2.95	68.49	69.98	-2.1%	10 ADCP; 1 MMB
7/10/2010	2.75	31.78	28.48	11.6%	10 ADCP; 5 MMB
7/10/2010	2.77	31.89	26.31	21.2%	10 ADCP; 4 MMB
7/12/2010	2.83	64.62	60.84	6.2%	10 ADCP; 9 MMB
7/13/2010	2.97	63.79	51.50	23.9%	10 ADCP; 5 MMB
7/13/2010	2.89	55.45	49.89	11.1%	10 ADCP; 5 MMB

Table 4: Discharge Measurement Comparison between Teledyne RDI Rio Grande 600 and USGS Gauge 07240000 - Lake Hefner Canal

Date	Mean Depth	ADCP	USGS GAUGE	ADCP % Diff.	Number of Measurements
10/1/2010	2.80	21.90	27	-18.9%	10 ADCP
10/1/2010	2.71	21.95	27	-18.7%	10 ADCP
10/28/2010	2.80	84.37	82	2.9%	11 ADCP
10/28/2010	2.80	85.47	82	4.2%	10 ADCP
10/28/2010	2.80	90.17	82	10.0%	10 ADCP
10/28/2010	2.80	89.27	82	8.9%	10 ADCP

Sediment monitoring has yet to be conducted, with the exception of a few samples collected to practice the methods of collection and analysis being used in the study. Comparisons of ADCP results with traditional methods therefore, have not been conducted. A rainy season, or even a couple of severe events, will change that.

Development of a frequency-duration curve for the Little River watershed

Development of frequency-duration curves, as described earlier, is being conducted using Vflo, calibrated to the hydrographs obtained from the study sites, to develop "historical" long term hydrographs, from which the required curves can be constructed. However, the required hydrographs have not been fully developed due to a lack of high flow measurements and the subsequent lack of sufficient discharge rating curves. Nevertheless, the methods described above were tested using data from Rock Creek and rainfall records from July 3rd and 4th, 2010. The Vflo model was calibrated by adjusting model parameters, primarily the imperviousness, which was set to 40 percent at the upper end of Rock Creek with its value decreasing downstream. A plot of the model calibration is provided in Figure 8. The red line is from the site hydrograph generated by the HOBOs and the discharge rating curve and the black line is the model output. Note that the calibration focused on the timing of the event and not the peak discharge, which is questionable due to the incomplete rating curve. Nevertheless, the output shows that the Vflo model can be effectively used to generate a representative hydrograph. More work remains to be done after more validation data has been collected.

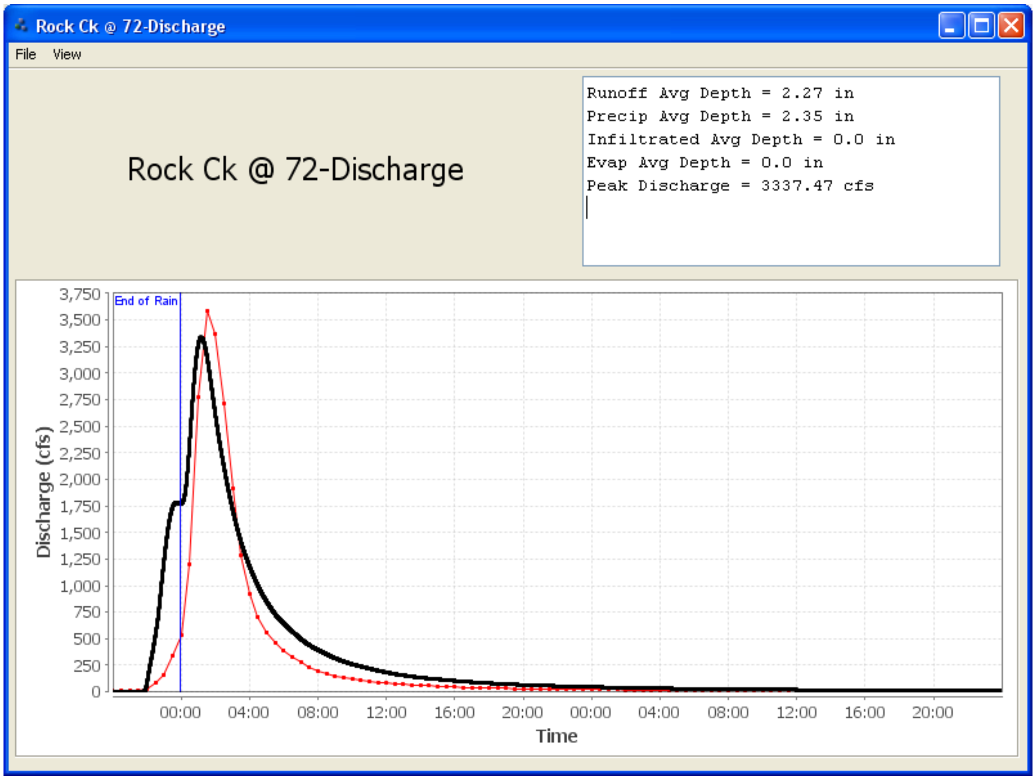

Figure 8: Vflo Calibration Plot for Rock Creek – July 3 and 4, 2010

Estimation of the annual and long-term sediment load to Lake Thunderbird

This work cannot be completed until the previous work is accomplished.

Estimation of the amount of expected channel degradation for the Little River

Early indications are that the channel has incised at least six feet over the last couple of decades but final estimation of the amount of anticipated channel degradation remains to be determined.

Potential recommendations for stopping or slowing the expected channel degradation

Due to the incomplete status of the project, recommendations for stopping or slowing the expected channel degradation cannot be made at this time.

Development of sediment loading rates estimation protocol

Due to the incomplete status of the project, a protocol for estimating sediment loading rates has yet to be developed, although development of such protocol remains a primary objective of the study.

The significance of the study is yet to be determined, but already it has provided data on the hydrology of the Lake Thunderbird watershed, in the form of a year's worth of stage data on the major tributaries to the lake. When the rating curves are complete this will provide a record of the discharge to the lake that would not have been developed without the current research, and the HOBOs will be maintained and continue to provide data as long as the researchers are physically capable of doing it. The FGM study is providing detailed information on the morphology of the Little River, which will provide a baseline for future researchers and could be extremely significant if they wanted to look at changes to the channel morphology over time, perhaps due to increased development or climate change. Without a baseline with which to compare, these studies would not be possible. The sediment data to be collected in the study will be invaluable. The samples being collected to validate the effectiveness of the ADCP will provide data that would not have been available without the funding of this project, and if the ADCP is proven to be an effective means of measuring both discharge and sediment, it would be a very significant contribution to science and would be beneficial to many fields of study.

The use of ADCPs for measuring discharge is fairly established. The use of ADCPs to measure sediment is a newly emerging field, a fact that became apparent at the 2011 USGS Surface-Water Conference and Hydroacoustics Workshop in Tampa, Florida. This project, though incomplete at this point, will continue until it addresses each of the stated objectives, and when complete, will add significantly to the research in the field.

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Appendix A – Example of FGM Assessment Forms

Bank Erosion Hazard Index (BEHI)									
Site No.	LR-02	Site Name:	Little River - LR Ranc		Bank No.:	1	Date:	12/17/2010	
									BEHI Score
								Bank Height/ Bankfull Height (C)	
		Bank Height (ft) (A)	24.1	Bankfull Ht (ft) (B)	15.1		(C) = (A)/(B) =	1.596026	7
								Root Depth / Bank Height (E)	
		Root Depth (ft) (D)	10	Bank Height (ft) (A)	24.1		(E) = (D)/(A) =	0.414938	5
								Weighted Root Density (G)	
				Root Density (%) (F)	10		(G) = (F) x (A) =	4.149378	10
								Bank Angle (H)	
						Bank Angle (Degrees) (H)		57.93226	4
						Surface Protection (I)			
						Surface Protection (%) (I)		5	10
Bank Material Adjustment									
Bedrock (Overall very low BEHI)						Bank Material Adjustment			0
Boulders (Overall very low BEHI)									
Cobble (Subtract 10 pts. If uniform med. to lrg. Cobble)									
Gravel or Composite (Add 5-10 pts depending on percentage of bank material composed of sand)						Stratifiaction Adjustment			
Sand (Add 10 points)						Add 5-10 points depending on position of unstable layers in relation to bankfull stage			5
Silt/Clay (No adjustment)									
Very Low	Low	Moderate	High	Very High	Extreme		Adjective Rating and Total Score		41
5-9.5	10-19.5	20-29.5	30-39.5	40-45	46-50				Very High

Figure A-1: Example Bank Erosion Hazard Index (BEHI) Form

Near-Bank Stress (NBS)							
Site No.	LR-02	Site Name:	Little River - LR Ranch		Bank No.:	1	Date: 12/17/2010
Stream Type:	E5	Valley Type:	X				

Methods for estimating Near-Bank Stress (NBS)		
(1) Channel pattern, transverse bar or split channel/central bar creating NBS	**Level I**	**Reconaissance**
(2) Ratio of radius of curvature to bankfull width (R_c/W_{bkf})	**Level II**	**General prediction**
(3) Ratio of pool slope to average water surface slope (S_p/S)	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p/S_r)	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb}/d_{bkf})	**Level III**	**Detailed prediction**
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb}/τ_{bkf})	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient	Level IV	Validation

Level	Method			
Level I	**(1)**	Transverse and/or central bars-short and/or discontinuous	NBS =	High / Very High
		Extensive deposition (continuous, cross-channel)	NBS =	Extreme
		Chute cutoffs, down-valley migration, converging flows	NBS =	Extreme

Level	Method				
Level II	**(2)**	Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	Ratio R_c/W_{bkf}	Near-Bank Stress (NBS)
		66.569679	52.5	1.2679939	**Extreme**
	(3)	Pool Slope S_p	Average Slope S	Ratio S_p/S	Near-Bank Stress (NBS)
		***	***	***	***
	(4)	Pool Slope S_p	Riffle Slope S_r	Ratio S_p/S_r	Near-Bank Stress (NBS)
		***	***	***	***
Level III	**(5)**	Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	Ratio d_{nb}/d_{bkf}	Near-Bank Stress (NBS)
		4.5	4.197547	1.0720548	**Low**

Dominant Near-Bank Stress
Extreme

Level	Method								
Level III	**(6)**	Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb}/τ_{bkf}	Near-Bank Stress (NBS)
		***	***	***	***	***	***	***	***

Level	Method		
Level IV	**(7)**	Velocity Gradient (ft/sec/ft)	Near-Bank Stress (NBS)
		***	***

Converting values to a Near-Bank Stress (NBS) rating							
Near-Bank Stress (NBS) ratings	**Method number**						
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
Very Low	N/A	> 3.00	<0.20	<0.40	<1.00	<0.80	<0.50
Low	N/A	2.21-3.00	0.20-0.40	0.41-0.60	**1.00-1.50**	0.80-1.05	0.50-1.00
Moderate	N/A	2.01-2.20	0.41-0.60	0.61-0.80	1.51-1.80	1.06-1.14	1.01-1.60
High	See	1.81-2.00	0.61-0.80	0.81-1.00	1.81-2.50	1.15-1.19	1.61-2.00
Very High	(1)	1.50-1.80	0.81-1.00	1.01-1.20	2.51-3.00	1.20-1.60	2.01-2.40
Extreme	Above	**<1.50**	>1.00	>1.20	>3.00	>1.60	>2.40
	Overall Near-Bank Stress (NBS) rating					**Extreme**	

Figure A-2: Example of Near Bank Stress (NBS) Form

Channel Stability Index

Site No.	LR-02	Site Name:	Little River - LR Ranch	Bank No.:	1	Date:	12/17/2010
Pictures (circle)	Upstream	Downstream	Cross-Section	**Slope:**	1.92	**Pattern:**	Meandering
							Shallow curve
							Straight

1. Primary bed material

	Bedrock	Boulder/ Cobble	Gravel	Sand	Silt/Clay	Value
	0	1	2	**3**	4	3

2. Bed/bank protection

	Yes	No	(with)	1 bank protected	2 banks protected	Value
	0	**1**		2	3	1

3. Degree of incision (Relative elev. of "normal" low water; floodplain/terrace @ 100%)

	0-10%	11-25%	26-50%	51-75%	76-100%	Value
	4	**3**	2	1	0	3

4. Degree of constriction (Relative decrease in top-bank width from up to downstream)

	0-10%	11-25%	26-50%	51-75%	76-100%	Value
	0	1	2	**3**	4	3

5. Streambank erosion (Each bank)

	None	Fluvial	Mass wasting (failures)	Value
Left	0	**1**	2	1
Right	**0**	1	2	0

6. Streambank instability (Percent of each bank failing)

	0-10%	11-25%	26-50%	51-75%	76-100%	Value
Left	0	0.5	1	1.5	**2**	2
Right	**0**	0.5	1	1.5	2	0

7. Established riparian woody-vegetative cover (Each bank)

	0-10%	11-25%	26-50%	51-75%	76-100%	Value
Left	**2**	1.5	1	0.5	0	2
Right	2	**1.5**	1	0.5	0	1.5

8. Occurrence of bank accretion (Percent of each bank with fluvial deposition)

	0-10%	11-25%	26-50%	51-75%	76-100%	Value
Left	**2**	1.5	1	0.5	0	2
Right	2	1.5	1	0.5	**0**	0

9. Stage of channel evolution

I	II	III	IV	V	VI	Value
0	1	2	**4**	3	1.5	4

TOTAL CHANNEL STABILITY INDEX (CSI)		**22.5**
CSI ≤10	STABLE	
10 < CSI < 20	MODERATELY UNSTABLE	
CSI ≥ 20	HIGHLY UNSTABLE	**HIGHLY UNSTABLE**

Figure A-3: Example of Channel Stability Index (CSI) Form

Ozark Eco-Region Bank Stability Index (OEBSI)

Site No.	LR-02	Site Name:	Little River - LR Ranch	Bank No.:	1	Date:	12/17/2010

0. Most Unstable Bank (circle one): **Left** Right

Bank Height, BH (ft):	24.1			
Bank Face Length, FL (ft):	15.1			
Reach Length Upstream of Cross Section, L_u (ft):		225.06562		
Reach Length Downstream of Cross Section, L_d (ft):		221.78478		
Coordinates of Cross Section:	Lat:	35.280115	Long:	97.367392

Metrics at Representative Cross Section

1. Bank Height (ft):

0-5	5-10	10-15	15-20	20+	Value
0	2.5	5	7.5	**10**	10

Notes:

2. Bank AngleDeg.)

	0-20°	21-60°	61-80°	81-90°	91-119°	>119°	
BH/FL=	(0.00-0.34)	(0.35-0.86)	(0.87-0.98)	(0.99-1.0)	(0.87-0.99)	(<0.87)	Value
	0	**2**	4	6	8	10	2

Notes:

3. Percentage of Bank Height with a Bank Angle Greater than 80°:

0-10%	11-25%	26-50%	51-75%	76-100%	Value
0	2.5	**5**	7.5	10	5

Notes:

Metrics for Entire Reach Length

4. Evidence of Mass Wasting (percentage of Bank):

0-10%	11-25%	26-50%	51-75%	76-100%	Value
0	2.5	5	7.5	**10**	10

Notes:

5. Unconsolidated Material (Percentage of Bank)

0-10%	11-25%	26-50%	51-75%	76-100%	Value
0	2.5	5	7.5	10	0

Notes:

6. Streambank Protection (Percentage of Streambank Covered by Plant Roots, Vegetation, Downed Logs and Branches, Rocks, etc.)

0-10%	11-25%	26-50%	51-75%	76-90%	91-100%	Value
15	12.5	10	7.5	2.5	0	15

Notes:

7. Established Beneficial Riparian Woody-Vegetation Cover:

0-10%	11-25%	26-50%	51-75%	76-90%	91-100%	Value
15	12.5	10	7.5	2.5	0	15

Notes:

8. Stream Curvature:

Meander	Shallow Curve	Straight	Value
5	2.5	0	5

TOTAL SCORE **62** Current Stability: **Highly Unstable**

0-25: Highly Stable	26-40: Stable	41-55: Unstable	56-85: Highly Unstable

Figure A-4: Example of Ozark Eco-Region Bank Stability Index (OEBSI) Form

Figure A-5: Example of Pfankuch Stream Stability Form

Pfankuch Stream Stability

Site No:	LR-02	Site Name:	Little River - LR Ranch	Bank No.:	1	Date:	12/17/2010

Location	Key	Category	Excellent Description	Rating	Good Description	Rating	Fair Description	Rating	Poor Description	Rating
Upper Banks	1	Landform slope	Bank slope gradient < 30%	2	Bank slope gradient 30-40%	4	Bank slope gradient 40-60%	6	Bank slope gradient >60%	8
	2	Mass erosion	No evidence of past or future mass erosion	3	Infrequent. Mostly healed over. Low future potential.	6	Frequent or large, causing sediment nearly year long	9	Frequent or large, causing sediment nearly year long OR imminent danger of same.	12
	3	Debris jam potential	Essentially absent from immediate channel area.	2	Present, but mostly small twigs and limbs.	4	Moderate ot heavy amounts, mostly larger sizes.	6	Moderate ot heavy amounts, predominantly larger sizes.	8
	4	Vegetative bank protection	> 90% plant density. Vigor and variety suggest a deep, dense soil-binding root mass.	3	70-90% density. Fewer species or less vigor suggest less dense or deep root mass.	6	50-70% density. Lower vigor and fewer species from a shallow, discontinuous root mass.	9	<50% density plus fewer species & less vigor indicating poor, discontinuous and shallow root mass.	12
Lower Banks	5	Channel capacity	Bank heights sufficient to contain the bankfull stage. W/D ratio departure from reference W/D ratio =1.0. Bank Height Ratio (BHR) =1.0	1	Bankfull stage is contained within banks. W/D ratio departure from reference W/D ratio = 1.0-1.2. Bank Height Ratio (BHR) = 1.0-1.1	2	Bankfull stage is not contained. W/D ratio departure from reference W/D ratio = 1.2-1.4. Bank Height Ratio (BHR) = 1.1-1.3.	3	Bankfull stage is not contained. Over bank flows are common with flows less than bankfull. W/D ratio departure from reference W/D ratio >1.4. Bank Height Ratio (BHR) >1.3.	4
	6	Bank rock content	>65% with large angular boulders. 12" common	2	40-65% cobbles and small boulders. 6-12"	4	20-40%. Most in the 3-6" class	6	<20% rock fragments of gravel sizes, 1-3" or less.	8
	7	Obstructions to flow	Rocks and logs firmly imbedded. Flow pattern w/o cutting or deposition. Stable bed.	2	Some present causing erosive cross currents and minor pool filling. Obstructions fewer and less firm.	4	Moderately frequent, unstable obstructions move with high flows causing bank cutting and pool filling.	6	Frequent obstructions and deflectors cause bank erosion yearlong. Sediment traps full, channel migration occurring.	8
	8	Cutting	Little or none. Infrequent raw banks <6"	4	Some, intermittently at outcurves and constrictions. Raw banks may be up to 12"	6	Significant. Cuts 12-24" high. Root mat overhangs and sloughing evident	12	Almost continuous cuts, some over 24" high. Failure of overhangs frequent.	16
	9	Deposition	Little or no enlargement of channel or point bars	4	Some new bar increase, mostly from coarse gravel.	8	Moderate deposition of new gravel and coarse sand on old and some new bars.	12	Extensive deposit of predominantly fine particles. Accelerated bar development.	16
Bottom	10	Rock angularity	Well rounded in all dimensions, surfaces smooth.	1	Corners and edges well rounded in 2 dimensions	2	Rounded corners and edges. Surface smooth and flat.	3	Sharp edges and corners. Plane surfaces rough.	4
	11	Brightness	Surfaces dull dark or stained. Generally not bright	1	Mostly dull, but may have <35% bright surfaces	2	Mixture dull and bright, i.e., 35-65% mixture range	3	Predominantly bright, >65%, exposed or scoured surfaces.	4
	12	Consolidation of particles	Assorted sizes tightly packed or overlapping	2	Moderately packed with some overlapping	4	Mostly loose assortment with no apparent overlap.	6	No packing evident. Loose assortment, easily moved.	8
	13	Bottom size distribution	No size change evident. Stable material 80-100%	4	Distribution shift light. Stabel material 50-80%.	8	Moderate change in sizes. Stable materials 20-50%.	12	Marked distribution change. Stable materials 0-20%	16
	14	Scouring and deposition	<5% of bottom affected by scour and deposition.	6	5-30% affected. Scour at constrictions and where grades steepen. Some deposition in pools.	12	30-50% affected. Deposits and scour at obstructions and bends. Some filling of pools.	18	More than 50% of the bottom in a state of flux or change nearly yearlong.	24
	15	Aquatic vegetation	Abundant growth moss-like, dark green perennial. In swift water too.	1	Common. Algae forms in low velocity and pool areas. Moss here too.	2	Present but spotty, mostly in back water. Seasonal algae growth makes rocks slick.	3	Perennial types scarce or absent. Yellow-green, short-term bloom may be present.	4
			Excellent Total =	10	Good Total =	0	Fair Total =	6	Poor Total =	100

