Oklahoma Water Resources Center

2015 Annual Research Report

Research conducted March 1, 2015 – February 29, 2016

Published June 2016

TABLE OF CONTENTS

2015-2016 Annual Report
Research and Information Transfer conducted March 1, 2015-February 29, 2016

Introduction

The Oklahoma Water Resources Center was under the leadership of Dr. Garey Fox (Director) and Mrs. Leslie Elmore (Program Coordinator). Staff housed in the Oklahoma Water Resources Center also expanded as part of taking a leadership role on a current National Science Foundation (NSF) Experimental Program to Stimulate Competitive Research (EPSCoR) Research Infrastructure and Improvement project. Significant progress was made in 2015-2016 to address priority research, outreach, and education needs related to water in Oklahoma. Some of the major accomplishments are highlighted below:

1. The Oklahoma Water Resources Center successfully administered three extended USGS 104(b) projects from 2014 and three USGS 104(b) grants of $25,000 each funded in 2015. Funding from the USGS 104(b) program provided $25,000, which was matched 2:1 with funding from the PI's university.

2. The Oklahoma Water Resources Center expanded its membership on the Water Research Advisory Board (Board) to include two other federal agencies working in water in Oklahoma: the USDA-ARS and the National Weather Service Tulsa River Forecast Office, and two tribes: the Choctaw and Chickasaw Nations.

3. The Oklahoma Water Resources Center awarded three research grants of $25,000 each that started March 1, 2016. Projects that were funded included the following (more details below):
    - *Algal Remediation of Waste Water Produced during Hydraulic Fracturing* (Nurhan Dunford)
    - *Western Oklahoma Irrigation Water and Energy Audits: Findings, Recommendations and Educational Materials* (Scott Frazier, Saleh Taghvaeian, Jason Warren, Don Sternitzke, Cameron Murley)
    - *Evaluating the Reuse of Swine Lagoon Effluent and Recycled Municipal Water for Agricultural Production* (Hailin Zhang, Doug Hamilton, Saleh Taghvaeian, Scott Carter)

4. Dr. Garey Fox was appointed as the Lead Researcher on $20 million NSF EPSCoR project on Adapting Socio-Ecological Systems to Climate Variability. The current Oklahoma NSF EPSCoR award is focused on understanding how social and ecological systems can adapt water resource management with increased climate variability, especially as it relates to

drought. It is a multi-institutional collaborative project that includes researchers from Oklahoma State University, University of Oklahoma, University of Tulsa, and the Noble Foundation. The project specifically provides for a full-time Program Coordinator (Mrs. Emma Kuster) housed in the Oklahoma Water Resources Center and a Post-Doctorate Researcher (Dr. Ron Miller).

5. The Oklahoma Water Resources Center initiated a new Faculty Fellows Program through our Thomas E. Berry Professorship in Integrated Water Research and Management. This program recognizes faculty, Extension educators, and district specialists who are making outstanding contributions in research, Extension, or education in water. The 2015-2017 Berry Fellows and their projects include the following:
    - **Dr. Francisco Ochoa-Corona**, Associate Professor in Entomology and Plant Pathology – *Field Deployable Water Filtration System with Bioinformatics and Pyrosequencing for Effective Monitoring and Survey of Water-Borne Viruses*
    - **Dr. Glenn Brown**, Regents Professor of Biosystems and Agricultural Engineering – *The Application of Fly Ash to Treat Storm Water around Poultry Houses*
    - **Ms. Cheryl Newberry**, District Program Specialist-4H, Oklahoma Cooperative Extension Service – *Youth Water Education and Water Fairs*
    - **Dr. Jason Warren**, Associate Professor of Plant and Soil Sciences – *On-Farm Subsurface Drip Irrigation: How does Soil Type Impact Efficiency and Management*

6. The Oklahoma Water Resources Center co-sponsored and co-hosted the 36th Annual Oklahoma Governor's Water Conference and Research Symposium at the Embassy Suites Hotel and Conference Center in Norman, OK on December 1-2, 2015. The theme of this year's meeting was Drought-Proofing Oklahoma. The meeting included over 400 attendees. The invited speaker of the Oklahoma Water Resources Center was Dr. James Butler, Jr. (Research Scientist with the Kansas Geological Survey), who discussed water monitoring in the state of Kansas under its prior appropriation groundwater system. (Video available at https://www.youtube.com/watch?v=mMd1cDJLLUA&feature=youtu.be). A special Café-Style Poster Session was held at the conference to encourage student participation and interaction with the registrants.

7. The Oklahoma Water Resources Center organized and hosted the 2015 Student Water Conference (http://water.okstate.edu/students/swc) held March 24-25, 2015, held in conjunction with Okstate Water Week (http://water.okstate.edu/activities/okstate-water-week) and its theme of "Water and Sustainable Development" (following the UN World Water Day Theme).

8. The Oklahoma Water Resources Center hired a part-time staff writer, partially funded through the Division of Agricultural Sciences and Natural Resources at Oklahoma State University to assist in documenting the impact of research grant projects, especially the USGS 104(b) grants program, and also create stories around successful water projects funded by our program. These stories were included in our newsletter.

9. Our newsletter, *The Aquahoman* (http://water.okstate.edu/library/aquahoman-newsletters), was published quarterly this past year (February 2015, May 2015, August 2015, December 2015, and March 2016). We continue to include a special student section of the newsletter to highlight student-related events such as the Student Water Conference and opportunities for undergraduates, including research through a funded National Science Foundation (NSF) Research Experience for Undergraduates (REU).

10. The Oklahoma Water Resources Center finished a video series called the *Foundations of Oklahoma Water*, accessible at www.youtube.com/user/OkstateWaterCenter. The video series includes an introduction to the Oklahoma Water Resources Center and information on hydrology, irrigation (ag and urban), water law/policy, and the Oklahoma Mesonet. The public and county Extension educators will also be able to readily identify appropriate Extension specialists to address specific water-related questions. The *Foundations of Oklahoma Water* video series was selected to receive national recognition with a Blue Ribbon Educational Aids Award through the American Society of Agricultural and Biological Engineers (ASABE) in July 2015.

11. The Oklahoma Water Resources Center organized and directed a summer NSF Research Experience for Undergraduates (REU) at Oklahoma State University. We hosted seven students (88 original applicants) from various universities across the United States: Clark University, Illinois Wesleyan University, Iowa State University, Southeastern Oklahoma State University, University of Connecticut, University of Maryland Baltimore County, and University of Puget Sound from May 25-July 31, 2015. The SUNUP TV program did a special segment on the students and their research projects: The students also participated in STEM outreach by interacting with the Jones STEM Academy for Native American Students. Information and videos are included on http://water.okstate.edu/students/nsf-reu/2015-reu.

Research Program

2015 Projects:

The Oklahoma Water Resources Center successfully administered three research projects funded in 2015:

1. *Threats to the Lugert-Altus Irrigation District: Untangling the Effects of Drought, Land Use Change, and Groundwater Pumping*
   PI: Tyson E. Ochsner, Yohannes Tadesse Yimam, and Erik S. Kruger

2. *Quantifying Streambank Erosion and Phosphorus Load for Watershed Assessment and Planning*
   PI: Dan Storm

3 *Optimizing the Economic Value of Water from the Ogallala used for Irrigation*
   PIs: Jason Warren, Rick Kochenower, Jody Campiche, Rodney Jones, and Art Stoecker

These 2015 projects have been successfully completed and final reports are included in this document

Selection of 2016 Projects:

Research pre-proposals were solicited from any Oklahoma university starting in late April 2015. One-page pre-proposals were due in June 2015. The 25-member Water Research Advisory Board (Board) then reviewed and discussed these pre-proposals at the summer Board meeting held in Ada, OK and hosted by the US EPA Kerr Laboratory (a member of the Board). The Oklahoma Water Resources Center is planning to host future summer meetings of the Board at the work location of one of the Board representatives.

The Board selected eight projects to submit full proposals. Six full proposals were submitted (one researcher declined to submit two proposals). Each full proposal was externally reviewed by three reviewers solicited by Dr. Garey Fox, Director of the Oklahoma Water Resources Center, with guidance from the PI. Reviewers included at least one reviewer with detailed knowledge of the project objectives as they relate to Oklahoma water and two experts in the broader scientific field outside of Oklahoma. In January 2016 the researchers presented their proposals to the Board in 30-minute presentations in Stillwater, OK. After the presentations, the Board deliberated on the selection of the top three proposals. The Oklahoma Water Resources Center provided a ranking/classification scheme that summarized the external reviews. This input assisted the Board in incorporating the feedback from experts in each of the fields. The following three projects were selected for funding:

Algal Remediation of Waste Water Produced during Hydraulic Fracturing
PI: Nurhan Dunford

Microalgae are ubiquitous photosynthetic microorganisms that are found both in marine and freshwater environments with a great potential to produce not only biomass as feedstock for renewable fuels, high-value natural products, food, and feed applications but also to provide a valid solution to the problem of environmental pollution. In particular, they are able to grow using different nutrients (mainly N and P), heavy metals and other contaminants from different wastewaters such as agricultural and animal, municipal, as well as industrial. In addition, they can thrive using the CO2 emitted for instance by coal fired power plants thereby reducing greenhouse gas level in the atmosphere.

Western Oklahoma Irrigation Water and Energy Audits: Findings, Recommendations and Educational Materials
PIs: Scott Frazier, Saleh Taghvaeian, Jason Warren, Don Sternitzke, and Cameron Murley
Western Oklahoma is a semi-arid region that is very susceptible to drought and utilizes considerable amounts of irrigation water. Most of this irrigation is pumped ground water. Some of the irrigation is also shallow well or surface water. With water resources being consumed at higher rates for agricultural irrigation, farmers need to be as efficient as possible with the extraction and application of this resource. With increasing competition between rural and urban water needs, it will be necessary to document how well agricultural systems are utilizing water resources in order to maintain access.

Evaluating the Reuse of Swine Lagoon Effluent and Recycled Municipal Water for Agricultural Production
PIs: Hailin Zhang, Doug Hamilton, Saleh Taghvaeian, and Scott Carter
Significant amount of water in Oklahoma is used for crop irrigation. Water shortage in Oklahoma and the Southern Great Plains has become a major limitation for crop production and other uses, which will have a major impact on local economy. Therefore, alternative sources of irrigation water need to be explored. Treated municipal wastewater (TWW) is one of the most readily available alternative water sources, although infrastructures to use TWW for crop irrigation are lacking in most places and public acceptance is probably low because of the lack of field evaluations in the state. Currently, most TWW in the state is directly discharged to streams and rivers rather than recycled for crop production.

Information Transfer Program

An essential part of the mission of the Oklahoma Water Resources Center 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. In 2015, the Oklahoma Water Resources Center engaged in four primary efforts: (1) publication of a newsletter containing previous grant impact statements, (2) meetings with state agency personnel, (3) maintenance of an up-to-date website, and (4) holding of an annual Water Research Symposium and a Student Water Conference.

Newsletter: The Oklahoma Water Resources Center'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 public, but also informs researchers throughout the state about water research activities. This project year the newsletter was published in May 2015, August 2015, December 2015, and March 2016. *The Aquahoman* was 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 it. All issues of *The Aquahoman* are available on our website. New special sections of the newsletter included educational opportunities through the Student Water Conference and newly funded NSF Research Experience for Undergraduates (REU) held at Oklahoma State University, grant impact statements from previous recipients of USGS 104(b) funding and also a highlight of a Water Center faculty member.

Grant impact statements were developed this year based on 2008-, 2009-, and 2010-funded USGS 104b projects:

	Streamside Aquifers Blur the Boundaries between Groundwater and Surface Water -- Dr. Garey Fox explains how surface water and groundwater are naturally connected... Water agencies must understand the interconnection of these waters, especially as groundwater demand continues to increase in the southern Great Plains. (a 2009 funded project)
	Building Plans for Deteriorating Infrastructure -- The impact of this grant is far-reaching, influencing water infrastructure for many rural communities beyond the four studied in this project by Drs. Art Stoecker and Brian Whitacre. (a 2008 funded project)

	Improving Soil Moisture Monitoring by the Oklahoma Mesonet -- Dr. Tyson Ochsner's research team is increasing the functionality of the Oklahoma Mesonet with soil moisture monitoring. (a 2010 funded project)
THINK WATER	Shaping Oklahoman Water Knowledge -- Dr. Justin Moss's program has changed how and why Oklahomans conserve water in the landscape. (a 2010 funded project)

Water Research Advisory Board: The Board consists of 25 water professionals representing state agencies, federal agencies, tribes, and non-governmental organizations. This advisory board was formed in 2006 to assist 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 semi-annual 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 Board is an important part of the Oklahoma Water Resources Center's efforts to disseminate research findings to state agencies for use in problem-solving.

Website: The Oklahoma Water Resources Center 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 (all reports from 1965 to the previous project year are available for immediate download). Also available are current and past issues of *The Aquahoman*, and information about the annual grants competition including the RFP and guidelines for applying. The website also contains valuable information regarding grant impact statements from previously funded USGS 104(b) projects. The website is also a major source of information about the annual Research Symposium, including online registration, and the annual Student Water Conference.

The Oklahoma Water Resources Center significantly expanded the video content on the website this past year. As part of Dr. Fox's leadership, the Oklahoma Water Resources Center finalized a water video series called ***Foundations of Oklahoma Water*** (www.youtube.com/user/OkstateWaterCenter.) The Oklahoma Water Resources Center cooperated with Extension professionals to identify topics and participate in videos, and Craig Woods (Ag Communications Services) to produce the videos. Videos were advertised to all

Extension offices throughout the state. Funding was provided by Dr. Dwayne Elmore through the Renewable Resources Extension Act ($10,000). This list includes the title, participating Extension expert, release date, and # of views as of May 15, 2016:

- *Introduction to the Water Center* – Dr. Garey Fox (635 views)
- *Surface Water Hydrology* – Dr. Garey Fox (205 views)
- *Groundwater Hydrology* – Dr. Garey Fox (123 views)
- *Oklahoma Mesonet* – Dr. Garey Fox and Mr. Al Sutherland (107 views)
- *Flood Irrigation* – Dr. Saleh Taghvaeian (833 views)
- *Sprinkler Irrigation* – Dr. Saleh Taghvaeian (168 views)
- *Subsurface Irrigation* – Dr. Saleh Taghvaeian (150 views)
- *Measuring the Ogallala Aquifer* – Dr. Saleh Taghvaeian (52 views)
- *Outdoor Urban Irrigation* – Dr. Justin Moss (96 views)
- *Water Law* – Dr. Shannon Ferrell (210 views)
- *Water Testing* – Dr. Hailin Zhang (65 views)
- *Water Quality* – Dr. Jason Vogel (29 views)

Additionally we produced a video on conducting soil erosion tests with the Jet Erosion Test instrument - A collaborative project between Dr. Garey Fox and the USDA-ARS Hydraulic Engineering Research Unit (Director, Dr. Sherry Hunt) in Stillwater, OK (302 views).

Oklahoma Research Symposium and Student Water Conference: The Oklahoma Water Resources Center has held an annual Water Research Symposium since 2003. 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 in 2015, the Symposium was integrated with the Oklahoma Water Resources Board's annual Governor's Water Conference. The two-day event in Norman, OK drew over 400 water professionals, agency staff, politicians, members of the press, researchers, and interested citizens. This combination of events affords 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).

Specific to information transfer from a research perspective, the Oklahoma Water Resources Center invited Dr. James Butler, Jr. (Research Scientist, Kansas Geological Survey) as a keynote presentation. He discussed water monitoring in the state of Kansas under its prior appropriation groundwater system (video available here). The state is now considering how to use Dr. Butler's techniques for water management in the state.

The 2015 symposium included a unique Café-style poster session, where 27 students from universities across Oklahoma orally presented a two-minute overview of their poster followed by the designated poster session. These factors in concert promoted interaction between the students and the conference participants. Awards were given to those students at the end of the day in a joint session between the Oklahoma Water Resources Center and the Oklahoma Water Resources Board. Undergraduate and graduate students were eligible for outstanding poster awards. Five outstanding poster awards were presented with funds from the USGS 104b program, the Oklahoma section of the AWRA, and the Thomas E. Berry Endowed Professorship. The professorship funds also supported free student registration at the symposium.

In this project year, the Oklahoma Water Resources Center will again host the Symposium in conjunction with the Governor's Water Conference, assisting in all aspects of the logistics for the events, including planning, registration, speaker selection, and disseminating the presentations via our website.

The Oklahoma Water Resources Center organized and hosted the 2015 Student Water Conference (http://water.okstate.edu/students/swc) held March 24-25, 2015, held in conjunction with Okstate Water Week (http://water.okstate.edu/activities/okstate-water-week) and its theme of "Water and Sustainable Development" (following the UN World Water Day Theme). The week featured water events across campus sponsored and supported by student organization working with the Oklahoma Water Resources Center. The week concluded with the 4th Annual Student Water Conference, consisting entirely of student presentations judged by a panel of faculty members for providing constructive feedback to students in regard to their research presentation skills. Awards were given for outstanding student presentations. Also, student activities promoted interaction among students of all disciplines and professional development. In 2015, 57 students presented (25 oral presentations, 32 poster presentations) with 31 presentations by students visiting from outside universities. Students not from Oklahoma State University applied for and received travel assistantship grants supported through the Buchanan Family Trust through the Buchanan Endowed Chair and USDA NIFA through a National Integrated Water Quality grant. The Oklahoma Water Resources Center will organize the 6th Annual Student Water Conference to be held on March 24-25, 2016.

Student Support

Student Status	Number	Disciplines
Undergraduate	1 3	Biosystems Engineering Plant and Soil Sciences, Agricultural Economics
M.S.	4	Plant and Soil Sciences, Agricultural Economics
Ph.D.	2	Biosystems Engineering
Post Doc		
Total	10	

Notable Awards and Achievements

Major Awards Received by Dr. Fox and Water Center:

- 2015 National Award for Excellence in College and University Teaching in the Food and Agricultural Sciences
- 2015 Educational Aids Blue Ribbon Award for video series titled *Foundations of Oklahoma Water*
- 2015 Regents Distinguished Research Award at Oklahoma State University

Honors and Recognition:

- *Cowboy Journal* Magazine feature titled "Reflecting Excellence: OSU professor Garey Fox wins national teaching award" – Vol. 18(1), Winter/Spring 2016, pages 26-28

REFLECTING EXCELLENCE

OSU professor Garey Fox wins national teaching award

From a first-generation college student from a small Texas town to a nationally recognized water researcher and professor, Oklahoma State University biosystems and agricultural engineering professor Garey Fox serves the OSU College of Agricultural Sciences and Natural Resources in many roles.

In addition to prestigious awards and accreditations, Fox has an unyielding passion to see students succeed, said Steve Damron, CASNR assistant dean.

"His work with undergraduate students is the best example of his dedication," Damron said. "He works continually with undergraduate research scholars, and that takes a lot of effort, but he feels strongly that effort is worthwhile."

As one of only 35 graduates from Godley High School in 1994, Fox said he was the first of his family to leave the farm and go to college.

"I really had no idea what I wanted to do in school," Fox said, "but I knew I was really good at math and science. I got some large FFA scholarships through Texas FFA that required me to go to a public school in Texas and major in something agriculture-related."

At that time, Texas A&M University had an agricultural engineering program. Fox chose the engineering path, and he said he found his passion for research during his undergraduate years.

"I got connected with a faculty member while I was there who asked me if I wanted to do research with him, and I was like, 'Wow, they'll pay you to do that?'"

Fox said he enjoyed doing research as an undergraduate student and decided to earn his master's degree on a U.S. Environmental Protection Agency graduate fellowship, which he said is a prestigious national fellowship for master's and doctoral students in environmentally related fields of study.

After graduating from TAMU with a master's degree in agricultural engineering in 2000, Fox continued his studies as a doctoral student in civil engineering at Colorado State University.

Fox said he decided he wanted to go into academia while he was obtaining his doctoral degree.

"It turned out to be the best thing I've ever done," he said. "My passion is being in the classroom, field or laboratory, interacting with students, watching them grow, and seeing their accomplishments. It's a real pleasure."

Fox joined the OSU BAE department in 2006 and continued his research and teaching. The National Science Foundation, U.S. Geological Survey, EPA and USDA have supported his research of stream and aquifer interaction through competitive grant funds.

"Everyone knows if Dr. Fox is teaching, it's going to be a good class."
— Whitney Lisenbee, BAE Master's Student

"His work with accreditation in his department is absolutely stellar," Damron said. "He's recognized nationally as an expert on assessment as it's done in engineering, and I think that's quite remarkable."

While he may be a research expert, teaching and interacting with students are where Fox truly shines, said Whitney Lisenbee, a BAE master's student.

"Everyone knows if Dr. Fox is teaching it's going to be a good class," she said. "He's been my professor, research mentor, Cowboy Waterworks club adviser, senior design adviser and overall role model for nearly six years.

"Although he wears many hats, he is still available for 'life talks' with his students and wants us to succeed," she added.

Fox said he wants to ensure when his students graduate they are prepared for what they are going to do outside of OSU.

"I challenge them every single day," he said. "When I was in school, I had a lot of professors who didn't challenge me much. I don't remember them, but I do remember the ones who cared about students and challenged them."

When Fox came to Stillwater, he wanted to make OSU "the" water place, he said. One of the ways he has worked toward this goal is by creating and implementing the annual Student Water

Garey Fox conducts research on flow and sediment transport in streams. *Photo by Todd Johnson.*

26 | WINTER/SPRING 2016

COWBOY JOURNAL | 27

Publications

Peer-Reviewed Journal Articles:

- Zou CB, Caterina GL, Will RE, Stebler E, Turton D. 2015. Canopy Interception for a Tallgrass Prairie under Juniper Encroachment. PLOS One, 10(11), e0141422.45.
- Dale J, Zou CB, Andrews WJ, Long JM, Liang Y, Qiao, L. 2015. Climate, water use, and land surface transformation in an irrigation intensive watershed—Streamflow responses from 1950 through 2010. Agricultural Water Management 160:144-152.
- Qiao L, Zou CB, Will R, Stebler E. 2015. Calibration of physically based hydrological transport model using experimental watershed data for application in woody plant encroachment. Journal of Hydrology 523: 231-239.
- Daly, E., G.A. Fox, A.-T. Al-Madhhachi and D.E. Storm. 2015. Variability of fluvial erodibility parameters for streambanks on a watershed scale. *Geomorphology* 231: 281-291, doi: 10.1016/j.geomorph.2014.12.016.
- Daly, E., R.B. Miller, and G.A. Fox. 2015. Modeling streambank erosion and failure along protected and unprotected composite streambanks. *Advances in Water Resources*, Special Issue on Fluvial Eco-Hydraulics and Morphodynamics: New Insights and Challenges 81: 114-127, doi: 10.1016/j.advwatres.2015.01.004.
- Heeren, D.M., G.A. Fox, and D.E. Storm. 2015. Heterogeneity of infiltration rates in alluvial floodplains as measured with a berm infiltration technique. *Transactions of the ASABE* 58(3): 733-745, doi: 10.13031/trans.58.11056.
- Daly, E.R., G.A. Fox, H.K. Enlow, D.E. Storm, and S.L. Hunt. 2015. Site-scale variability of streambank fluvial erodibility parameters as measured with a Jet Erosion Test. *Hydrological Processes* 29(26): 5451-5464, doi: 10.1002/hyp.10547.
- Wine ML, Hendrickx JMH, Cadol D, Zou CB, Ochsner TE. 2015. Deep drainage sensitivity to climate, edaphic factors, and woody encroachment, Oklahoma, USA. Hydrological Process. DOI: 10.1002/hyp.10470.
- Zou BC, Qiao L, Wilcox BP. 2015. Woodland expansion in central Oklahoma will significantly reduce streamflows—A modeling analysis. Ecohydrology. doi: 10.1002/eco.1684.
- Miller, R.B., D.M. Heeren, G.A. Fox, T. Halihan, and D.E. Storm. 2016. Heterogeneity influences on stream water–groundwater interactions in a gravel-dominated floodplain. Hydrological Sciences Journal, doi: 10.1080/02626667.2014.992790.
- Daly, E.R., G.A. Fox, and A.K. Fox. 2016. Correlating erodibility parameters from jet erosion tests to soil physical properties at a site scale. Transactions of the ASABE 59(1): 115-128, doi: 10.13031/trans.59.11309.
- Criswell, D.T., A.T. Al-Madhhachi, G.A. Fox, and R.B. Miller. 2016. Deriving erodibility parameters of a mechanistic detachment model for gravels. Transactions of the ASABE 59(1): 145-151, doi: 10.13031/trans.59.11490.
- Purvis, R.A., and G.A. Fox. 2016. Streambank sediment loading rates at the watershed scale and the benefit of riparian protection. *Earth Surface Processes and Landforms* (In Press, Accepted January 5, 2016), doi: 10.1002/esp.3901.

Peer-Reviewed Journal Articles in Review:

- Yimam, Y., T. Ochsner, and G.A. Fox. Hydrologic cost-effect ratio favors switchgrass production on marginal croplands over existing grasslands. *Transactions of the ASABE*.
- Fox, G.A., A. Sheshukov, R. Cruse, R.L. Kolar, K.R. Gesch, and R.C. Dutnell. Reservoir sedimentation and upstream sediment sources: Perspectives and future research needs on streambank and gully erosion. *Environmental Management*.
- Halihan, T., R.B. Miller, D. Correll, D.M. Heeren, and G.A. Fox. Hydrogeophysical evaluation of a tracer test in a gravel alluvial aquifer with a natural capillary barrier. *Water Resources Research*.
- Mittelstet, A.R., D.E. Storm, G.A. Fox and P.M. Allen. Using SWAT to Predict Watershed-Scale Streambank Erosion on Composite Streambanks, Transactions of the ASABE, manuscript NRES-11666-2015 (review complete, revisions requested, revisions submitted)

Presentations and Abstracts

- Gatlin, J. 2015. Corn and Sorghum yield response to limited irrigation supplied by sub-surface drip. MS Thesis. Department of Plant and Soil Sciences, Collage of Agricultural Sciences and Natural Resources, Oklahoma State University, Stillwater, OK, 40p
- Mittelstet, A.R. 2015. Quantifying Phosphorus Loads and Streambank Erosion in the Ozark Highland Ecoregion Using the Swat Model, Ph.D. Dissertation, Biosystems and Agricultural Engineering Department, Oklahoma State University, Stillwater, Oklahoma, College, University, City, State, 170 p.
- Warren, J. 2015. Planting Strategies for Wheat Under SDI. Presented at the Oklahoma Irrigation Conference. Fort Cobb, OK. 18 Aug.
- Warren, J., D. Sims, and C. Murley. 2015. Alternative planting strategies for sub-surface drip. Presented at the Fall Crops Tour. Goodwell, OK. 21 Aug.
- Warren, J. 2015. Economics of Irrigated Corn vs. Grain Sorghum. Presented at the Winter Crops Clinic. Goodwell, OK. 10 Apr.
- Gatlin, J., and J. Warren. 2014. Subsurface Drip Technology & Research. Fall Crops Tour. Goodwell, OK 13 Aug.
- Warren, J. 2014. Subsurface Drip Irrigation. Sorghum Tour. Goodwell, OK 25 July. Warren, J.G., R Kochenower, J. Gatlin, and C. Murley. 2013. Grain Sorghum and Corn Productivity under limted irrigation. Presented at the Oklahoma Water Research Symposium. Midwest City, OK on 23 Oct.
- Warren, J. 2013. Subsurface Drip Irrigation. Presented at the Oklahoma Panhandle Research and Extension Center Crops Clinic. Goodwell, OK. 14 Mar.

- Gatlin, J., and J.G. Warren. 2014. Comparison of grain sorghum and corn productivity under limited irrigation with subsurface drip. In ASA-CSSA and SSSA abstracts. Available online at: https://scisoc.confex.com/scisoc/2014am/webprogram/Paper86030.html
- Gatlin, J., and J.G. Warren. 2013. Comparison of grain sorghum and corn production with subsurface drip. In ASA-CSSA and SSSA abstracts. Available online at: https://scisoc.confex.com/scisoc/2013am/webprogram/Paper80177.html

Funding

Funding for the projects reported herein was provided by the U.S. Geological Survey and the Division of Agricultural Sciences and Natural Resources at Oklahoma State University. Additional support was provided by private donations to the Thomas E. Berry Endowed Professorship in Integrated Water Resources and Management and external grant funding from the NSF through a research infrastructure and improvement grant through EPSCoR and a USDA AFRI National Integrated Water Quality Program (NIWQP). Research projects through the USGS 104(b) program included in-kind services made available by the researchers' institutions. The Oklahoma Water Resources Center is grateful for their support.

Final Report – Ochsner et al. USGS 104b Project FY2015

Title: Threats to the Lugert-Altus Irrigation District: Untangling the Effects of Drought, Land Use Change, and Groundwater Development

Authors' Names and Affiliations:

Tyson E. Ochsner, Associate Professor, Department of Plant and Soil Sciences, 371 Agricultural Hall, Oklahoma State University, Stillwater, OK 74078. Phone: 405-744-3627. Email: tyson.ochsner@okstate.edu

Yohannes T. Yimam, Post-Doctoral Research Associate, Department of Soil and Crop Sciences, 542 Heep Center, Texas A&M University, College Station, TX 77843-2474. Phone: 979-845-4678. Email: yohannes.yimam@tamu.edu.

Erik S. Krueger, Research Associate, Department of Plant and Soil Sciences, 371 Agricultural Hall, Oklahoma State University, Stillwater, OK 74078. Phone: 906-249-1397. Email: erik.krueger@okstate.edu.

Start Date: 3/1/2015
End Date: 2/29/2016

Congressional District: 3rd

Focus Category: AG, DROU, GW, SW, WQN, WU

Descriptors: Streamflow, groundwater, climate.

Students: none

Principal Investigators:
Tyson E. Ochsner (PI), Associate Professor, Oklahoma State University.
Yohannes T. Yimam (co-PI), Post-Doctoral Research Associate, Texas A&M University.
Erik Krueger (co-PI), Research Associate, Oklahoma State University.

Publications:
Krueger, E.S., Y.T. Yimam, and T.E. Ochsner. 2016. Threats to a surface water irrigation district in the US southern Great Plains: Changes in streamflow driven more by human than climate factors. Manuscript in preparation.

Problem and Research Objectives:

Statement of Critical Regional or State Water Problem

As of October 1, 2014, Lake Altus-Lugert, the primary water supply for the Lugert-Altus Irrigation District (LAID) in southwest Oklahoma, was only 10% full, was recovering from a golden algae bloom which killed all fish in the lake, and did not contain enough water to produce an irrigated cotton crop until 2015. Severe drought in 2011 and 2012 played a major role in the demise of the lake, but local residents suspected upstream land use change and groundwater development may have contributed. Furthermore, according to the Southern Climatic Impact Planning Program (SCIPP), the climate of the region is changing in both precipitation and evapotranspiration, and the region may face increased frequency and severity of drought. The relative importance of these various contributing factors was unknown, and the future of the lake, the irrigation district, and the Altus community which depends on both is highly uncertain. There was a pressing need for research to better understand the drivers of change in this regionally-significant watershed.

Nature, Scope, and Objectives of the Project

The long term goal of this research group is to identify strategies by which the community of Altus can successfully adapt to changing water availability. *The objective of this proposal was to evaluate the effects of climate, groundwater development, and land use change on streamflow into Lake Altus-Lugert.* To accomplish our objective, we devised three specific aims:

Specific Aim #1: Quantify changes in streamflow, climate, groundwater use, and land use in the North Fork of the Red River watershed upstream from Lake Altus-Lugert from 1970-2014

Significant changes and trends in precipitation, reference evapotranspiration (ET_0), groundwater use (for irrigation and non-irrigation), land use (i.e. planted acres), streamflow, and baseflow were identified for the 45-yr period from 1970-2014 and also for relevant sub-periods within the study.

Specific Aim #2: Determine the relative contributions of climate and human factors to changes in flow.

The relative contributions of climate and human factors to changes in flow variables were determined using the climate elasticity model.

Specific Aim #3: Develop statistical models describing the relationships of climate and human variables with flow.

Multiple regression was used to model annual streamflow and baseflow using climate and human variables that were significantly correlated with each flow variable. Variables included precipitation, ET_0, ground water use for irrigation and non-irrigation in the Oklahoma and Texas portions of the watershed, and one year lagged values for each of these variables.

Methodology:

Streamflow

Inflow into Lake Altus-Lugert is determined from changes in reservoir storage volume each month by the United States Department of Interior Bureau of Reclamation (USDOI BOR) (USDOI BOR, 2015), and inflow data obtained from 1970-2014 were used to calculate baseflow, the portion of streamflow that comes from groundwater discharge. The period 1970-2014 was chosen because groundwater and land use datasets prior to 1970 were incomplete. Each flow variable was reported on a water year basis (1 October – 30 September) as a depth of water (water volume divided by watershed area). Baseflow was calculated using the recursive digital filter method (Nathan and McMahon, 1990) on monthly data (Smakhtin, 2001). For month *m*, baseflow was calculated as

$$q_m = \beta\, q_{m-1} + 0.5(1+\beta)(Q_m - Q_{m-1}) \quad [1]$$

$$QB_m = Q_m - q_m \quad [2]$$

where q is the filtered monthly inflow, Q is total monthly inflow, β is the filter parameter, and QB is the monthly baseflow. A default β value of 0.925 has been suggested (Nathan and McMahon, 1990), but the optimal value varies by stream. Although baseflow is typically calculated on a daily basis (Smakhtin, 2001), it was necessary to calculate it from monthly data because daily inflow data were not available through the USDOI BOR. Monthly baseflow for Lake Altus-Lugert was calculated after determining the optimal β value for this stream using daily streamflow data from nearby USGS gage station 07301500

(USGS WR, 2015). The station is located approximately 25 km upstream of Lake Altus-Lugert (Fig. 1), and 6870 km^2 of the watershed (94%) is upstream of this station.

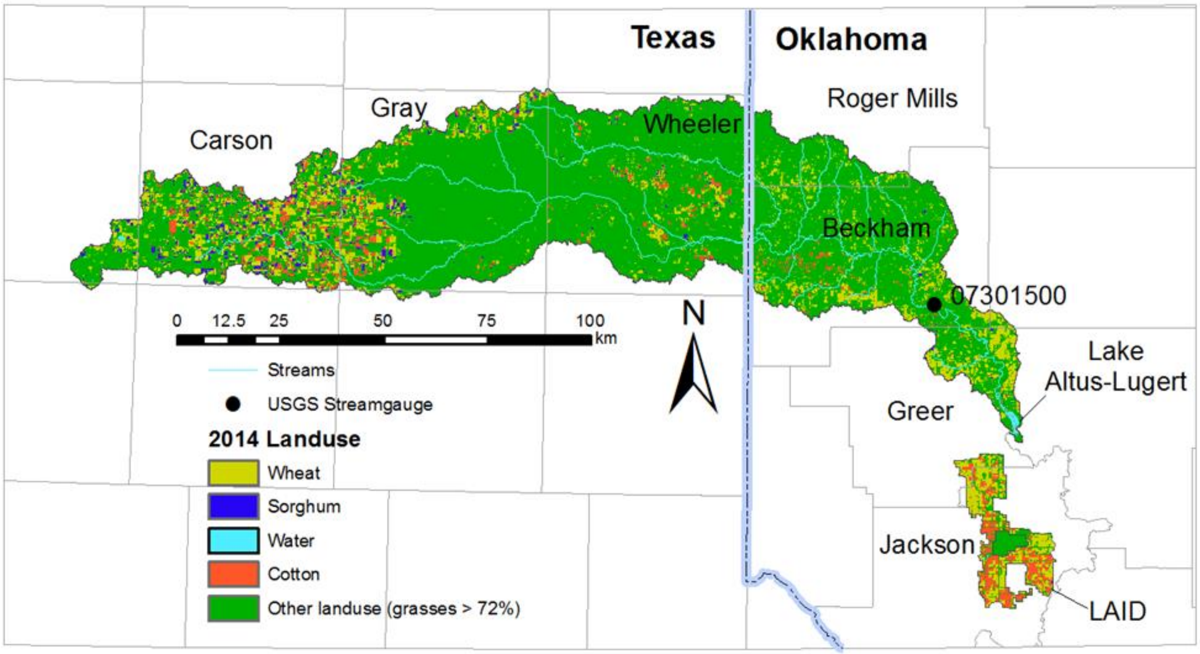


Figure 1. The North Fork of the Red River (North Fork) watershed upstream from Lake Altus-Lugert stretches from the central Texas Panhandle to southwest Oklahoma, covering approximately 7,300 km^2. The Lugert-Altus Irrigation District (LAID) is downstream (south) of Lake Altus-Lugert.

Monthly baseflow for Lake Altus-Lugert was determined by (1) calculating baseflow from daily data from nearby station 07301500 for a range of β values and comparing the results with previously published baseflow data for that station, (2) calculating baseflow from monthly data for station 07301500 and comparing the results with those from step 1, and (3) using the β from step 2 to calculate baseflow from monthly Lake Altus-Lugert inflow. In step one, annual baseflow for station 07301500 was calculated from daily streamflow data (1945-1999), with β adjusted until the resulting calculated baseflow was similar to that reported by Smith and Wahl (2003) for the 1945-1999 period. This step allowed us to determine the optimal β value for calculating baseflow from daily data for station 07301500 (β = 0.985). Baseflow calculated in this way resulted in a median annual baseflow of 4.4 mm, which is comparable to the value of 3.9 mm reported by Smith and Wahl (2003). In step 2, monthly baseflow was calculated after aggregating daily streamflow data for station 07301500 for each month. The value of β was adjusted until baseflow calculated from monthly streamflow data (step 2) most closely matched baseflow calculated from daily streamflow data (step 1) as suggested by Smakhtin (2001). A β value of 0.630 was optimal, resulting in a Pearson correlation coefficient of 0.91 ($P < 0.001$) between monthly baseflow calculated from daily and monthly streamflow data. Finally, in step 3, the β value of 0.630 was applied to monthly inflow data for Lake-Altus Lugert, and monthly baseflow was calculated.

Precipitation and ET_0

Areal average annual precipitation and reference evapotranspiration (ET_0) were calculated using monthly data retrieved from weather stations within or near the watershed, which included total monthly precipitation and monthly minimum, maximum, and mean temperature (NOAA-NCEI, 2015). Only weather stations with a data record completeness of at least 80% from 1965-2014 were included, resulting in 17 possible stations for precipitation and 15 for temperature. To fill missing data, monthly precipitation or temperature data for each station were correlated against data from all other stations, and data were filled using data from the station with the highest correlation (Peel et al., 2010). If data from the most highly correlated station were also missing, data from the next most highly correlated station were used. Data were generally filled after one attempt, but up to three attempts were necessary in some cases. The correlation coefficients of stations used to fill missing data ranged from 0.70-0.92 for precipitation and were > 0.99 for temperature.

Monthly ET_0 was calculated from filled temperature data using the Hargreaves method, which requires only temperature and extraterrestrial radiation as inputs (Hargreaves and Allen, 2003). The method is commonly used when temperature is the only available weather input (Peel et al., 2010; Sankarasubramanian et al., 2001; Tomer and Schilling, 2009) and has shown reasonable results without local calibration (Allen et al., 1998b). Reference evapotranspiration was calculated as:

$$ET_0 = 0.0023\, R_a\, (T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} \qquad [3]$$

where ET_0 is monthly reference evapotranspiration (mm), R_a is monthly extraterrestrial radiation (mm), and T_{mean}, T_{max}, and T_{min} are monthly mean, maximum, and minimum temperatures (°C), respectively. Extraterrestrial radiation was calculated according to Allen et al. (1998b) using the latitude of each weather station, with monthly sums calculated by multiplying the value at the midpoint of each month by the number of days in the month.

Areal average precipitation and reference evapotranspiration for each water year (1 October – 30 September) were calculated using the Thiessen polygon method (Thiessen, 1911), a commonly used area-weighted average technique (Wang, 2014). Averages were calculated by weighting each station by the proportion of its Thiessen polygon within the watershed, multiplying data values at each station by its weight, and summing values across all stations. For precipitation, data from 11 of a possible 17 stations had Thiessen weights > 0 and were used (i.e., their polygons overlapped the watershed), while data from 9 of a possible 15 stations were used for ET_0, resulting in a spatial measurement density of one station per 668 and 816 km^2 for precipitation and ET_0, respectively. For the stations used, 98% of data were present for precipitation and 95% of data were present for ET_0.

Groundwater and land use

Groundwater use data in the Oklahoma portion of the watershed from 1970-2014 were obtained from the Oklahoma Water Resources Board. Data included estimated annual water use for each permitted well in the North Fork Red River Alluvial Aquifer and were separated by use: irrigated agriculture, public, industrial, commercial, mining, power generation, and recreation. Groundwater use is not measured, but instead data were compiled by the Oklahoma Water Resources Board from estimates of individual waters users. Unlike Texas data that included groundwater use at the county level, Oklahoma data were limited only to those wells in the North Fork Red River Alluvial Aquifer. The aquifer is of major importance along the Oklahoma portion of the river (Ryder, 1996) where it sustains streamflow most of the year (Kent, 1980). A small portion of the alluvial aquifer extends across the state line into southeastern Wheeler County, Texas (Ryder, 1996), but data from this portion of the alluvial aquifer were not available. We did not attempt to assess the impact of surface water diversions upstream of Lake Altus-Lugert on streamflow because permitted diversions are minor, representing < 1% of average annual lake inflow (OWRB, 2016; USDOI BOR, 2015).

Groundwater use data in the Texas portion of the watershed were obtained for Carson, Gray, and Wheeler counties from 1970-1980 and 1985-2013 (TWDB, 2015). Data prior to 1970 were available only for the years 1958, 1964, and 1969. Data included estimated groundwater use for irrigated agriculture (1985-2013 only), municipalities, manufacturing, mining, power generation, and livestock.

Irrigation data for 1974, 1979, 1984, 1989, 1994, and 2000 were obtained from a secondary source (TWDB, 2001). The two datasets contained the same information during the years for which they overlapped (1989, 1994, and 2000), suggesting continuity between them. Groundwater use estimates for municipalities, manufacturing, mining, and steam-electric power sources were derived from annual surveys, whereas annual groundwater use by livestock was estimated from animal populations and typical water use per animal. Groundwater use for irrigated crop production was estimated using annual irrigated cropland data and ET_0, with final estimates reviewed by local authorities (TWDB, 2015). The aquifer from which the groundwater was withdrawn was included for most annual estimates, with 98% of groundwater use by volume in the Texas portion of the watershed coming from the High Plains Aquifer.

Unlike flow data that were presented on a water year basis, groundwater data were necessarily presented on an annual basis. We assume that all irrigation was applied during the growing season of a given year, approximately April through September in Oklahoma (Senay and Elliott, 2000), and therefore within the corresponding water year. Separate analyses for groundwater use for irrigation and non-irrigation purposes were performed for each state. Throughout the manuscript, groundwater use for irrigation in the Oklahoma and Texas portions of the watershed are referred to as Oklahoma irrigation and Texas irrigation, respectively. Likewise, Oklahoma non-irrigation and Texas non-irrigation refer to groundwater use for non-irrigation purposes in the Oklahoma and Texas portions of the watershed, respectively.

Land use trends were assessed using annual county level planted cropland data from 1969-2014 (USDA-NASS, 2015) and conservation reserve program (CRP) data from 1986-2014 (USDA-FSA, 2015). County level planted cropland data for Texas were unavailable prior to 1968. Annual data include crops planted the previous fall for harvest a given year, which is important for fall planted winter wheat. Planted area was used rather than harvested area because it includes land that was not harvested due to crop failure. Data were area weighted by multiplying county level values by the proportion of the county within the watershed and then summing across all counties to get watershed totals for each year (Tomer and Schilling, 2009). The planted area and CRP datasets were 97% and 100% complete, respectively. Missing planted area data were filled using nearest neighbor extrapolation for data at the beginning and end of the time series and linear interpolation for other missing data. These data filling techniques assume area planted is generally consistent from year to year, which was supported by the high autocorrelation of annual county level planted area data in our study. Averaged across counties and major crops (wheat, sorghum, and cotton), the autocorrelation coefficient (*r*) was 0.85 at a lag of one year and was greater than 0.5 for a lags of up to seven years. Average correlation coefficients were calculated from z-transformed data for each county and major crop and then back transformed (Silver and Dunlap, 1987).

Planted area data may have been missing for a given year because data were not collected, there were no planted acres for that crop and year, or because the number of reporting operations was low. When three or fewer operations report crop data for a given county and year or when one operation controls more than 60% of the reporting area, NASS data are withheld from public view (Allen et al., 1998a). To avoid filling data for years with no or low planted area, missing data was first subjected to a nearest neighbor test. If the value from the year nearest the missing year was low (< 809 ha), it was assumed that the data were not missing (i.e. actual planted area was zero); otherwise the missing value was interpolated or extrapolated as described above.

<u>Detecting Long Term Trends and Change Points</u>

Long term trends in flow, climate, and human factors were assessed using the non-parametric Mann-Kendall test, and Kendall's slope was used to quantify detected changes (Kendall, 1970; Mann, 1945). In small samples, the outcome of the Mann-Kendall test can be influenced by autocorrelation within the time series, with positive autocorrelation potentially increasing trend detection when one does not exist and negative autocorrelation decreasing trend detection when one does (Yue and Wang, 2002). Therefore, data were checked for autocorrelation, and significant positive autocorrelation (P < 0.05) was found for baseflow, Oklahoma and Texas irrigation and non-irrigation, and planted crop area. No variables displayed significant negative autocorrelation. Of the autocorrelated variables, significant trends, and consequently possible influences of autocorrelation, were found for Oklahoma irrigation, Oklahoma non-irrigation, and planted crop area. To protect against the influence of autocorrelation on the Mann-Kendall test, it is often recommended that the autocorrelation component of a trend be removed by prewhitening time series data, but prewhitening is not universally recommended because it can also reduce the power of the test (Bayazit and Önöz, 2007). We applied the approach of Bayazit and Önöz (2007) and found that prewhitening was not necessary because the low coefficients of variation and high absolute values of slope of the autocorrelated variables indicated that the potential impact of autocorrelation was low.

Absence of long term trends is not an indication that variables did not change within the study period, as multiple changes in opposite directions could counteract one another. Therefore, changes in variables without significant long term trends were also assessed using a change point analysis based on the cumulative sum (CUSUM) technique (Taylor, 2000), which is an iterative approach suitable for detecting multiple changes. Change points were identified as the year in which the CUSUM deviation from zero was greatest. The significance of each identified change was determined by performing the CUSUM analysis on 1000 bootstrap samples and assessing the magnitude of the difference (maximum CUSUM – minimum CUSUM) for each bootstrap sample. The significance level was the fraction of bootstraps for which the magnitude of the difference was smaller than the original sample. Next, the time series was divided at the point of the significant change, and the analysis was repeated. In our study, no more than two significant change points were identified.

Flow, climate, and human variables were then compared between three sub-periods defined based on the results of the change point analysis (1970-1986, 1987-2000, and 2001-2014). The second change points for inflow and baseflow were each adjusted by one year so the sub-periods were the same for each flow variable. Data between sub-periods were compared using either analysis of variance for normally distributed data or Kruskal-Wallis analysis for non-normally distributed data. Normality was determined using the Lilliefores test (P = 0.05), with non-normally distributed data including inflow, baseflow, Texas irrigation, and Texas non-irrigation. With the exception of Texas non-irrigation, between period differences were found for all variables, although differences for precipitation, ET_0, and Texas irrigation were significantly different only at P = 0.11, 0.06, and 0.07, respectively. Variables with significant between period differences were then subjected to a multiple comparisons test using Fishers LSD (P = 0.10) to determine which sub-periods differed from others.

Climate elasticity model

We quantified the relative effects of climate (precipitation and ET_0) and human factors on flow variables (inflow and baseflow) by (1) using the climate elasticity of streamflow model to estimate the response of flow variables to changes in climate (Sankarasubramanian et al., 2001; Schaake, 1990), and (2) using estimated elasticities to determine the relative influence of climate and human factors on observed changes between periods (Ma et al., 2010; Xu et al., 2013; Zheng et al., 2009). The climate elasticity model states that a change in a climate variable such as precipitation will produce a corresponding change in streamflow and is described by:

$$\frac{\Delta Q}{\bar{Q}} = \varepsilon \frac{\Delta P}{\bar{P}}, \qquad [4]$$

where $\Delta Q/\bar{Q}$ and $\Delta P/\bar{P}$ are proportional changes in streamflow and precipitation relative to the pre-change period, respectively, and ε is the elasticity of streamflow to changes in precipitation. Climate elasticity can be interpreted as the degree of sensitivity of streamflow to a change in climate. For ε = 2 in equation 4, for example, the proportional change in streamflow is twice the proportional change in precipitation. Zheng et al. (2009) used a two parameter model to assess the impacts of precipitation and ET_0 on streamflow:

$$\frac{\Delta Q}{\bar{Q}} = \varepsilon_P \frac{\Delta P}{\bar{P}} + \varepsilon_{ET_0} \frac{\Delta ET_0}{\overline{ET_0}} \qquad [5]$$

where $\Delta ET_0/\overline{ET_0}$ is the proportional change in reference evapotranspiration relative to the pre-change period, and ε_{ET0} is the reference evapotranspiration elasticity of streamflow. The advantage of using ET_0 rather than temperature is that it better reflects the impacts of climate on streamflow, and it can integrate multiple climate variables (Zheng et al., 2009).

Climate elasticities (ε) are typically estimated using either nonparametric methods or hydrologic models (Sankarasubramanian et al., 2001). Nonparametric methods use directly observed long-term climate and streamflow data to estimate the response of streamflow to climate, and this approach may be preferred to hydrologic modeling because the resulting elasticities are not influenced by the structure and calibration of the model from which they were derived (Sankarasubramanian et al., 2001). Therefore, we chose a nonparametric (i.e., data based) approach similar to Zheng et al. (2009) who proposed calculating elasticities for individual climate variables as linear regression coefficients:

$$\frac{\Delta Q_i}{Q_{mean}} = \varepsilon \frac{\Delta X_i}{X_{mean}}. \qquad [6]$$

Here, the subscript 'mean' signifies the mean calculated across the entire study period. $\Delta Q_i = Q_i - Q_{mean}$, where Q_i is the streamflow for year *i* and Q_{mean} is the long term mean and $\Delta X_i = X_i - X_{mean}$, where X_i is the climate variable for year *i* and X_{mean} is the long term mean.

Elasticities can be estimated separately in this way for each climate variable, but separate estimates can be inaccurate because precipitation and temperature (or temperature derived ET_0) are often correlated, and the residual effect of temperature on streamflow is difficult to determine compared with the direct effect of precipitation (Chiew et al., 2014). In our study, we found that precipitation and ET_0 had a Pearson correlation coefficient of -0.75 ($P < 0.001$). To overcome complications presented by collinearity between climate variables, Ma et al. (2010) proposed estimating elasticities simultaneously as multiple linear regression coefficients rather than using separate simple linear regressions. Multiple regression is preferable because any correlation between independent variables is incorporated into the coefficient (i.e., elasticity) estimation procedure (Potter et al., 2011). Following Ma et al. (2010), we calculated precipitation and ET_0 elasticities as multiple linear regression coefficients (partial slopes) using:

$$\frac{\Delta Q_i}{\bar{Q}} = \varepsilon_P \frac{\Delta P_i}{P_{mean}} + \varepsilon_{ET_0} \frac{\Delta ET_{0_i}}{ET_{0_{mean}}}, \qquad [7]$$

where *Q* represents individual flow variables (inflow and baseflow) and other variables were previously defined.

After estimating elasticities, we calculated the relative effects of climate and human factors on flow variables between periods, which were determined using the Taylor change point analysis above. The predicted change in each hydrologic variable due to climate factors was calculated by rearranging equation 5 as

$$\Delta Q_C = \left(\varepsilon_P \frac{\Delta P}{\bar{P}} + \varepsilon_{ET_0} \frac{\Delta ET_0}{\overline{ET_0}}\right) \bar{Q}\ , \qquad [8]$$

where ΔQ_c, ΔP, and ΔET_0 are changes in flow variable (inflow or baseflow), precipitation, and ET_0 between periods, respectively (Zheng et al., 2009). $\bar{Q}$, $\bar{P}$, and $\overline{ET_0}$ were calculated as averages across pre and post-change periods for each change (rather than the average for the pre-change period) (Zheng et al., 2009) to avoid the complication of asymmetry associated with standard relative change calculations (Törnqvist et al., 1985). The overbar notation was used to distinguish these means from long term means in equations 6 and 7. Assuming that changes in streamflow are the result of independent climate and human factors (Zheng et al., 2009), the contribution of human factors to the total change in hydrologic variables was then calculated as

$$\Delta Q_H = \Delta Q - \Delta Q_C \,, \qquad [9]$$

where ΔQ_c was calcualted using equation 8 and ΔQ is the total observed change in each hydrologic variable between periods.

Correlation and Multiple Regression

Relationships between flow (inflow and baseflow), climate (precipitation and ET_0) and human activities (groundwater use for irrigation, non-irrigation, and land area planted to crops) were also examined using Pearson's linear correlation. As is often the case with annual streamflow data (Vogel and Wilson, 1996), annual inflow and baseflow were log normally distributed and were therefore subjected to natural log transformation prior to the correlation analysis (Burt et al., 2002; Vogel et al., 1999). Climate and human activities were assessed for concurrent and one-year lagged values. Assessment of longer lags was not possible because Texas groundwater use data before 1969 were available for only two years (1958 and 1964), and no Texas cropland data were available before 1968.

Multiple linear regression models were constructed to explain inflow and baseflow patterns using climate and human variables. Candidate variables were those that were significantly ($P < 0.05$) related to inflow or baseflow in the correlation analysis above. We used a stepwise regression procedure with forward selection and backward elimination of variables, and the best model was identified by the minimization of the Schwarz Bayesian Information Criterion (BIC). An advantage of using BIC for variable selection instead of the commonly used Akaike Information Criteria (AIC) is that BIC often results in a model with a simpler explanatory equation because it is more restrictive than AIC (Hyndman and Athanasopoulos, 2013). Collinearity among included variables was assessed using the variance inflation factor (VIF), with VIF values of < 1.1 for both the inflow and baseflow final models indicating little or no collinearity (Menard, 2001). Our statistical approach is an alternative to comprehensive physical modeling, with such results often offering a meaningful comparison to those derived from modeling (Burt et al., 2002). All statistical analyses were conducted with Matlab R2012a (The MathWorks, Inc., Natick, MA).

Principal Findings and Significance:

Summary of Principle Findings and their Significance

Specific Aim #1:

We found no long-term trends in inflow or baseflow, but found counteracting increases (after 1986) and decreases (after 2000) in each flow variable. Likewise, we did not find a long term trend in precipitation and reference evapotranspiration (ET_0), but found a significant step increase in precipitation around 1984. ET_0 decreased around 1981 and increased around 2006. Groundwater withdrawal for irrigation and non-irrigation uses in the Oklahoma portion of the watershed increased at rates of 0.16 million m^3 yr^{-1} and 0.10 million m^3 yr^{-1}, respectively. No trends in groundwater use in Texas were found. Cropland area planted in the watershed decreased at a rate of 2366 ha yr^{-1}, or 0.32% of the watershed area per year

Specific Aim #2:

Human factors were responsible for more than half (52%-60%) of each of two observed changes in flow (around 1986 and 2000). The recent period of low inflow (2001-2014) corresponded with low precipitation, high ET_0, and a 66% increase in groundwater use for irrigation in the Oklahoma portion of the watershed.

Specific Aim #3:

Precipitation and ET_0 were highly correlated with each flow variable, but several human factors were also important. Of them, lagged and concurrent groundwater use for irrigation in Oklahoma were the most highly correlated with inflow and baseflow, and lagged Oklahoma and Texas irrigation were the only significant human variable in the final inflow multiple regression model. Conversely, cropland area planted was related to neither inflow nor baseflow. A multiple regression model containing precipitation and groundwater use for irrigation explained 81% and 75% of the variability in annual inflow and baseflow, respectively.

The statistical relationships between groundwater use and inflow into Lake Altus-Lugert suggest that ground and surface water interactions help drive streamflow changes and that effective conjunctive water management strategies may be necessary to sustain agricultural productivity in the region. Lake Altus-Lugert and a portion of its watershed have been labeled a water resources "hot spot" because of projected severe water scarcity. While conservation measures may partially improve the water supply outlook, other approaches are likely needed to ensure adequate ground and surface water availability in the region. Water use both upstream of Lake Altus-Lugert and within the LAID need to be critically evaluated. Oklahoma's current water permitting system typically does not recognize connections between ground and surface water, but studies like ours are evidence to the contrary. Effective conjunctive water management strategies may be key to sustaining Lake Altus-Lugert and the irrigated agricultural which depends on it, but a state-mandated conjunctive water use plan could infringe upon property rights of upstream landowners and may be met with resistance. On the other hand, a water conservation district organized by stakeholders in the watershed and focused on developing effective conjunctive management strategies would ensure that important water use decisions were being made by those who depend on water availability for their livelihoods. The difficulties of implementing conjunctive management may be great, but for North Fork watershed, and similar irrigation-dependent regions around the world, the looming prospect of water scarcity may mean that "business as usual" is not a valid option.

Principle Findings in Detail

Specific Aim #1: Quantify changes in streamflow, climate, groundwater use, and land use in the North Fork of the Red River watershed upstream from Lake Altus-Lugert from 1970-2014

The recent severe decline in the level of Lake Altus-Lugert on the North Fork of the Red River in southwestern Oklahoma, USA, caused substantial economic and ecological damage and prompted many in the region to wonder to what extent climate and human factors contributed to the decline. Despite recent annual inflow that was a fraction of its historical average and a lake level that reached an all-time low, we found no significant long-term trends in annual inflow or baseflow. The absence of long-term trends was a consequence of counteracting short-term trends. Two change points were identified for inflow and baseflow, with each variable displaying a pattern of low flow from 1970-1986, high flow from 1987 until 2001 (inflow) or 1999 (baseflow), and low flow thereafter (Fig. 2). The long term annual mean inflow was 17 mm, and long term mean annual baseflow was 10 mm. During the period when flow was high, inflow and baseflow were 16 mm and 12 mm greater, respectively, than during the preceding low-flow period. Average annual inflow then declined by 19 mm and baseflow declined by 11 mm from the period of high flow to the period of low flow from about 2000-2014. During the time of unprecedentedly low lake levels from 2011-2014, annual inflow averaged only 2.2 mm, by far the lowest four-year average for any time during the study, with the next lowest four-year average being 1970-1973 when annual inflow averaged 7.6 mm.

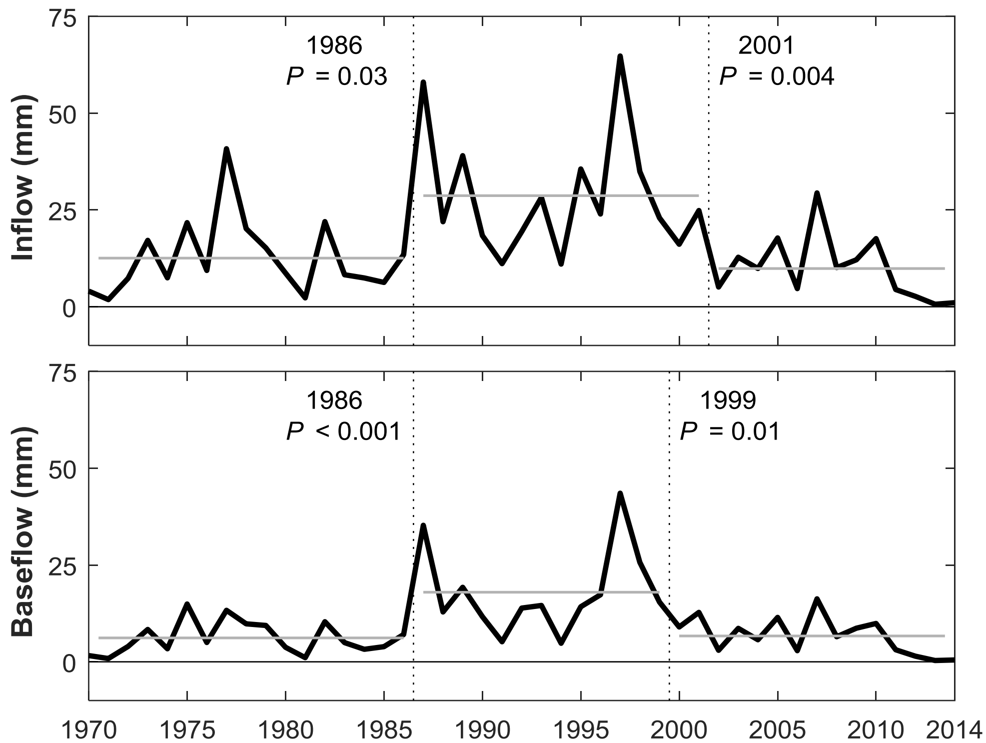


Figure 2. Annual inflow and baseflow for the North Fork watershed from 1970-2014. Year and significance of identified changes are given, with periods separated by vertical lines and period means represented by gray horizontal lines. While there was no long term trend in inflow or baseflow, each flow variable displayed low flow at the beginning and end of the study period, separated by a period of high flow.

Long term areal average precipitation was 593 mm, and the corresponding average for ET_0 was 1387 mm. Precipitation and ET_0 trends were similar to those for flow. While long term trends did not exist, annual precipitation increased 71 mm around 1984, and annual ET_0 decreased 46 mm around 1981 (Fig. 3); changes that were conducive to the higher flow that we observed from about 1986-2000. ET_0 then increased 69 mm around 2006, corresponding with the period of decreased inflow and baseflow after 2000. The recent period of extreme low inflow (2011-2014) corresponded with a period when precipitation was 25% below and ET_0 was 5% above their respective long term long term (1970-2014) averages. Four-year average precipitation from 2011-2014 was only 442 mm, 42 mm (9%) lower than the next lowest four-year period in the study (1968-1971). Likewise, four-year average ET_0 from 2011-2014 (1460 mm) was the second highest for any four-year period in the study, falling behind only 2009-2012. These trends suggest a close connection between climate and streamflow, as has been previously reported in Oklahoma (Esralew and Lewis, 2010) and throughout the Great Plains (Garbrecht et al., 2004).

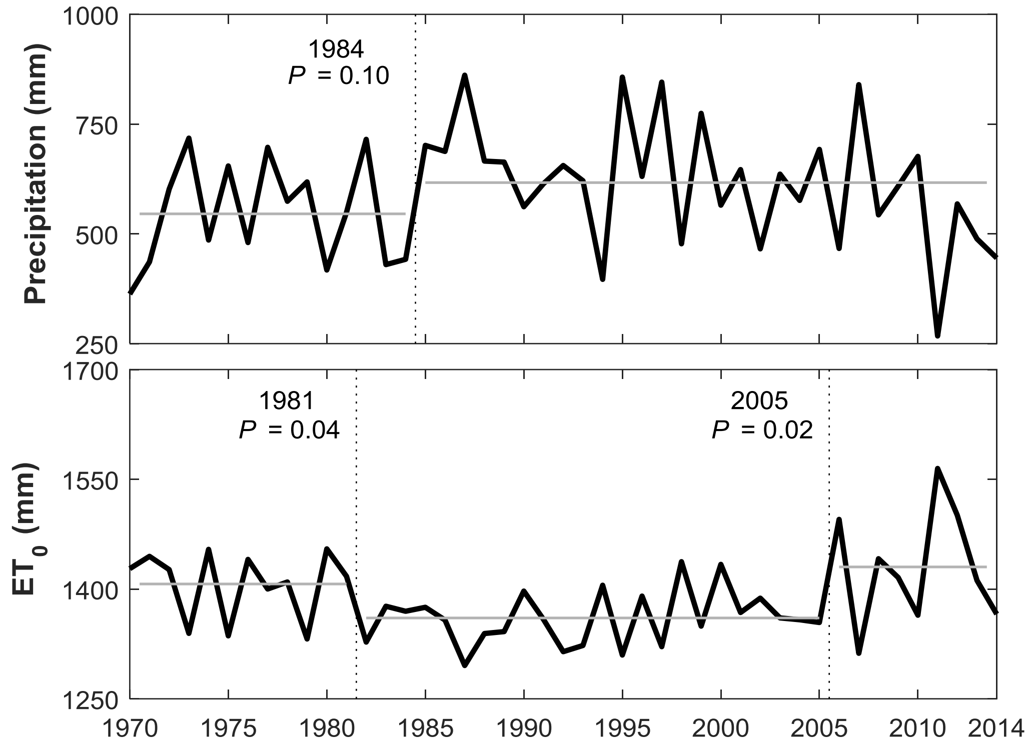


Figure 3. Annual Precipitation and reference evapotranspiration (ET_0) for the North Fork watershed from 1970-2014. Year and significance of identified changes are given, with periods separated by vertical dotted lines and period means represented by gray horizontal lines. While there was no long term trend for either variable, a significant increase in precipitation occurred around 1984, and ET_0 was higher at the beginning and end of the study period.

Unlike flow and climate variables, some human variables displayed significant long term trends. Oklahoma irrigation (i.e. groundwater withdrawal from the North Fork Red River alluvial aquifer for irrigation) increased at a rate of 0.16 million m^3 yr^{-1}, and Oklahoma non-irrigation groundwater use increased at a rate of 0.10 million m^3 yr^{-1} (Fig. 4). Notably, groundwater use was greatest when inflow and baseflow were at their lowest (approximately 2011-2014). Our observed increase in Oklahoma irrigation conflicts with trends reported for Oklahoma as a whole and for alluvial and terrace aquifers within the state. Assessed between 1990 and 2005, statewide groundwater use for irrigation was found to decrease after 1995, and groundwater withdrawal from alluvial and terrace aquifers remained steady or declined slightly (Tortorelli, 2009). Our observed increase was in part a result of the sharp increase after 2010, which had not been previously reported. In Texas, neither irrigation nor non-irrigation groundwater use displayed a significant long term trend, whereas others have reported declines in groundwater use for irrigation in the Texas High Plains beginning in the mid 1970's (Musick et al., 1990). The declines were attributed to a reduction in irrigated area and improved irrigation systems and water management. While our data suggest a similar decline, our inability to detect a statistically significant trend was possibly the result of data gaps before 1985.

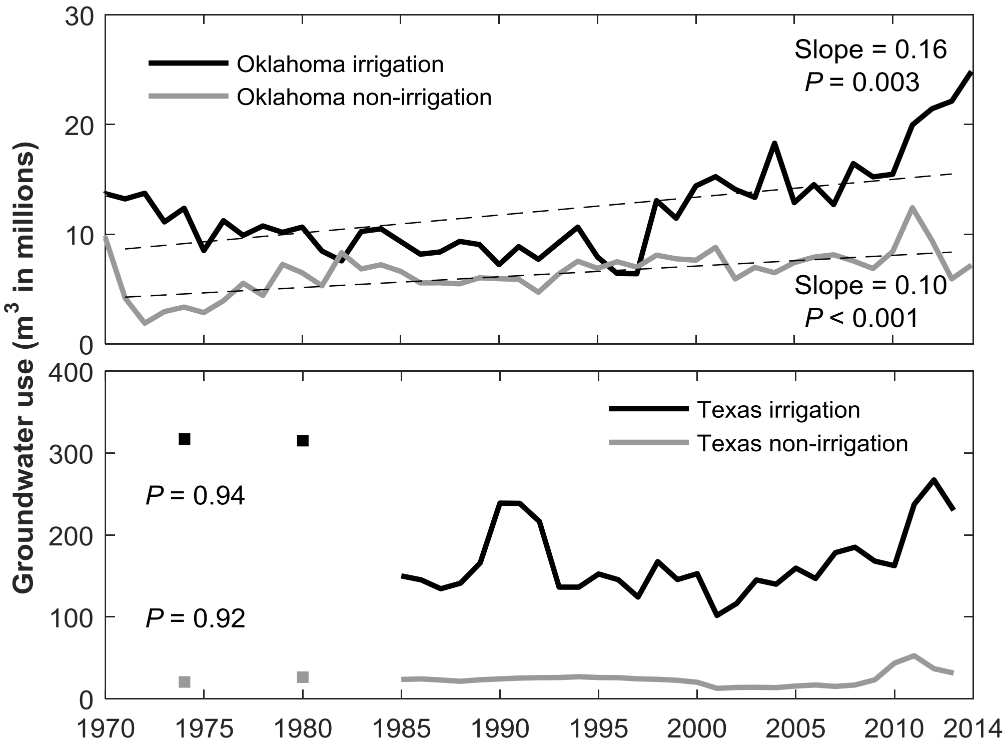


Figure 4. Annual groundwater withdrawals for irrigation and non-irrigation uses in the Oklahoma and Texas portions of the North Fork watershed from 1970-2014. In Oklahoma, groundwater use for irrigation and non-irrigation increased throughout the study (dashed black lines), whereas no significant trends for groundwater use in Texas were identified.

Cropland area planted in the watershed decreased at a rate of 2366 ha yr^{-1}, or 0.32% of the watershed area per year (Fig. 5). The proportion of the watershed planted to crops was at its maximum from the mid-1970's to the mid-1980's, before declining thereafter, with land enrolled in the conservation reserve program (CRP) likely accounting for much of the decline. CRP land area averaged 48,083 ha (6.5% of the watershed area) from 1986-2014, but decreased slightly over the study period (P = 0.06) (222 ha yr^{-1} or 0.03% of the watershed area per year). Our observed trend in planted cropland corroborates trends reported throughout the Great Plains, with agricultural land area reaching its maximum about 1980, before declining as land was converted to grassland in conjunction with the CRP (Drummond and Auch, 2013).

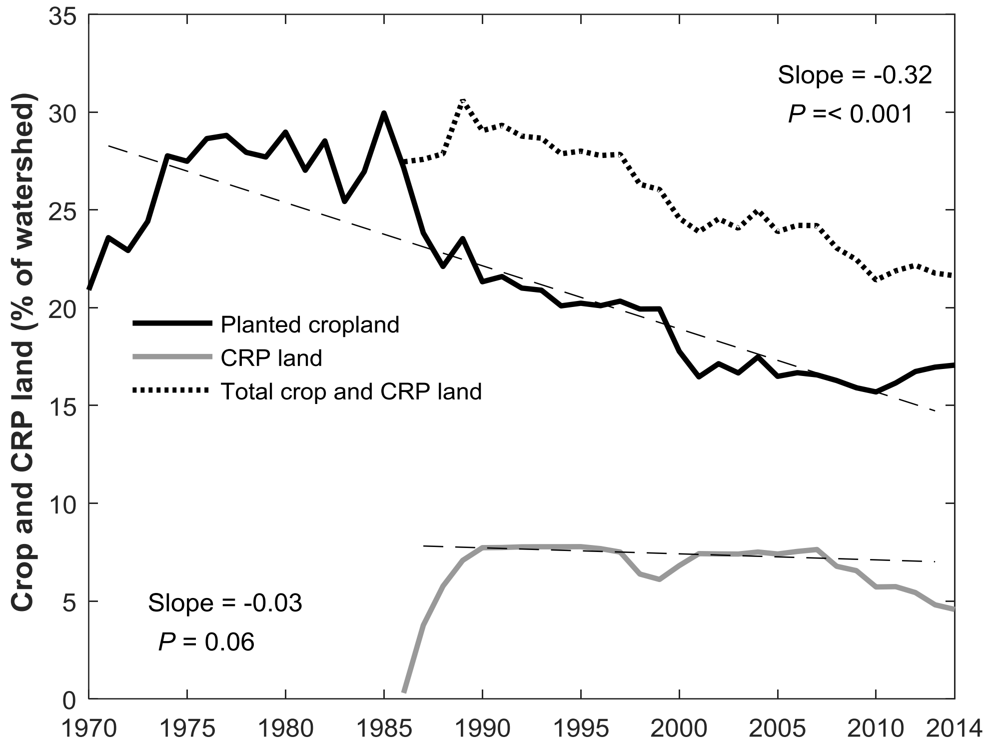


Figure 5. Cropland area planted and land in the conservation reserve program (CRP) as percentage of watershed area in the North Fork watershed from 1970-2014. Cropland area planted decreased from 1970-2014, and a slight decrease (*P* = 0.06) was detected for CRP land from 1986-2014.

Trends in climate and human factors suggested that each contributed to low inflow into Lake Altus-Lugert, with periods of low precipitation, high ET_0, and high irrigation corresponding with low flow. To more rigorously assess these relationships, we compared flow, climate, and human factors for each of the high and low flow periods (1970-1986, 1987-2000, and 2001-2014), and statistical comparisons (Table 1) reflect observed temporal trends (Figs 2-4). Average annual inflow, baseflow, and precipitation were highest from 1987-2000 when ET_0 and groundwater use for irrigation in Oklahoma and Texas were at their lowest (Table 1). Oklahoma irrigation was 66% higher during the low flow period from 2001-2014 than during previous periods, and Texas irrigation was 52% higher during the low flow period from 1970-1986 than during subsequent periods. Oklahoma non-irrigation increased each period, but the magnitude of water use averaged only 6.5 million m^3 yr^{-1} compared with Oklahoma and Texas irrigation, which averaged 12.3 and 170 million m^3 yr^{-1}, respectively. Texas non-irrigation groundwater use did not change. The large volume of groundwater use in the Texas compared with the Oklahoma portion of the watershed was likely a reflection of differing groundwater resources. In 1974, the estimated combined groundwater storage for Carson, Gray, and Wheeler counties in Texas, which are underlain by the High Plains aquifer, was 24,000 million m^3 (Bell and Morrison, 1979; Bell and Morrison, 1980; Bell and Morrison, 1982). This is nearly 8-fold greater than the 1973 estimated groundwater storage in the alluvial aquifer (3,200 million m^3) from which groundwater is drawn in Oklahoma portion of the watershed (Kent, 1980).

Table 1. Average annual flow, climate, and human factors (groundwater use for irrigation and non-irrigation and cropland area planted) during periods identified by the change point analysis in the Oklahoma (OK) and Texas (TX) portions of the North Fork watershed from 1970-2014.

	Inflow[1]	Baseflow	P	ET_0	Irrigation		Non-Irrigation		Planted
					OK	TX	OK	TX	
	mm				million m^3				%
1970-1986	12.6 a	6.2 a	563 a	1394 b	10.7 a	220 b	5.2 a	25 a	27 c
1987-2000	29.0 b	17.3 b	656 b	1358 a	9.7 a	140 a	6.6 b	24 a	21 b
2001-2014	10.9 a	6.5 a	566 a	1407 b	16.9 b	149 ab	7.8 c	24 a	17 a

1 Values within a given column followed by the same lower case letter are not significantly different at $P < 0.1$.

Cropland area planted showed no obvious relationship to inflow or baseflow, with low flow periods occurring when area planted was at its highest (1970-1986) and at its lowest (2001-2014). While others have found that streamflow was negatively related to cropland area and positively related to grassland area (Dale et al., 2015), the relationship is complex. An increase in CRP land can result in decreased runoff (Lindstrom et al., 1998) and increased evapotranspiration (Khanal et al., 2014), thereby decreasing streamflow. On the other hand, increased infiltration on CRP land can lead to increased groundwater levels (Rao and Yang, 2010), which in turn support increased baseflow (Barlow and Leake, 2012). The absence of a relationship in our study may have resulted because of these counteracting influences or because cropland was a relatively minor land use in our study, averaging < 22% of watershed area.

<u>Specific Aim #2: Determine the relative contributions of climate and human factors to changes in flow.</u>

Greater than 50% of each change in inflow and baseflow was attributable to human factors, but climate also contributed significantly to each change (Table 2). Average inflow increased by 16.4 mm and average baseflow increased by 11.2 mm around 1987, with changes in flow due to climate being 7.9 mm (48% of the total change) for inflow and 4.5 mm (40%) for baseflow. Inflow and baseflow then respectively decreased by 18.0 and 10.8 mm around 2000, with changes in flow due to climate being 7.9 mm (44% of the total change) for inflow and 4.8 mm (44%) for baseflow. Flow variables were related positively to precipitation and negatively to ET_0, and each flow variable was more sensitive to precipitation than ET_0. The proportional change in inflow, for example, was 2.37 times the change in precipitation but -1.23 times the change in ET_0. That is, a 10% increase in precipitation resulted in a 23.7% increase inflow, whereas a 10% increase in ET_0 resulted in a 12.3% decrease in streamflow. Our calculated precipitation elasticity of inflow is similar to that reported by Sankarasubramanian et al. (2001), which ranged from 1.5-2.5 for western Oklahoma and the Texas Panhandle, although values as high 3.0 have been reported for the area (Khanal et al., 2014).

Our observation that climate was responsible for less than half of each change in inflow and baseflow underscores the control humans can have on streamflow in the region. While previously unquantified, the importance of human influences on streamflow in the North Fork Red River watershed has been reported by others. Esralew and Lewis (2010), for example, found a significant decline in precipitation-adjusted streamflow in the North Fork Red River, and they suggested that human factors such as changes in water use and water-management practices were likely responsible for the decline. Likewise, Smith and Wahl (2003) reported an increase in watershed precipitation without an accompanying increase in streamflow, with human factors possibly counteracting the influence of increased precipitation. In the Cimarron river watershed in north central Oklahoma, Dale et al. (2015)

found that nearly half (48%) of streamflow variability was attributable to human factors. Among the human factors they studied, increased groundwater use was associated with decreased streamflow, and conversion of cropland to grasslands was associated with increased streamflow. Zume and Tarhule (2008) found a simulated 47% decline in streamflow due to groundwater pumping from the terrace and alluvial aquifer along the Beaver-North Canadian River in northwest Oklahoma. The decline was due to a reduction in baseflow and a reversal of the stream-aquifer hydraulic gradient, or stream leakage.

Table 2. Precipitation (P) and reference evapotranspiration (ET_0) elasticity of inflow and baseflow for the North Fork watershed from 1970-2014. Absolute and percentage changes in flow and climate are reported, as well as the percentage of each change in flow attributable to climate (C) and human (H) factors. Human factors explained >50% of both the first (around 1987) and second changes (around 2000).

	Climate Elasticity		Change 1			Change 2		
Variable	P	ET_0	mm	%C	%H	mm	%C	%H
Inflow	2.37	-1.23	16.4	48.4	51.6	-18.0	43.8	56.2
Baseflow	2.34	-1.48	11.2	40.0	60.0	-10.8	44.0	56.0

Our results and the results of these prior studies suggest that groundwater use was potentially an important human factor contributing to changes in inflow in our study. Groundwater use for irrigation and non-irrigation in the Oklahoma portion of the watershed were 74% and 18% higher, respectively, during the low flow period from 2000-2014 than during the previous high flow period. These increases occurred at the same time that the climate elasticity model indicated that human contribution to the change in inflow was at its greatest (57%), which is consistent with a connection between groundwater use and inflow. The connection may be especially strong in the Oklahoma portion of the watershed because of the close proximity of the alluvial aquifer (and therefore groundwater withdrawal) to the stream. By contrast, the High Plains aquifer that underlies the Texas portion of the watershed spans the entirety of some counties, and the distance between groundwater wells and the river can be large, which would reduce their impact on streamflow (Barlow and Leake, 2012).

We emphasize, however, that the relative contributions of climate and human factors to changes in flow are dependent on the elasticities assigned to climate variables, which can be calculated by a number of different techniques that give different results (Khanal et al., 2014; Zheng et al., 2009). Our methodology (Ma et al., 2010; Zheng et al., 2009) has been shown to produce slightly lower estimates of precipitation elasticity of streamflow compared with other methods. This uncertainty has implications when determining the contributions of climate and human factors on changes in streamflow. For example, a precipitation elasticity of inflow that is 20% higher than our value of 2.37, as has been found when comparing the methods of Zheng et al. (2009) and Sankarasubramanian et al. (2001), would reduce the calculated human contribution to our second observed change in inflow from 57% to 48%. This small change in precipitation elasticity of inflow would lead to the conclusion that climate factors, not human factors, were responsible for the largest portion of the change. Nonetheless, our calculated elasticities are typical of those for western Oklahoma and the Texas Panhandle (Khanal et al., 2014; Sankarasubramanian et al., 2001), and despite possible uncertainties regarding elasticities, we conclude that climate and human factors were each important drivers of changes in flow in our study.

<u>Specific Aim #3: Develop statistical models describing the relationships of climate and human variables with flow.</u>

The climate elasticity analysis showed that both human and climate factors were important drivers of inflow and baseflow in the North Fork Red River watershed, and the comparison of variables for each sub-period suggested that groundwater use was potentially an important human factor influencing inflow into Lake Altus-Lugert. Next, correlation was used to determine which climate and human factors were most closely related to annual flow, and multiple regression models were developed using significantly correlated variables.

Inflow and baseflow tended to be higher when precipitation was high and ET_0 was low (Table 3), and the directions of these relationships were also reflected in the signs of precipitation and ET_0 elasticities. Concurrent values of precipitation and ET_0 showed stronger linear relationships to flow than their values lagged by one year, with for example, the correlation between precipitation and inflow being more than double for concurrent compared with lagged precipitation (r = 0.67 vs. 0.32) (Table 3). Our observed correlation coefficients between concurrent climate variables and flow were consistent with previous reports for western Oklahoma and the Texas Panhandle, which have ranged from 0.3 to 0.7 for precipitation (Dale et al., 2015; Khanal et al., 2014) and from -0.2 to -0.6 for ET_0 (Dale et al., 2015). Of the human factors, concurrent and lagged Oklahoma irrigation had the strongest correlations to each flow variable. Neither concurrent nor lagged cropland area planted were significantly correlated to the flow variables (Table 3).

Table 3. Correlation coefficients for inflow and baseflow with concurrent and one year lagged precipitation (P), reference evapotranspiration (ET_0), groundwater use for irrigation and non-irrigation in Oklahoma (OK) and Texas (TX), and cropland area planted for the North Fork watershed from 1970-2014.

	Flow Variables		Climate		Irrigation		Non-Irrigation		Cropland
	Inflow[1]	Baseflow	P	ET_0	OK	TX	OK	TX	Planted
Baseflow	**0.98**								
P	**0.67**	**0.66**							
P -1 yr.	**0.32**	**0.36**	-0.15	0.07	-0.16	-0.11	0.05	-0.10	-0.07
ET_0	**-0.55**	**-0.53**	**-0.75**						
ET_0 -1 yr.	**-0.30**	**-0.32**	0.23	0.01	**0.34**	0.13	0.00	0.18	-0.11
OK irrigation	**-0.65**	**-0.62**	**-0.45**	**0.46**					
OK irrigation -1 yr.	**-0.60**	**-0.57**	-0.17	0.26	**0.84**	0.14	0.19	0.12	**-0.54**
TX irrigation	**-0.43**	**-0.46**	**-0.40**	**0.46**	0.18				
TX irrigation -1 yr.	**-0.46**	**-0.47**	-0.20	0.05	0.08	**0.61**	-0.30	0.24	**0.37**
OK non-irrigation	-0.05	-0.02	-0.19	0.26	**0.34**	-0.19			
OK non-irrigation -1 yr.	**-0.31**	-0.25	-0.11	0.29	**0.37**	-0.02	**0.50**	0.24	**-0.51**
TX non-Irrigation	-0.26	-0.25	-0.29	**0.40**	0.23	0.25	**0.45**		
TX non-irrigation -1 yr.	**-0.40**	**-0.40**	-0.27	**0.42**	0.33	**0.50**	**0.37**	**0.79**	0.02
Area planted	0.14	0.05	0.05	-0.13	**-0.57**	0.31	**-0.52**	-0.02	
Area planted -1 yr.	0.20	0.13	0.08	-0.19	**-0.62**	0.17	**-0.48**	-0.05	**0.95**

[1] Bold font indicates statistical significance at $P = 0.05$

Increased groundwater use was associated with decreased inflow and baseflow for all groundwater use variables (irrigation and non-irrigation in both states), and most of these correlations were stronger than those reported elsewhere in Oklahoma. For example, our observed correlation between inflow and Oklahoma irrigation was -0.66, whereas the streamflow-consumptive water use correlation (which incorporates groundwater use for irrigation) in the Cimarron River watershed ranged from -0.19 to -0.38 (Dale et al., 2015). The high correlation that we observed suggests that the North

Fork Red River may be more susceptible to alluvial aquifer withdrawals than is the Cimarron River, possibly because of the greater extent of the Cimarron River alluvial aquifer (Ryder, 1996).

Relationships among climate and human variables were also evaluated in order to understand their interrelations. For example, precipitation and concurrent irrigation were negatively related, which is expected since increased irrigation would likely be required during dry years. We considered the possibility that the correlation between Oklahoma irrigation and streamflow was a spurious relationship resulting from the fact that both low streamflow and high levels of irrigation were caused by low precipitation. However, precipitation and lagged irrigation were not significantly correlated, yet lagged Oklahoma irrigation was almost as strongly related to flow as concurrent irrigation (Table 3). This is evidence that groundwater withdrawal itself impacted inflow and baseflow and that streamflow changes were not simply the result of variable precipitation.

While many climate and human variables were significantly correlated with inflow and baseflow (Table 3), of these candidate variables, only precipitation, Oklahoma irrigation -1 year, and Texas irrigation -1 year were retained in the final multiple linear regression model for each flow variable (Table 4). Even with this limited number of predictor variables, our models explained 81% of annual inflow variability and 75% of annual baseflow variability. These results apply only to the period when data for each input parameter were available (1986-2014). Our results are similar to those of Burt et al. (2002) who found that precipitation, lagged precipitation, and the number of groundwater wells explained between 64% and 94% of the streamflow variability in southwest Nebraska. Unlike their study where lagged precipitation was important, precipitation -1 year was not significant in the regression models for inflow of baseflow. The importance of concurrent precipitation is not surprising, but it is important that Oklahoma and Texas irrigation -1 year were the only other significant variables, which is perhaps evidence of the negative impact that groundwater withdrawal can have on streamflow and lake levels as has been reported elsewhere (Brikowski, 2008). Groundwater withdrawal can reduce groundwater levels, thereby decreasing the amount discharging to streams, and when depletion is severe, groundwater withdrawal can reverse the hydraulic gradient causing recharge from the stream to the aquifer (Barlow and Leake, 2012).

Table 4. Stepwise multiple regression of inflow and baseflow against significantly correlated concurrent and one year lagged precipitation (P), reference evapotranspiration (ET_0), groundwater use for irrigation and non-irrigation in Oklahoma (OK) and Texas (TX), and cropland area planted for the North Fork watershed from 1970-2014. Variables retained by the stepwise procedure are displayed.