Stream Type	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	B6	C1	C2	C3	C4	C5	C6	D3	D4	D5	D6
Good (Stable)	38-43	38-43	54-90	60-95	50-80	50-80	38-45	38-45	40-60	40-64	48-68	40-60	38-50	38-50	60-85	70-90	70-90	60-85	85-107	85-107	85-107	67-98
Fair (mod. Unstable	44-47	44-47	91-129	96-132	81-110	81-110	46-58	46-58	61-78	65-84	69-88	61-78	51-61	51-61	86-105	91-110	91-110	86-105	108-132	108-132	108-132	99-125
Poor (unstable)	48+	48+	130+	133+	111+	111+	59+	59+	79+	85+	89+	79+	62+	62+	106+	111+	111+	106+	133+	133+	133+	126+

Stream Type	DA3	DA4	DA5	DA6	E3	E4	E5	E6	F1	F2	F3	F4	F5	F6	G1	G2	G3	G4	G5	G6
Good (Stable)	40-63	40-63	40-63	40-63	40-63	50-75	50-75	40-63	60-85	60-85	85-110	85-110	90-115	80-95	40-60	40-60	85-107	85-107	90-112	85-107
Fair (mod. Unstable	64-86	64-86	64-86	64-86	64-86	76-96	76-96	64-86	86-105	86-105	111-125	111-125	116-130	96-110	61-78	61-78	108-120	108-120	113-125	108-120
Poor (unstable)	87+	87+	87+	87+	87+	97+	97+	87+	106+	106+	126+	126+	131+	111+	79+	79+	121+	121+	126+	121+

Grand Total =	116
Existing Stream Type =	F5
Potential Stream Type =	E5

Channel Stability Rating	
Existing Stream	Fair-Mod. Unstable
Potential Stream	Poor-Unstable

Rating should be adjusted to potential stream type, not existing

Stream Bank Erosion Data Summary					
Site No.	LR-02	Site Name:	Little River - LR Ranch	Bank No.: 1	Date: 12/17/2010
Bank Location:	Latitude:	35.280115	Longitude:	97.367392	
REACH MORPHOLOGY					
Bankfull Width W_{bkf} (ft)	52.5		Mean Bankfull Depth, d_{bkf} (ft)	4.2	
Width of Flood Prone Area, (ft)	59.7		Max Bankfull Depth, d_{max} (ft)	5.4	
Width/Depth Ratio, W_{bkf}/d_{bkf}	12.507306		Entrenchment Ratio	1.1	
Stream Slope	0.0011		Sinuosity	1.9	
Existing Stream Type:	F5		Potential Stream Type:	E5	
Stage of channel evolution (I-VI)	IV				
BANK DATA					
Bank Height (ft)	24.1		Bank Angle (Deg)	57.9	
Bank Material	Silt		Bank Orientation (Right/Left)	Left	
Radius of Curvature Rc (ft)	66.6		Ratio Rc/Wbkf	1.27	
Mass Wasting (% of Bank):	100		Unconsolidated Matl (% of Bank)	0	
Bank Protection (% of bank)	5		Riparian Woody-Veg. Cover (%):	5	
STREAM BANK EROSION INDICES					
			Score	Stability Rating	
	Channel Stability Index (CSI)		22.5	HIGHLY UNSTABLE	
	Bank Erosion Hazard Index (BEHI)		41	Very High	
	Near Bank Stress (NBS)		***	Extreme	
	Pfankuch		116	Poor-Unstable	
	Ozark Eco-Region Bank Stability Index (OEBSI)		62	Highly Unstable	

Figure A-6: Example of Stream Bank Erosion Data Summary Form

Appendix B – FGM Site Summary Sheets

Site No.:	LR-02	Site Name:	Little River - 02

Legal Description:	SW 1/4, Sect. 1, T9N-R2W, Cleveland Co.
Drainage Area (mi²):	53.9

Cross Section Survey Control

OK State Plane NAD83, South Zone (U.S. Foot); NAVD88 (U.S. Foot)

Left Pin		*Right Pin*	
Name:	LR02-LT	Name:	LR02-RT
Easting:	2157712.814	Easting:	2157741.681
Northing:	709007.639	Northing:	708870.849
Elevation:	1062.15	Elevation:	1066.07

Geodetic Coordinates (Decimal Degrees)

Left Pin		*Right Pin*	
Lat. (N):	35.279874529	Lat. (N):	35.279498241
Long. (W):	97.366076193	Long. (W):	97.36598236

Channel Morphology Data

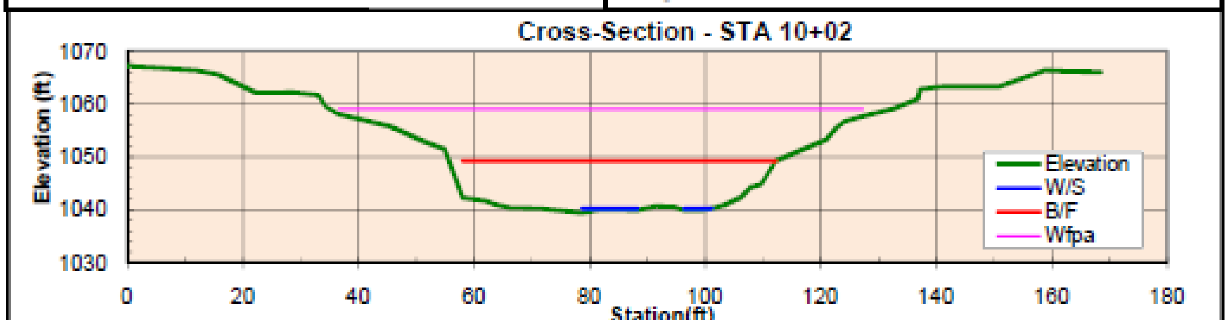
Bankfull Width (ft):	56.52
Mean Bankfull Depth (ft):	8.09
Maximum Bankfull Depth (ft):	9.78
Flood Prone Area Width (ft):	92.83
Bankfull Area (ft²):	457.52
Entrenchment Ratio:	1.64
Width/Depth Ratio:	6.98
Sinuosity:	1.92
Slope:	0.0011
Bed Material:	Sand

Rosgen Stream Type:
F5

Channel Evolution Stage:
IV

Stream Channel Stability Data

Bank No.	1	2	3	4
CSI Score:	22.5	22.5	24	25
Rating:	HIGHLY UNSTABLE	HIGHLY UNSTABLE	HIGHLY UNSTABLE	HIGHLY UNSTABLE
Pfankuch Score:	116	114	122	118
Rating:	Poor- Unstable	Poor- Unstable	Poor- Unstable	Poor- Unstable
BEHI Score:	41	34.5	34	37.5
Rating:	Very High	High	High	High
NBS Score:	***	***	***	***
Rating:	Extreme	Extreme	Low	Extreme
OEBSI Score:	62	62	65	69
Rating:	Highly Unstable	Highly Unstable	Highly Unstable	Highly Unstable



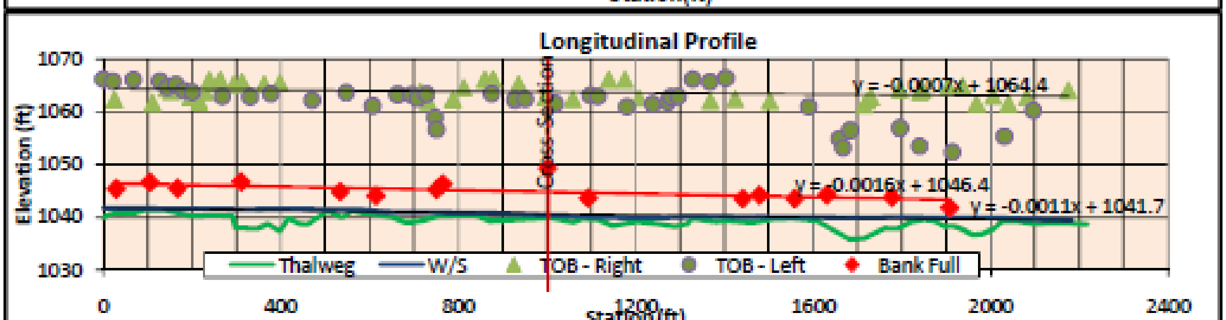


Figure B-1: Site Summary Sheet – Little River -02

Site No.:	LR-03	Site Name:	Little River - 03

Legal Description:	NW 1/4, Sect. 10, T9N-R2W, Cleveland Co.
Drainage Area (mi^2):	47.4

Cross Section Survey Control

OK State Plane NAD83, South Zone (U.S. Foot); NAVD88 (U.S. Foot)

Left Pin		*Right Pin*	
Name:	LR-03LT	Name:	LR-03RT
Easting:	2149376.872	Easting:	2149495.76
Northing:	707217.5692	Northing:	707184.9514
Elevation:	1081.0	Elevation:	1083.55

Geodetic Coordinates (Decimal Degrees)

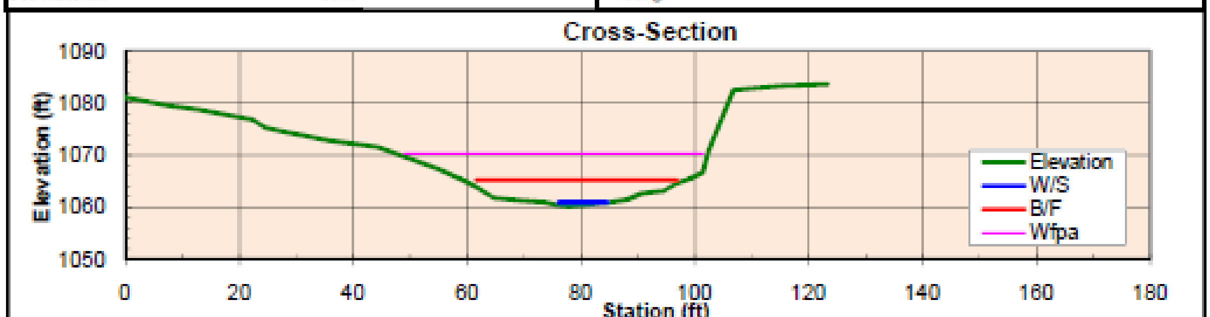
Left Pin		*Right Pin*	
Lat. (N):	35.275097464	Lat. (N):	35.275005895
Long. (W):	97.394039596	Long. (W):	97.39364197

Channel Morphology Data

Bankfull Width (ft):	39.10		
Mean Bankfull Depth (ft):	3.30		
Maximum Bankfull Depth (ft):	5.03		
Flood Prone Area Width (ft):	53.87		
Bankfull Area (ft^2):	128.90		
Entrenchment Ratio:	1.38	Rosgen Stream Type:	
Width/Depth Ratio:	11.86	G5c	
Sinuosity:	1.66	Channel Evolution Stage:	
Slope:	0.0009	IV	
Bed Material:	Sand		

Stream Channel Stability Data

Bank No.	1	2	3	4
CSI Score:	22.5	27	25	20.5
Rating:	Highly unstable	Highly unstable	Highly unstable	Highly unstable
Pfankuch Score:	116	99	109	99
Rating:	Poor-Unstable	Poor-Unstable	Poor-Unstable	Poor-Unstable
BEHI Score:	41	35.5	35.5	28.5
Rating:	Very High	High	High	Moderate
NBS Score:	***	***	***	***
Rating:	Extreme	Moderate	High	High
OESBI Score:	62	77	52	57
Rating:	Highly unstable	Highly unstable	Unstable	Highly unstable



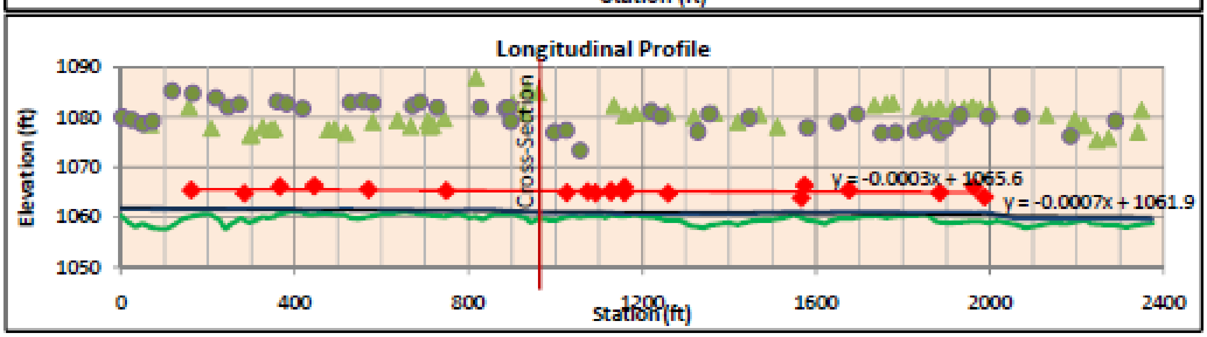


Figure B-2: Site Summary Sheet – Little River -03

Appendix C – FGM Site Photographs

Cross Section Photographs

Figure 1: LR-02 Cross Section - Facing upstream.

Figure 2: LR-02 Cross Section - Facing downstream.

Figure 3: LR-02 Cross Section - Left Bank.

Figure 4: LR-02 Cross Section - Right Bank.

Figure C-1: Cross-Section Photographs at LR-02

Assessment Banks Photographs

Figure 5: LR-02 Bank 1 - Bank

Figure 8: LR-02 Bank 2 - Bank

Figure 6: LR-02 Bank 1 - Facing upstream

Figure 9: LR-02 Bank 2 - Facing upstream

Figure 7: LR-02 Bank 1 - Facing downstream

Figure 10: LR-02 Bank 2 - Facing downstream

Figure C-2: Assessment Site Photographs at LR-02

Assessment Banks Photographs

Figure 11: LR-02 Bank 3 - Bank

Figure 12: LR-02 Bank 3 - Facing upstream

Figure 13: LR-02 Bank 3 - Facing downstream

Figure 14: LR-02 Bank 4 - Bank

Figure 15: LR-02 Bank 4 - Facing upstream

Figure 16: LR-02 Bank 4 - Facing downstream

Figure C-3: Assessment Site Photographs at LR-02 (Cont.)

Cross Section Photographs

Figure 1: LR-03 Cross Section - Facing upstream.

Figure 2: LR-03 Cross Section - Facing downstream.

Figure 3: LR-03 Cross Section - Left Bank.

Figure 4: LR-03 Cross Section - Right Bank.

Figure C-4: Cross-Section Photographs at LR-03

Assessment Banks Photographs

Figure 5: LR-03 Bank 1 - Bank

Figure 8: LR-03 Bank 2 - Bank

Figure 6: LR-03 Bank 1 - Facing upstream

Figure 9: LR-03 Bank 2 - Facing upstream

Figure 7: LR-03 Bank 1 - Facing downstream

Figure 10: LR-03 Bank 2 - Facing downstream

Figure C-5: Assessment Site Photographs at LR-03

Assessment Banks Photographs

Figure 11: LR-03 Bank 3 - Bank

Figure 14: LR-03 Bank 4 - Bank

Figure 12: LR-03 Bank 3 - Facing upstream

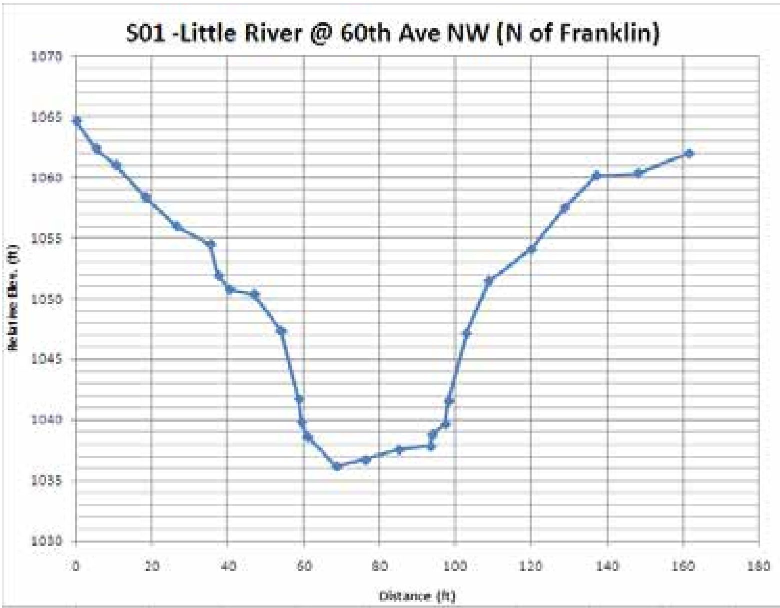
Figure 15: LR-03 Bank 4 - Facing upstream

Figure 13: LR-03 Bank 3 - Facing downstream

Figure 16: LR-03 Bank 4 - Facing downstream

Figure C-6: Assessment Site Photographs at LR-03 (Cont.)

Appendix D –Rating Curve Site Information



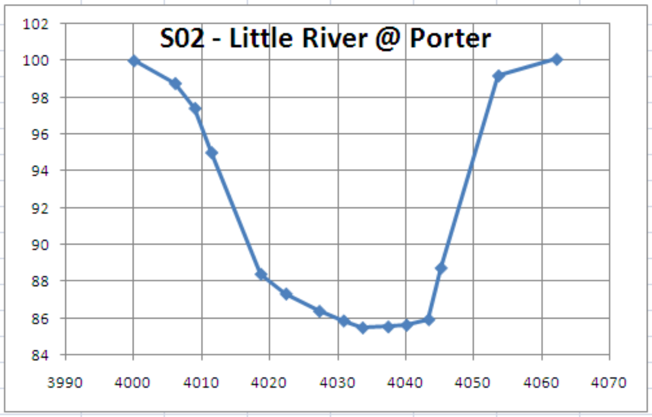
HOBO Deployment Information

Site ID:	S01
Site Name:	Little River @ 60th
Date:	3/6/2010
Time:	?
HOBO Depth:	1.23
Staff Gauge Rdg.:	2.16

BS(+)	HI	FS(-)	Elev.	Comment
6.99	1071.61		1064.62	Lt. Pin
		32.75	1038.86	W/S Elev @ HOBO

HOBO Elev.:	1037.63
Staff Gauge 0 Elev.:	1036.70

Figure D-1: Rating Curve Site Information – S01 – Little River @ 60th



HOBO Deployment Information

Site ID:	S02
Site Name:	Little River @ Porter
Date:	4/16/2010
Time:	1115
HOBO Depth:	0.7
Staff Gauge Rdg.:	NA

BS(+)	HI	FS(-)	Elev.	Comment
4.36	104.36		100.00	Lt. Pin
		17.85	86.51	W/S Elev @ HOBO

HOBO Elev.:	85.81
Staff Gauge 0 Elev.:	NA

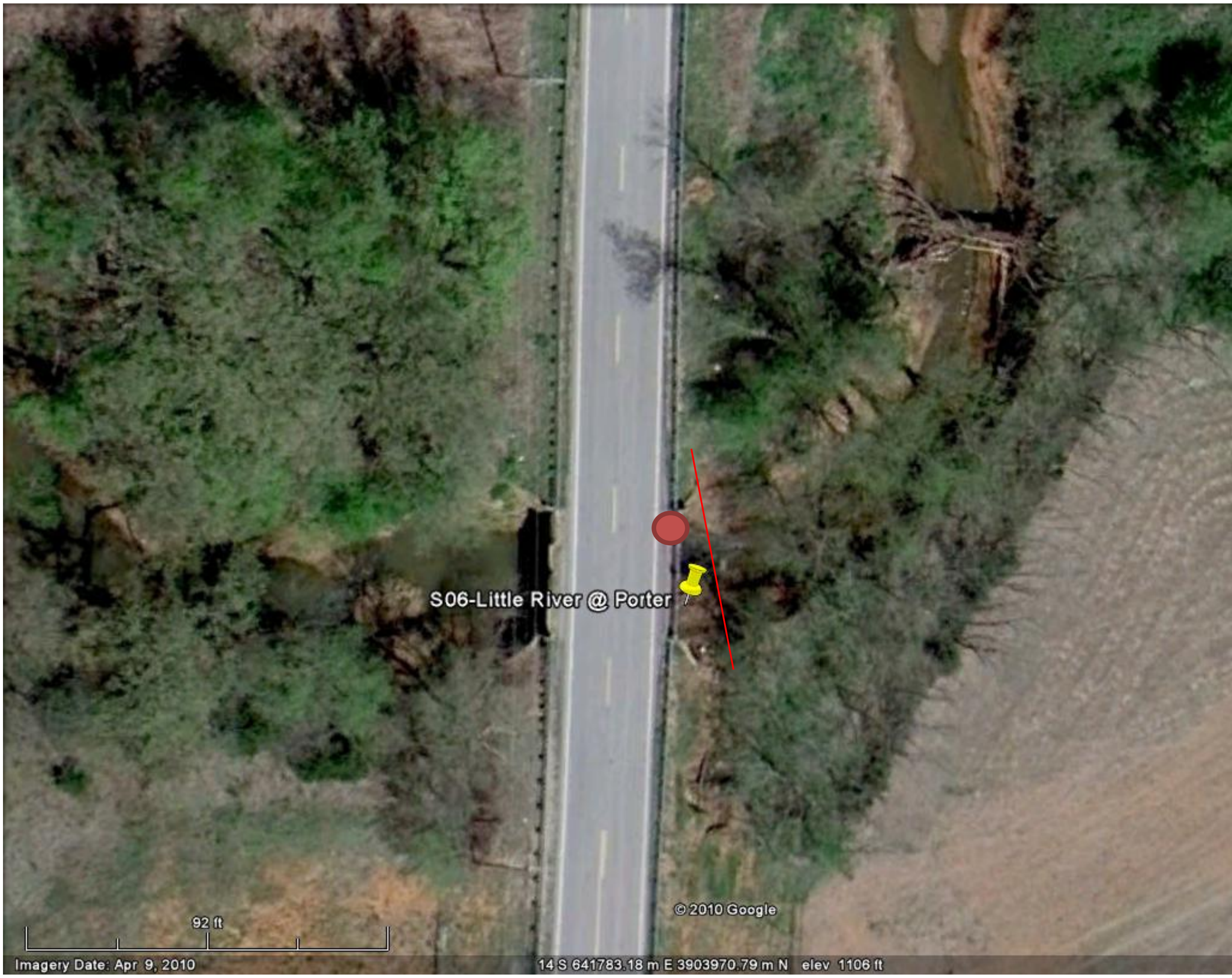
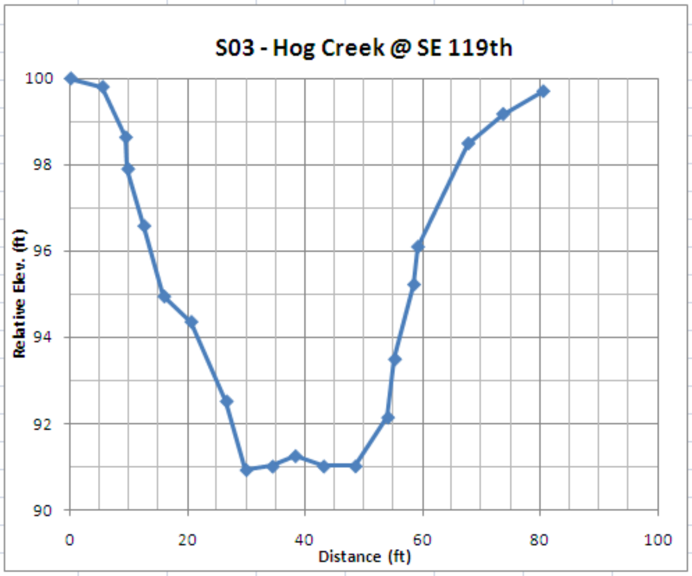


Figure D-2: Rating Curve Site Information – S02 – Little River @ Porter



HOBO Deployment Information

Site ID:	S03
Site Name:	Hog Creek
Date:	3/29/2010
Time:	
HOBO Depth:	0.78
Staff Gauge Rdg.:	1.02

BS(+)	HI	FS(-)	Elev.	Comment
9.88	109.88		100.00	Lt. Pin
		17.31	92.57	W/S Elev @ HOBO

HOBO Elev.:	91.79
Staff Gauge 0 Elev.:	91.55

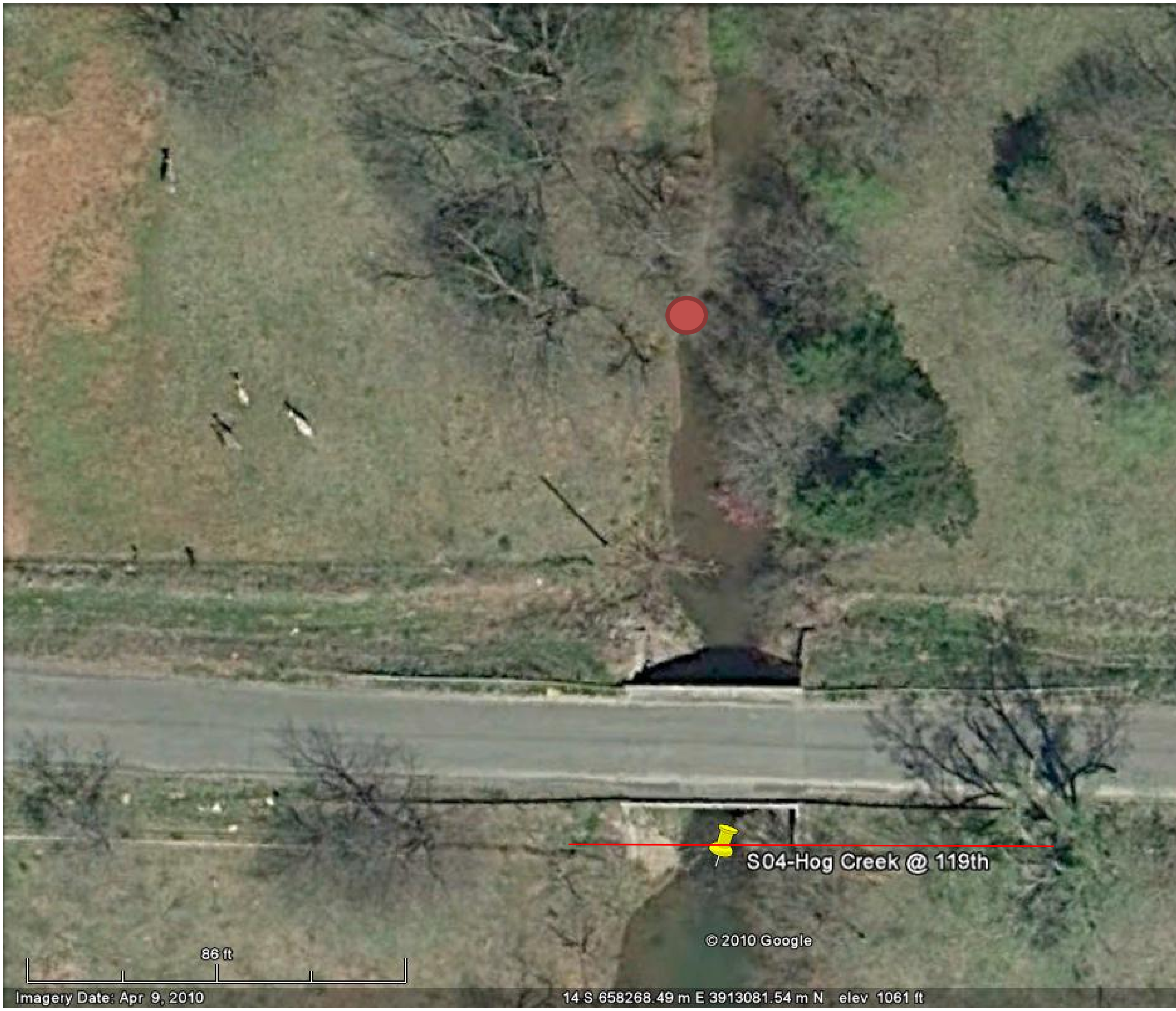
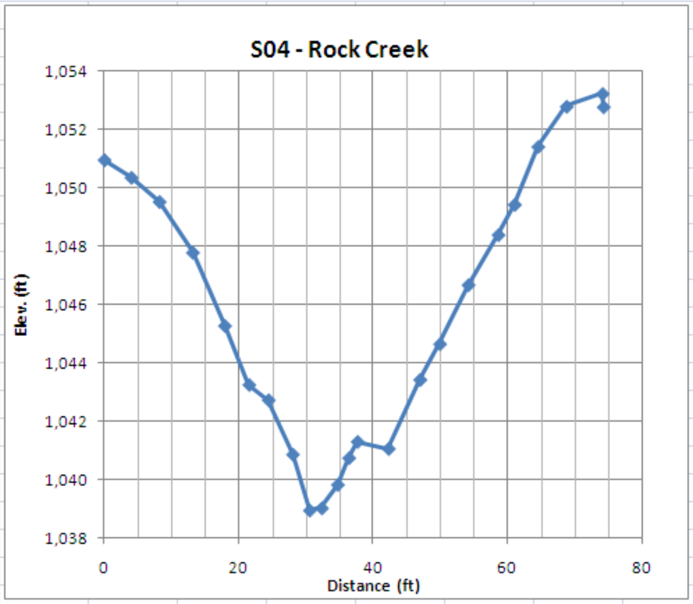


Figure D-3: Rating Curve Site Information – S03 – Hog Creek @ SE 119th



HOBO Deployment Information

Site ID:	S04
Site Name:	Rock Creek
Date:	3/29/2010
Time:	
HOBO Depth:	0.83
Staff Gauge Rdg.:	NA

BS(+)	HI	FS(-)	Elev.	Comment
4.52	1055.49		1050.97	Lt. Pin
		14.81	1040.68	W/S Elev @ HOBO

HOBO Elev.:	1039.85
Staff Gauge 0 Elev.:	NA

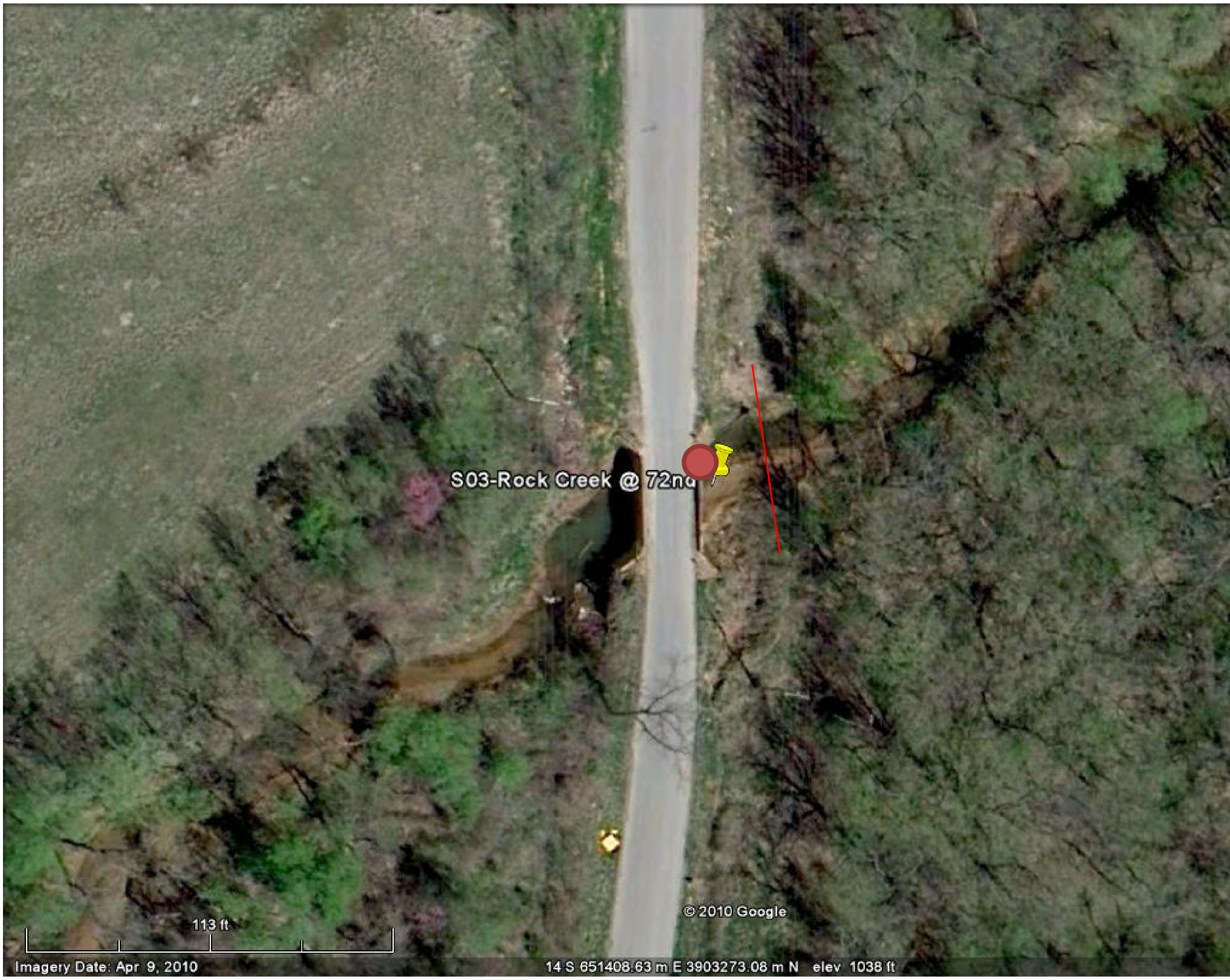
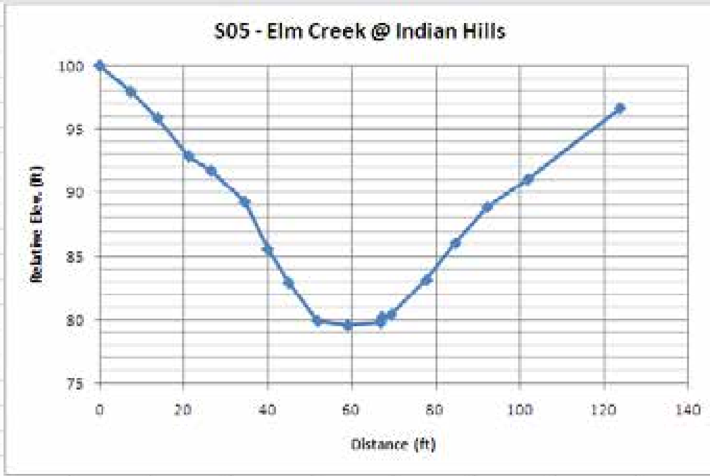


Figure D-4: Rating Curve Site Information – S04 – Rock Creek @ 72nd



HOBO Deployment Information

Site ID:	S05
Site Name:	Elm Creek
Date:	4/16/2010
Time:	1115
HOBO Depth:	0.68
Staff Gauge Rdg.:	NA

BS(+)	HI	FS(-)	Elev.	Comment
4.36	104.36		100.00	Lt. Pin
		17.85	86.51	W/S Elev @ HOBO

HOBO Elev.:	85.83
Staff Gauge 0 Elev.:	NA

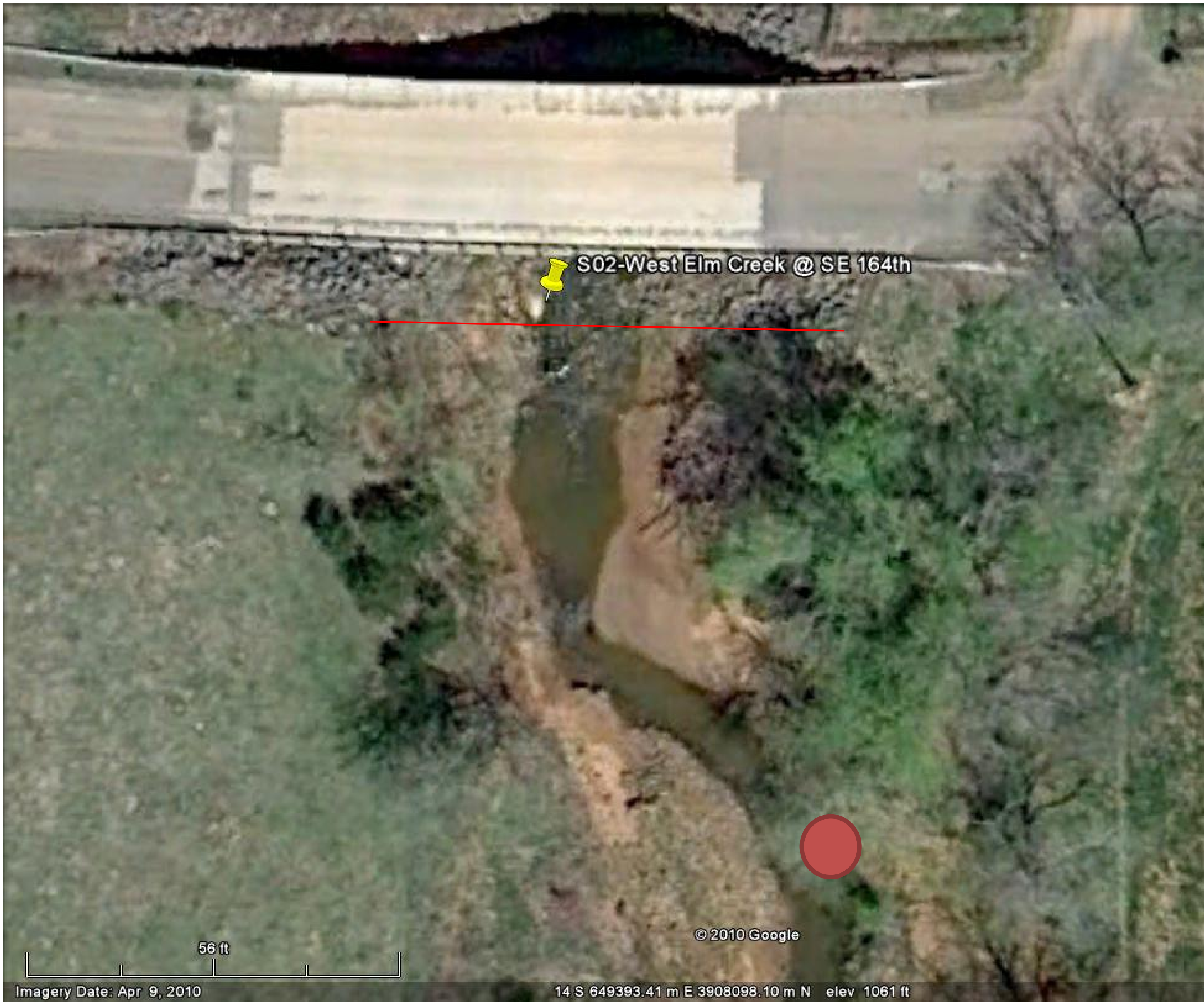
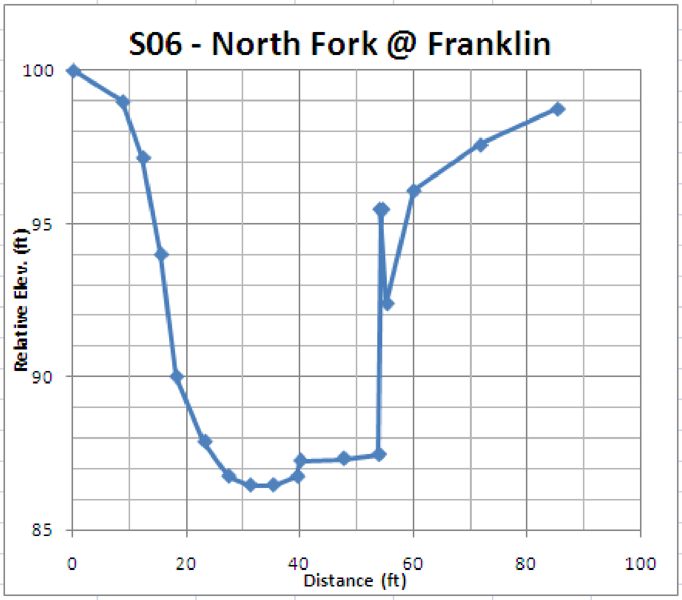


Figure D-5: Rating Curve Site Information – S05 – Elm Creek @ Indian Hills



HOBO Deployment Information

Site ID:	S06
Site Name:	North Fork @ Franklin
Date:	3/29/2010
Time:	
HOBO Depth:	0.77
Staff Gauge Rdg.:	NA

BS(+)	HI	FS(-)	Elev.	Comment
2.47	102.47		100.00	Lt. Pin
		18.73	83.74	W/S Elev @ HOBO