	Inflow				Baseflow			
	Parameter		Model		Parameter		Model	
Variable	Estimate	P value	Adj. R^2	P value	Estimate	P value	Adj. R^2	P value
Intercept	3.0	< 0.001	0.81	< 0.001	2.6	0.001	0.75	< 0.001
P	0.004	< 0.001			0.003	< 0.001		
OK irrigation -1 yr.	-0.122	< 0.001			-0.122	< 0.001		
TX irrigation -1 yr.	-0.008	0.003			-0.008	0.007		

We emphasize, however, that our analyses describe statistical associations, and unlike hydrologic modeling, they do not represent mechanistic controls that climate and human factors can have on flow. That is, our results are not evidence of cause and effect. We also acknowledge that there are factors for which we did not account. For example, increased forest and urban lands have been correlated with increased streamflow (Dale et al., 2015), whereas the proliferation of floodwater retarding structures can reduce streamflow (Van Liew et al., 2003). Likewise, salt cedar encroachment, a common problem throughout much of the southwestern United States, can result groundwater depletion and reduced streamflow (Di Tomaso, 1998). Irrigation itself can alter streamflow characteristics because it dictates antecedent soil moisture content, which can influence infiltration and runoff during precipitation events (Castillo et al., 2003), irrigation return can promote streamflow and recharge (Barlow and Leake, 2012), and large-scale irrigation can alter climate (Sacks et al., 2008). Furthermore, our analyses were restricted to available data, and may have been improved with a more complete groundwater use record for Texas or improved groundwater use data for Oklahoma, which were self-reported by users. The difficulty in untangling the effects of individual climate and human factors on streamflow is obvious.

Nevertheless, the results of each of our analyses suggest that streamflow in the North Fork Red River watershed has been substantially impacted by human factors. Without question, drought was a major contributing factor to the extremely low inflows to Lake Altus-Lugert in recent years, but humans, likely in part through groundwater withdrawals from the North Fork Red River alluvial aquifer, also contributed to the demise of the lake. The connection between groundwater use and inflow and baseflow is evidenced by the high correlation between these variables and the importance of lagged Oklahoma and Texas irrigation in the inflow and baseflow regression models. Moreover, Oklahoma irrigation was highest during the period from 2000-2014 when inflow was low, reaching its maximum during the extreme low flow years after 2010. This was also the time when the climate elasticity model suggested that the human contribution to the inflow change was largest. Our results suggest that if precipitation and groundwater use for irrigation remain near levels seen during 2000-2014, severe water scarcity will be an ongoing challenge for the region served by Lake Altus-Lugert.

Surface water supply shortages and groundwater depletion in the North Fork Red River watershed are projected to grow as demand for water increases (OWRB, 2012), and at the same time, climate change models suggest precipitation in the Texas Panhandle and western Oklahoma will become less frequent (Shafer et al., 2014). With these increased pressures on water resources, irrigation release from Lake Altus-Lugert at the levels that were typical before the 2010 drought may be impossible. Producers in parts of the Oklahoma Panhandle and western Kansas have faced just these circumstances, with dwindling reservoir storage resulting from groundwater withdrawal and changing climate (Brikowski, 2008). Projected water shortages in the North Fork Red River watershed may be partially addressed through conservation measures (OWRB, 2012), and improvements in irrigation efficiency have been credited with decreasing groundwater use elsewhere in Oklahoma (Tortorelli, 2009). But conservation will likely fill only a portion of the projected water supply gap, and other measures such as increased development of the North Fork Red River alluvial aquifer have also been suggested (OWRB, 2012).

Our results, however, suggest that increased groundwater development in the North Fork Red River alluvial aquifer could have negative consequences for Lake Altus-Lugert and for producers in the Lugert-Altus Irrigation District (LAID). For this reason, other innovative strategies to address water scarcity in the region are needed. The construction of new reservoirs and the sourcing of out-of-basin water are possible alternatives (OWRB, 2012), or perhaps the problem calls for a fundamental change in farming strategies in the region (Iglesias and Garrote, 2015). A transition from irrigated agriculture to rainfed ranching would be more in synch with the natural vegetation in the region both upstream and downstream of Lake Altus-Lugert. This transition may offer long term sustainability, but there are currently significant economic incentives for producers to continue growing irrigated crops (Conner et al., 2001). Unfortunately, these are potential long-term solutions to a problem that may demand attention in the near term.

Implementing conjunctive management of ground and surface water has been suggested as an important step toward meeting Oklahoma's water needs (OWRB, 2010), and based on our results, conjunctive management may be necessary to sustain irrigated agriculture in the North Fork Red River watershed. Currently, surface and groundwater are treated and permitted as separate and unrelated resources in Oklahoma water law and policy, with the exception of one isolated aquifer where conjunctive management is required (OWRB, 2012). This artificial separation in law and policy does not provide a suitable management framework for locations where surface and groundwater interact. For example, in the permitting process for wells in the North Fork Red River alluvial aquifer, current policy does not consider the potential impact of the proposed wells on the flow in the river. If groundwater pumping is impacting flows in Oklahoma rivers, as our results and others suggest, then there is a need for increased conjunctive management of surface and groundwater within the state.

One possible approach to implementing conjunctive water management would be the creation of a water conservation district (Blomquist et al., 2001) charged with developing conjunctive use strategies for the North Fork watershed. Our work has shown that people, as much as climate, dictate changes in water availability in the region. Concentrating decision making ability within the people dependent upon the watershed would entrust them to develop strategies to sustain it. The effort would require tremendous cooperation among stakeholders, decisions would unlikely be unanimous, and winners and losers would be almost unavoidable. Still, by banding together and using information from studies like ours, stakeholders in such a water conservation district would have the opportunity to cooperatively make conjunctive water management decisions and could avoid having decisions imposed upon them.

These findings will be disseminated to the broader scientific community through a peer reviewed journal article. Our manuscript is in preparation and will be submitted to Agricultural Water Management. We have also presented preliminary results to stakeholders in the LAID. This project has furthered our understanding the diverse factors that affect irrigation water quantity in the Lake Altus-Lugert watershed and our results will be a valuable tool to inform irrigation planning, water permits, and conservation measures throughout the watershed.

Literature Cited:

Allen, R., R. Bosecker and G. Hanuschak. 1998a. Policy issues associated with the utilization of geographic information systems (GIS) in the U.S. National Agricultural Statistics Service (NASS). USDA-NASS. Washington, D.C.

Allen, R.G., L.S. Pereira, D. Raes and M. Smith. 1998b. Crop evapotranspiration: Guidelines for computing crop water requirements, FAO Irrigation and Drainage Paper No. 56. Food and Agriculture Organization of the United Nation. Rome, Italy.

Barlow, P.M. and S.A. Leake. 2012. Streamflow depletion by wells—Understanding and managing the effects of groundwater pumping on streamflow: U.S. Geological Survey Circular 1376. U.S. Geological Survey, Reston, Virginia.

Bayazit, M. and B. Önöz. 2007. To prewhiten or not to prewhiten in trend analysis? Hydrolog. Sci. J. 52:611-624. doi:10.1623/hysj.52.4.611.

Bell, A.E. and S. Morrison. 1979. Analytical study of the Ogallala aquifer in Carson County, Texas. Projections of saturated thickness, volume of water in storage, pumpage rates, pumping lifts, and well yields. Report 242. Texas Water Development Board, Austin, TX.

Bell, A.E. and S. Morrison. 1980. Analytical study of the Ogallala aquifer in Gray County, Texas. Projections of saturated thickness, volume of water in storage, pumpage rates, pumping lifts, and well yields. Report 243. Texas Water Development Board, Austin, TX.

Bell, A.E. and S. Morrison. 1982. Analytical study of the Ogallala aquifer in Wheeler County, Texas. Projections of saturated thickness, volume of water in storage, pumpage rates, pumping lifts, and well yields. Report 266. Texas Water Development Board, Austin, TX.

Blomquist, W., T. Heikkila and E. Schlager. 2001. Institutions and conjunctive water management among three western states. Nat. Resources J. 41: 653.

Brikowski, T.H. 2008. Doomed reservoirs in Kansas, USA? Climate change and groundwater mining on the Great Plains lead to unsustainable surface water storage. J. Hydrol. 354:90-101. doi:http://dx.doi.org/10.1016/j.jhydrol.2008.02.020.

Burt, O.R., M. Baker and G.A. Helmers. 2002. Statistical estimation of streamflow depletion from irrigation wells. Water Resour. Res. 38:1296. doi:10.1029/2001WR000961.

Chiew, F.H.S., N.J. Potter, J. Vaze, C. Petheram, L. Zhang, J. Teng, et al. 2014. Observed hydrologic non-stationarity in far south-eastern Australia: implications for modelling and prediction. Stoch. Environ. Res. Risk Assess. 28:3-15. doi:10.1007/s00477-013-0755-5.

Dale, J., C.B. Zou, W.J. Andrews, J.M. Long, Y. Liang and L. Qiao. 2015. Climate, water use, and land surface transformation in an irrigation intensive watershed—Streamflow responses from 1950 through 2010. Agric. Water Mange. 160:144-152. doi:http://dx.doi.org/10.1016/j.agwat.2015.07.007.

Di Tomaso, J.M. 1998. Impact, Biology, and Ecology of Saltcedar (Tamarix spp.) in the Southwestern United States. Weed Technol. 12: 326-336.

Drummond, M.A. and R. Auch. 2013. Land-cover change in the United States Great Plains. US Geological Survey, Land Cover Trends Project. US Department of the Interior. U.S. Geological Survey, Washington, DC. (4 January 2016). http://landcovertrends.usgs.gov/gp/regionalSummary.html

Esralew, R.A. and J.M. Lewis. 2010. Trends in base fow, total flow, and base-flow index of selected streams in and near Oklahoma through 2008. Scientific Investigations Report 2010–5104. U.S. Department of the Interior. U.S. Geological Survey, Reston, VA.

Garbrecht, J., M. Van Liew and G. Brown. 2004. Trends in precipitation, streamflow, and evapotranspiration in the Great Plains of the United States. J. Hydrol. Eng. 9:360-367. doi:10.1061/(ASCE)1084-0699(2004)9:5(360).

Hargreaves, G. and R. Allen. 2003. History and evaluation of Hargreaves evapotranspiration equation. J. Irrig. Drain. Eng. 129:53-63. doi:10.1061/(asce)0733-9437(2003)129:1(53).

Hyndman, R.J. and G. Athanasopoulos. 2013. Forecasting: principles and practice. OTexts: Melbourne, Australia. (7 April 2016). http://otexts.org/fpp/.

Iglesias, A. and L. Garrote. 2015. Adaptation strategies for agricultural water management under climate change in Europe. Agric. Water Mange. 155:113-124. doi:http://dx.doi.org/10.1016/j.agwat.2015.03.014.

Kendall, M.G. 1970. Rank correlation methods. Griffin, London.

Kent, D.C. 1980. Evaluation of aquifer performance and water supply capabilities of alluvial and terrace deposits of the North Fork of the Red River in Beckham, Greer, Kiowa and Jackson Counties, Oklahoma. Oklahoma Water Resources Board. Oklahoma City, OK.

Khanal, S., R.P. Anex, C.J. Anderson and D.E. Herzmann. 2014. Streamflow impacts of biofuel policy-driven landscape change. PLoS ONE 9:e109129. doi:10.1371/journal.pone.0109129.

Lindstrom, M.J., T.E. Schumacher, N.P. Cogo and M.L. Blecha. 1998. Tillage effects on water runoff and soil erosion after sod. J. Soil Water Conserv. 53:59-63.

Ma, H., D. Yang, S.K. Tan, B. Gao and Q. Hu. 2010. Impact of climate variability and human activity on streamflow decrease in the Miyun Reservoir catchment. J. Hydrol. 389:317-324. doi:http://dx.doi.org/10.1016/j.jhydrol.2010.06.010.

Mann, H.B. 1945. Nonparametric tests against trend. Econometrica 13:245-259.

Menard, S. 2001. Applied logistic regression analysis. 2nd ed. Sage University paper series on quantitative applications in the social sciences, 07-106. Sage, Thousand Oaks, CA.

Musick, J.T., F.B. Pringle, W.L. Harman and B.A. Stewart. 1990. Long term irrigation trends in the Texas High Plains. Appl. Eng. Agric. 6:717-724.

Nathan, R.J. and T.A. McMahon. 1990. Evaluation of automated techniques for base flow and recession analyses. Water Resour. Res. 26:1465-1473. doi:10.1029/WR026i007p01465.

NOAA National Centers for Environmental Information. 2015. Climate Data Online. NOAA NCEI. Washington, DC. (18 September 2014). http://www.ncdc.noaa.gov/

OCS. 2015. Precipitation history - Annual, West Central. Oklahoma Climatological Survey Norman, OK. (10 December 2015). http://climate.ok.gov/index.php/climate/climate_trends/

OWRB. 2010. Oklahoma comprehensive water plan. 2011 Update. Technical memorandum: Conjunctive water management in Oklahoma and other states. Oklahoma Water Resources Board. Oklahoma City, OK.

OWRB. 2012. Oklahoma comprehensive water plan. Executive report. Oklahoma Water Resources Board. Oklahoma City, OK.

OWRB. 2016. Water Use permitting. Oklahoma Water Resources Board. Oklahoma City, OK. (7 April 2016). http://www.owrb.ok.gov/supply/watuse/permitting.php

Parsons Engineering Science. 1999. Surface water/groundwater interaction evaluation for 22 Texas river basins. Prepared for Texas Natural Resource Conservation Commission, Austin, TX.

Peel, M.C., T.A. McMahon and B.L. Finlayson. 2010. Vegetation impact on mean annual evapotranspiration at a global catchment scale. Water Resour. Res. 46:1-16. doi:10.1029/2009wr008233.

Potter, N.J., C. Petheram and L. Zhang. 2011. Sensitivity of streamflow to rainfall and temperature in south-eastern Australia during the Millennium drought. 19th International Congress on Modelling and Simulation. Perth, Australia. p. 3636–3642.

Rao, M.N. and Z. Yang. 2010. Groundwater impacts due to conservation reserve program in Texas County, Oklahoma. Appl. Geogr. 30:317-328. doi:http://dx.doi.org/10.1016/j.apgeog.2009.08.006.

Ryder, P.D. 1996. Ground water atlas of the United States: Oklahoma, Texas. HA 730-E. U.S. Geological Survey, Reston, VA.

Sacks, W.J., B.I. Cook, N. Buenning, S. Levis and J.H. Helkowski. 2008. Effects of global irrigation on the near-surface climate. Clim. Dyn. 33:159-175. doi:10.1007/s00382-008-0445-z.

Sankarasubramanian, A., R.M. Vogel and J.F. Limbrunner. 2001. Climate elasticity of streamflow in the United States. Water Resour. Res. 37:1771-1781. doi:10.1029/2000wr900330.

Schaake, J.C. 1990. From climate to flow. In: P. E. Waggoner, editor Climate Change and U.S. Water Resources. John Wiley, New York. p. 177– 206.

Senay, G.B. and R.L. Elliott. 2000. Combining AVHRR-NDVI and landuse data to describe temporal and spatial dynamics of vegetation. For. Ecol. Manage. 128:83-91. doi:http://dx.doi.org/10.1016/S0378-1127(99)00275-3.

Shafer, M., D. Ojima, J.M. Antle, D. Kluck, R.A. A. McPherson, S. Petersen, et al. 2014. Ch. 19: Great Plains. Climate Change Impacts in the United States: The Third National Climate Assessment, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 441-461. doi:10.7930/J0D798BC.

Silver, N.C. and W.P. Dunlap. 1987. Averaging correlation coefficients: Should Fisher's z transformation be used? J. Appl. Psychol. 72:146-148. doi:10.1037/0021-9010.72.1.146.

Smakhtin, V.U. 2001. Estimating continuous monthly baseflow time series and their possible applications in the context of the ecological reserve. Water SA 27:213-218.

Smith, J. and K.L. Wahl. 2003. Changes in streamflow and summary of major-ion chemistry and loads in the North Fork Red River basin upstream from Lake Altus, northwestern Texas and western Oklahoma, 1945–1999. Water-Resources Investigations Report 03–4086. United States Geological Survey, Reston, VA.

Taylor, W.A. 2000. Change-point analysis: a powerful new tool for detecting changes. (22 October 2015). http://www.variation.com/cpa/tech/changepoint.html

Thiessen, A.H. 1911. Precipitation averages for large areas. Mon. Weather Rev. 39:1082-1089.

Tomer, M.D. and K.E. Schilling. 2009. A simple approach to distinguish land-use and climate-change effects on watershed hydrology. J. Hydrol. 376:24-33. doi:http://dx.doi.org/10.1016/j.jhydrol.2009.07.029.

Törnqvist, L., P. Vartia and Y.O. Vartia. 1985. How Should Relative Changes be Measured? Am. Stat. 39:43-46. doi:10.1080/00031305.1985.10479385.

Tortorelli, R.L. 2009. Water Use in Oklahoma 1950–2005. Scientific Investigations Report 2009–5212. U.S. Department of the Interior U.S. Geological Survey, Reston, VA.

TWDB. 2015. Historical Groundwater Pumpage. Texas Water Development Board. Austin, TX. (7 October 2015). http://www.twdb.texas.gov/waterplanning/waterusesurvey/historical-pumpage.asp

TWDB. 2001. Inventories of irrigation in Texas 1958, 1964, 1969, 1974, 1979, 1984, 1989, 1994 and 2000. Report 347. Texas Water Development Board. . Austin, TX.

USDA-Farm Service Agency. 2015. CRP enrollment and rental payments by county, 1986-2014. USDA-FSA, Washington, DC. (18 September 2015). http://www.fsa.usda.gov/programs-and-services/conservation-programs/reports-and-statistics/conservation-reserve-program-statistics/index

USDA-National Agricultural Statistic Service. 2015. Data and statistics-Quick Stats. USDA-NASS, Washington, DC. (18 September 2015). http://quickstats.nass.usda.gov/

USDOI Bureau of Reclamation. 2015. W.C. Austin Project. USDOI BOR. Washington, D.C. (15 October 2015). http://www.usbr.gov/projects/Project.jsp?proj_Name=W.C.+Austin+Project

USGS Water Resources. 2015. National Water Information System: Web Interface. Washington, DC. (11 October 2015). http://waterdata.usgs.gov/nwis

Van Liew, M.W., J.D. Garbrecht and J.G. Arnold. 2003. Simulation of the impacts of flood retarding structures on streamflow for a watershed in southwestern Oklahoma under dry, average, and wet climatic conditions. J. Soil Water Conserv. 58:340-348.

Vogel, R. and I. Wilson. 1996. Probability distribution of annual maximum, mean, and minimum streamflows in the United States. J. Hydrol. Eng. 1:69-76. doi:10.1061/(ASCE)1084-0699(1996)1:2(69).

Vogel, R.M., I. Wilson and C. Daly. 1999. Regional regression models of annual streamflow for the United States. J. Irrig. Drain. Eng. 125:148-157.

Wahl, K.L. and R.L. Tortorelli. 1997. Changes in flow in the Beaver-North Canadian River basin upstream from Canton Lake, western Oklahoma. Water-Resources Investigations Report 96-4304. United States Geological Survey, Reston, VA.

Wang, X. 2014. Advances in separating effects of climate variability and human activity on stream discharge: An overview. Adv. Water Resour. 71:209-218. doi:http://dx.doi.org/10.1016/j.advwatres.2014.06.007.

Xu, X., B.R. Scanlon, K. Schilling and A. Sun. 2013. Relative importance of climate and land surface changes on hydrologic changes in the US Midwest since the 1930s: Implications for biofuel production. J. Hydrol. 497:110-120. doi:http://dx.doi.org/10.1016/j.jhydrol.2013.05.041.

Yue, S. and C.Y. Wang. 2002. Applicability of prewhitening to eliminate the influence of serial correlation on the Mann-Kendall test. Water Resour. Res. 38:4-1-4-7. doi:10.1029/2001WR000861.

Zheng, H., L. Zhang, R. Zhu, C. Liu, Y. Sato and Y. Fukushima. 2009. Responses of streamflow to climate and land surface change in the headwaters of the Yellow River Basin. Water Resour. Res. 45:1-9. doi:10.1029/2007wr006665.

Zume, J. and A. Tarhule. 2008. Simulating the impacts of groundwater pumping on stream–aquifer dynamics in semiarid northwestern Oklahoma, USA. Hydrogeol. J. 16:797-810. doi:10.1007/s10040-007-0268-8.

Quantifying Streambank Erosion and Phosphorus Load for Watershed Assessment and Planning

Daniel E. Storm, Professor, Room 121 Ag Hall, Stillwater, OK 74078, 405-762-1510, dan.storm@okstate.edu, Oklahoma State University, Department of Biosystems and Agricultural Engineering.

Aaron Mittelstet, Assistant Professor, 245 L.W. Chase Hall, Lincoln, NE, (402) 472-5527, amittelstet2@unl.edu, University of Nebraska-Lincoln, Biological Systems Engineering Department.

Start Date: 3/1/2015

End Date: 2/29/2016

Congressional District: 3

Focus Category: AG, GEOMOR, HYDROL, M&P, MOD, NPP, NU, SED, SW, WQL

Descriptors: Nonpoint Source Pollution, Streambank Erosion, Sediments, Nutrients

Students:

Student Status	Number	Disciplines
Undergraduate	1	Biosystems Engineering
M.S.	0	
Ph.D.	2	Biosystems Engineering
Post Doc	0	
Total	3	

Principal Investigators:

Daniel E. Storm, Professor, Oklahoma State University
Aaron Mittelstet, Assistant Professor, University of Nebraska

Publications:

Mittelstet, Aaron Ray, 2015, Quantifying Phosphorus Loads and Streambank Erosion in the Ozark Highland Ecoregion Using the Swat Model, Ph.D. Dissertation, Biosystems and Agricultural Engineering Department, Oklahoma State University, Stillwater, Oklahoma, College, University, City, State, 170 p.

Mittelstet, A.R., D.E. Storm, G.A. Fox and P.M. Allen. Using SWAT to Predict Watershed-Scale Streambank Erosion on Composite Streambanks, Transactions of the ASABE, manuscript NRES-11666-2015 (review complete, revisions requested, revisions submitted)

EXECUTIVE SUMMARY

Problem and Research Objectives

Streambanks can be a significant source of sediment and P to aquatic ecosystems. Although the streambank-erosion routine in the Soil and Water Assessment Tool (SWAT) has improved in recent years, the lack of site or watershed-specific streambank data increases the uncertainty in SWAT predictions. For the first part of the project, the objectives were: 1) improve and apply the current streambank-erosion routine in SWAT on composite streambanks and 2) compare SWAT-default channel parameters to field-measured values and assess their influence on erosion. The second part of the project addressed the lack of previous SWAT modeling efforts to account for the contribution of stream banks as a P source due to lack of field data and model limitations. This was hypothesized to cause under predicting total and particulate P during large storm events. Therefore, the final objective was to 3) model the streambank erosion and P for the Barren Fork Creek using a modified SWAT model.

Methodology

For the first part of the project, modifications were made to the current streambank-erosion routine in SWAT: 1) replaced the empirical applied-shear stress equation with a process-based equation, 2) replaced bankfull width and depth with top width and bank height, and 3) incorporated an area-adjustment factor to account for heterogeneous trapezoidal cross-sections. The updated streambank-erosion routine was tested on the gravel-dominated streambanks of the Barren Fork Creek in northeastern Oklahoma. The study used data from 28 cross-sectional surveys, including bank height and width, bank slope, bank-gravel d_{50} and bank composition. Gravel d_{50} and k_d-τ_c relationships were used to estimate the critical shear stress (τ) and the erodibility coefficient (k_d), respectively. For the second part of the project, measured streambank and channel parameters were incorporated into a flow-calibrated SWAT model and used to estimate streambank erosion and P for the Barren Fork Creek using the latest streambank-erosion routine and newly incorporated process-based applied shear stress equation.

Principal Findings and Significance

For the first part of the project, incorporating the process-based shear stress equation increased erosion by 85%, the area-adjustment factor increased erosion by 31% and the erosion decreased 30% when using top width and bank height. Incorporating the process-based applied shear stress equation, sinuosity, radius of curvature and measured bed slope improved the predicted vs observed Nash-Sutcliffe Efficiency and R^2 at the ten study sites from -0.33 to 0.02 and 0.49 to 0.65, respectively. Although the process-based applied shear stress equation was the most influential modification, incorporating the top width, bank height and area-adjustment factor more accurately represented the measured irregular cross-sections and improved the model predictions compared to observed data.

For the second part of the project, the predicted streambank erosion was 215,000 Mg/yr versus the measured 160,000 Mg/yr (34% relative error), which was considered excellent. Streambank erosion contributed 47% of the total P to the Barren Fork Creek and also improved P predictions compared to observed data, especially during the high flow events. Due to this influx of streambank P to the system and the current in-stream P routine's limitations, the in-stream P routine was modified by introducing a long-term storage coefficient, thus converting some of the particulate P to long-term storage. Of the total P entering the stream system, approximately 65% left via the watershed outlet and 35% was stored in the floodplain and stream system. This study not only provided local, state and federal agencies with accurate estimates of streambank erosion and P contributions for the Barren Fork Creek watershed, it demonstrated how watershed-scale model, such as SWAT, can be used to predict both upland and streambank P.

CHAPTER 1

USING SWAT TO PREDICT WATERSHED-SCALE STREAMBANK EROSION ON COMPOSITE STREAMBANKS

Abstract

Streambanks can be a significant source of sediment and P to aquatic ecosystems. Although the streambank-erosion routine in the Soil and Water Assessment Tool (SWAT) has improved in recent years, the lack of site or watershed-specific streambank data increases the uncertainty in SWAT predictions. There were two primary objectives of this research: (1) improve and apply the current streambank-erosion routine in SWAT on composite streambanks and (2) compare SWAT-default channel parameters to field-measured values and assess their influence on erosion. Three modifications were made to the current streambank-erosion routine: replaced the empirical applied-shear stress equation with a process-based equation, replaced bankfull width and depth with top width and bank height and incorporated an area-adjustment factor to account for heterogeneous trapezoidal cross-sections. The updated streambank-erosion routine was tested on the gravel-dominated streambanks of the Barren Fork Creek in northeastern Oklahoma. The study used data from 28 cross-sectional surveys, including bank height and width, bank slope, bank-gravel d_{50} and bank composition. Gravel d_{50} and k_d - τ_c relationships were used to estimate the critical shear stress (τ_c) and the erodibility coefficient (k_d), respectively. Incorporating the process-based shear stress equation increased erosion by 85%, the area-adjustment factor increased erosion by 31% and the erosion decreased 30% when using top width and bank height. Incorporating the process-based applied shear stress equation, sinuosity, radius of curvature and measured bed slope improved the predicted vs observed Nash-Sutcliffe Efficiency and R^2 at the ten study sites from -0.33 to 0.02 and 0.49 to 0.65, respectively. Although the process-based applied shear stress equation was the most influential modification, incorporating the top width, bank height and area-adjustment factor more accurately represented the measured irregular cross-sections and improved the model predictions compared to observed data.

Introduction

Sediment is a primary pollutant to surface waters and the fifth leading cause of water quality impairment in the US (USEPA, 2015a). Though erosion is a natural process, the rate of erosion has been accelerated due to anthropogenic activities, such as farming and urbanization. Although sediment loss from agricultural fields, deforestation, and construction sites is significant, in some watersheds streambank erosion can be the most significant contributor of sediment to rivers and streams (Simon and Darby, 1999; Simon et al., 2002; Wilson et al., 2008). Streambank erosion has been observed to increase 10 to 15 times with the advent of European settlement. Rates cited range from 37% to up to 92% (Walling et al., 1999; Simon, et al., 1996). Excess sediment in our streams and reservoirs affects water chemistry, water clarity, increases the cost of treating drinking water, harms fish gills and eggs, reduces benthic macroinvertebrates densities and diversities and increases turbidity. Increased turbidity not only affects the water aesthetics, but reduces photosynthesis and organisms' visibility. Siltation alters flow in streams and decreases the storage area in our reservoirs, which in turn affects flooding, drinking water and recreation.

Although streambank erosion can contribute a significant quantity of sediment and phosphorus to stream systems (Miller et al., 2014; Kronvang et al., 2012), most watershed-scale models are limited in their ability to predict streambank erosion (Merritt et al., 2003). Two types of models are used to predict streambank erosion: empirical and process-based (Lai et al., 2012). Empirical models, those that predict erosion based on data alone, do a poor job of predicting erosion with changing boundary conditions (Narasimhan et al., 2015). Process-based models simulate the streambank erosion processes, i.e. subaerial processes, fluvial erosion and mass wasting. While process-based models, such as the Bank-Stability and Toe-Erosion Model (BSTEM) (USDA ARS, 2013; Daly et al., 2015a) and CONservation Channel Evolution and Pollutant Transport System (CONCEPTS) (USDA-ARS, 2000), estimate erosion on a single cross-section or reach (Staley et al., 2006), data requirements on a watershed scale are vast and often not practical for most projects. While HEC-RAS recently incorporated BSTEM into the watershed-scale model (Gibson, 2013), few projects have the resources to gather and incorporate the required data. In order to estimate streambank erosion for an entire watershed and require relatively simple inputs, the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998) uses both process-based and empirical routines. This combination of processes allows SWAT to model the physical properties involved in streambank erosion, yet make it more practical to use for large watersheds.

Background

Streambank Erosion Routine and Parameter Estimation

The current streambank erosion routine from SWAT 2005 (Neitsch et al., 2011) only permits streambank erosion if there is sufficient transport capacity and after the deposited sediment from the previous time step is removed (Table 1.1). The routine uses the excess shear stress equation (Partheniades, 1965; Neitsch et al., 2011) to calculate the streambank erosion rate, ε (m s^{-1}), given as:

$$\varepsilon = k_d\left(\tau_e - \tau_c\right) \tag{1.1}$$

where k_d is the erodibility coefficient (cm^3 N-s^{-1}), τ_e is the effective shear stress (N m^{-2}), and τ_c is the soil's critical shear stress (N/m^2). The k_d and τ_c coefficients are functions of numerous soil properties. SWAT estimates the critical shear stress based on silt and clay content (Julian and Torres, 2006) using the following equation:

$$\tau_c = 0.1 + 0.1779(SC) + 0.0028(SC)^2 - 0.0000235(SC)^3 \tag{1.2}$$

where SC is the percent silt and clay content. SWAT predicts k_d using the relationship proposed by Hanson and Simon (2001) based on 83 *in situ* jet erosion tests:

$$k_d = 0.2 * \tau_c^{-0.5} \quad (1.3)$$

Effective shear stress is calculated using the following equations (Eaton and Miller, 2004):

$$\frac{\tau_e}{\gamma * d * s} = \frac{SF_{bank}}{100}\left(\frac{(W + P_{bed}) * \sin\theta}{4 * d}\right) \quad (1.4)$$

$$\log(SF_{bank}) = -1.40 * \log\left(\frac{P_{bed}}{P_{bank}} + 1.25) + 2.25\right) \quad (1.5)$$

where SF_{bank} is the proportion of shear force acting on the bank (N m^{-2}), γ is the specific weight of water (9800 N m^{-3}), d is the depth of water in the channel (m), W is the top width of the bank (m), P_{bed} is the wetted perimeter of the bed (m), P_{bank} is the wetted perimeter of the channel bank (m), θ is the angle of the channel bank from horizontal and s is the slope of the channel (m m^{-1}).

SWAT uses a digital elevation model (DEM) to estimate bed slope and drainage area, assumes the channel has a 2:1 side slope and uses regression equations to estimate bankfull height and width (Neitsch et al., 2011). Currently the same equations are applied worldwide to estimate bankfull width, *BW*, and bankfull height, *BH*, given as:

$$BW = 1.278 * A^{0.6004} \quad (1.6)$$

$$BD = 0.1291 * A^{0.4004} \quad (1.7)$$

where *BW* and *BD* are in meters, and *A* is the drainage area in km^2.

The current streambank-erosion routine has several limitations. Although streambanks on the outside of a meander experience more shear stress (Sin et al., 2012) and erosion (Purvis, 2015), the current routine does not account for the sinuosity of the stream system. The routine does a poor job of redefining channel dimensions after streambank erosion occurs. Therefore, most users assume a balance between erosion and deposition at a cross-section and thus channel dimensions remain constant. Unlike BSTEM and CONCEPTS, which can model multiple bank layers and simulate mass wasting, SWAT assumes a uniform bank and only considers fluvial erosion. Modeling only one layer can lead to large errors in erosion estimates if the critical shear stress and erodibility coefficients of a multilayer streambank are significantly different. Modeling on a large spatial scale leads to many assumptions and simplifications since data are not often available. Some assumptions include average shear stress on the bank, *BW* and *BD* correctly define channel dimensions and the channel is homogeneous and symmetrical.

Proposed Streambank Erosion Routine

Streambank erosion dependent on transport capacity and bed erosion can underestimate the erosion and does not represent the actual processes. A proposed routine (Narasimhan et al., 2015), currently being beta tested, also uses the excess shear stress equation, but erodes the streambank independent of transport capacity and bed erosion (Table 1.1). The new routine increases the applied shear stress based on the radius of curvature and sinuosity of the reach. The maximum effective shear stress occurs on the outside of the meander and is affected by the degree of sinuosity. Sin et al. (2012) developed a dimensionless multiplication bend factor to adjust the effective shear stress on the meander, which was the ratio of the maximum shear stress experienced at the bends divided by the average channel shear. The dimensionless bend factor (K_b) is estimated using (Sin et al., 2012; Narasimhan et al., 2015):

$$K_b = 2.5\left(\frac{R_c}{W}\right)^{-0.32} \quad (1.8)$$

where R_c is the radius of curvature (m) and W is the top width (m). R_c is estimated using the empirical relationship based on several studies and has a wide range of applicability over widths ranging from 1.5 m (Friedkin, 1945) to 2,000 m (Fisk, 1947) given as (Williams, 1986):

$$R_c = 1.5 * W^{1.12} \quad (1.9)$$

The maximum effective shear stress on the outside of the meander, τ_e^*, is calculated using:

$$\tau_e^* = K_b * \tau_e \quad (1.10)$$

To calculate the total mass of sediment eroded from streambanks, the channel is divided into straight and meandering reaches. The length of the reach affected by meandering is calculated using the inverse of the sinuosity (ratio of channel length to the straight-line length). The effective shear stress of the reach affected by the sinuosity is then multiplied by K_b while the straight section is not. For the meandering section of a reach, erosion is only calculated from the critical bank while both banks erode for the straight section.

Objectives

The proposed routine has only been tested on cohesive soils in the Cedar Creek watershed in North-Central Texas with lateral bank erosion rates ranging from 0.025 to 0.37 m yr^{-1}. More testing is needed before the routine is incorporated into the official SWAT release and used by watershed modelers worldwide. Although the proposed routine addressed some of the current model limitations, several additional limitations and assumptions remain. Therefore, three modifications were made to the proposed routine and tested on the Barren Fork Creek watershed in northeastern Oklahoma. The Barren Fork Creek watershed has non-cohesive soils and lateral bank erosion rates ranging from 0.5 to 8.7 m yr^{-1} (Heeren et al., 2012; Midgley et al., 2012; Daly et al., 2015a). The Barren

Fork Creek is representative of non-cohesive gravel-dominated channels and will add important information to the streambank erosion routine validation and assessment.

At a watershed-scale there is typically limited site specific streambank data, both spatially and temporally. While stream reaches range in length from a few hundred meters to several kilometers, only one value for each parameter may be used to characterize the reach in SWAT. Gathering data for channel parameters by reach is a daunting task and for most projects is not feasible; therefore, the most critical parameters need to be identified to focus data collection efforts. Although there is considerable uncertainty in each of these parameters (Chaubey et al., 2005; Wechsler, 2007; Bieger et al., 2015), no study has compared field-measured to SWAT derived parameters and their influence on streambank erosion.

The objectives of this research were to (1) improve the current SWAT streambank erosion routine, (2) test the routine on the composite streambanks and (3) compare SWAT-default channel parameters to field-measured values and assess their influence on erosion. Results of this study will provide recommendations to watershed modelers and managers to focus data collection and parameter estimation efforts on the most critical streambank erosion parameters, thus providing more accurate model predictions.

Methods

Proposed SWAT Streambank Erosion Modifications

Three proposed modifications were made to the SWAT 2015 streambank-erosion routine beta version to address some of the model's current limitations. The first replaced the empirical applied shear stress equation with a process-based equation. The second replaced the bankfull width and depth with the top width and bank depth. Finally, the third added an area-adjustment factor to account for heterogeneous stream channels (Table 1.1).

To accurately predict streambank erosion, a good estimate of the applied shear stress is essential. Currently, SWAT uses an empirical equation derived from laboratory studies using symmetrical trapezoidal channels (Eaton and Miller, 2004). This can introduce error when used outside the conditions under which the equation was developed. The proposed replacement equation is process-based and used by CONCEPTS (USDA-ARS, 2000):

$$\tau = \gamma * R * S_f \tag{1.11}$$

where R is the hydraulic radius (m) and S_f is the friction slope (m m^{-1}). The friction slope is computed using the following equation:

$$S_f = \frac{n^2 * Q^2}{A^2 * R^{\frac{4}{3}}} \tag{1.12}$$

where Q is the average flow rate ($m^3\ s^{-1}$), n is Manning's roughness coefficient and A is the cross-sectional area (m^2).

SWAT currently assumes a symmetric trapezoidal channel with dimensions derived from bankfull width and depth. There are two primary reasons to replace bankfull parameters with top width and bank height. First, identifying and measuring bankfull width is subjective and thus carries considerable uncertainty (Johnson and Heil, 1996). Second, bankfull measurements are often less than top width and bank height measurements, thus resulting in inaccurate modeling of stream flow depth (Figure 1.1). In summary, replacing bankfull parameters with top width and bank height more accurately defines the stream system being modeled.

To accurately model streambank erosion, channel dimensions must mimic those of the studied stream system. Although the current SWAT model is constrained by its symmetrical trapezoidal channel dimensions, a simple area-adjustment factor to account for a heterogeneous channel cross-section is proposed (Figure 1.2). No natural channel is symmetrical with a flat and level streambed, and thus assuming a trapezoidal channel will result in errors predicting flow depth. The proposed equation is:

$$A_{adj} = a * A \quad (1.13)$$

where A_{adj} is the adjusted channel cross-sectional area (m^2), A is the irregular cross-sectional area (m^2), and a is a dimensionless adjustment factor less than or equal to 1.0. The variable a is calculated by dividing the irregular cross-sectional area by the trapezoidal area. The trapezoidal area is based on the SWAT input for top width, channel depth and side slope.

Study Site

The streambank erosion routine was tested on the Barren Fork Creek watershed, located in the Ozark Highland Ecoregion in northeast Oklahoma and northwest Arkansas. Recent research on the Barren Fork Creek, an Oklahoma designated Scenic River, has shown that streambank erosion is a significant P source (Miller et al., 2014). Miller et al. (2014) estimated that 36% of the streambanks in the Barren Fork Creek watershed were unstable and eroding. In another study by Heeren et al. (2012), lateral bank erosion on 23 reaches on the Barren Fork Creek and Spavinaw Creek, approximately 50 km north, averaged more than 7 m from 2003 to 2008, with one reach losing 55 m.

The watershed has a drainage area of 890 km^2 (Figure 1.3) and is composed of 55% forest, 30% pasture and 13% hay meadow (Storm and Mittelstet, 2015). The headwaters begin in Washington County, Arkansas, flow through Adair County, Oklahoma before discharging into the Illinois River in Cherokee County, Oklahoma just north of Ferry Tenkiller Lake. The streambanks consist of a fining upward sequence of basal gravels and overlying silts and clays derived from overbank deposition (Figure 1.4). Due to readily available information, the ten study sites from Miller et al. (2014) were used in this study (Figure 1.3). Available information for each site included pebble counts used to define the median particle size (d_{50}), bank height, and streambank total and water soluble soil P. Seven of the ten sites historically had riparian vegetation protection while three were unprotected. Since SWAT only models one streambank layer, the entire streambank was modeled as a gravel layer. Although fluvial erosion is the dominant streambank process in the watershed, ignoring mass wasting of the cohesive layer may lead to the under prediction of the streambank erosion, especially during those events where the top cohesive layer becomes saturated and unstable (Fox and Wilson, 2010).

Parameter Measurement

Parameter measurement was divided into two categories, data mining and field data collection. Data mining included existing online digital data and derivatives, such as bed slope, R_c and sinuosity. Field data included measured stream and streambank information, i.e. *BW, BD*, top width, bank height, side slope and τ_c .

Kocian (2012) found that aerial images and topographic maps were highly correlated with measured data. Therefore, bed slope for each study site reach was calculated using 1:24,000 USGS topography maps and National Aerial Imagery Program (NAIP) aerial images to estimate elevation change and stream length, respectively. Both sinuosity and R_c were calculated using NAIP images from 2003, 2008 and 2013 and averaging the calculated values. The R_c was calculated for each of the meandering reaches by visually overlaying and fitting a circle to each bend (Figure 1.5), and then comparing estimates obtained from Equation 1.9 using *BW* and top width.

A total of 28 stream cross-sections, starting from the Oklahoma/Arkansas state line to the confluence of Barren Fork Creek and the Illinois River (Figure 1.6; Appendix A) were surveyed using a laser level, measuring tape and survey rod; eight at cross-over points, nine at meanders and eleven at straight cross sections (Figures 1.6 and 1.7). Locations of cross-sections were based on available access points. Cross-over points were defined as the river reaches where the thalweg crossed from one side of the channel centerline to the other, straight reaches were defined as reaches with a sinuosity less than 1.1 (Dey, 2014) and meanders were the remaining reaches with a sinuosity greater than 1.1. Two of the straight reaches included surveys completed at the USGS gage stations near Eldon, Oklahoma (07197000) and Dutch Mills, Arkansas (07196900). At each of the 28 sites, the following data were collected: *BW*, *BD*, top width, bank height and side slope.

The measured irregular channel cross section for each of the straight and meandering reaches were compared to the trapezoidal cross section, which was calculated from the measured top width and side slope to obtain the *a*. FlowMaster V8 (Bentley, 2015) was used to estimate the water depth of the irregular cross-section versus the water depth using a trapezoidal cross-section with and without using *a*. Three representative cross-sections were chosen: meander, and heterogeneous and homogenous straight reaches. Flow depths were calculated assuming uniform flow and Manning's formula.

BW was identified by physical stream indicators, such as change in elevation, deposited sediment and vegetation (USGS, 2004). The bankfull area, calculated using the cross-sectional survey, was divided by *BW* to obtain the average *BD*. The measured bankfull parameters were compared to the values calculated by SWAT as well as two equations proposed by Bieger et al. (2015). The equations currently used by the SWAT model to estimate *BW* and *BD* were derived several years ago based on limited measured data. Bieger et al. (2015) compiled *BW* and *BD* data from 51 studies across the US, one equation for the entire US and eight regional equations based on physiographic divisions. The entire US equations for BW_{us} and BD_{us}, in m, are (Bieger et al., 2015):

$$BW_{US} = 2.70 * A^{0.352} \quad (1.14)$$

$$BD_{US} = 0.30 * A^{0.213} \quad (1.15)$$

Dutnell (2000) developed regional equations for the Internal Highland Region, which includes the Barren Fork Creek, for BW_{ihr} and BW_{ihr}, in m, given as:

$$BW_{ihr} = 23.23 * A^{0.121} \quad (1.16)$$

$$BD_{ihr} = 0.27 * A^{0.267} \quad (1.17)$$

Measured d_{50} coupled with an alternative τ_c equation were used to estimate τ_c for the streambank gravel layer using the following algorithm developed specifically for non-cohesive gravel particles (Millar, 2005):

$$\tau_c = 0.05 * \tan(\varphi) * \rho * g(SG - 1) d_{50} * \sqrt{1 - \frac{\sin^2 * \theta}{\sin^2 * \phi}} \quad (1.18)$$

where ρ is the density of water (1000 kg m^{-3}), g is gravitational acceleration (9.81 m s^{-2}), *SG* is the specific gravity of the bank soil (assumed to be 2.65 for all soils), d_{50} is the mean particle diameter of the soil (m), φ is the angle of repose (degrees), and θ is the bank angle (assumed to be 25° for all streambank soils and 0° for all streambed sediments) (Daly et al., 2015a). Although Equation 1.3 was derived using cohesive soils, the equation was successfully used for gravel layers at similar sites by Daly et al. (2015a) and Midgley et al. (2012) and thus will be used in this study.

SWAT Model Setup

The landcover dataset, developed from 2010 and 2011 Landsat images, was used as well as the 10-m USGS DEM and SSURGO soil data. The watershed had minor point sources at Westville, Oklahoma and Lincoln, Arkansas, two USGS stream gages located near Eldon, Oklahoma and Dutch Mills, Arkansas, and three weather stations (Figure 1.8). Outlets were added to the model upstream and downstream of the ten study sites (Miller et al., 2014) to produce SWAT output files for each study reach to predict stream flow and streambank erosion. Management practices, litter application rates and Soil Test Phosphorus for each subbasin were obtained from Mittelstet (2015). The final SWAT model consisted of 73 subbasins, 2,991 HRUs and eight land covers. The primary land covers were forest (55%), pasture (30%) and hay meadow (13%).

Model Evaluation

Streamflow and Flow Depth

The SWAT model was calibrated to observed daily and monthly baseflow, peak flow and total flow at USGS gage stations 07197000 and 07196900. Since Oklahoma's Mesonet began in November 1994, streamflow was calibrated and validated from 2004 to 2013 and 1995 to 2003, respectively. The USGS Hydrograph Separation Program (HYSEP) was used to estimate baseflow (Sloto and Crouse, 1996). Channel dimensions, obtained from the cross-sectional surveys at the two USGS gage stations, were used in the SWAT model along with an initial Manning's *n* of 0.025 (Daly et al., 2015a). Manning's *n*, the only value not measured, was manually adjusted to calibrate flow depth. The Coefficient of Determination (R^2) and Nash Sutcliff Efficiency (NSE) (Nash and Sutcliffe, 1970) were used to evaluate the model's performance (Moriasi et al., 2007).

Streambank Erosion

NAIP images from 2003 to 2013 were used to estimate the lateral streambank retreat (Figure 1.9) (Heeren et al., 2012; Miller et al., 2014). The NAIP images were used to estimate the eroded streambank widths and lengths, and to calculate the eroded surface area (*EA*). Streambank depth (D_{ts}), in m, was based on Miller et al. (2014) and the 28 surveys, which was used to calculate the total sediment loading (*TS*), in kg, from each reach using:

$$TS = EA * D_{ts} * \rho_b \quad (1.19)$$

where ρ_b is the soil bulk density (g cm^{-3}). A weighted ρ_b based on the bank composition (Miller et al., 2014) was used to estimate the average ρ_b for the bank.

Results and Discussion

Area Adjustment Factor Verification

Figure 1.10 illustrates differences in *a* and flow depth for three cross-sectional reaches: meander (a=0.72), heterogeneous straight reach (a=0.77) and homogenous straight reach (a=0.93). Due to land cover changes and deforestation, gravel has eroded from the upland areas throughout the Barren Fork Creek watershed. Much of this gravel has reached the Barren Fork Creek, resulting in changes in the channel dimensions and flow dynamics of the creek. The highly irregular cross-sections (Figure 1.10a,b) were more representative of the cross-sections on the Barren Fork Creek. The more irregular the measured channel cross section, the more important *a* becomes in accurately estimating the flow depth. For each cross-section, the flow depth was simulated more accurately when using a.

Flow and Flow Depth Calibration

Streamflow calibration predictions were 'very good' (Moriasi et al., 2007) with monthly R^2 and NSE for the calibration (2004 to 2013) and validation (1995 to 2003) periods ranging from 0.78 to 0.82. Based on the cross-sectional surveys, a trapezoidal channel with a top width of 136 m, D_{ts} of 4.97 m and side slopes of 1.35 m m^{-1} were used to calculate *A* at USGS gage station 07197000. This *A* was then compared and adjusted using *a* (Equation 1.13) until it matched the irregularly-shaped surveyed *A* (see Figure 1.2). An α of 0.66 was calculated, which signifies that water is not flowing in 34% of the trapezoidal *A* at a flow depth of 4.97 m. The procedure was repeated at the upstream USGS gage station 07196900 using an α of 0.95.

Flow-depth calibration at the two USGS gage stations yielded the same Manning's *n*, 0.05, which was applied to each reach in the watershed. The calibrated daily flow depth at gage station 07197000 had an R^2 of 0.64 and NSE of 0.56 (Figure 1.11), while the USGS gage station upstream near Dutch Mills, Arkansas had an R^2 and NSE of 0.49. The calibrated Manning's *n* of 0.05 was in the range for other gravel bed streams (Chow, 1959; USGS, 1989) based on the procedure developed by Cowan (1956).

SWAT Calculated Vs Measured Parameters

Data Mining Parameters

The estimated bed slope using topographic maps and NAIP aerial images were not normally distributed; therefore, a Mann-Whitney Rank Sum Test was used to compare bed slopes. At a 95% confidence level, the bed slope calculated using the topographic maps and NAIP aerial images was not significantly different than the bed slope estimated from the 10-m DEM (Figure 1.12). However, the DEM underestimated the bed slope near the watershed outlet and overestimated the bed slope in the head waters. Kocian (2012) also found low accuracy with the 10-m DEM in estimating bed slope compared to LIDAR and topographic maps. Based on these findings and those by Kocian (2012), the bed slope measurements derived from aerial images and topographic maps were utilized.

The sinuosity at the ten study sites ranged from 1.0 to 2.5 with an average of 1.3. Of the ten study sites, four were classified as straight reaches (less than 1.1), three sinuous (1.1-1.5) and three meandering (greater than 1.5) (Dey, 2014). Note that Equation 1.9 was valid for reaches with a sinuosity greater than 1.2 (Williams, 1986). The average radius of curvature for the four study reaches with a sinuosity greater than 1.2 was 151 m. Applying Equation 1.9, the average R_c of the four sites was 131 m and 216 m using *BW* and top width, respectfully (Figure 1.13). An analysis of covariance was conducted at a 95% confidence level to compare the measured R_c versus those derived from Equation 1.9 and the top width or *BW*. Neither the slope nor slope intercept were significantly different for either the top width or *BW*.

Field-measured Parameters

Field measurements at cross-over points and the corresponding drainage area were used to derive equations for *BW* and *BD* (Dutnell, 2000). The measured *BW* had an R^2 of 0.72 and was compared to the values derived from the three empirical equations using an analysis of covariance with a 95% confidence level (Figure 1.14). Neither the slope nor the slope intercept for the SWAT global regression (Equation 1.6) were significantly different with p-values of 0.23 and 0.07, respectively. For the proposed regional regression (Equation 1.17), the slope was significantly different, but the slope intercept was not with a p-value of 0.08. Both the slope and slope intercept were significantly different for the proposed US regression (Equation 1.15).

The measured *BD* versus *DA* had an R^2 of 0.66 and was also compared to the values derived from the three empirical equations using an analysis of covariance with a 95% confidence level (Figure 1.15). The slope was not significantly different for the SWAT global regression (Equation 1.6), yet the slope intercept was significantly different with p-values of 0.07 and 0.02, respectively. For the proposed regional and US regression (Equation 1.17 and 1.15), neither the slope nor the slope intercept were significantly different with p-values of 0.49 and 0.11 for the proposed regional regression and 0.19 and 0.72 for the US regression, respectively.

These results support the findings by Bieger et al. (2015) that concluded that the regional curves were more reliable than the US equations. The regional equations can be improved by incorporating additional sites, especially for the Internal Highlands (seven sites) and Laurentian Upland (six sites) (Bieger et al., 2015). With the large number of SWAT users outside the US, there is a need for counties outside the US to develop their own regional or watershed specific regression equations; however, in this study the global regression estimated the bankfull parameters adequately.

SWAT defined the gravel bank containing 65% gravel, 15% sand, 15% silt and 5% clay, which was similar to the ten study sites that measured 68% gravel, 15% sand, 10% silt and 7% clay. Based on the measured *SC* content of the banks (Julian and Torres, 2006), τ_c was 4.6 Pa and k_d was 0.093 $cm^3\ N^{-1}\ s^{-1}$ (Equations 1.2, 1.3). Using the measured d_{50} of the ten study sites (1.3 to 2.5 cm) and Equation 1.18, τ_c ranged from 3.5 Pa to 8.7 Pa with an average of 5.6 Pa. Both methods produced similar results for τ_c, 4.6 versus 5.6, which agrees with Daly et al. (2015b).

The field surveys measured stream channel side slope, top width and D_{ts}. Average measured side slopes for the straight reaches and meanders were 4.8:1 and 1.4:1, respectively (Figure 1.16). Based on an ANOVA with a Tukey's multiple comparison test at a 95% confidence level, the measured side slopes from straight and meandering reaches and SWAT default values were all significantly different. Top width measurements taken at straight reaches were used to characterize all the stream reaches (Figure 1.17). Measurements were attempted at cross-over and meandering reaches, but many of the cross sections had 25 to 100 m of thick vegetation preventing accurate measurements. Based on an analysis of covariance at a 95% confidence level, the measured *BW* and top width were not significantly different. However, both the slope and slope intercept were significantly different for the measured D_{ts} and *BD* (Figure 1.18).

Observed vs Simulated Streambank Erosion

SWAT-estimated parameters were replaced with parameter estimates based on measured data using a regression equation with watershed area as the independent variable or an average measured value. The following regression equations were derived using measured bed slope and top width:

$$BS = 4.3*10^{-9}*WA^2 - 6.7*10^{-6}*DA + 0.00369 \quad (1.20)$$

$$TW = 0.0787*DA + 35.384 \quad (1.21)$$

where *BS* is the bed slope in m m^{-1}, *TW* is the top width in m and *DA* is the watershed area in km^2. The sinuosity measured at each site using aerial photographs was used in the model. However, R_c could not be measured using aerial photographs for large reaches. Therefore, Equation 1.9 was used to estimate the R_c based on *DA*. It should be noted that the R_c measurements were taken from the aerial photographs were not significantly different at the 95% confidence level from the estimates using Equation 1.9. Since there was no longitudinal trend with *DA* along the length of the Barren Fork Creek, the average τ_c (5.6 Pa), k_d (0.085 cm^3 N^{-1} s^{-1}), side slope (3.1:1), D_{ts} (2.8 m) and *a* (0.78) were used for each reach in the model simulations.

The average observed streambank erosion (gravel and topsoil) from 2004 to 2013 at the ten sites was 2,830 Mg yr^{-1}, and ranged from 219 Mg yr^{-1} at site J to 10,300 Mg yr^{-1} at site F (Figure 1.19). Using the SWAT model with default parameters, the SWAT 2015 streambank erosion routine beta version was tested using two methods, the empirical and proposed applied shear stress equations. The average simulated streambank erosion using the empirical equation was 1,360 Mg yr^{-1} compared to 2,510 Mg yr^{-1} for the process-based equation (Figure 1.19). Both models under predicted the streambank erosion at sites F and E and over predicted the erosion at several other sites, such as D and J. Though the correlation with observed erosion was poor for both equations, the NSE was better for the proposed shear stress equation (Table 1.2).

Data Mining

Incorporating measured *BS* into the model resulted in an improvement in both the R^2 and NSE (Table 1.2). Much of this improvement was due to the incorporation of measured *BS* for sites E and F. Based on the SWAT default using DEM, the *BS* at sites E and F were 0.00095 and 0.00054, respectively. The measured values using the topographic maps and NAIP images were 0.0015 for both sites, which were slope increases of 58 and 180 percent. Incorporating the measured sinuosity and R_c further improved model predictions. Though the average erosion for the data mining scenario decreased overall by 4 to 5% using the two applied shear stress equations, the simulated erosion at the meandering reaches (sites E and F) increased as did the R^2 and NSE (Table 1.2). Based on these results, model simulations can be improved by incorporating measured *BS*, sinuosity and R_c, which can all be measured without field-collected data. The correlation between observed and measured streambank erosion for both the empirical and process-based model had an R^2 of 0.65, even though the average erosion was under predicted using the empirical equation.

Bankfull Parameters

Replacing SWAT default *BW* and *BD* with measured values resulted in an average streambank erosion reduction of 41% and 30% for the empirical and process-based equations, respectively. While the *BW* and *BD* from the proposed regional equation reduced the average erosion by only 4 to 10%, the quantity of erosion increased 46 to 126% when the bankfull parameters derived from the US equation were incorporated into the model (Table 1.3). Using an ANOVA and Tukey's comparison test at 95% confidence level, none of the simulation results using the proposed shear stress equation were significantly different, yet the simulation results using the empirical shear stress equation and the US regression equations was significantly different compared to the other simulation results using the empirical equations. This re-enforces the need for US SWAT applications to use the regional regression equation instead of the US regression equation.

Field Data

Incorporating measured τ_c into the model resulted in a 22 to 25% reduction in the predicted average erosion for the two applied shear stress equations. Increasing τ_c by just one Pa influenced the erosion significantly and corroborates the findings by Narasimhan et al. (2015) that streambank erosion is very sensitive to τ_c. This supports the need for further research evaluating τ_c and k_d using empirical equations and field-measured data. Although the τ_c using the silt and clay content was within the range of measured values in this study, Daly et al. (2015b) found out the Julian and Torres (2006) relationship predicted a smaller range of values over a large range of silt and clay content for cohesive soils.

Replacing the SWAT default side slope of 2:1 with the field-measured side slope of 3.1:1 increased erosion at each site by 34% and 80% for the empirical and applied shear stress equation, respectively (Table 1.3). Issues arise when adjusting side slope, but not the *W* and bank height. Modifying the side slope, but using the smaller bankfull width instead of the *W*, decreases the stream channel *A* and results in excessive shear stress applied to the banks. Replacing the default *BW* and *BH* with the measured *W* and bank height increased the stream channel *A* and reduced the erosion by approximately 30% for the two applied shear stress equations. Replacing all of the measured values, side slope, T*W* and D_{ts}, with the measured values only increased the erosion by 15% using the empirical equation and reduced the erosion by 2% using the process-based equation. Incorporating *a* resulted in an increase of 172% for the empirical equation and 28% for the process based equation. The sensitivity of the empirical applied shear stress equation to decreases in the *A* is a result of more shear stress applied to the streambank instead of the streambed (Equations 1.4 and 1.5). Although replacing the default values with field measurements did not improve model predictions in this study (Table 1.3), more confidence can be given to the model predictions. Further research is needed to determine if replacing the *BS*, sinuosity and R_c is sufficient or if cross-sectional surveys should be conducted.

Cover Factor

Seven of the ten study sites were protected with riparian vegetation while three sites (F, E, and A) were unprotected (Miller et al., 2014). The average observed erosion from 2003 to 2013 at the three unprotected sites was 6,160 Mg yr^{-1} compared to 1,450 Mg yr^{-1} for the protected sites. Although quantifying the impact of riparian vegetation on streambank erosion is challenging on a watershed scale, vegetation can significantly impact the streambank erosion (Daly et al., 2015a; Harmel et al., 1999). While vegetation does not reduce the erodibility of the gravel layer, the stability of the cohesive top layer increases with root density. Micheli and Kirchner (2002) studied similar banks in California and found that the protected sedge banks only failed after the bank was significantly undercut. After the geotechnical streambank failure, the overbank soil remained partially attached providing temporary armoring against further erosion. The unprotected meadow banks failed more frequently and detached completely from the bank, thus preventing temporary armoring. Although the gravel layer is not affected by vegetation, the streambank erosion of the top cohesive soil layer is reduced. Therefore, due to the current limitations of the model, the τ_c was increased for the seven banks with riparian protection based on the following equation (Julian and Torres, 2006):

$$\tau_c^* = \tau_c * CH_{cov} \tag{1.22}$$

where τ_c^* is the effective critical shear stress (N m^{-2}) adjusted for vegetative cover and CH_{COV} is the multiplication factor called channel cover factor. Based on Narasimhan et al. (2015), we chose to use a CH_{COV} of two for forest. Therefore, the τ_c for the seven protected sites was increased from 5.6 to 11.2 N m^{-2} and the k_d was decreased to 0.06 cm^3 N^{-1} s^{-1} using Equation 1.3. Including the channel CH_{COV} improved the R^2 and overall model predictions (Figure 1.20). R^2 and NSE were 0.58 and 0.42 using the empirical equation and 0.66 and 0.52 using the process-based equation, respectfully. Both shear stress equations using the CH_{COV} adequately predicted streambank erosion except at reaches E and I. Reach E had an unusually large quantity; more than twice as much as the other two unprotected sites. Although reach I had good riparian protection in 2003 (Figure 1.21), it had 4,330 Mg yr^{-1} streambank erosion compared to a combined total of 5,800 Mg yr^{-1} for the remaining six protected sites. Results from these two reaches demonstrate that models cannot account for all processes occurring in the natural world.

Conclusions

The modified streambank-erosion routine for the SWAT model improved the predicted streambank erosion for composite streambanks. Although the process-based applied shear stress equation was the most influential modification, incorporating the top width, streambank depth and area-adjustment factor more accurately represented the measured irregular cross-sections and improved the model predictions compared to observed data. Since field-data collection is not feasible for every project, simulations were performed using literature and field-based data.

If collecting stream data to estimate channel parameters is not possible due to financial, geographic or time constraints, literature-based data can provide good streambank-erosion estimates. The current SWAT and proposed regional regression equations adequately estimated bankfull width and bankfull depth. The proposed US equation, on the other hand, produced poor results and therefore should not be used for the conditions studied. While Equation 1.9 provided an adequate estimate of the radius of curvature, the measured bed slope using aerial images and topography maps should be used in place of the DEM-derived estimates. Incorporating the radius of curvature, sinuosity, bed slope and the global or regional bankfull parameters improved model predictions at the ten study sites. The R^2 increased from 0.01 to 0.65 and the NSE increased from -0.92 to 0.49.

Although results from this study demonstrated that using field-measured parameter estimates may not statistically improve model predictions for the conditions studied, other time periods or watersheds may be different. If limited field work can be conducted, multiple measurements of the critical shear stress (τ_c) are recommended. The τ_c was one of the most sensitive parameters and it can be incorporated into the model without affecting the cross-sectional area of the stream channel. If resources permit, complete cross-section surveys should be conducted throughout the stream system to quantify the top width, streambank depth, side slope and area-adjustment factor. Each of these parameters affects the cross-sectional area and should be replaced together. In general, the more watershed-specific measured data incorporated into the model, the more confident the user can be in the model predictions.

Further testing of the ability to predict τ_c using the silt and clay content is needed as well as exploring other τ_c and erodibility coefficient relationships. More research is also needed to quantify how root density from different types of riparian vegetation impact τ_c. Future research also needs to address the streambank-erosion routine limitations, specifically incorporating multiple-layer banks and the modification of channel dimensions throughout the simulation.

Table 1.1. Streambank erosion processes and equations for the current version (SWAT 2005), the 2015 beta version and the proposed modifications to the beta version.

Process	2005 SWAT	2015 Proposed Subroutine	2015 Proposed Subroutine Modifications
Streambank erosion	Excess shear stress equation; function of transport capacity	Excess shear stress equation	Excess shear stress equation
Applied shear stress equation	Equations 1.4, 1.5	Equations 1.4, 1.5	Equations 1.15, 1.16
Incorporates sinuosity	No	Yes	Yes
Bank dimensions	Bankfull width/depth	Bankfull width/depth	Top width/bank depth
Channel heterogeneity	No	No	Yes; area adjustment factor

Table 1.2. SWAT simulated streambank erosion using different methods to estimate streambank erosion parameters using both the empirical and proposed process-based equations for Barren Fork Creek. Empirical is the empirical applied shear stress equation currently used by the SWAT model. Process-Based is the proposed process-based applied shear stress equation. Methods include SWAT default parameters and replacing default parameters with several measured parameters: bed slope, literature based and bankfull width and depth. Literature based parameters include bed slope, sinuosity and radius of curvature. NS=Nash Sutcliff Efficiency.

Parameter	Applied Shear Stress Equation					
	Empirical			Process-Based		
	Erosion (Mg yr^{-1})	R^2	NSE	Erosion (Mg yr^{-1})	R^2	NSE
SWAT default	1,150	0.02	-0.33	2,510	0.01	-0.16
Bed slope	1,000	0.03	-0.20	2,230	0.57	0.38
Literature based	1,090	0.02	-0.12	2,410	0.65	0.49
Measured bankfull parameters	680	0.01	-0.55	1,750	0.05	-0.14
Regional bankfull regression	1,100	0.55	-0.35	2,260	0.01	-0.26
Proposed United States regression	2,600	0.65	-0.47	3,660	0.01	-0.92

Table 1.3. Influence field-measured parameters have on simulated streambank erosion using both the empirical and proposed process-based applied shear stress equations. Empirical is the empirical applied shear stress equation currently used by the SWAT model and Process-Based is the proposed process-based applied shear stress equation. Each method includes literature based parameters, which includes bed slope, sinuosity and radius of curvature. All measured data includes the following: critical shear stress, side slope, top width and bank height. A_{adj} = area adjustment factor.

Parameter	**Applied Shear Stress Equation**					
	Empirical			**Process-Based**		
	Erosion (Mg yr^{-1})	R^2	NSE	Erosion (Mg)	R^2	NSE
Literature based (baseline)	1,090	0.65	-0.12	2,410	0.65	0.49
Critical shear stress	850	0.27	-0.37	1,800	0.32	0.10
Side slope	1,960	0.38	0.16	3,240	0.35	0.31
Top width and bank height	720	0.30	-0.42	1,740	0.46	0.15
All measured data	1,250	0.28	-0.14	2,350	0.46	0.32
All measured data + A_{adj}	2,960	0.34	0.31	3,080	0.47	0.41

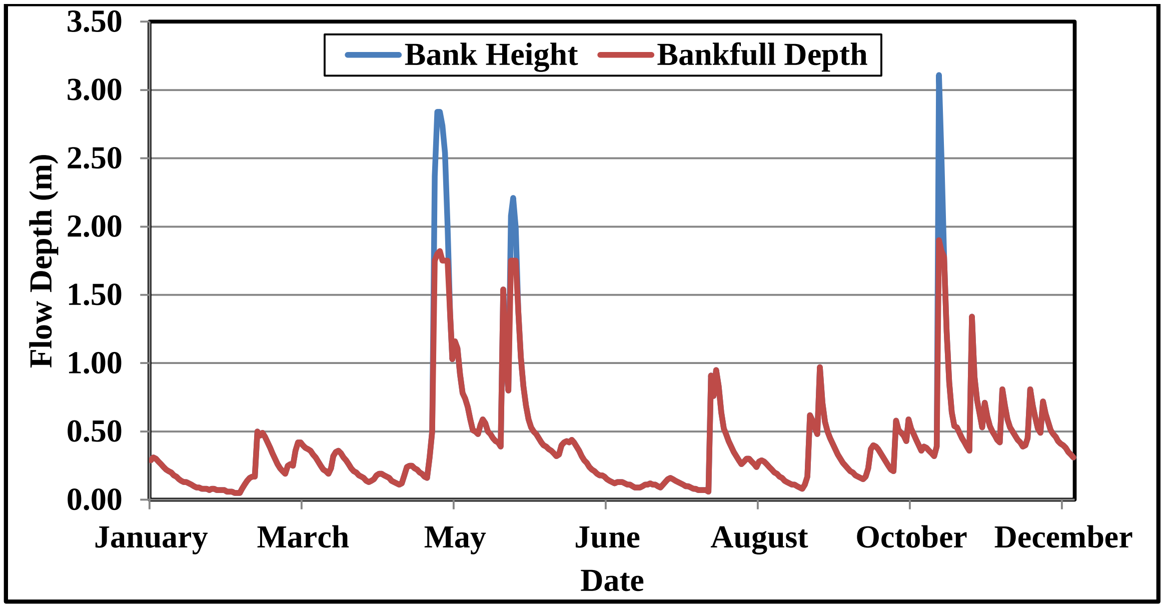


Figure 1.1. SWAT simulated flow depth when using bankfull depth or bank depth to define the channel cross section on the Barren Fork Creek for 2011.

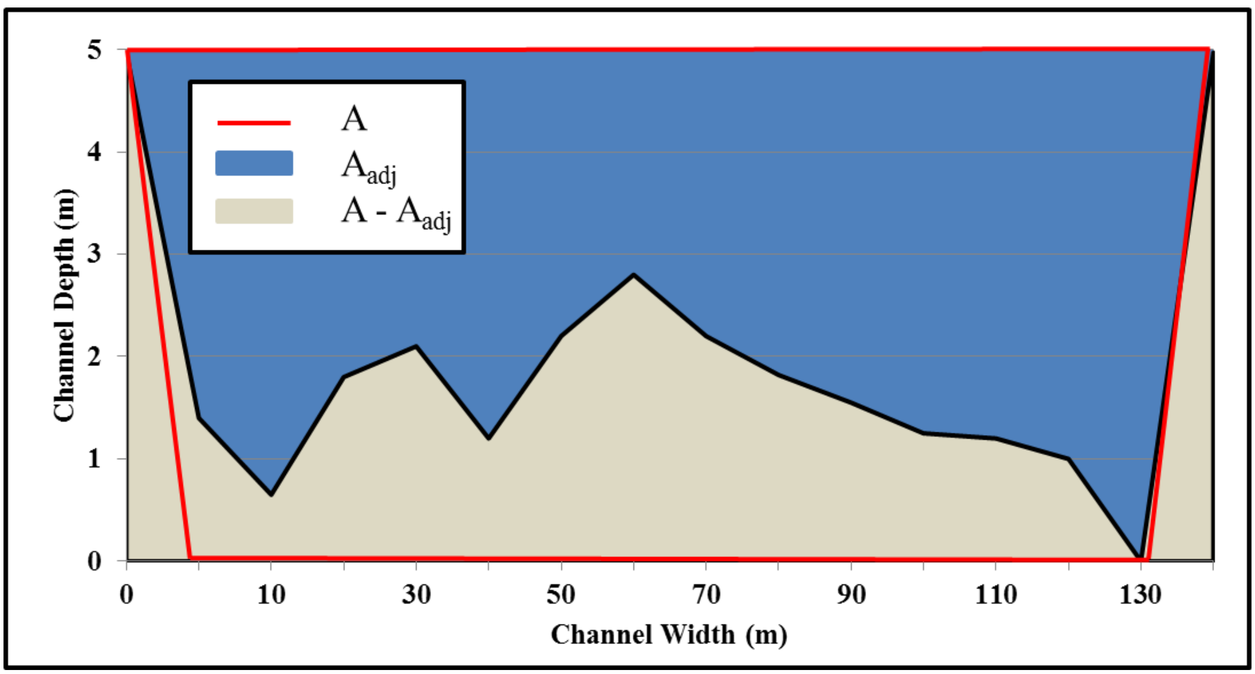


Figure 1.2. SWAT trapezoidal and measured stream cross sections at the United States Geological Survey gage station 07197000 used to adjust cross sectional area and calibrate flow depth. A_{adj} is the measured cross-sectional area of the natural channel, A is the cross-sectional area of an assumed trapezoidal channel, $A\text{-}A_{adj}$ is the difference between the trapezoidal and measured cross sections.

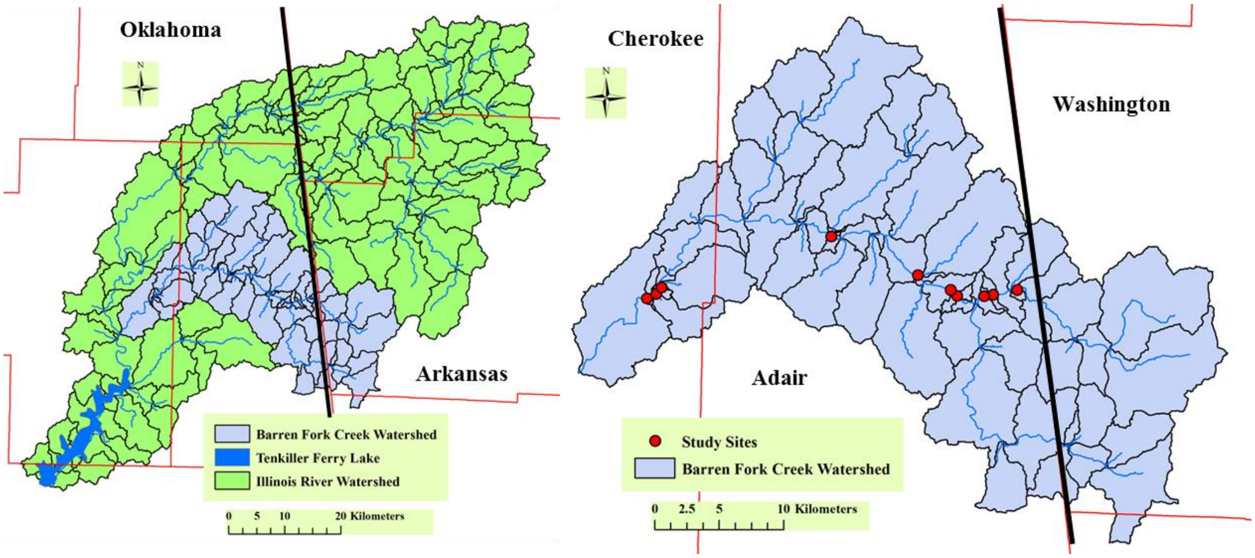


Figure 1.3. Illinois River and Barren Fork Creek watersheds in Oklahoma and Arkansas (left) and the Barren Fork Creek watershed showing ten study sites (right).

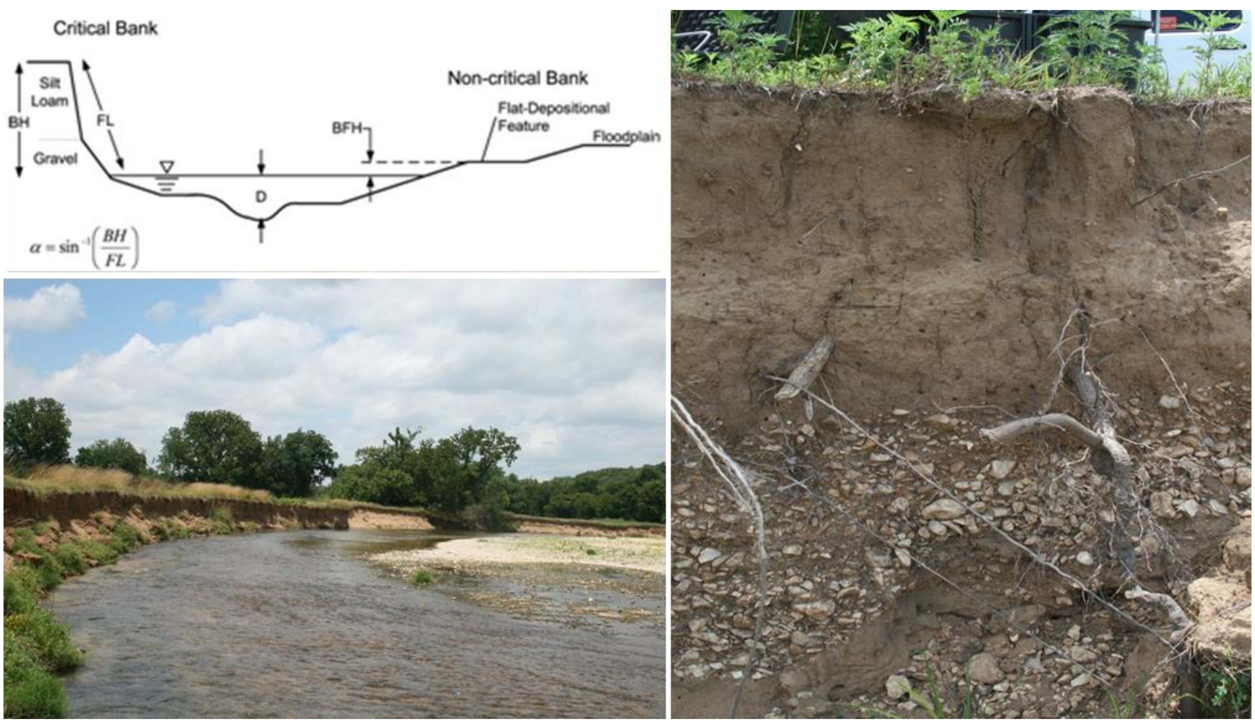


Figure 1.4. Typical stream channel profile in the Barren Fork Creek with one critical bank and one non-critical bank. Right image illustrates the underlying gravel layer and the silty loam topsoil for the critical bank (Heeren et al., 2012).

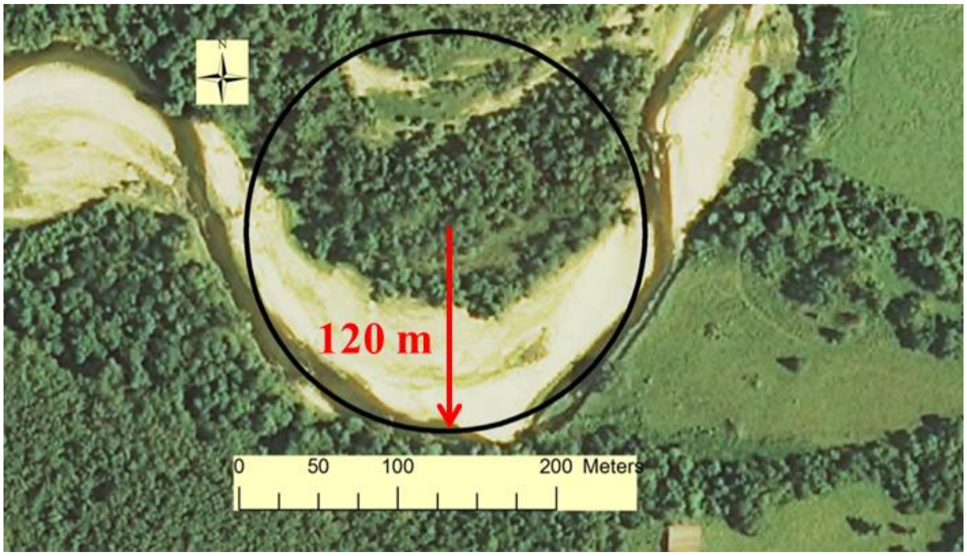


Figure 1.5. Radius of curvature estimate at site F on the Barren Fork Creek using a 2013 National Agriculture Imagery Program image.

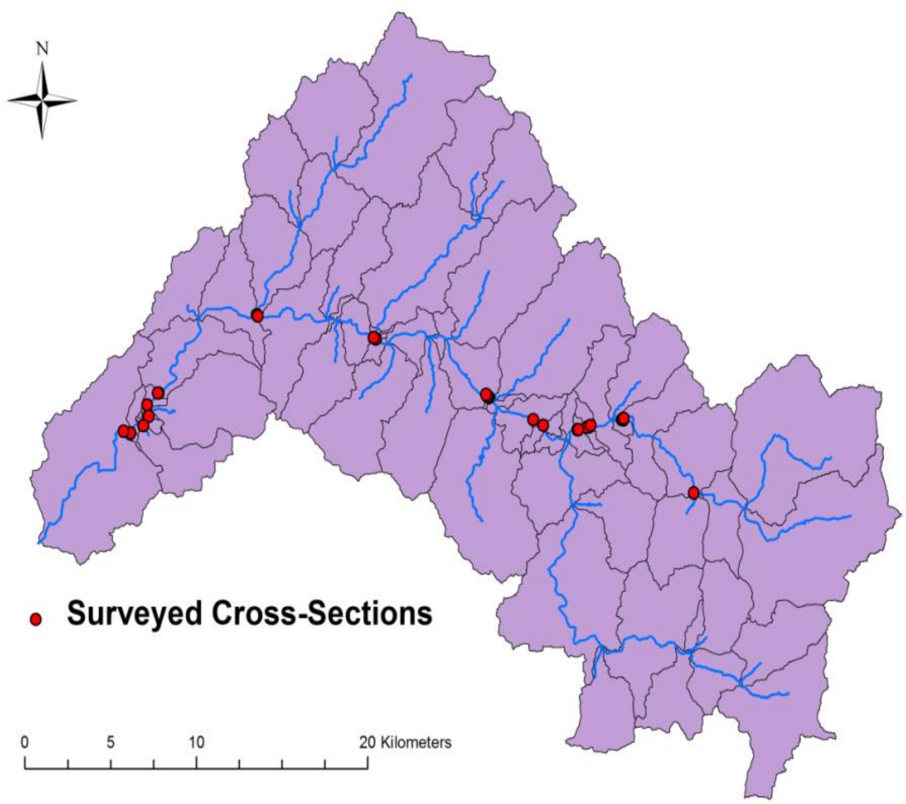


Figure 1.6. Location of 28 surveyed cross-sections surveyed on the Barren Fork Creek 2015.

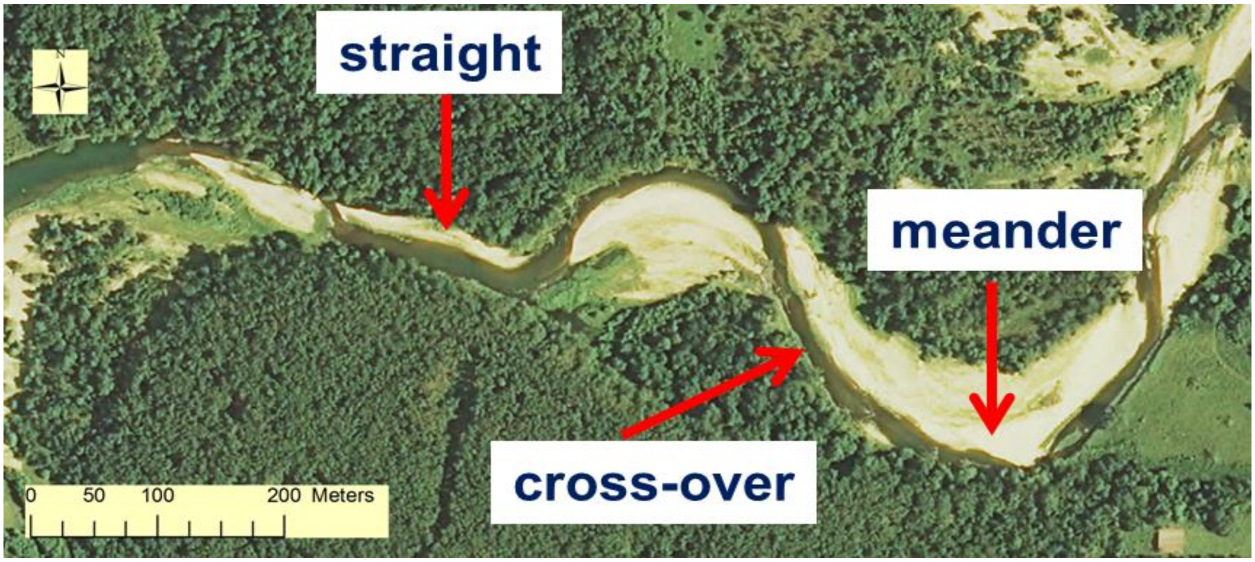


Figure 1.7. Examples of straight, meandering and cross-over stream reaches on a 2013 National Agriculture Imagery Program image.

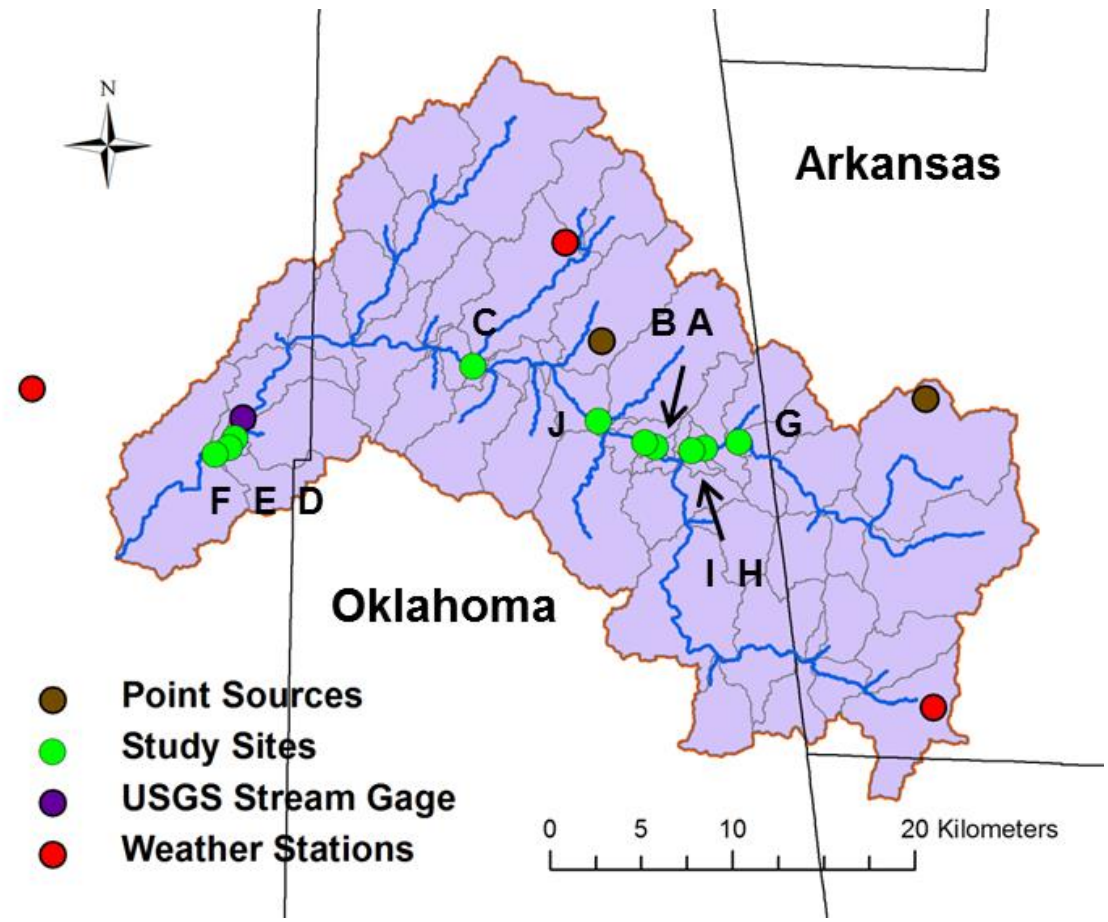


Figure 1.8. United States Geological Survey gage station, weather stations and stream reach study sites for the Barren Fork Creek watershed.

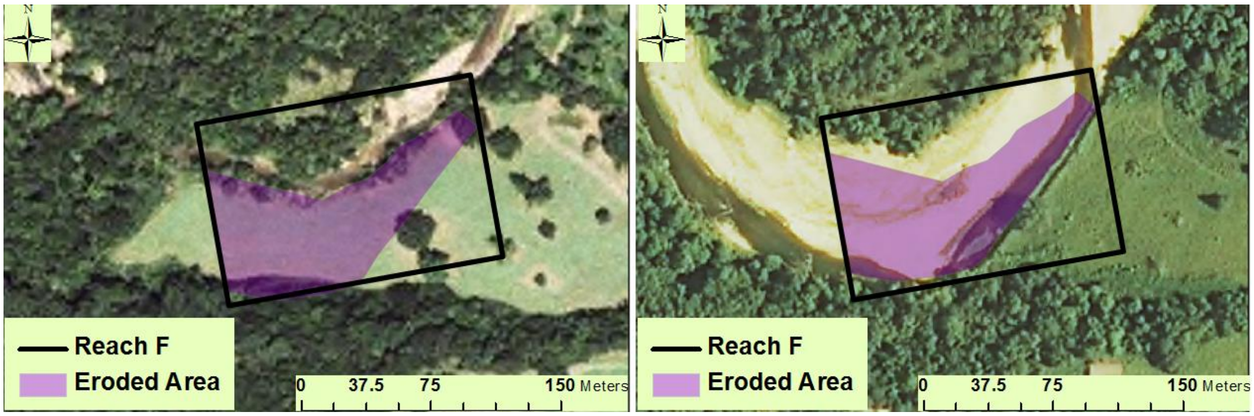


Figure 1.9. 2003 (left) and 2013 (right) National Agricultural Imagery Program aerial images with polygons illustrating the streambank retreat (purple) during the period for study Site F on the Barren Fork Creek.