HOBO Elev.:	82.97
Staff Gauge 0 Elev.:	NA

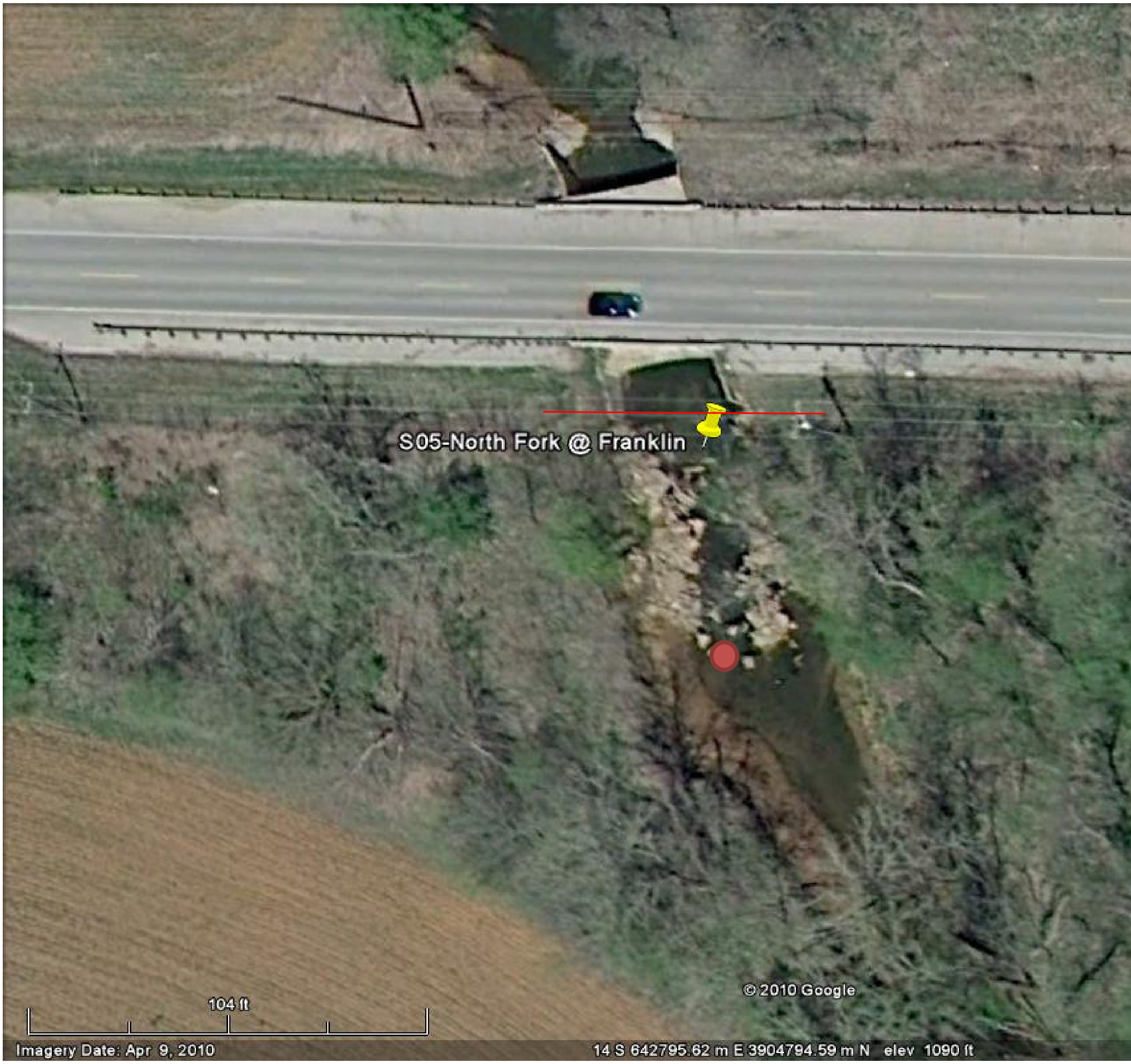
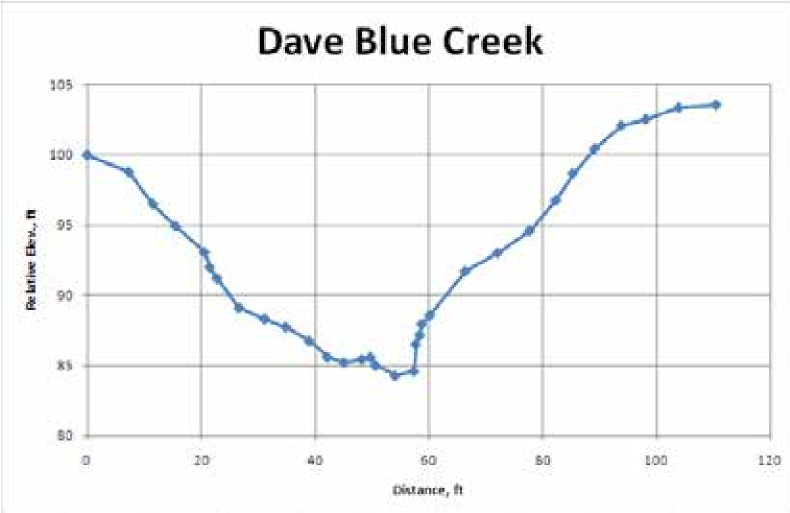


Figure D-6: Rating Curve Site Information – S06 – North Fork @ Franklin



HOBO Deployment Information

Site ID: 507
Site Name: Dave Blue Creek @ 72nd
Date: 4/16/2010
Time: 1210
HOBO Depth: 0.63
Staff Gauge Rdg.: NA

BS(+)	HI	FS(-)	Elev.	Comment
2.37	102.37		100.00	Lt. Pin
		16.63	85.74	W/S Elev @ HOBO

HOBO Elev.: 85.11
Staff Gauge 0 Elev.: NA

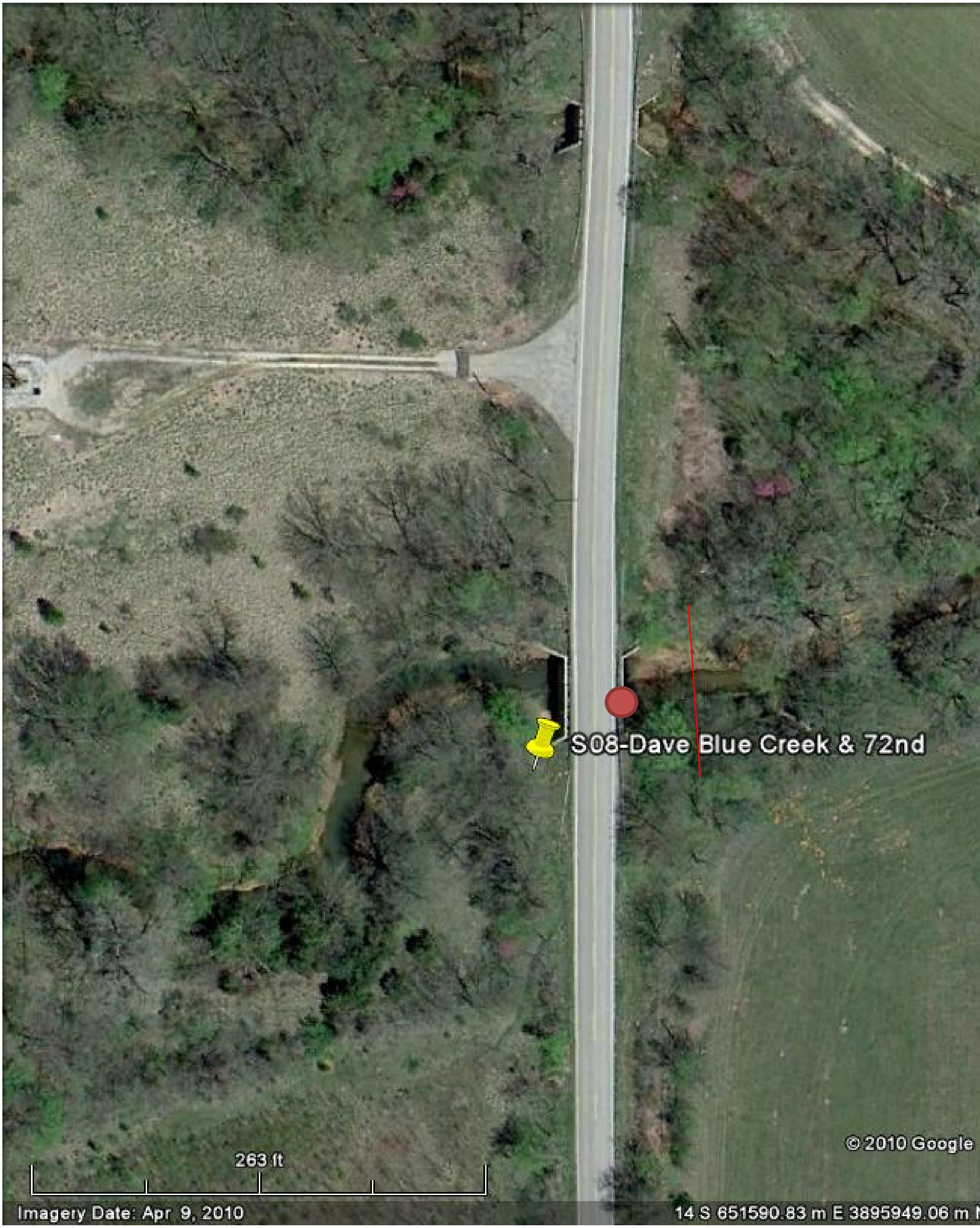

S08-Dave Blue Creek & 72nd
© 2010 Google
263 ft
Imagery Date: Apr 9, 2010
14 S 651590.83 m E 3895949.06 m N

Figure D-7: Rating Curve Site Information – S07 – Dave Blue Creek @ 72nd

Appendix E – HOBO Stage Plots

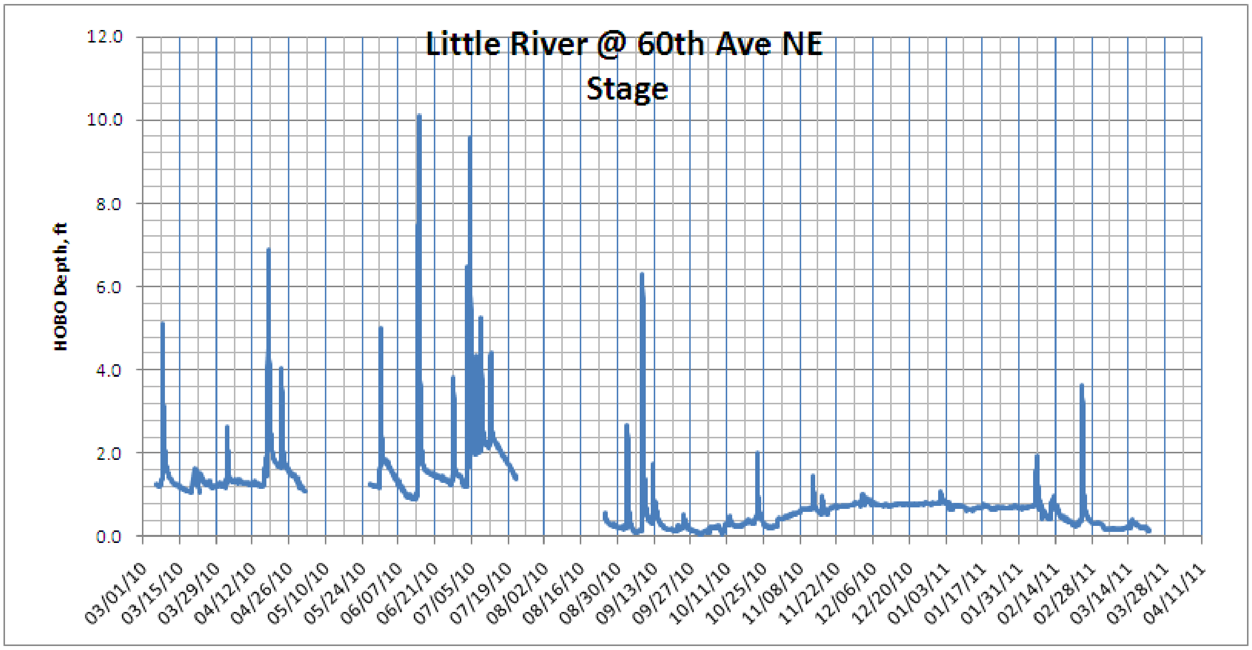


Figure E-1: Stage Record – Site S01 – Little River @ 60th

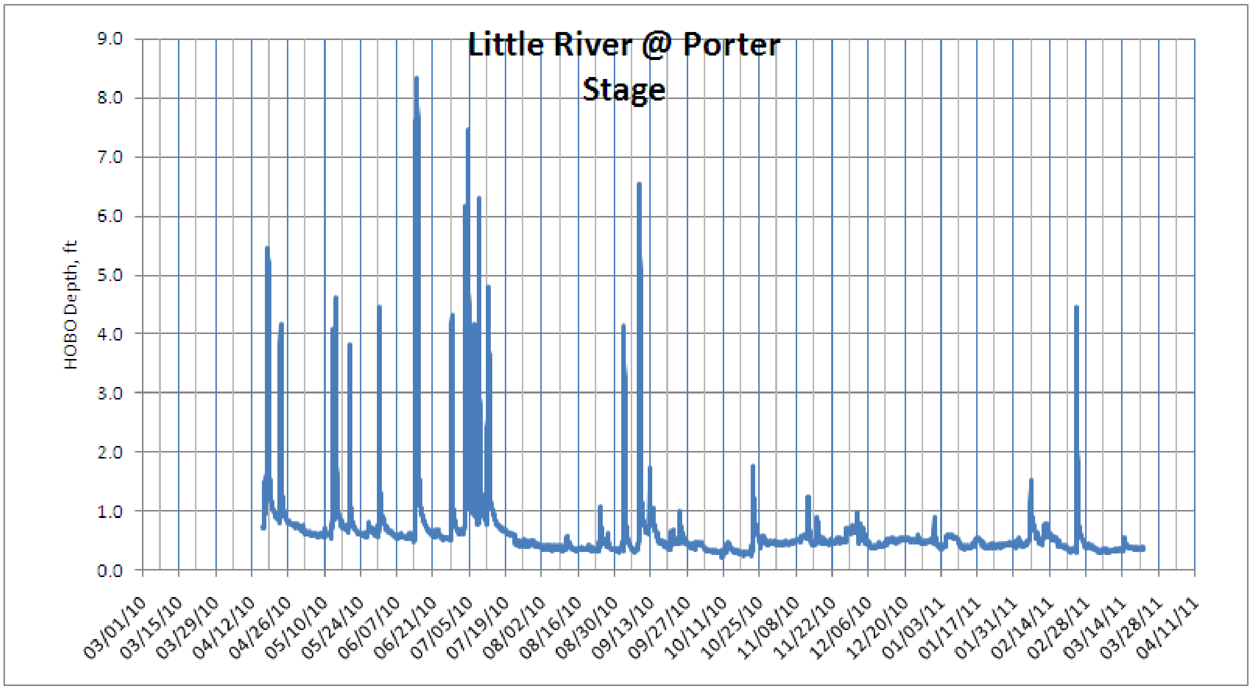


Figure E-2: Stage Record – Site S02 – Little River @ Porter

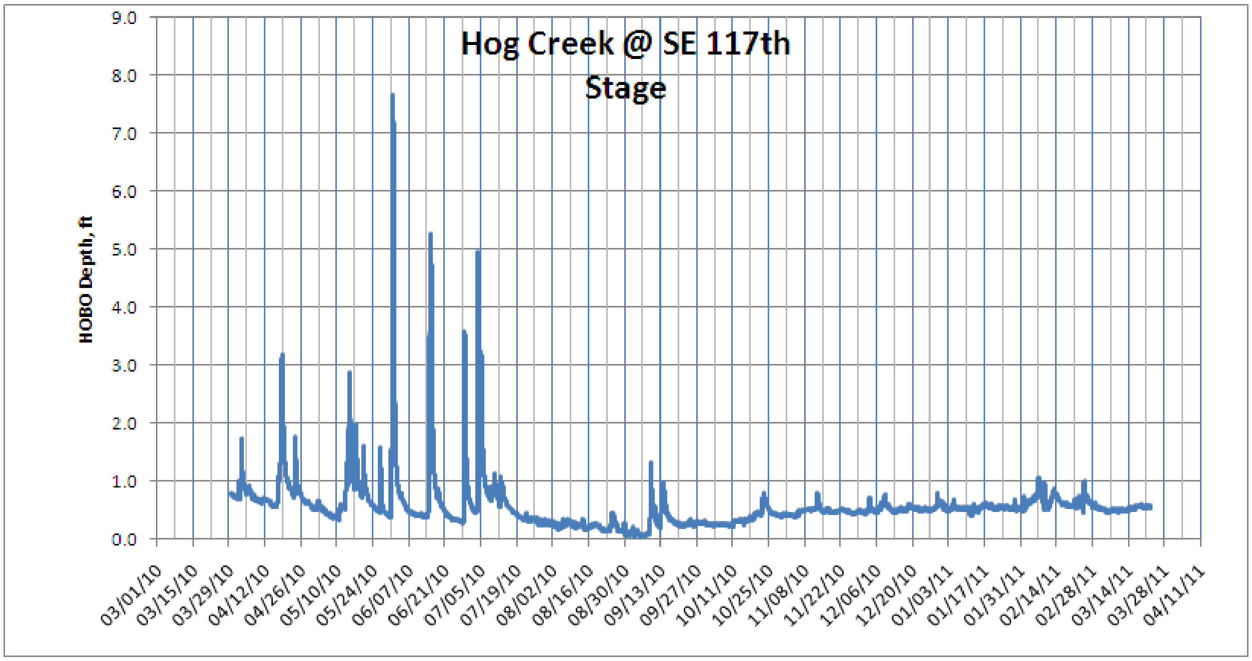


Figure E-3: Stage Record – Site S03 – Hog Creek @ 117th

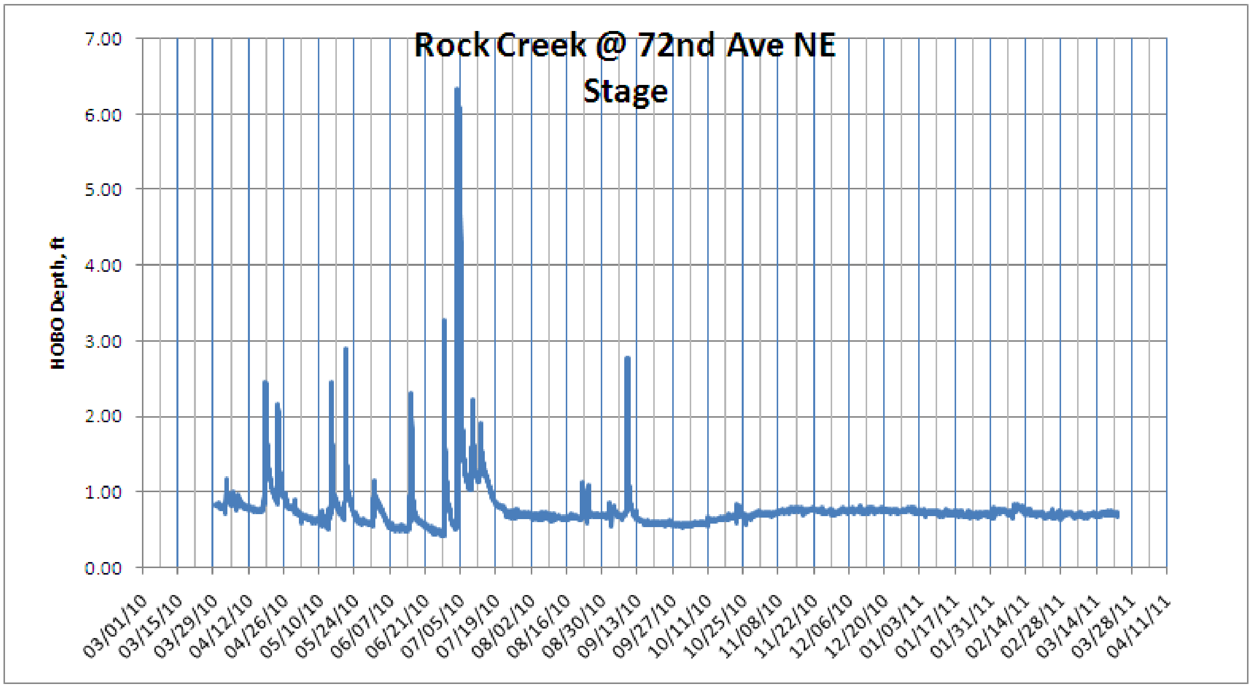


Figure E-4: Stage Record – Site S04 – Rock Creek @ 72nd

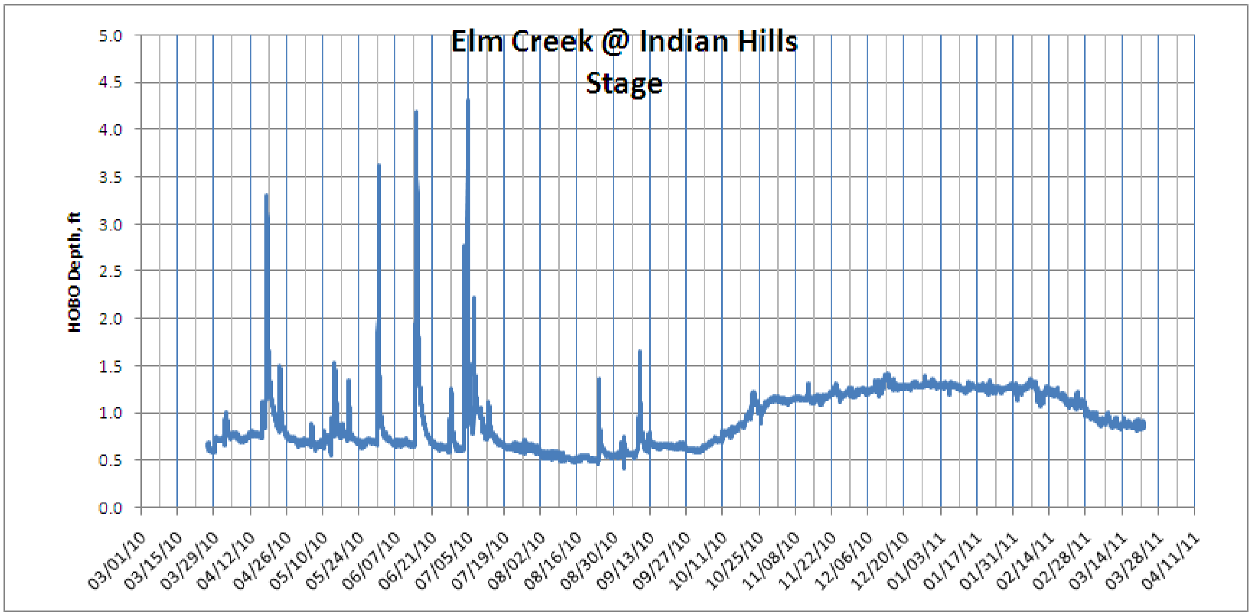


Figure E-5: Stage Record – Site S05 – Elm Creek @ Indian Hills

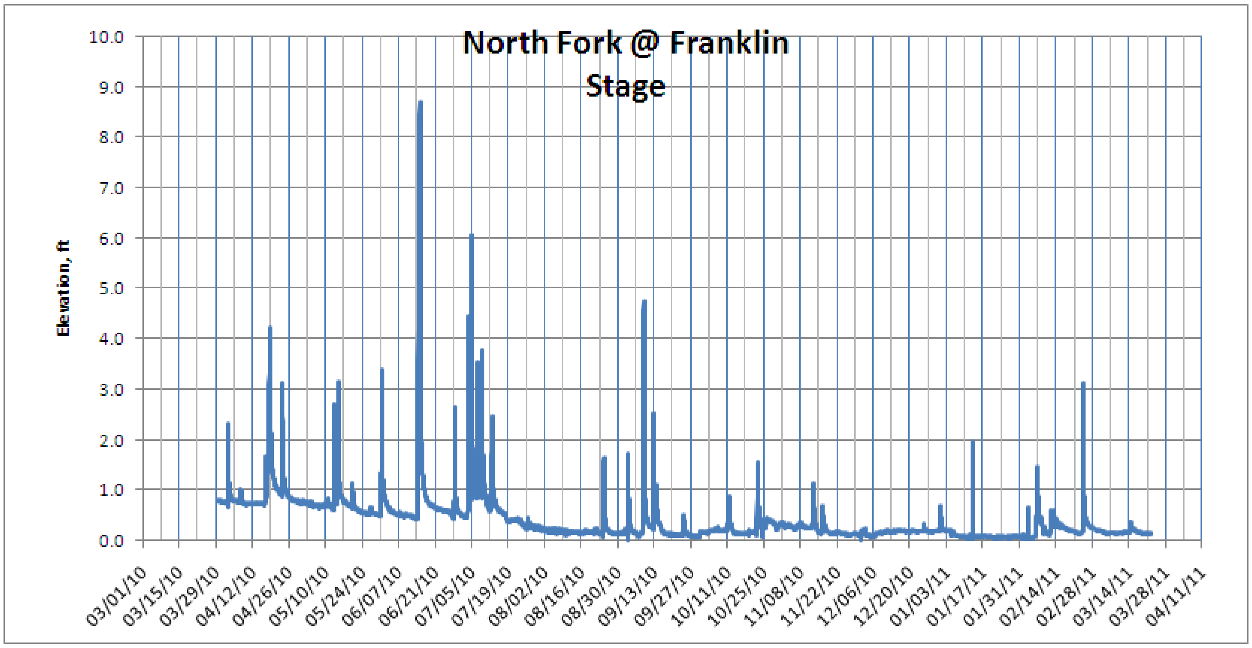


Figure E-6: Stage Record – Site S06 – North Fork @ Franklin

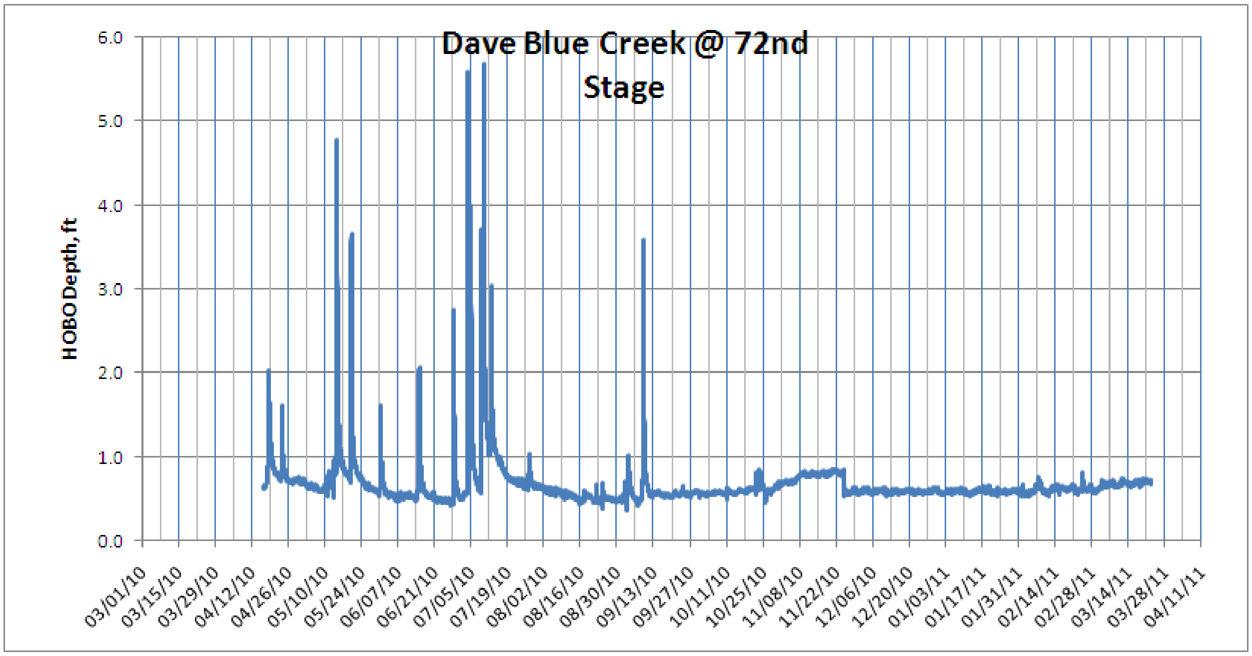


Figure E-7: Stage Record – Site S07 – Dave Blue Creek @ 72nd

Appendix F –Stage-Discharge Plots

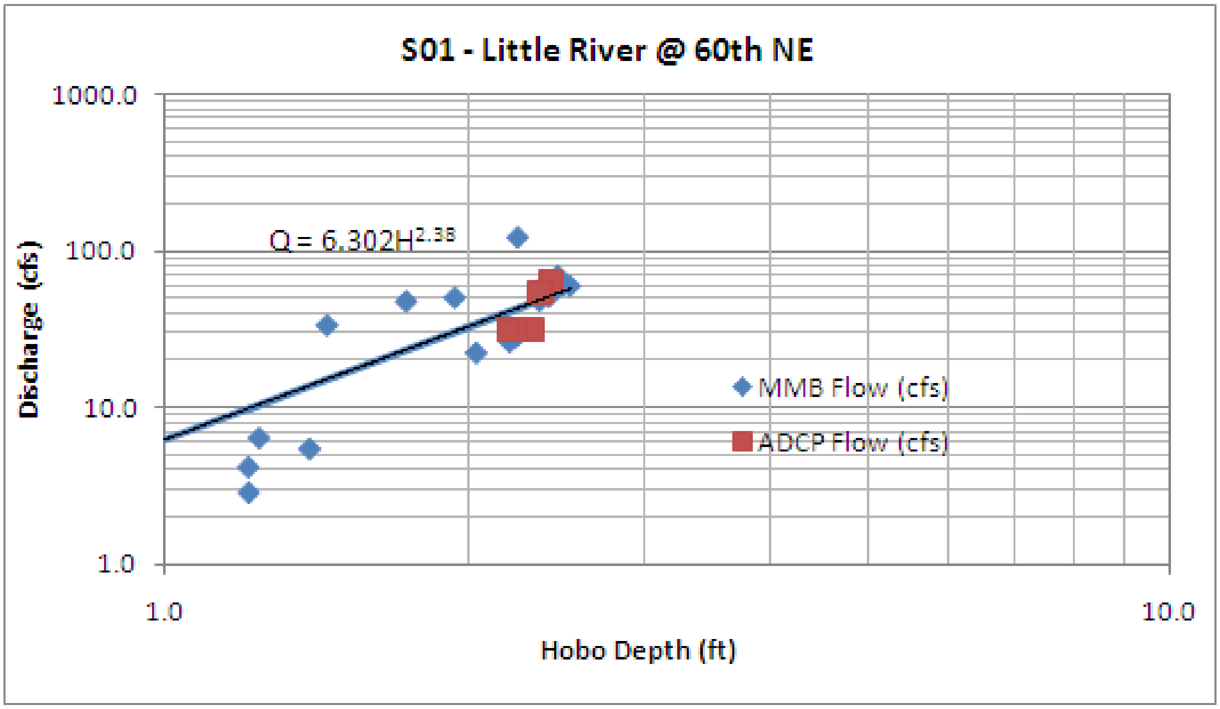


Figure F-1: Stage-Discharge Plot – S01 - Little River @ 60th

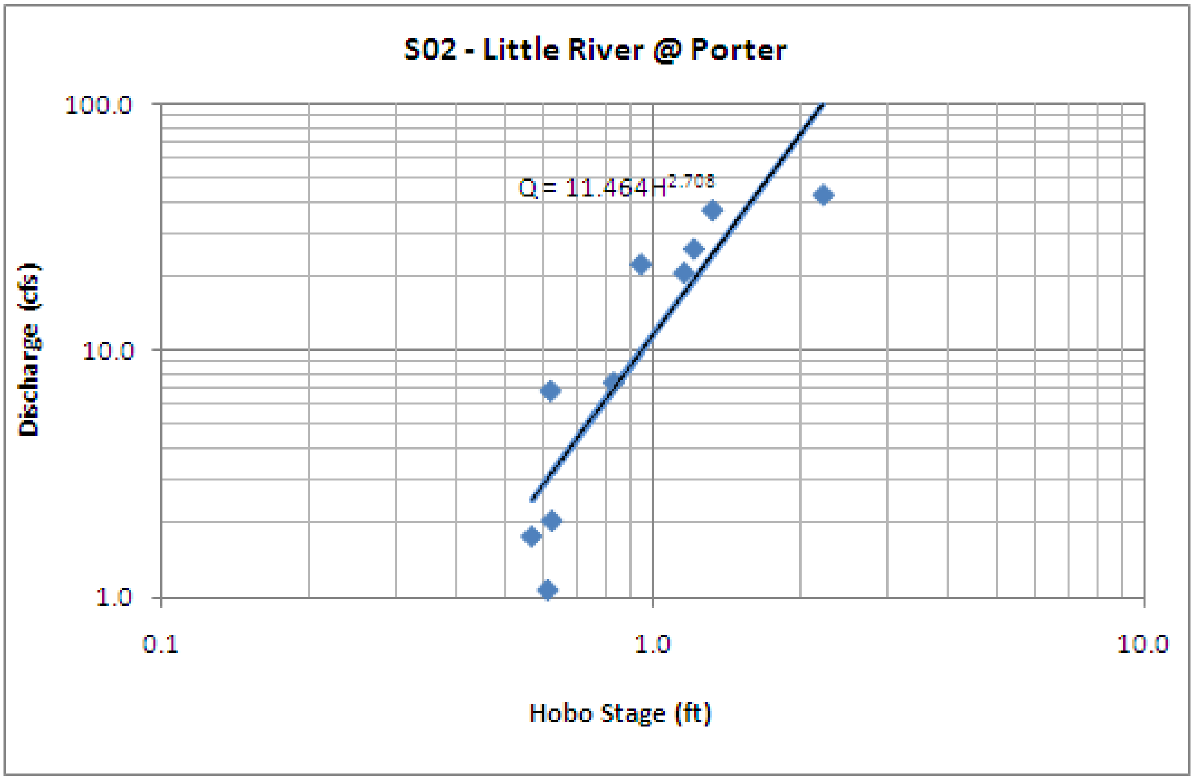


Figure F-2: Stage-Discharge Plot – S02 - Little River @ Porter

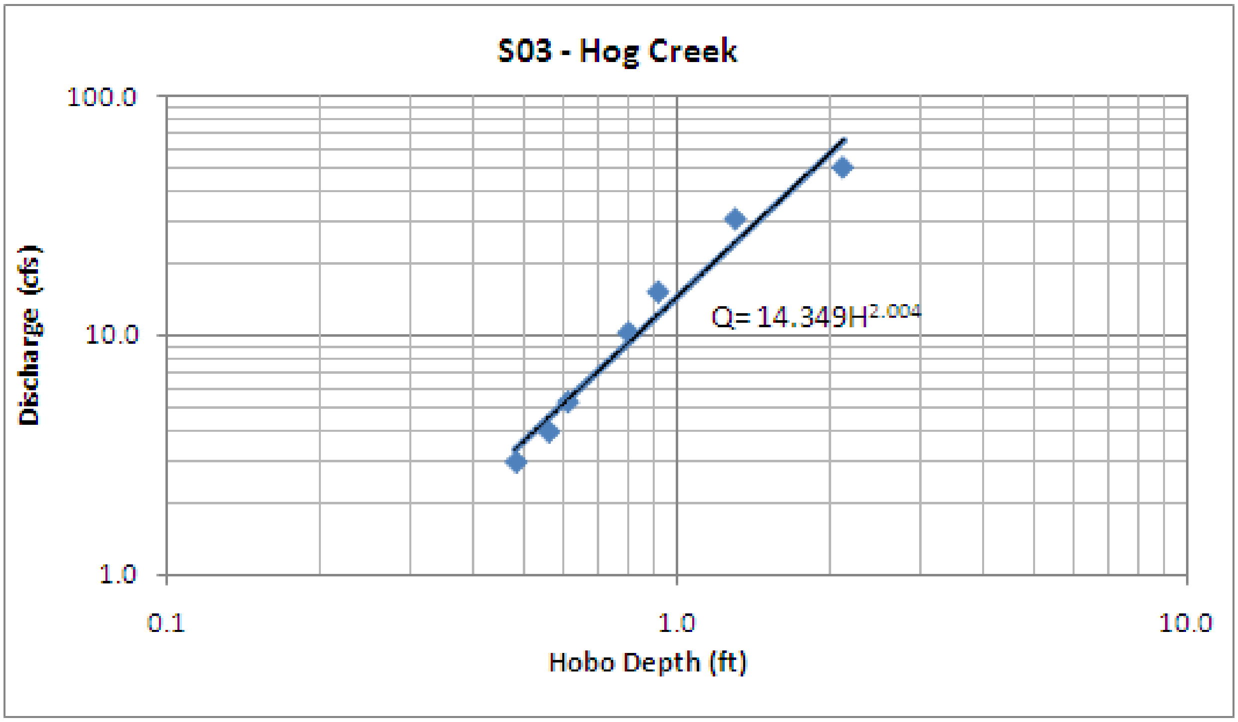


Figure F-3: Stage-Discharge Plot – S03 – Hog Creek

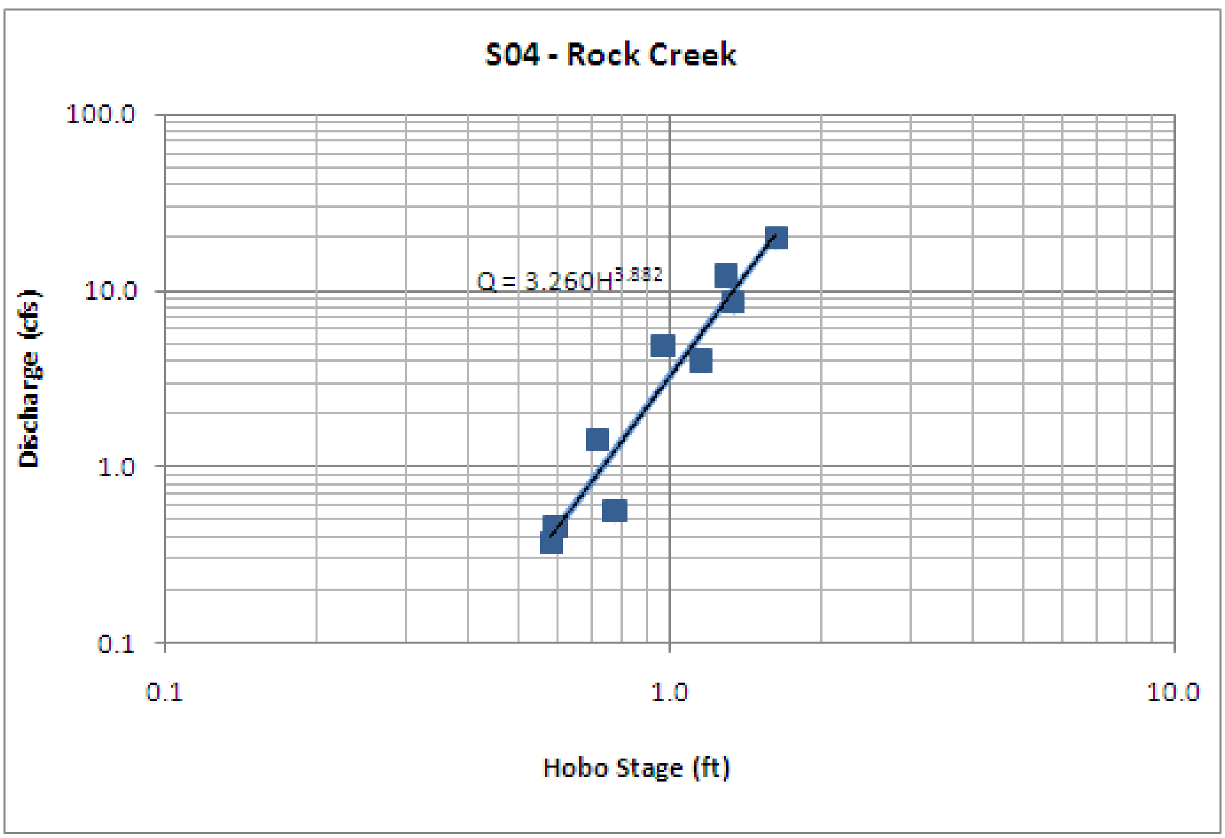


Figure F-4: Stage-Discharge Plot – S04 – Rock Creek

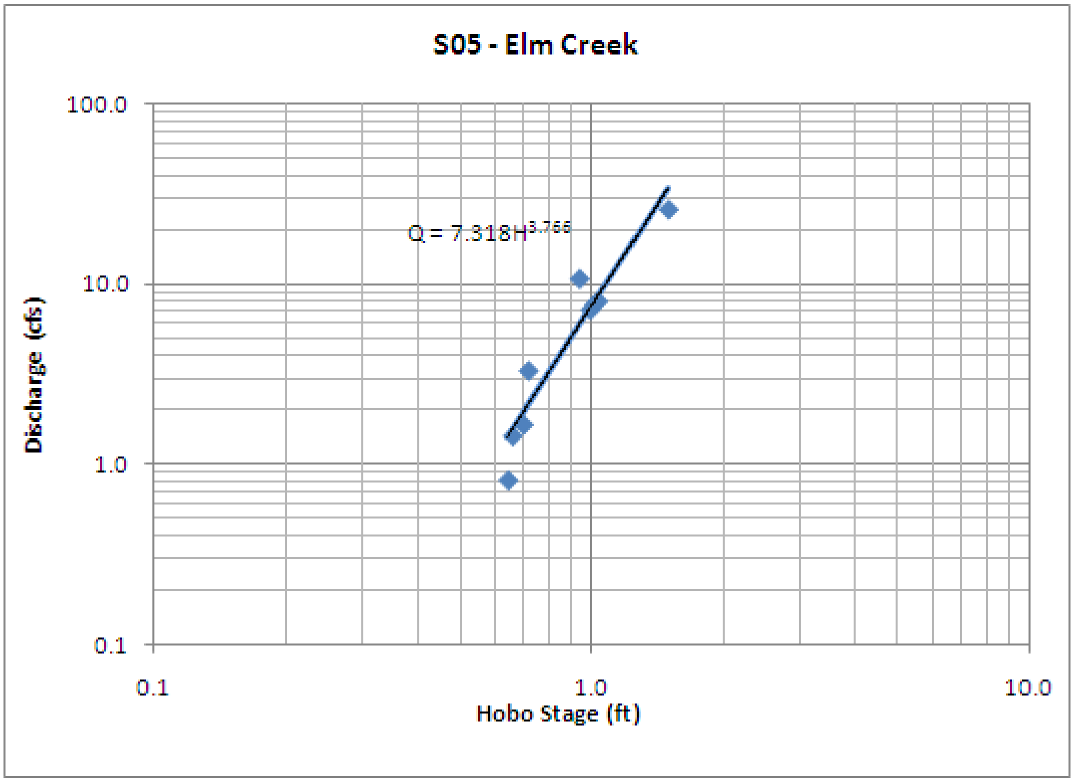


Figure F-5: Stage-Discharge Plot – S05 – Elm Creek

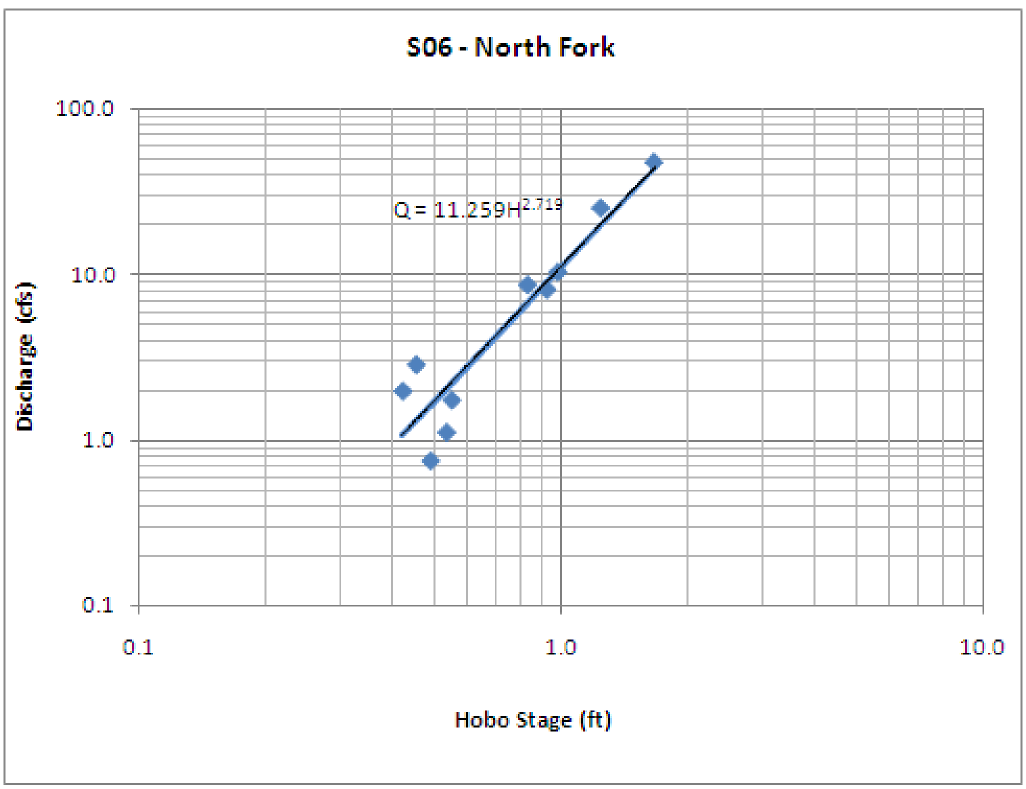


Figure F-6: Stage-Discharge Plot – S06 – North Fork

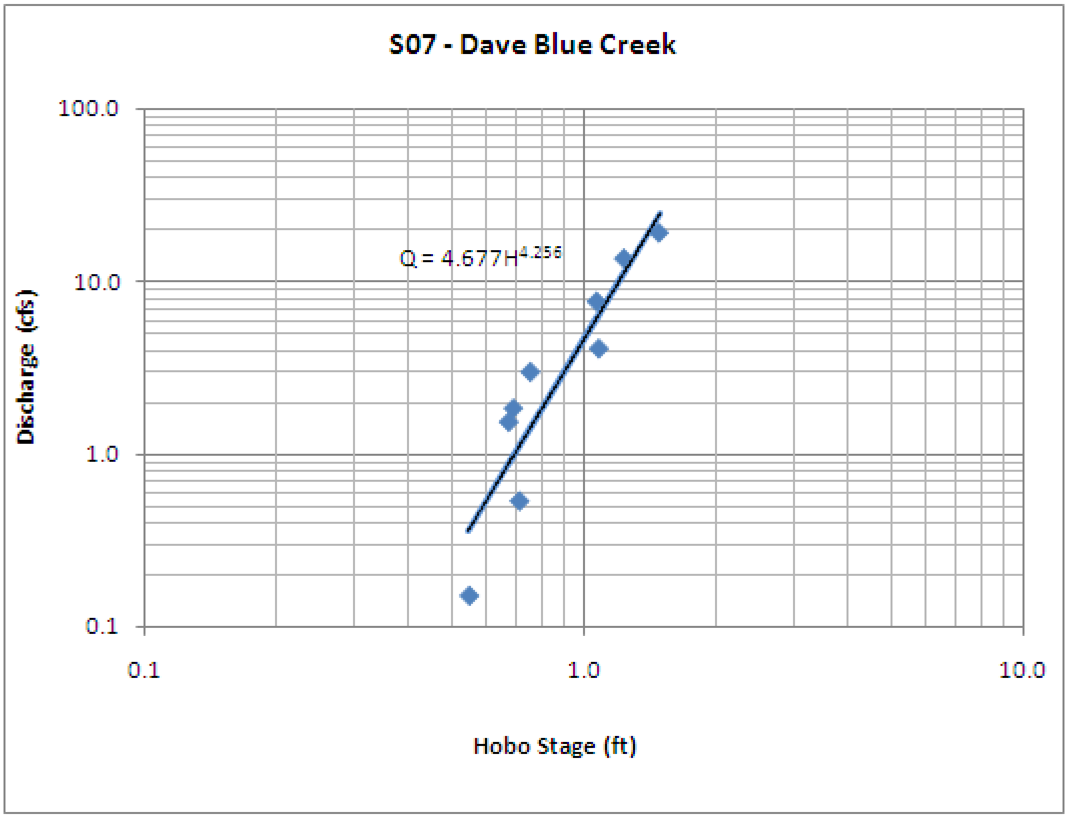


Figure F-7: Stage-Discharge Plot – S07 – Dave Blue Creek

Drought monitoring: a system for tracking plant available soil moisture based on the Oklahoma Mesonet

Basic Information

Title:	Drought monitoring: a system for tracking plant available soil moisture based on the Oklahoma Mesonet
Project Number:	2010OK184B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	3
Research Category:	Climate and Hydrologic Processes
Focus Category:	None, None, None
Descriptors:	None
Principal Investigators:	Tyson Ochsner, Jeffrey Basara, Chris Fiebrich, Albert Sutherland

Publication

1. Ochsner, T.E., B.L. Scott, J. Basara, B. Illston, A. Sutherland, and C. Fiebrich. 2010. Drought monitoring: A system for tracking plant available water based on the Oklahoma Mesonet. Oklahoma Water Resources Research Symposium. Norman, OK. Oct. 26, 2010.

Drought monitoring: a system for tracking plant available soil moisture based on the Oklahoma Mesonet

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Start Date: March 1, 2010
End Date: February 28, 2011

Congressional District: Oklahoma's 3rd Congressional District

Focus Category: AG, CP, DROU, ECL, HYDROL, M&P, WQN

Descriptors: drought, soil moisture, Oklahoma Mesonet

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Publications:

Ochsner, T.E., B.L. Scott, J. Basara, B. Illston, A. Sutherland, and C. Fiebrich. 2010. Drought monitoring: A system for tracking plant available water based on the Oklahoma Mesonet. Oklahoma Water Resources Research Symposium. Norman, OK. Oct. 26, 2010.

Ochsner, T.E., B.L. Scott, J. Basara, B. Illston, C. Fiebrich, and A. Sutherland. 2011. Drought monitoring: A system for tracking plant available water based on the Oklahoma Mesonet. Oklahoma Water Resources Advisory Board. Stillwater, OK. Jan. 7, 2011. invited.

Problem and Research Objectives:

Real-time drought monitoring is essential for early detection and adaptive management to mitigate the negative impacts of drought on the people, economy, and ecosystems of Oklahoma, and improved drought monitoring is a key need identified in the 1995 Update of the Oklahoma Comprehensive Water Plan. Drought impacts can be severe in Oklahoma. For example, the 2006 drought cost the state's economy over $500 million from lost crop production alone. While drought monitoring is critical to Oklahoma's resource managers, it is hampered by a lack of data on a crucial drought indicator: plant available water. Crop yield losses and, by extension, the economic impacts of drought, are strongly linked to plant available water (i.e. the amount of soil moisture which is available for plant uptake). Real-time monitoring of plant available water requires two components: (1) sensors which monitor soil moisture and (2) knowledge of the site-specific soil properties controlling the plant availability of soil moisture. In Oklahoma, the first of these requirements is already met via the Oklahoma Mesonet (Brock et al., 1996; McPherson et al., 2007), an automated network of 120 stations that collect real-time observations of soil and atmospheric variables across the state. However, the component needed to monitor plant available water and dramatically improve drought monitoring across Oklahoma is increased knowledge of the soil properties at the Mesonet sites.

The *long term goal* of the team of collaborators representing Oklahoma State University, the Oklahoma Mesonet, the Oklahoma Climatological Survey, and the University of Oklahoma is to develop and implement a system for accurately monitoring soil moisture and plant available water at each Mesonet station and to predict those values in near real-time for all other locations across Oklahoma. The *objective of this project* is to complete a critical first stage of the research and improve drought monitoring in Oklahoma through the development of a Mesonet-based system for tracking plant available water. The project has the following specific aims:

Specific aim #1: Determine the soil properties controlling the plant availability of soil moisture at each Mesonet site.

Specific aim #2: Develop a routine to calculate plant available water by integrating the sensor output and the site-specific soil properties.

Methodology:

Specific aim #1: Determine the soil properties controlling the plant availability of soil moisture at each Mesonet site. Plant available water is the difference between the current amount of soil moisture and the amount of soil moisture retained at a matric potential of -1500 kPa. This matric potential approximates the threshold at which plants wilt irreversibly, and the soil moisture at this matric potential is called the permanent wilting point. This threshold soil moisture value varies between locations and with depth at a given location. Therefore, we will collect soil samples at every operational Mesonet site for laboratory measurements of soil moisture retained at -1500 kPa.

The soil samples will be taken on the west side of each Mesonet station within 2-3 m of the soil moisture sensors. Soil samples will be collected using a hydraulic sampler (Giddings Machine Co., Windsor, CO) with a 3.5 inch outer diameter steel sampling tube (no liner). The diameter of the resulting soil core will be 7.47 cm. This relatively large diameter helps to minimize the potential for compaction during sampling. The soil core will be extruded onto a cutting tray, and the core length will be measured. The depth of the hole resulting from removal of the core will also be measured. If the core length differs from the depth of the hole by more than 10%, the core will be discarded and a new core will be collected.

Soil segments will be cut from the core for the 3-10, 20-30, 40-50, 55-65, and 70-80 cm depth intervals. Preliminary work has shown that the 0-3 cm layer at most sites contains a thick mat of grass roots which preclude accurate measurement of soil properties (Mohanty et al., 2002). The 40-50 cm sample does not correspond to an existing sensor depth, but is being considered as a target depth for future sensor deployment. The 70-80 cm sample corresponds to sensors installed at 75 cm at some sites, but these sensors are being decommissioned. Still the soil properties can be used to re-analyze archived data. Impenetrable layers may prevent the deeper segments from being sampled at some sites. Each core segment will be sealed in a plastic bag to prevent moisture loss. Two cores will be collected per site (Mohanty et al., 2002) and care will be taken to keep the soil samples intact. The samples will be stored in plastic boxes. The boxes will be placed inside a foil-lined insulated bag, kept shaded, and transported to the laboratory within 24 hours.

In the laboratory, each sample will be weighed. The intact portion of each sample will be trimmed to a length of ~4 cm and placed inside an 8.9 cm o.d. brass ring. The gap between the ring and the soil will be sealed with paraffin wax (Ahuja et al., 1985). These intact samples will be used in Tempe cells to determine the soil moisture retained at -33 kPa (Dane and Hopmans, 2002). A sub-sample of the remaining soil will be dried at 105°C for 24 hr. The data from this sub-sample will permit calculation of bulk density and soil moisture at the time of sampling. Next, the sub-sample which was dried at 105°C will be ground to pass a 2 mm sieve. The pressure plate method will be used to determine the soil moisture retained at -1500 kPa (Dane and Hopmans, 2002).

Specific aim #2: Develop a routine to calculate plant available water by integrating the sensor output and the site-specific soil properties. Plant available water (mm or inches) will be calculated as

$$\mathrm{PAW} = \sum_{i=1}^{n}\left(\theta_i - \theta_{\mathrm{wp}i}\right) dz_i \qquad [1]$$

where q_i is the current volumetric water content of layer *i*, q_{wpi} is the permanent wilting point for layer *i*, dz_i is the thickness of layer *i*, and *n* is the number of layers considered. For 81 Mesonet sites with sensors at 5, 25, and 60 cm, n = 3, and PAW would summarize water available in the top 80 cm of soil. For 25 additional sites, n = 2, and PAW would summarize water available in the top 40 cm. Sites which lack sensors at 60 cm typically have impenetrable layers above depth. The thickness of the soil layers represented are 10, 30, and 40 cm for the sensors at 5, 25, and 60 cm, respectively.