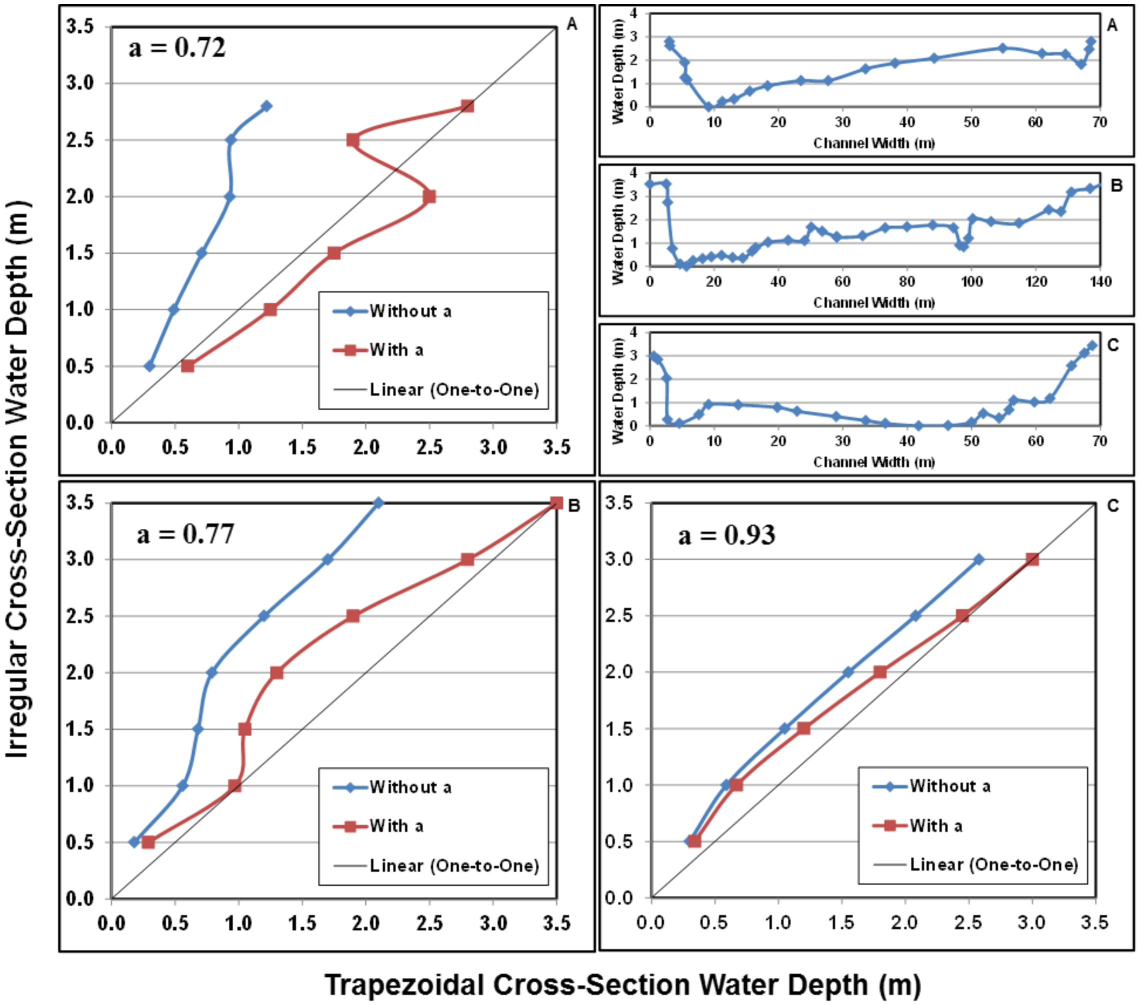


Figure 1.10. FlowMaster-calculated flow depth for the irregular cross-section compared to the trapezoidal cross-section with and without the area adjustment factor (a). Cross-section A is a meander, B is a heterogeneous straight reach and C is a homogenous straight reach.

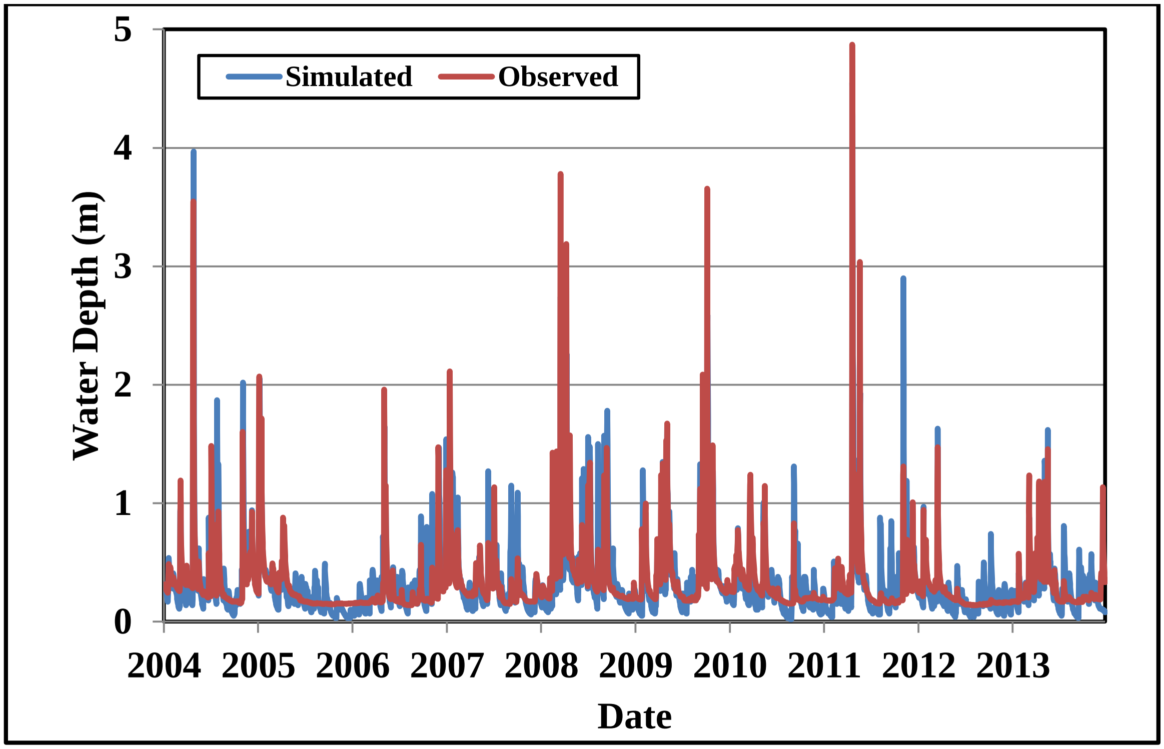


Figure 1.11. Observed and simulated water depth at the United States Geological Survey gage station 07197000 for the period 2004 to 2013.

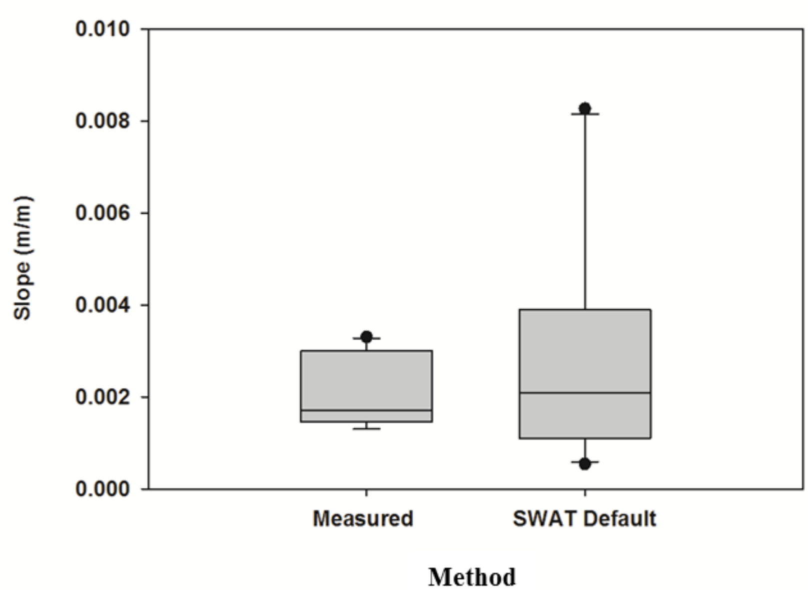


Figure 1.12. Channel bed slope calculated from the topographic map and aerial images (measured) and digital elevation model (SWAT default) for the Barren Fork Creek.

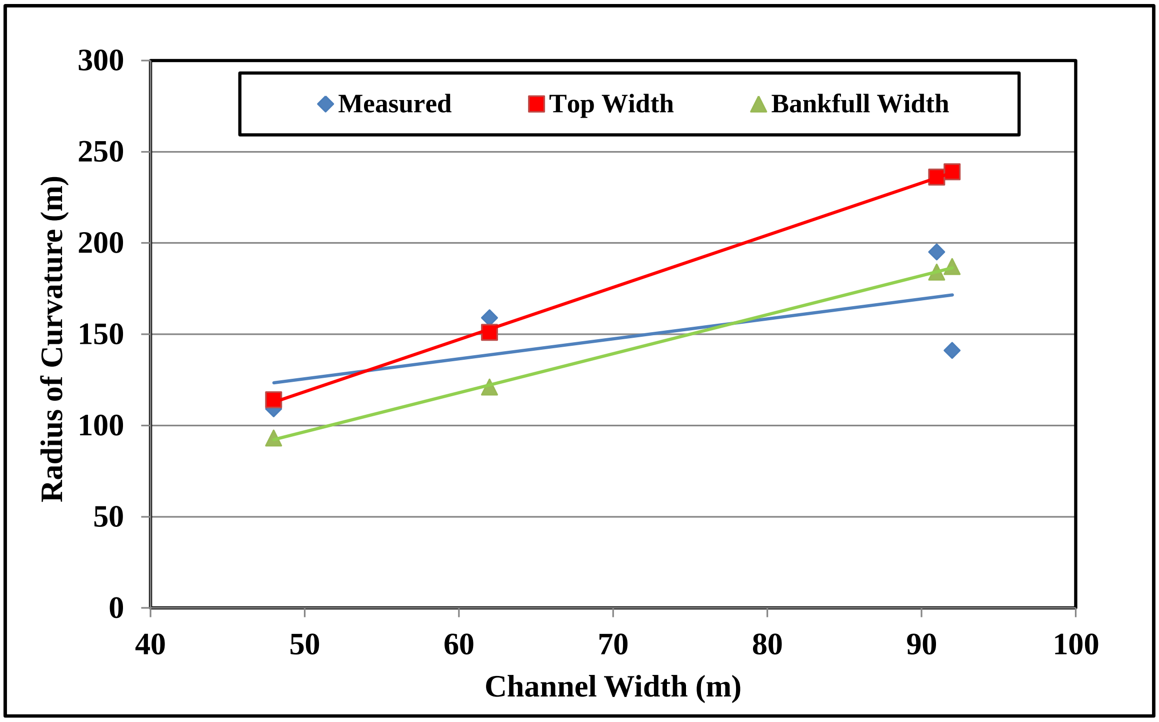


Figure 1.13. Measured and calculated radius of curvature for four reaches with a sinuosity greater than 1.2 on the Barren Fork Creek. The radius of curvature was calculated using Equation 4.9 ($R_c = 1.5*W^{1.12}$), where *W* is the measured bankfull width or top width.

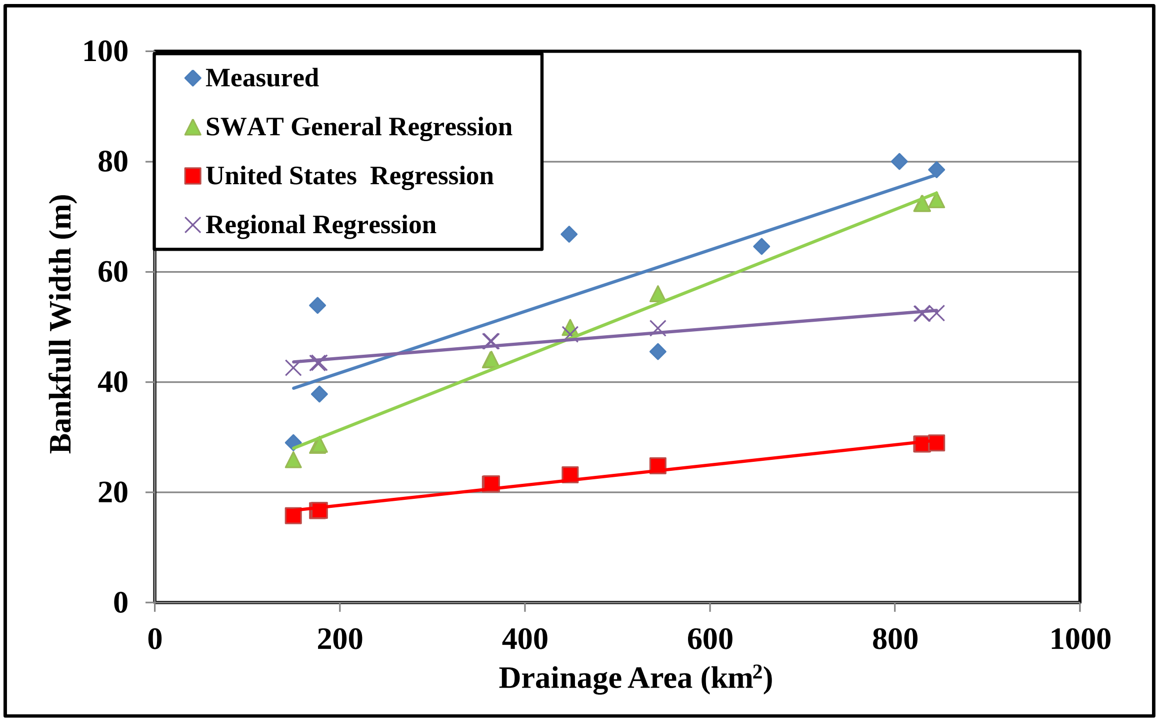


Figure 1.14. Measured bankfull width and calculated bankfull width using three empirical equations vs drainage area for the Barren Fork Creek.

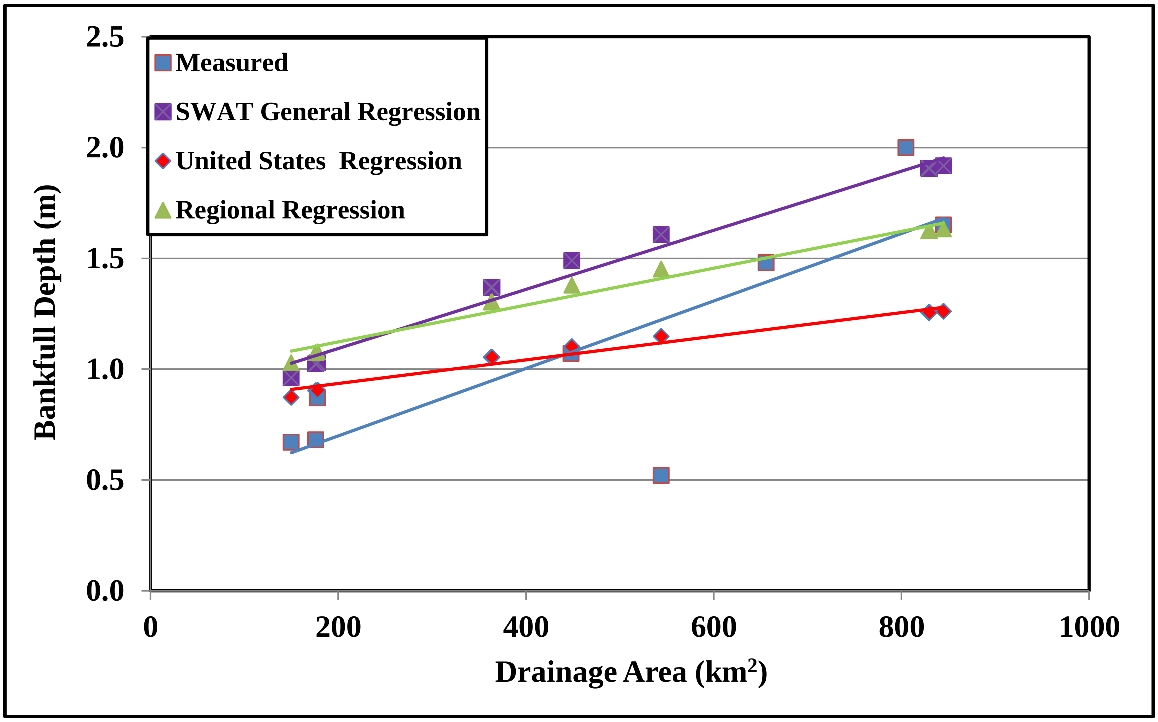


Figure 1.15. Measured bankfull depth and calculated bankfull depth using three empirical equations vs drainage area for the Barren Fork Creek.

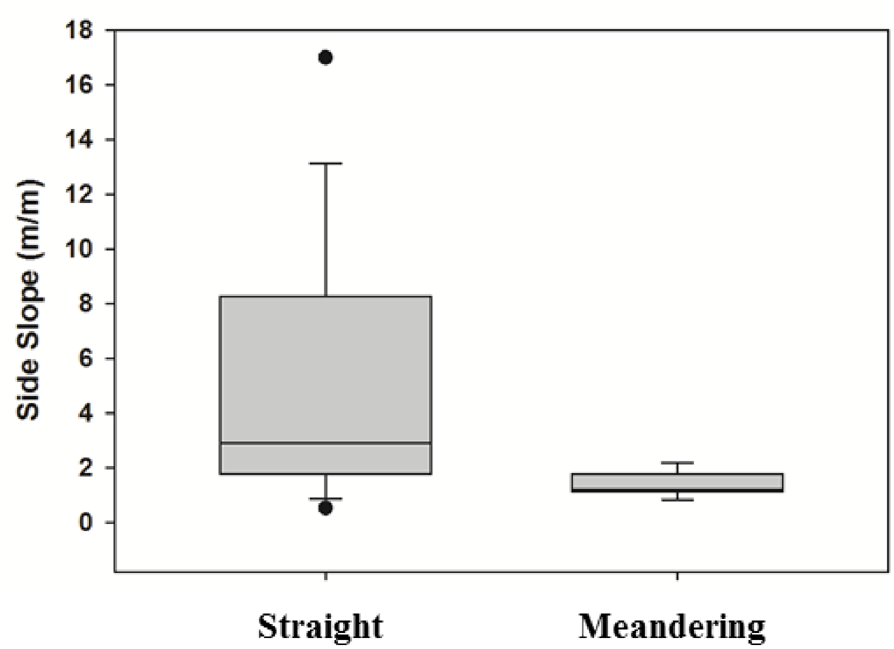


Figure 1.16. Measured side slopes for straight and meandering reaches on the Barren Fork Creek.

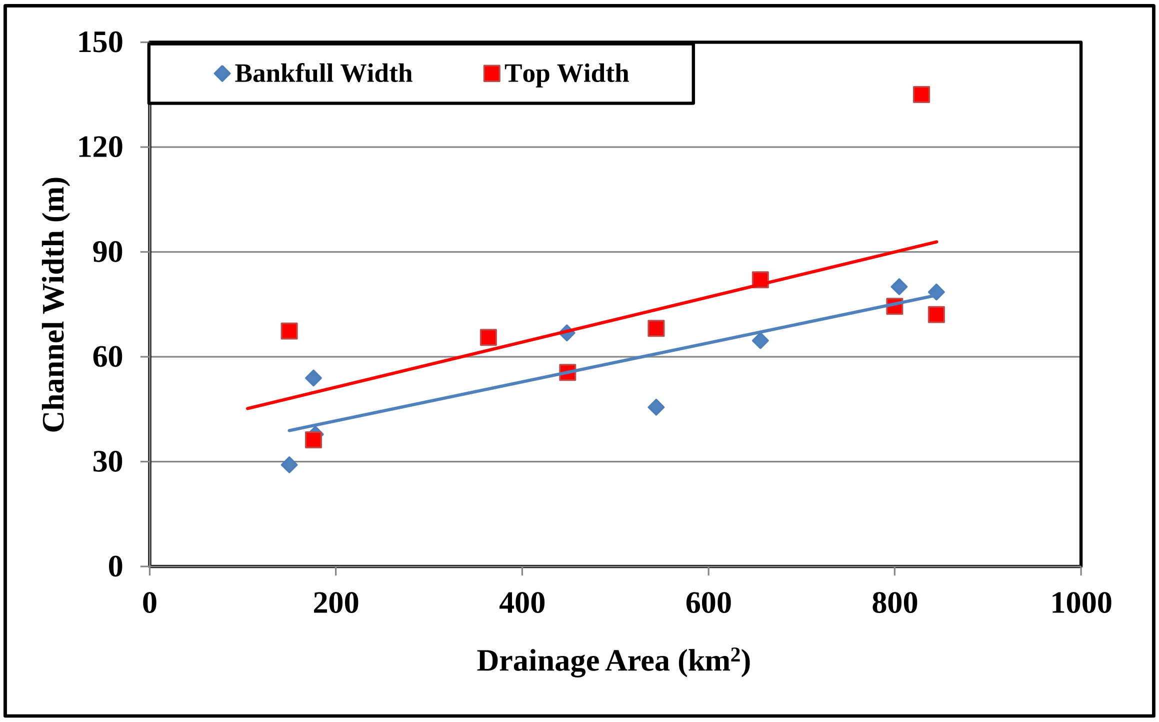


Figure 1.17. Measured straight reach top width and bankfull width for the Barren Fork Creek.

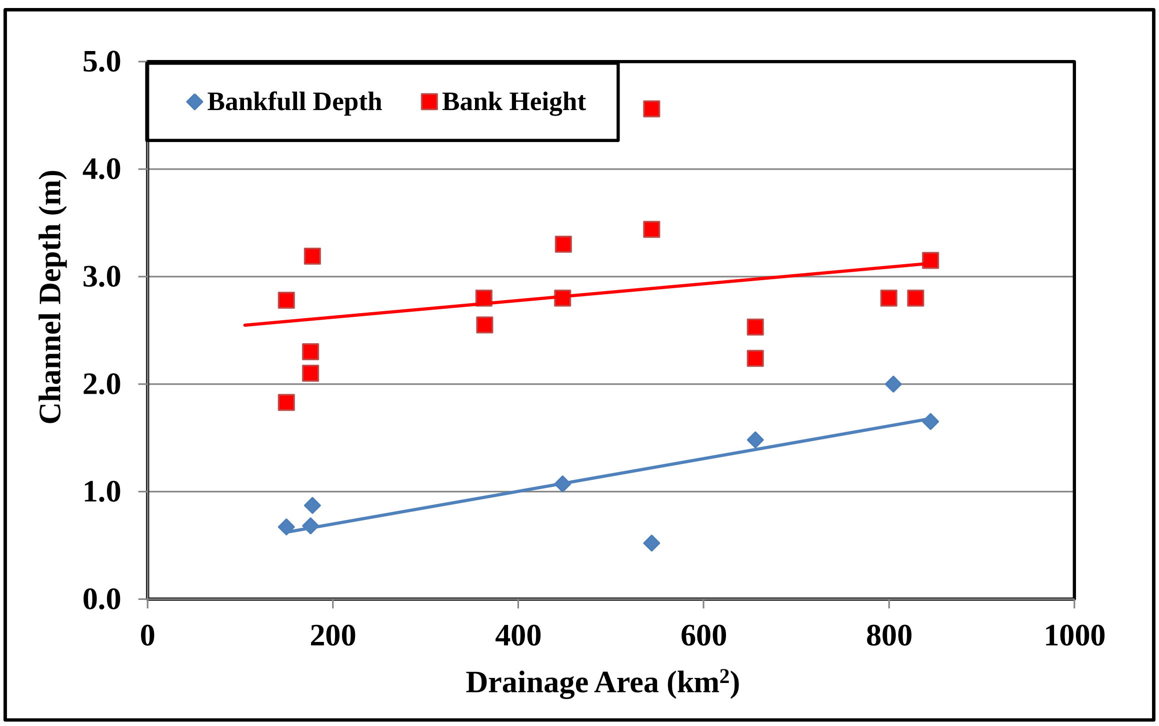


Figure 1.18. Measured straight reach bankfull depth and bank height for the Barren Fork Creek.

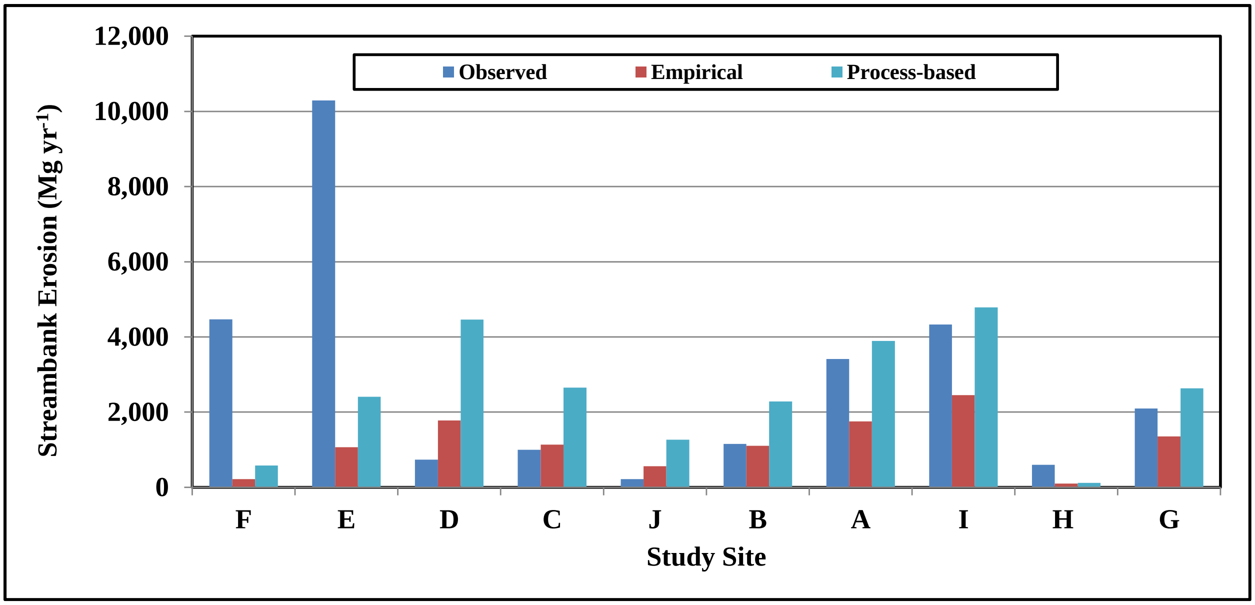


Figure 4.19. Measured and simulated streambank erosion using empirical and process-based applied shear stress equations using the SWAT model with default parameters at ten study sites on the Barren Fork Creek from 2004 to 2013. Empirical is the applied shear stress equation currently used by the SWAT model and process-based is the proposed process-based applied shear stress equation.

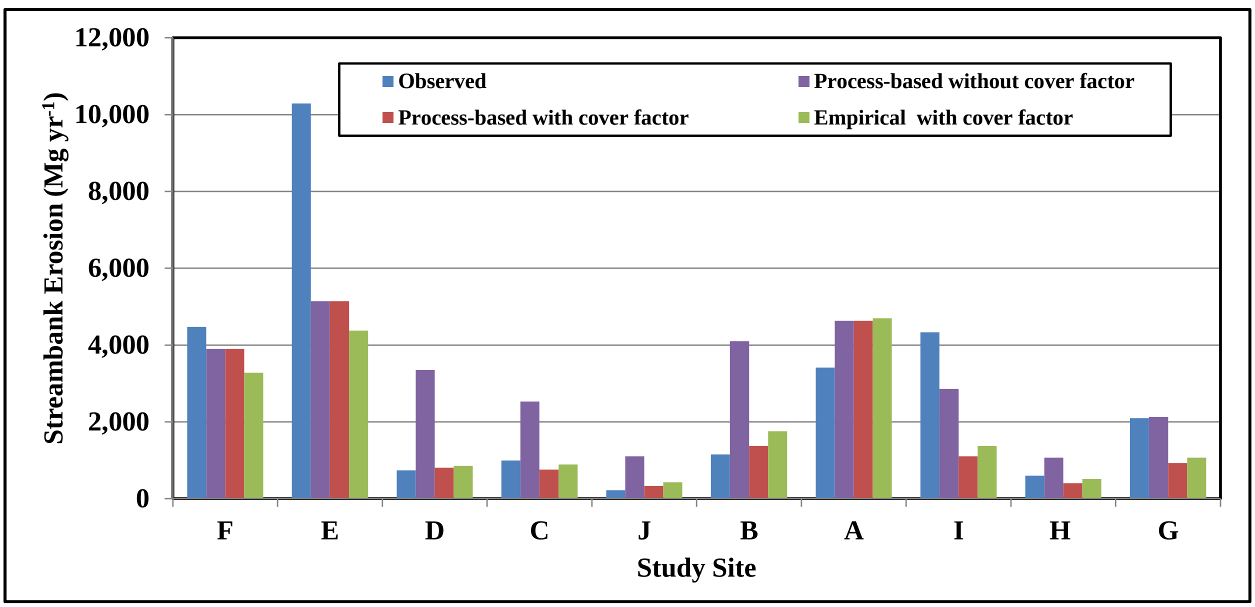


Figure 1.20. Observed streambank erosion compared to SWAT simulated erosion with and without the streambank cover factor for the Barren Fork Creek from 2004 to 2013. Empirical equation is the applied shear stress equation currently used by the SWAT model and process-based is the proposed process-based applied shear stress equation.

Figure 1.21. Streambank erosion at reach I on the Barren Fork Creek from National Agricultural Imagery Program aerial 2003 (left) to 2013 (right) images. The red line is the location of the reach in 2003.

CHAPTER 2

ESTIMATING STREAMBANK EROSION AND PHOSPHORUS LOADS FOR THE BARREN FORK CREEK WATERSHED USING A MODIFIED SWAT MODEL

Abstract

Phosphorus (P) and streambank erosion are problematic in the Barren Fork Creek watershed in northeast Oklahoma and northwest Arkansas. Previous SWAT modeling efforts of the watershed have not accounted for the contribution of stream banks as a P source due to lack of field data and model limitations. This is believed to be the cause for under predicting total and particulate P during large storm events. The objectives of this research were to model the streambank erosion and P for the Barren Fork Creek using a modified SWAT model. Measured streambank and channel parameters were incorporated into a flow-calibrated SWAT model and used to estimate streambank erosion and P for the Barren Fork Creek using the latest streambank-erosion routine and newly incorporated process-based applied shear stress equation. The predicted streambank erosion was 215,000 Mg yr^{-1} versus the measured 160,000 Mg yr^{-1}. Streambank erosion contributed 47% of the total P to the Barren Fork Creek and also improved P predictions compared to observed data, especially during the high flow events. Due to this influx of streambank P to the system and the current in-stream P routine's limitations, the in-stream P routine was modified by introducing a long-term storage coefficient, thus converting some of the particulate P to long-term storage. Of the total P entering the stream system, approximately 65% left via the watershed outlet and 35% was stored in the floodplain and stream system. This study not only provided local, state and federal agencies with accurate estimates of streambank erosion and P contributions for the Barren Fork Creek watershed, it demonstrated how watershed-scale model, such as SWAT, can be used to predict both upland and streambank P.

Introduction

Excess phosphorus (P) and sediment are two major stream and reservoir pollutants. Often non-point sources, such as livestock, urbanization and commercial fertilizer, and point sources are responsible for elevated P and turbidity. Currently, over $3.7 billion is spent in the United States annually on natural resource conservation (Monke and Johnson, 2010; White et al., 2014), with much of this spent on the implementation of conservation practices to reduce the quantity of P and sediment reaching waterways from agricultural activities. White et al. (2014) found that row crops and point sources were the most significant contributors of P reaching the Gulf of Mexico, although in some watersheds, streambanks can contribute up to 80% of the total sediment (Simon et al., 1996) and a significant quantity of total P (Kronvang et al., 2012; Laubel et al., 2003; Langendoen et al., 2012). Conservation practices aimed at reducing

P runoff from agricultural land and point sources will thus be less effective if streambank erosion is not addressed.

One area of concern is the highly-sinuous stream system of the Barren Fork Creek in northeast Oklahoma and northwest Arkansas. The Barren Fork Creek, along with its receiving waterbodies Illinois River and Tenkiller Ferry Lake, are on the Oklahoma 303(d) list of impaired waters due to excess P (DEQ, 2012). In the last sixty years, the once-clear waters have become eutrophic due to pollutant loads from urbanization and livestock production, especially poultry (Cooke et al., 2011). Although tens of millions of dollars have been spent on improving the water quality of one of Oklahoma's few state-designated scenic rivers, most of these monies have been used for the implementation of conservation practices in the upland areas. In previous SWAT modeling efforts of the Illinois River watershed (Storm et al., 2006; Storm et al., 2010; Storm and Mittelstet, 2015), streambank erosion was not addressed due to lack of data and model limitations. Due to the meandering stream system and highly erosive streambanks, P derived from streambank erosion is hypothesized to be the cause for underestimating P during the high flow events. Recent work by Miller et al. (2014) has strengthened this hypothesis. They found that 36% of the streambanks on the Barren Fork were unstable and contribute approximately 90 Mg of TP annually, almost half the total P reaching the watershed outlet.

In the last decade, the streambank-erosion routine in the Soil and Water Assessment Tool (SWAT) (Arnold et al, 1998) has undergone considerable improvements. The latest beta version, previously only tested on cohesive soils in the Cedar Creek watershed in Texas (Narasimhan et al., 2015), uses an excess shear stress equation to calculate the erosion rate, ε (m/s), given as:

$$\varepsilon = k_d(\tau_e - \tau_c) \tag{2.1}$$

where k_d is the erodibility coefficient (cm^3 N^{-1} s^{-1}), τ_e is the effective shear stress (N m^{-2}), and τ_c is the soil's critical shear stress (N m^{-2}). The k_d and τ_c coefficients are functions of numerous soil properties. Improvements on predicting applied shear stress to streambanks were accomplished by incorporating sinuosity and radius of curvature to account for the effects of meander. Though the current routine uses an empirical equation to estimate the applied shear stress (Eaton and Millar, 2004), Mittelstet (Chapter 1) proposed an alternative process-based equation (USDA-ARS, 2000) for SWAT:

$$\tau = \gamma * R * S_f \tag{2.2}$$

where γ is the specific weight of water (N/m^3), R is the hydraulic radius (m) and S_f is the friction slope (m/m). The friction slope is computed using the following equation:

$$S_f = \frac{n^2 * Q^2}{A^2 * R^{\frac{4}{3}}} \tag{2.3}$$

where Q is the average flow rate (m^3), n is Manning's roughness coefficient and A is the area (m^2).

This study will test and validate this updated routine on a flow-calibrated SWAT model of the Barren Fork Creek watershed. Specifically, the objectives of this study are (1) to predict streambank erosion for the Barren Fork Creek using the proposed streambank-erosion routine (Chapter 1), (2) model P in the watershed with and without incorporating P derived from streambank erosion and (3) determine the significance of streambank erosion relative to upland P sources.

Methods

Study Site

The Barren Fork Creek watershed has a drainage area of 890 km^2 and is composed of approximately 55% forest, 24% well-managed pasture, 6% over-grazed pasture and 13% hay meadow (Storm and Mittelstet, 2015). The Barren Fork Creek, a fourth-order stream, is approximately 73 km in length and is located in the Ozark Highland Ecoregion in northeast Oklahoma and northwest Arkansas (Figure 2.1). The headwaters begin in Washington County, Arkansas, and flow through Adair County, Oklahoma before discharging into the Illinois River in Cherokee County, Oklahoma just north of Tenkiller Ferry Lake. Barren Fork Creek is a State-designated Scenic River and is on the Oklahoma 303(d) list for nutrient and sediment related impairments (USEPA, 2015b). Typical of the Ozark Highland Ecoregion, the watershed is characterized by cherty soils and gravel-bed streams (Heeren et al., 2012). The highly dynamic streambanks consist of alluvial gravel deposits underlying silty loam topsoil (Figure 2.2). The sinuous stream often has a critical bank on the outside of the meander and a gravel bed on the inside bank.

SWAT Model Description

SWAT is a basin-scale hydrological/water-quality model used to predict streamflow and pollutant losses from watersheds composed of mixed land covers, soils and slopes. The model was developed to assist water resource managers to assess water quantity and/or quality in large river watersheds and as a tool to evaluate the impact of agricultural conservation practices. The SWAT model, a product of over 30 years of model development by the US Department of Agriculture Agricultural Research Service, has been extensively used worldwide (Gassman et al., 2007, 2014). The model is process-based and can simulate the hydrological cycle, crop yield, soil erosion, and nutrient transport.

An ArcGIS interface can be used to develop model input of land cover, soils, elevation, weather, and point sources, and define the flow network. The interface divides the watershed into subbasins, which are further split into hydrological response units (HRUs). Each HRU has one soil type, one land use and one slope. The model uses the Modified Universal Soil Loss Equation (MUSLE) to calculate sediment yield for each HRU. This sediment, along with nutrients, are combined for each subbasin and routed through the stream reach. The water and sediment, along with any other pollutants, are routed from reach to reach until arriving at the watershed outlet. Many field-scale activities, such as planting dates, irrigation, fertilization, grazing, harvesting and tillage, are utilized by

SWAT as management options scheduled by date. Further details on the model inputs and the theoretical aspects of hydrology, nutrient cycling, crop growth and their linkages are provided in Neitsch et al. (2009).

This study used SWAT 2012 version 583 and the recently incorporated simplified in-stream P routine (White et al., 2012), which consists of two components. The first component represents the transformation of soluble P to particulate P (i.e. the uptake of soluble P by algae and P precipitation) and its interactions with sediment, which is based on an equilibrium P concentration (EPC). EPC is the concentration at which there is no net sorption or desorption from benthic sediments into the water column. If the EPC is greater than the concentration of soluble P in the water column, P moves from the benthos to the water column; the reverse occurs if the EPC is less than the soluble P. The second component represents the deposition and scour of particulate P (sediment-bound P and algal P) to/from the benthos, which is based on the ratio of flow to bankfull discharge.

SWAT Model Modifications

As Figure 2.3 illustrates, the Barren Fork Creek is very dynamic. Within ten years, sediment was deposited on the gravel bar and the riparian vegetation became fully established (see yellow arrows). Much of eroded particulate P, from both uplands and streambanks, is deposited on the floodplain or within the stream system, particularly on the non-critical bank. Since the water only overtopped its bank a few times from 2004 to 2013, most of the excess P is believed to be stored in the stream system.

A floodplain ratio, currently in the beta version of the streambank-erosion routine (Narasimhan et al., 2015), calculates the sediment and particulate P that settles on the floodplain using:

$$FP_{ratio} = \frac{area_1 - area_2 - area_3}{area_1} \tag{2.4}$$

where FP_{ratio} is a fraction of sediment and particulate P deposited in the floodplain, $area_1$ and $area_2$ are the total and top of the bank submerged cross sectional area (m^2), respectfully, and $area_3$ is the submerged cross sectional area from the top of bank to the total water depth multiplied by the top width (m^2). This equation assumes the velocity and particulate P are uniformly distributed.

The in-stream P routine scours all benthic P during large storm events, although much of the P deposited within the stream system is believed to remain stored in the stream system (Figure 2.3). Thus, in order to simulate the long-term storage of the particulate P, the in-stream P routine was modified.

Two new variables were added to the subroutine, F_{stor} and S_{max}. F_{stor} is the fraction of bankfull flow when P from the benthic pool is converted to long-term P storage, and ranges from 0 to 1. The flow corresponding to long-term P storage, Q_{stor} in $m^3\ s^{-1}$, is calculated using:

$$Q_{stor} = F_{stor} * Q_{bankfull} \tag{2.5}$$

where $Q_{bankfull}$ is the flow when the water reaches the top of the bank ($m^3 s^{-1}$). When the flow exceeds Q_{stor}, a storage ratio, S_{ratio}, is calculated using:

$$S_{ratio} = \frac{Q_{stor}}{Q} \tag{2.6}$$

where Q is the stream flow in $m^3 s^{-1}$. The quantity of P moved from the benthic P storage into the long term P storage is calculated using:

$$P_{lts} = (1 - S_{ratio}) * P_{benthic} \tag{2.7}$$

where P_{lts} is P moved to long term storage (kg), and $P_{benthic}$ in the P stored in the benthic pool (kg). Note that P in long term storage is stored indefinitely. To limit the quantity of P converted to long term storage, S_{max} is the maximum allowable S_{ratio}.

A sensitivity analysis was conducted on F_{stor} and S_{max}. Each parameter was varied from 0.25 to 1.0 and the results compared to the SWAT-predicted total P load without the new parameters, i.e. baseline conditions (Table 2.1). The greatest change occurred when both variables were at 0.25. As F_{stor} increases, more flow is required to convert P to long-term stored P. As S_{max} converges to 1.0, less P is converted to long term stored P.

SWAT Model Setup

The landcover dataset, developed from 2010 and 2011 Landsat images, was used as well as the 10-m USGS DEM and SSURGO soil data. The watershed had minor point sources at Westville, Oklahoma and Lincoln, Arkansas, two United States Geological Survey (USGS) stream gages located near Eldon, Oklahoma and Dutch Mills, Arkansas and three weather stations (Figure 2.4). The two point sources contributed an average of 2.5 kg of dissolved P and 0.63 kg of particulate P daily from 2004 to 2013. Management practices, litter application rates and Soil Test Phosphorus (STP) for each subbasin were obtained from the Illinois River SWAT model. The final SWAT model consisted of 73 subbasins, 2,991 HRUs and eight land uses: forest (55%), well-managed pasture (24%), over-grazed pasture (5.8%) hay meadow (13%) and other (2.2%).

Of the 73 subbasins, 36 were on the Barren Fork Creek. Streambank erosion for tributaries was ignored. Data to characterize each stream reach were obtained from aerial images, topography maps, 28 cross-sectional surveys (Chapter 1) and previous studies (Miller et al., 2014; Narasimhan et al., 2015). These data included bed slope, cover factor, sinuosity, radius of curvature, top width, streambank depth, area-adjustment factor, bank composition, side slope, τ_c, k_d and total and dissolved P. For each measured parameter, the values for each reach were derived either from (1) a longitudinal trend relating the variable to watershed area or distance to confluence with the Illinois River or (2) an average from measured data. The bed slope was measured using National Agricultural Imagery Program (NAIP) images and 1:24,000 topography maps, and used to derive the following equation:

$$BS = 4.3 * 10^{-9} * DA^2 - 6.7 * 10^{-6} * DA + 0.00369 \tag{2.8}$$

where BS is the bed slope (m m^{-1}) and DA is the drainage area (km^2).

Previous streambank modeling results showed that riparian protection significantly impacted the quantity of erosion in the watershed (Daly et al., 2015a; Chapter 1). In Chapter 1, a channel cover factor of 2.0 for the protected sites and a channel cover factor of 1.0 for the unprotected sites were used. Since only a portion of the streambank reaches were protected, a value between 1.0 and 2.0 was assigned to each reach proportional to the percentage of riparian protection (Narasimhan et al., 2015). The critical shear stress was then modified based on the equation proposed by Julian and Torres (2006):

$$\tau_c^* = \tau_c * CH_{\text{cov}} \tag{2.9}$$

where τ_c^* is the effective critical shear stress (N m^{-2}) adjusted for vegetation and CH_{COV} is channel cover factor (Julian and Torres, 2006).

The sinuosity for each reach was calculated by measuring both the stream length and straight-line distance for each reach using NAIP images. Based on the sinuosity, SWAT divided each reach into the fraction of straight (*1/sinuosity*) and meandering (*1-*(*1/sinuosity*)) reach sections. For example, for a 100 m reach with a sinuosity of 1.5, 67% (*1/1.5*) of the reach is defined as straight, or 67 m. The remaining reach section (*1*-(*1/1.5*)) or 33 m would be defined as a meander. Streambank erosion occurs on both banks for the straight reaches, but only one bank for the meandering sections. In this example, streambank erosion would occur on both banks for 67 m of the reach and on one bank for 33 m of the reach. Effective shear stress, calculated from Equations 2.2 and 2.3, is multiplied by a dimensionless bend factor, K_b, (Sin et al., 2012; Narasimhan et al., 2015) for the meandering section of each reach using:

$$K_b = 2.5 * \left(\frac{R_c}{W}\right)^{-0.32} \tag{2.10}$$

$$R_c = 1.5 * W^{1.12} \tag{2.11}$$

where R_c is the radius of curvature (m) and W is the top width (m).

Data from the cross-sectional surveys were used to estimate the W, streambank depth, side slope, area-adjustment factor and bank composition for each reach. These data were used with drainage area to derive:

$$W = 0.0765 * DA + 35.6 \tag{2.12}$$

where W is top width (m) and DA is the drainage area (km^2). Since here was no longitudinal trend, the average side slope (3.1:1) and streambank depth (2.84 m) were used for each reach. Since SWAT assumes a simple trapezoidal channel cross section, an area-adjustment factor was proposed (Chapter 1) to account for the heterogeneous cross-section given as:

$$A_{adj} = a * A \tag{2.13}$$

where A_{adj} is the adjusted channel cross-sectional area (m^2), *a* is a dimensionless adjustment factor less than or equal to 1.0 and *A* is the trapezoidal cross-sectional area. An average *α* of 0.78 was found for the surveyed cross sections (Chapter 1), which signifies that when flow is at the top of the bank, only 78% of the cross-sectional area is submerged**.** The percentage of gravel for each measured bank ranged from 0 to 100% with an average of 62% gravel and 38% cohesive (Figure 2.5).

Streambank data obtained from Miller et al. (2014) included τ_c and total and water soluble P for the soil. There was no longitudinal trend relating the τ_c with the *DA*. Therefore, an average τ_c of 5.6 Pa, a function of the measured d_{50}, was used. The k_d was calculated based on the k_d to τ_c relationship proposed by Hanson and Simon (2001):

$$k_d = 0.2 * \tau_c^{-0.5} \tag{2.14}$$

Although Equation 2.14 was derived using cohesive soils, the equation was successfully used for gravel layers at similar sites by Daly et al. (2015a) and Midgley et al. (2012) and thus will be used in this study. Total P concentrations for the streambanks from Miller et al. (2014) ranged from 250 to 427 mg P kg^{-1} soil, which were similar to Tufekcioglu (2010) (246 to 349 mg P kg^{-1} soil) and Zaimes et al. (2008) (360 to 555 mg P kg^{-1} soil). Water soluble P concentrations ranged from 1.2 to 8.1 mg P kg^{-1} soil. Total and water-soluble P for the streambank soil was obtained using:

$$TP = 1.7546 * d + 249.49 \tag{2.15}$$

$$WSP = 0.1121 * d + 0.3278 \tag{2.16}$$

where *TP* and *WSP* are the total and water soluble P in the streambank (mg P kg^{-1} soil) and *d* is the distance from the confluence of the Illinois River (km) (Figure 2.6). The P concentrations are higher upstream, believed to be a result of the higher density of poultry houses in Arkansas. The quantity of P eroded was adjusted based on the percentage of the bank containing cohesive soil, since gravel was assumed to not contain P.

Model Evaluation

Streamflow

SWAT was manually calibrated for monthly baseflow, peak flow and total flow at the USGS gage stations 07197000 and 07196900. A sensitivity analysis was conducted on eleven parameters based on previously used calibration parameters and SWAT documentation (Neitsch et al., 2009). Parameters were adjusted within the SWAT recommended range. Their sensitivity was calculated and used to determine the influence each parameter had on peak flow and baseflow. The streamflow was calibrated and validated from 2004 to 2013 and 1995 to 2003, respectively. The USGS Hydrograph separation program (HYSEP) was used to estimate baseflow (Sloto and Crouse, 1996). Coefficient of Determination, R^2, and Nash-Sutcliffe Efficiency (NSE) were used to evaluate the model's performance (Moriasi et al., 2007). Model performance ratings for NSE for total monthly flow were the following: Very good >0.75, Good 0.65-0.75, Satisfactory 0.50-0.65, Unsatisfactory <0.50 (Moriasi et al., 2007).

Phosphorus

The SWAT in-stream P routine was calibrated and validated on a monthly time step from 2009 to 2013 and 2004 to 2008, respectfully, at the USGS gage station 07197000. The USGS gage station 07196900 was not used due to poor LOADEST results (Miller et al., 2014). R^2 and NSE were used to evaluate model performance. Note that the model was calibrated prior to and after the incorporation of the streambank erosion.

Streambank Erosion

Using a method by Heeren et al. (2012) and Miller et al. (2014), streambank erosion was measured using 2003 and 2013 NAIP images for each of the 36 SWAT defined reaches on the Barren Fork Creek (Figure 2.7). The NAIP images were used to estimate the average eroded width and length and then used to calculate the eroded area (*AE*, m^2). The total sediment loading (*TS, kg*) from each reach was calculated using:

$$TS = EA * D_{ts} * \rho_b \tag{2.17}$$

where D_{ts} is the streambank depth (m) from Miller et al. (2014) and Chapter 1, and ρ_b is the soil bulk density (g cm^{-3}). A weighted ρ_b based on the bank composition (Miller et al., 2014) was used to estimate the average ρ_b for the bank.

Results and Discussion

Streamflow

During calibration, six parameters were modified to obtain the best goodness-of-fit statistics for each gage station (Table 2.2). SWAT predictions at USGS gage station 07197000 were 'very good' (Moriasi et al., 2007) for the calibration and validation periods, with NSE of 0.82 and 0.78, respectfully. R^2 for the calibration and validation periods were 0.82 and 0.80, respectfully. At the upstream USGS gage station (0719690), calibration and validation predictions 'good' (Moriasi et al., 2007) based on the NSE of 0.72 and 0.70 for the calibration and validation periods, respectfully. R^2 for the calibration and validation periods were 0.72 and 0.71, respectfully.

Total Phosphorus without Streambank Erosion

Each of the in-stream P parameters was manually adjusted during P calibration (Table 2.3). Overall the model performed exceptionally well predicting total P, except for some of the peaks loads (Figure 2.8). During the calibration process, any attempt to increase the predicted total P for the peaks resulted in an over prediction for a number of smaller events (Figure 2.8, see arrows). For the 2009 to 2013 calibration period, the R^2 was 0.82 and the NSE 0.60. The lower NSE was due to the under prediction of the total P during the large storm event in April 2011. The R^2 and NSE for the 2004 to 2008 validation period was 0.80 and 0.77, respectively. The predicted average annual P load from 2004 to 2013 originating from the uplands was 53.9 Mg yr^{-1}, with 42% from well-managed pasture, 32% from overgrazed pasture, 21% from hay meadows and 5.6% from forest.

Streambank Erosion

The measured streambank erosion for the Barren Fork Creek from 2003 to 2013 was 160,000 Mg yr^{-1}. The reach-weighted streambank erosion was 42 kg m^{-1} compared to 34 kg $m^{-1}$for Spavinaw Creek (Purvis, 2015), approximately 60 km north of the Barren Fork Creek. The Barren Fork Creek streambank erosion increased further downstream as reaches approached the confluence of the Illinois River. For example, the average erosion 0 to 25 km from the confluence with the Illinois River was 78 kg m^{-1}, compared to 28 kg m^{-1} 25 to 65 km from the confluence. Therefore, future streambank stabilization projects should focus their efforts on the lower 25 km of the creek.

The uncalibrated cover factors for the 36 reaches ranged from 1.0 to 2.0 with an average of 1.6 (Figure 2.9). Using these cover factors, the uncalibrated SWAT predictions compared to measured streambank erosion resulted in an R^2 and NSE of 0.36 and 0.33, respectively (Figure 2.10). SWAT simulated mass of eroded soil was 215,000 Mg yr^{-1} or a reach-weighted 40 kg m^{-1} from 2004 to 2013, which compares to the measured erosion of 160,000 Mg yr^{-1} or 42 kg m^{-1}. Some of this over prediction was due to assumptions in estimating the streambank-erosion parameters and failing to account for the armored banks. From personal observations, approximately 5% of the banks are armored, with the majority located in the head waters of the Barren Fork Creek. Armored banks, with a k_d of 0.0 $cm^3\ N^{-1}\ s^{-1}$, would reduce the simulated erosion by approximately 10,800 Mg yr^{-1} and the relative error for the measured versus simulated erosion from 34 to 27%. SWAT-predicted streambank erosion was then calibrated by adjusting the cover factor, which modified τ_c and k_d. The average calibrated cover factor was 1.9 (Figure 2.9), which equates to τ_c of 11 Pa and k_d of 0.06 $cm^3\ N^{-1}\ s^{-1}$.

Total Phosphorus with Streambank Erosion

The calibrated streambank erosion contributed a total of 48 Mg yr^{-1} of total P from 2004 to 2013, which is approximately half the total P estimated by Miller et al. (2014). The higher estimate by Miller et al. (2014) was likely due to the ten study sites not being representative of the entire creek. Two of their study sites had the second and third most erosion per length of stream (see ovals in Figure 2.10). The total P from the combined uplands and Barren Fork Creek streambanks from 2004 to 2013 was 103 Mg yr^{-1}, of which 47% originated from streambanks. Langendoen et al. (2012) found that 36% P entering Missisquoi Bay was from streambank erosion. Streambanks in Denmark contributed 21 to 62% of the annual P loads (Kronvang et al., 2012). This study supports other studies around the world that P derived from streambank erosion can be a significant source of

P in a watershed. It should be noted that while the quantity of particulate P from streambank erosion exceeded the particulate P from the upland area, the majority of the dissolved P originated from the upland areas. The dissolved P, which is easily accessible to aquatic plants, is more important to water quality than the tightly-bound particulate P. In addition, the two point sources contributed a small percent of the total P in the watershed (Figure 2.11).

After incorporating streambank-derived P into the SWAT model, the two proposed in-stream P routine variables were calibrated. F_{stor} was calibrated to 0.35 and S_{max} was calibrated to 0.25. If bankfull flow is 1000 $m^3 s^{-1}$, for example, P will be converted into long-term storage when flow exceeds 350 $m^3 s^{-1}$. At a flow of 7000 $m^3 s^{-1}$, 95% of the benthic P is converted to long-term storage. However, S_{max} limits the P converted to long-term storage to 75%.

P calibration improved with streambank erosion compared to without streambank erosion (Table 2.4). The R^2 and NSE improved for both the calibration and validation periods except for the R^2 for the calibration period, which was due to over predicting streamflow and P load in November 2011. The relative errors for total, dissolved and particulate P were all less than 6% for both the calibration and validation periods (Table 2.5). The inclusion of P from streambank erosion also improved the prediction of particulate and total P during large storm events (Figure 2.12), with most of the peaks comparing favorably with observed loads, except for the large storm in 2009.

From 2004 to 2013, approximately 103 Mg yr^{-1} of P entered the Barren Fork Creek from the upland areas, streambank erosion and point sources. Of this total, over 35 Mg yr^{-1} (39 kg yr^{-1} km^{-2}) was converted to long-term storage (Figure 2.13). Mittelstet (2015) estimated the total P stored in the Illinois River watershed at 7.7 to 290 kg yr^{-1} km^{-2} during the period of 1925 to 2015. Based on the results of this study, the total P stored in the Illinois River stream system is probably closer to 7.7 than 290 kg yr^{-1} km^{-2}. During this same time period, 75 kg yr^{-1} km^{-2} of total P left via the watershed outlet to the Illinois River and 1.7 kg yr^{-1} was deposited on the floodplain. A large quantity of P from the benthos was scoured and converted to long-term stored P in 2004. Therefore, the net P added to the benthos was -1.7 kg yr^{-1} km^{-2}. Of the total quantity of P added to the system, approximately 65% left via the outlet and 35% was stored in the stream system and floodplain.

Conclusions

The modified streambank-erosion routine, with the process-based applied shear stress equation and the area-adjustment factor, was applied to the Barren Fork Creek. Uncalibrated, the average reach-weighted predicted streambank erosion from 2004 to 2013 was 40 kg m^{-1} compared to the measured 42 kg m^{-1}. Over 100 Mg of P was added to the Barren Fork Creek annually from 2004 to 2013, of which 47% was from streambank erosion. Due to this influx of streambank P to the system and the current in-stream P routine's limitations, the in-stream P routine was modified by introducing a long-term storage coefficient. This long-term storage coefficient converted particulate P to long-term storage as a function of flow. P calibration with the proposed long-term storage coefficient improved P calibration results, especially for peak flow events. Of the total quantity of P added to the system from 2004 to 2013, approximately 65% left via the watershed outlet and 35% was stored in the stream system and floodplain. This accumulation of P in the stream system, or legacy P, will likely be a source of P for several years or even decades.

The modified SWAT streambank-erosion routine produced reasonable estimates of streambank erosion. Incorporating particulate P from the streambank erosion can improve SWAT predicted P loads. Streambank erosion can be a significant contributor of P at a watershed scale and thus should be considered when addressing water quality in watershed management plans. For watersheds around the world with dynamic and eroding streambanks with elevated P, the modified streambank erosion and in-stream P routines can be used to improve modeling results and provide watershed managers a better understanding of the significance of both streambank erosion and streambank P in the watershed.

Table 2.1. Sensitivity of instream-phosphorus routine proposed parameters F_{stor} and S_{max} on SWAT predicted total phosphorus load. At baseline F_{stor} and S_{max} are equal to 0.35 and 0.25, respectively.

F_{stor}	S_{max}	Total P (kg yr^{-1})	Percent Change
Baseline	Baseline	101,200	N/A
0.25	0.25	74,200	-26.7
0.50	0.25	83,500	-17.5
0.75	0.25	89,900	-11.2
1.0	0.25	93,100	-8.0
0.35	0.25	78,600	-22.3
0.35	0.50	80,100	-20.8
0.35	0.75	84,200	-16.8
0.35	1.0	101,200	0

Table 2.2. SWAT default and calibrated parameter estimates used to calibrate flow on the Barren Fork Creek watershed SWAT model.

Original Value or Range	Calibrated Value or Range	Parameter	Description
0.95	0.85	ESCO	Soil evaporation compensation coefficient
0.05	0.25	RCHRG_DP	Aquifer percolation coefficient
0.048	0.75	ALPHA_BF	Baseflow Alpha Factor (Days)
39-94	-4	CN2	SCS curve number adjustment
0.0	10	CH_K2	Effective hydraulic conductivity in main channel alluvium (mm hr^{-1})
0.5	105	CH_K1	Effective hydraulic conductivity in tributary channel alluvium (mm hr^{-1})
0.014	0.05	Manning’s n	Manning’s ‘n’ in main channel

Table 2.3. SWAT default and calibrated in-stream phosphorus (P) model parameter estimates for the Barren Fork Creek watershed SWAT model.

Parameter	Default	Calibrated	Description
DI	250	90	Period of influence (d)
K_{in}	0.10	0.15	Soluble P transformation into the benthic sediment (hr^{-1})
K_{out}	0.10	0.001	Soluble P transformation out of the benthic sediment (hr^{-1})
F_{dep}	0.01	0.01	Fraction of bankfull discharge at 100% deposition
F_{eq}	0.15	0.26	Fraction of bankfull discharge at which scour and deposition of particulate P is at equilibrium
F_{scr}	0.80	0.75	Fraction of bankfull discharge at which all P is scoured from the streambed
SPT	0.01	0.001	Soluble to particulate transformation coefficient

Table 2.4. Calibration and validation statistics for SWAT predicted total phosphorus load with and without streambank erosion. NSE is Nash Sutcliff Efficiency.

Statistic	Without Streambank Erosion		With Streambank Erosion	
	Calibration	Validation	Calibration	Validation
R^2	0.82	0.80	0.80	0.95
NSE	0.60	0.77	0.78	0.95

Table 2.5. Observed and simulated total, dissolved and particulate phosphorus and their relative errors for the calibration (2009 to 2013) and validation periods (2004 to 2008) with and without streambank erosion.

	Total Phosphorus ($kg\ yr^{-1}$)	Error (%)	Dissolved Phosphorus (kg^{-1})	Error (%)	Particulate Phosphorus (kg^{-1})	Error (%)
Calibration						
Observed	59,500		16,800		42,700	
Simulated	60,000	0.84	16,700	-0.60	43,200	1.2
Validation						
Observed	55,800		18,100		37,700	
Simulated	57,800	3.6	19,100	5.5	38,700	2.7

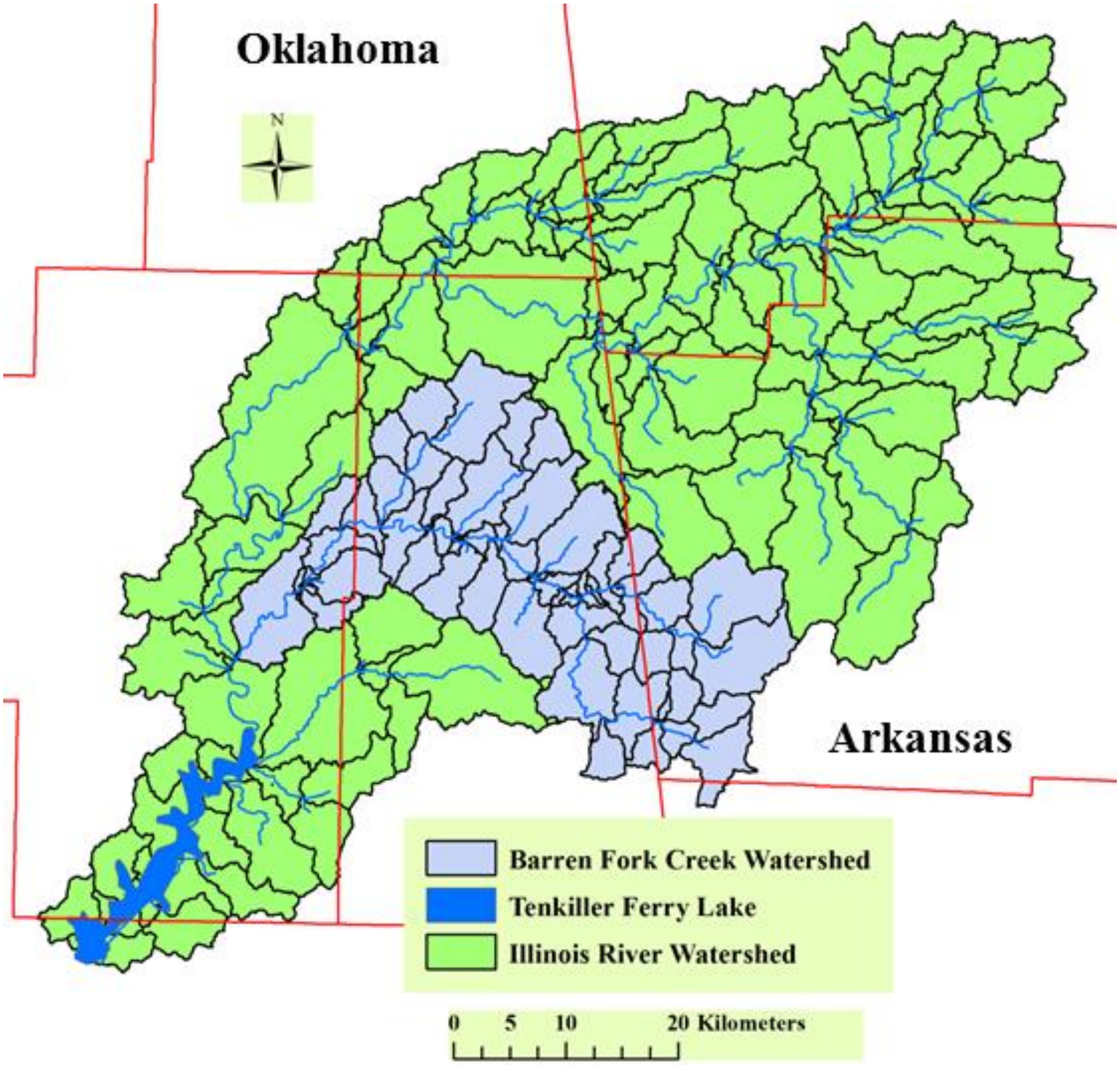


Figure 2.1. Illinois River and Barren Fork Creek watersheds in northeast Oklahoma and northwest Arkansas.

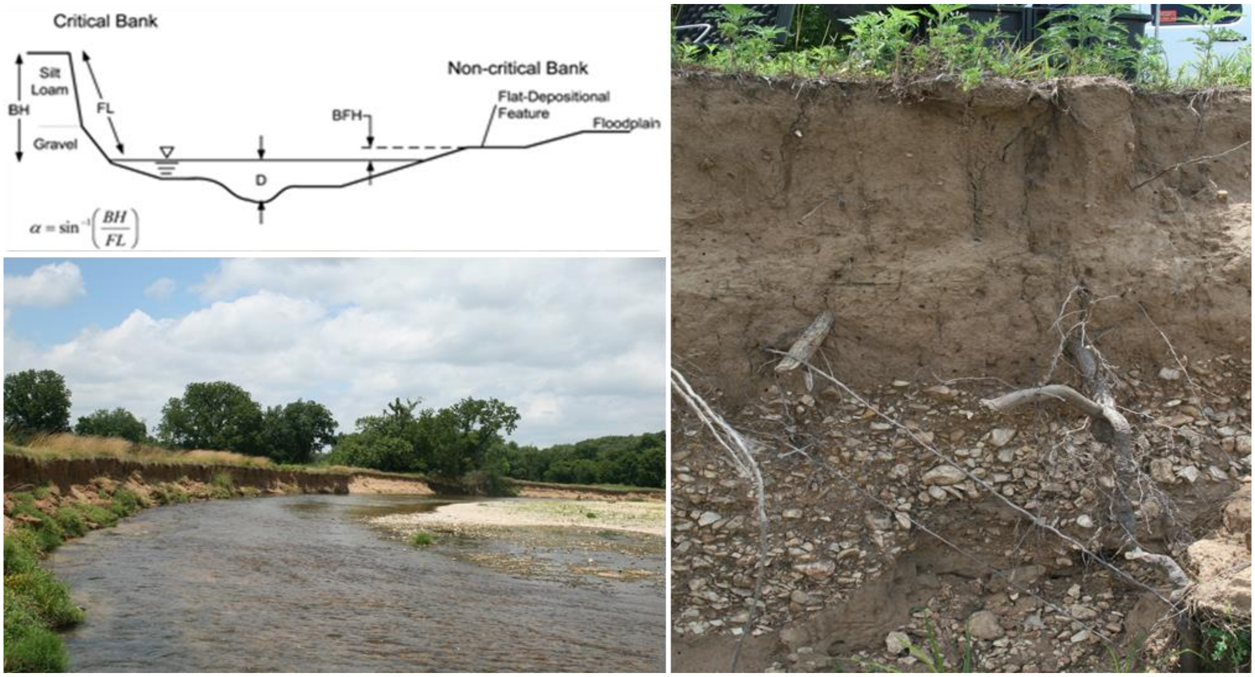


Figure 2.2. Typical stream channel profile in the Barren Fork Creek with one critical bank and one non-critical bank. Right image illustrates the underlying gravel layer and the silty loam topsoil for the critical bank (Heeren et al., 2012).

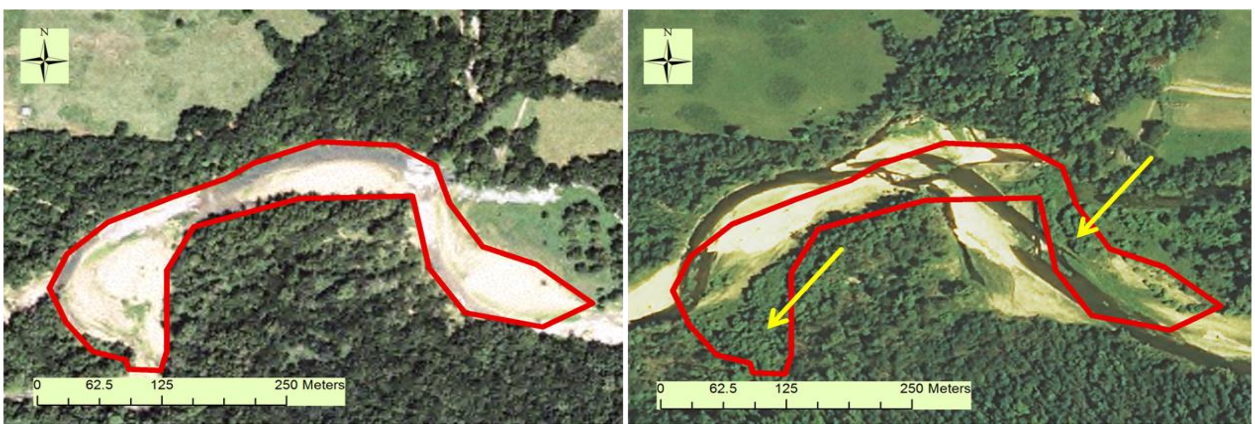


Figure 2.3. Barren Fork Creek reach illustrating the large quantity of streambank erosion and deposition that occurred from 2003 (left) to 2013 (right). Red lines illustrate the location of the gravel bar in 2003 and the yellow arrows show the newly established riparian vegetation.

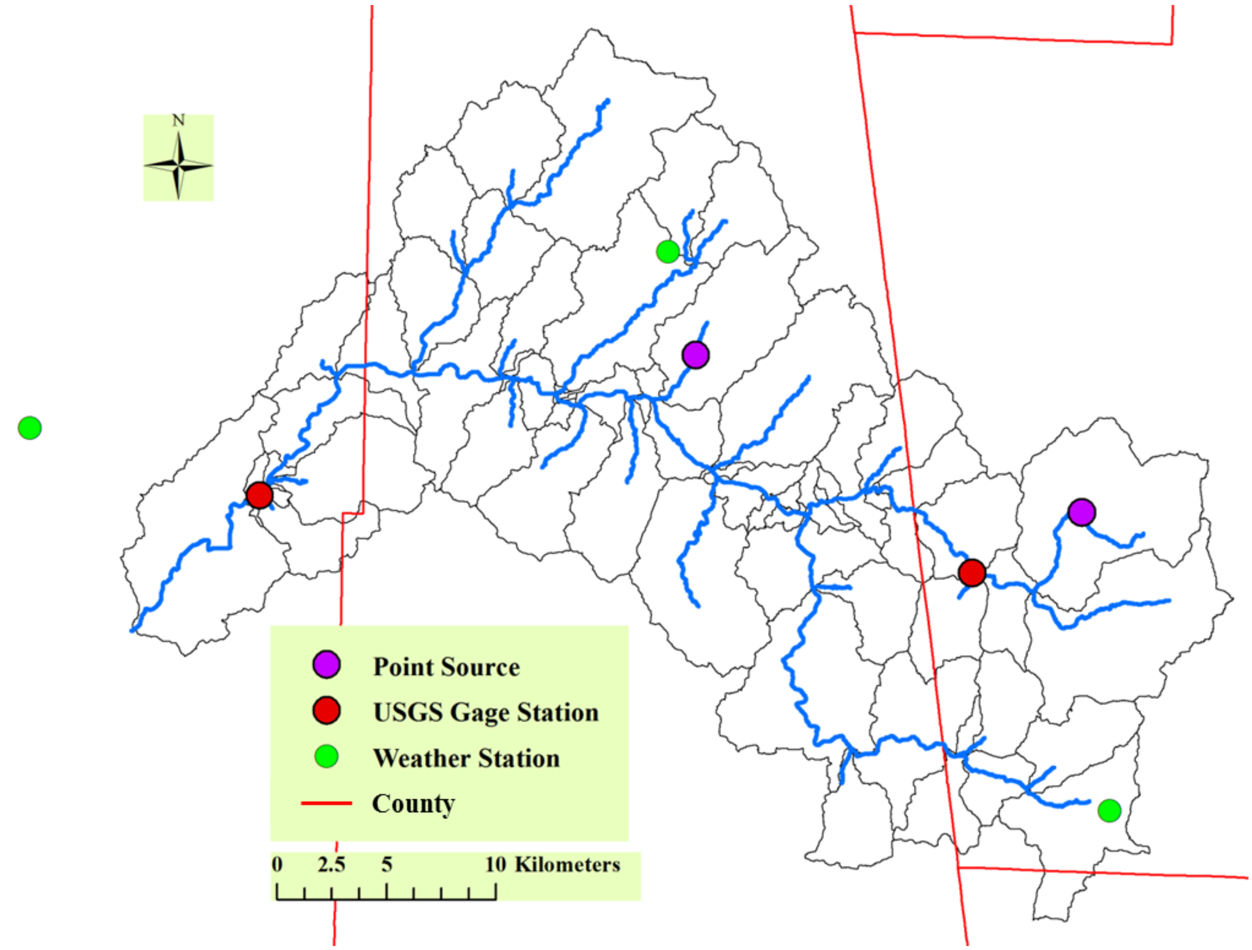


Figure 2.4. United States Geological Survey (USGS) gage stations, weather stations and point sources located in the Barren Fork Creek watershed in northeast Oklahoma and northwest Arkansas.

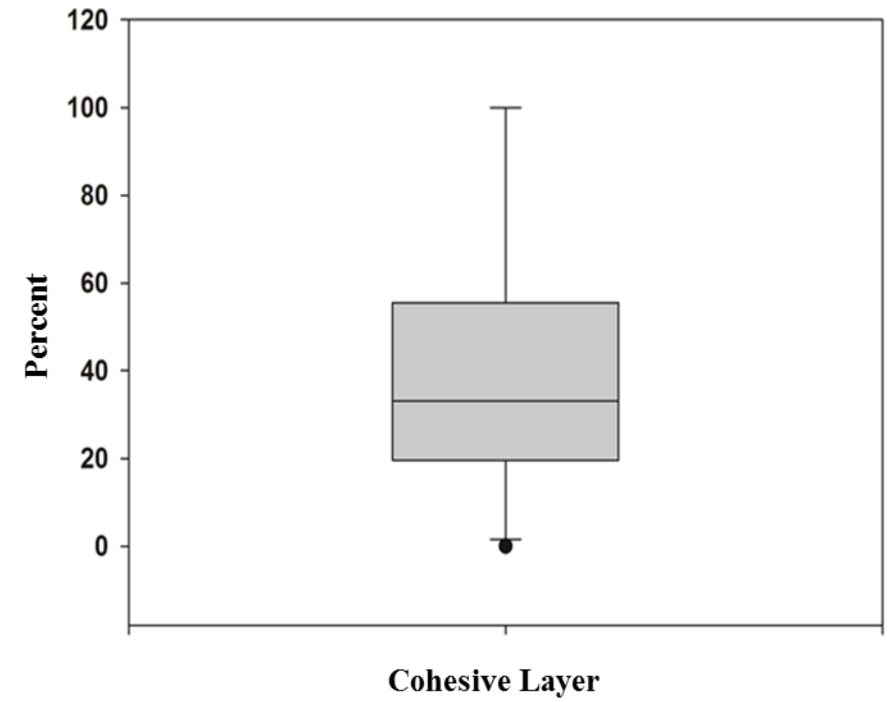


Figure 2.5. Percent cohesive layer for each of the surveyed banks.

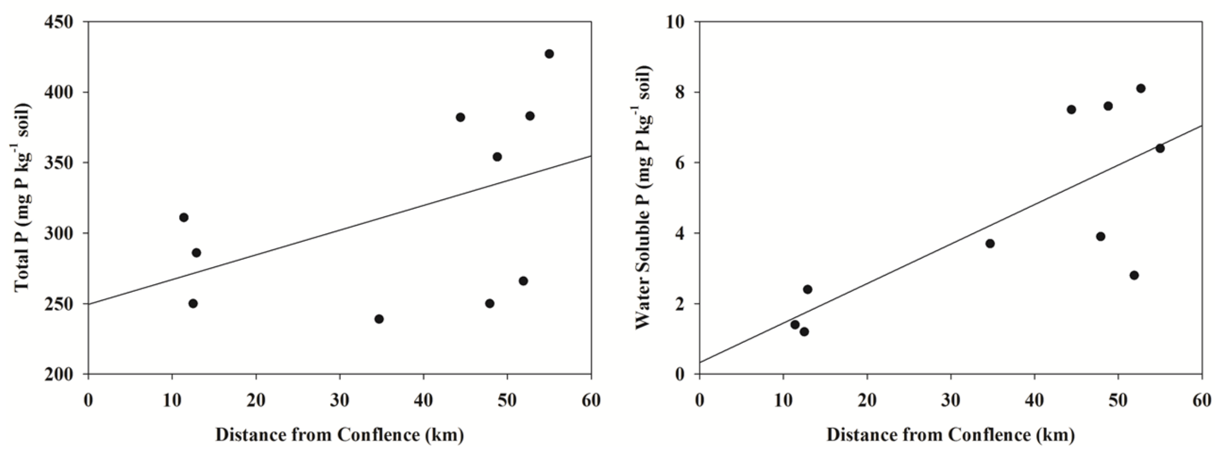


Figure 2.6. Total and water soluble phosphorus (P) concentrations for streambanks with distance from the Barren Fork Creek to the confluence with the Illinois River in Oklahoma.

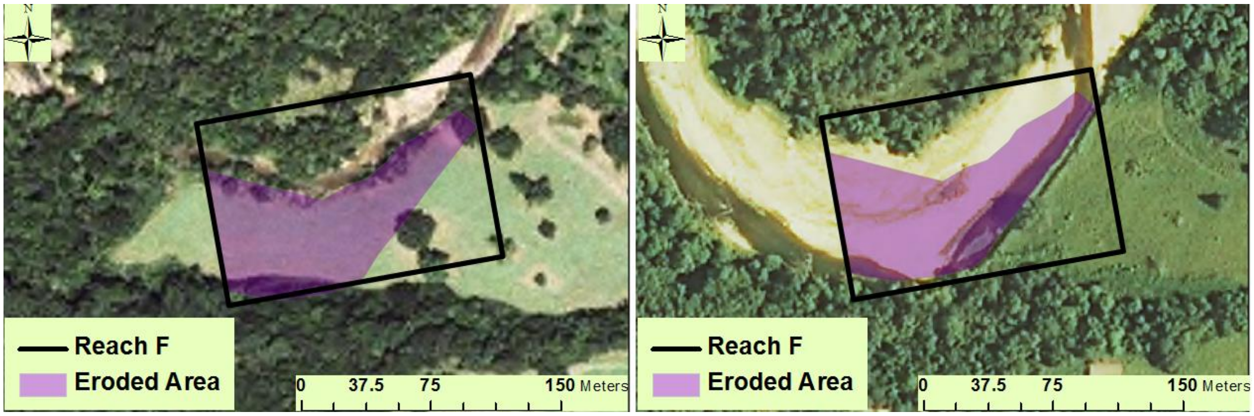


Figure 2.7. National Agricultural Imagery Program (NAIP) aerial images for 2013 (left) and 2013 (right) with polygons showing the bank retreat (purple) during the period.

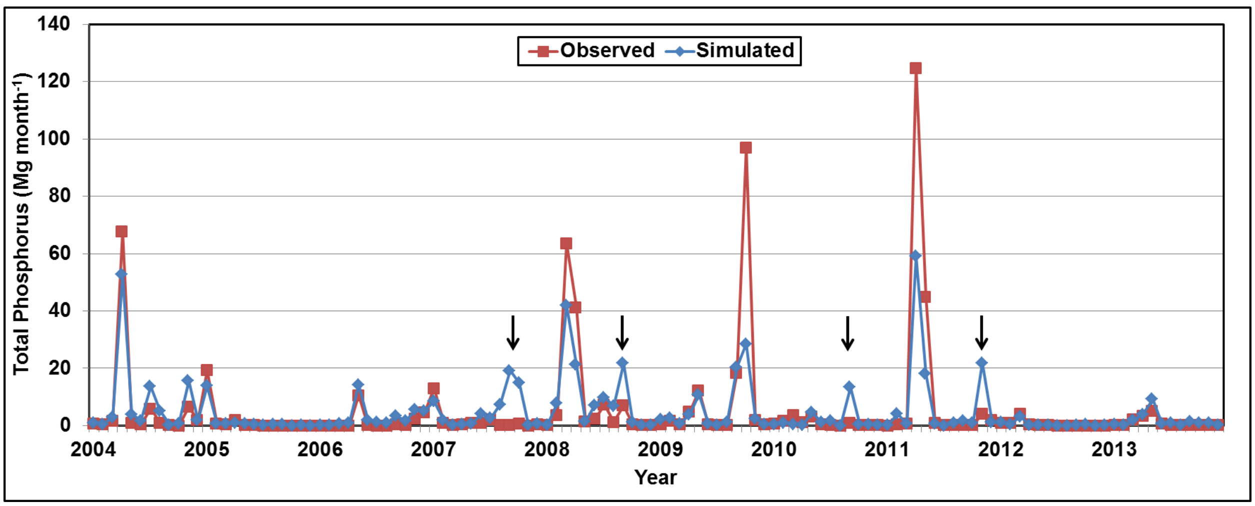


Figure 2.8. Time series illustrating monthly SWAT predicted and observed total phosphorus (P) load from 2004 to 2013 at the United States Geological Survey gage station 07197000 on the Barren Fork Creek. Black arrows indicate storm events where the SWAT model over predicted P.

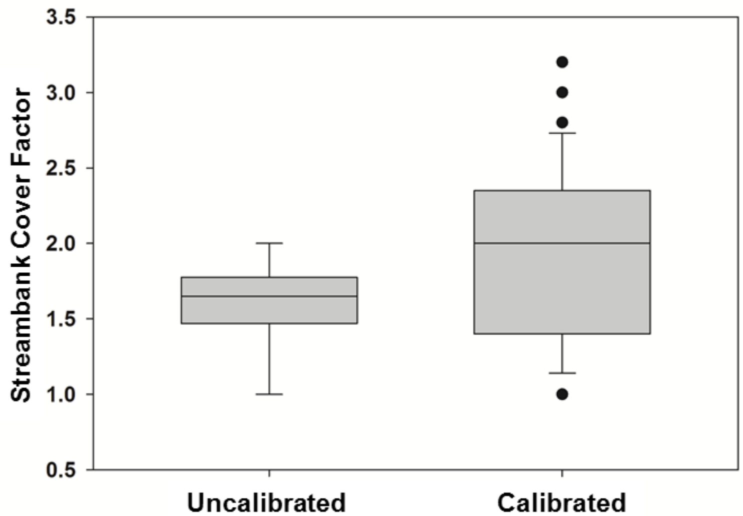


Figure 2.9. Uncalibrated and calibrated cover factors for the 36 reaches on the Barren Fork Creek.

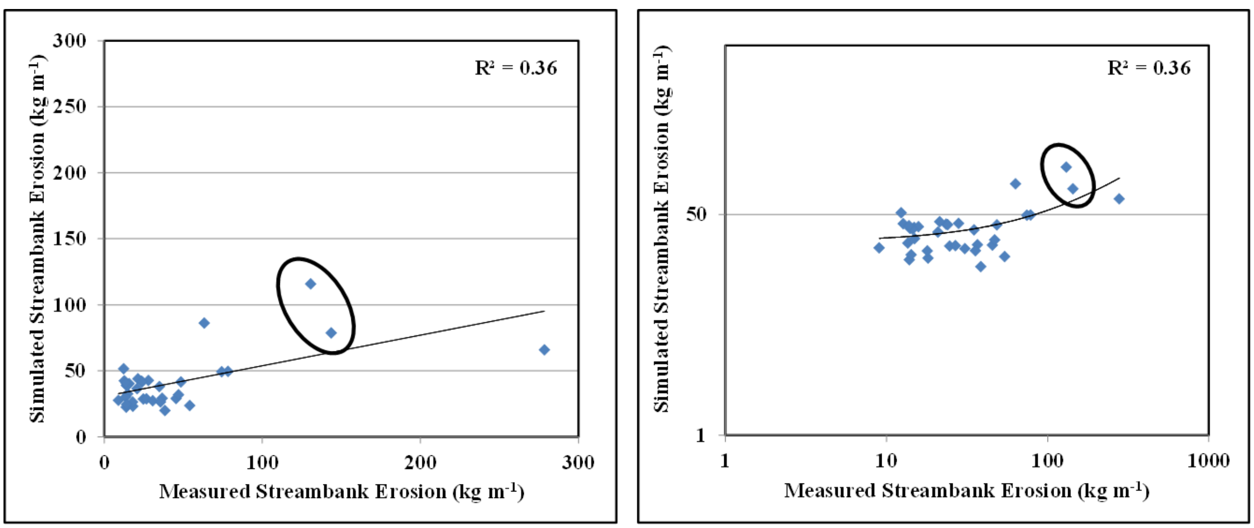


Figure 2.10. Measured vs uncalibrated SWAT streambank erosion predictions for the Barren Fork Creek from 2004 to 2013 on linear (left) and log (right) scales. The two circled points are two of the ten study sites from Miller et al. (2014), which were two of the most erosive reaches of the SWAT-defined 36 reaches on the Barren Fork Creek.

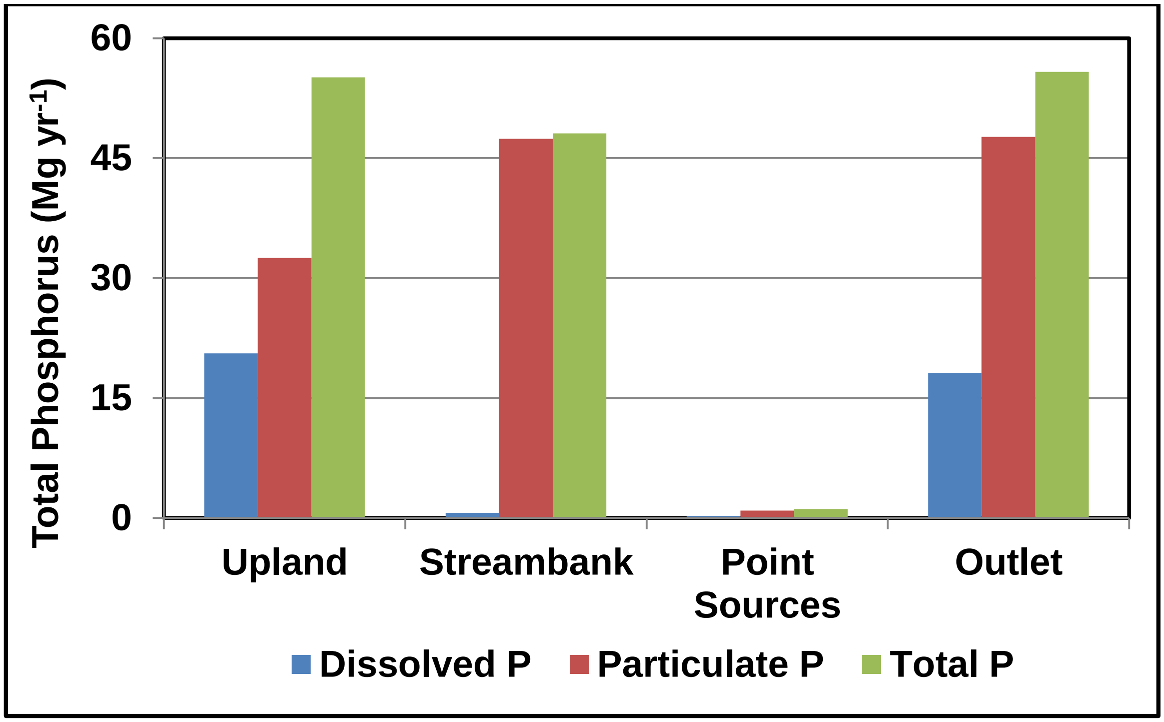


Figure 2.11. Average annual total phosphorus (P) contributions from the Barren Fork Creek watershed upland areas, streambank and point sources compared to the total P load reaching the outlet.