Accurate plant available water measurements are contingent upon knowing the soil water retention curve (soil moisture versus matric potential) for each site and depth. The retention curve is required because the 229 sensors measure matric potential, not soil moisture directly (Starks, 1999). The water retention curve is used to convert the sensor readings to soil moisture estimates. Water retention curves for each Mesonet site have been previously estimated (Illston et al., 2008) using the modeling approach of Arya and Paris (1981). This was one of the earliest approaches developed to estimate water retention curves from basic soil data like the particle size distribution and bulk density. The Arya and Paris (1981) method does not account for the effects of soil structure, thus large errors can result when applying it to medium and fine-textured soils (Basile and D'Urso, 1997). This fact helps to explain why errors in the soil moisture data often exceed 0.05 m^3 m^{-3} with the existing calculation routines.

A sub-objective of the project is, therefore, to improve the accuracy of the Mesonet soil moisture estimates on which plant available water monitoring will depend. These improvements will be gained by more accurate estimation of the water retention curve. Up to this time these curves have been estimated based only upon the particle size distribution and measured or estimated soil bulk density, because no better data were available. Now, through the proposed project, direct measurements of bulk density, soil moisture retention at -33 kPa and -1500 kPa, and soil organic matter will be obtained. These data will lead to improved estimation of the water retention curve. Schaap et al. (2001) found a RMSE in soil moisture at a given matric potential of 0.068 m^3 m^{-3} when only particle size distribution and bulk density are known. Others have shown that, with direct measurements of soil moisture at -33 kPa and -1500 kPa, the RMSE can be cut in half to 0.034 m^3 m^{-3} (Twarakavi et al., 2009).

Gains in accuracy such as those discussed above arise not only from the use of more complete input data, but also from the use of models more accurate than that of Arya and Paris (1981). This project will employ the widely used ROSETTA pedotransfer functions (Schaap et al., 2001). These models were developed using advanced numerical methods, i.e. artificial neural networks, and an extensive soil property database. The ROSETTA pedotransfer functions have been successfully employed in a number of prior studies. Our preliminary data show that, with direct measurement of key soil properties and use of ROSETTA, the accuracy of the soil moisture data can be improved from RMSE = 0.066 m^3 m^{-3} to RMSE = 0.032 m^3 m^{-3}. Therefore, significant improvement in the accuracy of Mesonet soil moisture data is likely using the methods described here. In summary, the steps to achieve specific aim #2 are as follows:

(1) Use measured soil properties and the ROSETTA pedotransfer functions to improve the existing estimates of the site- and depth-specific water retention curve.
(2) Convert the 229 sensor measurements of matric potential into soil moisture estimates using the improved water retention curves.
(3) Calculate the plant available water in the soil profile based on the soil moisture estimates and the measured permanent wilting points (Eq. [1]).
(4) Develop prototype plant available water maps.

Principal Findings and Significance:

We have made great progress toward the development of a system for tracking PAW based on mesoscale observations from the Oklahoma Mesonet. The Mesonet is an automated network of 120 stations that collect real-time observations of soil and atmospheric variables across the state (McPherson et al., 2007). Principal findings and their significance are summarized for each specific aim below.

Specific aim #1: Determine the soil properties controlling the plant availability of soil moisture at each Mesonet site. We completed the soil sampling in August 2010 and collected 1,107 discrete soil samples from the Mesonet sites (Fig. 1). Soil samples were stored at 4°C pending analysis.

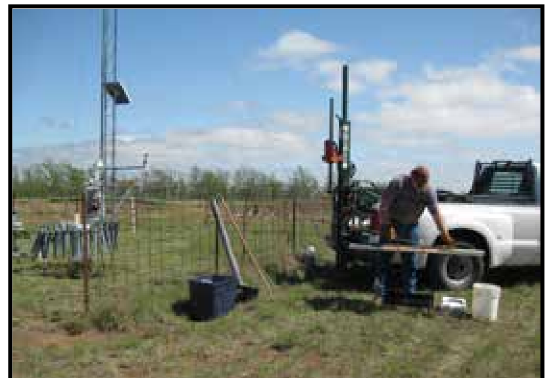

Fig. 1. Soil sampling at the Camargo Mesonet

We are measuring seven soil physical properties for each of these samples in the laboratory (Fig. 2). Currently, we have completed 3,924 of the necessary 7,749 soil property determinations, thus the lab work is 51% complete. We aim to reach 100% completion in July 2011. Once the database of seven measured properties is finished, those data will be used in the pedotransfer function, ROSETTA, resulting in estimates of seven additional soil properties. Thus, the final database will contain 15,498 soil property values for the 120 Mesonet stations. This comprehensive soil property database, connected with the Mesonet environmental sensing capabilities, will create an unprecedented and powerful tool for water resources research and management. The database is likely to have impact for decades to come.

Fig. 2. Measuring soil water retention at -1500 kPa and soil particle size distribution.

Specific aim #2: Develop a routine to calculate plant available water by integrating the sensor output and the site-specific soil properties. We have also developed the numerical routine to integrate the measured soil properties with the sensor data to calculate PAW at each Mesonet site. Example outputs from that routine are shown below in Figs. 3 and 4. These examples are based on pre-existing soil property estimates and are proto-types only. When the lab work is finished, we will incorporate the new soil properties into the calculation routine.

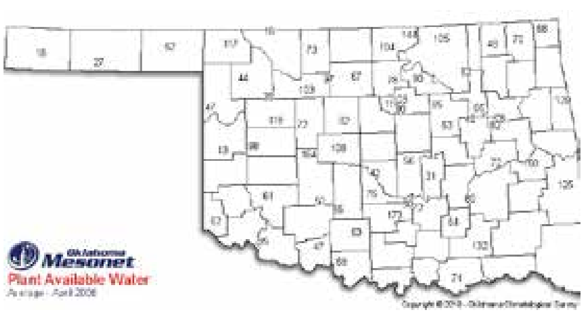

Fig. 3. Average PAW (mm of available water in the top 80 cm of soil) at the Mesonet sites, April 06.

Fig. 4. Time-series of PAW for the El Reno Mesonet site in 2009.

The new calculation routine, supported by the measured soil properties, is significant because it will drive the world's first system for monitoring plant available water at the regional or state level. In the second year of this project, we will be developing procedures to interpolate (estimate) plant available water between the Mesonet sites and to generate daily maps of plant available water for public release. The final plant available water maps will have great value for water resources research and management. They will help farmers and ranchers make more informed management decisions. They will help researchers understand how hydrologic processes are influenced by soil moisture and plant available water. They will also be useful for calibrating and validating new satellite remote-sensing approaches for estimating soil moisture.

A significant outcome of this project is that it contributed to the development and initiation of a major new project on soil moisture sensing. Scientists with the USDA-ARS Hydrology and Remote Sensing Laboratory in Beltsville, MD selected the Marena, OK Mesonet site as the location for a testbed to intercompare existing and emerging technologies for soil moisture sensing. That selection was due, in large part, to the ongoing work under this project. The Marena, OK In Situ Testbed (MOIST) was launched in 2010 and has attracted researchers from eight US states and from Netherlands. The testbed is led by Michael Cosh (USDA-ARS) and Tyson Ochsner (OSU). The process of locating the testbed in Oklahoma was initiated by conversations between Jeff Basara (OCS) and Michael Cosh. The testbed has good potential to attract research funding in the near future and to play a significant role in calibration and validation of NASA's forthcoming SMAP soil moisture satellite mission.

This project has also been significant in that it has provided an excellent training opportunity in water resources research for a M.S. level graduate student and two undergraduate students at Oklahoma State University. The students have benefitted from interaction with PI's at two different institutions and have gained familiarity with the Oklahoma Mesonet, with the geography and soils of Oklahoma, and with the topic of drought monitoring.

Student Status	**Number**	**Disciplines**
Undergraduate	2	Environmental Sci., Biosystems and Ag. Engineering
M.S.	1	Plant and Soil Sciences
Total	3	

Scale Dependent Phosphorus Leaching in Alluvial Floodplains

Basic Information

Title:	Scale Dependent Phosphorus Leaching in Alluvial Floodplains
Project Number:	2010OK192G
Start Date:	9/1/2010
End Date:	8/30/2012
Funding Source:	104G
Congressional District:	3
Research Category:	Water Quality
Focus Category:	Nutrients, Groundwater, Water Quality
Descriptors:	None
Principal Investigators:	Garey Fox, Brian E. Haggard, Todd Halihan, Phil D Hays, Chad Penn, Andrew Sharpley, Daniel E. Storm

Publications

There are no publications.

First Annual Progress Report

SCALE-DEPENDENT PHOSPHORUS LEACHING IN ALLUVIAL FLOODPLAINS

USGS Award No. G10AP00137

Garey Fox, Todd Halihan, Chad Penn, and Daniel Storm
Oklahoma State University

Brian Haggard, Andrew Sharpley, and Phil Hayes
University of Arkansas and USGS

This report is the first of two annual progress reports for this two-year project.

Because it is concise, no executive summary is provided.

SCALE-DEPENDENT PHOSPHORUS LEACHING IN ALLUVIAL FLOODPLAINS
USGS AWARD NO. G10AP00137

Principal Investigators:

Garey Fox, Todd Halihan, Chad Penn, and Daniel Storm
Oklahoma State University

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Phil Hayes
University of Arkansas and Arkansas USGS

Start Date: 9/1/2010

End Date: 8/31/2012

Congressional District: 2nd and 3rd in Oklahoma; 3rd in Arkansas

Focus Category: AG, GEOMOR, GW, HYDROL, NPP, NU, ST, SW, WQL

(1) Problem and Research Objectives

This research hypothesizes that macropores and gravel outcrops in alluvial floodplains have a significant, scale-dependent impact on contaminant leaching through soils; therefore, both soil matrix and macropore infiltration must be accounted for in an analysis of nutrient transport. However, quantifying the impact and spatial variability of macropores and gravel outcrops in the subsurface is difficult, if not impossible, without innovative field studies. This research proposes an innovative plot design that combines these and other methods in order to characterize water and phosphorus movement through alluvial soils.

The specific objectives of this research are twofold. The first objective is to quantify the phosphorus (P) transport capacity of heterogeneous, gravel soils common in the Ozark ecoregion. Two characteristics of the soil are expected to promote greater infiltration and contaminant transport than initially expected: (1) macropores or large openings (greater than 1-mm) in the soil (Thomas and Phillips, 1979; Akay et al., 2008; Najm et al., 2010) and (2) gravel outcrops at the soil surface (Heeren et al., 2010). This research will estimate P concentration and P load of water entering the gravelly subsoil from the soil surface for various topsoil depths, storm sizes, and initial P concentrations. Second, the impact of experimental scale on results from P leaching studies will be evaluated. If a material property is measured for identical samples except at various sample sizes, a representative element volume (REV) curve can be generated showing large variability below the REV. This provides a helpful framework for evaluating scales in P leaching. What minimum land area is necessary to adequately measure P leaching? It is hypothesized that measured P leaching (kg m^{-2} s^{-1}) will generally increase as the scale increases from point (10^{-3} m^2) to plot (10^2 m^2) scales. This will be evaluated by measuring P leaching at the point scale in the laboratory and at plot scales with bermed infiltration experiments for three plot sizes (approximately 10^0, 10^1, and 10^2 m^2).

If subsurface transport of P to alluvial groundwater is significant, these data will be critical for identifying appropriate conservation practices based on topsoil thickness. Riparian buffers are primarily aimed at reducing surface runoff contributions of P; however, their effectiveness within floodplains may be significantly reduced when considering heterogeneous subsurface pathways.

Methodology and Principal Findings/Significance

The three selected riparian floodplain sites are located in the Ozark region of northeastern Oklahoma and western Arkansas. The Ozark ecoregion of Missouri, Arkansas, and Oklahoma is characterized by karst topography, including caves, springs, sink holes, and losing streams. The erosion of carbonate bedrock (primarily limestone) by slightly acidic water has left a large residuum of chert gravel in Ozark soils, with floodplains generally consisting of coarse chert gravel overlain by a mantle of gravelly loam or silt loam (Figure 1). The three floodplain sites are located adjacent to the Barren Fork Creek, Pumpkin Hollow and Clear Creek (Figure 2).

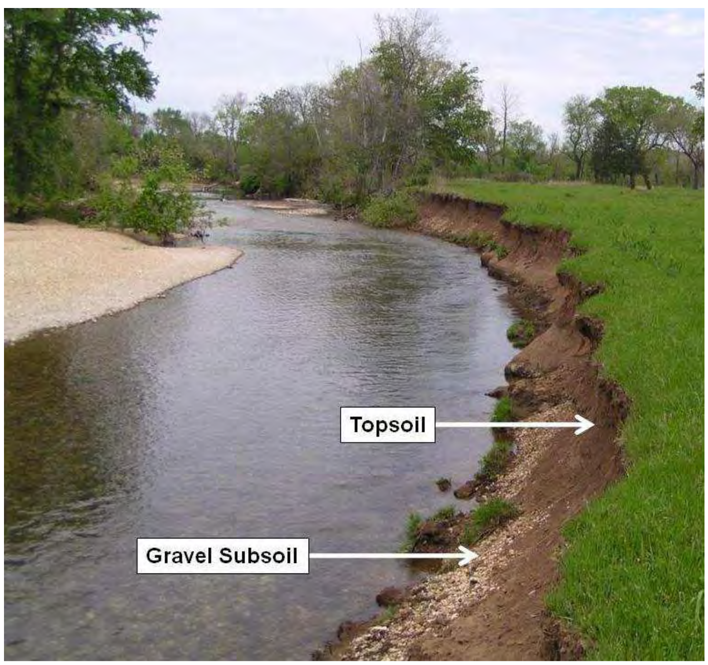


Figure 1. Floodplains in the Ozark ecoregion generally consist of coarse chert gravel overlain by a mantle (1-300 cm) of topsoil.

Figure 2. Location of riparian floodplain sites in the Ozark ecoregion of Oklahoma and Arkansas.

Barren Fork Creek Site (Oklahoma)

The Barren Fork Creek site, five miles east of Tahlequah, Oklahoma, in Cherokee county (latitude: 35.90°, longitude: -94.85°), is located just downstream of the Eldon U.S. Geological Survey (USGS) gage station (07197000). A tributary of the Illinois River, the Barren Fork Creek has a median daily flow of 3.6 m^3 s^{-1} and an estimated watershed size of 845 km^2 at the study site. Historical aerial photographs of the site demonstrate the recent geomorphic activity including an abandoned stream channel that historically flowed in a more westerly direction than its current southwestern flow path (Figure 3).

Fuchs et al. (2009) described some of the soil and hydraulic characteristics of the Barren Fork Creek floodplain site. The floodplain consists of alluvial gravel deposits underlying 0.5 to 1.0 m of topsoil (Razort gravelly loam). Topsoil infiltration rates are reported to range between 1 and 4 m/d based on USDA soil surveys. The gravel subsoil, classified as coarse gravel, consists of approximately 80% (by mass) of particle diameters greater than 2.0 mm, with an average particle size (d_{50}) of 13 mm. Estimates of hydraulic conductivity for the gravel subsoil range between 140 and 230 m d^{-1} based on falling-head trench tests (Fuchs et al., 2009). Soil particles less than 2.0 mm in the gravelly subsoil consist of secondary minerals, such as kaolinte and noncrystalline Al and Fe oxyhydroxides. Ammonium oxalate extractions on this finer material estimated initial phosphorus saturation levels of 4.2% to 8.4% (Fuchs et al., 2009).

Figure 3. Aerial photos for 2003 (left) and 2008 (right) show the southward migration of the stream toward the bluff and the large deposits of gravel in the current and abandoned stream channels. The study site is the hay field in the south-central portion of each photo (red arrow).

The floodplain site is a hay field with occasional trees (Figure 4). The field has a Soil Test Phosphorus (STP) of 33 mg/kg (59 lb/ac) and has not received fertilizer for several years. The southern border of the floodplain is a bedrock bluff that rises approximately 5 to 10 m above the floodplain elevation and limits channel migration to the south. The floodplain width at the study site is 20 to 100 m from the streambank (based on the 100 year floodplain); however, water was observed 200 m from the streambank (to the bluff) during a 6 year recurrence interval flow event (Figure 4).

Figure 4. The Barren Fork site is a hay field (left). The site becomes completely inundated during large flow events (right).

Pumpkin Hollow Site (Oklahoma)

The Pumpkin Hollow site, 12 miles northeast of Tahlequah, Oklahoma, in Cherokee County (Figure 5, latitude: 36.02°, longitude: -94.81°) has an estimated watershed area of 15 km^2. A small tributary of the Illinois River, Pumpkin Hollow is an ephemeral stream in its upper reaches. The Pumpkin Hollow site is pasture for cattle (Figure 6). The entire floodplain is 120 to 130 m across. Soils in the study area include Razort gravelly loam and Elsah very gravelly loam.

Figure 5. Pumpkin Hollow is a narrow valley ascending from the Illinois River to the plateau.

Figure 6. The Pumpkin Hollow site in spring (left) and winter (right). The site includes soils with shallow layers of topsoil and gravel.

Clear Creek Site (Arkansas)

The Clear Creek site is 5 miles northwest of Fayetteville, Arkansas, in Washington County (Figure 7, latitude: 36.125°, longitude: -94.235°). Clear Creek is a fourth order stream, and is a tributary to the Illinois River. Streamflow during baseflow conditions is estimated to be around 0.5 cms. The Clear Creek site is also pasture for cattle (Figure 8). The floodplain is approximately 300 to 400 m across. The soils included intermixed layers of gravel and silt loam (Figure 8).

Figure 7. Clear Creek and an overflow channel at the Clear Creek floodplain site.

Figure 8. The Clear Creek site is pasture (left). Soils are composed of gravel and silt loam alluvial deposits (right).

Electrical Resistivity Imaging

Electrical Resistivity Imaging (ERI) is a geophysical method commonly used for near-surface investigations which measures the resistance of earth materials to the flow of DC current between two source electrodes. The method is popular because it is efficient and relatively unaffected by many environmental factors that confound other geophysical methods. According to Archie's Law (Archie, 1942), earth materials offer differing resistance to current depending on grain size, surface electrical properties, pore saturation, and the ionic content of pore fluids.

Normalizing the measured resistance by the area of the subsurface through which the current passes and the distance between the source electrodes produces resistivity, reported in ohmmeters (Ω-m), a property of the subsurface material (McNeill, 1980). Mathematical inversion of the measured voltages produces a two-dimensional profile of the subsurface showing areas of differing resistivity (Loke and Dahlin, 2002, Halihan et al., 2005).

ERI data were collected using a SuperSting R8/IP Earth Resistivity Meter (Advanced GeoSciences Inc., Austin, TX) with a 56-electrode array. Fourteen lines were collected at the Barren Fork Creek site, three at the Pumpkin Hollow site, and eight lines at the Clear Creek site. One line at the Barren Fork Creek site and all of the lines at Pumpkin Hollow were “roll-along” lines that consisted of sequential ERI images with one-quarter overlap of electrodes. The profiles at the Barren Fork Creek site employed electrode spacing of 0.5, 1.0, 1.5, 2.0 and 2.5 m with associated depths of investigation of approximately 7.5, 15.0, 17.0, 22.5 and 25.0 m, respectively. All other sites utilized a 1.0-m spacing. The area of interest in each study site was less than 3 m below the ground surface and thus well within the ERI window. The resistivity sampling and subsequent inversion utilized a proprietary routine devised by Halihan et al. (2005), which produced higher resolution images than conventional techniques.

The OhmMapper (Geometrics, San Jose, CA), a capacitively-coupled dipole-dipole array, was effectively deployed at the relatively open Barren Fork Creek site for large scale mapping. The system used a 40 m array (five 5 m transmitter dipoles and one 5 m receiver dipole with a 10 m separation) that was pulled behind an ATV. Two data readings per second were collected to create long and data-dense vertical profiles. The depth of investigation was limited to 3 to 5 m. Positioning data for the ERI and OhmMapper were collected with a TopCon HyperLite Plus GPS with base station. Points were accurate to within 1 cm.

Barren Fork Creek

Resistivity at the Barren Fork Creek site appeared to conform generally to surface topography with higher elevations having higher resistivity, although the net relief was minor (~1 m). This was most evident in the OhmMapper resistivity profiles which covered most of the floodplain and which revealed a pattern of high and low resistivity that trended SW to NE (Figure 9). More precise imaging with reduced spatial coverage was obtained with the ERI. A composite ERI line collected from the site is shown in Figure 10. The line, which is approximately parallel to the stream, begins only 5 m from the stream. Gravel outcrops are indicated by gray colors reaching closer to the surface and will be the location for induced leaching experiments at different spatial scales at this site.

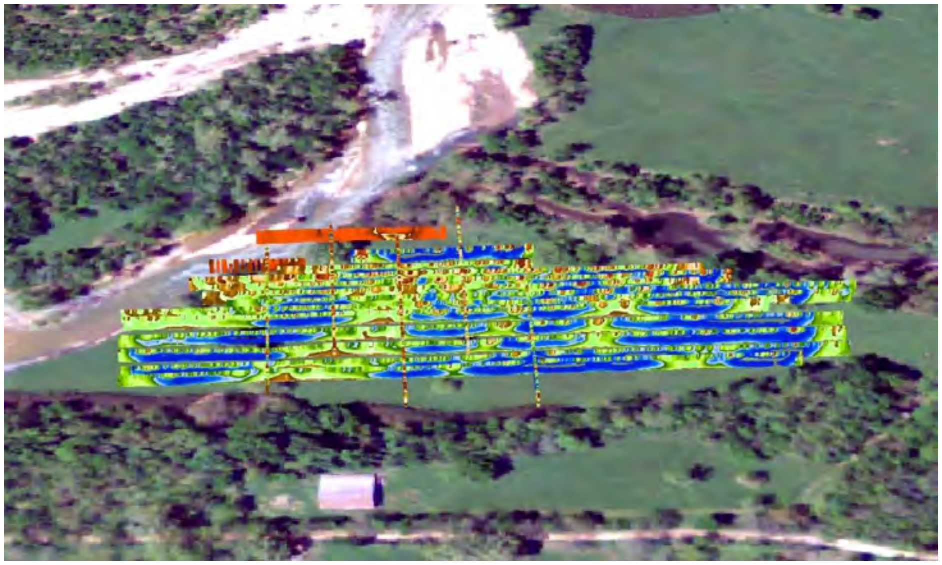


Figure 9. OhmMapper coverage of the Barren Fork Creek alluvial floodplain showing SW to NE trends of low (blue) and high (orange) resistivity. View is to the North and subsurface resistivity profiles are displayed above the aerial image for visualization purposes. Modified from Heeren et al. (2010).

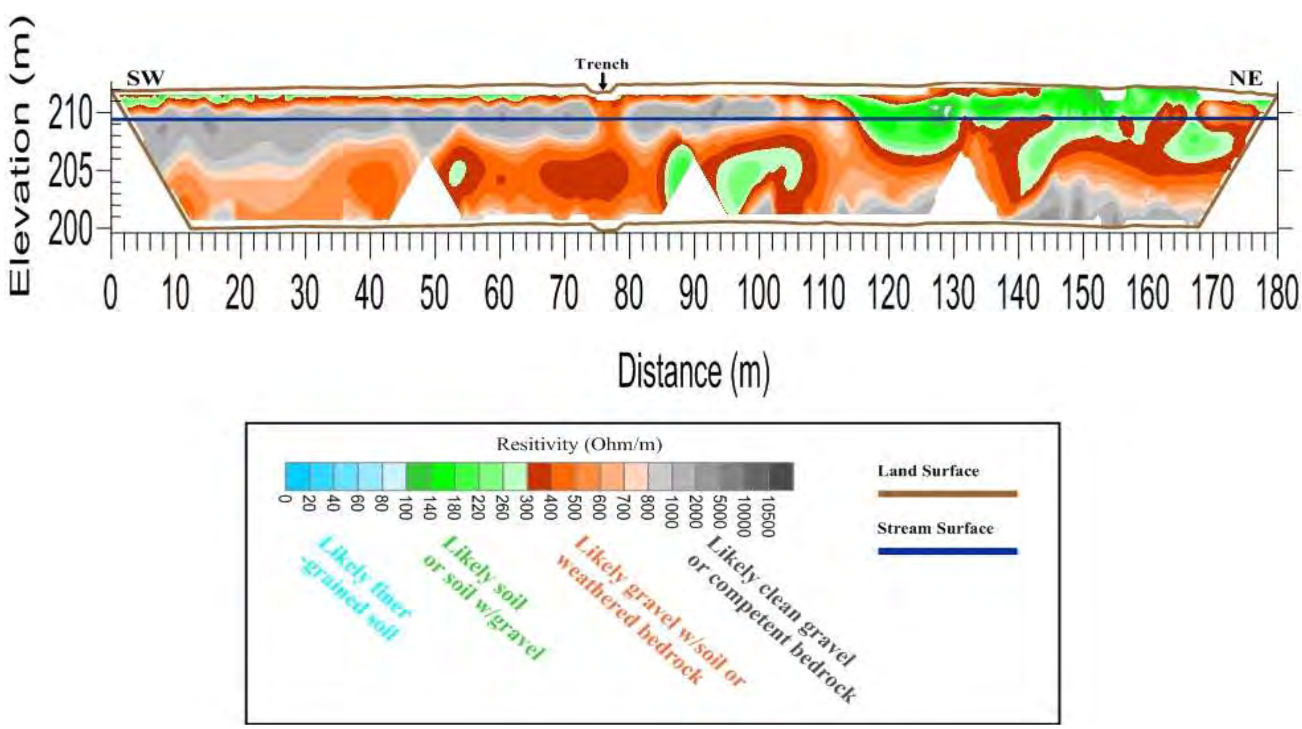


Figure 10. Composite SuperSting image, showing mapped electrical resistance (Ω-m), running southwest to northeast along a trench installed for studying subsurface phosphorus transport in the gravel subsoils by Fuchs et al. (2009). The *x*-axis represents the horizontal distance along the ground; the *y*-axis is elevation above mean sea level. Source: Heeren et al. (2010).

Pumpkin Hollow

Pumpkin Hollow differed from the other streams because it was a headwater stream with a smaller watershed area. The valley at the study site was approximately 200 m wide and the roll-along lines spanned nearly the entire valley width, crossing Pumpkin Hollow Creek at about the midpoint of the line. The ERI survey at Pumpkin Hollow consisted of three lines oriented W-E with 1 m electrode spacing, 12.5 m depth, and 97 m (lines 1-2 and 3-4) or 139 m (line 5-6-7) length (Figure 11).

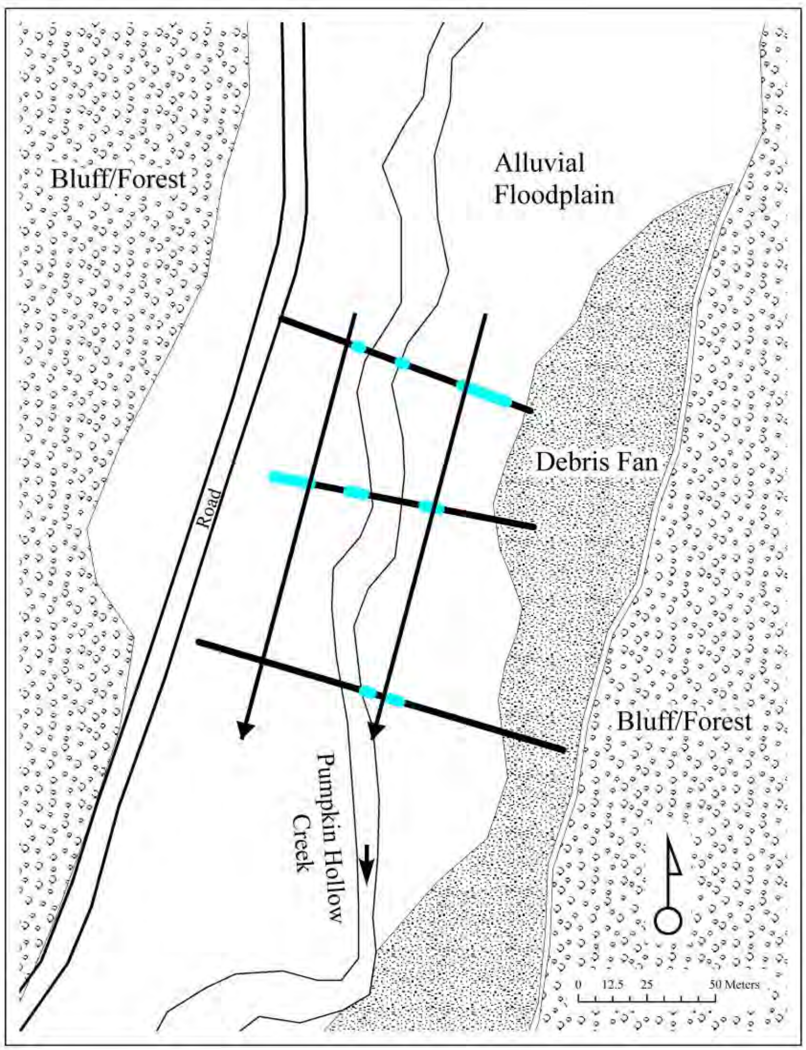


Figure 11. High resistivity feature locations on ERI lines at the Pumpkin Hollow site are shown in blue. Arrows represent potential connections between them and the direction of flow.

The Pumpkin Hollow ERI profiles also had a unique configuration consisting of a low resistivity layer between a high resistivity surface layer and high resistivity at depth (Figure 12). Observations at the site included the close proximity of large gravel debris fans originating from nearby upland areas. Jacobson and Gran (1999) noted similar pulses of gravel in Ozark streams in Missouri and Arkansas originating from 19th and early 20th century deforestation of plateau surfaces, implying that a possible interpretation of the low resistivity layer in the ERI profiles was a soil layer buried by gravel from the nearby plateau surfaces. The streambed elevation was approximately 262 m with the general floodplain surface being about 1 m above that elevation. The area of interest included the elevations above 262 m (note that the mean elevation was 262.9 m and that the maximum elevation 265 m occurred at the valley edge) and was therefore thin compared to the other study sites. The resistivity at Pumpkin Hollow ranged from 58 to 3110 Ω-m with a mean of 387 Ω-m. Like the other sites, the Pumpkin Hollow resistivity suggested a pattern of discrete areas of high resistance that indicated gravel outcrops (Figure 12). These were generally associated with topographic high areas and appeared to have the potential to direct flow down-valley parallel to the stream.