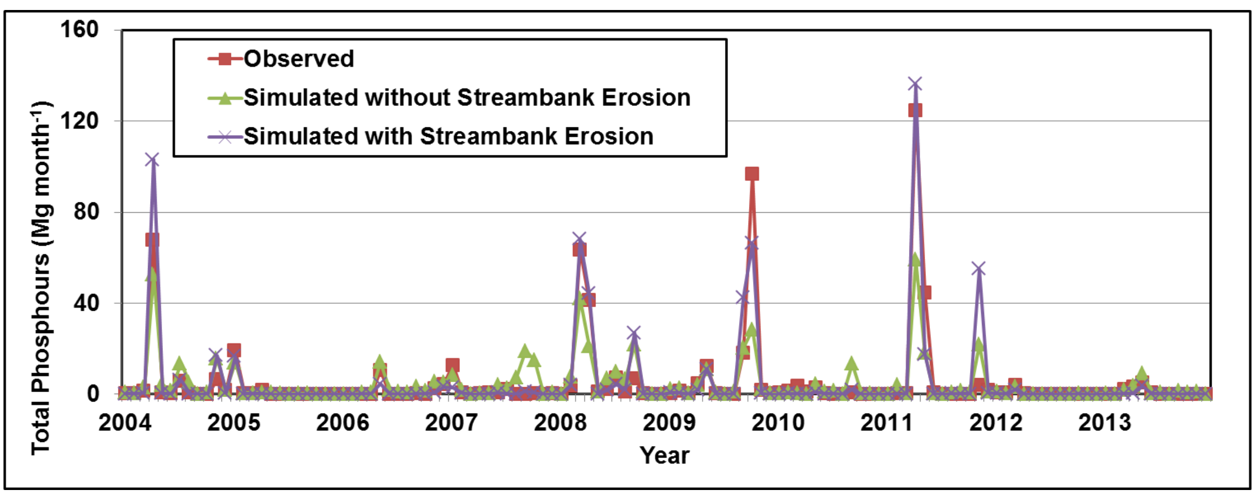


Figure 2.12. Monthly SWAT time series for observed and predicted total phosphorus load from 2004 to 2013 for the Barren Fork Creek watershed with and without streambank erosion.

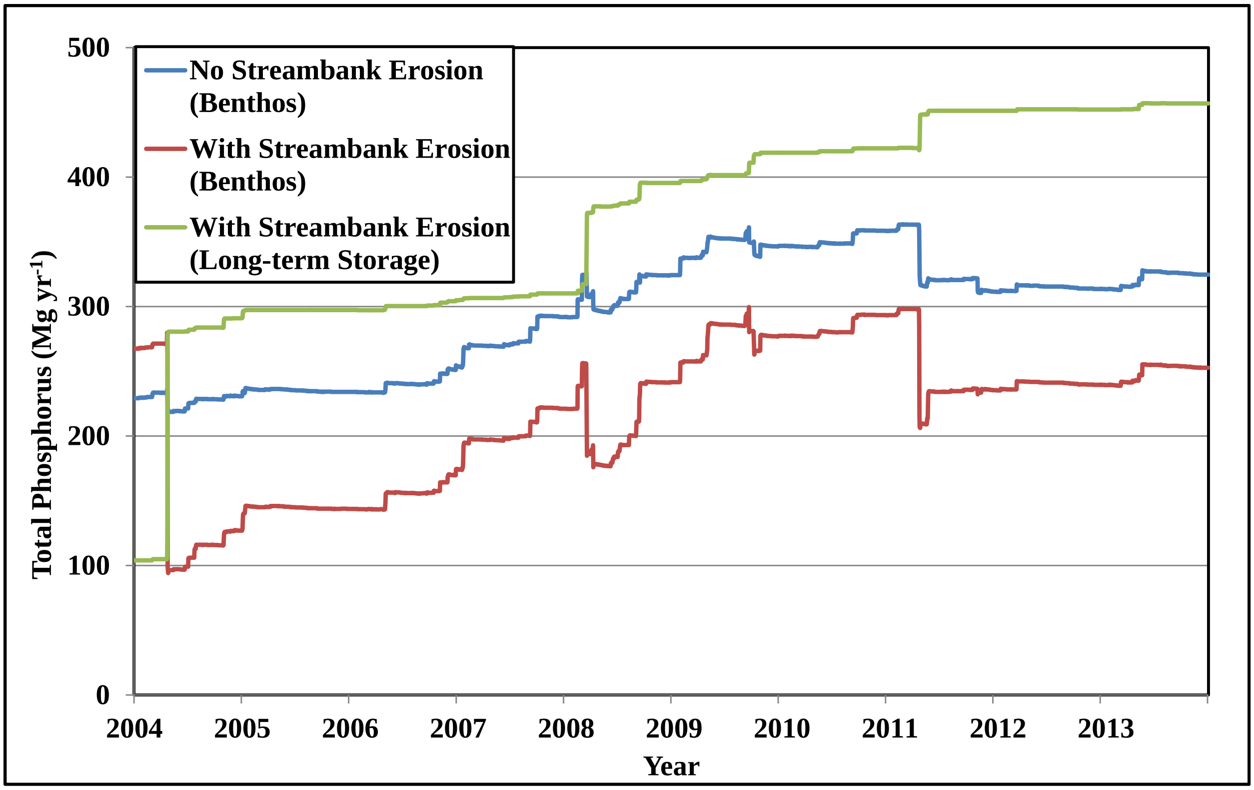


Figure 2.13. Total phosphorus stored in the benthos and long-term storage for SWAT predictions of the Barren Fork Creek from 2004 to 2013 with and without streambank erosion.

REFERENCES

Arnold J.G., R. Srinivasan, R.S. Muttiah and J.R. Williams. 1998. Large-area hydrologic modeling and assessment. Part 1: Model development. *J. Am. Water Resour. Assoc.* 34(1):73-89.

Bentley, 2015. FlowMaster Hydraulic Calculator Software. Available at: https://www.bentley.com/en/products/product-line/hydraulics-and-hydrology-software/flowmaster.

Bieger, K, H. Rathjens, P.M. Allen and J.G. Arnold. 2015. Development and evaluation of bankfull hydraulic geometry relationships for the physiographic regions of the United States. *J. Am. Water Resour. Assoc.* Paper No. JAWRA-13-0228-P.

Chaubey, I., A.S. Cotter, T.A. Costello and T.S. Soerens., 2005. Effect of DEM data resolution on SWAT output uncertainty. *Hydrol. Proc.* 19(3):621-628.

Cooke, D.G., E.B. Welch and J.R. Jones. 2011. Eutrophication of Tenkiller Reservoir, Oklahoma, from nonpoint agricultural runoff. *Lake Reserv. Manage*. 27(3):256-270.

Daly, E.R., G.A. Fox, A.T. Al-Madhhachi and D.E. Storm. 2015b. Variability of fluvial erodibility parameters for streambanks on a watershed scale. *Geomorphology* 231:281-291.

Daniel, T.C., A.N. Sharpley and J.L. Lemunyon. 1998. Agricultural phosphorus and eutrophication; a symposium overview. *J. Environ. Qual*. 27:251-257.

DEQ. Oklahoma Department of Environmental Quality, 2012. Integrated Water Quality Assessment. http://www.deq.state.ok.us/wqdnew/305b_303d/.

Dey, S. Fluvial Hydrodynamics, GeoPlanet: Earth and Planetary Sciences, DOI: 10.1007/978-3-642-19062-9_9, Springer-Verlag Berlin Heidelberg 2014. pp. 529.

Dutnell, R.C., 2004. Development of bankfull discharge and channel geometry relationships for natural channel design in Oklahoma using a fluvial geometric approach. Master’s Thesis, University of Oklahoma, Norman, Oklahoma.

Eaton, B.C. and Millar, R.G. 2004. Optimal alluvial channel width under a bank stability constraint. *Geomorphology* 62:35-45.

Fisk, H.N. 1947. Fine-grained alluvial deposits and their effects on Mississippi River activity, Vol. 2. U.S. Army Corps Eng., Waterways Exp. Stn., Vicksburg, 74 plates.

Fox, G. A. and G.V. Wilson. 2010. The role of subsurface flow in hillslope and streambank erosion: A review. *Soil Sci. Soc. Am. J*., 74(3), 717–733.

Friedkin, J.F. 1945. A Laboratory Study of the Meandering of Alluvial Rivers. U.S. Army Corps Eng., Waterways Exp. Stn., Vicksburg, 40 pp.

Gassman, P.W., M.R. Reyes, C.H. Green, and J.G. Arnold. 2007. The Soil and Water Assessment Tool: Historical development, applications, and future research directions. *Trans. ASABE* 50(4):1211-1250.

Gassman, P.W., Balmer C., Siemers M., Srinivasan, R. The SWAT literature database: overview of database structure and key SWAT literature trends. 2014. Available at: https://www.card.iastate.edu/swat_articles/.

Gibson, S. 2013. The USDA-ARS bank stability and toe erosion model (BSTEM) in HEC-RAS. Advances in Hydrologic Engineering. Davis, CA: USACE, Institute for Water Resources, Hydrologic Engineering Center.

Hanson, G.J. and A. Simon. 2001. Erodibility of cohesive sediment in the loess area of the Midwestern USA. *Hydrol. Proc.* 15:23–28.

Harmel, R.D., C.T. Haan, and R.C. Dutnell. 1999. Evaluation of Rosgen's streambank erosion potential assessment in northeast Oklahoma. *J. Am. Water Resourc. Assoc.* 35(1):113-121.

Heeren, D.M., Mittelstet, A.R., Fox, G.A., Storm, D.E., Al-Madhhachi, A.T., Midgley, T.L., Stringer, A.F., Stunkel, K.B. and Tejral R.B. 2012. Using rapid geomorphic assessments to assess streambank stability in Oklahoma Ozark streams. *Trans. ASABE*. 55(3): 957–968.

Johnson, P.A. and T.M. Heil. 1996. Uncertainty in estimating bankfull conditions. *J. Am. Water Resour. Assoc.* 32(6):1283-1291.

Julian, J.P. and R. Torres. 2006. Hydraulic erosion of cohesive river banks. *Geomorphology.* 76:193-206.

Kocian, M.J. Assessing the accuracy of GIS-derived stream length and slope estimates. Master's thesis, University of Minnesota, 2012.

Kronvang, B., J. Audet, A. Baattrup-Pedersen, H.S. Jensen and S.E. Larson. 2012. Phosphorus loads to surface waters from bank erosion in a Danish lowland river basin. *J. Envion. Qual.* 41:304-313.

Langendoen, J., A. Simon, L. Klimetz, N. Bankhead and M.E. Ursic. 2012. Quantifying sediment loadings from streambank erosion in selected agricultural watersheds draining to Lake Champlain. US Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory, Watershed Physical Processes Research Unit, Oxford, Mississippi.

Laubel, A., B. Kronvang, A.B. Hald and C. Jensen. 2003. Hydromorphological and biological factors influencing sediment and phosphorus loss via bank erosion in small lowland rural streams in Denmark. *Hydrol. Proc.* 17(17):3443-3463.

Merritt, W.S., Letcher, R.A. and Jakeman, A.J. 2003. A review of erosion and sediment transport models. *Environ. Modell. Softw.* 18:761-799.

Micheli, E.R. and J.W. Kirchner. 2002. Effects of wet meadow riparian vegetation on streambank erosion. Measurements of vegetated bank strength and consequences for failure mechanics. *Earth Surf. Process. Landforms* 27:687-697.

Midgley, T.L., G.A. Fox and D.M. Heeren. 2012. Evaluation of the bank stability and toe erosion model (BSTEM) for predicting lateral streambank retreat on composite streambanks. *Geomorphology* 145-146:107-114.

Millar, R.G. 2005. Theoretical regime equations for mobile gravel-bed rivers with stable banks. *Geomorphology* 64(3-4): 207-220.

Miller, R.B., G.A. Fox, C.J. Penn, S. Wilson, A. Parnell, R.A. Purvis and K. Criswell. 2014. Estimating sediment and phosphorus loads from streambanks with and without riparian protection. *Agric. Ecosyst. Environ.* 189:70-81.

Mittelstet, A.R., D.M. Heeren, G.A. Fox, D.E. Storm, M.J. White and R.B. Miller. 2011. Comparison of subsurface and surface runoff phosphorus transport rates in alluvial floodplains. *Agric. Ecosyst. Environ.* 141:417-425.

Monke, J., and R. Johnson. 2010. Actual Farm Bill spending and cost estimates. Rep. Congr. 7-5700/R41195. Congr. Res. Serv. Washington, DC. http://www.nationalaglawcenter.org/assets/crs/R41195.pdf

Moriasi, D.N., J.G. Arnold, M.W. Van Liew, R. L. Bingner, R.D. Harmel and T.L. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE* 50(3):885-900.

Narasimhan, B., P. Allan, L. Arnold and R. Srinivasan. 2015. Development and testing of a physically based model of stream bank erosion for coupling with a basin-scale hydrologic model SWAT. *Hydro. Proc.* In Reviw.

Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting throughconceptual models: Part 1. A discussion of principles. *J. Hydrology* 10(3):282-290.

Neitsch, S.L., J.G. Arnold, J.R. Williams. 2011. Soil and Water Assessment Tool User's Manual Version 2009. Blackland Research Center.

Partheniades, E. 1965. Erosion and deposition of cohesive soils. *J. Hydraul. Div.* ASCE. 91:105-139.

Purvis, R. *Sediment and phosphorus loads from streambank erosion and failure: a source of legacy phosphorus in watersheds*. Master's Thesis, Oklahoma State University. Stillwater, Oklahoma, 2015.

Simon, A., M. Rinaldi, and G. Hadish, 1996 Channel evolution in the loess area of the midwestern United States. Sixth Federal Interagency Sedimentation Conference, Las Vegas, pp III-86 to iIII-93.

Simon, A., and S.E. Darby. 1999. The nature and significance of incised river channels, In *Incised River Channels*, 3-18. S.E. Darby and A. Simon, eds. Chichester, UK: John Wiley and Sons.

Simon, A., R. L. Bingner, E. J. Langendoen, and C. V. Alonso. 2002. Actual and reference sediment yields for the James Creek Watershed, Mississippi. USDA Agricultural Research Service National Sedimentation Laboratory Research Report No. 31.

Sin, K. C.I. Thornton, A.L. Cox and S.R. Abt. 2012. Methodology for calculating shear stress in a meandering channel. Colorado State University, Fort Collins, Colorado.

Sloto, R.A. and M.Y. Crouse. 1996. HYSEP: A computer program for streamflow hydrograph separation and analysis: U.S. Geological Survey Water-Resources Investigations Report 96-4040, 46 p.

Staley, N.A., T. Wynn, B. Benham and G.Yagow. 2006. Modelling channel erosion at the watershed scale: Model review and case study. Center for TMDL and Watershed Studies, Biological Systems Engineering, Virginia Tech.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database. Available online at http://sdmdataaccess.nrcs.usda.gov/. Accessed May 10, 2012).

Storm, D.E., M.J. White and M.D. Smolen. 2006. Illinois River upland and in-stream phosphorus modeling: Final Report submitted to the Oklahoma Department of Environmental Quality. Submitted June 28, 2006. Oklahoma State University, Department of Biosystems and Agricultural Engineering, Stillwater, Oklahoma 74078.

Storm, D.E., P.R. Busteed, A.R. Mittelstet and M.J. White. 2010. Oklahoma/Arkansas Illinois river basin using SWAT 2005: Final Report submitted to the Oklahoma Department of Environmental Quality. Submitted October 8, 2009. Oklahoma State University, Department of Biosystems and Agricultural Engineering, Stillwater, Oklahoma 74078.

Storm, D.E. and A.R. Mittelstet. 2015. Watershed Based Plan Support for the Illinois River and Spavinaw Creek Watersheds. DRAFT FINAL REPORT. Oklahoma Conservation Commission for the US EPA Region VI. Oklahoma State University, Department of Biosystems and Agricultural Engineering, Stillwater, Oklahoma 74078.

Tufekcioglu, M. 2010. Stream bank soil and phosphorus losses within grazed pasture stream reaches in the Rathbun Watershed in southern Iowa. Ph.D. Dissertation, Iowa State University, Ames, Iowa.

USDA ARS, 2013. Bank Stability and Toe Erosion Model Homepage. USDA Agricultural Research Service National Sedimentation Laboratory. Oxford, MS. http://www.ars.usd.gov/research/docs.htm?docid=5044. Accessed September 12, 2014.

USDA ARS, 2000. CONCEPTS – Conservational Channel Evolution and Pollutant Transport System. USDA Agricultural Research Service National Sedimentation Laboratory. Oxford, MS. http://www.ars.usd.gov/research/docs.htm?docid=5044. Accessed July 21, 2015.

USEPA, 2015a. National Summary of Impaired Waters and TMDL Information. U.S. Environmental Protection Agency. Available at: http://iaspub.epa.gov/waters10/attains_nation_cy.control%3Fp_report_type=T.

USEPA, 2015b. Progress towards Adopting Total Nitrogen and Total Phosphorus Numeric Water Quality Standards. Environmental Protection Agency. Available at: http://www2.epa.gov/nutrient-policy-data/progress-towards-adopting-total-nitrogen-and-total-phosphorus-numeric-water.

USGS, 2004. Determination of channel-morphology characteristics, bankfull discharge, and various design-peak discharges in western Montana. U.S. Department of the Interior. U.S. Geological Survey: Available at http://pubs.usgs.gov/sir/2004/5263/pdf/sir_2004_5263.pdf. Accessed on September March 10, 2015.

Walling, D.E., P.N. Owens and G.J.L. Leeks. 1999. Fingerprinting suspended sediment sources in the catchment of the River Ouse, Yorkshire, UK. *Hydro. Proc.* 13(7):955-975.

Wechsler, S. P. 2007. Uncertainties associated with digital elevation models for hydrologic applications: a review. *Hydrol. Earth Syst. Sci*. 11:1481-1500.

Williams, G.P. 1986. River meanders and channel size. *J. Hyrol.* 88:147-164.

White, M.J., C. Santhi, N. Kannan, J.G. Arnold, D. Harmel, L. Norfleet, P. Allen, M. DiLuzio, X. Wang, J. Atwood, E. Haney and M. Vaughn Johnson. 2014. Nutrient delivery from the Mississippi River to the Gulf of Mexico and effects of cropland conservation. *J. Soil Water Conserv.* 69(1):26-40.

Wilson, C. G., R. A. Kuhnle, D. D. Bosch, J. L. Steiner, P. J. Starks, M. D. Tomer, and G. V. Wilson. 2008. Quantifying relative contributions from sediment sources in Conservation Effects Assessment Project watersheds. *J. Soil Water Conserv.* 63(6):523-531.

Zaimes, G.N., R.C. Schultz, and T.M. Isenhart. 2008. Total phosphorus concentrations and compaction in riparian areas under different riparian land-uses of Iowa. *Agric. Ecosyst. Environ*. 127:22-30.

APPENDIX A

BARREN FORK CREEK CROSS SECTIONS

A total of 28 cross-sections were surveyed on the Barren Fork Creek using a laser level, measuring tape and survey rod: eight at cross-over points, nine at meanders and eleven at straight cross sections (Figure A.1). These data were then used to derive regression equations or averages for each of the streambank parameters used in the SWAT model.

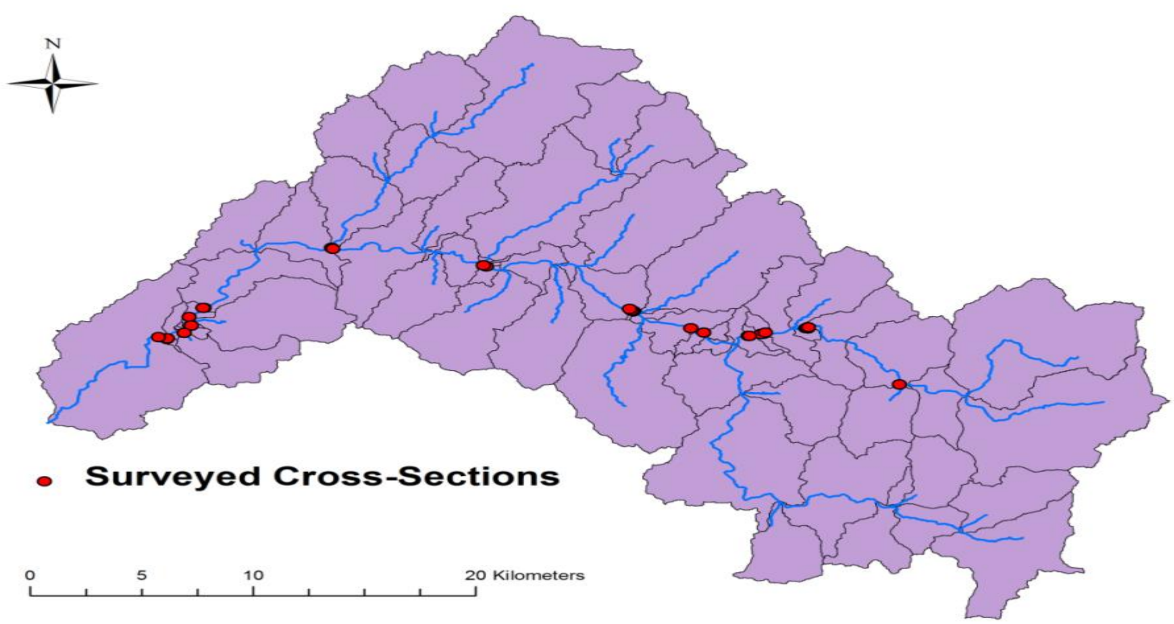


Figure A.1. Locations of the 28 cross sections surveyed on the Barren Fork Creek.

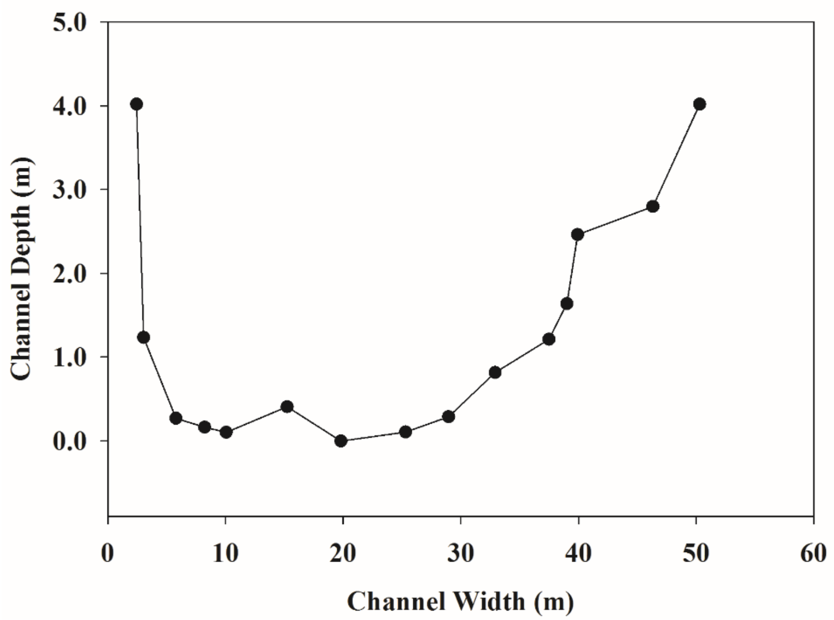


Figure A.2. Cross-sectional survey located on a straight reach at the U.S. Geological Survey gage station near Dutch Mills, Arkansas (365480 N, 3971663 E) on the Barren Fork Creek.

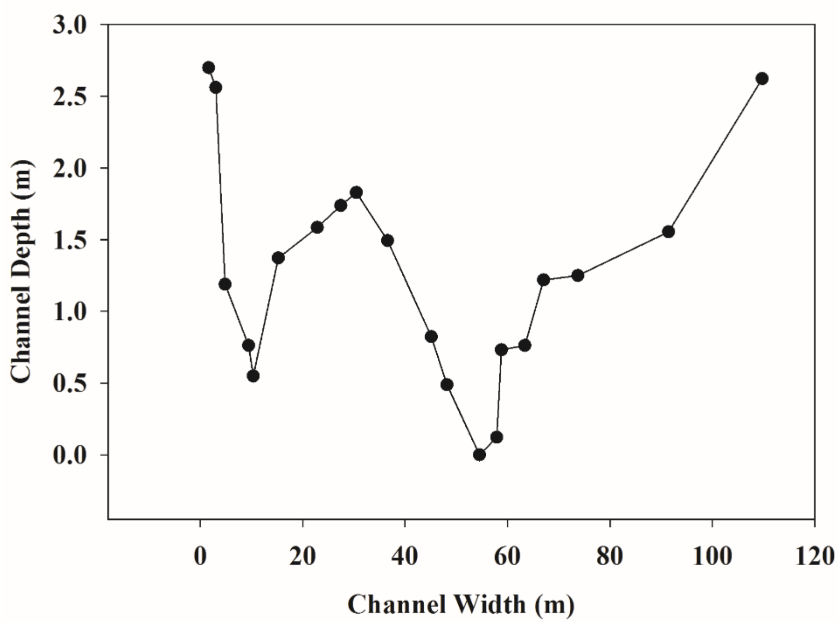


Figure A.3. Cross-sectional survey located on a straight reach at 361417 N, 3975506 E on the Barren Fork Creek.

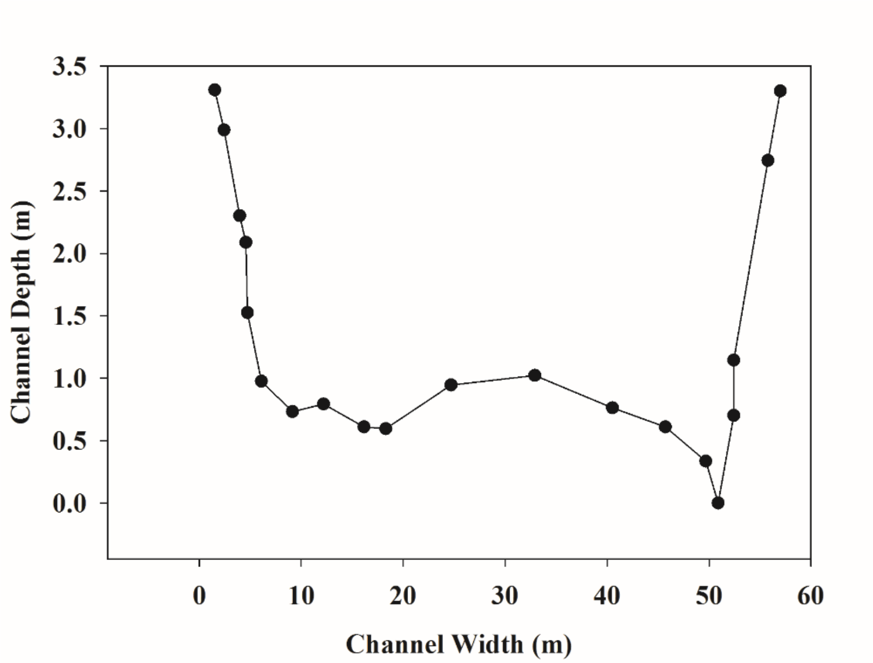


Figure A.4. Cross-sectional survey located at a cross-over at 361364 N, 3975435 E on the Barren Fork Creek.

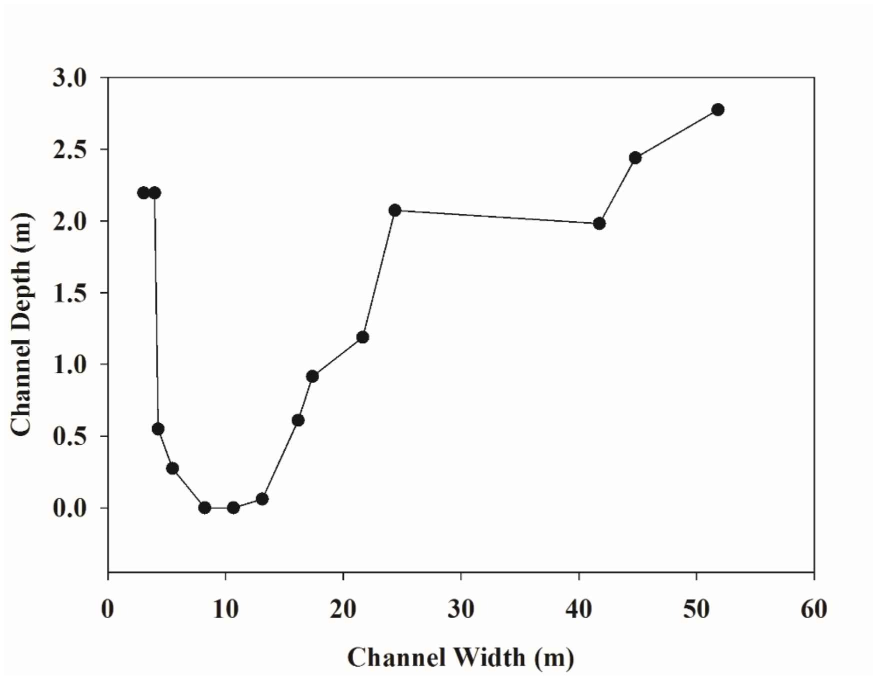


Figure A.5. Cross-sectional survey located on a meander at 361272 N, 3975458 E on the Barren Fork Creek.

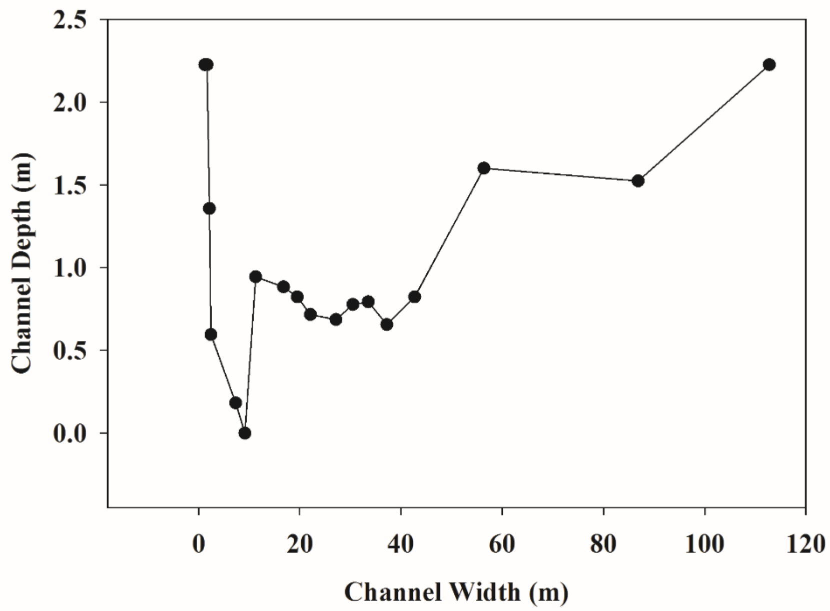


Figure A.6. Cross-sectional survey located at a cross-over at 359447 N, 3975165 E on the Barren Fork Creek.

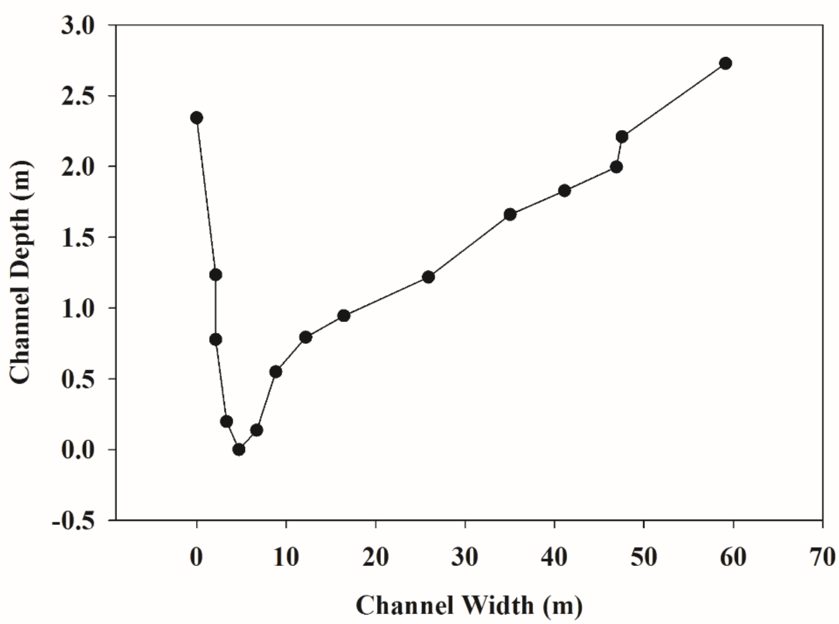


Figure A.7. Cross-sectional survey located on a meander at 3594405 N, 3975097 E on the Barren Fork Creek.

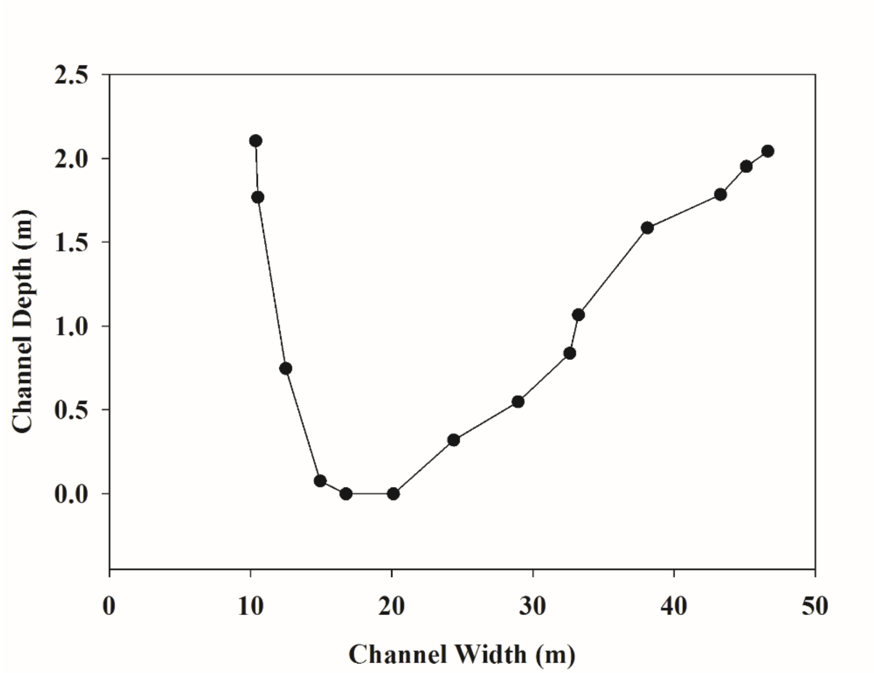


Figure A.8. Cross-sectional survey located on a straight reach at 359273 N, 3975070 E on the Barren Fork Creek.

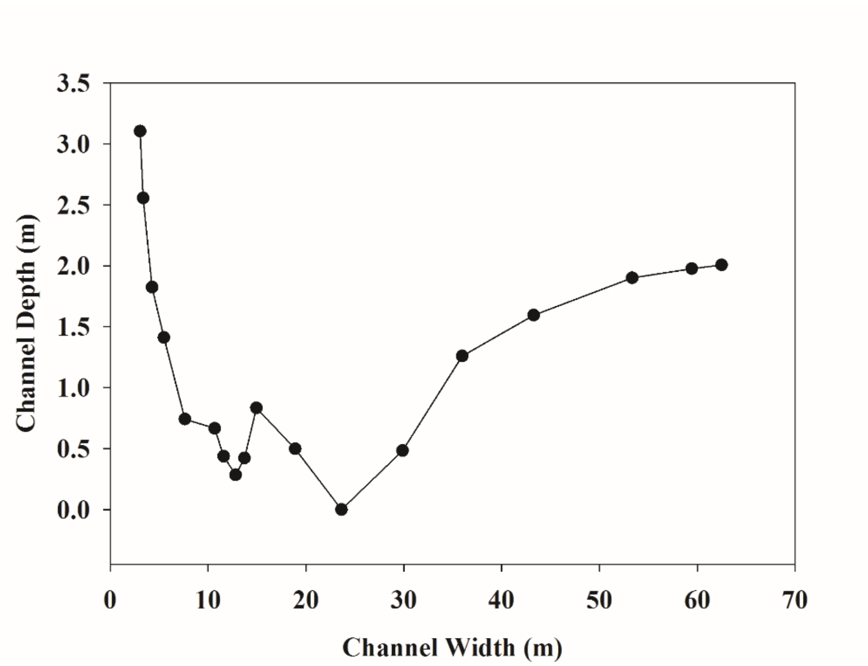


Figure A.9. Cross-sectional survey located at a cross-over at 358773 N, 3974947 E on the Barren Fork Creek.

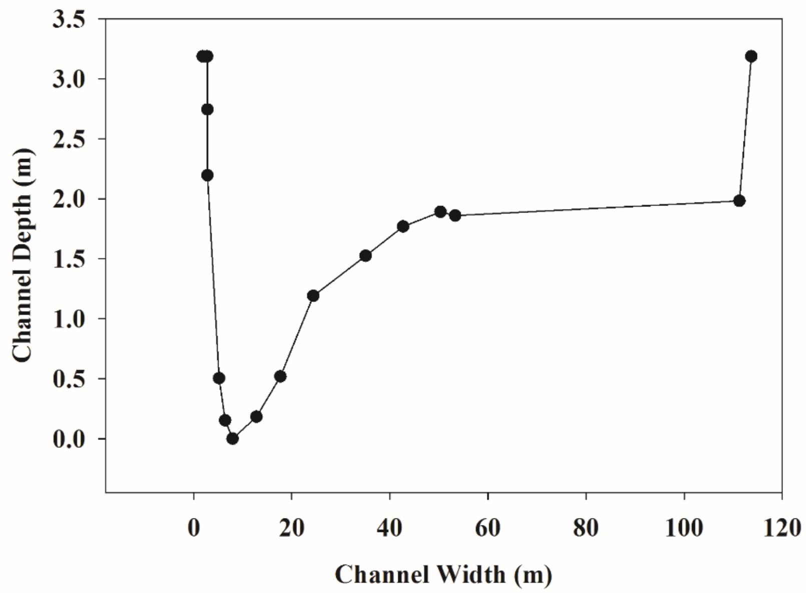


Figure A.10. Cross-sectional survey located on a meander at 358705 N, 3974940 E on the Barren Fork Creek.

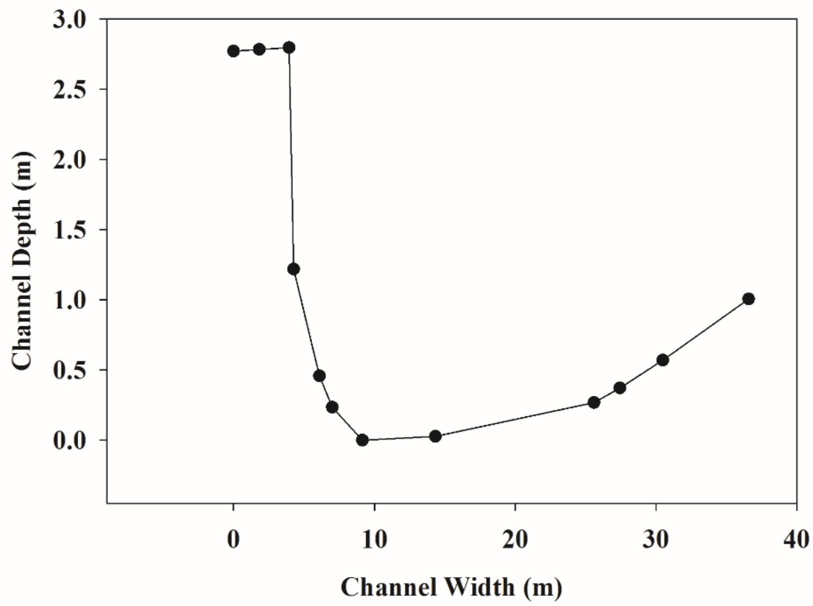


Figure A.11. Cross-sectional survey located on a meander at 356712 N, 3975175 E on the Barren Fork Creek.

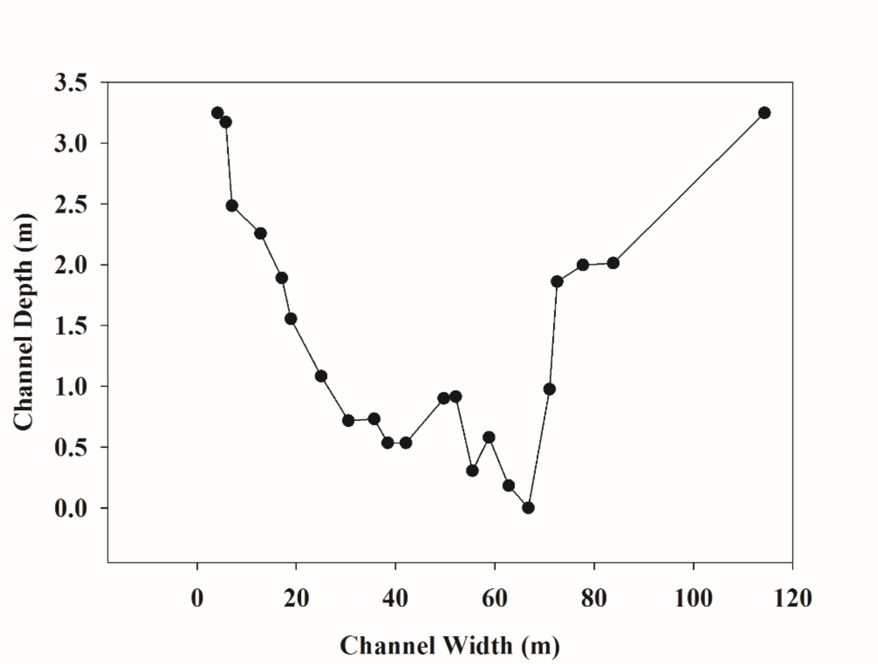


Figure A.12. Cross-sectional survey located at a cross-over at 353555 N, 3976619 E on the Barren Fork Creek.

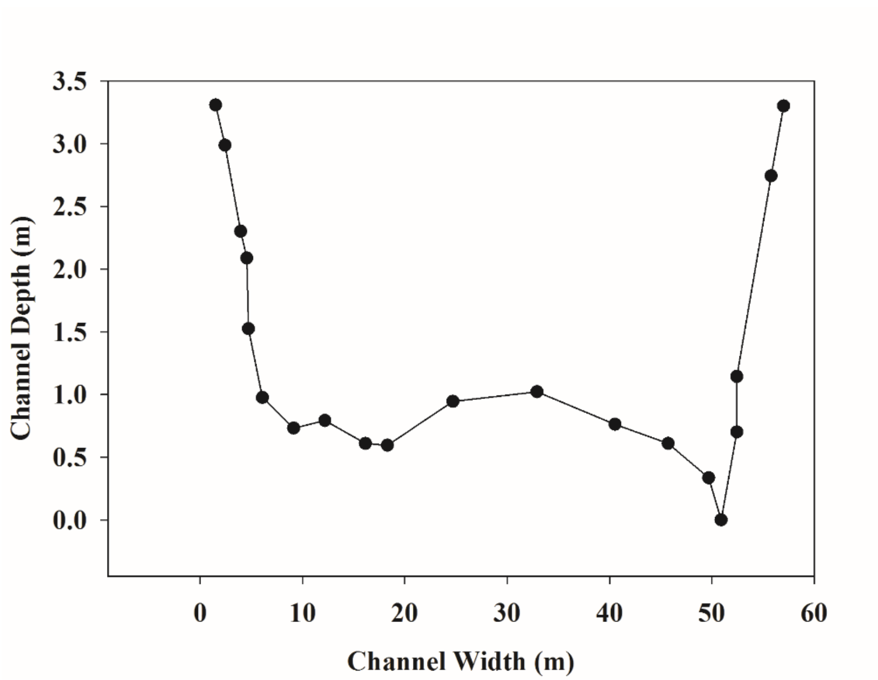


Figure A.13. Cross-sectional survey located on a straight reach at 353469 N, 3976687 E on the Barren Fork Creek.

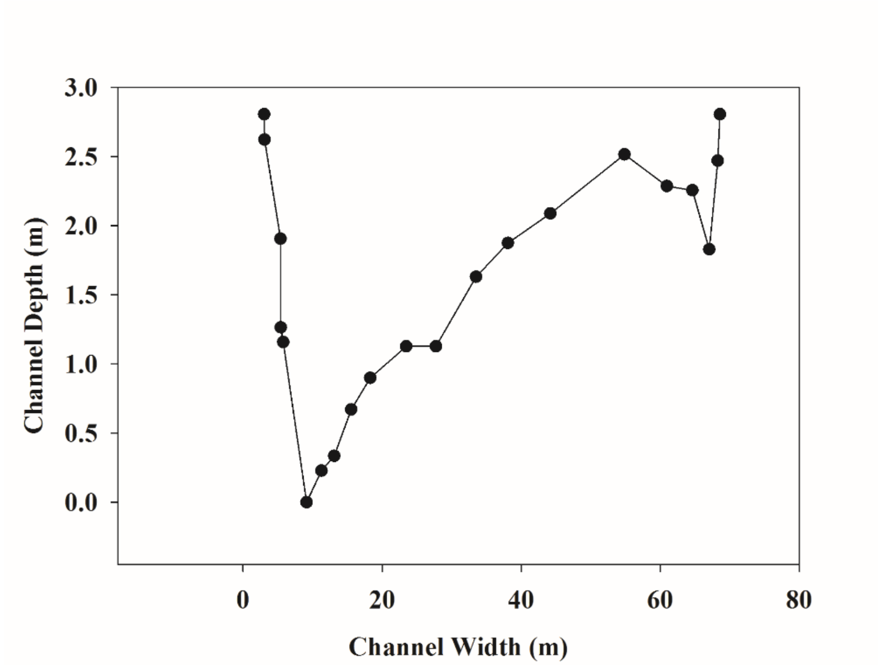


Figure A.14. Cross-sectional survey located on a meander at 353356 N, 3976777 E on the Barren Fork Creek.

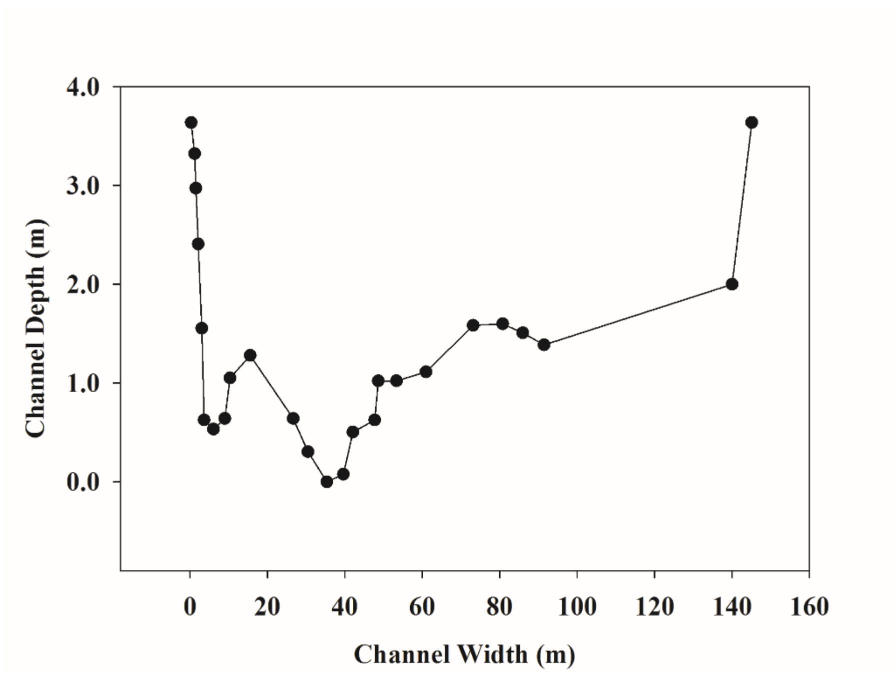


Figure A.15. Cross-sectional survey located on a cross-over at 346927 N, 3979630 E on the Barren Fork Creek.

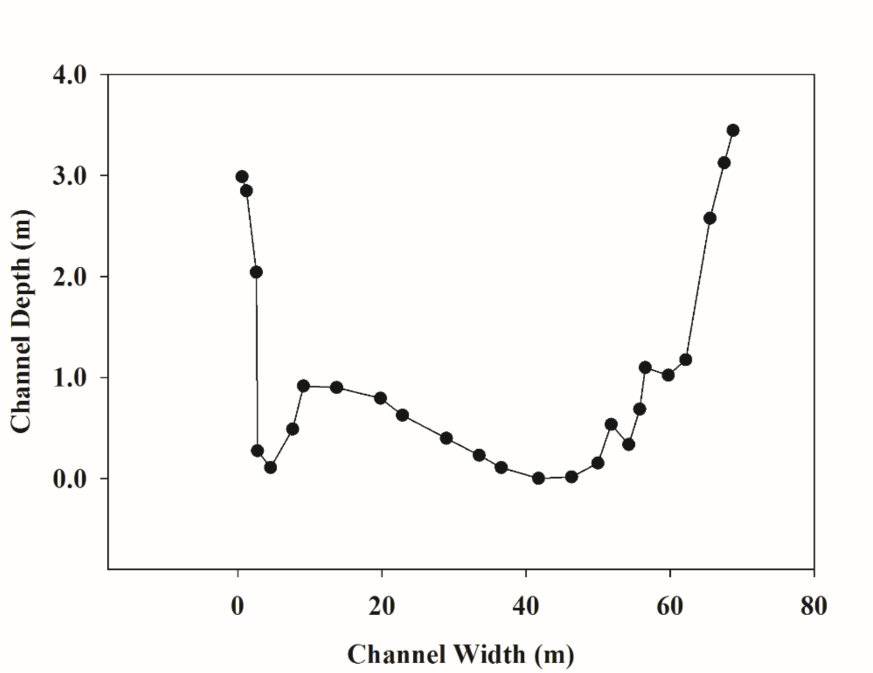


Figure A.16. Cross-sectional survey located on a straight reach at 346884 N, 3979651 E on the Barren Fork Creek.

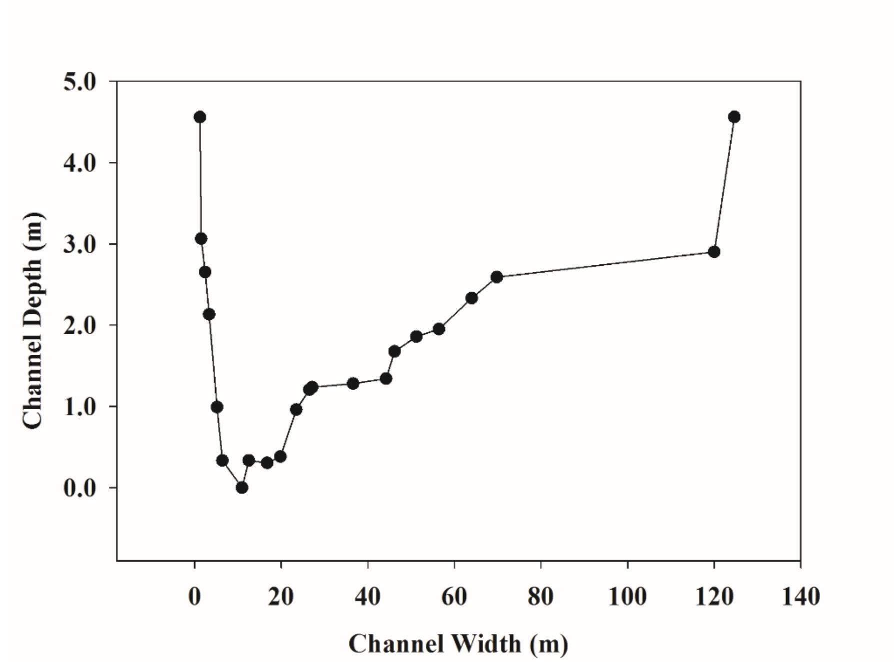


Figure A.17. Cross-sectional survey located on a meander at 346815 N, 3979706 E on the Barren Fork Creek.

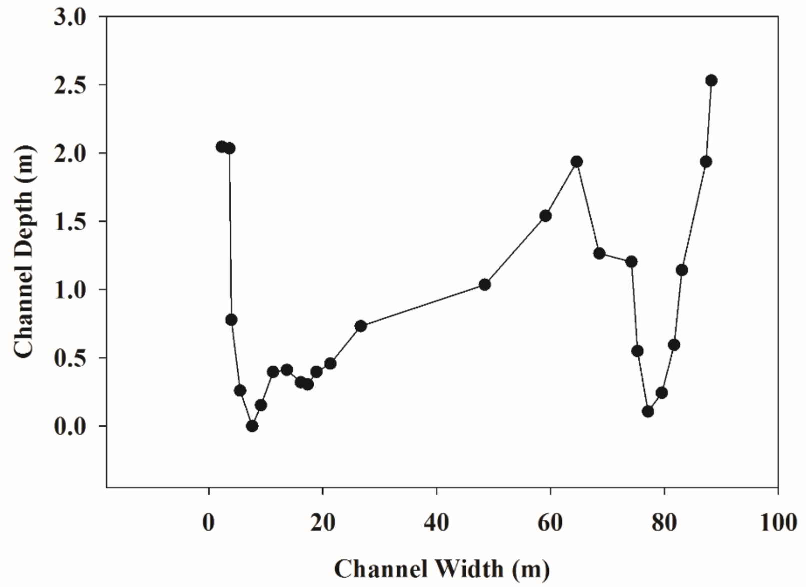


Figure A.18. Cross-sectional survey located on a meander at 340047 N, 3980843 E on the Barren Fork Creek.

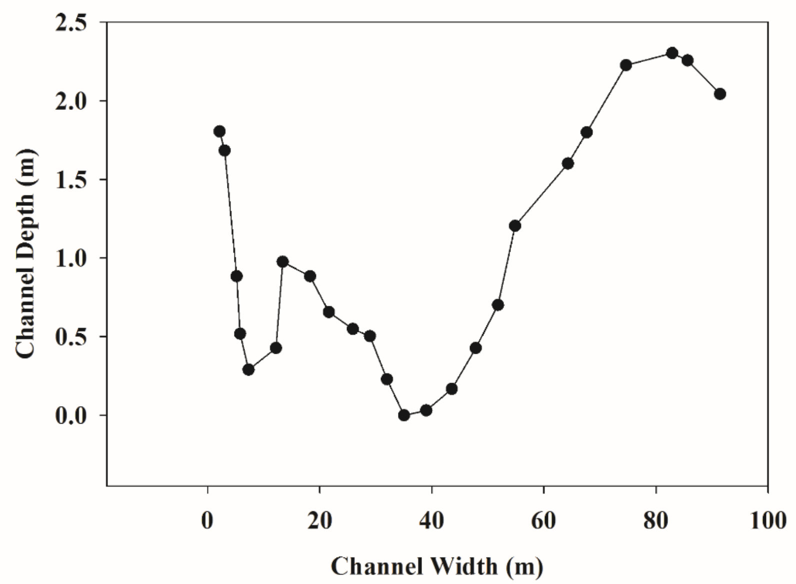


Figure A.19. Cross-sectional survey located on a cross-over at 340029 N, 3980855 E on the Barren Fork Creek.

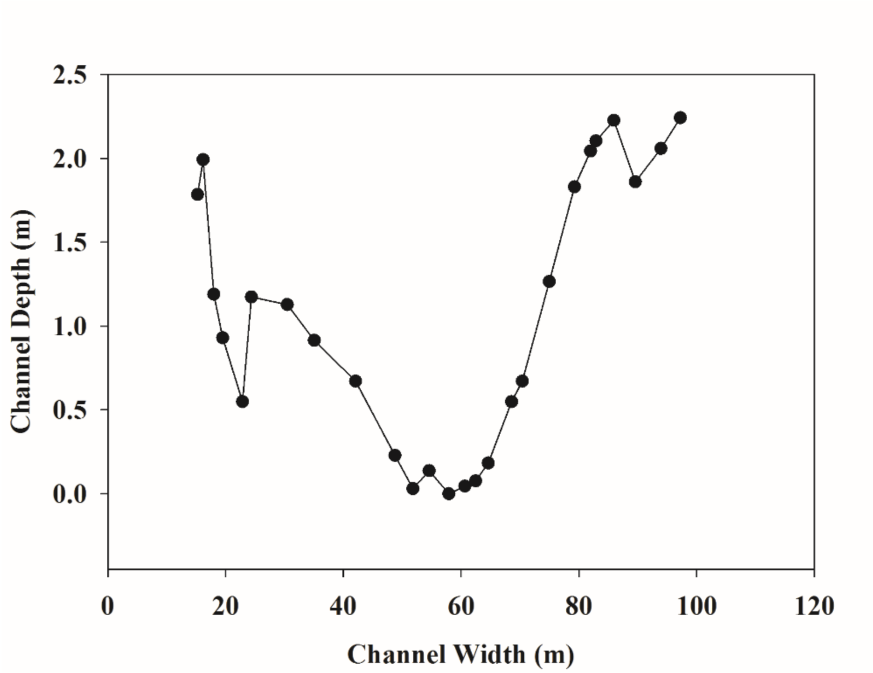


Figure A.20. Cross-sectional survey located on a straight reach at 339979 N, 3980899 E on the Barren Fork Creek.

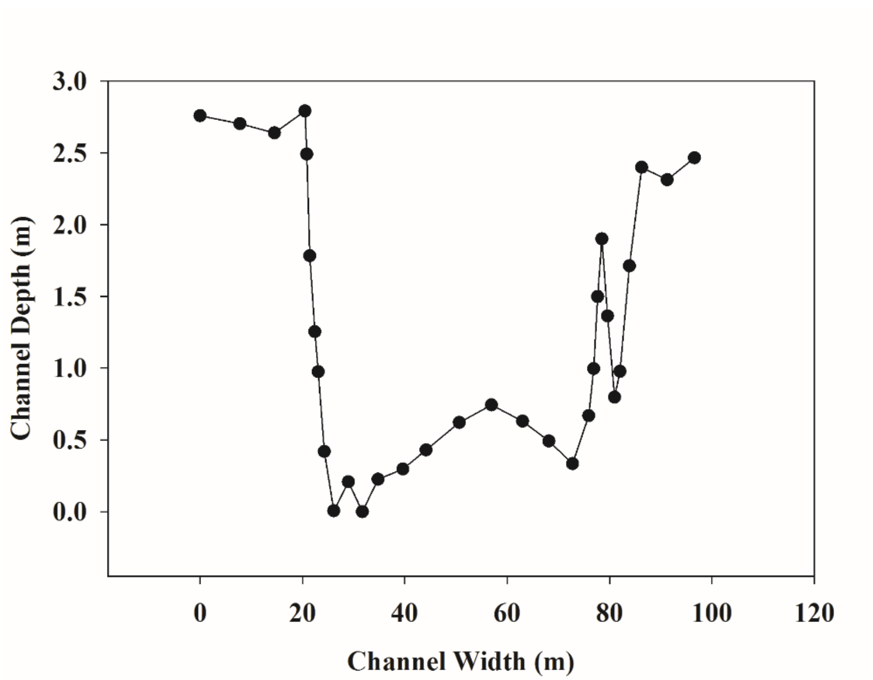


Figure A.21. Cross-sectional survey located on a straight reach at 333579 N, 3976229 E on the Barren Fork Creek.

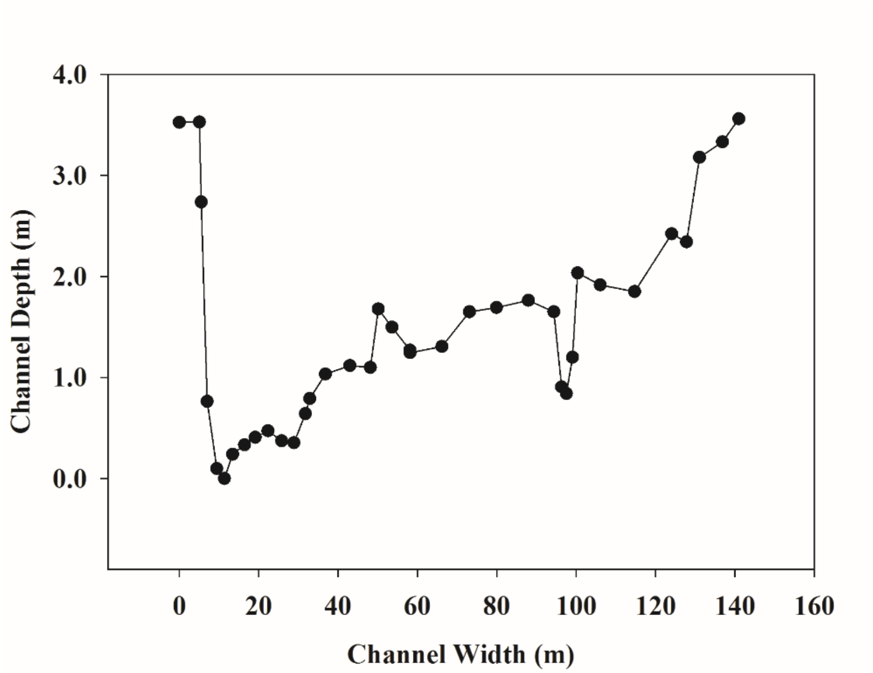


Figure A.22. Cross-sectional survey located on a straight reach at 333451 N, 3975536 E on the Barren Fork Creek.

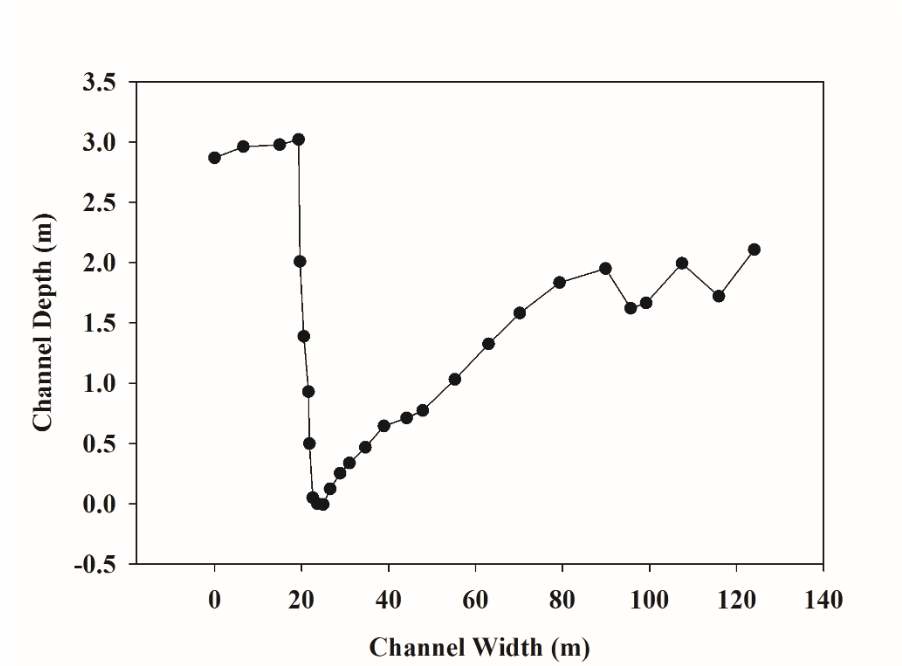


Figure A.23 Cross-sectional survey located on a meander at 333413 N, 3975106 E on the Barren Fork Creek.

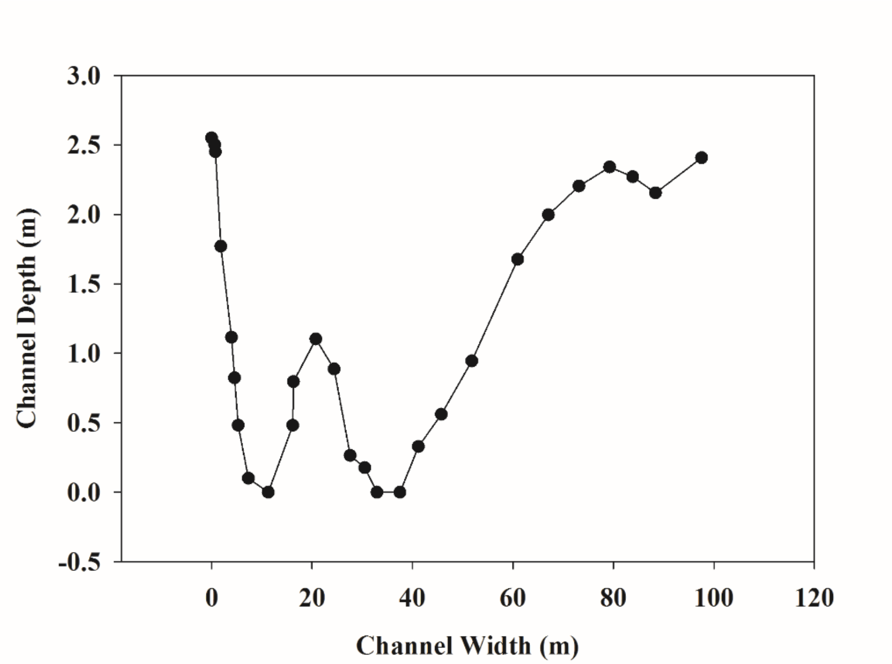


Figure A.24. Cross-sectional survey located on a straight reach at 332633 N, 3974785 E on the Barren Fork Creek.

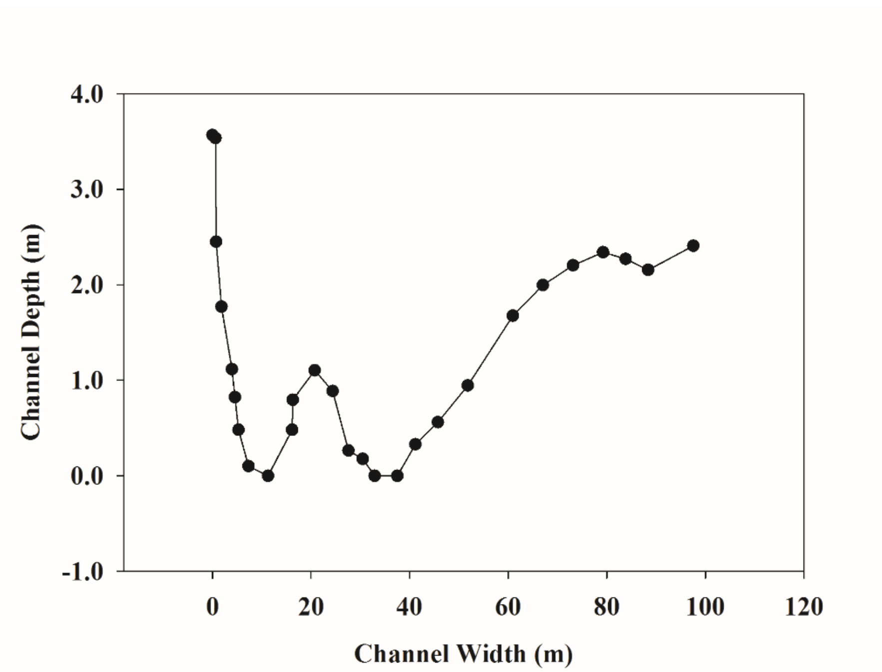


Figure A.25. Cross-sectional survey located on a cross-over at 332596 N, 3974712 E on the Barren Fork Creek.

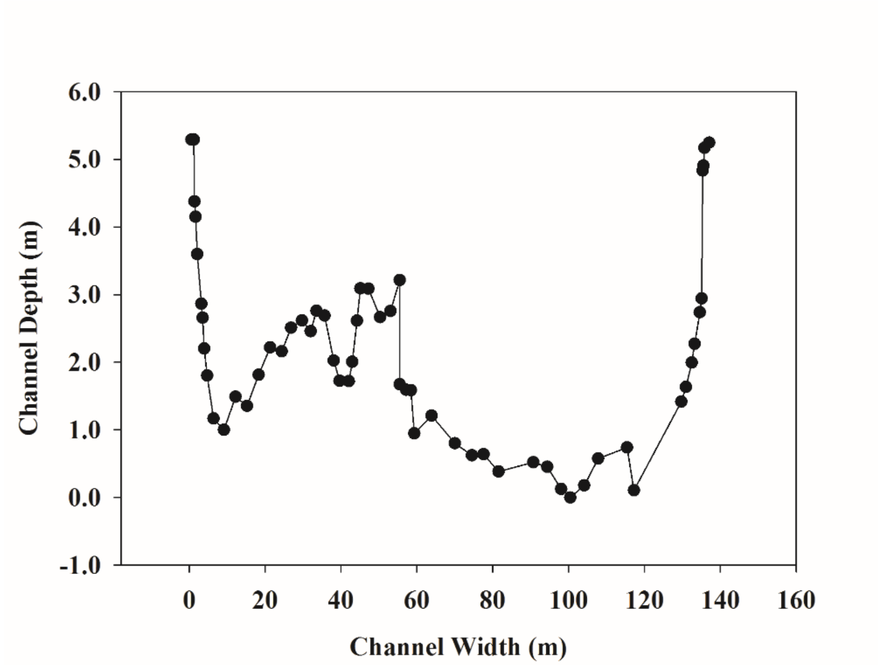


Figure A.26. Cross-sectional survey located on a straight reach at the U.S. Geological Survey gage station near Eldon, Oklahoma (334227 N, 3976830 E) on the Barren Fork Creek.

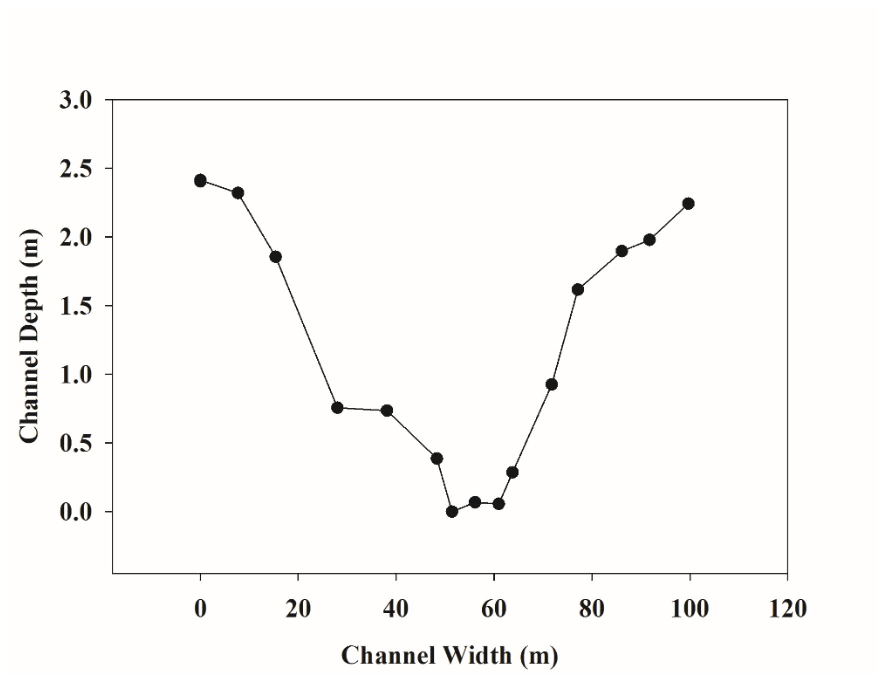


Figure A.27. Cross-sectional survey located on a cross-over at 332644 N, 3974899 E on the Barren Fork Creek.

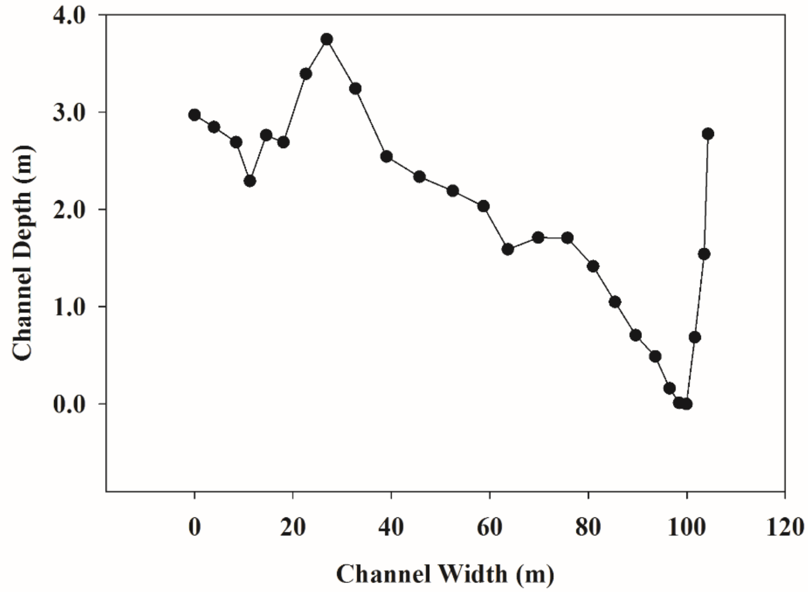


Figure A.28. Cross-sectional survey located on a meander at 332274 N, 3974867 E on the Barren Fork Creek.

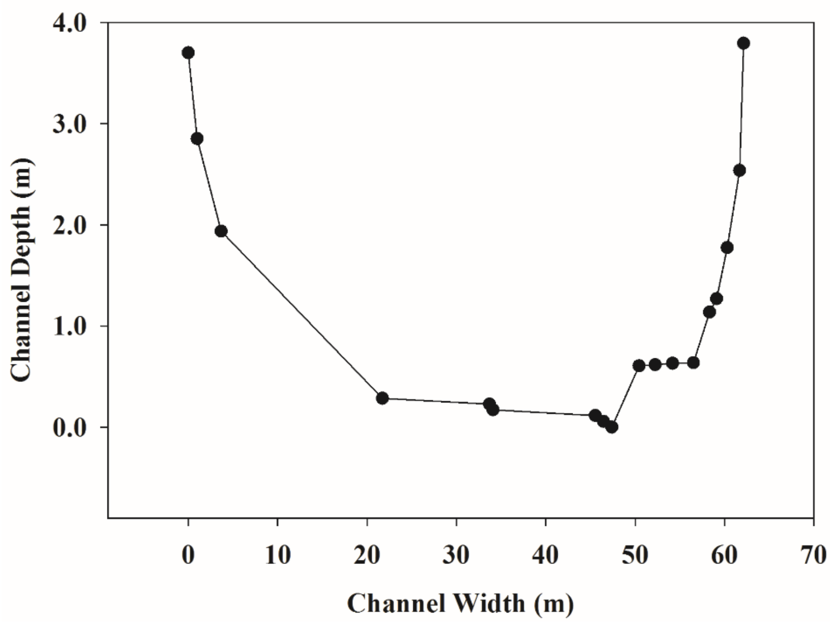


Figure A.29. Cross-sectional survey located on a straight reach at 331669 N, 3973131 E on the Barren Fork Creek.

Title: Optimizing the Economic Value Water from Ogallala Aquifer used for Irrigation

Start Date: 3/1/2015

End Date: 8/28/16.

Congressional District: 3rd Oklahoma Congressional district

Focus Category: AG, ECON, WS, WU

Descriptors: Irrigation, Corn, Sorghum, Ogallala

Student Status	Number	Disciplines
Undergraduate	3	Plant and Soil Sciences, Agriculture Economics
M.S.	4	Plant and Soil Sciences, Agricultural Economics
Ph.D.		
Post Doc		
Total	7	

Principal Investigators: Jason Warren, Art Stoecker, Jordan Gatlin, Karthik Ramaswamy, Rodney Jones, Jody Campiche, and Andrew Paul; Oklahoma State University

Publications:

Abstracts:

1. Gatlin, J., and J.G. Warren. 2014. Comparison of grain sorghum and corn productivity under limited irrigation with subsurface drip. *In* ASA-CSSA and SSSA abstracts. Available online at: https://scisoc.confex.com/scisoc/2014am/webprogram/Paper86030.html
2. Gatlin, J., and J.G. Warren. 2013. Comparison of grain sorghum and corn production with subsurface drip. In ASA-CSSA and SSSA abstracts. Available online at: https://scisoc.confex.com/scisoc/2013am/webprogram/Paper80177.html

Thesis:

1. Gatlin, Jordan. 2015. Corn and Sorghum yield response to limited irrigation supplied by sub-surface drip. MS Thesis. Department of Plant and Soil Sciences, Collage of Agricultural Sciences and Natural Resources, Oklahoma State University, Stillwater, OK, 40p

Extension Presentations:

1. Warren, J. 2015. Planting Strategies for Wheat Under SDI. Presented at the Oklahoma Irrigation Conference. Fort Cobb, OK. 18 Aug.
2. Warren, J., D. Sims, and C. Murley. 2015. Alternative planting strategies for sub-surface drip. Presented at the Fall Crops Tour. Goodwell, OK. 21 Aug.
3. Warren, J. 2015. Economics of Irrigated Corn vs. Grain Sorghum. Presented at the Winter Crops Clinic. Goodwell, OK. 10 Apr.
4. Gatlin, J., and J. Warren. 2014. Subsurface Drip Technology & Research. Fall Crops Tour. Goodwell, OK 13 Aug.

5. Warren, J. 2014. Subsurface Drip Irrigation. Sorghum Tour. Goodwell, OK 25 July. Warren, J.G., R Kochenower, J. Gatlin, and C. Murley. 2013. Grain Sorghum and Corn Productivity under limted irrigation. Presented at the Oklahoma Water Research Symposium. Midwest City, OK on 23 Oct.
6. Warren, J. 2013. Subsurface Drip Irrigation. Presented at the Oklahoma Panhandle Research and Extension Center Crops Clinic. Goodwell, OK. 14 Mar.

Grant Proposals Written:

1. Schipanski, M., J. Warren, et al. 2015. Sustaining Agriculture through Adaptive Management Resilient to a Declining Ogallala Aquifer and Changing Climate. Submitted to AFRI Coordinated Agricultural Project Program for $9,900,000. Funded.

Summary

This report serves as the final report for 3 years of research and extension efforts funded by the USGS 104b funding provided to support efforts in subsurface drip irrigation of corn, sorghum, and wheat. These funds have been utilized to directly support 3 undergraduate research assistance and 4 masters level graduate research assistance in their efforts attaining degrees in plant and soil sciences and agricultural economics. These funds also served to provide very valuable support to the initiation of OSU's efforts in irrigation research in the southern high plains. In fact, as a direct result of research capacity that these funds helped to develop OSU is known a partner institution on a $9.9 million AFRI-CAP project aimed at optimizing the use of Ogallala ground water. Furthermore, the finding of this research have been utilized to provide 6 presentations related to the agronomy and economics of subsurface drip irrigation, with current efforts to develop factsheets highlighting the results.

The following agronomic report shows that at irrigation capacities of 30-45 LPM ha-1 grain sorghum could achieve similar yields to that produced by corn with less irrigation water applied. As a result grain sorghum optimized irrigation water use efficiency. Furthermore, water use efficiency was increased by 17% when sorghum was produced. These findings support the hypothesis that irrigation of grain sorghum in the Oklahoma panhandle increases the amount of grain that can be produced per cm of water. Efforts to evaluate wheat grain yield response to irrigation applied during the 2014-15 crop year were not successful in generated a significant difference in yield among irrigation depths between 14-34 cm. Although grain yields were maximized at 4109 kg ha-1 at the highest irrigation rate the remaining irrigation treatments were not significantly different than this treatment due to above normal rainfall in the spring.

The economic analysis shows that irrigated corn provide opportunity to maximize short-term profit at irrigation capacities above 3.3 GPM acre-1 (30 LPM ha-1). However, when the goal is to maximize the net present value of the groundwater supply the analysis suggest that production of grain sorghum under center pivot irrigation is advantageous at all irrigation capacities because it maximizes the profit produced per volume of water pumped through the life of the aquifer. When comparing center pivot and subsurface drip irrigation, the subsurface drip irrigation gained advantage for the same reason but corn was more often produced because the increased water use efficiency of the subsurface drip irrigation and the increased cost of the irrigation system per

acre. The greater number of acres planted to corn with the subsurface drip irrigation cause a more rapid simulated decline of the aquifer.

The results of this economic analysis begged the question of why are producers resistant to adopting the production of grain sorghum under their current center pivots. Discussions with producers highlighted to reduced crop insurance protection available for grain sorghum under irrigation in the region. Therefore, an analysis of the crop insurance coverage for corn and grain sorghum in Texas County was conducted. This analysis utilized simulated corn and grain sorghum yields to determine the likelihood of an indemnity payment for both crops and evaluated the profitability of grain sorghum with and without the use of insurance. The analysis found that at well capacities of 3.3 GPM $acre^{-1}$ or more there is less risk of losing money if crop insurance is not purchased. This fact occurs because the county T yields for sorghum are well below the yields achieved under high levels of management in experimental conditions. In contrast, county T yields for corn are comparable to those expected based on the simulations. These discrepancies in the T yield for corn vs grain sorghum occur because producers in the region apparently impose generally high levels of management on corn planted to the most productive soils. In contrast the grain sorghum is grown under sub optimum conditions. These discrepancies suggest that incentive programs may be needed to incentivize the production of high yielding grain sorghum in replacement of the less efficient high yielding corn.

In addition to adjustments to the current crop insurance structure for grain sorghum, policy makers should consider the impact of policy on a producer's capacity to utilize a business plan that maximized net present value of future production over a business plan that maximizes single year profit. Currently it is certainly in the best interest of each individual to maximize the single year provide however, this maximizes the rate of withdrawal and life of the aquafer.

Agronomic Report

INTRODUCTION

The Ogallala aquifer is a vital resource for the entire economy of the Oklahoma Panhandle. Agricultural irrigation is the primary use of water in the region overlaying the Ogallala aquifer, representing 86% of water used (OWRB, 2012). This water is used to produce a variety of crops, however much of the irrigation water is used for the production of corn grain. In fact, the 2007 National Agricultural Statistic Survey shows that approximately 84,000 acres of corn were irrigated, producing approximately 18.4 million bushels of corn to be fed at regional animal production facilities (NASS, 2007). Recent production estimates show that corn production in the region has increased to as high as 26.8 million bushels in 2010 (NASS, 2010). Additional value, for the State of Oklahoma and the broader Southern High Plains Region, is added to this corn as a component of feed for cattle and hogs produced in the region.

The loss of pumping capacity resulting from drawdown of the Ogallala aquifer and/or future restrictions on withdrawal for irrigation poses a significant risk to the future of irrigated crop production and the animal production systems in the region which depend on this local source of grain. Numerous studies have been published in the past 20 years showing that the water levels in this aquifer are declining. For example, the USGS found that water levels declined by as much as 100 ft under Texas County, OK between the 1940s and 1990s. The report went on to suggest that if withdrawal continued at the same rate as in 1996, the water level would decrease by an additional 20-25 ft under Texas County, OK by 2020 (Luckey, et al. 2000).

The effects of these aquifer drawdowns are being felt by an increasing number of crop producers in the Panhandle region. Specifically, irrigation well pumping capacities are declining to levels insufficient to irrigate corn for optimum yields. Historically, various strategies have been used to overcome these declines in well pumping capacity. First, the drilling of additional wells can maintain production potential. Another option is to decrease irrigated acreage by using a smaller portion of the center pivot or combine wells to increase the capacity on a specific field. The cost of drilling a new well combined with the uncertainty of its pumping capacity has made this option less attractive to many producers. Combining wells or otherwise decreasing the acreage irrigated per well will allow for effective use of available water for corn production but in time will cause a net decrease in the feed grain production capacity of the region. This will have a negative impact on the regional animal production complex and the overall economy of the Oklahoma panhandle because of reduced availability of local feed grain.

The producers are now left with very serious decisions about water use and management. One proven technology to increase water use efficiency is subsurface drip irrigation. Subsurface drip irrigation delivers water at low pressure through plastic tape buried below ground. This eliminates evaporative water losses during application thereby resulting in 100% application efficiency. This is a significant improvement in the efficiency of water application when compared to common pivot irrigation systems that apply water at 70 to 90% efficiency. Water use efficiency is additionally improved by the fact that in a subsurface drip system, the soil surface is dry, which allows for improved infiltration of precipitation. The dry soil surface also minimizes evaporative water loss, which further improves efficiency. Interception of irrigation water by the crop canopy is nonexistent in a drip irrigation system, resulting in additional improvements in water use efficiency.

Various research projects have demonstrated the utility of subsurface drip irrigation to improve water use efficiency for crops in the U.S. High Plains. Lamm and Trooien (2003) summarized 10 years of research in Kansas and concluded that irrigation water use for corn can be reduced by 35-55% using subsurface drip irrigation compared to commonly used irrigation systems in the region. The pool of knowledge demonstrating the efficiency of drip irrigation negates the need for further comparison of drip to center pivot irrigation. This project does not seek to do so, but rather this project will be utilized to demonstrate drip irrigation and to develop local knowledge in the successful utilization of this irrigation practice.

Irrigated grain producers also have the option of growing alternative crops with lower water requirements than corn. Grain sorghum provides an ideal alternative crop. It is well adapted to the region and can serve as a replacement for corn in the animal production systems in the region. Historically, grain sorghum has not been competitive with corn as a component of animal feed due to the perception of lower feed quality and milling characteristics. However, modern sorghum varieties have equivalent feed quality characteristics to corn and feed mills are becoming more accepting of sorghum as a feed ingredient. This along with the use of grain sorghum as a feedstock for ethanol production has caused sorghum prices (currently $4.44/bushel) to be competitive with corn prices ($4.44/bushel). This makes sorghum an ideal alternative to corn for irrigation in the Panhandle.