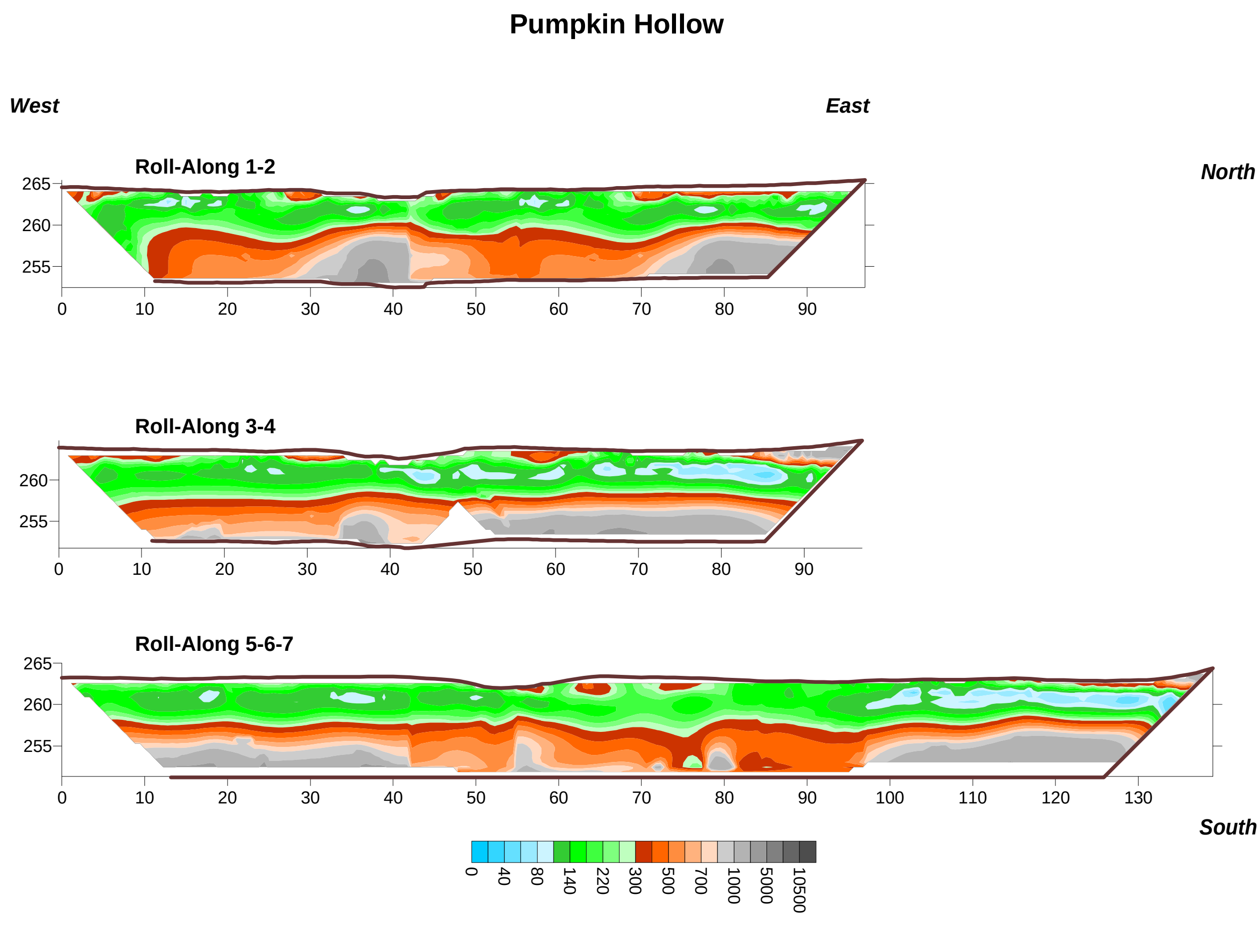
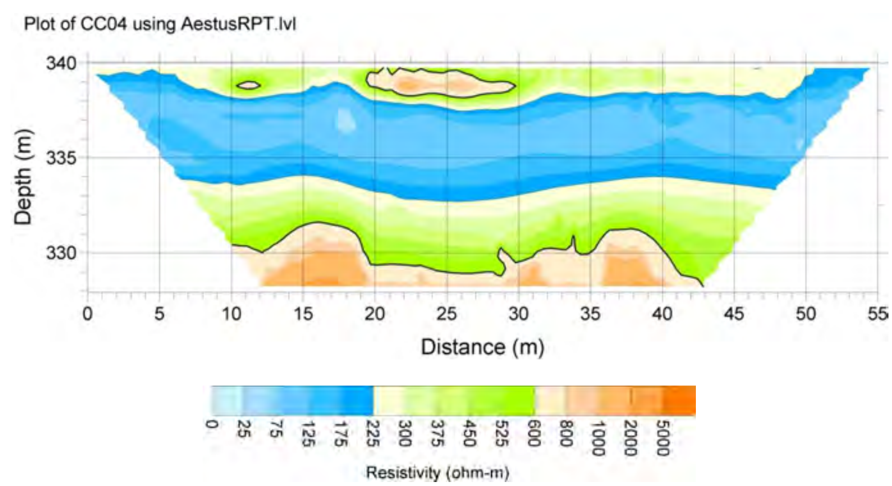


Figure 12. ERI images of three “roll-along” lines for the Pumpkin Hollow site. The *x*-axis represents the horizontal distance along the ground; the *y*-axis is elevation above mean sea level. The color bar is the electrical resistivity in Ohm-meters.

Clear Creek

Geophysical mapping was first performed between the overflow channel and Clear Creek shown in Figure 7; however, limited gravel outcrops were observed in this area and therefore the control (non-gravel outcrop) leaching experiments will be performed at this location (Figure 13a). Most of the shallow profile possessed electrical resistivities less than 450 Ω-m. On the east side of Clear Creek, layered profiles demonstrated the potential for lateral flow and transport to the stream, and this feature was clearly visible based on exposed streambanks and supported by the ERI data. Electrical resistivities at the surface were on the order of 600 to 1000 Ω-m with lower resistivity soils below this surface feature (Figure 13b).

(a)



(b)

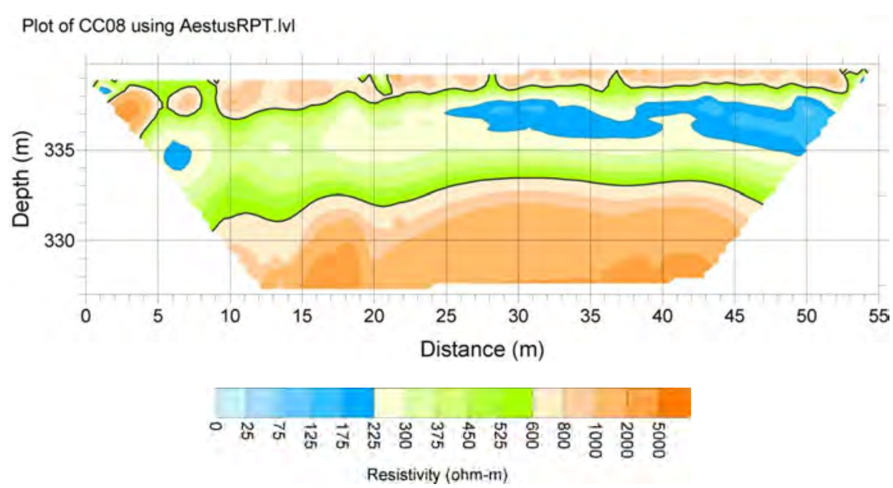


Figure 13. ERI images of two lines at the Clear Creek site where (a) is a line between the overflow channel and the creek with limited gravel outcrop area and (b) is a line on the east side of Clear Creek with gravel outcrops at the surface. The *x*-axis represents the horizontal distance along the ground; the *y*-axis is elevation above mean sea level.

Point Scale Laboratory Testing: Flow-Cell Experiments

Fine material (diameter less than 2.0 mm) from the Clear Creek site in Arkansas was used in laboratory flow-through experiments to investigate the P sorption characteristics with respect to the flow velocity (DeSutter et. al., 2006). Approximately 5.0 g of the fine materials was placed in each flow-through cell. A Whatman 42 filter was placed at the bottom of each cell to prevent the fine material from passing through the bottom. Each cell had a nozzle at the bottom with a hose running from the nozzle to a peristaltic pump (Figure 14). The pump pulled water with predetermined P and potassium chloride (KCl) concentrations through the cells and fine material at a known flow rate (mL/min).

Two different flow rates were used on the peristaltic pumps to evaluate the effect of velocity on P sorption. The flow rates were 0.20 mL/min for the low flow experiments and 0.75 mL/min for the high flow experiments. These flow rates corresponded to average flow velocities of 0.42 and 1.59 m/d, respectively. First, a 0.01M KCl solution was pulled through the soil to determine the background P that was removed from the soil. Then, a KH_2PO_4 and 0.01M KCl solution was injected into each cell at different concentrations (1.0 to 10.0 mg/L of P) and kept at a constant head using a Mariott bottle system (Figure 14). The experiments were run for approximately 8 hours. Samples were taken periodically throughout each experiment. The samples were analyzed in the laboratory for P using the Murphy-Riley (1962) method.

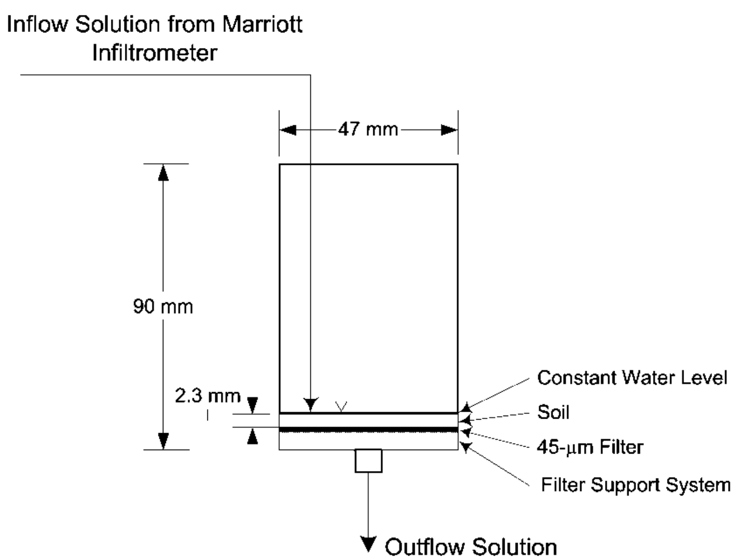
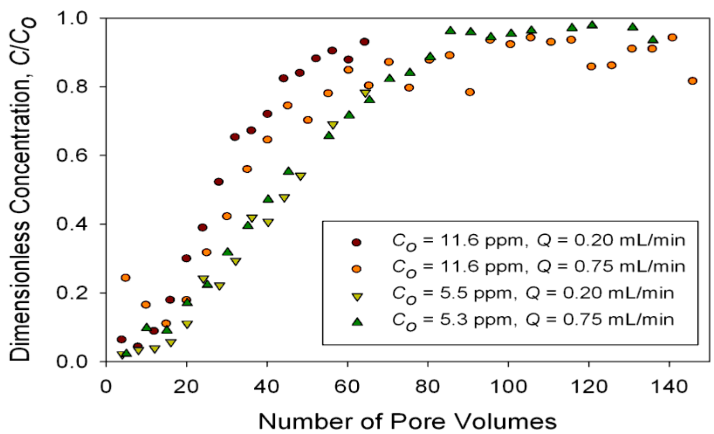


Figure 14. Laboratory flow-through experimental setup. The experimental setup follows that of DeSutter et al. (2006) and Fuchs et al. (2009).

Data were analyzed based on concentrations of P in the outflow compared to the total amount of P added to the system for both low flow and high flow scenarios. The principle of this method was that the measured P concentrations in the outflow should be approximately equal if flow velocity does not have an effect on P sorption. The mass of P added per kilogram of soil (mg P/kg soil) was found by multiplying *Q* (mL/min) by the inflow P concentration (mg/L) and by the elapsed time of the experiment (min). These data were plotted against the P concentrations (mg/L) detected in the outflow solutions for both flow velocities. If equivalent sorption was occurring, the curves associated with each data set would be approximately equal. Data were also analyzed using contaminant transport theory relative to the dimensionless concentration and number of pore volumes passed through the soil.

Both the contaminant transport and load perspectives suggested that the flow velocities in the experimental range had no effect on the sorption capabilities of the system, but instead illustrated that the initial P concentrations were important (Figure 15).

(a)



(b)

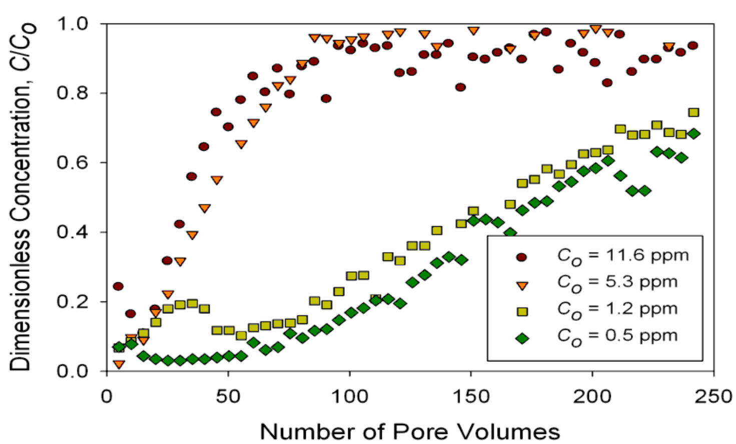


Figure 15. Phosphorus (P) breakthrough curves demonstrating (a) no influence of flow velocity on transport at the range of conditions studied and (b) influence of initial P concentration on transport.

Plot Scale Testing: Tracer/Rhodamine WT/P Infiltration Tests

As of May 2011, two leaching experiments (one 1 m^2 plot and one 9 m^2 plot) have been performed at both the Clear Creek and Pumpkin Hollow field sites. The Clear Creek experiments were performed in areas with limited gravel outcrops due to flooding in the area preventing access to the east side of Clear Creek. The Pumpkin Hollow leaching experiments were performed on areas of gravel outcrops as indicated from the electrical resistivity images.

A unique soil infiltration system was designed through the use of four steel connectors and 15.24-cm diameter hose (Figure 16). Specified lengths of the hose were placed in shallow trenches filled with bentonite clay, the hoses were then filled with water, and then the edges of the hoses were sealed with additional bentonite to prevent solutes from flowing underneath the berm. Therefore, water and solutes must travel through the soil matrix to leave the bermed area.

Figure 16. Filling of a 3 m by 3 m (9 m^2) bermed plot for the leaching experiments at Pumpkin Hollow with chloride tracer, Rhodamine WT, and phosphorus solution.

Prior to the leaching tests, two SuperSting DC resistivity meter (Advanced Geosciences, Inc., Austin, TX) electrode lines, crossing in the middle of the injection area, were setup to image the injection. Background images were obtained prior to water injection and then images were collected periodically throughout the experiment. The difference between the background image and the successive images will show the migration of the plume, and these images are currently being analyzed for each of the injection tests performed thus far.

Observation wells surrounding the plots were instrumented with water level loggers to automatically monitor water table elevation and temperature at 1-minute intervals during the experiments. Observation wells were installed to a depth of approximately 2.4 to 3.0 m at Clear Creek. Because of the unique layering at Pumpkin Hollow, both shallower (approximately 0.6 m below ground surface) and deeper (approximately 1.8 m below ground surface) observation wells were installed around the infiltration plot.

Stream water was pumped into the plot area through a water tank. A constant head of 3 to 5 cm was maintained inside the berm area. Pressure transducers were installed in the water tanks to monitor the water level change over time to quantify the total infiltration rate. Stream water was injected with a combination of potassium chloride (conservative and nonsorbing), Rhodamine WT (slightly sorbing), and P (highly sorbing). The target concentration in the ponded water was 100 mg/L chloride and Rhodamine WT, and 10 mg/L P (potassium phosphate). The inflow water was sampled throughout the experiment.

Conductivity sensors were used to indicate the initial detection of the leaching plume into the shallow groundwater based on periodic sampling from the observation wells. Approximately 250 mL samples were collected from each observation well at numerous times throughout the experiment from the top 10 to 25 cm of groundwater with a peristaltic pump using low-volume pumping as performed by Fuchs et al. (2009). Sampling continued for 24 to 48 hrs, or until the P concentration approached the inflow concentration in the ponded water. Samples from these first four leaching experiments are currently being tested for both total phosphorus and dissolved reactive phosphorus in the AWRC Water Quality Laboratory on the University of Arkansas campus.

Preliminary results from the early leaching tests are promising in terms of both the experimental design and results. Detection of Rhodamine WT was observed in deep observation wells at the Clear Creek site three to six hours after starting the leaching experiments, suggesting the presence of preferential flow. Tests at Pumpkin Hollow demonstrated rapid leaching in the shallow gravel layers at the soil surface and rapid lateral subsurface transport to the stream located approximately 15 m from the 9 m^2 plot. Rhodamine WT injected in the 9 m^2 plot at Pumpkin Hollow was visibly present in the stream approximately 1.5 hours after initiating the leaching experiment (Figure 17).

Figure 17. Leaching test on a 3 m by 3 m (9 m^2) plot at Pumpkin Hollow which demonstrated rapid leaching in the shallow gravel layers at the soil surface and rapid lateral subsurface transport to the stream located approximately 15 m from the plot. Rhodamine WT injected in the plot was visibly present in the soil approximately 1.5 hours after initiating the leaching experiment.

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(2) PUBLICATIONS

None to report at this time.

(3) INFORMATION TRANSFER PROGRAM

A project website on subsurface P transport has been created with links to relevant publications and data from the project (http://biosystems.okstate.edu/Home/gareyf/ AlluvialPTransport.htm). Because the results are preliminary at this time, no presentations have been given on the project, but multiple future presentations are planned. The PI and co-PIs were scheduled to give a field tour and research demonstration on April 27, 2011 in conjunction with a karst hydrology working group meeting of the USGS. However, due to flooding in Arkansas and Oklahoma, the field demonstration was cancelled. The research team has been invited to present initial research results to the Arkansas Water Quality Research Conference on July 6-7, 2011. The PI, co-PIs, and students will appear on an informative segment on the Oklahoma State University SUNUP

TV program for the Oklahoma agricultural community this summer. Research results and field methods will be incorporated immediately into an environmental contaminant transport class for graduate students this summer.

(4) STUDENT SUPPORT

Support has been provided for two graduate students (Ph.D. student in Biosystems and Agricultural Engineering at Oklahoma State and a Master of Science student in Environmental Sciences at Oklahoma State University) and two undergraduate students. Also, the research supported a 2010-2011 Oklahoma State University Wentz Research Scholars project for an additional undergraduate student.

Student Status	Number	Disciplines
Undergraduate	3	Biosystems Engineering
M.S.	1	Environmental Sciences (Geology)
Ph.D.	1	Biosystems Engineering
Post Doc		
Total	5	

(5) STUDENT INTERSHIP PROGRAM

No students completed an internship during the reporting period.

(6) NOTABLE ACHIEVEMENTS AND AWARDS

None to report at this time.

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:	2010OK191B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	3
Research Category:	Not Applicable
Focus Category:	Education, Law, Institutions, and Policy, Management and Planning
Descriptors:	None
Principal Investigators:	Will J Focht, Jeri Fleming, Mike Langston

Publications

There are no publications.

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 2010, OWRRI undertook five 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) holding a 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 2010, *The Aquahoman* was produced three times: May, September, and December. 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. It is also posted on our website.

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 2010, the WRAB met twice. 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. The July 2010 meeting included an update on the State's water planning effort, presentations on the results of the 2009 OWRRI-funded projects, and selection of the funding priorities for 2011. The funding priorities are distributed as part of the RFP for the annual competition.

Website: The OWRRI continues to maintain an up-to-date website 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 offer 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: 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 addition, she regularly speaks as an invited guest at events that offer CLE credit for those in the legal profession.

In another training effort, OWRRI, the Oklahoma Academy for State Goals, and the Oklahoma Water Resources Board conducted a three-day Water Town Hall as part of the effort to revise the state's water plan. The purpose of the meeting was to develop policy options for the water plan, but the preparation process required that the 150 attendees read a 200-page background document ensuring that they would all have a good understanding of state water issues.

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 Scott Huler, author of *On the Grid*. The two-day event drew over 500 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, Choctaw, Iowa and Chickasaw Nations). At the 2010 Symposium, the 29 student posters from three universities were joined by professional posters from seven state agency personnel or university professors.

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	6	3	0	0	9
Masters	5	2	0	0	7
Ph.D.	1	2	0	0	3
Post-Doc.	1	0	0	0	1
Total	13	7	0	0	20

Notable Awards and Achievements

In 2010, 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, thirty half-day workshops in 2009 to develop potential solutions to these issues, and in 2010 a Water Town Hall meeting to refine and select the final solutions to be included in the water plan.

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

1. 2003OK16B ("Algal-nutrient dynamics in fresh waters: direct and indirect effects of zooplankton grazing and nutrient remineralization") - Articles in Refereed Scientific Journals - Remmel, Emily J., Nicoel Kohmescher, James H. Larson, and K. David Hambright. 2011. An experimental analysis of harmful algae-zooplankton intereactions and the ultimate defense. Limnolo. Oceanogr., 56(2), 461-470.