Irrigated grain sorghum has not been given the attention that corn has received due to the historic popularity and profitability of corn. Therefore, irrigation requirements for sorghum have yet to be fully evaluated in the Panhandle region of Oklahoma. Previous research clearly shows that sorghum can be produced with dramatically less irrigation water than corn. For example, the NRCS irrigation guide (NRCS, 2010) suggests that at Goodwell, OK, optimum production of corn requires 20 inches of supplemental water, while grain sorghum only requires 15.5 inches. A preliminary report by Rees and Anderson (2010) confirmed the lower water requirements of sorghum by showing that evapotranspiration (ET) by sorghum was 30% less than that of corn in south central Nebraska. A study conducted at Garden City, KS showed that maximum sorghum yields of 120 bushels/acre could be achieved with an average of 4 inches of irrigation water. In comparison, maximum corn yields of 205 bushels required 12 inches of irrigation (Klocke and Curri, 2009). Additionally, average yields in Oklahoma State University sorghum variety trials conducted in the Oklahoma Panhandle between 2009-2012 were 150 bushels/acre with an average annual irrigation rate of 9.4 inches/acre. In contrast, corn yields in variety trials conducted in the Panhandle produced an average of 190 bushels/acre with an average irrigation rate of 22 inches of water/acre. These data demonstrate the lower water requirement for grain sorghum in the growing environment presented in the Panhandle region of Oklahoma. Similar data collected in the Southern High Plains of Texas near Lubbock on producer's fields were combined with economic analysis to show that grain sorghum yields of 115 bushels/acre produced more value/inch of water ($31.4/inch) than corn yields of 214 bushels/acre which provided a value of $27.6/inch of water. In this research, the sorghum received an average of 7.9 inches compared to 17.4 inches of water for the corn. It should be noted that corn was more profitable/acre ($479/acre) than sorghum ($248/acre) (Texas Alliance for Water Conservation, 2011). Of course, as water becomes more scarce, returns per unit of water will become a more important driver of the decision making process.

Despite this limited data, there has not yet been a comprehensive economic analysis of irrigated sorghum that encompasses both profitability and risk at a wide range of irrigation application rates. This study is expected to show that producers who follow long-term profit maximization principles in the choice of crops, irrigation water use, and equipment selection will be able to gain more grain production and greater discounted profits from current water supplies than producers who choose maximization of immediate profits.

Commercially available irrigation scheduling technologies provide opportunity to improve irrigation water use efficiency by providing producers with science based recommendations for daily irrigation requirements. Technologies which estimate water requirements based on estimates of evapotranspiration, combined with short-term weather forecasts, provide the most promise for the region. These tools use meteorological data to estimate evapotranspiration and irrigation rates scheduled to replace the daily loss of water from the soil system. The proposed project will evaluate one such scheduling tool as well as provide valuable water use data for high yielding sorghum that will be useful in improving the accuracy of such technologies for irrigated sorghum.

The **OBJECTIVES** of this project are to compare the yield potential and water use efficiency of sorghum and corn under limited irrigation with subsurface drip. This data will serve to validate estimates used in the economic analysis to evaluate the profitability of irrigated grain sorghum and its risk relative to that of corn production under limited water availability.

The funding of this project will also be used to demonstrate a number of technologies proven to improve water use efficiency of irrigated crop production. Specifically, this project will demonstrate the use of subsurface drip irrigation and a commercially available irrigation scheduling product. This will increase the knowledge levels of producers in the region and improve the adoption of these technologies.

METHODOLOGIES

Irrigation system and plot layout

This research utilized the subsurface drip irrigation system located at the Oklahoma Panhandle Research and Extension center. This system provided 48 individually plumbed experimental units that could be irrigated independently. These plots are 15.24 m long and 4.57 m wide. The drip tapes are located at a depth of 0.35 m below the soil surface and 1.52 m apart such that one tape irrigates two crop rows spaced 0.76 m apart. The plots are six rows wide (4.6 m), which means there are three tapes located in each plot, and 15.3 m long. The emitters on the tape are located every 0.30 m and were set to emit 4.5 L/min each. This resulted in a target application rate of 4mm/ha/hour. Flow meters with analog totalizers were installed during the 2013 growing season on each plot to assess instantaneous flow and to monitor cumulative irrigation applied to each plot during the growing season.

Experimental Design

The experimental design is a randomized complete block with split plot design. Main plots were crop (corn or sorghum), and subplots were irrigation rate. The four sorghum treatments and the four corn treatments simulated application rates achievable with well pumping capacities shown in Table 1 when applied to a 50.6 ha center pivot. The sorghum treatments included all pumping capacities included in the table except for the 3028 L min^{-1} because this rate exceeds water requirements for sorghum. The corn treatments included all pumping capacities listed except for the 379 L min^{-1} rate because this is well below the required water for irrigated corn. In 2013 the target irrigation depth was 38.1 mm per irrigation event which resulted in return intervals and application rates shown in Table 1.

Table 1: 2013 Irrigation Treatments.

Treatment		Well Capacity	Application per Interval	Minimum Irrigation Interval	Application Rate
Corn	Sorghum	L min^{-1}	mm	days	L min^{-1}ha^{-1}
C1	--	3028	38.1	4.24	60
C2	S1	2271	38.1	5.66	45
C3	S2	1514	38.1	8.49	30
C4	S3	757	38.1	16.94	15
--	S4	379	38.1	29.02	7.5

Treatments are meant to simulate a center pivot system irrigating a 50.6 ha circle with specific well pumping capacities.

In 2014-15, the target irrigation depth was 25.4 mm per irrigation event which resulted in return intervals and application rates shown in Table 2.

Table 2: 2014-15 Irrigation Treatments.

Treatment		Well Capacity	Application per Interval	Minimum Irrigation Interval	Application Rate
Corn	Sorghum	L $min^{-1}ha^{-1}$	mm	days	L $min^{-1}ha^{-1}$
C1	--	3028	25.4	2.9	60
C2	S1	2271	25.4	3.7	45
C3	S2	1514	25.4	5.9	30
C4	S3	757	25.4	11.8	15
--	S4	379	25.4	23.1	7.5

Treatments are meant to simulate a center pivot system irrigating a 50.6 ha circle with specific well pumping capacities.

Summer Crop Management

Prior to planting corn and sorghum in 2013 and 2014, plots were fertilized using a strip-till fertilizer applicator. Corn plots received 225 kg N ha^{-1} as liquid UAN (28-0-0) and sorghum plots received 140 kg N ha^{-1} as liquid UAN (28-0-0). Strip tillage was conducted April 5, 2013 and April 15th, 2014. At planting, 19 L of 10-34-0 liquid fertilizer were applied as starter fertilizer. In 2013, corn was planted on April 15th and sorghum was planted June 17th. Inaccurate row placement of the corn rows relative to the drip tape caused unacceptable distribution of water to the corn rows in the April planting; therefore this crop was terminated and corn was replanted on June 4th. In 2014, corn was planted on April 16th and sorghum was planted June 3rd. In each year, dry conditions in April (Table 3) presented stand establishment challenges. Specifically, the strip tillage appeared to reduce capillary movement of water from the drip tape to the corn crop row. Therefore, in order to initiate emergence the corn rows were hand watered. In 2013, the June planted corn did not require hand watering, nor did the sorghum in either year.

Table 3: In-Season Rainfall, Goodwell, OK (mm)

	Month						Total
Year	April	May	June	July	August	September	
2013	8	4	49	26	103	50	240
2014	12	87	95	74	25	41	334
2015	48	162	46	104	82	34	436

Corn hybrids utilized in each years were Pioneer 1768AMX, planted at 81,500 seeds ha^{-1} on treatments receiving 60 and 45 LPM ha^{-1}, and Pioneer 1151YXR4, planted at 43,200 seeds ha^{-1} on treatments receiving 30 and 15 LPM ha^{-1}. Sorghum hybrids used were Pioneer 84G62, planted at 154,400 seeds ha^{-1} for treatments receiving 45 and 30 LPM ha^{-1}, and DeKalb 3707, planted at 74,100 seeds per ha^{-1} on treatments receiving 15 and 7.5 LPM ha^{-1}. The practice of planting shorter season hybrids on the treatments with lower well capacities is common in this region. The earlier maturing varieties are better suited to limited irrigation systems because they do not require as much water throughout the season as the longer full season varieties. They also are planted at lower populations than the full-season hybrids to ensure better plant survival with limited water. Using these different planting populations also allows the data to be more realistic when utilized for future economic analyses evaluating economic returns from the range of irrigation treatments imposed in this study. In 2013, corn was harvested on October 16th and sorghum was harvested on October 24th with a small plot combine. In 2014, corn was harvested on October 8th and sorghum was harvested on October 15th. The center two rows from each plot were harvested to determine plot weight, test weight and moisture with a harvest master weighing system. Yields presented were corrected to 15.5% moisture for corn and 14% moisture for grain sorghum and 25 kg test weight.

Wheat Crop Management:

On October 20, 2014 the wheat variety Iba was planted with a Sunflower No till drill at a seeding rate of 100 kg ha^{-1} on all irrigation rates. Surface soil moisture was adequate for stand establishment. This combined with night time temperatures falling below freezing in early Nov. prevented fall applications of irrigation. Irrigation was initiated on March 10 and continued through May 3, after which time the occurrence of above average rainfall negated the need for further irrigation. In fact, total rainfall between planting and March 1 was 5.34 cm, between March 1 and May 1 was 10.9 cm, with an additional 28 cm falling between May 1 and harvest. Nitrogen Fertilizer was applied to wheat plots via fertigation through the drip tape. Urea ammonium nitrate (32-0-0) fertilizer was injected into the system to supply 33.6 kg N ha^{-1} per application starting on March 16th and continuing weekly for 6 weeks for a total application of 200 kg N ha^{-1}. Wheat was harvested with a small plot combine on June 25th.

Soil Sampling

Soil cores (4.4 cm diameter) were collected on June 11, 2013 prior to planting of sorghum. The cores were also collected from the corn plots on this date after the second planting. These cores were taken to a target depth of 2.4 m or resistance with a tractor-mounted hydraulic probe. One core per plot was collected in October 2013 post-harvest to assess residual soil moisture to the target depth of 2.4 m. Due to dry subsurface conditions, this target depth was not attainable in all plots, and so the target depth was adjusted to 1.2 m.

In 2014, soil cores were taken from the corn plots on May 7 and from the sorghum plots on June 4 with a hydraulic probe to determine soil water content. One core per plot was collected October 22, 2014 to assess residual soil moisture post-harvest to a target depth of 1.2 m. One core per plot was collected and cut into 0.3 m sections before being weighed, dried at 100°C for 24 hours, and then weighed again to determine gravimetric water content and bulk density. These values were used to determine volumetric water content of the soil. This was then used to calculate the depth of water per depth of soil (m m^{-1}).

Irrigation Management

In 2013, approximately 76 mm of pre-season irrigation was applied to the corn plots prior to the first planting. Between the first planting and the collection of soil samples on June 11th an additional 100 mm was applied to the corn plots in an effort to germinate the first planting.

During this time 38 mm was applied to the sorghum plots. The in-season irrigation was initiated on June 15th for the corn plots and June 28th for the sorghum plots as advised by the Aquaplanner program.

In 2014, 81 mm of irrigation was applied prior to planting the corn and collection of initial soil samples. However, no pre-plant irrigation was applied to the sorghum plots because 85 mm of rainfall was received during the 2 weeks prior to sorghum planting. In season irrigation initiated on May 9th for the corn crop and on June 24th for the sorghum crop.

After initiation, irrigation was applied to treatments at the frequencies presented in Tables 1 and 2. When rainfall was experienced irrigation was postponed if the Aquaplanner program calculated that the soil profile was at or near field capacity.

An irrigation log was maintained which consisted of irrigation duration and volume of water applied to each plot. Water volumes were measured with flow meters attached to the valves on each of the 32 plots to confirm actual flow applied to each plot. This flow meter data was collected throughout the growing season. This flow meter data allowed for the discovery of leaks and incorrect flow rates within the system, and so application times were adjusted accordingly. It was found that in 2013, flow rates were estimated incorrectly, and so the target application of 38.1 mm per event was not realized; instead, the application per event was closer to 22.9 mm. This discrepancy was caused by a difference in the instantaneous flow and the time weighted average flow which was caused by reduced flow during filter flush events. The flows were corrected in 2014 by reducing the frequency of filter flush events and by using the average flow instead of instantaneous flow rate to schedule irrigation event duration such that actual applications were much closer to the target application of 25.4 mm per application event in 2014.

Corn and Sorghum Water Balance

The fallowing water balance equation (Eq. 1) adapted from Kanemasu, et al (1983) was used in this study

Eq 1 $$SM_c = SM_{ini} + I_{eff} + P_{eff} - D - RO - E - T$$

Where:

SM_c current soil moisture content
SM_{ini} initial soil moisture content
I_{eff} effective irrigation
P_{eff} effective precipitation
D drainage from the root zone
RO runoff
E evaporation
T transpiration

The soil texture and bulk density as measured on soil samples collection in April and June of 2013, were input into the ROSETTA software program to estimate hydraulic parameters of water held at field capacity (FC, -33 kPa) and permanent wilting point (PWP, -1500 kPa). A soil water characteristic curve (SWC) was used to describe the amount of water retained in a soil at a given matric potential (Tuller et al, 2003). The curve can be constructed using a known volumetric water content (θ) of a soil and relating it to the matric potential, as shown in eq. 2 (van Genuchten, 1980).

Eq. 2 $$\frac{\theta-\theta r}{\theta s-\theta r} = \frac{1}{[1-(-\alpha \times MP)^{n}]^{m}}$$

Where:

θ	water content
θ_r	residual water content
θ_s	saturated water content
α	
n	parameters dependent on the matric potential
m	
MP	matric potential

The pedotransfer functions utilized in the Rosetta software allow users to input limited physical data such as texture to provide estimates for hydraulic parameters (Schaap et al, 2001). The values given by the Rosetta software using the van Genuchten Eq. 2 allow for SMC curves to be extrapolated, calculating the θ_v at various matric potentials. The water contents at the matric potentials of FC and PWP can be used to calculate how much water can be stored in the profile, and how much of that water is plant available water (PAW).

Initial and Ending Soil Moisture Collection

The volumetric water content calculated from the soil cores collected prior to planting was used to determine SM_{ini} for each treatment. These pre-plant soil moisture values were used as the starting point of the water balance, and the postharvest data was used to validate the water budget ending soil moisture.

Rainfall Data Collection

Precipitation data was collected from the Mesonet (2015) and it was not adjusted, due to the fact that there was no hourly rainfall data available. Also, the crop coefficient (Kcmid) of 1.2 used for the middle of the growing season was selected to account for increased evaporation due to interception. This meant that an efficiency of 100% was assumed to achieve the P_{eff} factor for the water balance.

Irrigation Data Collection

As previously mentioned, irrigation data was collected using flowmeters on each plot. Irrigation data was modified, to assume an efficiency of 95% for SDI (Lamm,) to achieve the I_{eff} value for the water balance.

Calculation of RO and D

Runoff was assumed to be zero, because of the lack of hourly rainfall data needed to determine if its intensity was in excess of infiltration rate. Furthermore, due to the low average seasonal rainfall at this location and the dry nears surface soil conditions presented by the use of subsurface drip irrigation, it was assumed that runoff would be negligible. Drainage was assumed to occur under saturated conditions, when the profile moisture content exceeded FC.

Calculation of ETc

Crop ET (ET_c) was calculated from a reference ET (ET_o) using the single-crop coefficient method outlined in FAO-56 (eq. 3).

Eq.3 $$ET_c = ET_o + K_c$$

Where:

ET_c crop evapotranspiration
ET_o reference evapotranspiration
K_c crop coefficient

This equation adjusts the ET_o based on the crop coefficient (K_c), and the reference ET (ET_o). The K_c can be derived using a single-crop coefficient or a dual-crop coefficient. The single-crop method is recommended for irrigation planning, design, and management utilizing basic irrigation schedules, through computing a daily water balance using the ET_c .In the single-crop coefficient, the calculations are much simpler, because they combine crop transpiration and soil evaporation into one Kc coefficient. This gives only time-averaged effects of ETc (FAO-56).

The ET_o comes from the Penman-Monteith (ASCE-PM) equation from ASCE Manual 70 (Jensen et al, 1990) for calculating a standardized reference ET, or ET_{sz} (eq.4). According to the Task Committee on Standardization of Reference Evapotranspiration, the equation for ET_{sz} uses meteorological data and characteristics of a defined vegetative surface to create a standard reference for calculating ET_c (2005). This defined vegetative surface is defined as “a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of the same vegetation” (ASCE, 2005). The short crop used for reference (ET_{os}) is clipped cool-season grass, and the tall crop reference (ET_{rs}) used is alfalfa. For the this study the following equation was used in combination with data from the Mesonet to calculate the ET_{rs},

Eq. 4 $$ET_{sz} = \frac{0.408\ \Delta(R_n - G) + \Upsilon(C_n/T+273)u_2(e_s - e_a)}{\Delta + \Upsilon(1 + C_d u_2)}$$

Where:

ET_{sz} standardized reference crop evapotranspiration for short (Et_{os}) or tall (Et_{rs}) surfaces (mm d^{-1} for daily time steps or mm h^{-1} for hourly time steps)
R_n calculated net radiation at the crop surface ($MJm^{-2}d^{-1}$ for daily time steps or $MJm^{-1}h^{-1}$ for hourly time steps)
G soil heat flux density at the soil surface (MJ m^{-2} d^{-1} for daily time steps or MJ m^{-2} h^{-1} for hourly time steps)
T mean daily or hourly air temperature at 1.5 to 2.5-m height (°C)
u_2 mean daily or hourly wind speed at 2-m height (m s^{-1})

e_s saturation vapor pressure at 1.5 to 2.5-m height (kPa), calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperature

e_a mean actual vapor pressure at 1.5 to 2.5-m height (kPa)

Δ slope of the saturation vapor pressure-temperature curve (kPa $°C^{-1}$)

Υ psychrometric constant (kPa $°C^{-1}$)

C_n numerator constant that changes with reference type and calculation time step (K mm s3 Mg^{-1} d^{-1} or K mm s^3 Mg^{-1} h^{-1})

C_d denominator constant that changes with reference type and calculation time step (s m^{-1})

Corn Crop Coefficients

For this study, the crop coefficient was found using the single-crop coefficient method from FAO-56. The K_{cini} was adjusted for wetting, using the average rainfall events during the 30-day period after the 2014 planting date from 2011-2014. This meant that during the initial period, the K_c was very low, only 0.0325. The K_{cmid} used was 1.2. A linear increase was used to determine the K_c during the K_{cdev} stage. For corn, a 15-day period was used for the decline from the K_{cmid} of 1.2 to the K_{cend} of 0.35. After harvest in October, the K_c drops back to 0.0325.

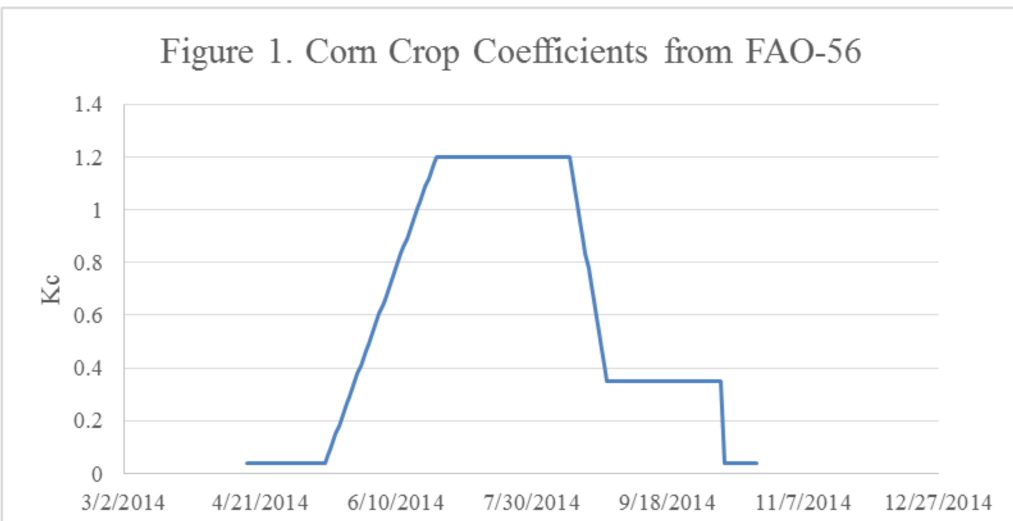
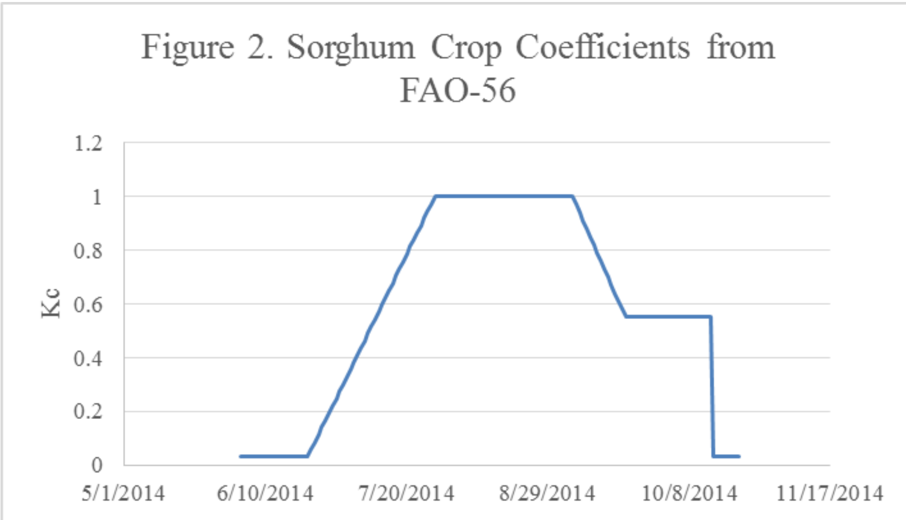


Figure 1. Corn Crop Coefficients from FAO-56

Sorghum Crop Coefficients

For sorghum, the Kcini was determined using the rainfall data from 2011-2014 using the average rainfall for the 30-day period following a June 4 planting. The Kcmid was selected from Table 12 and was 1. The Kcend was 0.55, and the curve decreased linearly over a fifteen-day period just as with the corn. The Kcend remained 0.55 until harvest, and then it was assumed to return to 0.0375.



RESULTS:

Wheat Yield Data:
Table 4 shows the irrigation applied, wheat grain yields and resulting irrigation water use efficiency for the 2015 harvest year. There were no significant differences in wheat grain yield among the well capacity treatments. Despite a difference of 20 cm of irrigation water applied between the 45 and 7.5 LPM ha-1 treatments. This lack of yield response appears to result from the late planting and lack of fall irrigation on the fully irrigated treatments which appeared to limit crop vigor. This also resulted is substantially dry conditions in these treatments that could not be effectively over cop with irrigation starting in early march. These factors limited the maximum attainable yield in the fully irrigated treatments. Furthermore the above average rainfall occurring in April-June allow the low irrigation treatments to preform relatively well further preventing the development of significant differences in yield. Due to similar yields under very much different irrigation rates the 7.5 LPM ha-1 treatment resulted in the highest irrigation water use efficiency due to the greater proportion of the yield having come from spring rainfall.

Table 4. In season Irrigation applied, resulting yield and irrigation water use efficiency (WUE_{irr}) in 2014-15 wheat crop

Irrigation Capacity	Irrigation	Yield	Irrigation WUE
LPM† ha^{-1}	cm	Kg ha^{-1}	Kg ha^{-1} cm^{-1}
45	34	4109	121
30	25	3606	142
15	16	3744	234
7.5	14	3725	272

†LPM, liters per minute

‡ Means followed by the same letter are not statistically different. Corn and sorghum data were analyzed together to allow comparison between species.

Sorghum and Corn Yield and Irrigation Data

In 2013, corn yields were maximized at 11173 kg ha^{-1}, reached in the highest irrigation treatment (60 LPM ha^{-1}). There were 32.8 cm of water applied to this treatment. There were no significant differences in corn yield between the 60, 45, and 30 LPM ha^{-1} treatments. Sorghum yields were maximized in the highest irrigation treatment (45 LPM ha^{-1}), with 9478 kg ha^{-1} produced with 25.9 cm irrigation water applied. Furthermore there were no differences in sorghum yields among the irrigation capacity treatments 45, 30, and 15 LPM ha^{-1}. Comparison of corn and sorghum yields found that at the 45, 30, and 15 LPM ha^{-1} irrigation capacities the corn and sorghum yields were not significantly different. In fact, sorghum yields produced with the 15 LPM ha^{-1} treatment were not significantly different from the corn yields produced with 30 LPM ha^{-1}.

As is generally observed, water use efficiency increased with decreasing irrigation water applied in 2013. The with in a irrigation treatment water use efficiency was significantly higher for sorghum compared to corn only in the 15 LPM ha^{-1} treatment.

In 2014, Grain yields were again maximized when corn was irrigated at the 60 LPM ha-1 irrigation capacity. However these yields were not significantly greater than those achieved with 45 LPM ha-1. At the 45 LPM ha-1 irrigation capacity sorghum yields were significantly lower than corn yields. At irrigation capacities below this level there were no differences between corn and sorghum. However, it must be noted that corn yields were numerically higher than sorghum yields at each irrigation capacity treatment accept for in 2015 where sorghum yields were numerically higher.

Because of lower irrigation water application to sorghum under each irrigation capacity treatment, the water use efficiency was consistently higher for sorghum than for corn. In fact, the irrigation WUE was numerically higher within each irrigation capacity in every instance accept in 2013 at the 30 LPM ha-1 treatment because of suppress yields in this treatment.

Table 4. In season Irrigation applied, resulting yield and irrigation water use efficiency (WUE_{irr}) in 2013

Irrigation Capacity	Irrigation		Yield		Irrigation WUE	
	Corn	**Sorghum**	**Corn**	**Sorghum**	**Corn**	**Sorghum**
LPM† ha^{-1}	-----------cm----------		----------Kg ha^{-1}---------		--------Kg ha^{-1} cm^{-1}-------	
60	32.8		11173a‡		341e	
45	29.0	25.9	10482ab	9478bc	362e	366e
30	21.8	19.6	9980abc	8787cd	457cd	449cd
15	15.5	14.7	7532d	8599cd	486c	584b
7.5		9.9		7218d		729a

†LPM, liters per minute

‡ Means followed by the same letter are not statistically different. Corn and sorghum data were analyzed together to allow comparison between species.

Table 5. In season Irrigation applied, resulting yield and irrigation water use efficiency (WUE_{irr}) in 2014

Irrigation Capacity	Irrigation		Yield		Irrigation WUE	
	Corn	**Sorghum**	**Corn**	**Sorghum**	**Corn**	**Sorghum**
LPM† ha^{-1}	-----------cm----------		----------Kg ha^{-1}---------		--------Kg ha^{-1} cm^{-1}------	
60	55.1		12123a		194d	
45	45.0	33.8	11496ab	9365c	224d	273cd
30	37.3	30.0	10046bc	8789cd	218d	352b
15	22.1	18.5	6985de	5806e	213d	331bc
7.5		13.5		6446e		629a

†LPM, liters per minute

‡ Means followed by the same letter are not statistically different. Corn and sorghum data were analyzed together to allow comparison between species.

Table 6. In season Irrigation applied, resulting yield and irrigation water use efficiency (WUE_{irr}) in 2015

Irrigation Capacity	Irrigation		Yield		Irrigation WUE	
	Corn	**Sorghum**	**Corn**	**Sorghum**	**Corn**	**Sorghum**
LPM† ha^{-1}	-----------cm----------		----------Kg ha^{-1}---------		--------Kg ha^{-1} cm^{-1}------	
60	53		13831a		261a	
45	48	40	12016ab	10784bc	250a	270a
30	35	31	9084cd	10038bc	260a	324ab
15	22	22	7179d	8933cd	326ab	406b
7.5		12		9438cd		787c

†LPM, liters per minute

‡ Means followed by the same letter are not statistically different. Corn and sorghum data were analyzed together to allow comparison between species.

Water Use Efficiency

Tables 4 and 5 present the irrigation water use efficiency (WUE_{irr}), which does not take into account any other source of water besides irrigation. The WUE_{irr} is simply yield divided by in-season irrigation water applied, without taking into account precipitation or soil water used by the crop during the season. This number served to provide a comparison between not only treatments within each crop, but also between the two crops. When other variables are taken into account using the water balance, which accounts for all water that moves into and out of the system, the total water use efficiency (WUE_{total}) can be estimated.

Table 7 shows the total water use and water use efficiency for each summer crop in 2013 through 2015. This presentation of data demonstrates that the water use efficiency of sorghum is higher than that found for corn at each irrigation treatment. This is in agreement with prior research presented above. This suggests that sorghum will produce more grain per cm of water at all irrigation capacities evaluated in this study.

Table 7: The water use efficiency for corn and sorghum during the 2013 through 2015 crop years.

Irrigation Capacity	------------------Water Use Efficiency--------------					
	------2013------		------2014------		------2015------	
	Corn	Sorghum	Corn	Sorghum	Corn	Sorghum
LPM† ha^{-1}	------------------------------$Kg\ ha^{-1}\ cm^{-1}$-------------------------					
60	151		136		120	
45	149	166	151	159	112	131
30	165	162	130	164	95	135
15	135	115	115	128	86	134
7.5		97		148		163

Water Balance

The water balance was initiated at the time of initial soil sample collection. The effective irrigation (I_{eff}), the effective precipitation (P_{eff}) were added to this value on a daily time step. The Crop ET (Etc) was subtracted from this value on a daily time step. When the soil water content to a depth of 120 cm was found to be able field capacity the difference between the current soil water content and field capacity was assumed to be equal to drainage for that day and was subtracted from the soil water. The resulting cumulative values for these variables for the 2014 and 15 crop year are presented in table 8 and 10 for each corn treatment and table 9 and 11 for each sorghum. The measured post-harvest soil moisture (Sm_{final}) is also presented for comparison to the estimated to allow for assessment of the accuracy of the water balance. The measured values were generally larger than the estimated value in the corn treatments in 2014 and lower than estimated values in 2015, especially at the C1 and C2 treatments. In contrast, the measure value for the sorghum was 6 cm greater than the estimate in the S1 treatment but the estimate was similar to measure values in the S4 treatment. In 2015, the estimates for the sorghum treatments were elevated compared to all measure values. Although there were substantional differences (as much as 10 cm) between the measured and estimated final soil moisture, this maximum difference only represented 14% of the estimate crop ET.

Table 8: Individual components of the Water Balance for each Corn treatment in 2014

							Sm_{final}	
Treatment	Sm_{ini}	I_{eff}	P_{eff}	D	RO	Etc	Estimate	Measured
	---------------------------------------cm--							
C1	39	55	37	4.5	0	93	34	36
C2	37	45	37	1.8	0	84	33	35
C3	40	37	37	7.2	0	77	30	33
C4	39	22	37	4.1	0	63	30	32

Table 9: Individual components of the Water Balance for each sorghum treatment in 2014.

Treatment	Sm_{ini}	I_{eff}	P_{eff}	D	RO	Etc	Sm_{final} Estimate	Sm_{final} Measured
	-------------	-------------	-------------	-------------	cm	-------------	-------------	-------------
S1	38	34	27	6.3	0	65	28	34
S2	34	30	27	2.3	0	61	28	30
S3	35	19	27	3.5	0	51	26	29
S4	35	14	27	3.4	0	47	25	25

Table 10: Individual components of the Water Balance for each corn treatment in 2015.

Treatment	Sm_{ini}	I_{eff}	P_{eff}	D	RO	Etc	Sm_{final} Estimate	Sm_{final} Measured
	-------------	-------------	-------------	-------------	cm	-------------	-------------	-------------
C1	40	53	51	16	0	95	34	27
C2	39	45	51	17	0	90	32	28
C3	40	34	51	16	0	79	28	28
C4	40	21	51	17	0	65	28	28

Table 11: Individual components of the Water Balance for each sorghum treatment in 2015.

Treatment	Sm_{ini}	I_{eff}	P_{eff}	D	RO	Etc	Sm_{final} Estimate	Sm_{final} Measured
	-------------	-------------	-------------	-------------	cm	-------------	-------------	-------------
S1	40	40	30.5	6	0	70	38	28
S2	39	32	30.5	2.7	0	68	34	27
S3	39	22	30.5	3.9	0	61	32	25
S4	40	13.5	30.5	2.8	0	55	31	26

SUMMARY:

Corn provides the yield potential to allow for the maximization of grain production at irrigation capacities equal to or greater than 45 LPM ha^{-1}. At the remaining irrigation capacities corn and sorghum yields were similar, suggesting that this is the irrigation capacity where it becomes advantageous to grow sorghum instead of corn due to the lower production costs. Furthermore, the water use efficiency was higher for sorghum at irrigation well capacities less than 45 LPM ha^{-1}. This shows that the production of sorghum will result in more grain produced per L of water.

The incorporation of wheat into the rotation with sorghum and corn did achieve the goal of improving the ease with which weed control could be attained in the grain sorghum. However, the lack of yield response to irrigation treatment resulting from inadequate fall irrigation and above average spring rainfall suggests that there is still a great deal to learn about how to manage SDI for the optimization of wheat production in the panhandle region.

This work has highlighted the improved water use efficiency of irrigated sorghum as compared to corn and that sorghum can be a viable alternative as well capacity declines. Furthermore, the water balance data suggests that current irrigation scheduling tools based on water budgets consistently under estimate soil water availability for subsurface drip irrigation.

Works Cited

Carreira, R.I. (2004) Economic Study of Alternative Best Management Practices for Swine Effluent Application to Corn in a Semiarid Climate, Ph.D. Dissertation, Edmond Low Library, Oklahoma State University.

Carreira, R.I., A.L. Stoecker, F.M. Epplin, J.A. Hattey, and M.A. Kizer, (2006) Subsurface Drip Irrigation Verus Center-Pivot Sprinkler for Applying Swine Effluent to Corn. Journal of Agriculture and Applied Economics. Vol. 38(3), PP 645-648.

Harris, T.R. and H.P. Mapp. 1988. A Stochastic Dominance Comparison of Water-Conserving Irrigation Strategies. Amer. J. Agricultural Economics, 68:298-305.

Klocke, N, and R. S. Curri. 2009. Corn and Grain Sorghum Production with Limited Irrigation. In the Southwest Research-Extension Center, Field Day 2009 Report. pgs 35-38. Kansas State University Agricultural Experiment Station and Cooperative Extension Service, Manhattan, KS. Available online at: http://www.ksre.k-state.edu/library/crpsl2/SRP1014.pdf. Verified on Oct. 24, 2011.

Lamm, F.R., D.M. O'Brien, D.H. Rogers, and T.J. Dumler. 2012. Comparison of SDI and Center Pivot Sprinkler Economics. Proceedings of the 2012 Irrigation Association Technical Conference, Orlando, Florida, Nov. 2-6. Available from the Irrigation Association, Falls Church, VA

Lamm, F.R., and T.P. Tooien. 2003. Subsurface drip irrigation for corn production: a review of 10 years of research in Kansas. Irrigation Science. 22: 195-200.

Luckey, R.R., N.L.Osborn, M.F. Beker, and W. J. Andrews. 2000. Water Flow in the High Plains Aquifer in Northwestern Oklahoma. USGS Fact Sheet 081-00.

NASS. 2007. Census of Agriculture: Oklahoma. State and County Data. Volume 1. Geographic Area Series. Part 36. Available online at: http://www.agcensus.usda.gov/Publications/2007/Full_Report/Volume_1,_Chapter_1_State_Level/Oklahoma/ Verified on Oct. 8, 2012.

NASS. 2010. Oklahoma Corn County Estimates. Available online at: http://www.nass.usda.gov/Statistics_by_State/Oklahoma/Publications/County_Estimates/2011/ok_corn_county_estimates_2011.pdf Verified on Oct. 8, 2012.

NRCS. 2010. National Engineering Handbook - Part 652, National Irrigation Guide and Oklahoma Supplements. Available online at: http://www.ok.nrcs.usda.gov/technical/Manuals/ig.html. Verified on Oct. 01, 2012.

OWRB 2012. Oklahoma Comprehensive Water Plan, Panhandle Watershed Planning Region Report. Available online at: https://www.owrb.ok.gov/supply/ocwp/pdf_ocwp/WaterPlanUpdate/regionalreports/OCWP_Panhandle_Region_Report.pdf Verified on Oct. 8, 2012

Prescott, E.C. (1972) The multi-period control problem under uncertainity, Econometrica, vol 72, 1972

Rees, J., and D. Anderson 2009. Comparison of Crop Water Consumptive Use of Sorghum, Corn, and Soybeans. Annual Report, available online at: http://water.unl.edu/c/document_library/get_file?folderId=1242079&name=DLFE-14668.pdf. Verified on Oct. 08, 2012.

Sick, G.A. (1986) A Certainty-Equivalent Approach to Capital Budgeting, *Financial Management* Vol. 15, pp 23-32

Stoecker, A.L., A. Siedman, and G.S. Lloyd. 1985. A Linear Dynamic Programming Approach to Irrigation System Management with Depleting Groundwater. Management Science, 31(4)422-434.

Texas Alliance for Water Conservation. 2011. When Water Determines your Success. Observed Cotton, Grain Sorghum and Grain Corn Fields in the Texas High Plains, 2005-2011. Available online at: http://www.depts.ttu.edu/tawc/documents/Water_determines%20success.pdf Verified on Oct. 08, 2012.

Economics of Crop Insurance and Variability of Yields and Groundwater use from Irrigated Corn vs. Grain Sorghum with Center Pivot or Subsurface Drip Systems

Final Report to OWRRI at Oklahoma State University

April 20, 2016

By

Dr. Art Stoecker, Associate Professor, Department of Agricultural Economics, Oklahoma State University, Stillwater, OK 74078
Brooke Lane, Undergraduate Assistant, Department of Agricultural Economics, Oklahoma State University, Stillwater, OK, 74078
Karthik Ramaswamy, Graduate Research Assistant, Department of Agricultural Economics, Oklahoma State University, Stillwater, OK 74078
Dr. Jason Warren, Associate Professor, Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK 74078
Dr. Rodney Jones, Professor, Department of Agricultural Economics, Oklahoma State University, Stillwater, OK 74078

Report Summary

The report is divided into two chapters. The first chapter is a senior honors thesis by Ms. Lane who has been working with the project over the past two years. The report from the previous year (Stoecker, et al., 2015) showed that adoption of grain sorghum would greatly increase the benefits producers could gain from the remaining groundwater. That report did not consider the role of crop insurance (which is required by many lenders) in making the transition from irrigated corn to irrigated sorghum more difficult and expensive than previously assumed. Ms. Lane discussed how the lack of a yield history in producing grain sorghum does force producers to use transitional yields (T-yields) until a yield history can be established. Ms. Lane finds T-yields for grain sorghum in Texas County are significantly lower than the variety trials for grain sorghum while T-yields for irrigated corn are similar to both producer yields and variety trial yields for irrigated corn. Because the T-yields for sorghum are much lower than yields that can be reasonable expected with current technology, the additional insurance cost for grain sorghum deters its adoption. This is an impediment to being able to implement previous results that showed the conversion from irrigated corn to grain sorghum would greatly increase long term discounted profits from the remaining ground water supply.

The second chapter of the report contains a tabular and graphical analysis of the variability of yields and water use by irrigated corn and grain sorghum under well capacities of 600, 500, 400, 300, 200, and 100 GPM in combination of different levels deficit irrigation. The analysis is for both center pivot and subsurface drip irrigation systems. One notable feature is that while both yields and water use decline with reduced water availability, the range of yields and water use does expand but the bulk of the observations as measured by quartiles or standard deviations does not increase and in many cases decreases. The means that long term planning models remain viable.

The analysis of optimal investment and crop choice under stochastic conditions in in process but has not been finished by the time of this report. Preliminary results however support the findings reported using deterministic mixed integer programming

CHAPTER 1

Crop Insurance Limitation to Adoption of Irrigated Grain Sorghum

(Honors Thesis in Progress)

By:

Brooke Lane

Honors Director: Art Stoecker

Second Reader- Rodney Jones

Introduction

The area of concern is the three counties in the Oklahoma Panhandle, Beaver, Cimarron, and Texas. The water table in the Ogallala aquifer which lies under the Panhandle is declining significantly over time. Due to high levels of irrigation, USGS found that the water-level has declined 100 feet under Texas County between 1940 and 1990. (USGS, 2014). It was estimated that if the water-level declined at the same rate as it did in 1996 it would decrease another 25 feet under Texas County by 2020 (Luckey, 2000).

In effort to determine how producers can gain the maximum value from the remaining groundwater, studies have been conducted to compare the value in producing corn compared to the value in producing grain sorghum. According to one model, the net present value of growing sorghum using center pivot irrigation on 160 acres over 30 years with a discount rate of four percent and grain sorghum price of $4.16 per bushel is $106,607. In this instance irrigation occurred when the soil moisture was .6 for the first 13 years and .5 for years 14 and 15. Starting in year 16 all dryland was produced because the estimated 1680 available acre feet of water a producer would have, was depleted. Corn was not grown in this model because the crop that would produce the maximum net present value was chosen each year. With a corn price if $4.48 per bushel, grain sorghum at $4.18 per bushel has the bigger net present value over the 30 year span. When analyzed using a grain sorghum price of $5.09 and a corn price of $5.48, the water supply isn't depleted until year 24. Over the 24 years corn was grown is years 15 through 17, the three years following the purchase of a new center pivot (Stoecker et al., 2015).

According to other research done at Oklahoma State, at irrigation capacities less than $45_{\text{LPM ha}}{}^{-1}$ sorghum yields are similar to those of corn, making it advantageous to grow sorghum because sorghum production costs are less than corn's. The study also found that water use efficiency was high for sorghum (Warren, 2014).

Even though sorghum maximizes returns over the long-run, more irrigated corn is grown in the panhandle region than irrigated sorghum. Table 1.1 and Figure 1.1 below illustrate the number of acres of each crop planted in each county and a total for all three counties. Since 1997 there have generally been more acres of corn grown than sorghum in Texas County. However there have been more total acres of sorghum grown in Beaver and Cimarron and in the Panhandle region as a whole.

Table 1.1. The average number of acres planted of corn and irrigated grain sorghum from 1989-2014 in Beaver, Cimarron, and Texas counties.

	Average Number of Irrigated Acres Planted					
	BEAVER		CIMARRON		TEXAS	
	Corn	Sorghum	Corn	Sorghum	Corn	Sorghum
1989-2008	5,763	5,989	24,842	11,667	77,330	19,905

Figure 1.2 illustrates the number of irrigated grain sorghum acres planted in the three counties compared with the number of acres of corn planted. Producers using irrigation have planted more corn since 1989 than they have grain sorghum in the Panhandle region. Because sorghum maximizes long-run returns it would be most beneficial for producers to adopt more grain sorghum acres in order to maximize returns from the diminishing aquifer. According to (Warren et al., 2016), the process for producers to obtain crop insurance on for a crop they have not previously produced is preventing producers from switching from corn to grain sorghum.

Figure 1.1. The number of acres of corn and grain sorghum planted in Beaver, Cimarron, and Texas counties, and the sum of acres planted between the three counties, from 1989-2014.

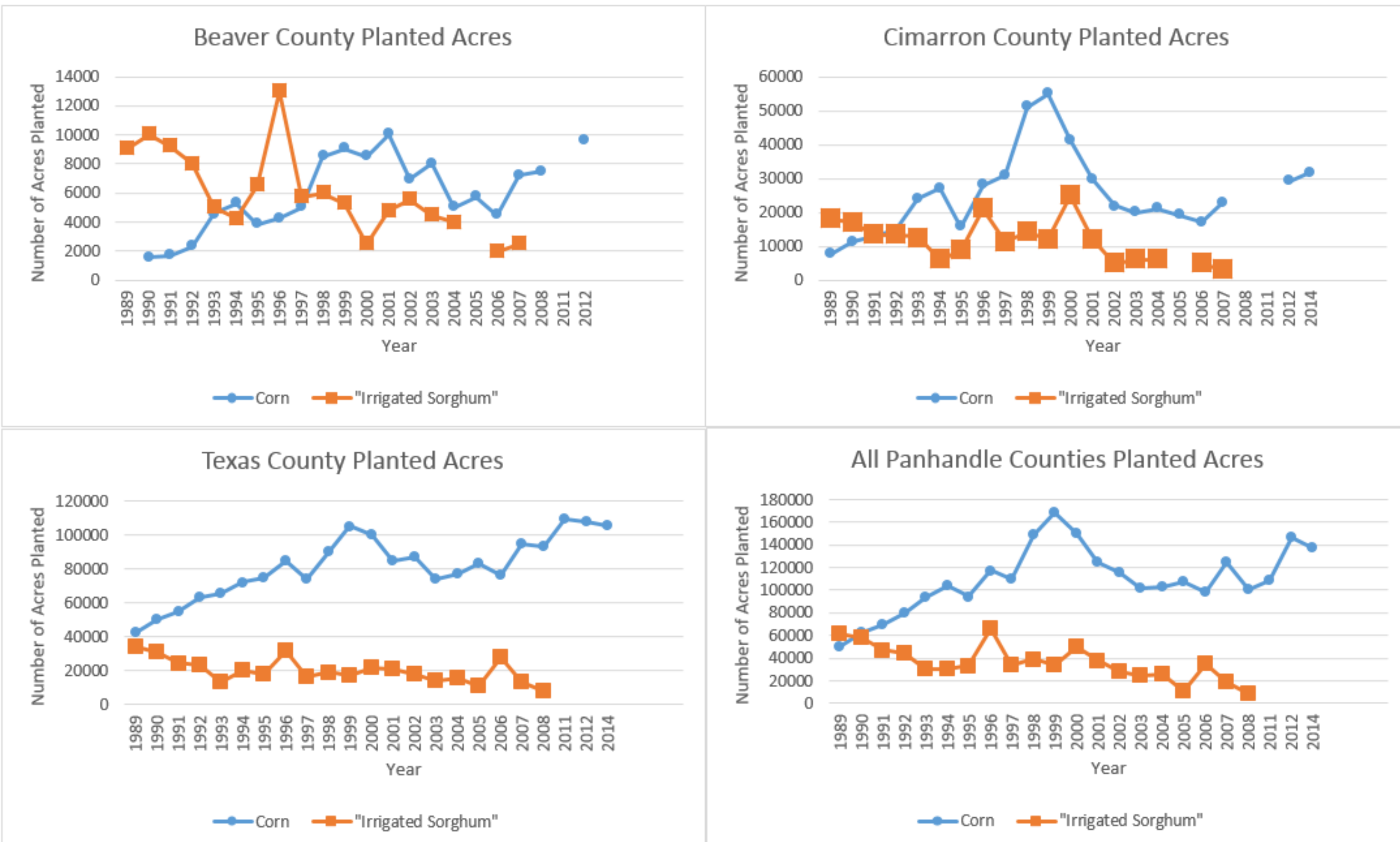
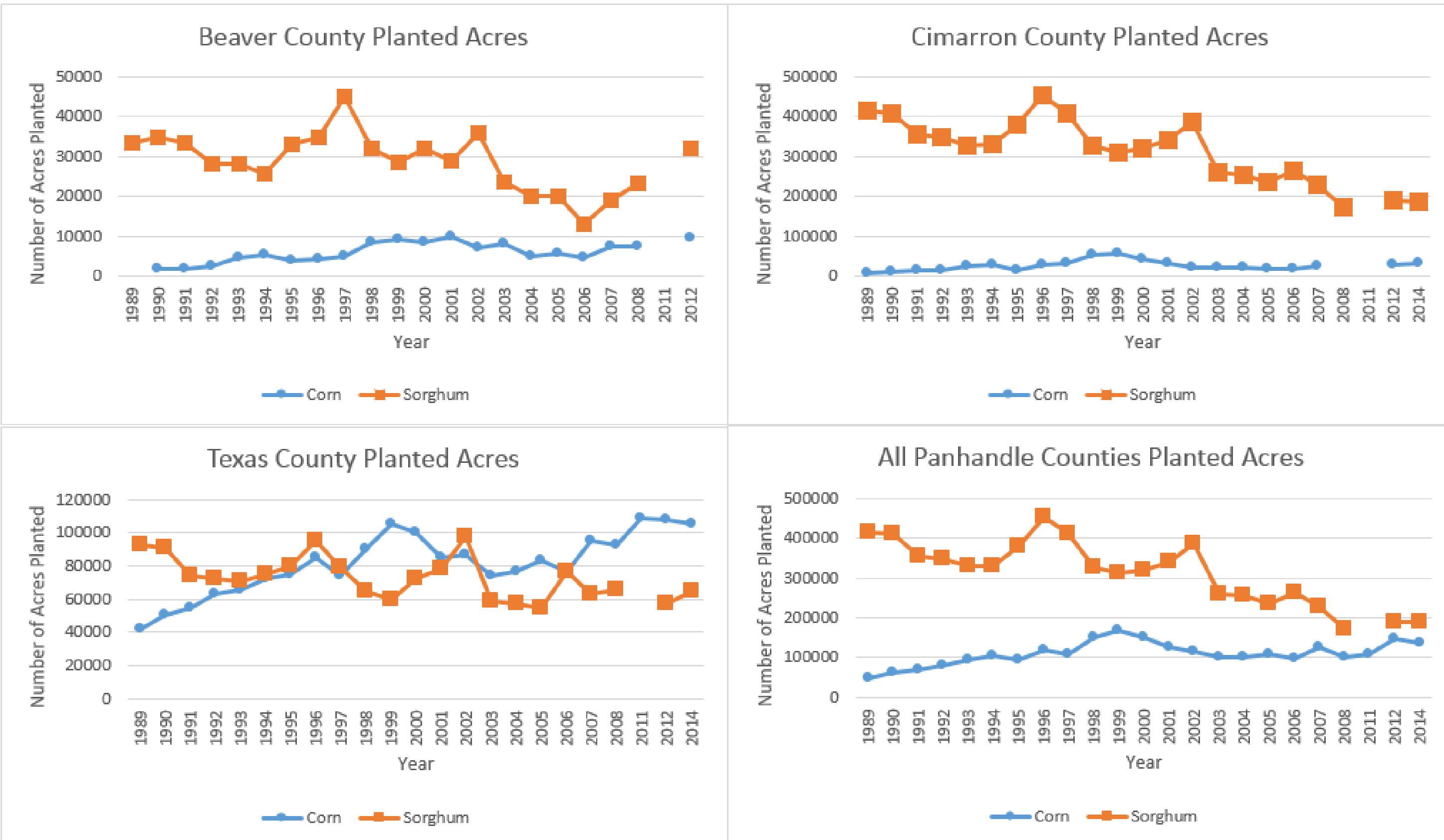


Figure 1.2. The number of acres of corn and irrigated grain sorghum planted in Beaver, Cimarron, and Texas counties, and the sum of acres planted between the three counties, from 1989-2014.



Purpose

The purpose of this research is to evaluate the number of grain sorghum and corn acres grown in Oklahoma as well as the county yield history used to calculate crop insurance payments, to determine if the yield average and crop insurance availability could affect the crop production decision.

Objectives

Determine if:

- There is a difference in availability for crop insurance for corn and for grain sorghum.
- Historical yield data, used to determine crop insurance protection, impacts the decision of which crop to plant if the choice is between two crops, corn and grain sorghum

Hypothesis

Transitional yields, yields used in the place of actual production historic yields as determined by the Federal Crop Insurance Corporation (FCIC), are not reflective of possible yields for grain sorghum, making it a limiting factor in why producers are hesitant to switch from producing corn to sorghum in the Oklahoma panhandle, even though sorghum holds more economic value.

Crop Insurance

Crop insurance is purchased by farmers as a risk management tool in the case of a natural disaster causing crop loss. Crop insurance is a widely used tool because many banks require it before a producer can get an operating loan. There are two types of crop insurance available; federal crop insurance, and private crop insurance products.

Private insurance companies provide Crop-Hail insurance which covers losses from against hail, and in most cases, fire, lightening, vandalism, and upset during transit. Crop-Hail insurance can be purchased at any time during the growing season. Farmers choose the amount of coverage they wish to receive up to a per acre limit established by the insurance company. Crop-Hail insurance is not subsidized or government regulated. In Oklahoma $95 million was spent on Crop-Hail insurance during 2014 (Shields, 2015).

Federal crop insurance is regulated by the Federal Crop Insurance Corporation (FCIC) which is ran by the Risk Management Agency (RMA) of the United States Department of Agriculture (USDA). The FCIC insures approximately 130 crops against yield or revenue loss. Under federal crop insurance, crops are insured against hail, drought, floods, and other natural disasters, as well as against sudden decline in the price of the commodity. This type of insurance is known as multi-peril crop insurance (MPCI). There are specific dates set for each crop by which the insurance must be purchased, and other date at which acreage must be reported by the insured.

MPCI guarantees levels of yield and price based on historical data. There are different levels of coverage that the producer may choose. As coverage increases, so does the cost of the insurance premium. The FCIC pays out an average of 62% of premiums, but in cases of major disaster can pay as much as 100%. Once a producer files a claim form, they generally receive their crop loss check within one month. The USDA determines what crops are covered by insurance policies for each county (Shields, 2015).

There are two main types of MPCI coverage, yield-based and revenue-based. Yield based insurance is based on a four to ten year average of a producers actual crop yield history. Price is based on current market conditions. Producers determine the percentage of their approved mean yield, can include T-yields if a new producer or use their own production history, and price at which they wish to insure the yield. Revenue based insurance involves an assignment of a revenue target based on yield history and current market prices and conditions. Producers insured using revenue-based insurance can receive an indemnity if their revenues are lower than the target regardless of whether the loss was caused by low yields or low prices (Shields, 2015).

There are several different types of yield and revenue based policies. Actual Production History (APH) policies are yield based policies that allow producers to select between 55 and 85 percent of their average yield and 55 to 100 percent of predicted price to insure. Actual Revenue History (ARH) is a revenue based policy that is similar to APH but uses revenues as opposed to yields. Adjusted Gross Revenue (AGR) is a revenue based policy that insures the whole farm, instead of an individual crop, using tax returns and revenue histories. Area Risk Protection Insurance (ARPI) provides coverage based on historical county data as opposed to producer histories. Indemnities are paid when the county yield falls below a trigger level that is selected by the farmer. Dollar Plan (DP) policies use the cost of growing the crops in the area to determine the amount of insurance provided. Group Risk Plan (GRP) policies are yield based but use historical county data instead of individual producer histories. GRP only pays a premium if there is widespread loss. An individual producer may have losses but not get an indemnity if the county losses did not fall below the trigger. Producers can insure up to 90 percent of their acres under GRP. Group Risk Income Protection (GRIP) works the same was as GRP but is revenue based as opposed to yield based. Crop Revenue Coverage (CRC) is revenue protection that pays for losses below the guarantee at the higher of an early-season price or the harvest price. Revenue protection policies are revenue based policies that allow 50 to 85 percent of yields and 100 percent of projected prices to be insured. Yield Protection works like APH but allows for 55 to 100 percent of projected prices to be insured.

When an actual production history is not available transitional yields (T-yields) are used. T-yields are determined for each crop by each county. T-yields are calculated by using the simple average of all approved actual production history yields for the same crop, production practices, and county (Ackerman, 2001). T-yields are calculated based on different production practices. Irrigated, dryland, and organic practices all have different T-yields. The RMA does not use NASS or FSA yields in their calculations. After a county T-yield is approved, the amount that can be insured is based upon the number of years a producer has of APH history. T-yields are only used to fill in the years where APH is not available. The T-yield calculation method is shown in Table 1.2.

Table 1.2. Method using T-yields to calculate the producers' insurable yield[1].

Number of Years Crop Has Been Produced	Percent of T-Yield	Number of APH Years
0	65%	0
1	80%	1
2	90%	2
3	100%	3

In addition to the main policies, there are also endorsements and options available as supplemental coverage for some crops. Catastrophic Risk Protection Endorsement (CAT Coverage) is the most basic level of crop insurance and gives the least amount of coverage. A producer forgoes CAT coverage to purchase the other APH policies that offer additional coverage. CAT coverage is completely subsidized by the federal government and therefore only costs producers a $300 administration fee. Under CAT coverage producers can receive a

[1] For example if a producer has zero years of production history and the county average yield (T-yield) is 100 bushels, then the producer can insure up to 65 bushels per acre. If a producer has three years of production history with average yields being 110 bushels per acre then he can insure 107.5 bushels per acre ((110*3+100)/4).

government paid indemnity on yield losses greater than 50% of the producer's insured yield and 55% of the RMA determined price. CAT coverage participation is declining and in 2014 out of all insured acres in the U.S., only approximately 5% were insured using CAT coverage (Shields, 2015).

In an effort to increase the adoption of MPCI, the FCIC started subsidizing crop insurance rates in 1980. The subsidies on insurance premiums have increased in recent years. The subsidized rates decrease the price of crop insurance for farmers significantly making it more attractive as a low cost risk management tool (O'Donoghue, 2014). Government subsidies cover an average of 65% of the cost of crop insurance policies (Shields, 2015).

Two new programs have been introduced by the 2014 farm bill, Supplemental Coverage Option (SCO) and Stacked Income Protection Plan (STAX). STAX is only available to upland cotton producers (Coble, 2014). SCO is available as supplemental coverage option for barley, corn, soybeans, wheat, sorghum, cotton, and rice. The federal government covers 65% of SCO costs. SCO works similar to the other crop insurance policies, except that an indemnity is paid if the county has a loss as opposed to on an individual bases. This means that there may be cases where a producer gets one payment but not the other. STAX works similarly except that the government covers 80% of the costs.

Because of the high volatility of the agricultural industry, risk management is major concern to many farmers. The government adapted federal crop insurance as a tool to manage risk to ensure that farmers can control losses and therefore continue producing. Crop producers in Oklahoma use crop insurance commonly. Seven million acres of Oklahoma crop land were covered by crop insurance in 2015. Of these acres 270,937 were corn and 272,799 were grain sorghum. 2014 MPCI covered over $1 billion in Oklahoma (RMA, 2015).

Problem

County T-yields used to calculate crop insurance coverage do not accurately represent what irrigated grain sorghum can produce in Beaver, Texas, and Cimarron counties. Paired comparison t-tests were ran using SAS 9.4 to compare the difference between T-yields and variety trial yields and T-yields and NASS county average yields for sorghum and corn were conducted for each county. A t-test was used to evaluate if there was significant difference between the difference between T-yields and variety trial yields for sorghum and corn. The results are summarized in Table 1.3. Corn T-yields are more representative of actual production yields than are irrigated sorghum yields. This is illustrated in Figure 1.3. For grain sorghum county average yields are well under the variety trial averages every year while the corn county averages and variety trial averages more closely follow each other. It is important to note more grain sorghum is grown in the area, even so there is a discrepancy between T-yields and variety trial yields. The T-yields from corn from 2001-2014 have averaged 81% of the variety trial yields and 76% of the NASS county average yields. The T-yields for sorghum from 2001-2014 have averaged 54% of the variety trial yields and 92% of the NASS county average yields.

Table 1.3. Paired Comparison showing the mean difference between T-yield vs. Variety Trial yields and NASS yields for corn and grain sorghum. The third section shows the difference in the differences between each of the yields for sorghum vs. corn.

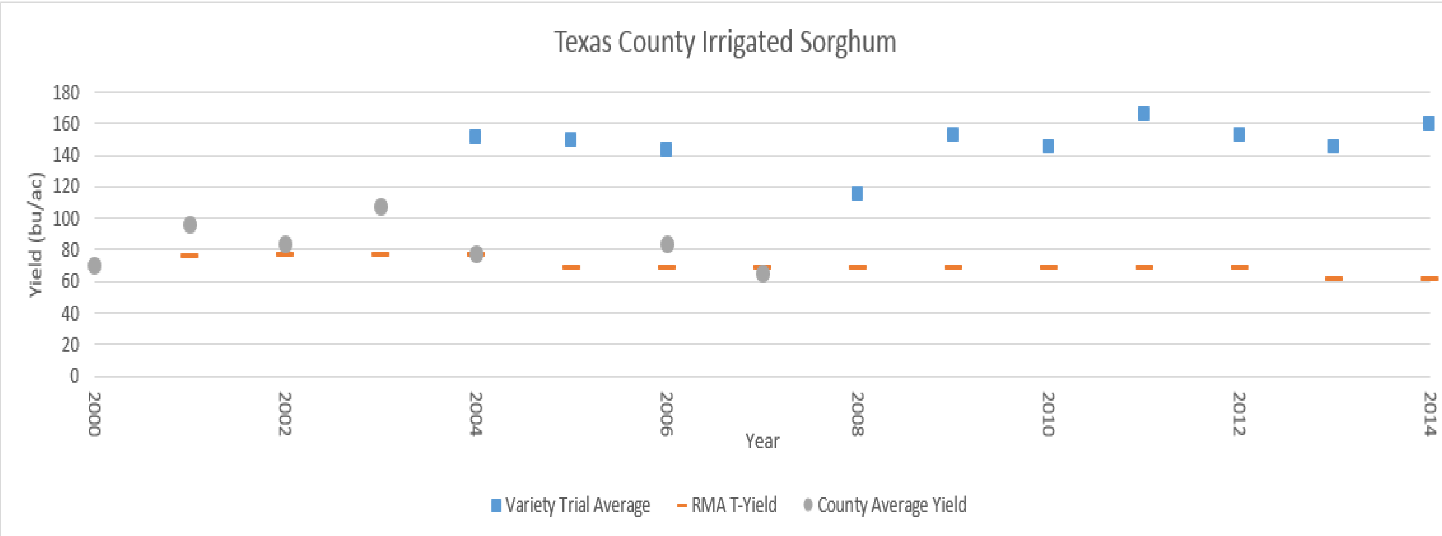
	Sorghum						
	Mean	95% CL	Mean	Std Dev	95% CL	Std Dev	t Value
T-yield vs. Variety Trial	-68.1	-79.847	-56.354	15.2816	10.3221	29.2761	-13.37
T-yield vs. NASS	-45.691	-71.795	-19.587	38.8569	27.15	68.1913	-3.9

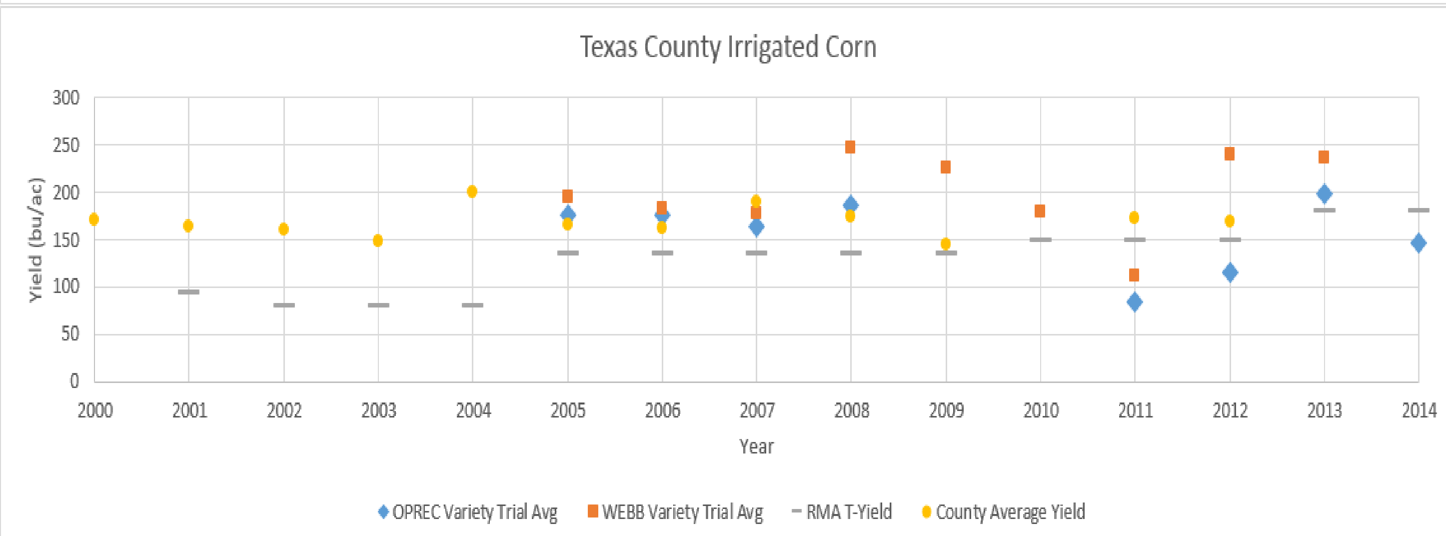
	Corn						
	Mean	95% CL	Mean	Std Dev	95% CL	Std Dev	t Value
T-yield vs. Variety Trial	3.4286	-39.061	45.9182	45.9423	29.6049	101.2	0.2
T-yield vs. NASS	-9.725	-18.302	-1.1485	10.2588	6.7828	20.8794	-2.68

	Sorghum Difference vs. Corn Difference						
	Mean	95% CL	Mean	Std Dev	95% CL	Std Dev	t Value
T-yield vs. Variety Trial	-71.7	-103.5	-39.947	34.333	22.1239	75.6035	-5.53
T-yield vs. NASS	52.125	29.7652	74.4848	26.7456	17.6835	54.4345	5.51

The difference in mean T-yield from the sorghum variety trial mean and the sorghum NASS mean is almost nine and five times as great as that of corn. It is also obvious from comparing the differences that corn T-yields are much more representative of the actual production ability of the crops. For grain sorghum the t-value for T-yield vs. variety trial was -13.37 which is significant at less than 1.0% proving that variety trial yields are much higher than T-yields. For corn T-yield vs. variety trial yield there was not a significant difference with a t-value of 0.2 significant at 85%. The difference between the T-yield and NASS yields had a t-value of -3.9 significant at 0.3% showing that NASS yields are also significantly higher than county T-yields. The same was true for corn with a t-value of -2.68 with a p-value of 3.2%. The differences between T-yields and variety trial yields for the two crops has a p-value of 0.01% showing that there is a greater difference between the sorghum yields than the corn.

Figure 1.3. Average county T-yields, NASS county average yields and the average variety trial yields for Texas County.





NASS county average yields closely follow T-yields for sorghum, but both are below the variety trial yields. It is important to note that county average yields for corn are still slightly higher than variety trial yields most years. This shows that producers are able to get higher yields in this area on average. Once a production history is built their crop insurance coverage will be higher than when county T-yields are used. It is realistic to assume that if more producers grew grain sorghum using efficient production practices then they would also outperform the variety trials and therefore have even more coverage.

When making the production decision between corn and grain sorghum, for a first time producer, or for a producer who might switch from corn to grain sorghum, if the producer wants risk protection may be more likely to choose corn because they can insure their crop using more accurate yields. County T-yields which will be used for a new producer with no production history do not accurately reflect the growing potential of grain sorghum.

Crop Insurance Availability and Policies Sold

Before looking further into if crop insurance is factor in the adoption of grain sorghum, it is important to look at how often an indemnity is being paid to purchasers. Out of all the policies sold in the three Panhandle counties from 1989-2015, there have only been 7 years that there was a policy that didn’t pay an indemnity. The percent of indemnities paid in relation to the number of policies sold are illustrated in Tables 1.4 through 1.9. Because insurance indemnities are paid so often, crop insurance could be a factor in the production decision between corn and grain sorghum.

Table 1.4. The percent of policies sold on which an indemnity was paid for Beaver County corn policies from 1994-2014. Blanks indicate that no policies were sold.

	Percent of Policies Sold on which a Indemnity was Paid				
	Beaver County Corn Policies				
Year	APH	CRC	RA	RP	YP
1994	75%				
1995	80%				
1996	71%				
1997	62%	100%			
1998	72%	83%			
1999	73%	71%			
2000	82%	100%			
2001	56%	50%			
2002	20%	44%	100%		
2003	21%	24%	75%		
2004	39%	50%	100%		
2005	39%	38%	63%		
2006	40%	44%	40%		
2007	53%	56%	80%		
2008	56%	36%	75%		
2009	55%	58%	60%		
2010	59%	62%	75%		
2011				61%	72%
2012				35%	54%
2013				52%	38%
2014				46%	55%

Table 1.5. The percent of policies sold on which an indemnity was paid for Beaver County sorghum policies from 1989-2015. Blanks indicate that no policies were sold.

	Percent of Policies Sold on which a Indemnity was Paid Beaver County Sorghum Policies					
Year	APH	CRC	RP	SCOR	SCOY	YP
1989	98%					
1990	44%					
1991	76%					
1992	75%					
1993	61%					
1994	51%					
1995	85%					
1996	67%					
1997	61%	80%				
1998	50%	64%				
1999	57%	56%				
2000	61%	60%				
2001	55%	71%				
2002	54%	66%				
2003	34%	47%				
2004	28%	51%				
2005	25%	42%				
2006	22%	32%				
2007	26%	39%				
2008	32%	39%				
2009	33%	43%				
2010	43%	50%				
2011			61%			39%
2012			53%			48%
2013			60%			49%
2014			54%			48%
2015			47%	45%	0%	41%

Table 1.6. The percent of policies sold on which an indemnity was paid for Cimarron County corn policies from 1989-2015. Blanks indicate that no policies were sold.

	Percent of Policies Sold on which a Indemnity was Paid Cimarron County Corn Policies						
Year	APH	CRC	GRIP	RA	RP	YP	
1989	88%						
1990	59%						
1991	75%						
1992	58%						
1993	88%						
1994	62%						
1995	87%						
1996	67%						
1997	70%	78%					
1998	72%	72%					
1999	78%	70%					
2000	73%	48%					
2001	55%	55%					
2002	59%	61%		100%			
2003	52%	46%		63%			
2004	52%	57%		55%			
2005	50%	50%		44%			
2006	34%	32%	57%	50%			
2007	57%	49%	33%	22%			
2008	41%	52%	67%	34%			
2009	51%	47%	100%	36%			
2010	44%	52%		37%			
2011					57%		45%
2012					52%		43%
2013					53%		39%
2014					39%		40%
2015					41%		50%

Table 1.7. The percent of policies sold on which an indemnity was paid for Cimarron County sorghum policies from 1989-2015. Blanks indicate that no policies were sold.

	Percent of Policies Sold on which a Indemnity was Paid Cimarron County Sorghum Policies				
Year	APH	CRC	GRIP	RP	YP
1989	98%				
1990	82%				
1991	84%				
1992	86%				
1993	95%				
1994	75%				
1995	82%				
1996	81%				
1997	69%	94%			
1998	65%	82%			
1999	70%	80%			
2000	73%	78%			
2001	63%	78%			
2002	70%	86%			
2003	65%	57%			
2004	62%	63%			
2005	53%	48%	100%		
2006	47%	58%	29%		
2007	45%	46%	100%		
2008	45%	58%			
2009	24%	32%			
2010	26%	32%			
2011				61%	43%
2012				26%	16%
2013				48%	30%
2014				32%	22%
2015				29%	29%

Table 1.8. The percent of policies sold on which an indemnity was paid for Texas County corn policies from 1989-2015. Blanks indicate that no policies were sold.

	Percent of Policies Sold on which a Indemnity was Paid Texas County Corn Policies					
Year	APH	CRC	RP	SCOR	SCOY	YP
1989	98%					
1990	83%					
1991	91%					
1992	93%					
1993	96%					
1994	97%					
1995	95%					
1996	84%					
1997	75%	83%				
1998	81%	88%				
1999	73%	87%				
2000	76%	90%				
2001	57%	79%				
2002	64%	74%		70%		
2003	53%	58%		73%		
2004	61%	71%		75%		
2005	56%	64%		59%		
2006	53%	66%	56%	50%		
2007	61%	74%	100%	77%		
2008	59%	61%	100%	76%		
2009	64%	70%		61%		
2010	70%	69%		67%		
2011					69%	69%
2012					69%	68%
2013					66%	68%
2014					66%	65%
2015					63%	68%

Table 1.9. The percent of policies sold on which an indemnity was paid for Texas County sorghum policies from 1990-2015. Blanks indicate that no policies were sold.

	Percent of Policies Sold on which a Indemnity was Paid Texas County Sorghum Policies							
Year	APH	CRC	GRIP	RP	RPHPE	SCOR	SCOY	YP
1990	54%							
1991	67%							
1992	76%							
1993	66%							
1994	65%							
1995	85%							
1996	71%							
1997	60%	69%						
1998	50%	43%						
1999	52%	55%						
2000	58%	59%						
2001	50%	74%						
2002	51%	75%						
2003	37%	52%						
2004	37%	50%						
2005	36%	47%						
2006	36%	52%	67%					
2007	37%	51%	0%					
2008	41%	50%	0%					
2009	33%	40%						
2010	46%	51%						
2011				58%				46%
2012				46%				27%
2013				53%	0%			35%
2014				48%	0%			36%
2015				49%	0%	0%	67%	48%

Tables 1.4 through 1.9 show the percent of policies sold for corn and grain sorghum in Beaver, Cimarron, and Texas counties on which a premium was paid.

Tables 1.4 through 1.9 also show that availability is not a factor. There are only two cases where crop insurance for irrigated crops was available for one crop but not the other, in Beaver county sorghum insurance was available five years before corn, and in Texas county corn crop insurance was available one year before sorghum. There are also a few years where supplemental programs for sorghum were available that were not an option for corn. Crop insurance for dryland corn is not available in the region, but is available for grain sorghum.

The percent of policies on which an indemnity was paid, was compared using a paired comparison for corn and grain sorghum policies in each county. This comparison used the data in Tables 1.4 through 1.9. The SAS results are in Table 1.10.

Table 1.10. Paired comparison results for each crop insurance policy for corn and

	Beaver County						
	Mean	95% CL	Mean	Std Dev	95% CL	Std Dev	t Value
Yield Protection	0.0875	-0.2014	0.3764	0.1815	0.1028	0.6769	0.96
Revenue Protection	-0.085	-0.2023	0.0323	0.0737	0.0418	0.2748	-2.31
Crop Revenue Coverage	0.0543	-0.0526	0.1612	0.1851	0.1342	0.2982	1.1
Actual Production History	0.0994	0.0168	0.182	0.1607	0.1197	0.2445	2.55

	Cimarron County						
	Mean	95% CL	Mean	Std Dev	95% CL	Std Dev	t Value
Yield Protection	0.154	0.0309	0.2771	0.0991	0.0594	0.2849	3.47
Revenue Protection	0.092	-0.045	0.229	0.1103	0.0661	0.317	1.86
Crop Revenue Coverage	-0.0879	-0.1746	-0.0011	0.1503	0.109	0.2421	-2.19
Actual Production History	-0.04	-0.0976	0.0176	0.1298	0.0999	0.1855	-1.45

	Texas County						
	Mean	95% CL	Mean	Std Dev	95% CL	Std Dev	t Value
Yield Protection	0.292	0.1887	0.3953	0.0832	0.0498	0.239	7.85
Crop Revenue Coverage	0.19	0.1181	0.2619	0.1245	0.0902	0.2005	5.71
Actual Production History	0.2067	0.1736	0.2398	0.0727	0.0556	0.105	13.03

Table 1.10. Illustrates that more corn policies are paid on than grain sorghum. The comparison compared the difference between the percentage of policies that paid an indemnity

for corn and the percentage for grain sorghum. Negative values indicate that more indemnities were paid on sorghum than on corn. For Beaver County the RP policies were significant at 10% and the APH policies were significant at 2%. For Cimarron County, YP and CRC were significant at less than 5% and RP and APH were significant at 10%. For Texas County all were significant at less than 1%. This is expected to be especially true as the water table declines, because corn is much more sensitive to changes in water. The less irrigation that occurs decreasing corn yields more than it decreases sorghum yields. The difference in change in yield increases as less water is applied (Stoecker et al., 2015).

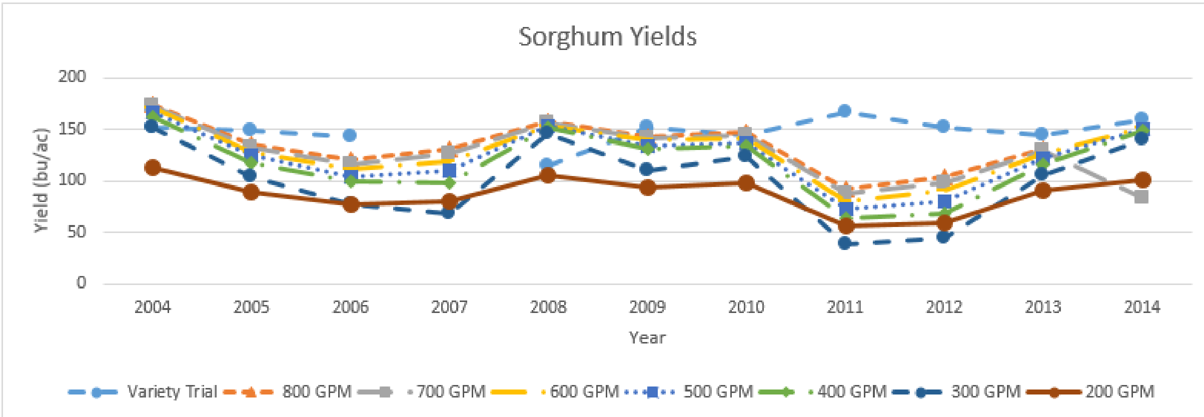
Texas County for different capacities and soil moisture triggers was used to determine variability from fifty years of daily weather data and thirty year periods for the area. The model used a fifty year weather data set, enterprise budgets, but assumed today’s technology and production practices. The simulation applied 36 mm after a soil moisture trigger was hit (Stoecker et al., 2015). The simulated cumulative average yields from under 1970 to 2014 weather at different well capacities and soil moisture triggers for corn and grain sorghum are in Tables 1.11 and 1.12. Figure 1.4 shows the variety trial data in comparison with the averages simulated yields at each well capacity. The simulation model missed the 2011 upturn, but closely followed the trends in the variety trail data.

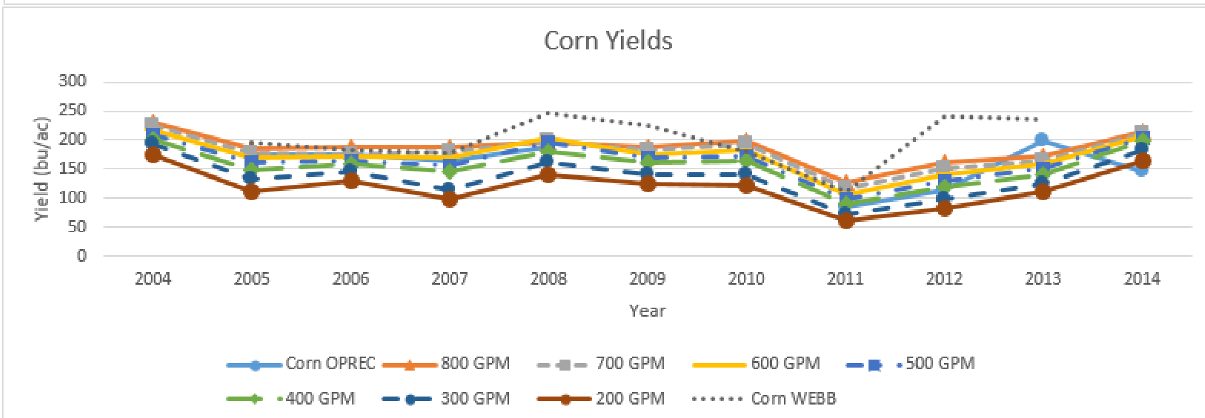
Tables 1.11 and 1.12 show the average yield for corn and grain sorghum from the EPIC simulation model (Lane, 2016).

	Corn Average Yield (bu/ac) from 1970-2014						
Well Capacity	Stress Level						
GPM	0.3	0.4	0.5	0.6	0.7	0.8	0.9
800	159	163	167	181	194	206	213
700	158	162	165	176	186	195	199
600	157	160	163	171	177	183	187
500	154	156	158	162	168	172	175
400	148	150	152	155	158	161	164
300	134	135	137	138	139	141	143
200	117	118	119	119	120	121	122
Overall Average	147	149	152	157	163	169	172

	Sorghum Average Yield (bu/ac) from 1970-2014						
Well Capacity	Stress Level						
GPM	0.3	0.4	0.5	0.6	0.7	0.8	0.9
800	119	122	126	136	145	153	159
700	122	125	129	137	142	148	152
600	122	125	128	134	140	145	148
500	121	123	126	130	134	138	141
400	117	120	122	125	129	131	134
300	105	107	109	110	112	115	117
200	88	89	90	90	91	91	92
Overall Average	114	116	119	123	128	131	135

Figure 1.4. The average simulated yields at different well capacities and the variety trial yield data for Texas County.





The simulated yields were used to estimate the amount of time an indemnity would be paid on a 100 acre farm in the Panhandle. The results are in Table 1.13 below. Seventy bushels per acre is the average T-yield for irrigated grain sorghum and 150 bushels per acre is the average variety trial yield at OPREC from year to year (Oklahoma State Variety Trials). The yield triggers are the levels each producer decides to cover his crops at when purchasing the crop insurance policy.

Table 1.13. The average percent of time an indemnity would be paid at different yield triggers for crop insurance based on simulated irrigated grain sorghum yields using 50 years of weather data for Goodwell . Yields are from a 400 GPM well with a 0.5 trigger.

	Percent of Time an Indeminty is Paid at each Yield Trigger							
Guaranteed Yield	50%	55%	60%	65%	70%	75%	80%	85%
70	11%	13%	17%	17%	17%	24%	26%	26%
80	13%	17%	17%	24%	26%	26%	27%	30%
90	17%	17%	24%	26%	27%	30%	30%	33%
100	17%	24%	26%	27%	30%	30%	33%	37%
110	24%	27%	30%	30%	33%	37%	47%	54%
120	26%	30%	30%	33%	37%	47%	62%	63%
130	27%	30%	33%	37%	54%	62%	63%	67%
140	30%	33%	37%	54%	62%	63%	67%	68%
150	30%	37%	47%	62%	63%	67%	68%	71%

Crop insurance companies pay an average of only 34% of the indemnities on crops with a guaranteed yield of 70 bushels as they do on crops with a guaranteed yield of 150 bushels. If producers were able to insure their crops at their full growing potential, they would have more risk protection than they do at the average T-yield of 70 bushels per acre.

Crop Insurance Cost

In addition to not being able to insure grain sorghum efficiently. The cost per bushel insured of corn is 18% less than that of sorghum in Beaver and Cimarron counties and 20% less in Texas County. The base county rate at a 65% coverage level for each county is presented in Table 1.14. The difference in cost of crop insurance could be an addition factor in why producers are hesitant to switch from corn to grain sorghum production.

Table 1.14. shows the base county rate of crop insurance from irrigated corn and grain sorghum in Beaver, Cimarron, and Texas counties for 2014.

	Base County Rate at 65% Coverage Level Cost Per Bushel Insured	
	Irrigated Corn	Irrigated Grain Sorghum
Beaver	$ 0.013	$ 0.071
Cimarron	$ 0.014	$ 0.080
Texas	$ 0.014	$ 0.065

As coverage increases, the amount of risk held by the producer decreases because their guaranteed yield of revenue increases. Table 1.17 shows the maximum, minimum, and mean net revenue for different coverage levels using yields irrigated with a center pivot with a 400 GPM well for grain sorghum. Net revenue was calculated using the simulated yields times the $4.15 price for grain sorghum set by the RMA this year. The costs used is shown in Table 1.16 (Stoecker et al., 2016). Table 1.15 shows the cost per acre for insuring grain sorghum in Texas County using the 2014 price of $0.81 per bushel. As coverage increases, the amount of risk decreases because you are guaranteed a higher yield. Using the 100% of the year average T-yield of 80 bushels per acre, the net revenue at 400, 500, and 600 GPM wells at different irrigation triggers was calculated. The results are in Tables 1.17 through 1.19. Using the simulated yields and insuring different levels of the 80 bushel T-yield, with a 400 GPM well an indemnity was paid four times. As coverage increased the net revenue decreased because of the higher cost of insurance without paying an indemnity, as illustrated in Table 1. 5. An indemnity was never paid using the other two wells.

Table 1.15. Cost per acre for YP or TP insurance assuming an 80 bu/ac APH yield.

80 bushel T-yield		
Crop Insurance Coverage Level	Number of Insured bushels/acre	Cost per acre
50%	40	$ 16.06
55%	44	$ 19.43
60%	48	$ 23.12
65%	52	$ 27.13
70%	56	$ 31.47
75%	59	$ 36.12
80%	63	$ 41.10
85%	67	$ 46.40

Table 1.16. Estimated costs used in determining net revenue (Stoecker et al., 2016).

GPM		800	700	600	500	400	300	200	100
Yield	(bu/acre)	162.5	154.4	146.1	138.6	130.9	114.2	92.3	88.9
Nitrogen	(lbs/a)	181.2	172.1	162.9	154.5	145.9	127.3	102.8	99.2
Phosphorus	(lbs/a)	29.3	27.8	26.3	25	23.6	20.6	16.6	16
Irrigation (acre inches)		13.6	12	10.6	9.6	8.7	6.9	3.4	2.3
Fertilizer-nitrogen		$99.67	$94.67	$89.59	$85.00	$80.25	$70.04	$56.56	$54.54
Fertilizer-Phosphorus		$15.24	$14.48	$13.70	$12.99	$12.27	$10.71	$8.65	$8.34
Seed Cost		$16.13	$16.13	$16.13	$16.13	$16.13	$16.13	$16.13	$16.13
Herbicide cost		$52.40	$52.40	$52.40	$52.40	$52.40	$52.40	$52.40	$52.40
Insecticide Cost		-	-	-	-	-	-	-	-
Crop Consulting		$6.25	$6.25	$6.25	$6.25	$6.25	$6.25	$6.25	$6.25
Drying ($)		$21.13	$20.07	$18.99	$18.02	$17.01	$14.85	$11.99	$11.56
Miscellaneous		$10.00	$10.00	$10.00	$10.00	$10.00	$10.00	$10.00	$10.00
Custom Hire		$132.39	$128.80	$125.16	$121.87	$118.46	$111.13	$101.47	$100.02
Non Machinery Labor		$18.00	$18.00	$18.00	$18.00	$18.00	$18.00	$18.00	$18.00
Interest Cost		$15.65	$14.94	$14.21	$13.55	$12.87	$11.41	$9.48	$9.19
Irrigation Cost		$78.85	$67.98	$59.32	$52.86	$47.30	$37.40	$18.40	$12.36
		$465.71	$443.72	$423.75	$407.07	$390.94	$358.32	$309.33	$298.79

Table 1.17. Maximum, minimum, and average net revenue using a 400 GPM well at different producer selected insurance coverage levels. If the simulated yield falls below the average T-yield of 80 bu/ac then an indemnity to cover the loss is paid. If no indemnities are paid because the yields never fall below the T-yield then the producer only pays a premium.

400 GPM Well

	Coverage Level- 50%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 368.81	$ 405.60	$ 405.27	$ 403.95	$ 403.95	$ 404.81	$ 422.34
Min	$ (178.62)	$ (174.18)	$ (135.67)	$ (131.96)	$ (130.51)	$ (130.51)	$ (135.47)
Mean	$ 78.02	$ 89.91	$ 100.93	$ 110.18	$ 126.87	$ 138.12	$ 148.16
	Coverage Level- 55%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 365.43	$ 402.23	$ 401.90	$ 400.57	$ 400.57	$ 401.43	$ 418.97
Min	$ (181.99)	$ (177.55)	$ (139.04)	$ (135.33)	$ (133.88)	$ (133.88)	$ (138.84)
Mean	$ 74.65	$ 86.53	$ 97.56	$ 106.81	$ 123.50	$ 134.74	$ 144.79
	Coverage Level- 50%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 361.74	$ 398.54	$ 398.21	$ 396.88	$ 396.88	$ 397.74	$ 415.28
Min	$ (185.68)	$ (181.25)	$ (142.73)	$ (139.03)	$ (137.57)	$ (137.57)	$ (142.53)
Mean	$ 70.96	$ 82.84	$ 93.87	$ 103.12	$ 119.81	$ 131.05	$ 141.09
	Coverage Level- 65%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 357.73	$ 394.52	$ 394.19	$ 392.87	$ 392.87	$ 393.73	$ 411.27
Min	$ (189.69)	$ (185.26)	$ (146.75)	$ (143.04)	$ (141.58)	$ (141.58)	$ (146.55)
Mean	$ 66.94	$ 78.83	$ 89.85	$ 99.10	$ 115.79	$ 127.04	$ 137.08
	Coverage Level- 70%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 353.39	$ 390.19	$ 389.86	$ 388.53	$ 388.53	$ 389.39	$ 406.93
Min	$ (192.08)	$ (189.60)	$ (151.08)	$ (147.37)	$ (145.92)	$ (145.92)	$ (150.88)
Mean	$ 62.65	$ 74.49	$ 85.52	$ 94.77	$ 111.46	$ 122.70	$ 132.75
	Coverage Level- 75%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 348.74	$ 385.53	$ 385.20	$ 383.88	$ 383.88	$ 384.74	$ 402.27
Min	$ (196.74)	$ (194.25)	$ (155.74)	$ (152.03)	$ (150.57)	$ (150.57)	$ (155.54)
Mean	$ 58.00	$ 69.84	$ 80.86	$ 90.11	$ 106.80	$ 118.05	$ 128.09
	Coverage Level- 80%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 343.76	$ 380.55	$ 380.22	$ 378.90	$ 378.90	$ 379.76	$ 397.30
Min	$ (185.26)	$ (185.26)	$ (160.71)	$ (157.01)	$ (155.55)	$ (155.55)	$ (160.51)
Mean	$ 53.38	$ 65.17	$ 75.89	$ 85.14	$ 101.83	$ 113.07	$ 123.11

Table 1.18. Maximum, minimum, and average net revenue using a 500 GPM well. If the simulated yield falls below the average T-yield of 80 bu/ac then an indemnity to cover the loss is paid. If no indemnities are paid because the yields never fall below the T-yield then the producer only pays a premium.

500 GPM Well

	Coverage Level- 50%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 352.68	$ 389.47	$ 389.14	$ 387.88	$ 387.88	$ 388.68	$ 406.41
Min	$ (130.88)	$ (140.41)	$ (140.48)	$ (140.81)	$ (114.47)	$ (114.47)	$ (93.76)
Mean	$ 77.06	$ 89.25	$ 99.57	$ 114.92	$ 133.51	$ 147.57	$ 162.30
	Coverage Level- 55%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 352.68	$ 389.47	$ 389.14	$ 387.88	$ 387.88	$ 388.68	$ 406.41
Min	$ (130.88)	$ (140.41)	$ (140.48)	$ (140.81)	$ (114.47)	$ (114.47)	$ (93.76)
Mean	$ 77.06	$ 89.25	$ 99.57	$ 114.92	$ 133.51	$ 147.57	$ 162.30
	Coverage Level- 50%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 352.68	$ 389.47	$ 389.14	$ 387.88	$ 387.88	$ 388.68	$ 406.41
Min	$ (130.88)	$ (140.41)	$ (140.48)	$ (140.81)	$ (114.47)	$ (114.47)	$ (93.76)
Mean	$ 77.06	$ 89.25	$ 99.57	$ 114.92	$ 133.51	$ 147.57	$ 162.30
	Coverage Level- 65%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 352.68	$ 389.47	$ 389.14	$ 387.88	$ 387.88	$ 388.68	$ 406.41
Min	$ (130.88)	$ (140.41)	$ (140.48)	$ (140.81)	$ (114.47)	$ (114.47)	$ (93.76)
Mean	$ 77.06	$ 89.25	$ 99.57	$ 114.92	$ 133.51	$ 147.57	$ 162.30
	Coverage Level- 70%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 352.68	$ 389.47	$ 389.14	$ 387.88	$ 387.88	$ 388.68	$ 406.41
Min	$ (130.88)	$ (140.41)	$ (140.48)	$ (140.81)	$ (114.47)	$ (114.47)	$ (93.76)
Mean	$ 77.06	$ 89.25	$ 99.57	$ 114.92	$ 133.51	$ 147.57	$ 162.30
	Coverage Level- 75%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 352.68	$ 389.47	$ 389.14	$ 387.88	$ 387.88	$ 388.68	$ 406.41
Min	$ (130.88)	$ (140.41)	$ (140.48)	$ (140.81)	$ (114.47)	$ (114.47)	$ (93.76)
Mean	$ 77.06	$ 89.25	$ 99.57	$ 114.92	$ 133.51	$ 147.57	$ 162.30
	Coverage Level- 80%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 352.68	$ 389.47	$ 389.14	$ 387.88	$ 387.88	$ 388.68	$ 406.41
Min	$ (130.88)	$ (140.41)	$ (140.48)	$ (140.81)	$ (114.47)	$ (114.47)	$ (93.76)
Mean	$ 77.06	$ 89.25	$ 99.57	$ 114.92	$ 133.51	$ 147.57	$ 162.30

Table 1.19. Maximum, minimum, and average net revenue using a 600 GPM well. If the simulated yield falls below the average T-yield of 80 bu/ac then an indemnity to cover the loss is paid. If no indemnities are paid because the yields never fall below the T-yield then the producer only pays a premium.

600 GPM Well

	Coverage Level- 50%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 336.13	$ 372.79	$ 372.53	$ 371.20	$ 371.20	$ 372.06	$ 390.86
Min	$ (156.56)	$ (135.59)	$ (111.76)	$ (104.02)	$ (89.33)	$ (71.26)	$ (64.25)
Mean	$ 67.68	$ 79.57	$ 93.38	$ 116.47	$ 139.67	$ 160.20	$ 176.00
	Coverage Level- 55%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 336.13	$ 372.79	$ 372.53	$ 371.20	$ 371.20	$ 372.06	$ 390.86
Min	$ (156.56)	$ (439.81)	$ (111.76)	$ (104.02)	$ (89.33)	$ (71.26)	$ (64.25)
Mean	$ 67.68	$ 69.04	$ 93.38	$ 116.47	$ 139.67	$ 160.20	$ 176.00
	Coverage Level- 50%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 336.13	$ 372.79	$ 372.53	$ 371.20	$ 371.20	$ 372.06	$ 390.86
Min	$ (156.56)	$ (439.81)	$ (111.76)	$ (104.02)	$ (89.33)	$ (71.26)	$ (64.25)
Mean	$ 67.68	$ 69.04	$ 93.38	$ 116.47	$ 139.67	$ 160.20	$ 176.00
	Coverage Level- 65%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 336.13	$ 372.79	$ 372.53	$ 371.20	$ 371.20	$ 372.06	$ 390.86
Min	$ (156.56)	$ (439.81)	$ (111.76)	$ (104.02)	$ (89.33)	$ (71.26)	$ (64.25)
Mean	$ 67.68	$ 69.04	$ 93.38	$ 116.47	$ 139.67	$ 160.20	$ 176.00
	Coverage Level- 70%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 336.13	$ 372.79	$ 372.53	$ 371.20	$ 371.20	$ 372.06	$ 390.86
Min	$ (156.56)	$ (439.81)	$ (111.76)	$ (104.02)	$ (89.33)	$ (71.26)	$ (64.25)
Mean	$ 67.68	$ 69.04	$ 93.38	$ 116.47	$ 139.67	$ 160.20	$ 176.00
	Coverage Level- 75%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 336.13	$ 372.79	$ 372.53	$ 371.20	$ 371.20	$ 372.06	$ 390.86
Min	$ (156.56)	$ (439.81)	$ (111.76)	$ (104.02)	$ (89.33)	$ (71.26)	$ (64.25)
Mean	$ 67.68	$ 69.04	$ 93.38	$ 116.47	$ 139.67	$ 160.20	$ 176.00
	Coverage Level- 80%						
	Stress Level						
	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Max	$ 336.13	$ 372.79	$ 372.53	$ 371.20	$ 371.20	$ 372.06	$ 390.86
Min	$ (156.56)	$ (439.81)	$ (111.76)	$ (104.02)	$ (89.33)	$ (71.26)	$ (64.25)
Mean	$ 67.68	$ 69.04	$ 93.38	$ 116.47	$ 139.67	$ 160.20	$ 176.00

If the insured yield is changed to 100% of 124 which is the overall average of the simulated yields across all well capacities and irrigation triggers, an indemnity is paid 176 times for the 400 GPM well, 97 times for the 500 GPM well, and 50 times for the 600 GPM well. If grain sorghum is grown at its full potential, you take on less risk of losing money if you do not insure your sorghum using the county T-yields. Once a production history is established crop insurance reduces the risk of loss of money. The net revenues keeping all else the same but not paying for crop insurance are illustrated in Table 1.20.

Table 1.20. Net revenue without crop insurance.

600 GPM Well							
Max	$ 384.86	$ 421.66	$ 421.32	$ 420.00	$ 420.00	$ 420.86	$ 438.40
Min	$(162.56)	$(158.13)	$(119.61)	$(115.91)	$(114.45)	$(114.45)	$(119.41)
Mean	$ 94.08	$ 105.96	$ 116.99	$ 126.24	$ 142.93	$ 154.17	$ 164.21
500 GPM Well							
Max	$ 352.18	$ 388.85	$ 388.58	$ 387.26	$ 387.26	$ 388.12	$ 406.91
Min	$(140.51)	$(119.53)	$ (95.71)	$ (87.96)	$ (73.27)	$ (55.21)	$ (48.19)
Mean	$ 83.73	$ 95.63	$ 109.44	$ 132.52	$ 155.73	$ 176.26	$ 192.06
400 GPM Well							
Max	$ 368.73	$ 405.53	$ 405.19	$ 403.94	$ 403.94	$ 404.73	$ 422.47
Min	$(114.83)	$(124.36)	$(124.43)	$(124.76)	$ (98.42)	$ (98.42)	$ (77.70)
Mean	$ 93.11	$ 105.30	$ 115.63	$ 130.97	$ 149.57	$ 163.63	$ 178.36

Reasons for Low T-yields

There are several factors that play into why T-yields do not accurately represent the growing potential of grain sorghum. These include the T-yield calculations and grain sorghum production practices.

Because T-yields only take into account the yields from APH production histories, all of the acres of grain sorghum produced are not accounted for. The FCIC uses T-yields for uninsured relief policies for corn and grain sorghum determined by the FSA (Crop Insurance Program Models). The FSA uses NASS data when available, however it is supplemented with failed acres data from the RMA. The yield calculation for each year is (NASS county production/(NASS county harvested acres + RMA county failed acres)) (FSA yields). This calculation more accurately represents the yields throughout the whole county. If NASS data was taken into consideration a more accurate representation of county yields would be determined. In addition, NASS doesn't consistently report irrigated and dryland acres separately. From 1971 to 2008 irrigated and non-irrigated acres were reported by NASS every year except for 2005 and 2008. Since 2008 only total acres planted has been reported. This could make it difficult to determine a proper T-yield using NASS data because a distinction between irrigated and dryland is necessary.

In addition to the yield calculations Leon Richards believes that production practices play a major role. He states, "I think the biggest reasons the T-yields are lower than those shown by research is because a portion of grain sorghum is doubled cropped after wheat is harvested or put in behind corn, cotton or some other crop after a hail storm. Therefore the yield is lower due to late planting or use of shorter maturity hybrids which generally have lower yields and these are sometimes caught by a frost which results in low yields or no harvest at all which causes a decline in T-yields. In addition a lot of producers plant their poorest ground to sorghum and also place it on the ground that has the least amount of water and plant corn on the best ground and with the best water. I also think there are cases of when a farmer is in financial trouble and they can't afford the expenses of a corn crop so they plant sorghum hoping to make a little money with less expenses but also in these cases the sorghum is not going to reach its potential because they are trying to cut cost and they short the crop of its needs. These low yields are then used to produce the T-yields for all sorghum even that that is planted to a full or medium maturity hybrid and on the best ground with the best water. There are irrigated producers in the Panhandle producing very good sorghum that actually treat the crop like a crop and fertilize it to its potential and apply the water when it is needed instead of when they have extra water. If the T-yields were divided out according to if it was a full season crop compared to a double cropped or replacement crop would help. The T-yields only influence the plans on irrigated ground because you cannot insure dry land corn in Texas County."

Richards points out several factors as to why T-yields may be so low. The first is that grain sorghum is often double-crop planted which leads to lower yields. The second is that producers often use their best resources to plant corn and do not allow sorghum to reach its full growing potential. In order to factor these problem into the grain sorghum T-yield calculation, variety trial and simulated yields could be used because they capture the full growing potential of sorghum in the area.

Conclusion

Crop insurance is a limiting factor in the adoption of grain sorghum over corn in the panhandle. Although crop insurance availability is not different, county T-yields for grain sorghum do not accurately represent the growing potential of grain sorghum in the Oklahoma Panhandle. Simulated yields and variety trial data more accurately represent what county T-yields should be for producers with a good corn yield history.

References:

Ackerman, Kenneth D. "BULLETIN NO.: MGR-00-019.3." Risk Management Agency. USDA, 31 Dec. 2001. Web. 13 Mar. 2016.

"Code of Federal Regulations." Title 7- Agriculture 6 (2012). Web. 20 Feb. 2016. <https://www.gpo.gov/fdsys/pkg/CFR-2012-title7-vol6/xml/CFR-2012-title7-vol6-part400-subpartG.xml>.

Leon Richards (Grain chairman of the Oklahoma Sorghum Commission and grain sorghum producer) in discussion with the author, March 2016.

Luckey, R.R., N.L.Osborn, M.F. Beker, and W. J. Andrews. 2000. Water Flow in the High Plains Aquifer in Northwestern Oklahoma. USGS Fact Sheet 081-00.

"Oklahoma Crop Variety Trials." Oklahoma Crop Variety Trials. Web. 18 Jan. 2016. <http://croptrials.okstate.edu/>.

O'Donoghue, Erik J. "The Effects of Premium Subsidies on Demand for Crop Insurance." United States Department of Agriculture. Economic Research Service, July 2014. Web. 19 Mar. 2016.

"Oklahoma Water Resources Research Institute Annual Technical Report." USGS. Oklahoma Water Resources Research Institute, 2014. Web. 4 Feb. 2016.

Schnitkey, Gary. "FSA Yields Used in Computing ARC-CO Payments Compared to NASS Yields." Farmdoc Daily. University of Illinois, 1 Dec. 2015. Web. 19 Feb. 2016.

Shields, Dennis A. "Federal Crop Insurance: Background." *Federation of American Scientists*. Congressional Research Service, 13 Aug. 2015. Web. 18 Jan. 2016.

Stoecker, Dr. Art, Karthik Ramaswamy, Dr. Jason Warren, Dr. Rodney Jones, Dr. Jody Campiche, Andrew Paul, and Brooke Lane. "Economic Modeling of Irrigated Corn vs. Grain Sorghum Using Center Pivot or Subsurface Drip Systems." (2015). Web. 18 Apr. 2016

CHAPTER 2 Risk Analysis of Crop Yields and Water Use

The yield data in this report are the same as in the previous report (Stoecker, et al., 2015). The irrigation yield and water use data were from EPIC (Environmental Policy Indicator Calculator) simulation model. As explained in the previous report the EPIC yields were validated against experimental data from the OPREC (Oklahoma Panhandle Research and Extension Center) at Goodwell Oklahoma and from experimental data and variety trials conducted in the Texas Panhandle and at Garden City, Kansas.

The yield simulation followed the experimental design used at OPREC (Warren, 2015) where irrigation frequency was determined by soil moisture levels and by the length of time required to complete a circle with a pivot system. When the producer has a well yield of 300 GPM the minimum days between applications is nearly three times as long as when the well yield is 800 GPM. The minimum days between applications by well capacity following completion of pivot revolution are presented for the readers' convenience in Table 2.1.

Table 2.1 Center Pivot System Irrigation Frequency and Application Rates

	Frequency	Application per Revolution	
GPM	**DAYS**	**inches**	**mm**
800	4	1.42	36
700	5	1.42	36
600	6	1.42	36
500	7	1.42	36
400	8	1.42	36
300	11	1.42	36
200	16	1.42	36
100	32	1.42	36

In addition the ability to practice deficit irrigation to test the economics of prolonging aquifer life was simulated by waiting after completion of an application until the remaining soil moisture declined below a stated percentage from 90 to 30 percent before the next irrigation began. The average application rates on corn are illustrated in below in Table 2.2. Upon completion of a revolution, the simulation model was instructed to wait until the available soil moisture declined to 90 percent, 80 percent, 70 percent, 60 percent, 50 percent, 40 percent, or 30 percent of capacity before beginning the next application. As expected this reduced the total application for each well size except for 200 and 100 GPM wells. For the smaller wells where it required approximately 2 weeks or a month respectively to complete a revolution, the soil moisture was generally below the target level so the simulated pivot operated almost continuously.

Table 2.2. Average Application Rates from Simulated Deficit Irrigation on Corn by Center Pivot with 85 Percent Application Efficiency.

Well Size	Deficit Irrigation Simulated by Delaying Next Irrigation Until Remaining Percent Soil Moisture Declined to						
	30%	40%	50%	60%	70%	80%	90%
GPM	Average Annual Gross Irrigation on Corn (acre inches)						
800	14.6	15.3	16.2	18.8	21.5	22.5	22.5
700	14.6	15.3	16.1	18	20.4	22.1	23.1
600	14.6	15	15.9	17.2	19	20.4	21.6
500	14.1	14.6	15.3	16	17.4	18.6	19.5
400	13.5	13.9	14.4	15	15.9	17	17.6
300	11	11.3	11.8	12.3	12.8	13.4	13.9
200	8.7	8.8	9.1	9.4	9.7	10.1	10.3
100	5.4	5.5	5.7	5.8	5.9	6	6.1

The box and whisker plots in Figures 2.1 and 2.2 used with the yields of irrigated corn and grain sorghum show the quartiles range of yields (25 percent above and 25 percent below the medium yield). As anticipated, there was a steady decline in the respective mean and median corn and sorghum yields as the water table and well capacity decline. With sorghum the greater range in the variability of irrigated yields occurs when well yields were between 500 and 300 GPM. In this range the simulated producer was able to maintain adequate soil moisture during the crucial growing period in some but not all years. When the well yields declined into the 200 and 100 GPM ranges, the producer was able to make an application only once or twice per month respectively. The decline in rainfall during July and August meant the producer had little chance of keeping up with the irrigation demands of the crop. As a result yield are low (though higher than dryland yields). The range of variability for the middle quartiles is also low.

The corn yields show a similar pattern to those of grain sorghum except that there is a greater decline in yield to increases in deficit irrigation for all well capacities and a greater decline as well capacities decline. The box and whisker plots in Figures 2.3 and 2.4 show the quartiles of range of yields for the center pivot irrigated corn. Yields from 100 GPM well with a 120 acre pivot fall into the 90-110 bushel per acre range with some yields with some yields declining into the 50 bushel range. The whisker and standard deviation plots of water use show that with deficit irrigation, the water requirements for corn remained higher than for grain sorghum.

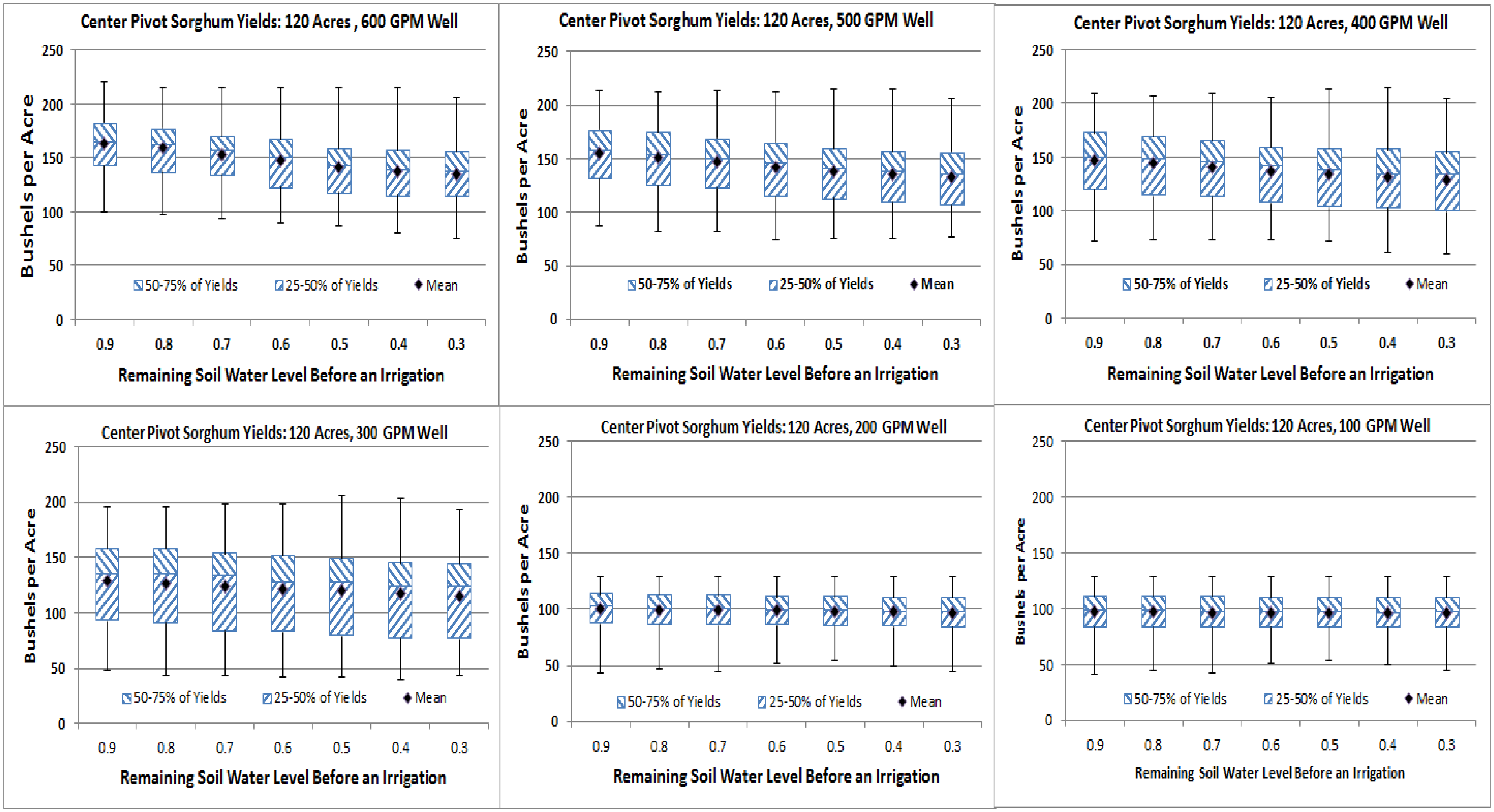


Figure 2.1 Quartile Plots of Grain Sorghum Yields by Well Size and by Remaining Proportion Available Soil Water before an Irrigation was initiated

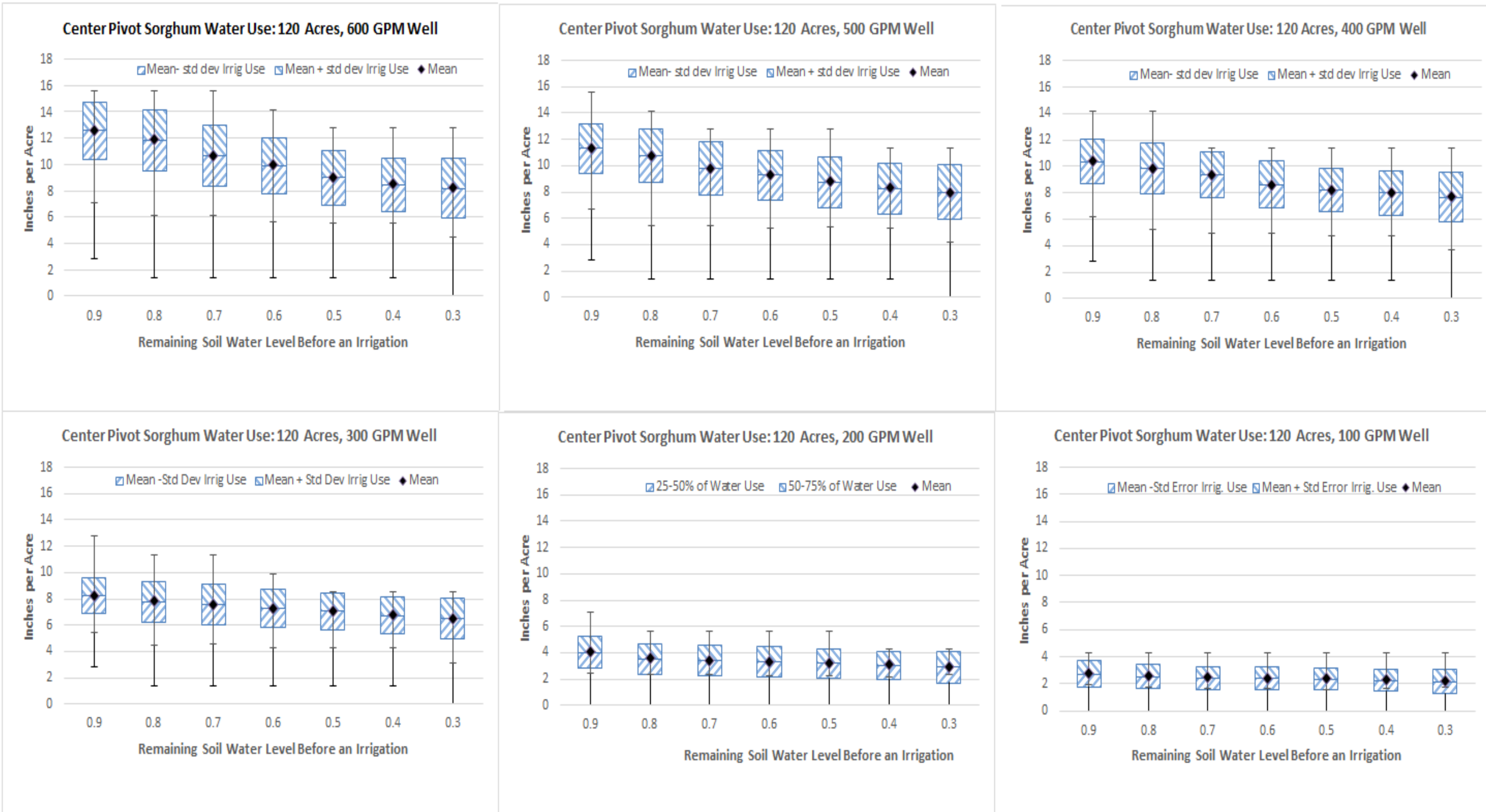


Figure 2.2.Mean and Standard Deviation of Simulated Average Sorghum Irrigation Applications by Well Capacity and Remaining Proportion Soil Moisture Level before an Irrigation was Initiated.

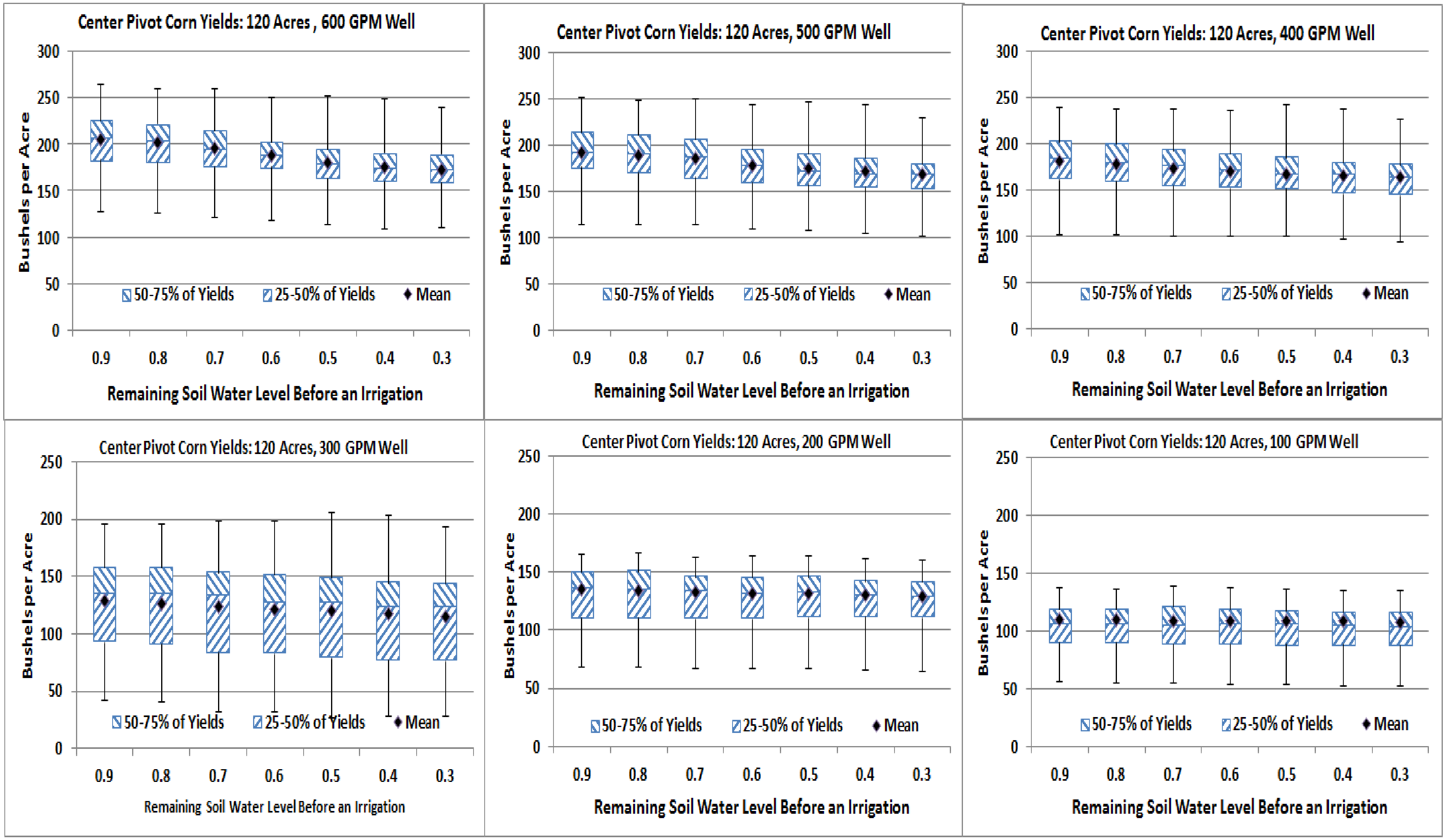


Figure 2.3 Quartile Plots of Irrigated Corn Yields by Well Size and by Remaining Proportion Available Soil Water before an Irrigation was Initiated

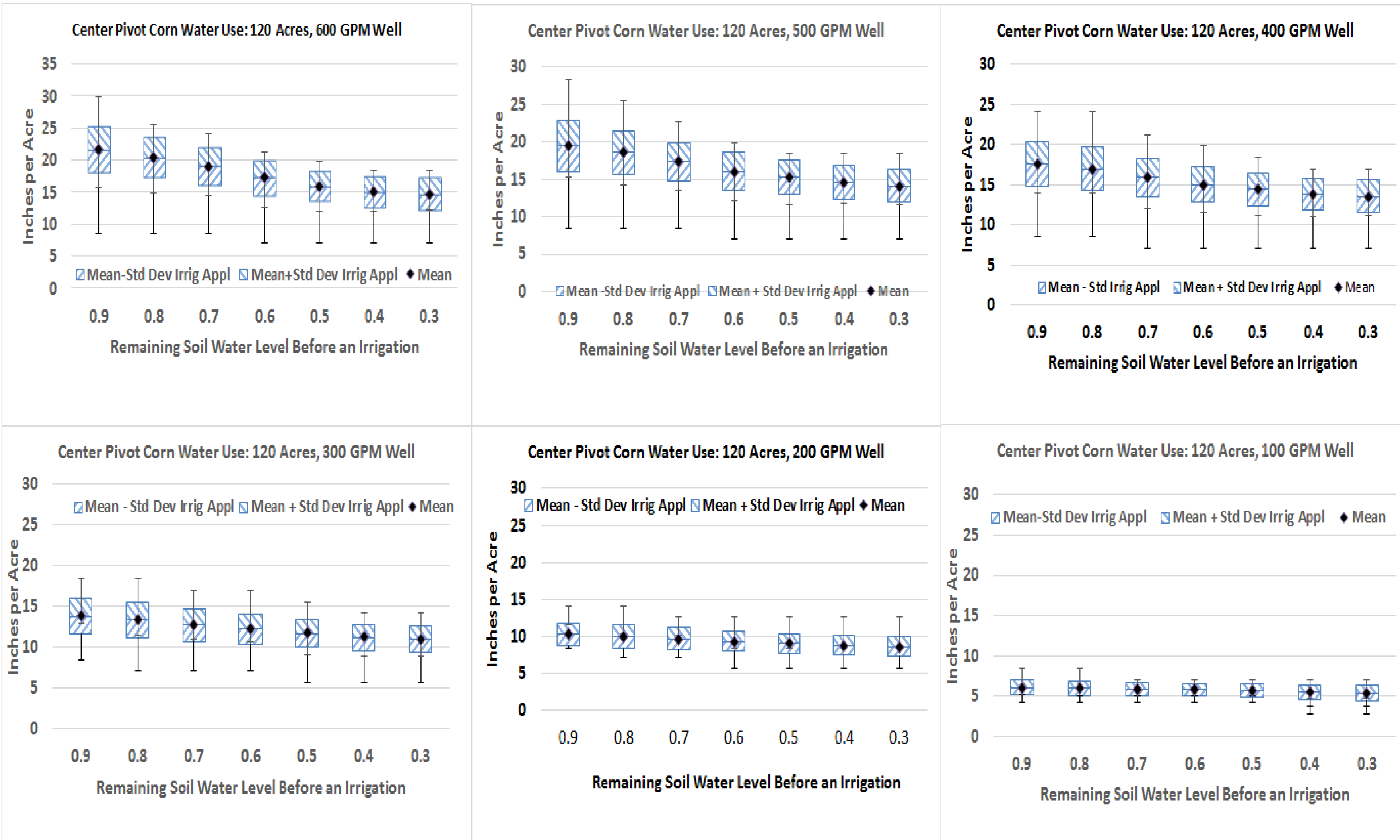


Figure 2.4 Mean and Standard Deviation of Simulated Average Corn Irrigation Applications by Well Capacity and Remaining Proportion Soil Moisture Level before an Irrigation was Initiated

Tables 2.3 through 2.5 compare the simulated variability of center pivot irrigated corn and grain sorghum yields at Goodwell, Oklahoma at 600 through 100 GPM well capacities and with different soil moisture depletion levels between irrigations. For 600 through 300 GPM wells the maximum corn yield was 215 bushels for 0.8-.04 soil moisture triggers. The maximum yield did not decrease across those ranges, however the mean yield did slightly decrease as more soil is depleted before irrigation

Comparing between Tables 2.3 and 2.4 the standard deviation of the grain sorghum yields is greater at the 400 GPM level than at the 600 GPM level. This is not necessarily bad as the maximum yields available with the 400 GPM well are nearly as high as with the 400 GPM well. However for corn the comparison between Tables 2.3 and 2.4 and Figure 2,2 show the potential to obtain the maximum yields declines rapidly with both well size and increased deficit irrigation.

In summary, the tabular and graphic analysis of irrigated corn and grain sorghum yields and water use show a relative smooth downward trend with declining well yields and with increased deficit irrigation.

Table 2.3. Comparison of Simulated Variability of Center Pivot Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with 600 and 500 GPM Wells and Soil Moisture Depletion Levels between Irrigations.

Item	unit	Remaining Proportion of Soil Water before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at 600 GPM						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	220	215	215	215	215	215	205
Mean Yield	bus	163	159	153	147	141	138	134
Std. Dev.	bus	28	27	26	27	28	29	29
Min. Yld	bus	99	98	93	89	87	81	75
Mean and Range of Irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	15.6	15.6	15.6	14.2	12.8	12.8	12.8
Mean	inches/ac	12.6	11.9	10.7	10.0	9.0	8.5	8.2
Std. Dev.	inches/ac	2.1	2.3	2.4	2.1	2.1	2.0	2.3
Min Applied	inches/ac	2.8	1.4	1.4	1.4	1.4	1.4	0.0
Mean and Range of Irrigated Corn Yields								
Max Yield	bus	293	282	273	265	266	266	266
Mean Yield	bus	206	201	195	188	180	176	173
Std. Dev.	bus	32	30	29	28	27	28	27
Min. Yld	bus	128	125	121	118	113	108	110
Mean and Range of Irrigation Applications for Corn								
Max Applied	inches/ac	29.8	25.5	24.1	21.3	19.8	18.4	18.4
Mean	inches/ac	21.6	20.4	19.0	17.2	15.9	15.0	14.6
Std. Dev.	inches/ac	3.6	3.1	3.0	2.8	2.4	2.4	2.5
Min Applied	inches/ac	8.5	8.5	8.5	7.1	7.1	7.1	7.1
		Well Capacity at 500 GPM						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	220	215	215	215	215	215	205
Mean Yield	bus	155	151	147	142	138	136	132
Std. Dev.	bus	31	31	29	30	30	30	30
Min. Yld	bus	87	82	82	75	75	75	77
Mean and Range of Irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	15.6	14.2	12.8	12.8	12.8	11.3	11.3
Mean	inches/ac	11.3	10.8	9.8	9.3	8.8	8.3	8.0
Std. Dev.	inches/ac	1.9	2.0	2.0	1.9	1.9	1.9	2.1
Min Applied	inches/ac	2.8	1.4	1.4	1.4	1.4	1.4	0.0
Mean and Range of Irrigated Corn Yields								
Max Yield	bus	288	278	272	263	263	263	263
Mean Yield	bus	193	190	186	179	175	172	170
Std. Dev.	bus	33	31	30	28	28	28	28
Min. Yld	bus	114	114	114	109	107	104	102
Mean and Range of Irrigation Applications for Corn								
Max Applied	inches/ac	28.3	25.5	22.7	19.8	18.4	18.4	18.4
Mean	inches/ac	19.5	18.6	17.4	16.0	15.3	14.6	14.1
Std. Dev.	inches/ac	3.4	2.9	2.5	2.5	2.3	2.3	2.3
Min Applied	inches/ac	8.5	8.5	8.5	7.1	7.1	7.1	7.1

Table 2.4. Comparison of Simulated Variability of Center Pivot Irrigated Corn and Grain Yields at Goodwell Oklahoma with 400 and 300 GPM Wells and Soil Moisture Depletion Levels Between Irrigations.

Item	unit	Remaining Proportion of Soil Water before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
	Well Capacity at 400 GPM							
Mean and Range of Grain Sorghum Yields								
Max Yiel	bus	220	215	215	215	215	215	205
Mean Yie	bus	147	144	141	137	134	132	128
Std. Dev.	bus	35	34	33	32	33	33	33
Min. Yld	bus	72	73	73	73	72	62	60
Mean and Range of Irrigation Applications for Grain Sorghum								
Max App	inches/ac	14.2	14.2	11.3	11.3	11.3	11.3	11.3
Mean	inches/ac	10.4	9.9	9.4	8.6	8.3	8.0	7.7
Std. Dev.	inches/ac	1.7	1.9	1.7	1.8	1.7	1.7	1.9
Min Appl	inches/ac	2.8	1.4	1.4	1.4	1.4	1.4	0.0
Mean and Range of Irrigated Corn Yields								
Max Yiel	bus	281	269	260	260	260	260	261
Mean Yie	bus	181	178	174	171	168	165	164
Std. Dev.	bus	33	31	30	29	29	29	29
Min. Yld	bus	102	102	100	100	100	97	94
Mean and Range of Irrigation Applications for Corn								
Max App	inches/ac	24.1	24.1	21.3	19.8	18.4	17.0	17.0
Mean	inches/ac	17.6	17.0	15.9	15.0	14.4	13.9	13.5
Std. Dev.	inches/ac	2.8	2.8	2.4	2.2	2.1	2.0	2.1
Min Appl	inches/ac	8.5	8.5	7.1	7.1	7.1	7.1	7.1
	Well Capacity at 300 GPM							
Mean and Range of Grain Sorghum Yields								
Max Yiel	bus	218	215	215	215	215	215	205
Mean Yie	bus	129	126	123	121	120	118	115
Std. Dev.	bus	42	42	41	41	41	41	40
Min. Yld	bus	48	43	43	41	41	40	43
Mean and Range of Irrigation Applications for Grain Sorghum								
Max App	inches/ac	12.8	11.3	11.3	9.9	8.5	8.5	8.5
Mean	inches/ac	8.3	7.8	7.6	7.3	7.1	6.8	6.5
Std. Dev.	inches/ac	1.3	1.5	1.6	1.4	1.4	1.4	1.6
Min Appl	inches/ac	2.8	1.4	1.4	1.4	1.4	1.4	0.0
Mean and Range of Irrigated Corn Yields								
Max Yiel	bus	272	264	257	257	244	245	245
Mean Yie	bus	158	156	154	153	151	149	147
Std. Dev.	bus	35	35	33	33	32	31	31
Min. Yld	bus	84	83	81	81	78	78	78
Mean and Range of Irrigation Applications for Corn								
Max App	inches/ac	18.4	18.4	17.0	17.0	15.6	14.2	14.2
Mean	inches/ac	13.9	13.4	12.8	12.3	11.8	11.3	11.0
Std. Dev.	inches/ac	2.2	2.2	2.0	1.8	1.7	1.6	1.6
Min Appl	inches/ac	8.5	7.1	7.1	7.1	5.7	5.7	5.7

Table 2.5. Comparison of Simulated Variability of Center Pivot Irrigated Corn and Grain Yields at Goodwell Oklahoma with 200 and 100 GPM Wells and Soil Moisture Depletion Levels Between Irrigations.

Item	unit	Remaining Proportion of Soil Water before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
Well Capacity at 200 GPM								
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	129	129	129	129	129	129	129
Mean Yield	bus	101	100	99	99	98	98	97
Std. Dev.	bus	16	16	16	16	16	16	17
Min. Yld	bus	63	63	63	63	62	61	61
Mean and Range of Irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	7.1	5.7	5.7	5.7	5.7	4.3	4.3
Mean	inches/ac	4.1	3.6	3.4	3.3	3.2	3.1	2.9
Std. Dev.	inches/ac	1.2	1.2	1.2	1.1	1.1	1.1	1.2
Min Applied	inches/ac	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mean and Range of Irrigated Corn Yields								
Max Yield	bus	259	253	252	240	241	240	241
Mean Yield	bus	135	134	133	132	132	130	130
Std. Dev.	bus	35	34	34	32	32	32	32
Min. Yld	bus	68	68	67	67	67	65	65
Mean and Range of Irrigation Applications for Corn								
Max Applied	inches/ac	14.2	14.2	12.8	12.8	12.8	12.8	12.8
Mean	inches/ac	10.3	10.1	9.7	9.4	9.1	8.8	8.7
Std. Dev.	inches/ac	1.5	1.6	1.6	1.4	1.3	1.3	1.4
Min Applied	inches/ac	8.5	7.1	7.1	5.7	5.7	5.7	5.7
Well Capacity at 100 GPM								
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	129	129	129	129	129	129	129
Mean Yield	bus	97	97	97	97	97	96	96
Std. Dev.	bus	18	18	18	18	18	18	18
Min. Yld	bus	54	54	55	55	54	54	55
Mean and Range of Irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	4.3	4.3	4.3	4.3	4.3	4.3	4.3
Mean	inches/ac	2.8	2.6	2.5	2.4	2.4	2.3	2.2
Std. Dev.	inches/ac	1.0	0.9	0.8	0.8	0.8	0.8	0.9
Min Applied	inches/ac	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mean and Range of Irrigated Corn Yields								
Max Yield	bus	239	238	237	238	238	240	227
Mean Yield	bus	110	110	109	109	109	108	107
Std. Dev.	bus	33	33	32	32	32	32	30
Min. Yld	bus	56	55	55	53	53	52	52
Mean and Range of Irrigation Applications for Corn								
Max Applied	inches/ac	8.5	8.5	7.1	7.1	7.1	7.1	7.1
Mean	inches/ac	6.1	6.0	5.9	5.8	5.7	5.5	5.4
Std. Dev.	inches/ac	0.9	0.8	0.8	0.8	0.8	0.9	0.9
Min Applied	inches/ac	4.3	4.3	4.3	4.3	4.3	2.8	2.8

Declining Well Yields and Subsurface Drip Irrigation

The producer faced with declining well yields has additional flexibility over the center pivot system in that the initial size of the irrigated area can be varied. Accordingly the simulation analysis was conducted with 50, 75, 100, 125, and 150 acre irrigated areas being served by wells with 600, 500, 400, 300, 200, and 100 GPM capacities. This results in a total of 30 possible combinations. Choice of the irrigated area is an additional way the producer might adjust to declining aquifer levels.

The box and whisker plots in Figures 2.5 through 2.10 use the yields of irrigated corn showing the quartiles range of yields for subsurface drip irrigation across different field sizes. As anticipated there is a steady decline in the respective mean and median corn yields as the water GPM wells as the well capacity declines. The greatest yield variability occurs between 600, 500, and 400 GPM wells. There is an increase in the overall range of annual applications though the range containing one standard deviation above and below the mean remains tightly grouped.

In the simulation process, the total water use from the subsurface drip irrigation sometimes increased over that of the center pivot system. This may be a result of the simulation process where water was assumed to be applied continuously over the entire field. Irrigation could be initiated anytime the soil moisture level declined below the irrigation trigger. That is there was no minimum time between irrigations for the subsurface drip irrigation as in the case with the center pivot where it was necessary to finish one rotation before the next irrigation could begin.

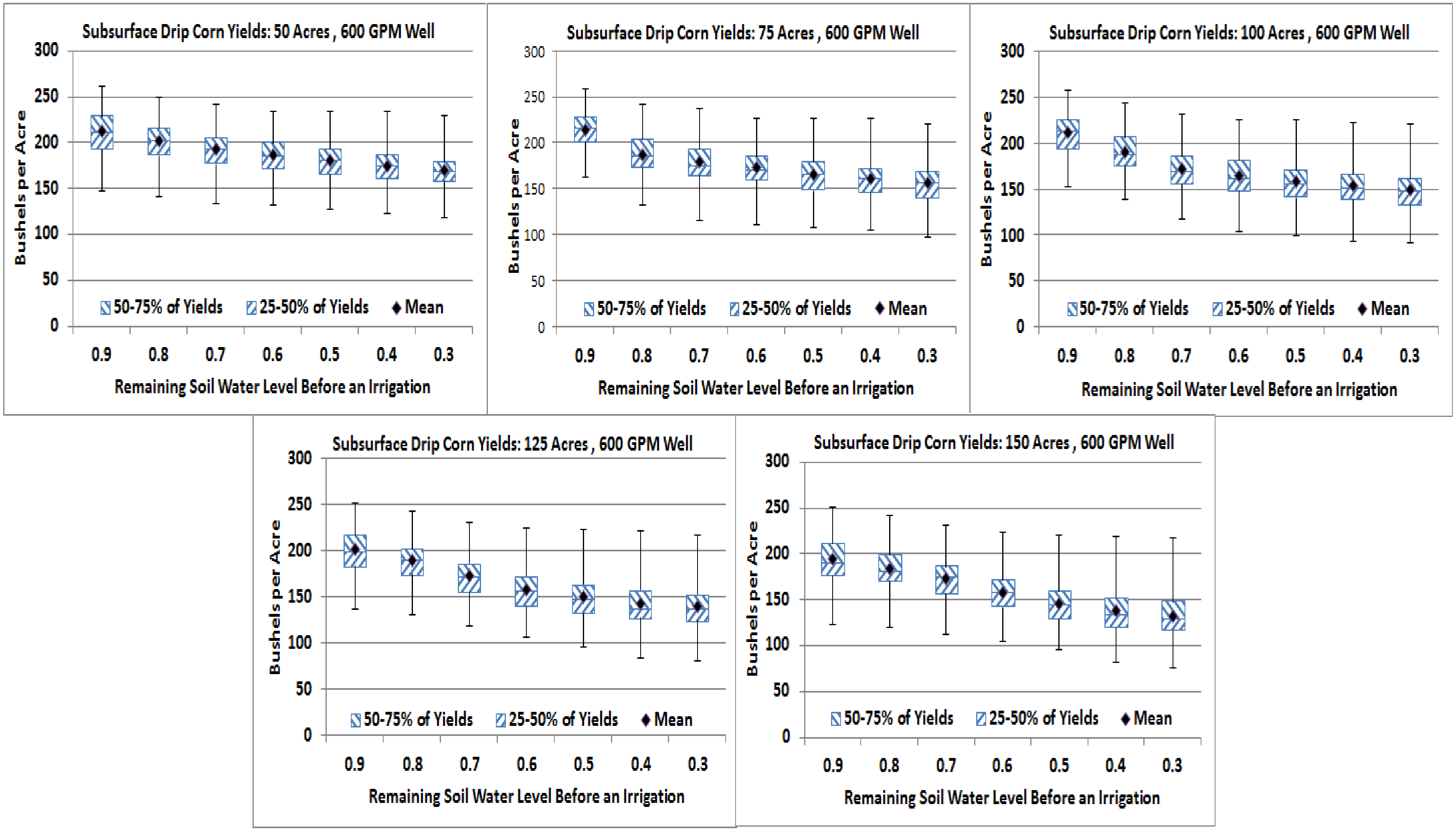


Figure 2.5 Range and Quartile Distribution of Subsurface Drip Irrigated Corn Yields using a 600 GPM well with 50, 75, 100, 125, or a 150 acre field

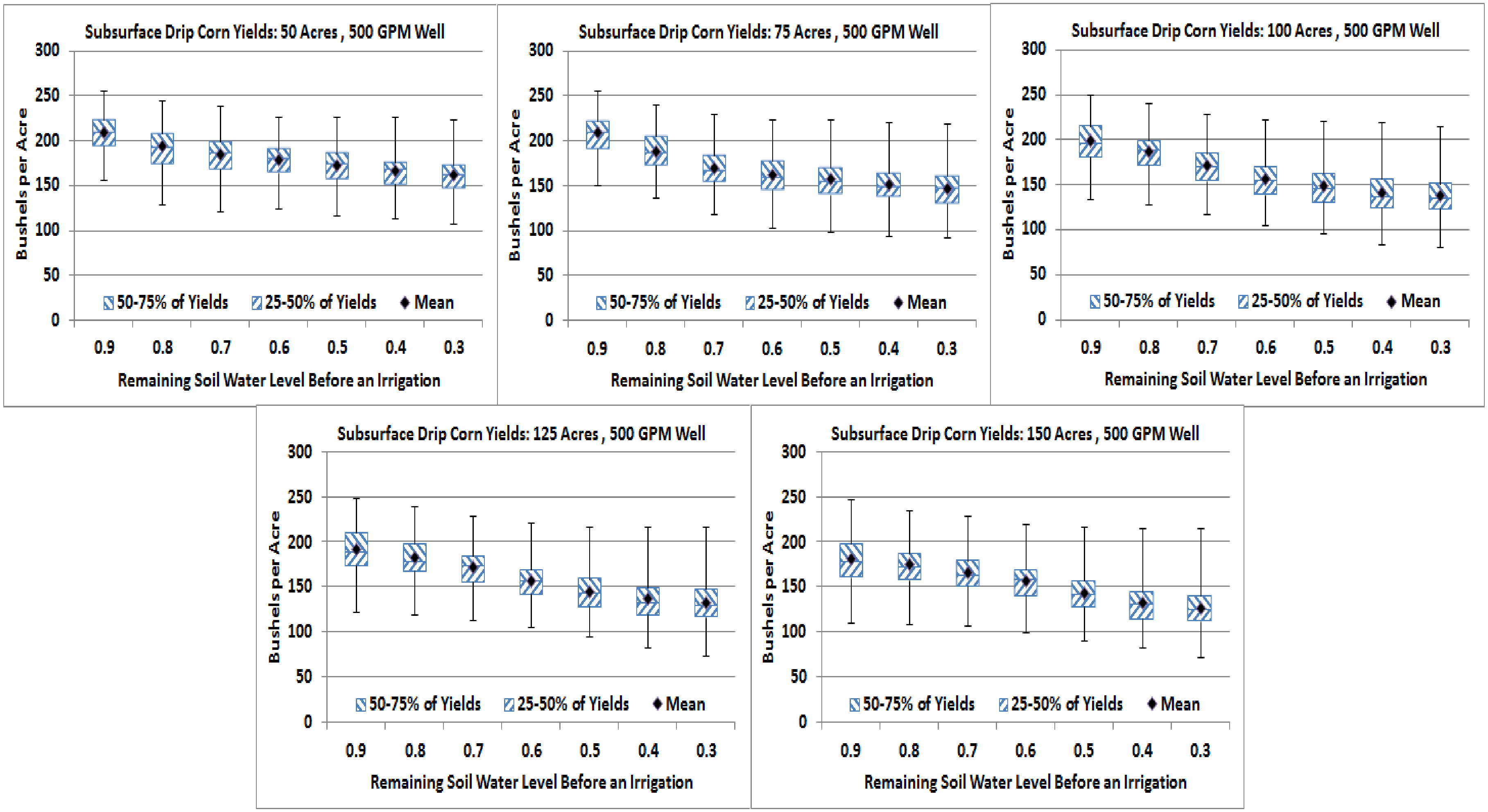


Figure 2.6 Range and Quartile Distribution of Subsurface Drip Irrigated Corn Yields using a 500 GPM well with 50, 75, 100, 125, or a 150 Acre Field

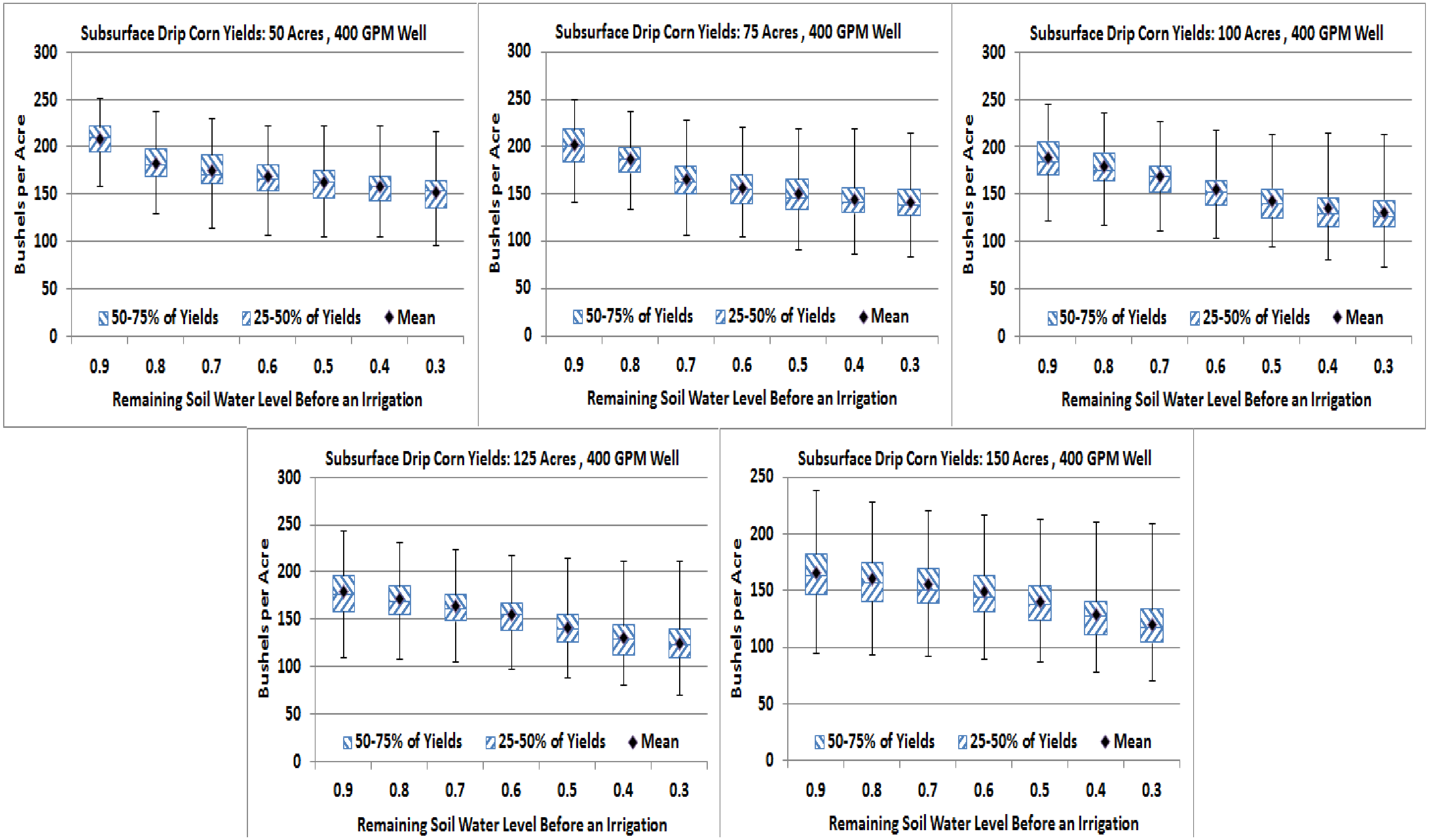


Figure 2.7. Range and Quartile Distribution of Subsurface Drip Irrigated Corn Yields using a 400 GPM well with 50, 75, 100, 125, or a 150 Acre Field

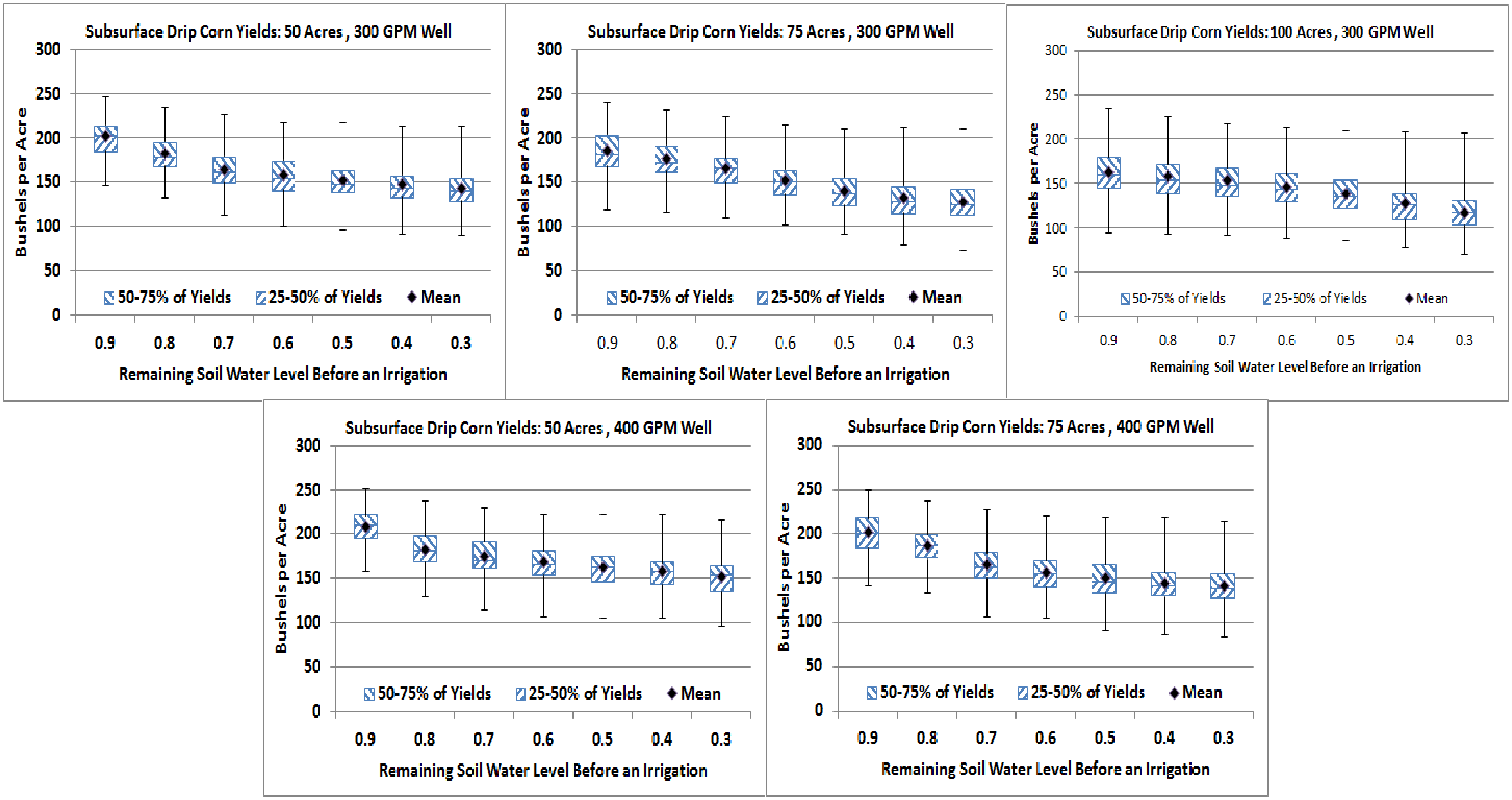


Figure 2.8. Range and Quartile Distribution of Subsurface Drip Irrigated Corn Yields using a 300 GPM well with 50, 75, 100, 125, or a 150 Acre Field

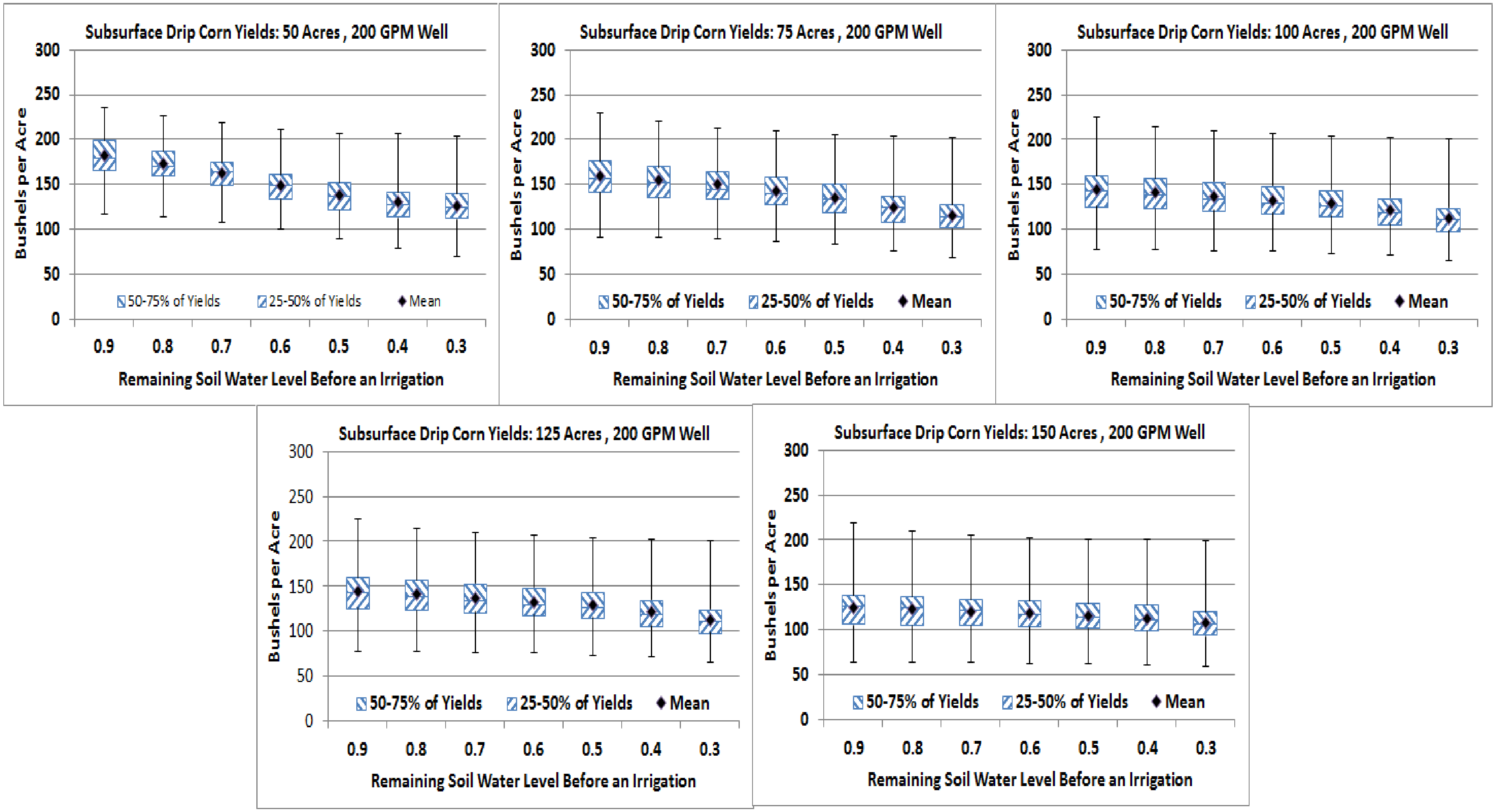


Figure 2.9 Range and Quartile Distribution of Subsurface Drip Irrigated Corn Yields using a 200 GPM well with 50, 75, 100, 125, or a 150 Acre Field

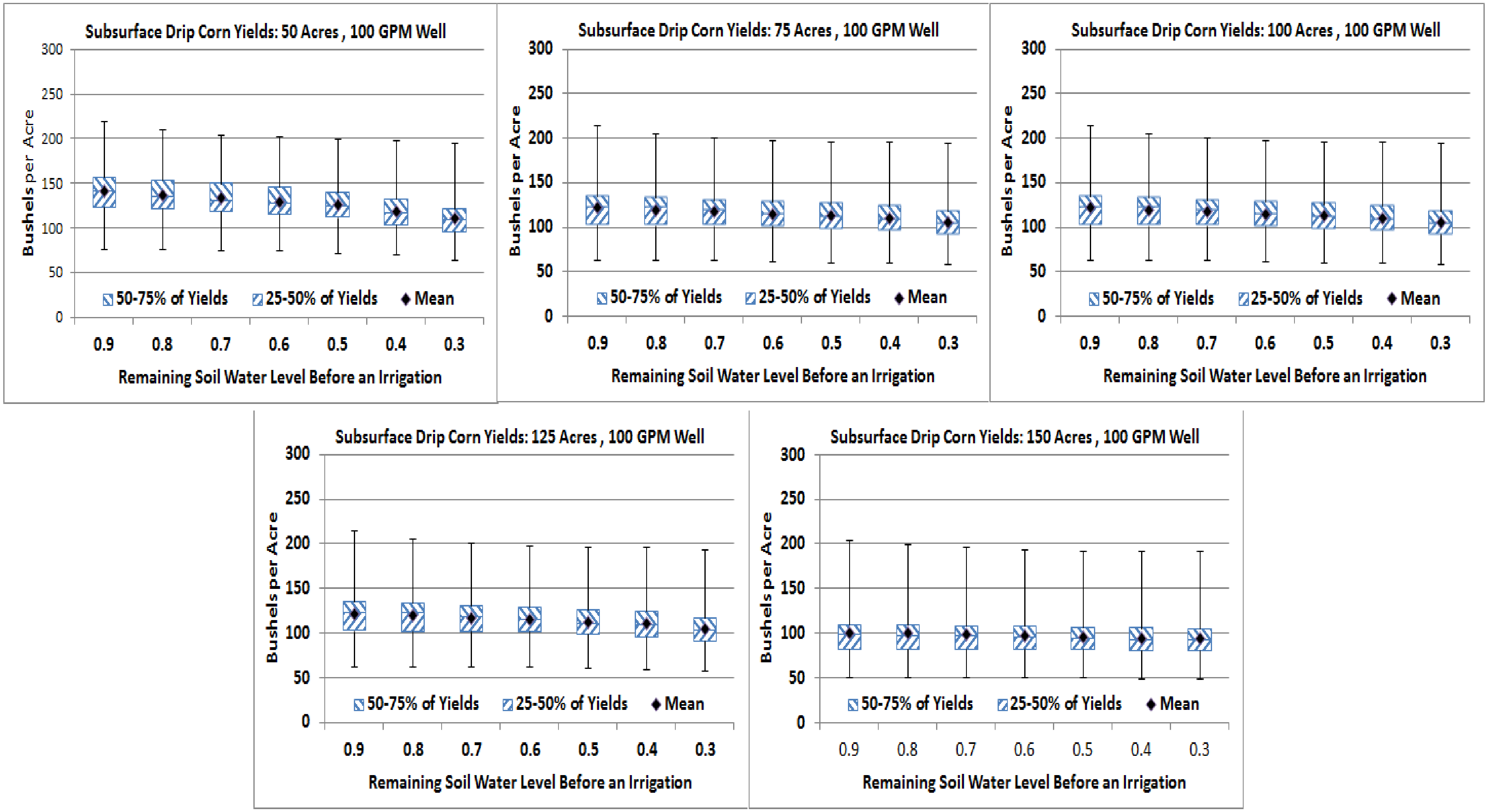


Figure 2.10. Range and Quartile Distribution of Subsurface Drip Irrigated Corn Yields using a 100 GPM well with 50, 75, 100, 125, or a 150 Acre Field

Tables 2.6 through 2.18 compare the variability of corn and grain sorghum yields under subsurface drip irrigation with different soil moisture depletion levels on different field sizes with a 600, 500, and 400 GPM wells. Each table compares the results for irrigated corn and grain sorghum at a specific well capacity along with a deficit irrigation strategy. The difference from one table to the next (example 150 acres and 125 acres) shows the impact of taking the output form a stated well capacity and spreading over more or less acres. This is a tabular summary of the results shown above in Figures 2.5- 2.10.

The main items of interest are the expected yields and the water use. The variability is measured by the standard deviation. Maximum, minimum, and mean yields decline steadily as the soil moisture is depleted more before the next irrigation is initiated. The standard deviation of irrigation application at all field sizes and well capacities decline as the degree of deficit irrigation is increased. However, the level of water applied increases as the field size decreases for both corn and grain sorghum. That is when a particular minimum level of soil moisture is maintained with a particular size of well, it is easier to keep up with a smaller size of irrigated area.

Note all of the combinations are expected to be economically viable, especially those with lower GPM wells. The long term analysis of profitability with expected yields and water for alternate sizes of subsurface drip investments at each well size has reported in the previous project report (Stoecker et al., 2015)/

Table 2.6.Comparison of Simulated Variability of Subsurface Drip Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with a 600 GPM well and 150 and 125 acres Irrigated

Item	Unit	Remaining Proportion of Soil Water before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at 600 GPM and 150 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	199	194	191	191	189	189	187
Mean Yield	bus	155	147	138	125	113	103	97
Std. Dev.	bus	22	22	22	26	29	33	35
Min. Yield	bus	101	96	89	77	65	44	34
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	13.9	12.5	11.1	9.4	8.3	7.1	5.9
Mean	inches/ac	10.3	9.0	7.7	6.4	5.3	4.6	4.1
Std. Dev.	inches/ac	2.0	2.0	2.0	1.7	1.5	1.2	1.1
Min. Applied	inches/ac	48.0	24.0	12.0	12.0	6.0	6.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	251	241	231	223	220	218	217
Mean Yield	bus	194	184	173	158	146	138	133
Std. Dev.	bus	28	26	25	25	26	27	27
Min. Yield	bus	123	120	113	105	96	82	75
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	21.7	19.8	17.5	15.4	13.7	11.6	10.4
Mean	inches/ac	18.1	16.0	14.0	11.7	9.8	8.4	7.6
Std. Dev.	inches/ac	2.5	2.4	2.3	2.1	1.8	1.6	1.4
Min. Applied	inches/ac	8.7	6.6	5.2	4.3	3.8	3.3	3.1
		Well Capacity at 600 GPM and 125 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	200	195	191	191	189	189	187
Mean Yield	bus	161	151	138	125	116	109	104
Std. Dev.	bus	20	20	22	26	29	32	32
Min. Yield	bus	112	106	92	80	59	48	44
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	15.4	13.2	11.9	9.9	8.5	7.4	6.9
Mean	inches/ac	11.4	9.7	7.9	6.5	5.7	5.1	4.7
Std. Dev.	inches/ac	2.3	2.2	2.1	1.7	1.5	1.3	1.3
Min. Applied	inches/ac	56.0	28.0	14.0	14.0	7.0	7.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	252	242	230	224	223	221	217
Mean Yield	bus	202	189	173	158	150	142	139
Std. Dev.	bus	26	25	24	25	26	27	26
Min. Yield	bus	136	129	118	106	96	84	79
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	23.7	20.9	18.5	16.0	14.1	12.4	11.9
Mean	inches/ac	20.0	17.2	14.3	11.8	10.5	9.3	8.6
Std. Dev.	inches/ac	2.8	2.6	2.4	2.1	1.9	1.7	1.6
Min. Applied	inches/ac	9.4	7.2	5.5	4.7	4.1	3.9	3.3

Table 2.7. Comparison of Simulated Variability of Subsurface Drip Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with a 600 GPM well and 100 and 75 acres Irrigated

Item	Unit	Remaining Proportion of Soil Water Before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at 600 GPM and 150 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	200	195	193	193	190	190	187
Mean Yield	bus	166	151	137	131	126	121	116
Std. Dev.	bus	18	20	24	26	26	27	28
Min. Yield	bus	124	110	93	76	71	67	62
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	17.4	14.2	12.0	10.6	9.9	8.9	8.5
Mean	inches/ac	12.7	9.9	8.0	7.2	6.7	6.2	5.7
Std. Dev.	inches/ac	2.9	2.4	1.9	1.7	1.7	1.6	1.6
Min. Applied	inches/ac	54.0	27.0	18.0	18.0	9.0	9.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	258	244	231	225	226	222	220
Mean Yield	bus	211	190	171	164	158	153	149
Std. Dev.	bus	25	24	26	26	26	25	25
Min. Yield	bus	153	138	118	104	99	93	92
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	27.6	24.4	19.5	17.0	15.6	15.2	14.9
Mean	inches/ac	22.5	18.1	14.6	13.2	12.1	11.2	10.5
Std. Dev.	inches/ac	3.3	3.0	2.4	2.2	2.1	2.1	2.0
Min. Applied	inches/ac	10.6	7.8	6.0	5.0	5.0	4.6	4.3
		Well Capacity at 600 GPM and 125 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	200	197	194	194	191	191	187
Mean Yield	bus	168	149	143	139	134	128	123
Std. Dev.	bus	16	21	23	24	24	24	25
Min. Yield	bus	129	105	89	85	84	80	71
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	18.6	14.3	13.0	12.1	10.8	10.4	10.0
Mean	inches/ac	13.2	9.9	8.9	8.3	7.7	7.1	6.4
Std. Dev.	inches/ac	3.1	2.3	2.0	1.9	1.9	1.9	1.8
Min. Applied	inches/ac	55.0	33.0	22.0	22.0	11.0	11.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	258	242	237	227	226	226	221
Mean Yield	bus	214	187	179	173	166	161	156
Std. Dev.	bus	24	26	26	25	25	25	25
Min. Yield	bus	162	132	115	110	108	104	97
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	31.6	23.8	20.4	19.1	18.6	18.2	16.9
Mean	inches/ac	23.6	17.8	16.1	14.9	13.8	12.9	12.0
Std. Dev.	inches/ac	3.7	2.8	2.5	2.5	2.4	2.3	2.3
Min. Applied	inches/ac	11.3	7.8	6.9	5.6	5.6	5.6	4.8

Table 2.8. Comparison of Simulated Variability of Subsurface Drip Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with a 600 GPM well and 50 acres Irrigated

Item	Unit	Remaining Proportion of Soil Water Before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at 600 GPM and 50 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	201	197	192	192	193	193	187
Mean Yield	bus	169	161	154	149	144	140	134
Std. Dev.	bus	18	18	18	19	20	20	21
Min. Yield	bus	121	119	107	107	101	97	92
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	20.1	16.7	16.1	14.7	14.1	13.4	12.7
Mean	inches/ac	13.7	12.1	10.9	10.2	9.4	8.8	8.1
Std. Dev.	inches/ac	3.0	2.8	2.7	2.5	2.5	2.3	2.3
Min. Applied	inches/ac	68.0	34.0	17.0	17.0	17.0	17.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	262	249	242	233	234	234	229
Mean Yield	bus	213	202	193	187	181	175	170
Std. Dev.	bus	26	25	24	24	23	23	23
Min. Yield	bus	148	141	134	132	127	123	118
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	30.8	28.1	26.1	24.1	24.1	22.1	21.4
Mean	inches/ac	24.4	21.7	19.7	18.3	17.3	16.1	15.1
Std. Dev.	inches/ac	3.5	3.3	3.2	3.1	3.1	3.0	3.0
Min. Applied	inches/ac	13.4	10.7	9.4	8.0	8.0	8.0	7.4

Table 2.9. Comparison of Simulated Variability of Subsurface Drip Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with a 500 GPM well and 150 and 125 acres Irrigated

Item	Unit	Remaining Proportion of Soil Water Before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at 500 GPM and 150 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	199	195	190	190	189	189	187
Mean Yield	bus	147	141	134	124	111	98	89
Std. Dev.	bus	25	25	25	26	30	34	37
Min. Yield	bus	88	86	81	71	56	48	29
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	12.2	11.0	10.0	9.1	7.7	6.5	5.5
Mean	inches/ac	9.0	8.1	7.2	6.2	5.1	4.1	3.6
Std. Dev.	inches/ac	1.6	1.7	1.7	1.6	1.4	1.2	1.0
Min. Applied	inches/ac	50.0	25.0	10.0	10.0	5.0	5.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	246	235	227	219	216	214	214
Mean Yield	bus	181	174	166	157	143	132	125
Std. Dev.	bus	29	27	25	25	25	26	27
Min. Yield	bus	110	108	105	98	89	82	70
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	19.1	17.5	16.3	14.2	12.4	10.6	9.1
Mean	inches/ac	15.7	14.2	12.8	11.2	9.3	7.6	6.6
Std. Dev.	inches/ac	2.1	2.2	2.1	2.0	1.7	1.5	1.2
Min. Applied	inches/ac	8.1	5.9	4.7	3.7	3.3	3.0	2.8
		Well Capacity at 500 GPM and 125 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	199	194	191	191	189	189	187
Mean Yield	bus	155	147	138	125	113	103	97
Std. Dev.	bus	22	22	22	26	29	33	35
Min. Yield	bus	101	96	89	77	65	44	34
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	13.9	12.5	11.1	9.4	8.3	7.1	5.9
Mean	inches/ac	10.3	9.0	7.7	6.4	5.3	4.6	4.1
Std. Dev.	inches/ac	2.0	2.0	2.0	1.7	1.5	1.2	1.1
Min. Applied	inches/ac	48.0	24.0	12.0	12.0	6.0	6.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	247	239	228	221	216	216	215
Mean Yield	bus	192	182	171	157	145	136	131
Std. Dev.	bus	27	25	24	24	25	26	27
Min. Yield	bus	122	118	112	104	94	82	73
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	21.7	19.8	17.2	15.4	13.2	11.6	10.4
Mean	inches/ac	18.0	15.9	13.9	11.6	9.7	8.3	7.5
Std. Dev.	inches/ac	2.5	2.4	2.3	2.1	1.8	1.6	1.4
Min. Applied	inches/ac	8.5	6.6	5.2	4.3	3.5	3.3	3.1

Table 2.10. Comparison of Simulated Variability of Subsurface Drip Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with a 400 GPM well and 150 and 125 acres Irrigated

Item	Unit	Remaining Proportion of Soil Water Before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at 400 GPM and 150 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	198	194	191	190	190	188	187
Mean Yield	bus	135	130	124	118	109	96	83
Std. Dev.	bus	30	29	29	30	31	34	38
Min. Yield	bus	70	67	64	59	55	38	29
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	11.0	9.3	8.7	7.9	7.2	6.0	4.9
Mean	inches/ac	7.6	6.8	6.2	5.6	4.8	3.9	3.1
Std. Dev.	inches/ac	1.4	1.4	1.4	1.4	1.3	1.1	0.9
Min. Applied	inches/ac	44.0	24.0	12.0	8.0	8.0	4.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	238	228	220	216	212	211	209
Mean Yield	bus	165	160	155	148	140	129	119
Std. Dev.	bus	30	28	26	25	25	25	26
Min. Yield	bus	95	93	92	89	86	78	71
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	16.2	14.6	13.9	12.8	11.5	9.8	8.3
Mean	inches/ac	13.0	11.9	10.9	9.9	8.8	7.1	5.8
Std. Dev.	inches/ac	1.8	1.8	1.8	1.7	1.6	1.4	1.1
Min. Applied	inches/ac	6.8	5.0	3.9	3.3	2.8	2.7	2.2
		Well Capacity at 400 GPM and 125 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	199	195	190	190	189	189	187
Mean Yield	bus	147	141	134	124	111	98	89
Std. Dev.	bus	25	25	25	26	30	34	37
Min. Yield	bus	88	86	81	71	56	48	29
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	12.2	11.0	10.0	9.1	7.7	6.5	5.5
Mean	inches/ac	9.0	8.1	7.2	6.2	5.1	4.1	3.6
Std. Dev.	inches/ac	1.6	1.7	1.7	1.6	1.4	1.2	1.0
Min. Applied	inches/ac	50.0	25.0	10.0	10.0	5.0	5.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	243	232	224	217	214	211	211
Mean Yield	bus	179	172	164	155	141	131	124
Std. Dev.	bus	28	26	25	24	25	26	27
Min. Yield	bus	109	107	104	97	88	81	70
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	19.1	17.3	16.3	14.0	12.4	10.6	9.1
Mean	inches/ac	15.6	14.1	12.7	11.2	9.2	7.6	6.5
Std. Dev.	inches/ac	2.1	2.2	2.1	1.9	1.7	1.5	1.2
Min. Applied	inches/ac	7.9	5.9	4.5	3.7	3.3	3.0	2.8

Table 2.11. Comparison of Simulated Variability of Subsurface Drip Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with a 300 GPM well and 150 and 125 acres Irrigated

Item	Unit	Remaining Proportion of Soil Water Before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at 400 GPM and 150 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	197	193	190	190	189	188	187
Mean Yield	bus	119	115	109	105	100	91	80
Std. Dev.	bus	37	36	35	35	36	36	39
Min. Yield	bus	47	46	44	42	37	34	25
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	9.0	8.0	6.6	6.4	5.9	5.6	4.4
Mean	inches/ac	5.9	5.4	4.9	4.5	4.1	3.5	2.8
Std. Dev.	inches/ac	1.0	1.1	1.1	1.1	1.0	1.0	0.9
Min. Applied	inches/ac	39.0	18.0	9.0	9.0	6.0	3.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	230	220	213	210	208	206	204
Mean Yield	bus	147	143	139	135	131	124	115
Std. Dev.	bus	31	29	27	27	26	25	25
Min. Yield	bus	78	78	77	76	74	72	66
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	12.8	11.3	10.7	10.2	9.7	8.6	7.6
Mean	inches/ac	10.0	9.3	8.6	8.0	7.4	6.4	5.2
Std. Dev.	inches/ac	1.4	1.4	1.4	1.4	1.4	1.3	1.1
Min. Applied	inches/ac	5.7	3.9	3.1	2.7	2.4	2.1	1.9
		Well Capacity at 400 GPM and 125 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	198	194	191	190	190	188	187
Mean Yield	bus	135	130	124	118	109	96	83
Std. Dev.	bus	30	29	29	30	31	34	38
Min. Yield	bus	70	67	64	59	55	38	29
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	11.0	9.3	8.7	7.9	7.2	6.0	4.9
Mean	inches/ac	7.6	6.8	6.2	5.6	4.8	3.9	3.1
Std. Dev.	inches/ac	1.4	1.4	1.4	1.4	1.3	1.1	0.9
Min. Applied	inches/ac	44.0	24.0	12.0	8.0	8.0	4.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	233	224	217	213	209	208	206
Mean Yield	bus	163	158	153	146	138	127	117
Std. Dev.	bus	29	28	26	25	25	25	26
Min. Yield	bus	93	92	91	88	85	77	70
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	16.1	14.5	13.7	12.6	11.5	9.6	8.3
Mean	inches/ac	12.9	11.8	10.9	9.9	8.7	7.1	5.7
Std. Dev.	inches/ac	1.8	1.8	1.8	1.7	1.7	1.4	1.1
Min. Applied	inches/ac	6.6	4.9	3.9	3.3	2.8	2.7	2.2

Table 2.12. Comparison of Simulated Variability of Subsurface Drip Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with a 200 GPM well and 150 and 125 acres Irrigated

Item	Unit	Remaining Proportion of Soil Water Before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at 200 GPM and 150 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	118	118	118	118	118	118	118
Mean Yield	bus	93	92	91	90	89	88	86
Std. Dev.	bus	14	14	14	14	14	14	15
Min. Yield	bus	61	60	60	58	57	56	52
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	3.6	3.0	2.8	2.6	2.4	2.2	1.7
Mean	inches/ac	2.1	1.8	1.6	1.4	1.2	1.0	0.7
Std. Dev.	inches/ac	0.7	0.7	0.7	0.6	0.6	0.6	0.4
Min. Applied	inches/ac	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	219	210	205	202	201	201	199
Mean Yield	bus	125	123	120	118	115	112	108
Std. Dev.	bus	31	29	28	27	26	26	26
Min. Yield	bus	63	63	63	62	61	60	59
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	9.1	8.2	7.4	7.0	6.7	6.5	5.7
Mean	inches/ac	6.8	6.3	6.0	5.6	5.2	4.8	4.2
Std. Dev.	inches/ac	0.9	0.9	0.9	1.0	1.0	1.0	0.9
Min. Applied	inches/ac	4.3	2.8	2.3	1.8	1.7	1.6	1.3
		Well Capacity at 200 GPM and 125 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	118	118	118	118	118	118	118
Mean Yield	bus	97	95	94	92	90	88	87
Std. Dev.	bus	12	12	12	12	13	14	15
Min. Yield	bus	68	66	65	63	59	56	52
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	4.7	4.3	3.8	3.7	3.1	2.5	1.9
Mean	inches/ac	2.9	2.5	2.1	1.8	1.5	1.1	0.9
Std. Dev.	inches/ac	1.0	1.0	0.9	0.9	0.8	0.6	0.5
Min. Applied	inches/ac	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	225	215	209	206	204	203	200
Mean Yield	bus	144	140	137	133	128	122	113
Std. Dev.	bus	30	28	27	26	25	25	25
Min. Yield	bus	77	77	76	75	72	71	65
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	12.8	11.2	10.6	10.0	9.7	8.5	7.3
Mean	inches/ac	9.9	9.2	8.5	7.9	7.3	6.4	5.2
Std. Dev.	inches/ac	1.4	1.4	1.4	1.4	1.4	1.3	1.1
Min. Applied	inches/ac	5.4	3.7	3.1	2.7	2.2	2.1	1.8

Table 2.13. Comparison of Simulated Variability of Subsurface Drip Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with a 100 GPM well and 150 and 125 acres Irrigated

Item	Unit	Remaining Proportion of Soil Water before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at 100 GPM and 150 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	118	118	118	118	118	118	118
Mean Yield	bus	88	87	87	87	86	86	85
Std. Dev.	bus	16	16	16	16	16	16	16
Min. Yield	bus	53	52	52	52	51	50	48
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	2.3	1.6	1.5	1.4	1.3	1.2	1.2
Mean	inches/ac	1.1	1.0	0.9	0.8	0.7	0.6	0.5
Std. Dev.	inches/ac	0.4	0.3	0.3	0.3	0.3	0.3	0.3
Min. Applied	inches/ac	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	203	199	195	193	192	192	191
Mean Yield	bus	101	100	99	97	96	95	94
Std. Dev.	bus	29	28	27	26	26	26	26
Min. Yield	bus	50	49	49	49	49	49	48
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	4.8	4.4	4.1	3.8	3.4	3.3	3.3
Mean	inches/ac	3.4	3.2	3.1	2.9	2.7	2.5	2.4
Std. Dev.	inches/ac	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Min. Applied	inches/ac	2.4	1.7	1.3	0.9	0.8	0.8	0.7
		Well Capacity at 100 GPM and 125 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	118	118	118	118	118	118	118
Mean Yield	bus	93	92	91	90	89	88	86
Std. Dev.	bus	14	14	14	14	14	14	15
Min. Yield	bus	61	60	60	58	57	56	52
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	3.6	3.0	2.8	2.6	2.4	2.2	1.7
Mean	inches/ac	2.1	1.8	1.6	1.4	1.2	1.0	0.7
Std. Dev.	inches/ac	0.7	0.7	0.7	0.6	0.6	0.6	0.4
Min. Applied	inches/ac	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	214	205	200	198	196	196	194
Mean Yield	bus	122	120	117	115	112	110	105
Std. Dev.	bus	30	28	27	26	26	25	25
Min. Yield	bus	62	62	62	61	60	59	58
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	9.1	8.2	7.2	6.9	6.6	6.4	5.7
Mean	inches/ac	6.7	6.3	5.9	5.5	5.1	4.8	4.2
Std. Dev.	inches/ac	0.9	0.9	0.9	1.0	1.0	1.0	0.9
Min. Applied	inches/ac	4.1	2.8	2.2	1.8	1.7	1.6	1.3

Table 2.14. Comparison of Simulated Variability of Subsurface Drip Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with a 500 GPM well and 100 and 75 acres Irrigated

Item	Unit	Remaining Proportion of Soil Water before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at 500 GPM and 100 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	200	195	191	191	189	189	187
Mean Yield	bus	161	151	138	125	116	109	104
Std. Dev.	bus	20	20	22	26	29	32	32
Min. Yield	bus	112	106	92	80	59	48	44
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	15.4	13.2	11.9	9.9	8.5	7.4	6.9
Mean	inches/ac	11.4	9.7	7.9	6.5	5.7	5.1	4.7
Std. Dev.	inches/ac	2.3	2.2	2.1	1.7	1.5	1.3	1.3
Min. Applied	inches/ac	56.0	28.0	14.0	14.0	7.0	7.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	249	240	228	222	220	219	215
Mean Yield	bus	200	187	171	156	148	141	137
Std. Dev.	bus	26	25	24	25	26	26	26
Min. Yield	bus	134	128	117	105	95	83	80
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	23.7	20.9	18.5	16.0	13.8	12.4	11.9
Mean	inches/ac	19.9	17.1	14.2	11.7	10.5	9.2	8.6
Std. Dev.	inches/ac	2.8	2.6	2.4	2.1	1.9	1.7	1.7
Min. Applied	inches/ac	9.4	7.2	5.5	4.7	4.1	3.9	3.3
		Well Capacity at 500 GPM and 75 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	200	195	193	193	190	190	187
Mean Yield	bus	166	151	137	131	126	121	116
Std. Dev.	bus	18	20	24	26	26	27	28
Min. Yield	bus	124	110	93	76	71	67	62
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	17.4	14.2	12.0	10.6	9.9	8.9	8.5
Mean	inches/ac	12.7	9.9	8.0	7.2	6.7	6.2	5.7
Std. Dev.	inches/ac	2.9	2.4	1.9	1.7	1.7	1.6	1.6
Min. Applied	inches/ac	54.0	27.0	18.0	18.0	9.0	9.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	255	240	229	223	224	220	218
Mean Yield	bus	209	188	170	163	157	151	147
Std. Dev.	bus	24	24	25	26	25	25	25
Min. Yield	bus	150	136	117	103	97	94	92
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	27.3	24.1	19.5	17.0	15.6	15.2	14.9
Mean	inches/ac	22.3	18.0	14.5	13.1	12.1	11.1	10.5
Std. Dev.	inches/ac	3.3	3.0	2.4	2.2	2.1	2.0	2.0
Min. Applied	inches/ac	10.6	7.4	6.0	5.0	5.0	4.6	4.3

Table 2.15. Comparison of Simulated Variability of Subsurface Drip Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with a 400 GPM well and 100 and 75 acres Irrigated

Item	Unit	Remaining Proportion of Soil Water before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at 400 GPM and 100 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	199	194	191	191	189	189	187
Mean Yield	bus	155	147	138	125	113	103	97
Std. Dev.	bus	22	22	22	26	29	33	35
Min. Yield	bus	101	96	89	77	65	44	34
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	13.9	12.5	11.1	9.4	8.3	7.1	5.9
Mean	inches/ac	10.3	9.0	7.7	6.4	5.3	4.6	4.1
Std. Dev.	inches/ac	2.0	2.0	2.0	1.7	1.5	1.2	1.1
Min. Applied	inches/ac	48.0	24.0	12.0	12.0	6.0	6.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	244	235	226	218	213	214	212
Mean Yield	bus	189	180	168	155	143	135	130
Std. Dev.	bus	27	25	24	24	25	26	26
Min. Yield	bus	121	117	110	103	93	80	72
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	21.5	19.8	17.2	15.1	13.2	11.1	10.4
Mean	inches/ac	17.9	15.8	13.8	11.6	9.7	8.3	7.5
Std. Dev.	inches/ac	2.5	2.4	2.3	2.1	1.8	1.5	1.4
Min. Applied	inches/ac	8.5	6.4	5.2	4.3	3.5	3.3	3.1
		Well Capacity at 400 GPM and 75 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	200	196	192	192	190	190	187
Mean Yield	bus	164	153	137	127	121	116	110
Std. Dev.	bus	19	19	22	26	28	29	30
Min. Yield	bus	116	110	94	85	62	58	53
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	16.7	14.5	12.0	10.1	8.8	7.9	7.9
Mean	inches/ac	12.1	10.1	7.9	6.8	6.2	5.7	5.2
Std. Dev.	inches/ac	2.6	2.4	2.0	1.7	1.5	1.4	1.4
Min. Applied	inches/ac	56.0	32.0	16.0	16.0	8.0	8.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	249	237	227	220	219	219	214
Mean Yield	bus	202	187	166	157	150	145	141
Std. Dev.	bus	25	23	25	25	26	26	25
Min. Yield	bus	141	133	105	104	91	87	84
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	25.2	23.0	16.3	16.1	14.5	13.9	12.9
Mean	inches/ac	21.2	17.8	12.8	12.3	11.1	10.1	9.5
Std. Dev.	inches/ac	3.0	2.9	2.1	2.1	1.9	1.9	1.8
Min. Applied	inches/ac	10.1	7.2	4.7	5.0	4.4	4.4	3.8

Table 2.16. Comparison of Simulated Variability of Subsurface Drip Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with a 300 GPM well and 100 and 75 acres Irrigated

Item	Unit	Remaining Proportion of Soil Water before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at 300 GPM and 100 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	198	194	191	190	190	188	187
Mean Yield	bus	135	130	124	118	109	96	83
Std. Dev.	bus	30	29	29	30	31	34	38
Min. Yield	bus	70	67	64	59	55	38	29
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	11.0	9.3	8.7	7.9	7.2	6.0	4.9
Mean	inches/ac	7.6	6.8	6.2	5.6	4.8	3.9	3.1
Std. Dev.	inches/ac	1.4	1.4	1.4	1.4	1.3	1.1	0.9
Min. Applied	inches/ac	44.0	24.0	12.0	8.0	8.0	4.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	233	224	217	213	209	208	206
Mean Yield	bus	163	158	153	146	138	127	117
Std. Dev.	bus	29	28	26	25	25	25	26
Min. Yield	bus	93	92	91	88	85	77	70
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	16.1	14.5	13.7	12.6	11.5	9.6	8.3
Mean	inches/ac	12.9	11.8	10.9	9.9	8.7	7.1	5.7
Std. Dev.	inches/ac	1.8	1.8	1.8	1.7	1.7	1.4	1.1
Min. Applied	inches/ac	6.6	4.9	3.9	3.3	2.8	2.7	2.2
		Well Capacity at 300 GPM and 75 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	199	194	191	191	189	189	187
Mean Yield	bus	155	147	138	125	113	103	97
Std. Dev.	bus	22	22	22	26	29	33	35
Min. Yield	bus	101	96	89	77	65	44	34
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	13.9	12.5	11.1	9.4	8.3	7.1	5.9
Mean	inches/ac	10.3	9.0	7.7	6.4	5.3	4.6	4.1
Std. Dev.	inches/ac	2.0	2.0	2.0	1.7	1.5	1.2	1.1
Min. Applied	inches/ac	48.0	24.0	12.0	12.0	6.0	6.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	240	231	223	215	210	211	209
Mean Yield	bus	186	177	166	152	140	133	128
Std. Dev.	bus	27	25	24	24	24	26	26
Min. Yield	bus	119	116	109	101	91	79	73
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	21.5	19.6	17.0	15.1	13.0	11.1	10.4
Mean	inches/ac	17.7	15.7	13.7	11.5	9.6	8.3	7.4
Std. Dev.	inches/ac	2.5	2.4	2.3	2.1	1.8	1.5	1.4
Min. Applied	inches/ac	8.3	6.4	5.2	4.3	3.5	3.3	3.1

Table 2.17. Comparison of Simulated Variability of Subsurface Drip Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with a 200 GPM well and 100 and 75 acres Irrigated

Item	Unit	Remaining Proportion of Soil Water before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at 200 GPM and 100 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	118	118	118	118	118	118	118
Mean Yield	bus	97	95	94	92	90	88	87
Std. Dev.	bus	12	12	12	12	13	14	15
Min. Yield	bus	68	66	65	63	59	56	52
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	4.7	4.3	3.8	3.7	3.1	2.5	1.9
Mean	inches/ac	2.9	2.5	2.1	1.8	1.5	1.1	0.9
Std. Dev.	inches/ac	1.0	1.0	0.9	0.9	0.8	0.6	0.5
Min. Applied	inches/ac	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	225	215	209	206	204	203	200
Mean Yield	bus	144	140	137	133	128	122	113
Std. Dev.	bus	30	28	27	26	25	25	25
Min. Yield	bus	77	77	76	75	72	71	65
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	12.8	11.2	10.6	10.0	9.7	8.5	7.3
Mean	inches/ac	9.9	9.2	8.5	7.9	7.3	6.4	5.2
Std. Dev.	inches/ac	1.4	1.4	1.4	1.4	1.4	1.3	1.1
Min. Applied	inches/ac	5.4	3.7	3.1	2.7	2.2	2.1	1.8
		Well Capacity at 200 GPM and 75 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	118	118	118	118	118	118	118
Mean Yield	bus	99	97	95	93	91	89	88
Std. Dev.	bus	11	11	11	12	13	14	14
Min. Yield	bus	73	70	67	64	60	57	55
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	6.0	5.2	4.6	4.3	3.3	2.7	2.4
Mean	inches/ac	3.6	2.9	2.4	2.0	1.6	1.3	1.1
Std. Dev.	inches/ac	1.3	1.2	1.1	1.0	0.8	0.7	0.6
Min. Applied	inches/ac	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	229	220	213	209	205	204	201
Mean Yield	bus	159	155	150	143	136	124	115
Std. Dev.	bus	29	27	25	24	24	24	25
Min. Yield	bus	92	90	89	86	84	76	68
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	15.9	14.3	13.5	12.6	11.3	9.6	8.2
Mean	inches/ac	12.7	11.7	10.8	9.7	8.6	7.0	5.7
Std. Dev.	inches/ac	1.8	1.8	1.8	1.7	1.6	1.4	1.1
Min. Applied	inches/ac	6.5	4.7	3.9	3.3	2.7	2.7	2.0

Table 2.18. Comparison of Simulated Variability of Subsurface Drip Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with a 100 GPM well and 100 and 75 acres Irrigated

Item	Unit	Remaining Proportion of Soil Water before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at 100 GPM and 100 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	118	118	118	118	118	118	118
Mean Yield	bus	93	92	91	90	89	88	86
Std. Dev.	bus	14	14	14	14	14	14	15
Min. Yield	bus	61	60	60	58	57	56	52
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	3.6	3.0	2.8	2.6	2.4	2.2	1.7
Mean	inches/ac	2.1	1.8	1.6	1.4	1.2	1.0	0.7
Std. Dev.	inches/ac	0.7	0.7	0.7	0.6	0.6	0.6	0.4
Min. Applied	inches/ac	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	214	205	200	198	196	196	194
Mean Yield	bus	122	120	117	115	112	110	105
Std. Dev.	bus	30	28	27	26	26	25	25
Min. Yield	bus	62	62	62	61	60	59	58
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	9.1	8.2	7.2	6.9	6.6	6.4	5.7
Mean	inches/ac	6.7	6.3	5.9	5.5	5.1	4.8	4.2
Std. Dev.	inches/ac	0.9	0.9	0.9	1.0	1.0	1.0	0.9
Min. Applied	inches/ac	4.1	2.8	2.2	1.8	1.7	1.6	1.3
		Well Capacity at 100 GPM and 75 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	118	118	118	118	118	118	118
Mean Yield	bus	93	92	91	90	89	88	86
Std. Dev.	bus	14	14	14	14	14	14	15
Min. Yield	bus	61	60	60	58	57	56	52
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	3.6	3.0	2.8	2.6	2.4	2.2	1.7
Mean	inches/ac	2.1	1.8	1.6	1.4	1.2	1.0	0.7
Std. Dev.	inches/ac	0.7	0.7	0.7	0.6	0.6	0.6	0.4
Min. Applied	inches/ac	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	214	205	200	198	196	196	194
Mean Yield	bus	122	120	117	115	112	110	105
Std. Dev.	bus	30	28	27	26	26	25	25
Min. Yield	bus	62	62	62	61	60	59	58
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	9.1	8.2	7.2	6.9	6.6	6.4	5.7
Mean	inches/ac	6.7	6.3	5.9	5.5	5.1	4.8	4.2
Std. Dev.	inches/ac	0.9	0.9	0.9	1.0	1.0	1.0	0.9
Min. Applied	inches/ac	4.1	2.8	2.2	1.8	1.7	1.6	1.3

Tables 2.19 through 2.23 compare simulated variability of corn and grain sorghum yields under subsurface drip irrigation on 50 acres with 500, 400, 300, 200, and 100 GPM wells. There is more variability in corn yields across soil moisture depletion levels and different well capacities than for sorghum. The biggest decline in yield for both crops is seen between the 300 and 200 GPM wells. At 200 and 100 GPM the yields are more variable and the decline in yields across wells is greater.

Table 2.19. Comparison of Simulated Variability of Subsurface Drip Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with a 500 GPM well and 50 acres Irrigated

Item	Unit	Remaining Proportion of Soil Water before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at 500 GPM and 50 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	201	198	196	191	192	192	187
Mean Yield	bus	166	157	150	145	141	134	129
Std. Dev.	bus	17	21	20	21	21	21	22
Min. Yield	bus	122	106	101	100	97	92	84
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	18.7	16.0	14.3	13.8	12.7	12.1	11.0
Mean	inches/ac	13.1	11.2	10.1	9.3	8.8	8.0	7.3
Std. Dev.	inches/ac	3.0	2.4	2.4	2.3	2.3	2.3	2.1
Min. Applied	inches/ac	56.0	42.0	28.0	14.0	14.0	14.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	255	244	238	226	226	226	223
Mean Yield	bus	210	193	186	179	173	167	162
Std. Dev.	bus	24	25	25	24	24	23	23
Min. Yield	bus	156	129	121	124	116	113	108
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	31.4	24.8	23.1	22.0	20.9	20.9	19.3
Mean	inches/ac	23.7	19.8	18.1	16.7	15.8	14.6	13.6
Std. Dev.	inches/ac	3.6	3.1	2.8	2.8	2.7	2.8	2.7
Min. Applied	inches/ac	12.1	9.4	8.3	6.6	6.6	6.6	6.1

Table 2.20. Comparison of Simulated Variability of Subsurface Drip Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with a 400 GPM well and 50 acres Irrigated

Item	Unit	Remaining Proportion of Soil Water before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at 400 GPM and 50 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	200	197	194	194	191	191	187
Mean Yield	bus	168	149	143	139	134	128	123
Std. Dev.	bus	16	21	23	24	24	24	25
Min. Yield	bus	129	105	89	85	84	80	71
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	18.6	14.3	13.0	12.1	10.8	10.4	10.0
Mean	inches/ac	13.2	9.9	8.9	8.3	7.7	7.1	6.4
Std. Dev.	inches/ac	3.1	2.3	2.0	1.9	1.9	1.9	1.8
Min. Applied	inches/ac	55.0	33.0	22.0	22.0	11.0	11.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	251	237	230	222	221	222	216
Mean Yield	bus	208	182	174	168	163	157	152
Std. Dev.	bus	23	25	25	25	24	24	24
Min. Yield	bus	157	128	113	107	105	104	95
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	31.2	23.4	19.9	19.1	18.2	17.8	16.9
Mean	inches/ac	23.2	17.5	15.9	14.7	13.6	12.8	11.8
Std. Dev.	inches/ac	3.7	2.8	2.5	2.5	2.4	2.3	2.3
Min. Applied	inches/ac	10.8	7.8	6.5	5.6	5.6	5.6	4.8

Table 2.21. Comparison of Simulated Variability of Subsurface Drip Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with a 300 GPM well and 50 acres Irrigated

Item	Unit	Remaining Proportion of Soil Water before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at 300 GPM and 50 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	200	195	193	193	190	190	187
Mean Yield	bus	166	151	137	131	126	121	116
Std. Dev.	bus	18	20	24	26	26	27	28
Min. Yield	bus	124	110	93	76	71	67	62
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	17.4	14.2	12.0	10.6	9.9	8.9	8.5
Mean	inches/ac	12.7	9.9	8.0	7.2	6.7	6.2	5.7
Std. Dev.	inches/ac	2.9	2.4	1.9	1.7	1.7	1.6	1.6
Min. Applied	inches/ac	54.0	27.0	18.0	18.0	9.0	9.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	246	233	226	217	218	212	212
Mean Yield	bus	202	183	165	158	152	147	143
Std. Dev.	bus	24	24	25	25	24	24	24
Min. Yield	bus	146	133	113	100	95	92	89
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	26.9	23.7	18.8	16.7	15.6	15.2	14.5
Mean	inches/ac	22.0	17.7	14.3	12.9	12.0	11.0	10.3
Std. Dev.	inches/ac	3.3	3.0	2.3	2.1	2.1	2.1	2.0
Min. Applied	inches/ac	10.3	7.4	6.4	5.0	5.0	4.3	4.3

Table 2.22. Comparison of Simulated Variability of Subsurface Drip Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with a 200 GPM well and 50 acres Irrigated

Item	Unit	Remaining Proportion of Soil Water before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at 200 GPM and 50 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	118	118	118	118	118	118	118
Mean Yield	bus	101	98	95	93	92	91	89
Std. Dev.	bus	9	10	11	12	13	13	13
Min. Yield	bus	78	73	68	64	62	62	58
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	7.6	6.1	5.2	4.3	3.8	3.8	3.1
Mean	inches/ac	4.1	3.2	2.7	2.2	2.0	1.7	1.4
Std. Dev.	inches/ac	1.7	1.4	1.2	1.0	0.9	0.9	0.8
Min. Applied	inches/ac	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	236	226	219	211	207	207	204
Mean Yield	bus	182	173	163	149	138	130	125
Std. Dev.	bus	26	24	23	23	24	25	25
Min. Yield	bus	117	113	107	99	90	79	70
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	21.3	19.4	16.8	14.9	13.0	11.3	10.2
Mean	inches/ac	17.6	15.6	13.6	11.3	9.5	8.2	7.4
Std. Dev.	inches/ac	2.5	2.4	2.2	2.1	1.8	1.6	1.4
Min. Applied	inches/ac	8.3	6.1	5.2	4.3	3.5	3.3	2.8

Table 2.23. Comparison of Simulated Variability of Subsurface Drip Irrigated Corn and Grain Sorghum Yields at Goodwell Oklahoma with a 100 GPM well and 50 acres Irrigated

Item	Unit	Remaining Proportion of Soil Water before an Irrigation						
		0.9	0.8	0.7	0.6	0.5	0.4	0.3
		Well Capacity at1100 GPM and 50 acres Irrigated						
Mean and Range of Grain Sorghum Yields								
Max Yield	bus	118	118	118	118	118	118	118
Mean Yield	bus	97	95	94	92	90	88	87
Std. Dev.	bus	12	12	12	12	13	14	15
Min. Yield	bus	68	66	65	63	59	56	52
Mean and Range of irrigation Applications for Grain Sorghum								
Max Applied	inches/ac	4.7	4.3	3.8	3.7	3.1	2.5	1.9
Mean	inches/ac	2.9	2.5	2.1	1.8	1.5	1.1	0.9
Std. Dev.	inches/ac	1.0	1.0	0.9	0.9	0.8	0.6	0.5
Min. Applied	inches/ac	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mean and Range of Corn Yields								
Max Yield	bus	219	210	204	201	199	197	195
Mean Yield	bus	141	137	133	130	125	119	110
Std. Dev.	bus	29	27	26	25	25	24	24
Min. Yield	bus	76	75	75	74	71	69	64
Mean and Range of irrigation Applications for Corn								
Max Applied	inches/ac	12.6	11.2	10.5	9.9	9.4	8.5	7.3
Mean	inches/ac	9.8	9.0	8.4	7.8	7.2	6.3	5.1
Std. Dev.	inches/ac	1.4	1.4	1.4	1.4	1.4	1.3	1.1
Min. Applied	inches/ac	5.2	3.7	3.0	2.6	2.2	2.0	1.7

Stochastic Dynamic Programming analysis of Yield and Water Use Variability

The step of conducting a discrete stochastic dynamic programming analysis of the effects of yield and water use variability with and without crop insurance on long term water use has been partly completed.

The discrete stochastic dynamic programming model by Kennedy (1986) was used to analyze crop choice between corn or grain sorghum under center pivot has been completed. In the current version of the model, in each year, the operator is assumed to select either corn or grain sorghum based on expected returns and the level of deficit irrigation. That should the producer wait until soil moisture has declined to 90, 80, 70, 60, 50, 40, or 30 percent before the next irrigation is initiated. The expected net returns from the strategy are calculated from the simulated yield distribution. The producer is expected to know the current water table and the distribution (probabilities and amounts of water use) or expected water use associated with the choice of crop and the irrigation deficit choice. For each possible choice there will be distribution of probable aquifer levels. The results of the stochastic analysis supported the general conclusions derived under deterministic linear programming. That is the producer who maximized long term (15 years or more) discounted returns from the remaining groundwater supply would choose grain sorghum over corn because grain sorghum provides higher returns to water. This is in spite of the fact that conventional static budget analysis shows that for a producer with a 600 GPM well for a 120 field would gain more revenue per acre from growing corn. The static budgets are set up on a per acre basis and measure returns to land rather than to water. The latter is becoming the more limiting resource. The model for the center pivot system will be expanded to include length of cropping history so that crop insurance can be included. This is expected to provide a measure of the groundwater cost associated with switching from corn to grain sorghum without a yield history as discussed in chapter 1.

A discrete stochastic dynamic model is being prepared for the subsurface drip system. The model will be of the same structure as the center pivot model. When completed, we will be able to present a more complete analysis of the effects of yield risk, water risk, and crop insurance effects on the optimal long term of groundwater.

Revision of Well Interference and Pumping Drawdown Estimates.

Current and previous versions of the analysis used the commonly accepted estimate of 10 feet of drawdown for every 100 GPM pumped. Recent publications by the USGS (Qi and Christenson, 2012) have included county level aquifer maps of the High Plains and the Ogallala Aquifer with hydraulic conductivity.

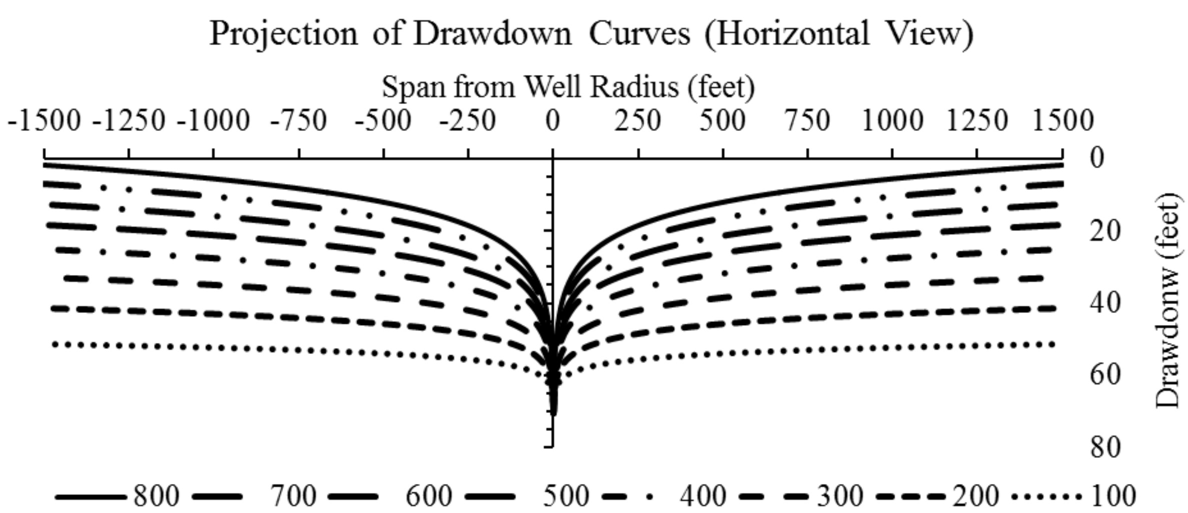


Figure 2.13. Approximate Single Well Drawdown Curves for Predetermined Discrete Set of Well Capacities that would occur after a 90-day period of pumping

These coefficients for Texas County, Oklahoma were used the Kansas State University model (Dhuyvetter and Dumler, 2011) to derive revised aquifer levels necessary to support various pumping rates.

The resulting diagrams and minimum levels of saturated thickness necessary to support 90 days of pumping are shown above in Figure 2.13 and below in Table 2.23. Compared to previous estimates, the well yields (at constant pump speed) decline faster per foot of drawdown for the higher aquifer levels and slower at the lower levels. Conversely, this means the minimum amount of saturated thickness above the safety zone for the 100 GPM well is thicker than was assumed before.

Table 2.23. Well Drawdown values in feet for predetermined well Capacities

Well Capacity (GPM)	Single Well Drawdown (feet)	Multiple Well Drawdown
800	69.55	71.41
700	63.69	65.70
600	57.83	59.44
500	51.80	52.50
400	44.81	45.67
300	36.60	37.62
200	27.98	28.27
100	16.73	16.82

The revised pumping costs and drawdown curves are being tested in a mixed integer programming model of a 640 acre Texas County parcel in an MS thesis. The thesis is partially completed. The nature of the results is similar to those obtained previously. Sorghum is selected over corn as water becomes limiting relative to land. When a producer downsizes the irrigated area (buys 2 pivots rather than 4 at replacement time), the area of irrigated land may become limiting relative to water and corn may be grown for a few years until declines in the well output limit the supply of water and sorghum is again grown. The optimal switching between irrigated corn and sorghum as the water table declines and the size of the irrigated land is reduced has implications for crop insurance.

Economic Modeling of Irrigated Corn vs. Grain Sorghum Using Center Pivot or Subsurface Drip Systems

Final Report to OWRRI at Oklahoma State University

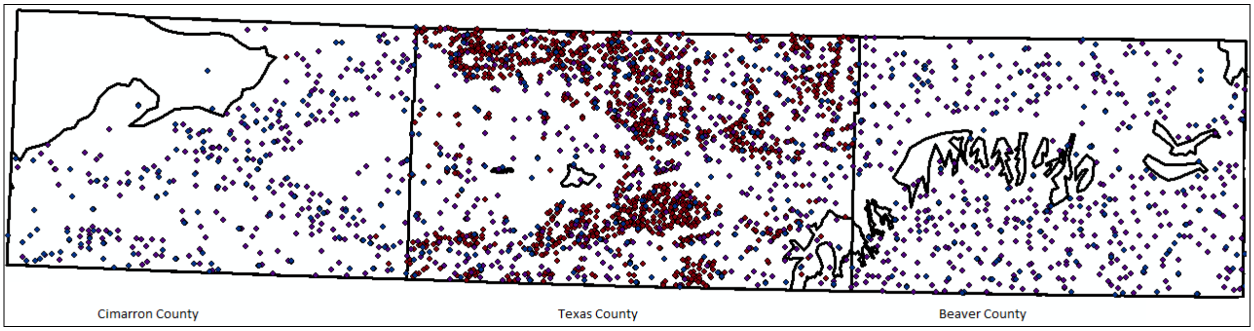
August 31, 2015

By

Dr. Art Stoecker, Associate Professor, Department of Agricultural Economics, Oklahoma State University, Stillwater, OK 74078
Karthik Ramaswamy, Graduate Research Assistant, Department of Agricultural Economics, Oklahoma State University, Stillwater, OK 74078
Dr. Jason Warren, Associate Professor, Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK 74078
Dr. Rodney Jones, Professor, Department of Agricultural Economics, Oklahoma State University, Stillwater, OK 74078
Dr. Jody Campiche, Professor, Department of Agricultural Economics, Oklahoma State University, Stillwater, OK 74078
Andrew Paul, Graduate Research Assistant, Department of Agricultural Economics, Oklahoma State University, Stillwater, OK 74078
Brooke Lane, Undergraduate Assistant, Department of Agricultural Economics, Oklahoma State University, Stillwater, OK, 74078

Introduction

The study area concerns the Ogallala Aquifer that underlies parts of Cimarron, Texas, and Beaver counties in the Oklahoma Panhandle. This area is intensively irrigated and there has been state and national concern over the fate of the Ogallala or Great Plains Aquifer (USGS). Figure 1 below shows the three county study area with the underlying Ogallala Aquifer and the location of wells in Cimarron, Texas, and Beaver counties.



Source: Geospatial Data Gateway and USGS website

Figure 1. Cimarron, Texas, and Beaver County Study Area with Wells and an Outline of the Ogallala Aquifer under the Oklahoma Panhandle

Both the USGS and the Oklahoma Department of Water Resources conduct measurements on water tables in wells. The USGS began publishing an annual series of water levels in wells in the High Plains Aquifer (Ogallala) across Colorado, Kansas, Nebraska, Oklahoma, Texas, and Wyoming in 1994. A simple average of the water levels measured in Beaver, Cimarron, and Texas counties is shown in Figure 2 below. The graph shows the trend is downward with considerable variation between years. A simple trend analysis shows the following water table declines in Beaver, Cimarron, and Texas counties were;

Beaver, County: 92.7 + 2.59 Yr, $r^2 = .68$,
Cimarron, County: 180.7 + 0.94 Yr, $r^2 = .28$, and
Texas, County: 178.4 + 1.87 Yr, $r^2 = .65$

The trend analysis shows that while the depth to the static water table was smaller in Beaver County, they have a greater rate of decline (2.59 feet per year) than do the deeper wells in Texas and Cimarron counties. The year to year variability is due in part to weather and in part to the fact that the location of all wells sampled changes from year to year.

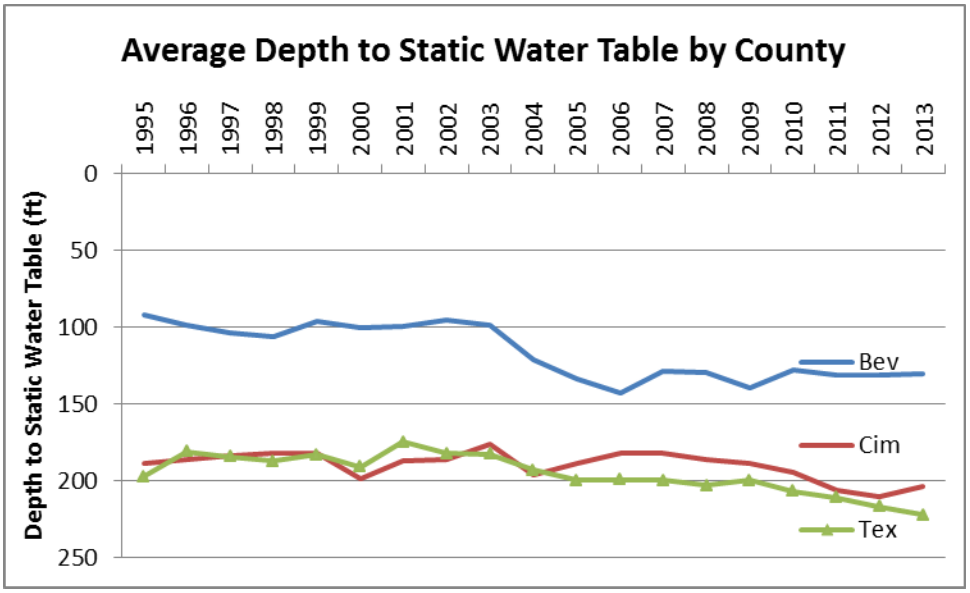


Figure 2. Average Depth to the Static Water Table in Wells in Beaver, Cimarron, Texas Counties from 1994 through 2013 as reported by the USGS.

Tex Co 178.4 + 1.87 Yr, R^2 = .65, Cim. Co. 180.7 + 0.94 Yr, R^2 = .28
Bev. Co. 92.7 + 2.59 Yr, R^2 = .68

A longer trend from 1950 would show greater declines in the level of the Ogallala in the Oklahoma Panhandle. The recharge rate to the aquifer in the Panhandle is dependent upon percolation of limited rainfall and has been estimated to be between 0.25 and 0.5 inches per year (Guru, 2000).

Luckey and others suggested that if withdrawal continued at the same rate as in 1996, the water level would decrease by an additional 20-25 feet under the Oklahoma Panhandle by 2020 (Luckey, et al. 2000). USGS found that water levels declined by as much as 100 feet under the Oklahoma Panhandle between the 1940s and the 1990s.

A primary problem for producers in the Oklahoma Panhandle is depleting ground water and ravaging droughts. The source of the irrigation water in Oklahoma Panhandle is the Ogallala aquifer. In Oklahoma, irrigation accounts for 86% of the withdrawal from the Ogallala aquifer (OWRB, 2012). It is in a state of disequilibrium, as the natural recharge to the aquifer is much less than the annual withdrawals. The continued decline in the water table causes the cost of pumping to increase. By 1989, Lacewell and Lee noted the cost of pumping irrigation water had increased from $5.98 per acre-foot in 1969 to $63.96 per acre-foot in 1988 for sprinkler irrigation (Lacewell and Lee, 1989). In response, many producers in the panhandle adopted advanced irrigation systems such as Pivot Systems and low energy precision application (LEPA) systems.

The panhandle's saturated stratum has relatively low permeability, which is the ultimate reason for the rapid water table decline. The Ogallala aquifer is an unconfined aquifer, under normal conditions in an unconfined aquifer the water percolation from the land surface is expected to freely join the saturated zone. However, due to poor permeability in the Ogallala aquifer and clay-soil characteristics the recharge rate is negligible or none. The recharge rate has been estimated to be between 0.25 to 0.5 inches per year (Guru, 2000).

Study Objectives

The overall objective of the economic portion of this study was to determine comparative advantages of irrigated corn relative to sorghum and the comparative advantages of center pivot irrigations systems relative to subsurface drip irrigation to aid producers to gain the maximum value from their remaining groundwater reserves. More specifically the objectives are to compare,

a. Long-term values and aquifer life with center pivot irrigated corn.
b. Long-term values and aquifer life with subsurface drip irrigated corn.
c. Long-terms values and aquifer life with center pivot irrigated grain sorghum.
d. Long-term values and aquifer life with subsurface drip irrigated grain sorghum.

Study Methods

The remaining ground water reserve could last from a few years to more than 50 years. The weather in the Oklahoma Panhandle is also highly variable. The analysis required estimates of crop yields and water use under a wide range of weather conditions. Actual observed and measured data relating to crop yields and water use are available for only limited periods of time. In addition future weather patterns are uncertain. Data sets reflecting alternative climate change values for the regions like the Oklahoma Panhandle are just becoming available. The approach followed was to use the EPIC (Environmental Policy Impact Calculator) simulation model to generate yields using a 50 year historical weather set for Goodwell, Oklahoma.

Construction of a 50 year daily weather set for Goodwell, Oklahoma

EPIC can utilize daily weather variables such as minimum temperature, maximum temperature, precipitation, relative humidity, solar radiation, and wind speed. EPIC will operate on daily precipitation, minimum daily temperature and maximum daily temperature. In this case, the remaining values are simulated. It was assumed a better data set could be obtained by using as much actual available weather data as possible from the area.

Two daily weather data sets were constructed for Goodwell, Oklahoma. A twenty-one year data set was constructed for the period from 1/1/1994 – 11/30/2014. This data set was based on the Oklahoma MESONET data for Goodwell, Oklahoma which can provide all of the variables listed above. Unfortunately the MESONET temperature values were not reported until February of 1997. In addition, there were many missing values for the remaining variables. Missing values were estimated by multiple regressions from the surrounding weather stations and MESONET stations with MESONET data from Hooker (in Texas County) and Boise City (in Cimarron County).

Construction of the 50 year daily weather file was more problematic. During the 50 year period from 1/1/1965 to 11/30/2014 there were many changes in weather stations and in the data collected. Variables like relative humidity, wind speed, were only reported by larger federal weather stations like Dodge City and Garden City Kansas, Amarillo, Texas, and from the airport at Liberal, Kansas. Solar Radiation data were not available outside the 1994-2014 period from the MESONET sites. Completion of the data set for the individual weather variables was done on a case by case basis.

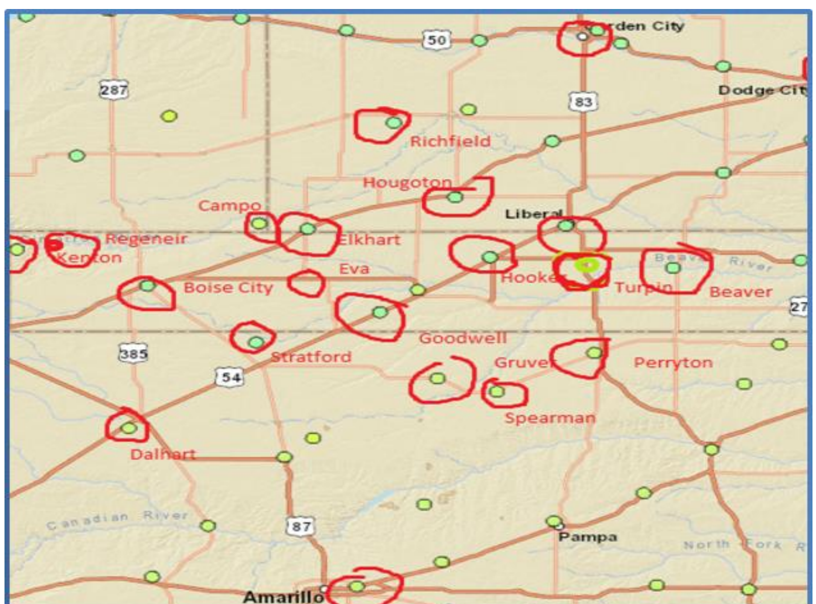


Figure 3. Locations of sites around Goodwell where Weather Variables were Obtained to Estimate Missing Goodwell Values

A common approach is to use inverse distance weighting of values from surrounding reporting sites to fill in data gaps. However this approach only uses the information in the weather values on a given day and does not use any statistically estimated relationships between sites where all data are present. A multiple regression was used in this study. Figure 3 above shows the locations of sites around Goodwell, Oklahoma where one or more weather values are reported. In order to estimate a missing temperature value for Goodwell, temperature values were obtained from Hooker, and Boise City in Oklahoma, and Liberal and Elkhart in Kansas, and Amarillo, and Perryton Texas. An OLS regression of the reported Goodwell temperature was regressed against the reported daily values (independent variables) as follows;

$$GW_t = a\ Hk_t + b\ BC_t + e\ Li_t + d\ Ek_t + ePy_t + f\ Am_t,$$

where the respective variables GW, Hk, BC, Li, Ek, Py andAm represent observations form Goodwell, Hooker, Boise City, Liberal, Perryton and Amarillo respectivelyThe estimated regression was then used to predict missing Goodwell temperature values. The limitation of the process is that the reported weather series from other locations also contain data gaps. If one of the independent sites has a missing value on the same day as Goodwell, then the regression cannot be used to estimate the Goodwell temperature. This problem was solved by estimating additional regression equations by omitting one of the independent variable. In some cases it was necessary to omit more than two variables. The equations were then ranked in order of decreasing r-square values. On days where the equation with all independent variables could not be used because one or more of the independent weather values was missing, the next best equation with no missing values was used. The estimation and predictions were carried out using SAS 9.1. SAS will not make a prediction on days when the values for one or more of the independent variables are missing.

Minimum Daily Temperature:

Goodwell was the dependent variable. The independent variables were Hooker, Boise City, Elkhart, Gruver, and Stratford. The estimated regression equations were,

$$GWm_t = -.54 + .057\,Hk_t + .279\,Elk_t + .242\,BC_t + .184\,Gru_t + .254\,Str_t, \quad r^2 = .96$$
$$GWm_t = .003 + .292\,Elk_t + .247\,BC_t + .196\,Gru_t + .280\,Str_t, \quad r^2 = .96$$
$$GWmt = .033 + .086Hk_t + .266BC_t + .266\,Gru_t + .318\,Str_t, \quad r^2 = .96$$
$$GWmt = -.154 + .044\,Hk_t + .389Elk_t + .244Gru_t + .329\,Str, \quad r^2 = .96$$
$$GWmt = .047 + .070Hk_t + .336Elk_t + .286BC_t + .326\,Str_t, \quad r^2 = .96$$
$$GWmt = -.193 + .107Hk_t + .324Elk_t + .310BC_t + .273Gru_t, \quad r^2 = .96$$

All coefficients were significant at the 10 percent level or better.

Maximum Daily Temperature:

The stations used as independent variables in the estimation of missing Goodwell maximum daily temperature values were the same as above for the minimum temperature. The estimated equations were,

$$GWmx_t = -.043 + .383Hk_t + .021\,Elk_t + .096\,BC_t + .017\,Gru_t + .487\,Str_t, \quad r^2 = .95$$
$$GWmx_t = -.319 + ,111\,Elk_t + ,130\,BC_t + .208\,Gru_t + ,567\,Str_t, \quad r^2 = .94$$
$$GWmx_t = -.066 + ,393\,Hk_t + .100\,BC_t + .015\,Gru_t + .496\,Str_t, \quad r^2 = .95$$
$$GWmx_t = .142 + 396\,Hk_t + .060\,Elk_t + .037Gru_t{*} + .504\,Str_t, \quad r^2 = .95$$
$$GWmx_t = -.026 + .392\,Hk_t + .025\,Elk_t + .099\,BC_t + .489\,Str_t, \quad r^2 = .95$$
$$GWmx_t = .720 + .403\,Hk_t + .336\,Elk_t + .033\,BC_t + .185\,Gru_t, \quad r^2 = .90$$

Unless indicated (*) all coefficients are significant at the 10% level or better.

Precipitation:

Daily precipitation was the hardest variable to estimate because of the unevenness of the rainfall over the High Plains area. The stations used as independent and dependent variables are listed below. Thirty-minute rainfall was reported by the Goodwell station for some of the dates. On some days when the daily total was missing, and there were two or more periods of 15 minute rainfall reported, an estimate for the day's rainfall, based on the reported 15 minute rainfall and the time of year, during the missing period could be made. However, there were still

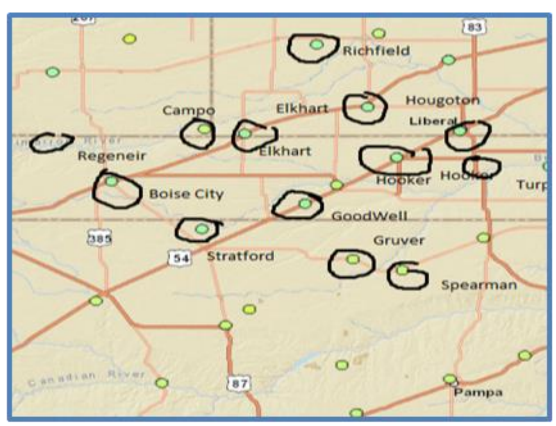


Figure 4. Location of Daily Rainfall Values used in the Regression Equations

many gaps in the precipitation values from the independent sites used in the regression. The approach was to collect all reported daily rainfall values between 1965 and the present from locations as near Goodwell as possible. Data were used from the stations circled on the map in Figure 3. The estimated regression equations were,

$$GWp_t = .352\,Str_t + .110\,Elk_t + .071Gru_t + .198\,Eva_t - .030\,Hug + .112Spr + .062\,Rch + .09DwtWrn_t^{*},\ r2 = .59$$
$$GWp_t = .189Str_t + .051\,Elk_t + .100\,Gru_t + .095Eva_t + .030Hug + .030Spr + .029\,Rch + .371DwtWrn_t,\ r2 = .59$$
$$GWp_t = .031\,Elk_t + .045\,Hug - .169\,Rch + .799\,DwtWrn_t,\ r2 = .46$$
$$GWp_t = .029Elk_t + .051Hug + .016Spr + .776\,DwtWrn_t,\ r2 = .44$$

The respective sites used were Stratford, Texas (Str), Elkhart, Kansas (Elk), Gruver, Texas (Gru), Eva, Oklahoma (Eva), Hugoton, Kansas (Hug), Spearman, Texas (Spr), and Richfield, Kansas (Rch). All coefficients are significant at the 10 percent level or better unless indicated (*).

The variable DwtWrn (inverse distance weighted rainfall) was not significant in the first equation, but was significant in the remaining three equations. The r-square values are in the .4-.5 range. It is notable that on days when all stations were reporting observations, the inverse distance weighting method was not significant. When only a few stations were available, the values of those stations were significant along with the inverse weighted distance value.

Relative Humidity:

Weather stations in the Central High Plains with long reported records of relative humidity (or dewpoint temperature) were limited. The regressions below utilize data from Liberal, Kansas, Elkhart, Kansas, Dalhart, Texas, and Clayton, New Mexico. Relative humidity data were only estimated from 1973-2014.

The regressions obtained were,

$$GWh_t = 6.92 + .313\,Li_t + .116\,Am_t + .062\,Da_t + .314\,Elk_t + .255Cy_t,\quad r^2 = .81$$
$$GWh_t = 8.53 + .321\,Li_t + .174\,Am_t + .491\,Da_t,\quad r^2 = .74$$
$$GWh_t = 10.23 + .423\,Li_t + .501Am_t,\quad r^2 = .69$$

Wind Speed:

Prior to the establishment of the MESONET in 1994, the Goodwell Research station was one of the few places in the study area reporting wind speeds. Unfortunately, there were many gaps in this data. Wind speed was recorded by the airport at Liberal, Kansas but the data were not electronically available before 1973. Amarillo, Texas, Dodge City and Garden City, Kansas (Figure 5) had wind

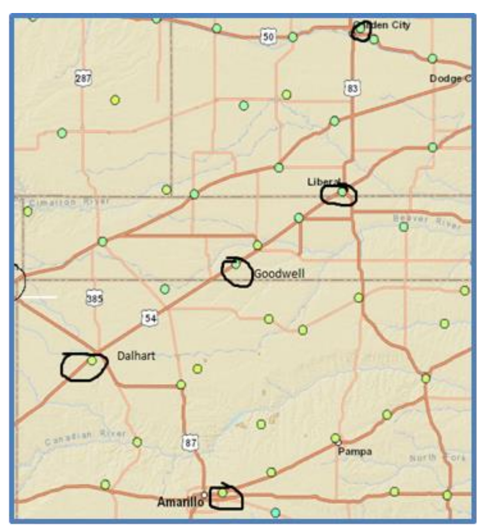


Figure 5. Location of Stations Reporting Windspeeds used in the Regression Analysis

speed records dating back to 1965. The estimated regression equations were,

$GWWt = -0.226 + 0.236\ Gc_t + 0.313\ Cy_t + -0.003\ Am_t + 0.183\ Dh_t + 1.196\ DC_t + 0.085\ Li_t$, r^2=0.41
$GWW_t = -0.104 + 0.361\ Cy_t + -0.003\ Am_t + 0.187\ Dh_t + 1.325\ DC_t + 0.109\ Li_t$, r^2= 0.41
$GWW_t = -0.150 + 0.303\ Gc_t + 0.000\ Am_t + 0.399\ Dh_t + 1.169\ DC_t + 0.076\ Li_t$, r^2= 0.37
$GWW_t = -0.226 + 0.236\ Gc_t + 0.314\ Cy_t + 0.182\ Dht + 1.197DC_t + 0.086\ Li_t$, r^2= 0.41
$GWW_t = -1.01 + 0.252\ Gc + 0.419\ Cy_t -0.0003\ Am_t + 1.202\ DC_t + 0.115Li_t$, r^2= 0.41
$GWW_t = 0.790 + 1.070\ Gc_t + 0.287\ Cy_t -0.005\ Am_t + 0.276\ Dh_t + 0.266\ Li_t$, r^2= 0.36
$GWW_t = -0.396 + 0.273\ Gc_t + 0.320\ Cy_t -0.004\ Am_t + 0.218\ Dh_t + 1.235\ DC_t$, r^2= 0.41
$GWW_t = -2.80 + 0.004\ Am_t + 1.852\ Dct$ r^2= 0.40

The respective cities were Garden City (GC), Clayton, New Mexico (Cy), Amrillo, Texas (Am), Dalhart, Texas (Dh), Dodge City, Kansas (DC), and Liberal, Kansas (Li).

Solar Radiation:

Solar Radiation data covers only the period from 1994 through the present and was found only at the more recent MESONET sites. The missing Goodwell MESONET solar radiation values were estimated by the following regressions based on data at Beaver and Boise City. The regression equations estimated were,

$GWS_t = -0.182 + 0.450\ BV_t + 0.561\ BCt$, r^2= 0.961
$GWS_t = 1.660 + 0.939\ BV_t$, r^2= 0.908
$GWS_t = -0.126 +0.985\ BC_t$, r^2= 0.923.
All coefficients significant at the 10 percent level or better.

The monthly mean values along with their standard deviations, maximum observed value, and maximum observed values for each month are shown below in Table 1.

Table 1. Fifty Year Averages of Monthly Means and Standard Deviations of the Daily Goodwell Weather set.

Item and Unit	Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Max. Daily Tmp Celsius	Mean	9.1	11.3	15.9	21.1	25.9	31.4	34.1	32.8	28.5	22.4	15.0	9.6	21.5
	Sdev	8.1	8.3	7.9	6.8	6.0	5.0	3.9	4.2	5.7	6.7	7.3	7.9	11.0
	MinObs	-13.3	-16.7	-12.5	-6.1	4.4	12.2	17.2	15.0	4.4	-6.1	-12.2	-17.2	-17.2
	MaxObs	27.2	30.6	34.4	37.8	39.6	43.9	42.1	42.2	42.8	35.8	31.7	32.7	43.9
Min. Daily Tmp. Celsius	Mean	-7.0	-5.3	-1.2	4.0	9.5	15.2	18.0	17.1	12.4	5.3	-1.3	-5.9	5.1
	Sdev	5.3	5.3	5.1	4.6	4.2	3.4	2.4	2.5	4.2	4.5	4.8	5.3	9.9
	MinObs	-25.6	-23.9	-19.0	-12.8	-4.3	4.4	8.3	7.2	-2.2	-11.7	-20.6	-25.0	-25.6
	MaxObs	17.8	9.4	22.2	23.3	32.8	33.9	24.5	23.4	23.3	20.6	10.7	10.4	33.9
Monthly Precp mm	Mean	7.6	10.3	25.4	34.1	67.8	64.2	58.8	58.4	36.9	32.4	14.8	11.3	34.7
	Sdev	1.2	1.7	3.2	4.3	7.6	6.1	6.2	6.1	5.1	5.0	2.4	2.0	4.8
	MinObs	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	MaxObs	17.8	23.6	38.4	46.0	91.4	49.8	76.7	80.3	74.7	86.9	28.7	53.3	91.4
Daily Rel. Hum. proportion	Mean	0.6	0.6	0.6	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
	Sdev	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
	MinObs	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.3	0.1	0.2	0.2	0.1	0.1
	MaxObs	1.0	1.0	1.0	1.0	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Daily Wind Speed m/sec	Mean	9.1	9.5	10.6	11.1	9.9	9.7	8.9	8.4	8.9	9.1	9.1	9.2	9.5
	Sdev	2.8	3.1	3.5	4.1	4.0	3.8	3.3	3.8	3.8	3.9	3.2	2.8	3.6
	MinObs	2.4	2.1	3.2	1.2	0.3	0.1	0.1	0.5	1.0	0.8	0.1	2.3	0.1
	MaxObs	26.3	25.5	25.2	30.7	27.4	31.3	28.6	75.5	27.3	33.3	26.2	22.1	75.5
Daily Solar Rad. Wats/m^2	Mean	10.8	13.7	17.8	24.5	26.4	25.4	22.2	19.3	15.2	11.6	9.9	18.3	22.2
	Sdev	3.0	4.2	5.5	6.5	5.2	4.9	5.0	4.6	4.4	3.3	3.0	7.4	6.1
	MinObs	1.3	1.3	1.8	2.0	3.1	3.4	4.2	2.3	1.1	1.2	0.5	0.5	2.3
	MaxObs	15.8	21.1	26.1	33.4	32.7	32.1	30.1	26.4	21.7	17.1	20.2	33.4	31.3

Simulated Yields

In this section, the Environmental Policy Impact Calculator (EPIC) yield responses using historical 50-year daily weather data at Goodwell are compared with experimental results from the Oklahoma Panhandle, Southwest Kansas, and the Texas Panhandle. The EPIC simulated yields were averaged over the 50 year weather period (1965-2014). The planting date and the harvesting date for both corn and grain sorghum was held constant for each year. For grain sorghum, the previous studies and experiments from Bushland, Texas, Goodwell, Oklahoma, Guymon, Oklahoma, Tribune, Kansas, and Garden City, Kansas suggests that the reasonable planting date (end of May or Beginning of June) is May 28, and harvested (end of October) on October 31. The plant population for corn and sorghum was 52,000 plants ac^{-1} and 32,000 plants ac^{-1} respectively, also held constant each year. The corn and grain sorghum yields under the center pivot were obtained from the EPIC simulations results where a 36 mm application could be applied any time after the minimum number of days since the previous application if the soil moisture was also below an irrigation stress level. The irrigation triggers (1- stress level) were .9, .8, .7, .6, .5, .4, and .3. The purpose of the irrigation triggers was to test if less than full irrigation would be profitable in the long run. The minimum days between irrigations for each size of well and the application levels when an irrigation did occur are shown in Table 2.

Table 2. Center Pivot System Irrigation Frequency and Application Rates

Well Capacity	**Frequency**		
GPM	**DAYS**	**inches**	**mm**
800	4	1.42	36.00
700	5	1.42	36.00
600	6	1.42	36.00
500	7	1.42	36.00
400	8	1.42	36.00
300	11	1.42	36.00
200	16	1.42	36.00
100	32	1.42	36.00

The subsurface drip was simulated under the assumption of a constant amount per acre being applied every day if the water depletion level was below the allowable limit. The amount per day was determined by spreading the output per well across fields of 50, 75, 100, 125, or 150 acres. As field size is increased, the amount applied per day declines. The yields can be expected to decline with an increase in field size. The amounts applied per day are shown in Table 3.

Table 3. Subsurface Drip System Irrigation Frequency and Application Rates

	Field Size	Maximum Daily Application									
		50 acres		75 acres		100 acres		125 acres		150 acre	
GPM	**DAYS to apply**	**inches**	**mm**	**inches**	**mm**	**inches**	**mm**	**inches**	**mm**	**inches**	**mm**
800	1	0.87	22	0.59	15	0.43	11	0.35	9	0.31	8
700	1	0.75	19	0.51	13	0.39	10	0.31	8	0.28	7
600	1	0.67	17	0.43	11	0.35	9	0.28	7	0.24	6
500	1	0.55	14	0.35	9	0.28	7	0.24	6	0.20	5
400	1	0.43	11	0.31	8	0.24	6	0.20	5	0.16	4
300	1	0.35	9	0.24	6	0.16	4	0.16	4	0.12	3
200	1	0.24	6	0.16	4	0.12	3	0.12	3	0.08	2
100	1	0.12	3	0.08	2	0.08	2	0.08	2	0.04	1

Results of Yield Simulation for Center Pivot System (CPS):

Actual irrigation research experiments with current corn and grain sorghum varieties are limited to a few locations over relatively short time periods. For the Panhandle research and extension site, this period was 2005-2014. Weather occurring during the 2005-2014 period will not have the same mean and variability as might be expected over the next 50 years. The purpose of the simulation was to extend and estimate yields of irrigated corn and grain sorghum that would occur under weather patterns of the past 50 years in the Oklahoma Panhandle counties and under irrigation levels not directly tested by budget limited experiments. The 50 year mean yields and irrigation water use by irrigated corn and grain sorghum using CPS are shown respectively in Tables 4 and 5 below. Mean yields of irrigated grain sorghum varied from 162.8 bushels (800 GPM well, irrigation trigger of .9) to 87.5 bushels per acre (100 GPM well, irrigation trigger of .3). The respective average annual irrigation amounts varied from 15.6 to 2.2 acre inches. It must be remembered that the yields present a static annual view but producers face a dynamic situation as the water table, and consequently the well capacity, declines annually.

Table 4. Results from EPIC Simulation of Irrigated Sorghum Yields and Irrigation rates Using Center Pivot System on a 120 acre Quarter Section

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**	**0.30**	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**
800	122.1	124.9	129.0	138.6	148.7	156.5	162.8	8.3	8.6	9.2	9.2	12.6	14.2	15.6
700	122.4	125.3	129.1	137.3	145.3	150.9	155.7	8.2	8.5	9.1	10.3	11.8	13.0	14.1
600	122.3	125.2	128.5	134.0	139.6	144.6	148.4	8.2	8.5	9.0	10.0	10.7	11.9	12.6
500	120.5	123.5	126.0	129.6	134.1	137.5	141.1	8.0	8.3	8.8	9.3	9.8	10.8	11.3
400	116.9	119.7	122.4	124.6	128.6	131.4	133.8	7.7	8.0	8.3	8.6	9.4	9.9	10.4
300	104.8	107.0	108.7	110.4	112.3	115.0	117.2	6.5	6.8	7.1	7.3	7.6	7.8	8.3
200	88.4	89.1	89.6	90.1	90.5	91.1	92.0	2.9	3.1	3.2	3.3	3.4	3.6	4.1
100	87.5	87.8	87.9	88.1	88.2	88.3	88.5	2.2	2.3	2.4	2.4	2.5	2.6	2.8

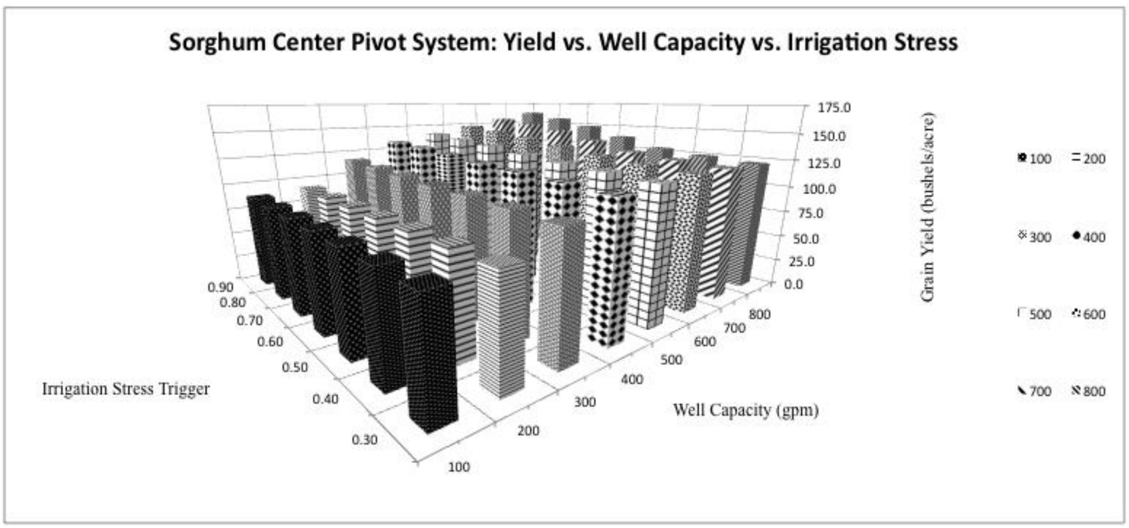


Figure 6. Simulated EPIC Grain Sorghum Yields with a 120 Acre Center Pivot Irrigation by Well Capacity when Irrigation Occurs if Soil Moisture Level Reach Specified Levels

The 50 year mean irrigated corn yields simulated by EPIC varied from 213.4 bushels (800 GPM well and a .9 irrigation trigger) to 96.8 bushels simulated with a 100 GPM well and a .3 irrigation trigger. With low GPM wells, the irrigation trigger had little effect with the center pivot simulation because the moisture level was usually below the trigger by the time the pivot could complete the revolution. That is the pivot system was usually in motion.

Table 5. Results from EPIC Simulation of Irrigated Corn Yields and Irrigation rates Using Center Pivot System on a 120 acre quarter section

	Irrigation Trigger													
GPM	**Yields (bushels/acre)**							**Gross Irrigation (acre-inches)**						
	0.30	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**	**0.30**	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**
800	159.3	163.4	166.9	180.8	193.9	206.3	213.4	14.6	15.3	16.2	18.8	21.5	22.5	22.5
700	158.4	161.9	165.1	176.0	186.3	194.6	198.9	14.6	15.3	16.1	18.0	20.4	22.1	23.1
600	156.9	159.8	163.0	170.7	177.2	182.9	186.9	14.6	15.0	15.9	17.2	19.0	20.4	21.6
500	153.8	156.1	158.3	162.2	168.4	172.4	175.0	14.1	14.6	15.3	16.0	17.4	18.6	19.5
400	148.5	150.1	152.1	154.7	157.7	161.2	164.4	13.5	13.9	14.4	15.0	15.9	17.0	17.6
300	133.7	134.9	136.9	138.4	139.3	141.2	142.6	11.0	11.3	11.8	12.3	12.8	13.4	13.9
200	117.5	117.7	118.9	119.2	120.1	121.2	122.2	8.7	8.8	9.1	9.4	9.7	10.1	10.3
100	96.8	97.7	98.1	98.1	98.4	98.9	99.1	5.4	5.5	5.7	5.8	5.9	6.0	6.1

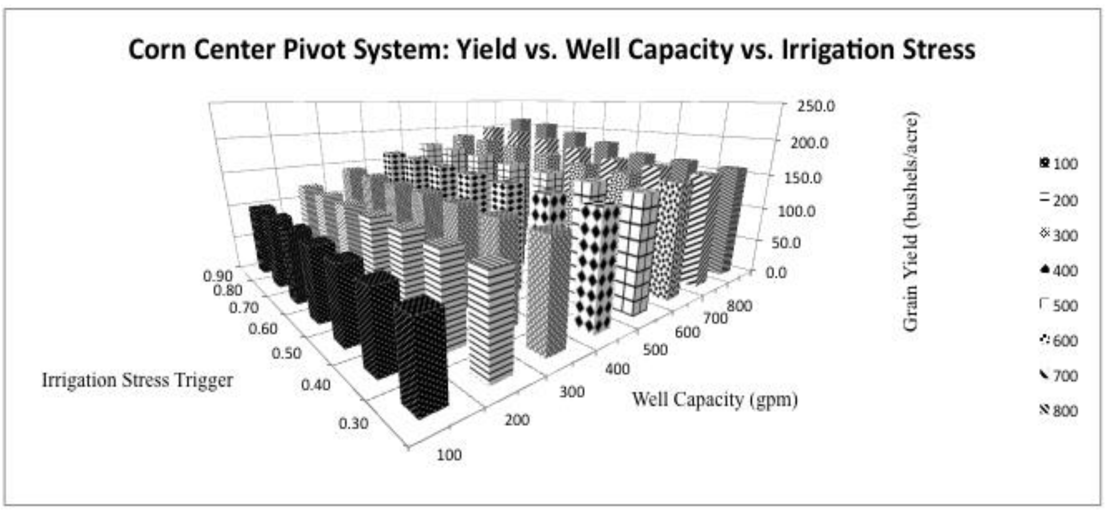


Figure 7. Simulated EPIC Corn Yields with 120 Acre Center Pivot Irrigation by Well Capacity when Irrigation occurs when Soil Moisture Levels fall below the Indicated levels.

Comparison of Simulated Yields and Water Use with Existing Experimental and Variety Trial Results

The general objective of variety trials is often to compare maximum yields among varieties. The averages of irrigated variety trials conducted at Goodwell, Oklahoma, Hereford, Texas, and Garden City, Kansas were used to check the simulated full irrigation yields of corn and grain sorghum. This was done by comparing the EPIC yields for the specific years when variety trials were conducted at the various locations. Variety trial results were available at Goodwell from 2005 through 2014. In Figure 8 below, the EPIC yields for each year from 2005-2014 are compared with the variety trial yields for those years. The simulated yields assume continuous irrigated production whereas crop rotations are often involved with the variety trials. The EPIC simulated corn yields followed the variety trial results reasonably well and caught the 2011 downturn but not the 2014 decline.

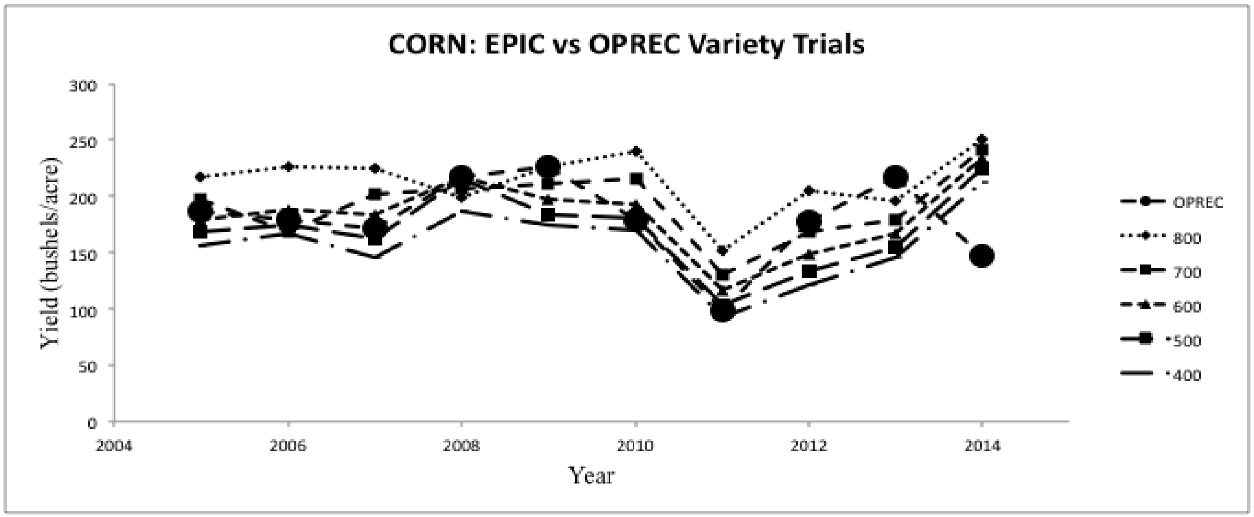


Figure 8. Results from EPIC corn simulation full irrigation comparing with OPREC Variety Trials

The simulated sorghum yields miss the downturn in 2011 but match the upturn in sorghum yields in 2013 and 2014. There are items related to planting dates and soil moisture conditions involved in the trial that cannot readily be simulated.

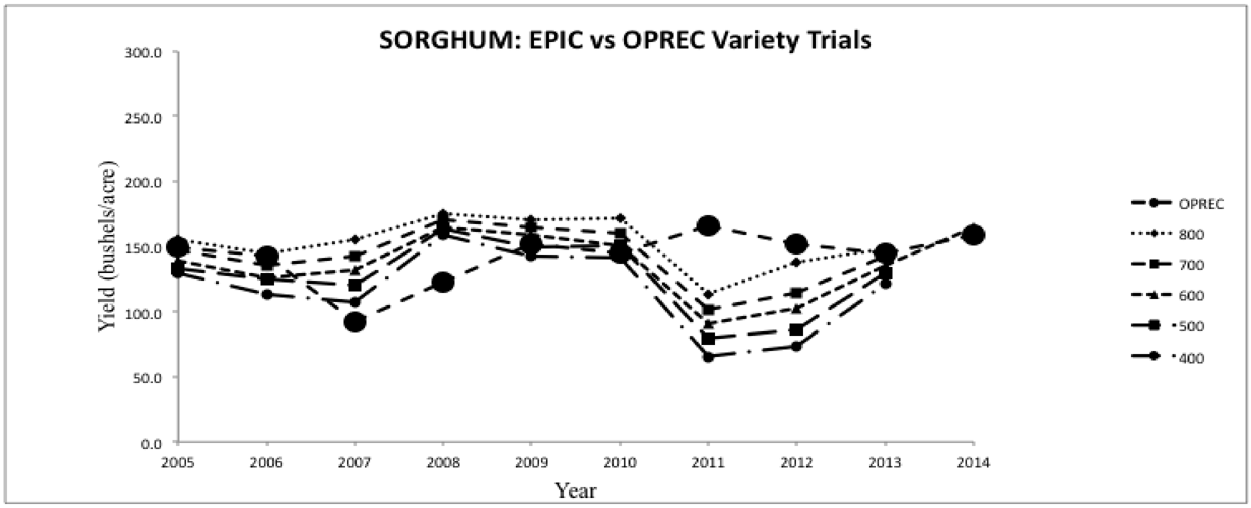


Figure 9. Results from EPIC sorghum simulation full irrigation comparing with OPREC Variety Trials

Water Use Efficiency

The simulated full (.9 trigger) yields and irrigation quantities by well capacity for corn and sorghum are shown below in Figure 10. As expected the corn yields and irrigation requirements for corn are greater than for sorghum.

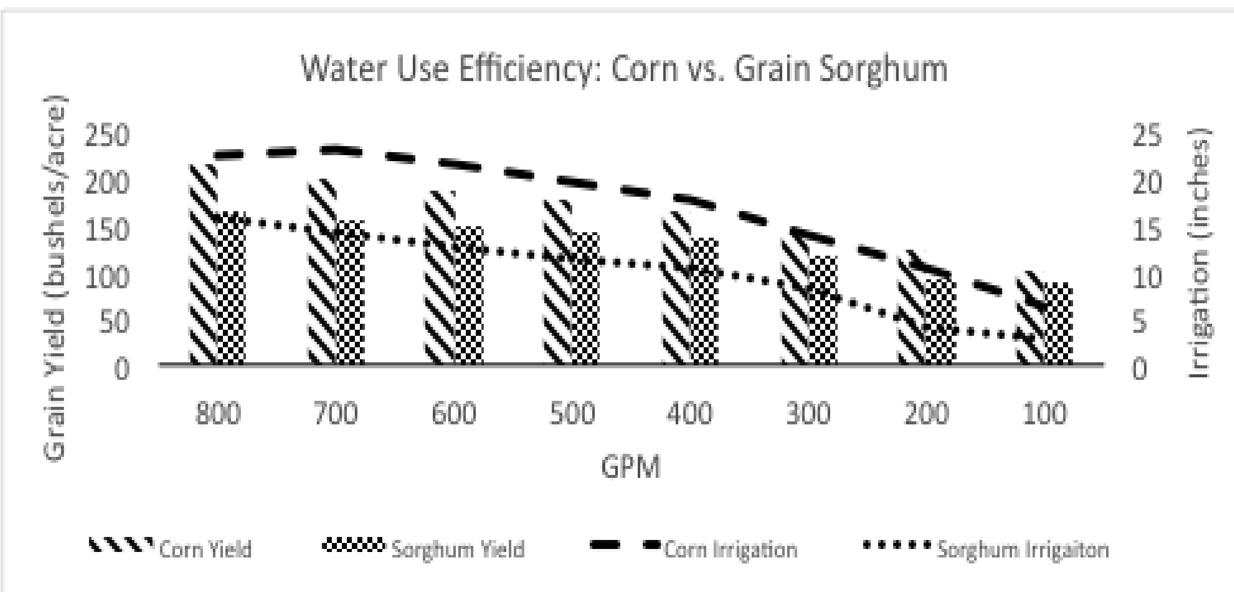


Figure 10. Results from EPIC Corn and Sorghum simulation full irrigation showing its water use efficiency.

The relative grain sorghum yields with irrigation plus rainfall from the simulation are compared with similar results in Garden City, Kansas (Figure 11a) and with an experiment at

Bushland, Texas (Figure 11b) below. The EPIC simulated yields are below those at Garden City where it is assumed there would less evapotranspiration than at Goodwell but approximately equal to those at Bushland where the expected transpiration would be somewhat higher than for Goodwell.

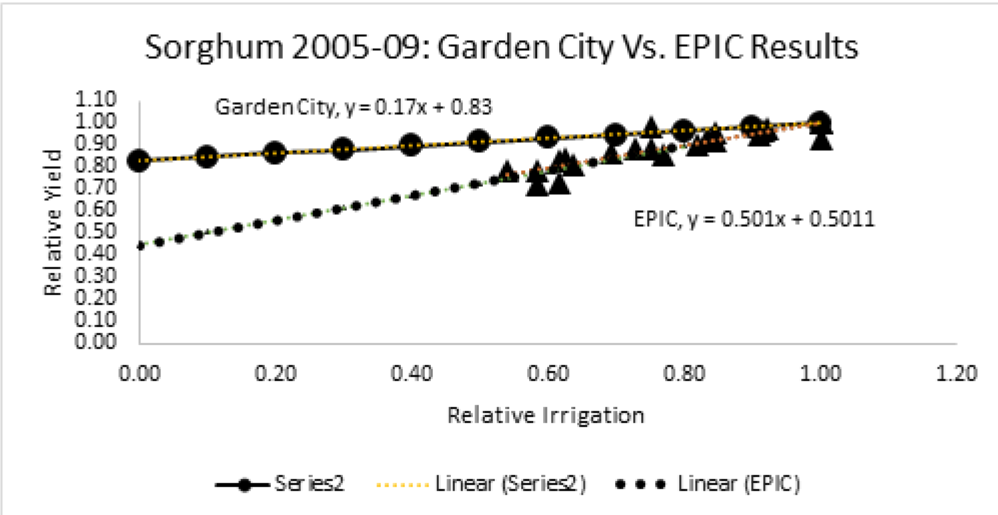


Figure 11a. Results from EPIC Sorghum Simulation as compared to Experimental Data from Garden City, Kansas

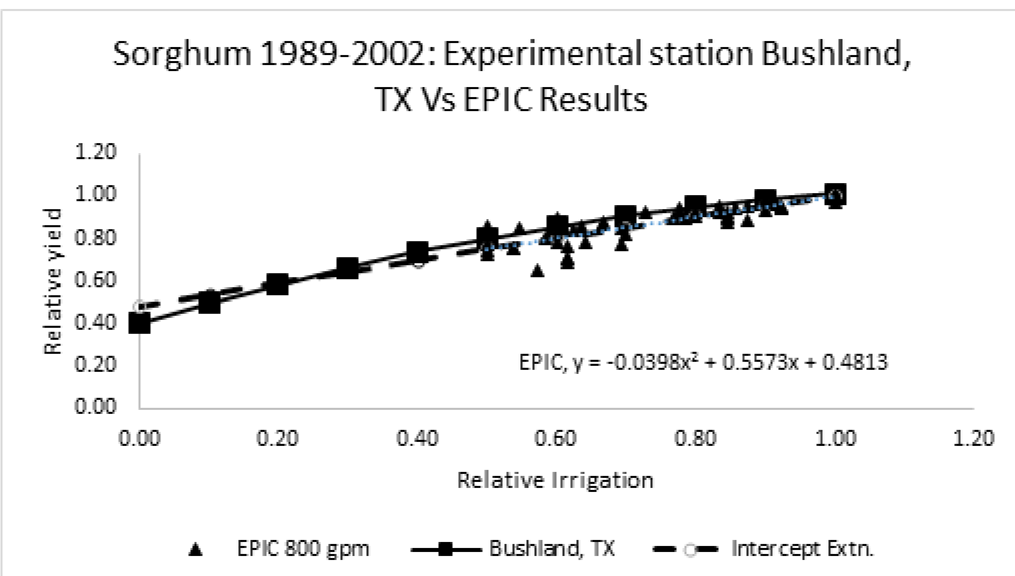


Figure 11b. Results from EPIC Sorghum Simulation as compared to Experimental Data from Bushland, Texas.

SUBSURFACE DRIP SIMULATION RESULTS

Simulations of Subsurface Drip Irrigated Grain Sorghum

There are large economies of size with the center pivot system so only one size was simulated. There are economies of size with the subsurface drip system but of a smaller magnitude than with the pivot system, thus the producer is more likely to consider the capacity of the well in selecting the size of the area to be irrigated by a subsurface drip system. Field sizes of 50, 75, 100, 125, and 150 acres were assumed. The EPIC simulations were based on the assumption of a constant amount per day per acre if soil moisture was below the irrigation trigger. As the field size covered by a given well is increased, the amount applied per day declines. The highest yields would be expected from the smaller fields.

The average simulated yields and average annual water use are shown in Tables 5 to 9 below. The simulated subsurface irrigated corn yields varied from 222.9 bushels (slightly higher than with the pivot) for the fifty acre field with an 800 GPM well down to 93.3 bushels for the 150 acre field with a 100 GPM well and a .3 irrigation trigger. Again the irrigation trigger had little effect when well capacity dropped below 300 GPM because the field moisture was usually below the trigger level.

Table 6. Results from EPIC Simulation of Irrigated Sorghum Yields and Irrigation Rates Using a Subsurface System on a 50 Acre field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	141.3	144.7	149.4	154.1	158.0	163.4	172.1	9.3	9.8	10.4	11.3	11.9	12.9	14.9
700	137.1	142.0	146.6	151.1	155.6	162.6	170.7	8.6	9.2	9.8	10.6	11.2	12.6	14.3
600	134.3	139.8	144.5	149.4	154.5	161.2	168.7	8.1	8.8	9.4	10.2	10.9	12.1	13.7
500	129.3	134.4	141.4	145.3	150.4	156.6	166.4	7.3	8.0	8.8	9.3	10.1	11.2	13.1
400	122.8	128.6	134.0	138.8	142.9	149.5	168.3	6.4	7.1	7.7	8.3	8.9	9.9	13.2
300	115.6	121.1	125.7	130.7	137.1	150.6	166.6	5.7	6.2	6.7	7.2	8.0	9.9	12.7
200	89.3	91.0	92.2	93.6	95.5	97.9	100.9	1.4	1.7	2.0	2.2	2.7	3.2	4.1
100	87.1	88.5	90.5	92.3	93.7	95.1	96.6	0.9	1.1	1.5	1.8	2.1	2.5	2.9

Table 7. Results from EPIC Simulation of Irrigated Sorghum Yields and Irrigation Rates Using a Subsurface System on a 75 Acre field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	131.6	136.5	142.2	147.2	151.9	158.5	166.1	7.6	8.3	9.0	9.7	10.4	11.5	13.0
700	128.2	133.7	138.6	143.4	148.6	154.1	167.8	7.1	7.8	8.3	9.0	9.8	10.7	13.2
600	122.8	128.6	134.0	138.8	142.9	149.5	168.3	6.4	7.1	7.7	8.3	8.9	9.9	13.2
500	115.6	121.1	125.7	130.7	137.1	150.6	166.6	5.7	6.2	6.7	7.2	8.0	9.9	12.7
400	110.2	115.8	120.8	127.6	136.8	152.9	164.5	5.2	5.7	6.2	6.8	7.9	10.1	12.1
300	96.7	103.1	112.7	124.8	137.7	147.4	155.2	4.1	4.6	5.3	6.4	7.7	9.0	10.3
200	87.9	89.3	90.8	92.8	94.9	96.9	99.1	1.1	1.3	1.6	2.0	2.4	2.9	3.6
100	86.4	88.1	89.4	90.3	91.1	91.9	93.0	0.7	1.0	1.2	1.4	1.6	1.8	2.1

Table 8. Results from EPIC Simulation of Irrigated Sorghum Yields and Irrigation Rates Using a Subsurface System on a 100 Acre Field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	122.8	128.6	134.0	138.8	142.9	149.5	168.3	6.4	7.1	7.7	8.3	8.9	9.9	13.2
700	119.9	125.2	130.3	135.0	140.0	149.2	167.8	6.1	6.7	7.2	7.8	8.4	9.7	13.0
600	115.6	121.1	125.7	130.7	137.1	150.6	166.6	5.7	6.2	6.7	7.2	8.0	9.9	12.7
500	104.3	109.5	116.2	124.7	137.9	150.7	161.0	4.7	5.1	5.7	6.5	7.9	9.7	11.4
400	96.7	103.1	112.7	124.8	137.7	147.4	155.2	4.1	4.6	5.3	6.4	7.7	9.0	10.3
300	83.4	95.9	108.8	118.1	124.5	130.1	135.4	3.1	3.9	4.8	5.6	6.2	6.8	7.6
200	87.1	88.5	90.5	92.3	93.7	95.1	96.6	0.9	1.1	1.5	1.8	2.1	2.5	2.9
100	86.4	88.1	89.4	90.3	91.1	91.9	93.0	0.7	1.0	1.2	1.4	1.6	1.8	2.1

Table 9. Results from EPIC Simulation of Irrigated Sorghum Yields and Irrigation Rates Using a Subsurface System on a 125 Acre Field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	115.6	121.1	125.7	130.7	137.1	150.6	166.6	5.7	6.2	6.7	7.2	8.0	9.9	12.7
700	110.2	115.8	120.8	127.6	136.8	152.9	164.5	5.2	5.7	6.2	6.8	7.9	10.1	12.1
600	104.3	109.5	116.2	124.7	137.9	150.7	161.0	4.7	5.1	5.7	6.5	7.9	9.7	11.4
500	96.7	103.1	112.7	124.8	137.7	147.4	155.2	4.1	4.6	5.3	6.4	7.7	9.0	10.3
400	89.5	98.4	111.0	124.1	133.7	140.8	147.0	3.6	4.1	5.1	6.2	7.2	8.1	9.0
300	83.4	95.9	108.8	118.1	124.5	130.1	135.4	3.1	3.9	4.8	5.6	6.2	6.8	7.6
200	87.1	88.5	90.5	92.3	93.7	95.1	96.6	0.9	1.1	1.5	1.8	2.1	2.5	2.9
100	86.4	88.1	89.4	90.3	91.1	91.9	93.0	0.7	1.0	1.2	1.4	1.6	1.8	2.1

Table 10. Results from EPIC Simulation of Irrigated Sorghum Yields and Irrigation Rates Using a Subsurface System on a 150 Acre Field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	110.2	115.8	120.8	127.6	136.8	152.9	164.5	5.2	5.7	6.2	6.8	7.9	10.1	12.1
700	104.3	109.5	116.2	124.7	137.9	150.7	161.0	4.7	5.1	5.7	6.5	7.9	9.7	11.4
600	96.7	103.1	112.7	124.8	137.7	147.4	155.2	4.1	4.6	5.3	6.4	7.7	9.0	10.3
500	89.5	98.4	111.0	124.1	133.7	140.8	147.0	3.6	4.1	5.1	6.2	7.2	8.1	9.0
400	83.4	95.9	108.8	118.1	124.5	130.1	135.4	3.1	3.9	4.8	5.6	6.2	6.8	7.6
300	80.3	91.0	99.8	104.9	109.6	114.7	119.1	2.8	3.5	4.1	4.5	4.9	5.4	5.9
200	86.4	88.1	89.4	90.3	91.1	91.9	93.0	0.7	1.0	1.2	1.4	1.6	1.8	2.1
100	85.2	85.7	86.2	86.6	87.0	87.5	88.2	0.5	0.6	0.7	0.8	0.9	1.0	1.1

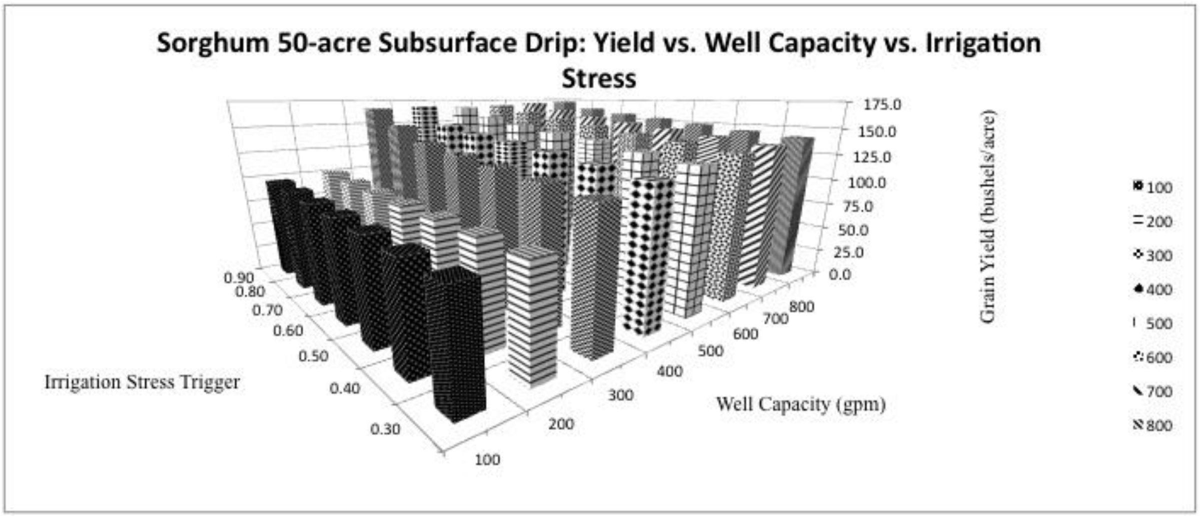


Figure 12. Results from EPIC Sorghum Subsurface Simulation showing Yields and Irrigation along with the Well Capacity for a 50 Acre Field.

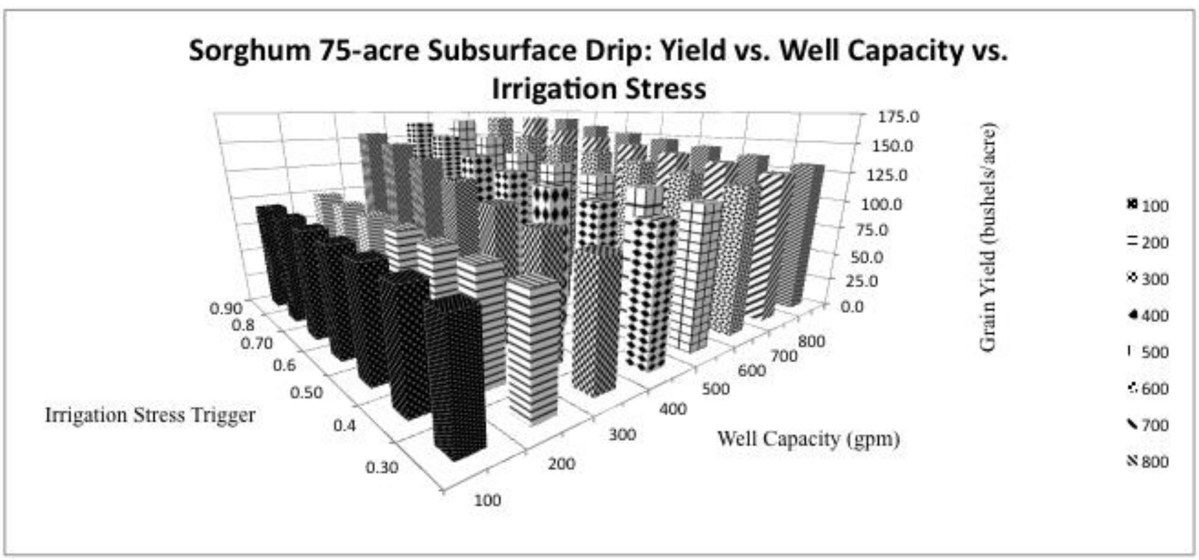


Figure 13. Results from EPIC Sorghum Subsurface Simulation showing Yields and Irrigation along with the Well Capacity for a 75 Acre Field.

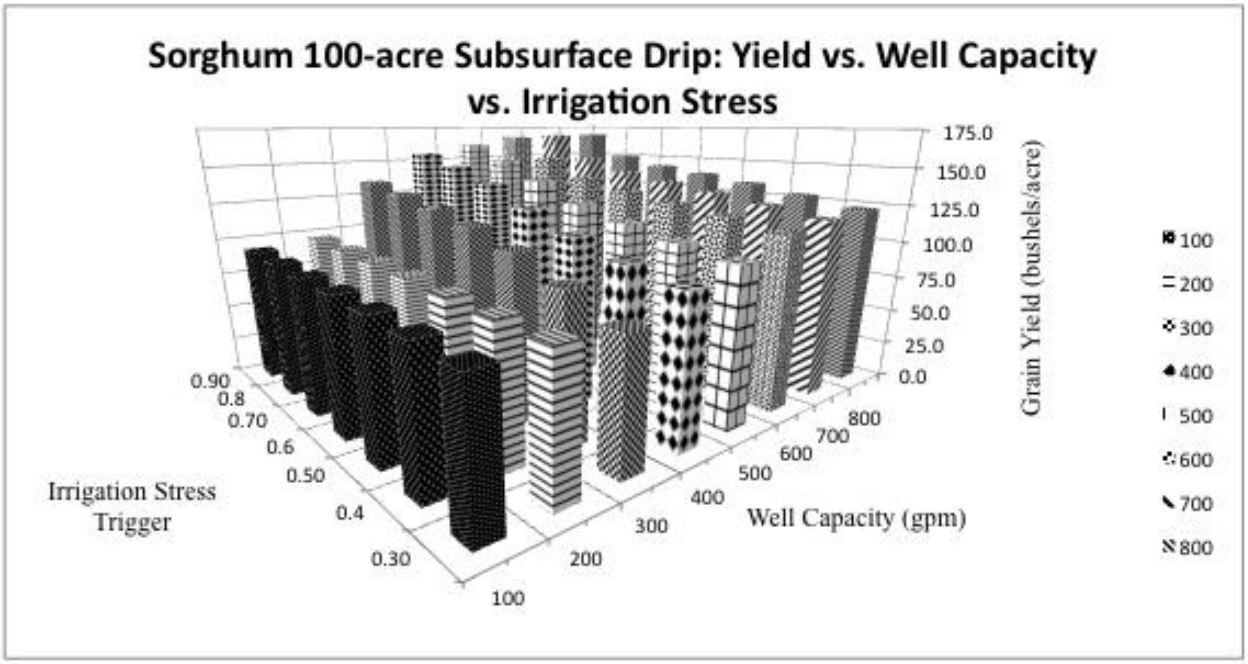


Figure 14. Results from EPIC Sorghum Subsurface Simulation showing Yields and Irrigation along with the Well Capacity for a 100 Acre Field.

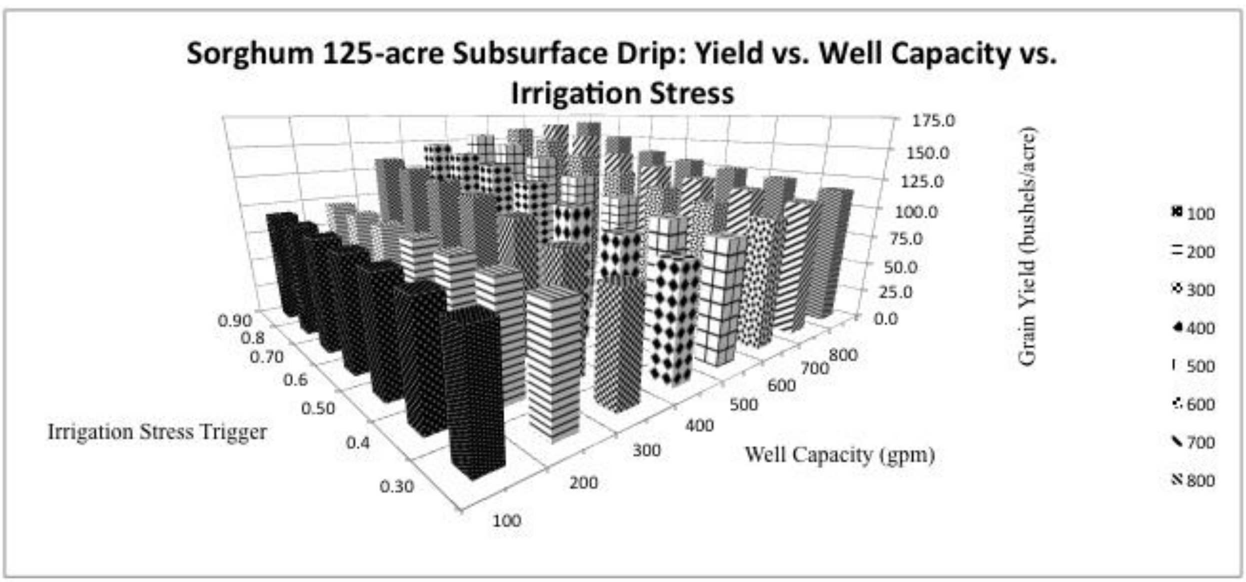


Figure 15. Results from EPIC Sorghum Subsurface Simulation showing Yields and Irrigation along with the Well Capacity for a 125 Acre field.

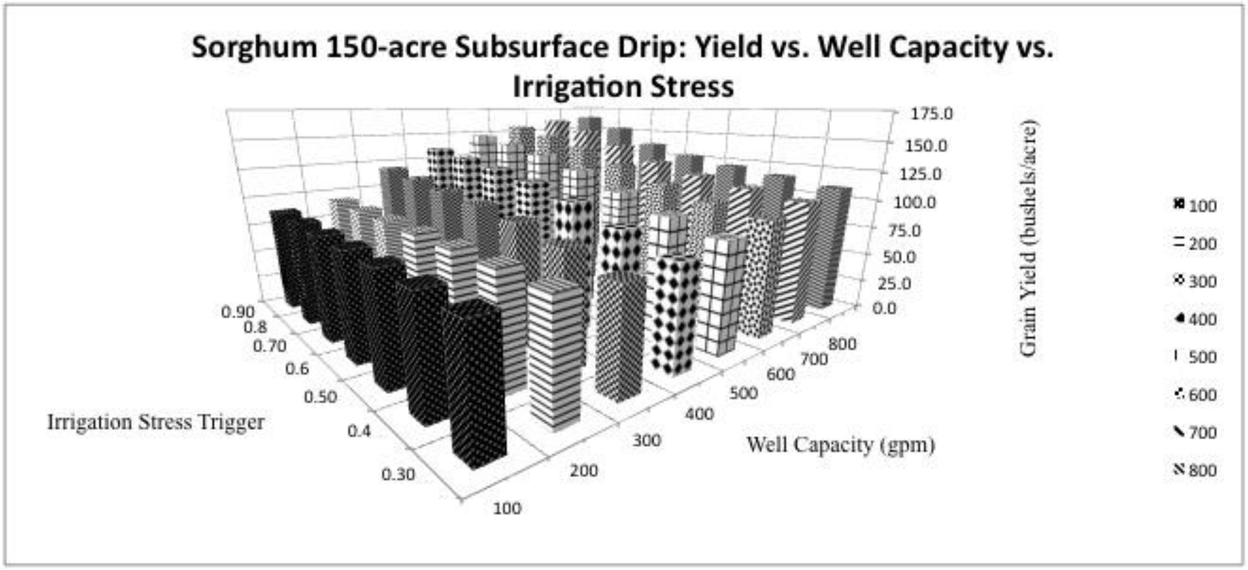


Figure 16. Results from EPIC Sorghum Subsurface Simulation showing Yields and Irrigation along with the Well Capacity for a 150 Acre field.

Simulation of Drip Irrigated Corn

The same field sizes, daily application rates, and irrigation triggers that were used in simulating irrigated grain sorghum were used in simulating subsurface drip irrigated corn. The simulated yields ranged from 222.9 bushels for the 50 acre field with an 800 GPM well, (.9 irrigation trigger) to 93.9 bushels per acre for the 150 acre field with a 100 GPM well (.3 irrigation trigger). The respective gross per acre application rates varied from 26.8 acre inches to 2.4 acre inches. The respective maximum CP yields and water use for the 120 acre pivot were 213.4 bushes and 22.5 acre inches. The maximum yield and related water use for the 125 acre drip field were 214.9 and 22.6 acre inches.

Table 11. Results from EPIC Simulation of Irrigated Corn Yields and Irrigation rates using a Subsurface Drip System on a 50 acre field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	179.6	184.9	190.7	196.1	201.5	209.4	222.9	17.1	18.1	19.3	20.3	21.7	23.5	26.8
700	174.3	179.9	185.2	191.2	197.0	205.6	218.5	16.0	17.0	18.1	19.2	20.5	22.4	25.6
600	169.8	175.0	181.0	186.8	192.9	202.2	213.0	15.1	16.1	17.3	18.3	19.7	21.7	24.4
500	161.8	167.0	173.6	179.0	185.9	193.6	210.0	13.6	14.6	15.8	16.7	18.1	19.8	23.7
400	152.3	157.6	162.7	168.6	174.5	182.3	208.4	11.8	12.8	13.6	14.7	15.9	17.5	23.2
300	143.3	147.4	152.6	158.0	164.9	182.7	202.3	10.3	11.0	12.0	12.9	14.3	17.7	22.0
200	125.4	130.2	137.8	149.0	162.7	173.2	182.0	7.4	8.2	9.5	11.3	13.6	15.6	17.6
100	110.4	119.0	125.5	129.7	133.4	137.2	140.6	5.1	6.3	7.2	7.8	8.4	9.0	9.8

Table 12. Results from EPIC Simulation of Irrigated Corn Yields and Irrigation rates using a Subsurface Drip System on a 75 acre field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	168.2	173.9	180.3	186.1	193.2	201.7	214.3	14.2	15.3	16.5	17.6	18.9	20.7	23.7
700	162.6	168.8	174.3	180.4	186.8	194.3	216.2	13.2	14.2	15.3	16.3	17.6	19.2	24.1
600	156.0	161.3	166.4	172.8	178.9	187.1	214.2	12.0	12.9	13.8	14.9	16.1	17.8	23.6
500	147.4	151.5	157.0	162.7	169.8	188.4	208.9	10.5	11.1	12.1	13.1	14.5	18.0	22.3
400	141.0	144.8	150.1	157.1	166.3	186.9	202.4	9.5	10.1	11.1	12.3	12.8	17.8	21.2
300	127.8	132.8	140.5	152.3	165.9	177.1	185.9	7.4	8.3	9.6	11.5	13.7	15.7	17.7
200	115.3	124.4	135.6	143.4	150.0	154.7	159.5	5.7	7.0	8.6	9.7	10.8	11.7	12.7
100	105.4	110.0	112.5	115.1	117.6	120.0	122.1	4.2	4.8	5.1	5.5	5.9	6.3	6.7

Table 13. Results from EPIC Simulation of Irrigated Corn Yields and Irrigation rates using a Subsurface Drip System on a 100 acre field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	158.3	164.0	169.2	175.6	181.6	190.0	217.9	12.1	13.0	13.9	15.0	16.2	17.9	23.8
700	153.7	159.2	164.3	169.9	176.3	188.0	215.5	11.3	12.2	13.0	14.1	15.3	17.6	23.3
600	148.8	153.4	158.4	164.3	171.5	190.7	211.4	10.5	11.2	12.1	13.2	14.6	18.1	22.5
500	137.6	141.1	148.4	156.0	171.2	186.8	199.8	8.6	9.2	10.5	11.7	14.2	17.1	19.9
400	129.9	134.9	142.8	154.8	168.6	179.9	189.1	7.5	8.3	9.7	11.6	13.8	15.8	17.9
300	117.6	126.8	138.3	146.3	152.7	157.8	162.9	5.7	7.1	8.7	9.9	10.9	11.8	12.9
200	117.6	121.7	128.5	132.9	136.7	140.6	144.1	5.2	6.4	7.3	7.9	8.5	9.2	9.9
100	105.4	110.0	112.5	115.1	117.6	120.0	122.1	4.2	4.8	5.1	5.5	5.9	6.3	6.7

Table 14. Results from EPIC Simulation of Irrigated Corn Yields and Irrigation rates using a Subsurface Drip System on a 125 acre field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	150.9	156.1	161.1	167.0	174.5	193.9	214.9	10.5	11.4	12.2	13.3	14.7	18.2	22.6
700	145.5	149.8	154.9	162.0	173.4	193.3	209.8	9.7	10.3	11.3	12.5	14.5	18.0	21.5
600	138.8	142.6	150.1	157.8	173.0	188.8	202.1	8.6	9.3	10.5	11.8	14.3	17.2	20.0
500	131.5	136.4	144.7	156.9	171.1	182.3	191.7	7.5	8.3	9.7	11.6	13.9	15.9	18.0
400	124.1	130.9	141.2	154.7	164.1	171.9	178.7	6.5	7.6	9.2	11.2	12.7	14.1	15.6
300	117.6	126.8	138.3	146.3	152.7	157.8	162.9	5.7	7.1	8.7	9.9	10.9	11.8	12.9
200	112.9	121.7	128.5	132.9	136.7	140.6	144.1	5.2	6.4	7.3	7.9	8.5	9.2	9.9
100	105.4	110.0	112.5	115.1	117.6	120.0	122.1	4.2	4.8	5.1	5.5	5.9	6.3	6.7

Table 15. Results from EPIC Simulation of Irrigated Corn Yields and Irrigation Rates Using a Subsurface Drip System on a 150 acre field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	146.5	150.6	156.0	163.3	174.6	194.8	211.3	9.7	10.4	11.3	12.6	14.5	18.1	21.6
700	140.1	143.8	151.2	159.1	174.7	190.6	204.1	8.7	9.3	10.6	11.9	14.4	17.3	20.1
600	132.8	137.8	146.3	158.6	172.8	184.3	140.1	7.6	8.4	9.8	11.7	14.0	16.0	8.7
500	125.5	132.3	143.0	156.7	166.3	174.2	181.1	6.6	7.6	9.3	11.2	12.8	14.2	15.7
400	119.4	128.8	140.5	148.6	155.1	160.4	165.6	5.8	7.1	8.8	9.9	10.9	11.9	13.0
300	115.1	124.0	131.0	135.5	139.3	143.4	147.0	5.2	6.4	7.4	8.0	8.6	9.3	10.0
200	107.8	112.5	115.1	117.7	120.4	122.8	125.0	4.2	4.8	5.2	5.6	6.0	6.3	6.8
100	93.9	94.7	96.1	97.4	98.6	99.7	100.8	2.4	2.5	2.7	2.9	3.1	3.2	3.4

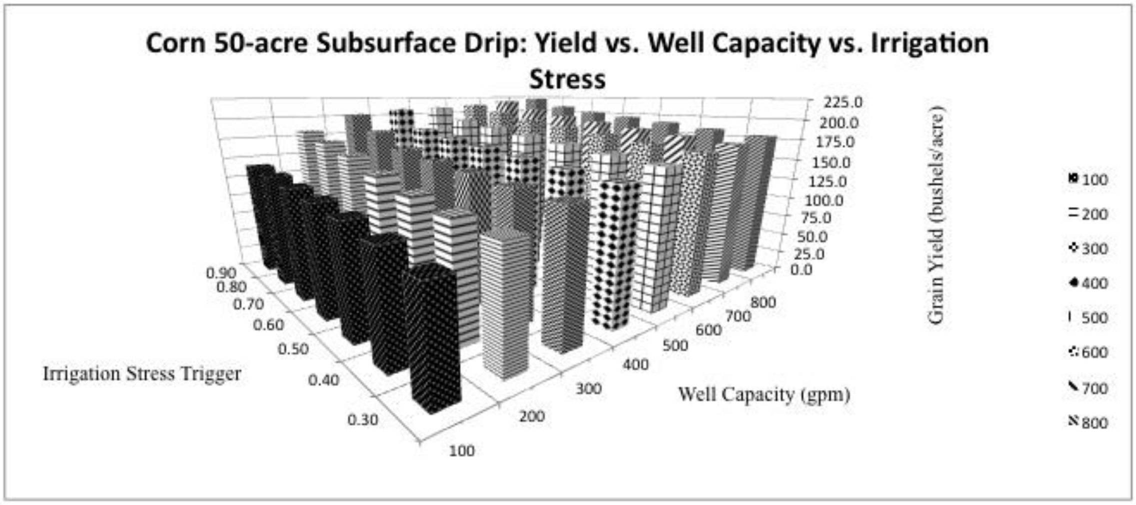


Figure 17. Results from EPIC Corn Subsurface Simulation showing Yields and Irrigation along the Well Capacity for a 50 Acre Field

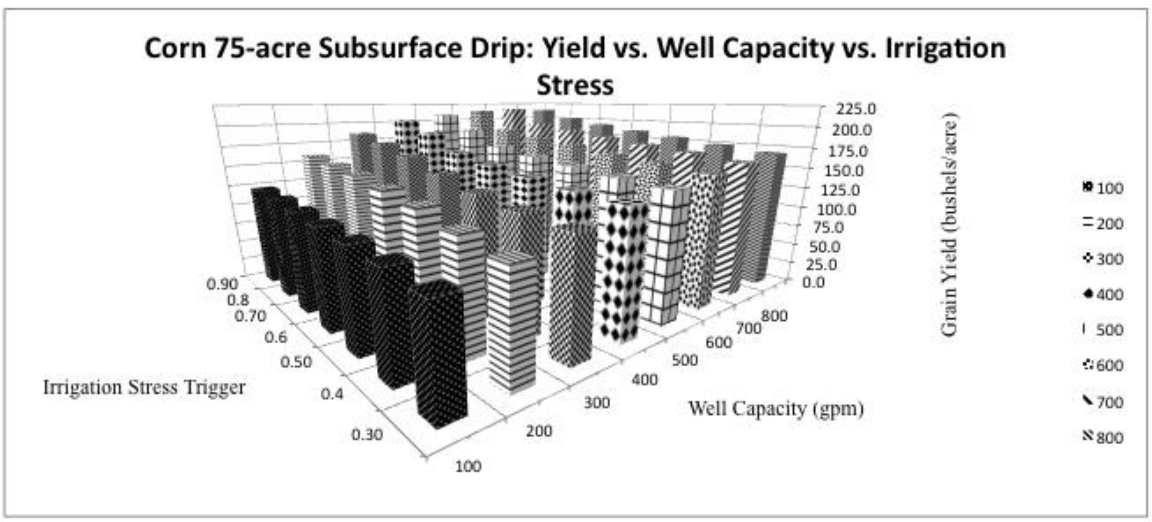


Figure 18. Results from EPIC Corn Subsurface Simulation showing Yields and Irrigation along the Well Capacity for a 75 Acre Field

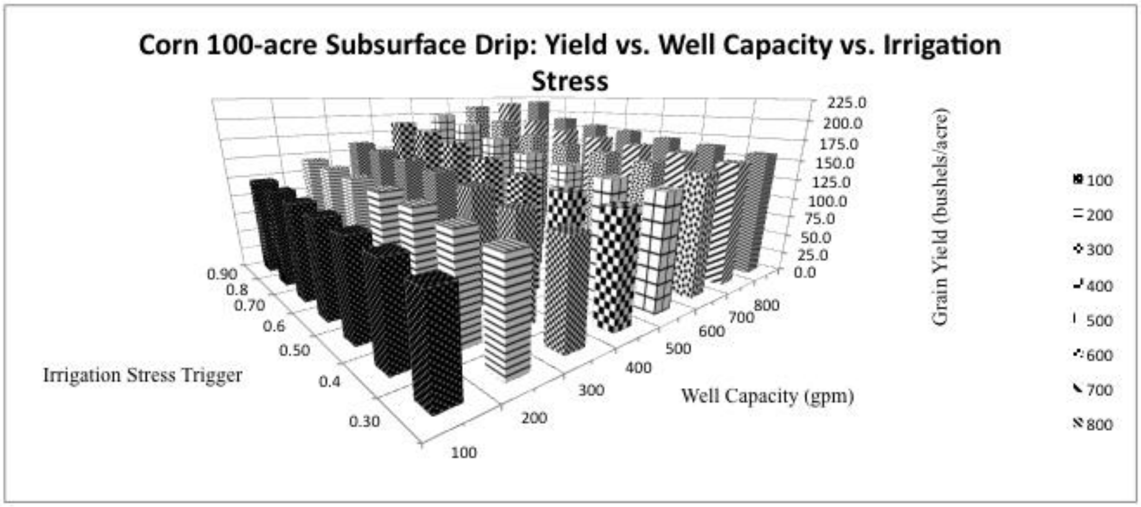


Figure 19. Simulated Yields Results from EPIC Corn Subsurface Simulation showing Yields and Irrigation along with the Well Capacity for a 100 Acre Field

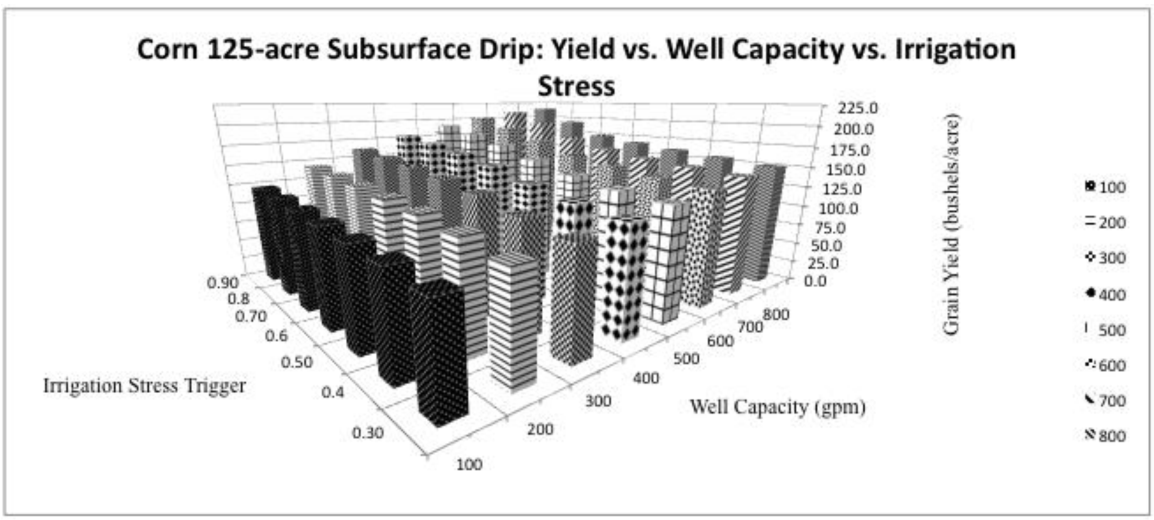


Figure 20. Results from EPIC Corn Subsurface Simulation showing Yields and Irrigation along the Well Capacity for a 125 Acre Field

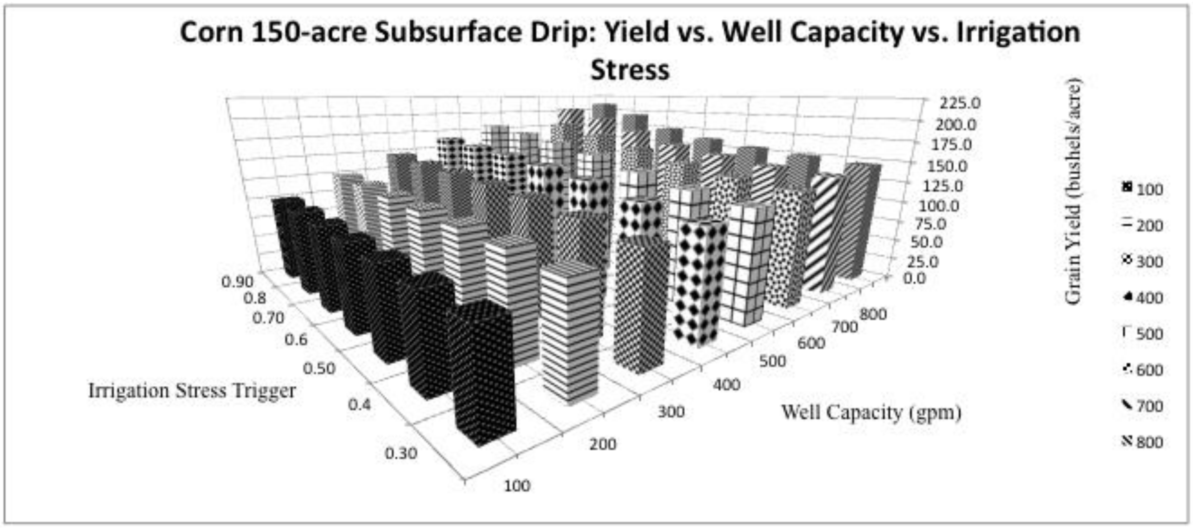


Figure 21. Results from EPIC Corn Subsurface Simulation showing yields and Irrigation along the Well Capacity for a 150 Acre Field.

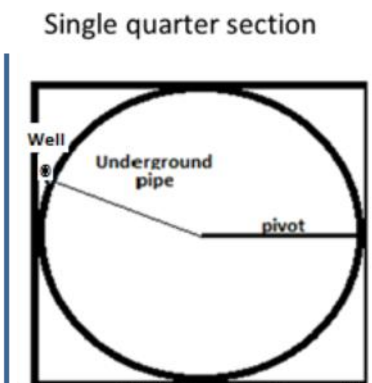


Figure 22. Illustration of a Single One-fourth Section with a 120 acre pivot

Static Budget Analysis

Pumping Cost:

Pumping cost for the case of a producer with a single 160 quarter section field with a 120 acre pivot irrigation system were based on the diagram in Figure 22. The well was assumed located outside the irrigated area.

It was assumed the maximum well capacity would be 800 GPM and that with 10 feet of drawn down per 100 GPM, the bowl height would be 5 feet, and the top of the safety zone would be 35 feet above the pump bowls. The static water table would be 140 feet above the base of

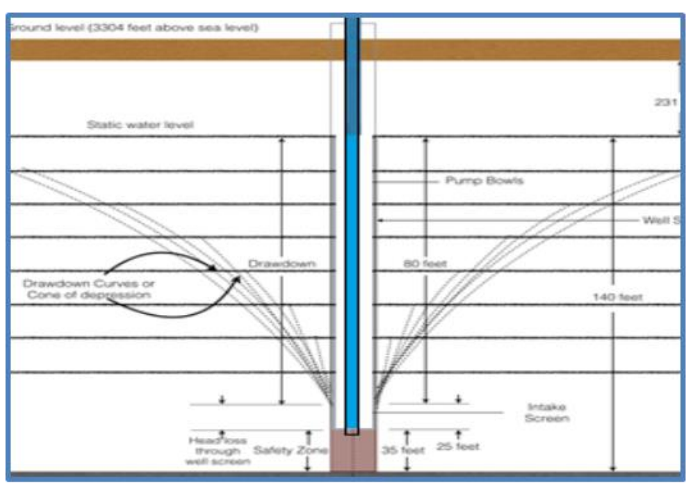


Figure 23. Illustration of well depth and water table level used in Pumping Cost Calculations

the aquifer. The land surface was assumed to be 200 feet above the 800 GPM water table.

Pumping cost calculations were based on the assumption of natural gas at $6 per thousand MCF. Pump efficiency was assumed to be 70 percent, the motor efficiency 17.7 percent, and the drive efficiency was 95 percent. The overall efficiency was 11.8 percent. The pressure at the pivot head was 35 PSI.

The cost of pumping an acre foot of water from each of the well sizes used in the Center Pivot Analysis are shown below in Table 15. It should be noted that because the bottom of the pumping draw down cone is always at the maximium depth (top of the safety zone), that the power required and cost decreases slightly as well capacity declines. This is because the total pumping height does not change. As the water table declines, the depth of the drawdown cone declines to match the increased height above the static water table. The water horse power (WHP) requirements decline with the water table because the volume of water being pumped each minute declines with the water table.

Table 16. Parameters used to Estimate the Cost of Pumping an Acre Foot of Water by Well Size for the Center Pivot Irrigation System.

Parameters and Pumping Costs used for Center Pivot							
800 GPM Well			700 GPM Well			600 GPM Well	
L8 S.W.T (ft)	200		L7 S.W.T. (ft)	210		L6 S.W.T. (ft)	220
Tot. Head (ft)	390		Tot. Head (ft)	381		Tot. Head (ft)	376
WHP	79		WHP	67		WHP	57
Cost/af	$ 69.46		Cost/af	$ 67.86		Cost/af	$ 66.97
500 GPM Well			400 GPM Well			300 GPM Well	
L5 S.W.T. (ft)	230		L4 S.W.T. (ft)	240		L3 S.W.T. (ft)	250
Tot. Head (ft)	372		Tot. Head (ft)	368		Tot. Head (ft)	365
WHP	47		WHP	37		WHP	28
Cost/af	$ 66.21		Cost/af	$ 65.53		Cost/af	$ 65.02
200 GPM Well			100 GPM Well				
L5 S.W.T. (ft)	260		L5 S.W.T. (ft)	270			
Tot. Head (ft)	363		Tot. Head (ft)	362			
WHP	18		WHP	9			
Cost/af	$ 64.71		Cost/af	$ 64.24			

Abbreviations used: S.W.T. is static water table, Tot. head is total dynamic head in feet, af is acre foot, WHP is water horse power.

Effect of System Choice on Pumping Cost and Annual Fixed Cost:

The first step in the economic analysis is the construction of standard static enterprise budgets for irrigated corn and sorghum with center pivot and subsurface drip irrigation. Static budgets are quite common but can also be deceiving in dynamic situations. In this study, the water table and well capacity are declining over time. Tables 17 and 18 provide estimates of returns over irrigation fixed costs for grain sorghum under CP and SDI. Similarly, Tables 19 and 20 provide estimates of returns over irrigation fixed costs for corn under CP and SDI. The budgets are based on the simulated crop yields and water use. The requirements for nitrogen and phosphorus are also given by the simulation model. The budgets assume the irrigation trigger is .9 or that the producer is essentially practicing full irrigation. The pivot and subsurface drip irrigation budgets are most closely comparable at the 120-125 acre sizes. At this size, the CP shows slightly lower profits per acre with the four dollar feed grain prices.

Table 17. Estimated Net Revenue over Variable Cost for Grain Sorghum Irrigated by Central Pivot when Irrigation Occurs with a 10 Percent or Greater Moisture Deficit by Well Capacity for a 120 Acre Pivot

Well Capacity	GPM	800	700	600	500	400	300	200	100
Yield	bu/ac	162.8	155.7	148.4	141.1	133.8	117.2	92.0	88.5
Nitrogen	lbs/ac	181.6	173.6	165.5	157.3	149.2	130.7	102.5	98.7
Phosphorous	lbs/ac	29.4	28.1	26.8	25.4	24.1	21.1	16.6	16.0
Irrigation	acre-inch	15.6	14.1	12.6	11.3	10.4	8.3	4.1	2.8
Net Revenue ($4.16/bu)	$	677.4	647.7	617.3	586.8	556.5	487.6	382.6	368.2
Fertilizer-Nitrogen	$	99.9	95.5	91.0	86.5	82.0	71.9	56.4	54.3
Fertilizer-Phosphorous	$	15.3	14.6	13.9	13.2	12.5	11.0	8.6	8.3
Seed Cost	$	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1
Herbicide Cost	$	52.4	52.4	52.4	52.4	52.4	52.4	52.4	52.4
Insecticide Cost	$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Crop Consulting	$	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
Drying	$	21.2	20.2	19.3	18.3	17.4	15.2	12.0	11.5
Miscelleneous	$	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Custom Hire	$	132.5	129.4	126.2	122.9	119.7	112.5	101.3	99.8
Non Machinery Labor	$	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Interest	$	15.7	15.1	14.4	13.8	13.1	11.7	9.5	9.2
Irrigation Cost	$	90.4	79.8	70.3	62.6	56.8	44.9	21.9	14.8
Sub Total	$	477.7	457.3	437.9	420.1	404.4	369.9	312.5	300.7
Crop Insurance	$	22.9	22.0	21.0	20.2	19.4	17.8	15.0	14.4
Total Varible Cost	$	500.6	479.3	458.9	440.3	423.8	387.7	327.5	315.1
Net Revenue-Var Cost	$	176.8	168.4	158.4	146.5	132.7	100.0	55.1	53.1
Annual System Cost[a]	$	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
Net Ret-system Cost	$	131.8	123.5	113.4	101.6	87.7	55.0	10.2	8.1

[a] Initial system cost of $60,000 over 15 years at four percent.

Table 18. Estimated net revenue over Irrigation Cost for Grain Sorghum Irrigated by Subsurface Drip if Irrigation Occurs with a Ten Percent or Greater Moisture Deficit by Well Capacity for a 125 Acre Field.

GPM		800	700	600	500	400	300	200	100
Yield (bu/acre)		166.6	164.5	161.0	155.2	147.0	135.4	96.6	93.0
N (lbs/a)		185.7	183.4	179.5	173.0	163.9	151.0	107.7	103.7
P (lbs/a)		30.0	29.7	29.0	28.0	26.5	24.4	17.4	16.8
Irrigation (inches)		12.7	12.1	11.4	10.3	9.0	7.6	2.9	2.1
Net Revenue ($4.48/bu)	$	693.0	684.3	669.7	645.4	611.6	563.3	401.9	387.0
Fertilizer-nitrogen	$	102.2	100.9	98.7	95.2	90.2	83.1	59.2	57.0
Fertilizer-phosphorus	$	15.6	15.4	15.1	14.6	13.8	12.7	9.1	8.7
Seed cost	$	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1
herbicide Cost	$	52.4	52.4	52.4	52.4	52.4	52.4	52.4	52.4
Insecticide Cost	$	-	-	-	-	-	-	-	-
Crop Consulting	$	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
Drying	$	21.7	21.4	20.9	20.2	19.1	17.6	12.6	12.1
Miscellaneous	$	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Custom Hire	$	134.2	133.3	131.7	129.2	125.6	120.5	103.4	101.8
Non Machinery Labor	$	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Interest	$	16.0	15.8	15.5	15.0	14.3	13.3	9.9	9.6
Irrigation Cost	$	66.7	62.3	57.6	51.6	44.7	30.7	14.2	10.1
Sub Total ($)	$	459.1	389.5	384.7	376.8	365.7	349.9	296.9	292.0
Crop Insurance	$	22.0	18.7	18.5	18.1	17.6	16.8	14.3	14.0
Total Variable Cost	$	481.1	473.6	463.6	449.0	430.1	398.9	326.0	316.6
Net Returns - Var. Cost	$	211.9	210.7	206.1	196.4	181.5	164.5	75.9	70.5
Annual System Cost* $/a	$	65.3	65.3	65.3	65.3	65.3	65.3	65.3	65.3
Net Returns - Syst. Cost	$	146.6	145.5	140.8	131.2	116.3	99.2	10.6	5.2

[a] Annual cost for 125 acre subsurface drip system costing 90,700 for a 125 acre field over 15 years at four percent interest.

Table 19. Detailed Costs and Returns for Center Pivot irrigated Corn by Well Capacity when irrigation occurs when the soil moisture depletion is 10 percent of capacity or less.

GPM		800	700	600	500	400	300	200	100
Yield	bu/ac	213.41	198.86	186.90	174.99	164.37	142.64	122.23	99.08
N	lbs/ac	196.8	183.0	171.9	160.9	151.0	130.9	112.1	90.9
P	lbs/ac	28.5	26.5	25.0	23.4	21.9	19.0	16.3	13.2
Irrigation (inches)	acre-inch	22.5	23.1	21.6	19.5	17.6	13.9	10.3	6.1
Net Revenue ($4.48/bu)	$	956.1	890.9	837.3	784.0	736.4	639.0	547.6	443.9
Fertilizer-Nitrogen	$	108.2	100.7	94.6	88.5	83.0	72.0	61.7	50.0
Fertilizer-Phosphorous	$	14.8	13.8	13.0	12.1	11.4	9.9	8.5	6.9
Seed Cost	$	112.6	112.6	112.6	112.6	112.6	112.6	112.6	112.6
Herbicide Cost	$	61.0	61.0	61.0	61.0	61.0	61.0	61.0	61.0
Insecticide Cost	$	16.0	15.7	15.5	15.2	15.0	14.6	14.1	13.6
Crop Consulting	$	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Drying	$	27.7	25.9	24.3	22.7	21.4	18.5	15.9	12.9
Miscelleneous	$	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Custom Hire	$	161.5	155.1	149.9	144.7	140.0	130.5	121.5	111.4
Non Machinery Labor	$	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Interest	$	20.0	19.0	18.1	17.3	16.5	14.9	13.4	11.8
Irrigation Cost	$	130.0	130.5	120.4	107.4	96.1	75.3	55.5	32.7
Sub Total	$	686.5	668.8	643.9	616.0	591.6	543.8	498.8	447.4
Crop Insurance	$	33.0	32.1	30.9	29.6	28.4	26.1	23.9	21.5
Total Varible Cost	$	719.4	700.9	674.8	645.6	620.0	569.9	522.7	468.8
Net Returns-Var Cost	$	236.6	190.0	162.5	138.4	116.4	69.1	24.9	-25.0
Annual System Cost[a]	$	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
Net Ret-system Cost	$	191.7	145.0	117.6	93.4	71.4	24.2	-20.1	-69.9

a Initial system cost of $60,000 over 15 years at four percent.

Table 20. Costs and Returns over Irrigation Costs for Subsurface Drip Irrigated Corn by Well Capacity on a 125 Acre Field if Irrigation Occurs when Soil Moisture is 10 Percent of Capacity or Less.

GPM		800	700	600	500	400	300	200	100
Yield (bu/acre)		214.9	209.8	202.1	191.7	178.7	162.9	144.1	122.1
N (lbs/a)		204.4	199.5	192.1	191.7	169.6	154.6	136.6	115.8
P (lbs/a)		29.5	28.8	27.7	26.3	24.5	22.3	19.7	16.7
Irrigation (inches)		22.6	21.5	20.0	18.0	15.6	12.9	9.9	6.7
Net Revenue ($4.48/bu)	$	962.9	939.9	905.5	859.0	800.5	729.8	645.4	547.2
Fertilizer-nitrogen	$	112.4	109.7	105.6	105.5	93.3	85.0	75.1	63.7
Fertilizer-phosphorus	$	15.3	15.0	14.4	13.7	12.7	11.6	10.3	8.7
Seed cost	$	112.6	112.6	112.6	112.6	112.6	112.6	112.6	112.6
herbicide Cost	$	61.0	61.0	61.0	61.0	61.0	61.0	61.0	61.0
Insecticide Cost	$	16.1	16.0	15.8	15.6	15.3	15.0	14.6	14.1
Crop Consulting	$	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Drying	$	27.9	27.3	26.3	24.9	23.2	21.2	18.7	15.9
Miscellaneous	$	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Custom Hire	$	162.2	159.9	156.6	152.0	146.3	139.4	131.1	121.5
Non Machinery Labor	$	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Interest	$	20.1	19.8	19.2	18.5	17.5	16.4	15.0	13.4
Irrigation Cost	$	119.1	110.6	101.4	90.0	77.1	52.3	48.0	32.3
Sub Total ($)	$	681.3	666.3	647.4	628.2	593.6	548.9	521.0	477.7
Crop Insurance	$	32.7	32.0	31.1	30.2	28.5	26.4	25.0	22.9
Total Variable Cost	$	714.0	698.3	678.5	658.4	622.1	575.3	546.0	500.7
Net Returns - Var. Cost	$	248.9	241.6	227.0	200.6	178.4	154.5	99.4	46.6
Annual System Cost*	$	65.3	65.3	65.3	65.3	65.3	65.3	65.3	65.3
Net Returns - Syst. Cost	$	183.7	176.4	161.8	135.3	113.1	89.3	34.2	-18.7

a Annual cost for an SDI system for a 125 acre field with initial cost of $90,700 over 15 years at four percent interest.

Crop and Irrigation Choices with Limited Groundwater Supplies

Two long term scenarios are examined in this analysis. The first is when the producer makes a series of "Best Single Year Choices" (BSYC). The second is when the producer makes a series of choices that "Maximize the Net Present Value" of returns (MNPV) over the life of a limited resource. The major objective of this research was to determine how producers could gain the maximum value from the remaining water supply. One factor affecting the value of the remaining water supply is the objective of the producers. Researchers have long known that optimal long term rates, MNPV of extracting a non-renewable resource differ from that which would be received by a series of BSYC annual rates of extraction. Analysis of the difference in expected returns from following a BSYC VS. a MNVP path are examined below.

Annual net crop returns over fixed costs are presented in an enterprise budget for a representative acre. The budget represents returns to land which is usually the producer's most limiting resource. Other choices may be made when labor or capital are limiting. This is also true when groundwater resources are limiting. The BSYC case is followed by always selecting the crop that has the highest single year return per acre. In the budget tables listed above, irrigated corn (if the producer's well supplies 500 GPM or more per quarter section), provides higher net returns over variable costs than grain sorghum. Under high feed grain prices, the annual profit advantage of corn over sorghum is even more pronounced than in the budgets shown in Tables 17 to 20 above. However the fact that corn requires more groundwater than sorghum, has long-term implications that may easily be overlooked when making a crop choice based only on expected one-year returns.

> Consider a producer who has one quarter section with one 600 GPM irrigation well. We assume that to continue irrigation, the producer must purchase a new pivot that will irrigate 120 acres at a cost of $60,000. The producer will choose between irrigated corn and grain sorghum based on the data shown above in Tables 17 and 19. Based on annual profits (Table 19), with a 600 GPM well, irrigated corn yielding approximately 187 bushels per acre provides the highest expected net return over variable cost at $165 per acre. The net return for the 160 acre field would be $20,443. An acre of irrigated corn is expected to require 1.79 acre feet of groundwater. The 120 acre field would use approximately 215 acre feet of ground water per year.

The results depend on the availability of groundwater to the producer's well. A 600 GPM well would mean the producer has about 60 feet of water saturated sand above a safety zone 35 feet above the aquifer base and pump bowls. The output of the well would decline about 100 GPM for each 10 feet of decline in water saturated sand. For this example, assume the producer has 1,680 acre feet of groundwater that can be extracted or about 280 acre feet in each 10 foot layer of saturated sand. This example represents the case for a producer with a single quarter section that is surrounded by irrigated fields so that the producer has access only to the water that underlies the 160 acre parcel.

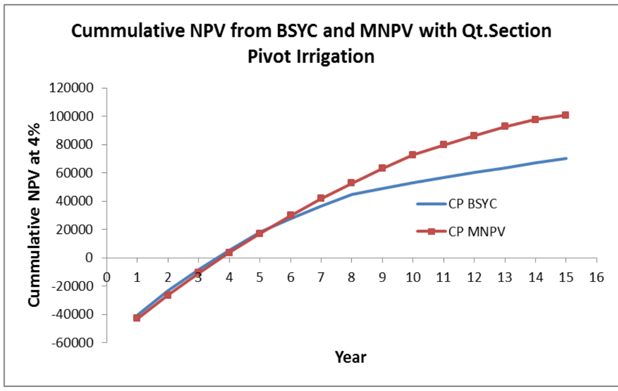
Table 21 shows that the 15 year returns for the MNPV strategy begin to exceed annual returns from the BSYC strategy by year 3 and Cumulative NPV (at four percent) after year 6. The Cumulative 15 year NPV for the BSYC is $69,959 as compared to the $100,681 for the MNPV strategy.

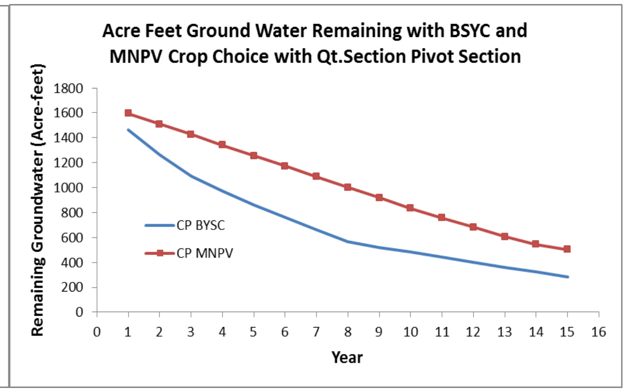
One reason for the lower eventual returns from the BSYC strategy is that the initial choice of irrigated corn draws down the aquifer at a faster rate (Figure 24, upper left). The returns from the MNPV strategy eventually begin to exceed returns from BSYC strategy because the higher groundwater level reduced pumping cost. The BYSC producer produces nearly three years of irrigated corn which draws down the aquifer. In contrast, the MNPV producer begins with stressed (IrT is .6) irrigated sorghum and uses less water per acre. The MNPV producer is still obtaining 300 GPM from the well by year 13 whereas the BYSC producer is pumping from the 100 GPM level of the aquifer.

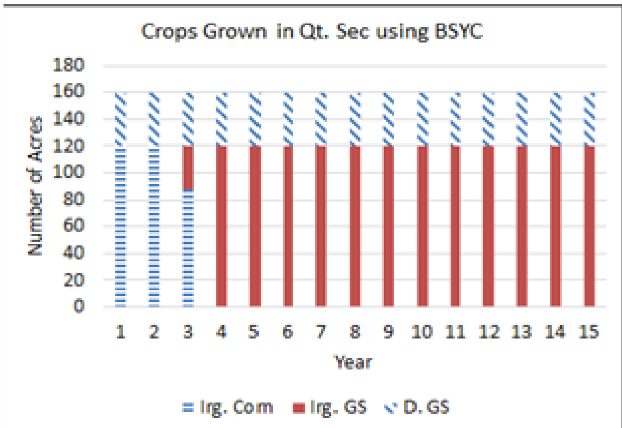
The BSYC was also compared with the MNPV strategy on a 640 acre field (section) where the available water supply (6,720 acre feet) was limited to that under the producer's field and where the producer had twice the water supply (13,440 acre feet). Center pivot irrigation was assumed in this analysis. The results shown in Figures 25 and 26 below again indicate the MNPV strategy yields the higher cumulative NPV in all of the situations.

Table 21. Importance of Considering Long-Returns from Crop Choice of Irrigated Corn or Grain Sorghum when Initial Groundwater Supplies are 1680 Acre Feet

BSYC Qt. Section Pivot Irrigation								MNPV Qt. Section Pivot Irrigation							
	Crop,	Well				Cumulative	GW		Crop,	Well				Cumulative	GW
Year	Irt	GPM	Ir Yield	Dac	Net Ret.	NPV	(aft)	Year	Irt	GPM	Ir Yield	Dac	Net Ret.	NPV	(aft)
1	C, .9	600	187	20	20422	$ (40,363)	1464	1	S, .6	600	120	40	17760	$ (42,923)	1595
2	C, .9	500	187	20	18334	$ (23,413)	1263	2	S, .6	600	120	40	17760	$ (26,503)	1511
3	C,.9,S.9	400	182	20	17005	$ (8,295)	1090	3	S, .6	600	120	40	17760	$ (10,714)	1426
4	S, .9	400	133	20	15767	$ 5,182	975	4	S, .6	500	120	40	16732	$ 3,589	1341
5	S, .9	400	133	20	15767	$ 18,142	860	5	S, .6	500	120	40	16320	$ 17,002	1256
6	S, .9	300	94	20	12239	$ 27,814	759	6	S, .6	500	120	40	16320	$ 29,900	1172
7	S, .9	200	89	20	11506	$ 36,558	662	7	S, .6	400	120	40	15654	$ 41,796	1087
8	S, .9	200	89	20	11506	$ 44,966	564	8	S, .6	400	120	40	14760	$ 52,581	1003
9	S, .4	200	89	20	5894	$ 49,106	522	9	S, .6	400	120	40	14760	$ 62,951	918
10	S, .4	200	89	20	5662	$ 52,931	482	10	S, .6	300	120	40	14377	$ 72,663	835
11	S, .4	100	88	20	5662	$ 56,609	442	11	S, .6	300	120	40	10680	$ 79,601	758
12	S, .4	100	88	20	5662	$ 60,145	402	12	S, .6	300	120	40	10680	$ 86,272	682
13	S, .4	100	88	20	5662	$ 63,545	362	13	S, .6	300	120	40	10680	$ 92,686	605
14	S, .4	100	88	20	5662	$ 66,815	322	14	S, .5	200	120	40	8422	$ 97,549	545
15	S, .4	100	88	20	5662	$ 69,959	282	15	S, .5	200	120	40	5640	$100,681	504


Cummulative NPV from BSYC and MNPV with Qt.Section Pivot Irrigation
Cummulative NPV at 4%
Year
CP BSYC
CP MNPV


Acre Feet Ground Water Remaining with BSYC and MNPV Crop Choice with Qt.Section Pivot Section
Remaining Groundwater (Acre-feet)
Year
CP BYSC
CP MNPV


Crops Grown in Qt. Sec using BSYC
Number of Acres
Year
Irg. Com
Irg. GS
D. GS

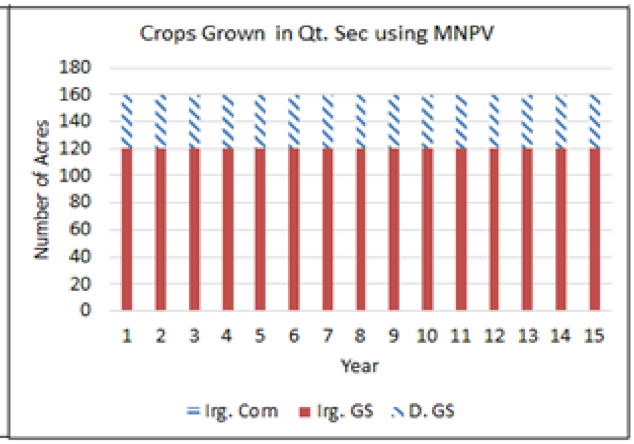

Crops Grown in Qt. Sec using MNPV
Number of Acres
Year
Irg. Com
Irg. GS
D. GS

Figure 24. BSYC and MNPV strategies from a 120 Acre Pivot with Limited Groundwater.

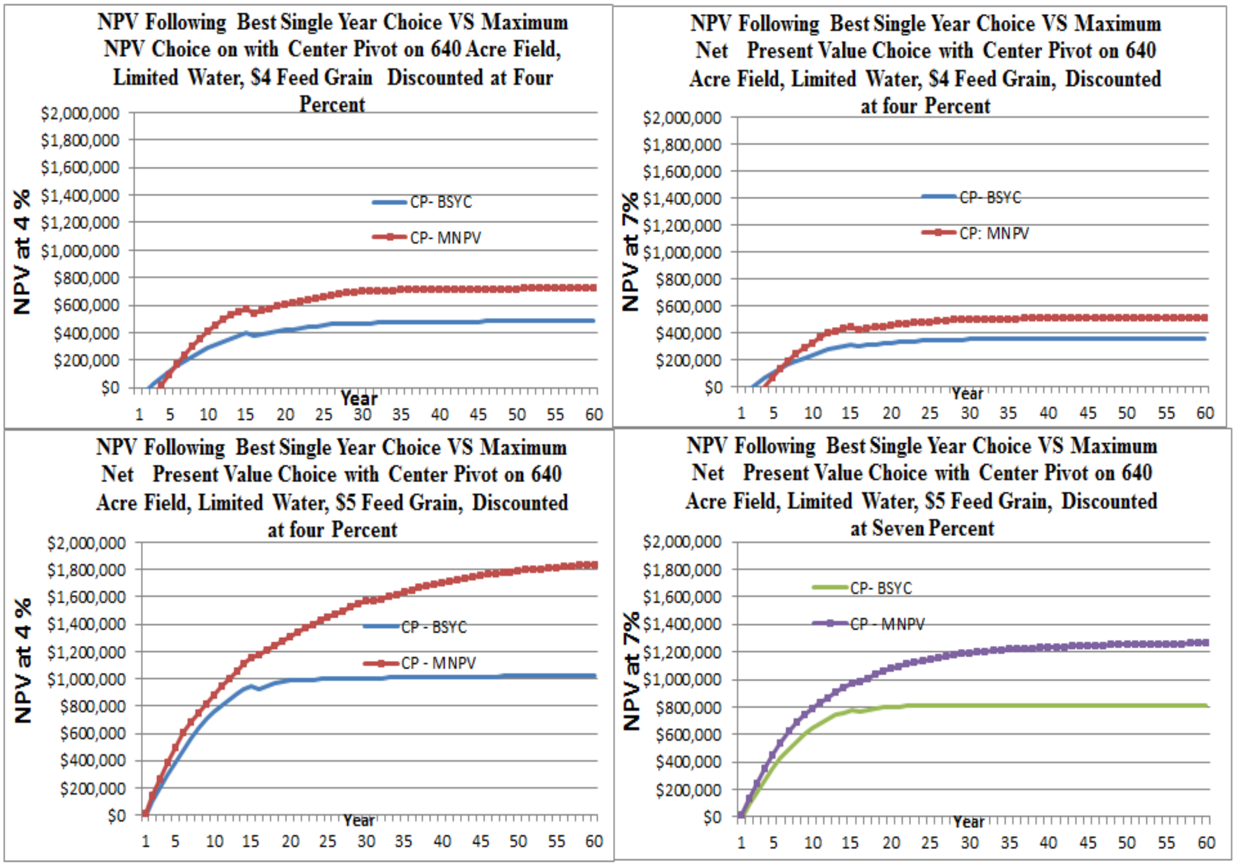


Figure 25. Comparison of BSYC VS MNPV Paths on Cumulative NPV from 640 Acre Field with a CP system with 6720 Acre Feet, Four and Five Dollar Feed Grain, Discounted at Four and Seven Percent

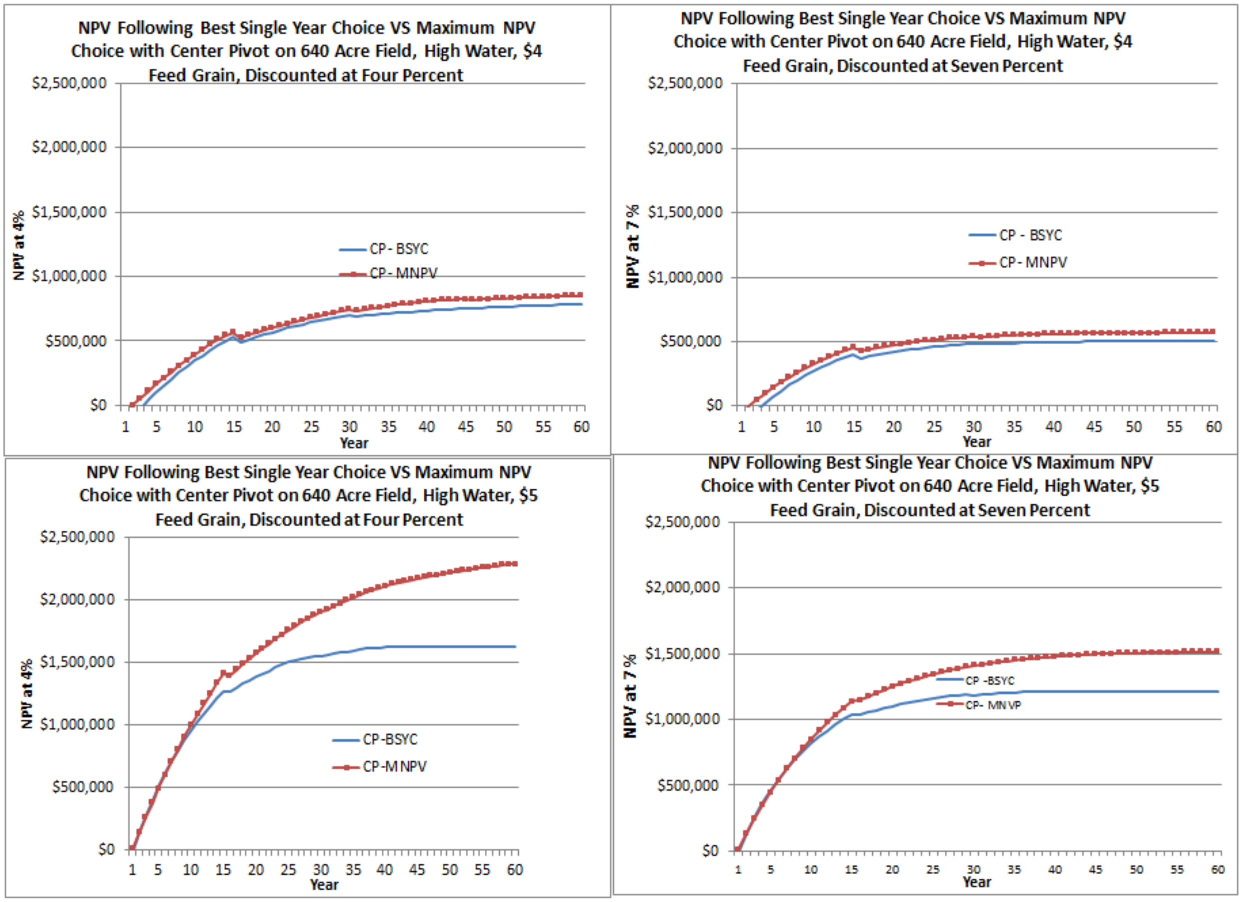


Figure 26. Comparison of BSYC VS MNPV Paths on Cumulative NPV from 640 Acre Field with a CP system with 13,440 Acre Feet, Four and Five Dollar Feed Grain, Discounted at Four and Seven Percent

Determination of Maximum Net Present Value for Center Pivot and Sub Surface Drip Systems

The MNPV optimal investment and groundwater use paths are compared over a 30 year planning horizon for the 160 acre field and over a 60 year planning horizon for the 640 acre field. Two initial water supplies are considered for the 640 acre field. The sensitivity of discounted returns and economic length of irrigation for the SDI and CP were compared with two crop prices for producers with a quarter section of land and with a full section of land. The returns for a producer with 160 acres of land and 60 feet of water saturated sand were estimated with SDI and CP over a 30 year period. For the quarter section case, it was assumed that 100 percent of the surrounding land was irrigated. Then, returns were estimated for producers with a 640 acre section of land with 60 feet of water saturated sand over a 60 year period. Two water supply cases were considered. In one case, it was assumed 100 percent of the surrounding land was irrigated and in the second case that only 50 percent of the surrounding land was irrigated. The 60 year period was used for the 640 acre producer because it was desirable to test whether the producer would leave one or more quarters unirrigated but would increase the supply of water to the irrigated portion by drawing water from all four wells.

One size of CP system was considered while five alternative sizes of SDI systems were budgeted. The irrigation system costs used for the CP and SDI systems were,

	CP		SDI
Acres	Cost	Acres	Cost
120	$60,000	50	$ 43,000
		75	$ 58,000
		100	$ 74,300
		125	$ 90,700
		150	$ 107,000.

The feed grain prices used were,

	Four Dollar Feed Grain	Five Dollar Feed Grain
Corn	$4.48/bus	$5.48/bus
Grain Sorghum	$4.16/bus	$5.09/bus.

MNPV Quarter Section Results with Pivot Irrigation and Sub Surface Drip Irrigation

This part of the analysis compares producer returns from CP and SDI systems. Each system is assumed to have a 15 year life. The initial cost of the center pivot is $60,000. The five sizes of SDI systems range from 50 to 150 acres in 25 acre increments. The planning horizon is 30 years and it was assumed the producer has only 60 feet of water saturated sand underlying the 160 acre parcel. Based on the specific yield of .175, (USGS, 2012) for much of Texas County, it is assumed the producer has 1,680 acre feet of ground water that can be extracted from under the 160 acre field. The results are examined under two feed grain prices and two discount rates.

The optimal results were determined by solving a MIP model for each type of system with GAMS-CPLEX. The subheadings below are in the form of System (acres, Feed Grain Price, Discount Rate) and are used indicate which system and parameters are being discussed.

CP(160a, $4, 4%) The left side of Table 22 compares the NPV and water use over a 30 year period with the four dollar feed grain prices (Corn price = $4.48/bus, GS price = $4.16/bus.) with a four percent discount rate. If the producer chose the pivot system, the results indicate the crop choice would be GS (not corn) for the first 15 years and then the 160 acres would be converted to dryland with 504 acre feet of groundwater remaining. The optimal solution has the CP producer irrigating GS with some stress (irrigate when the IrT is .6 or less). The 30-year NPV from both irrigated and dry GS production over the 30 year period is $106,607.

Figure 27 compares the NPV from the quarter section CP and SDI investments under the four dollar feed grain prices (Corn price = $4.48/bus, GS price = $4.16/bus.) with four and seven percent discount rates and under the five dollar feed grain prices (Corn price = $5.48, GS price=$5.09) discounted at four and seven percent. As shown in Figure 27, the SDI system always had the higher NPV.

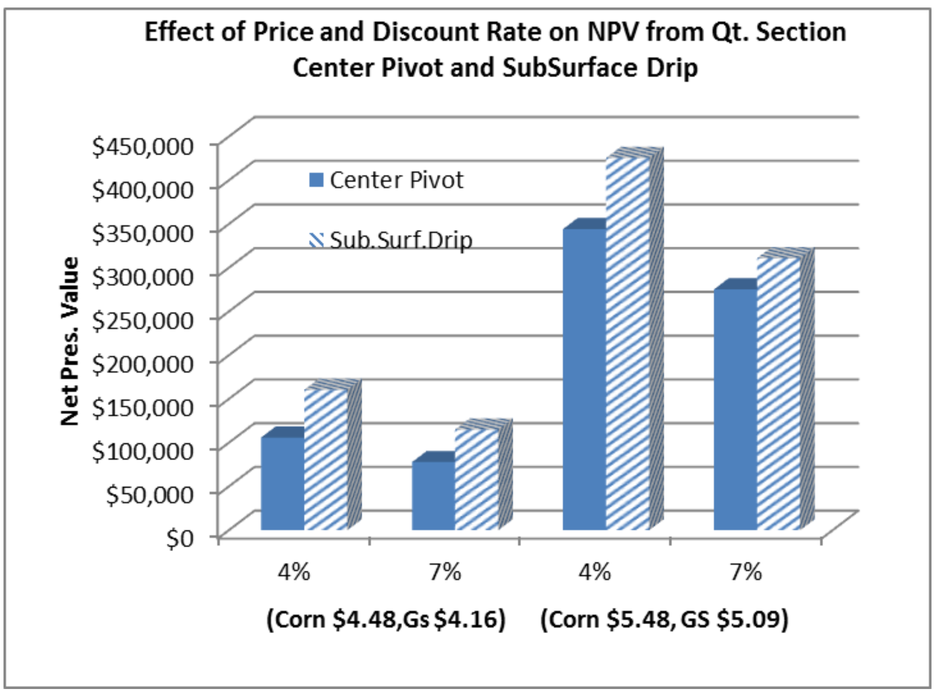


Figure 27. NPV of Center Pivot and Sub Surface Drip Systems with Feed Grain Prices at Four Dollars/bushel and Five Dollars/bushel when Discounted at Four and Seven Percent Interest

SDI(160a, $4, 4%) The right side of Table 22 presents the NPV and optimal groundwater use from an SDI system. The results indicate that for the first 15 years, the 125 acre SDI would be used which would be followed by a smaller 50 acre SDI system for years 16-30. During the first 15 years, it fully irrigated GS (irrigation initiated when soil moisture reaches the .9 level or less). The SDI system used slightly more water during the first 15 years (1,194 VS 1176 remaining) than did the CP. During years 16-21, with the smaller 50 acre SDI, water becomes relatively less limiting than the irrigated area and irrigated corn is produced. In years 22-30, the producer switches back to fully irrigated GS. The 1,680 acre feet of groundwater is exhausted by year 30. The NPV from the SDI system plus dryland GS production is estimated to be $160,861 or 50 percent higher than for the CP system.

CP(160a, $4, 7%) Table 23 (left side) shows effects of the higher discount rate on 30-year CP are shown in Table 23 with the same feed grain prices as in Table 22. In the case of the single quarter section producer with 1,680 acre feet of groundwater, the increase in the interest rate from four to seven percent did not affect either the level of investment or the rate of groundwater use. It was still optimal for the CP producer to buy a pivot only for the first 15 years.

SDI(160a, $4, 7%) For the SDI producer, (Table 23, right side), the optimal size was still 125 acres for the first 15 years and 50 acres for the second 15 years. The NPV for both systems were greatly reduced (NPV CP = $78,286 VS NPV SDI= $115,296). The NPV of the SDI system over the NPV of the CP system was reduced to 47 percent and the SDI has higher capital costs and is more sensitive to higher discount rates.

Table 22. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 160 Acres in Texas County when Corn price is $4.48 and the Grain Sorghum Price is $4.16 per Bushel and the Discount Rate is Four Percent

	Center Pivot Irrigation							Subsurface Drip Irrigation						
Year	Crop, IrT[a]	Yield bus	Irrig. Acres	Dry Acres	160acre Net.Rev.	Cumulative NPV $	GW(aft) 1680	Crop, IrT	Yield Bus	Irrig. Acres	Dry Acres	160 acre Net Rev.	Cumulative NPV $	GW(aft) 1680
1	S, .6	134	120	40	$17,760	$ (42,923)	1595	S, .9	155	125	35	$ 26,210	$(65,498)	1572
2	S, .6	134	120	40	$17,760	$ (26,503)	1511	S, .9	155	125	35	$ 26,210	$(41,265)	1465
3	S, .6	134	120	40	$17,760	$ (10,714)	1426	S, .9	160	125	35	$ 26,259	$(17,921)	1353
4	S, .6	132	120	40	$16,732	$ 3,589	1341	S, .9	147	125	35	$ 26,335	$ 4,590	1234
5	S, .6	130	120	40	$16,320	$ 17,002	1256	S, .9	147	125	35	$ 26,223	$ 26,143	1117
6	S, .6	130	120	40	$16,320	$ 29,900	1172	S, .9	147	125	35	$ 23,335	$ 44,585	1023
7	S, .6	128	120	40	$15,654	$ 41,796	1087	S, .9	141	125	35	$ 23,335	$ 62,318	929
8	S, .6	124	120	40	$14,760	$ 52,581	1003	S, .9	134	125	35	$ 23,170	$ 79,248	836
9	S, .6	124	120	40	$14,760	$ 62,951	918	S, .9	134	125	35	$ 20,085	$ 93,360	757
10	S, .6	124	120	40	$14,377	$ 72,663	835	S, .9	134	125	35	$ 20,085	$ 106,928	679
11	S, .6	105	120	40	$10,680	$ 79,601	758	S, .9	134	125	35	$ 20,085	$ 119,975	600
12	S, .6	87	120	40	$10,680	$ 86,272	682	S, .9	114	125	35	$ 14,637	$ 129,118	550
13	S, .6	87	120	40	$10,680	$ 92,686	605	S, .9	93	125	35	$ 9,085	$ 134,574	528
14	S, .5	87	120	40	$ 8,422	$ 97,549	545	S, .9	93	125	35	$ 9,085	$ 139,820	507
15	S, .5	87	120	40	$ 5,640	$ 100,681	504	S, .9	93	125	35	$ 9,085	$ 144,865	486
16	-	-	-	160	$ 960	$ 101,193	504	C, .9	182	50	110	$ 9,810	$ 127,144	413
17	-	-	-	160	$ 960	$ 101,686	504	C, .9	182	50	110	$ 9,810	$ 132,181	339
18	-	-	-	160	$ 960	$ 102,160	504	C, .9	161	50	110	$ 9,810	$ 137,023	266
19	-	-	-	160	$ 960	$ 102,616	504	C, .9	141	50	110	$ 9,062	$ 141,324	198
20	-	-	-	160	$ 960	$ 103,054	504	C, .9	141	50	110	$ 5,260	$ 143,725	158
21	-	-	-	160	$ 960	$ 103,475	504	C, .9	141	50	110	$ 5,260	$ 146,033	117
22	-	-	-	160	$ 960	$ 103,880	504	S, .9	96	50	110	$ 4,775	$ 148,048	95
23	-	-	-	160	$ 960	$ 104,270	504	S, .9	96	50	110	$ 4,510	$ 149,878	83
24	-	-	-	160	$ 960	$ 104,644	504	S, .9	96	50	110	$ 4,510	$ 151,637	71
25	-	-	-	160	$ 960	$ 105,004	504	S, .9	96	50	110	$ 4,510	$ 153,329	59
26	-	-	-	160	$ 960	$ 105,351	504	S, .9	96	50	110	$ 4,510	$ 154,956	47
27	-	-	-	160	$ 960	$ 105,684	504	S, .9	96	50	110	$ 4,510	$ 156,520	35
28	-	-	-	160	$ 960	$ 106,004	504	S, .9	96	50	110	$ 4,510	$ 158,024	23
29	-	-	-	160	$ 960	$ 106,311	504	S, .9	96	50	110	$ 4,510	$ 159,470	11
30	-	-	-	160	$ 960	$ 106,607	504	S, .9	96	50	110	$ 4,510	$ 160,861	0

IrT: Irrigation Trigger, Soil Moisture Content to trigger an irrigation

GW(aft): Acre feet of groundwater remaining at end of year

Table 23. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 160 Acres in Texas County when Corn price is $4.48 and the Grain Sorghum Price is $4.16 per Bushel and the Discount Rate is Seven Percent

Year	Center Pivot Irrigation							Sub Surface Drip Irrigation						
	Crop, IrT	Yield bus	Irrig. Acres	Dry Acres	160 acre N.Rev	Cumulative NPV $	GW (aft) 1680	Crop, IrT	Yield bus	Irrig. Acres	Dry Acre	160 acre Net Rev.	Cumulative NPV $	GW (aft) 1680
1	S, .6	134	120	40	$ 17,760	$ (43,402)	1595	S, .9	155	125	35	$26,210	-$66,205	1572
2	S, .6	134	120	40	$ 17,760	$ (27,890)	1511	S, .9	155	125	35	$26,210	-$43,312	1465
3	S, .6	134	120	40	$ 17,760	$ (13,392)	1426	S, .9	160	125	35	$26,259	-$21,876	1353
4	S, .6	132	120	40	$ 16,732	$ (627)	1341	S, .9	160	125	35	$26,335	-$1,785	1234
5	S, .6	130	120	40	$ 16,320	$ 11,009	1256	S, .9	147	125	35	$26,223	$16,911	1117
6	S, .6	130	120	40	$ 16,320	$ 21,884	1172	S, .9	147	125	35	$23,335	$32,460	1023
7	S, .6	128	120	40	$ 15,654	$ 31,632	1087	S, .9	147	125	35	$23,335	$46,992	929
8	S, .6	124	120	40	$ 14,760	$ 40,222	1003	S, .9	147	125	35	$23,170	$60,477	836
9	S, .6	124	120	40	$ 14,760	$ 48,251	918	S, .9	135	125	35	$20,085	$71,402	757
10	S, .6	124	120	40	$ 14,377	$ 55,559	835	S, .9	135	125	35	$20,085	$81,612	679
11	S, .6	105	120	40	$ 10,680	$ 60,633	758	S, .9	135	125	35	$20,085	$91,154	600
12	S, .6	87	120	40	$ 10,680	$ 65,375	682	S, .9	135	125	35	$14,637	$97,653	550
13	S, .6	87	120	40	$ 10,680	$ 69,807	605	S, .9	93	125	35	$9,085	$101,423	528
14	S, .5	87	120	40	$ 8,422	$ 73,073	545	S, .9	93	125	35	$9,085	$104,947	507
15	S, .5	87	120	40	$ 5,640	$ 75,117	504	S, .9	93	125	35	$9,085	$108,240	486
16	-	-	-	160	$ 960	$ 75,443	504	C, .9	182	50	110	$9,810	$96,997	413
17	-	-	-	160	$ 960	$ 75,746	504	C, .9	182	50	110	$9,810	$100,102	339
18	-	-	-	160	$ 960	$ 76,030	504	C, .9	182	50	110	$9,810	$103,005	266
19	-	-	-	160	$ 960	$ 76,296	504	C, .9	182	50	110	$9,062	$105,510	198
20	-	-	-	160	$ 960	$ 76,544	504	C, .9	141	50	110	$5,260	$106,870	158
21	-	-	-	160	$ 960	$ 76,776	504	C, .9	141	50	110	$5,260	$108,140	117
22	-	-	-	160	$ 960	$ 76,993	504	S, .9	141	50	110	$4,775	$109,218	95
23	-	-	-	160	$ 960	$ 77,195	504	S, .9	97	50	110	$4,510	$110,169	83
24	-	-	-	160	$ 960	$ 77,384	504	S, .9	97	50	110	$4,510	$111,058	71
25	-	-	-	160	$ 960	$ 77,561	504	S, .9	97	50	110	$4,510	$111,889	59
26	-	-	-	160	$ 960	$ 77,726	504	S, .9	97	50	110	$4,510	$112,666	47
27	-	-	-	160	$ 960	$ 77,881	504	S, .9	97	50	110	$4,510	$113,392	35
28	-	-	-	160	$ 960	$ 78,025	504	S, .9	97	50	110	$4,510	$114,070	23
29	-	-	-	160	$ 960	$ 78,160	504	S, .9	97	50	110	$4,510	$114,704	11
30	-	-	-	160	$ 960	$ 78,286	504	S, .9	97	50	110	$4,510	$115,296	0

Irt: Irrigation Trigger, moisture level to trigger an irrigation

GW(aft): Acre feet of remaining ground water at end of year

CP(160a, $5, 4%) The optimal 30-year investments (Table 24) and ground water use with the higher feed grain prices (corn price = $5.48/bus, GS price = $5.09/bus) with the discount rate at four percent are shown in Table 24. For the CP choice, the crop selection and rate of groundwater use over the first 15 years increased irrigation intensity slightly in the first 15 years ending with 442 acre feet rather than 540 shown in Table 22. The higher price did make it slightly profitable to purchase a replacement pivot and irrigate 120 acres in years 16-24. The irrigation ended in year 24 when the aquifer was exhausted. The 30 year NPV for the CP system was $344,489.

SDI(160a, $5, 4%) With the higher feed grain price, the SDI systems size was increased to 150 acres for the entire thirty year period. The crop choice is GS except for year 13 when corn was grown. (This is likely an anomaly in the budgets). The initial net revenue over variable costs was $52,100 (with 155 bushel GS) in year 1 and declined to $22,400 (with 88 bushel GS) by year 30. The 30-year cumulative NPV at seven percent reached $436,103 as compared to $344,489 for the above CP example.

CP(160a, $5, 7%) In general an increased discount discourages investments. However in this study, the irrigation investments are a lumpy yes or no choice. In this example, (Table 25), the profitability of the CP investment is reduced but it was still optimal to purchase a 120 acre system for use in years 1-15 and replace the system in year 16. Irrigation continued through 28 years of the 30 year planning horizon. The 30-year cumulative NPV, at a seven percent discount rate, was $260,312.

SDI(160a, $5, 7%) The 150 acre SDI was purchased for the first 15-year period and replaced in year 16 for the 16-30 year period. Intensively irrigated GS was the selected crop except for years 13 and 14. Irrigation continued for the 30 year period. The 30-year cumulative NPV, at a seven percent discount rate, reached $318,318 in year 30.

Table 24. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 160 Acres in Texas County when Corn price is $5.48 and the Grain Sorghum Price is $5.09 per Bushel and the Discount Rate is Four Percent

Year	Center Pivot Irrigation							Sub Surface Drip Irrigation						
	Crop, IrT	Yield bus	Irrig. Acres	Dry Acres	160 acre N.Rev	Cumulative NPV $	GW (aft) 1680	Crop, IrT	Yield bus	Irrig. Acres	Dry Acre	160 acre Net Rev.	Cumulativ NPV $	GW (aft) 1680
1	S, .6	134	120	40	$ 35,000	$(26,346)	1595	S, .9	155	150	10	$52,100	-$56,904	1551
2	S, .6	134	120	40	$ 35,000	$ 6,013	1511	S, .9	155	150	10	$52,100	-$8,734	1422
3	S, .6	134	120	40	$ 35,000	$ 37,128	1426	S, .9	155	150	10	$50,358	$36,034	1306
4	S, .6	132	120	40	$ 33,715	$ 65,948	1341	S, .9	147	150	10	$50,000	$78,774	1193
5	S, .6	130	120	40	$ 33,200	$ 93,236	1256	S, .9	147	150	10	$47,752	$118,023	1086
6	S, .6	130	120	40	$ 33,200	$119,475	1172	S, .9	135	150	10	$43,400	$152,322	992
7	S, .6	128	120	40	$ 32,277	$144,003	1087	S, .9	135	150	10	$43,400	$185,303	897
8	S, .6	124	120	40	$ 31,040	$166,683	1003	S, .9	135	150	10	$40,511	$214,904	811
9	S, .6	124	120	40	$ 31,040	$188,492	918	S, .9	119	150	10	$35,750	$240,022	737
10	S, .6	124	120	40	$ 30,058	$208,798	838	S, .9	119	150	10	$35,750	$264,173	664
11	S, .6	110	120	40	$ 25,400	$225,297	762	S, .9	119	150	10	$35,750	$287,395	590
12	S, .6	108	120	40	$ 25,400	$241,162	685	S, .9	119	150	10	$31,234	$306,904	511
13	S, .5	108	120	40	$ 24,800	$256,056	612	C, .9	125	150	10	$27,800	$323,600	426
14	S, .5	108	120	40	$ 23,141	$269,419	533	S, .9	93	150	10	$24,350	$337,661	401
15	C, .5	108	120	40	$ 19,760	$280,391	442	S, .9	93	150	10	$24,350	$351,182	375
16	C, .5	118	120	40	$ 19,760	$258,907	351	S, .9	93	150	10	$24,350	$307,055	350
17	C, .5	118	120	40	$ 19,263	$268,796	274	S, .9	93	150	10	$24,350	$319,555	324
18	S, .4	88	120	40	$ 17,840	$277,602	234	S, .9	93	150	10	$24,350	$331,575	299
19	S, .4	88	120	40	$ 17,840	$286,070	194	S, .9	88	150	10	$23,989	$342,962	275
20	S, .4	88	120	40	$ 17,840	$294,212	154	S, .9	88	150	10	$22,400	$353,185	262
21	S, .4	88	120	40	$ 17,840	$302,041	114	S, .9	88	150	10	$22,400	$363,014	248
22	S, .4	88	120	40	$ 17,840	$309,569	74	S, .9	88	150	10	$22,400	$372,466	235
23	S, .4	88	120	40	$ 17,840	$316,807	34	S, .9	88	150	10	$22,400	$381,554	221
24	S, .4	88	120	40	$ 16,439	$323,220	1	S, .9	88	150	10	$22,400	$390,293	208
25	-	-	-	160	$ 10,400	$327,121	1	S, .9	88	150	10	$22,400	$398,696	194
26	-	-	-	160	$ 10,400	$330,872	1	S, .9	88	150	10	$22,400	$406,775	181
27	-	-	-	160	$ 10,400	$334,479	1	S, .9	88	150	10	$22,400	$414,544	167
28	-	-	-	160	$ 10,400	$337,947	1	S, .9	88	150	10	$22,400	$422,014	154
29	-	-	-	160	$ 10,400	$341,282	1	S, .9	88	150	10	$22,400	$429,196	140
30	-	-	-	160	$ 10,400	$344,489	1	S, .9	88	150	10	$22,400	$436,103	127

Irt: Irrigation Trigger, moisture level to trigger an irrigation
GW(aft): Acre feet of remaining ground water at end of year

Table 25. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 160 Acres in Texas County when Corn price is $5.48 and the Grain Sorghum Price is $5.09 per Bushel and the Discount Rate is Seven Percent

Year	Center Pivot Irrigation							Sub Surface Drip Irrigation						
	Crop, IrT	Yield bus	Irrig. Acres	Dry Acres	160 acre N.Rev	Cumulative NPV $	GW (aft) 1680	Crop, IrT	Yield bus	Irrig. Acres	Dry Acre	160 acre Net Rev	Cumulati NPV $	GW (aft) 1680
1	S,.6	134	120	40	$35,000	$ (27,290)	1595	S, .9	155	150	10	$52,100	-$58,308	1551
2	S,.6	134	120	40	$35,000	$ 3,281	1511	S, .9	155	150	10	$52,100	-$12,802	1422
3	S,.6	134	120	40	$35,000	$ 31,851	1426	S, .9	155	150	10	$50,358	$28,305	1306
4	S,.6	134	120	40	$33,715	$ 57,572	1341	S, .9	147	150	10	$50,000	$66,450	1193
5	S,.6	130	120	40	$33,200	$ 81,244	1256	S, .9	147	150	10	$47,752	$100,496	1086
6	S,.6	130	120	40	$33,200	$ 103,366	1172	S, .9	135	150	10	$43,400	$129,416	992
7	S,.6	130	120	40	$32,277	$ 123,467	1087	S, .9	135	150	10	$43,400	$156,443	897
8	S,.6	125	120	40	$31,040	$ 141,532	1003	S, .9	135	150	10	$40,511	$180,021	811
9	S,.6	125	120	40	$31,040	$ 158,416	918	S, .9	119	150	10	$35,750	$199,467	737
10	S,.6	125	120	40	$30,510	$ 173,926	835	S, .9	119	150	10	$35,750	$217,640	664
11	S,.6	110	120	40	$25,400	$ 185,993	758	S, .9	119	150	10	$35,750	$234,625	590
12	S,.6	110	120	40	$25,400	$ 197,271	682	S, .9	119	150	10	$31,234	$248,493	511
13	S,.6	110	120	40	$25,400	$ 207,811	605	C, .9	125	150	10	$27,800	$260,029	426
14	S,.6	110	120	40	$22,335	$ 216,473	544	C, .9	125	150	10	$27,800	$270,810	342
15	S,.5	90	120	40	$18,560	$ 223,200	503	S, .9	93	150	10	$24,350	$279,636	316
16	S,.5	90	120	40	$18,560	$ 209,163	461	S, .9	93	150	10	$24,350	$251,639	291
17	S,.5	90	120	40	$18,560	$ 215,039	420	S, .9	93	150	10	$23,416	$259,052	271
18	S,.5	90	120	40	$18,560	$ 220,530	379	S, .9	88	150	10	$22,400	$265,679	257
19	S,.5	90	120	40	$18,560	$ 225,662	337	S, .9	88	150	10	$22,400	$271,873	244
20	S,.5	90	120	40	$18,560	$ 230,458	296	S, .9	88	150	10	$22,400	$277,661	230
21	S,.5	90	120	40	$18,139	$ 234,839	255	S, .9	88	150	10	$22,400	$283,071	217
22	S,.5	90	120	40	$17,840	$ 238,866	215	S, .9	88	150	10	$22,400	$288,127	203
23	S,.4	88	120	40	$17,840	$ 242,629	175	S, .9	88	150	10	$22,400	$292,852	190
24	S,.4	88	120	40	$17,840	$ 246,146	135	S, .9	88	150	10	$22,400	$297,269	176
25	S,.4	88	120	40	$17,840	$ 249,433	95	S, .9	88	150	10	$22,400	$301,396	163
26	S,.4	88	120	40	$17,840	$ 252,505	55	S, .9	88	150	10	$22,400	$305,253	149
27	S,.4	88	120	40	$17,840	$ 255,376	15	S, .9	88	150	10	$22,400	$308,858	136
28	S,.4	88	58	102	$14,011	$ 257,483	0	S, .9	88	150	10	$22,400	$312,227	122
29	S,.4	88	-	160	$10,400	$ 258,945	0	S, .9	88	150	10	$22,400	$315,375	109
30	-	-	-	160	$10,400	$ 260,312	0	S, .9	88	150	10	$22,400	$318,318	95

Irt: Irrigation Trigger, moisture level to trigger an irrigation

GW(aft): Acre feet of remaining ground water at end of year

In the one fourth section examples addressed above, investment is the SDI system always provided higher discounted net returns than did the CP system. In the four cases above, aquifer life was prolonged. However, there are periods where the SDI producer would irrigate a larger area than the CP producer and use more water in a given year. There are cases in the next section where the economic life of the aquifer was not prolonged by choosing the SDI over the CP.

One question is the the relation between adoption of the SDI system and "Conservation of Groundwater" of the Ogallala Aquifer. The definition of conservation given by Ciriacy-Wantrup (1963) can help answer this question. S. V. Ciriacy -Wantrup (1963) defined conservation as the wise use of resources over time. He went on to describe "the optimal state of conservation as that time distribution of use rates that maximizes the present value of the flow of expected net revenues". The total bushels of irrigated corn and sorghum produced over the 30-year period divided by the total acre-feet of groundwater used in Tables 22 and 24 above are presented below in Figure 28. The results show the SDI system would allow producers to produce more feed grain per acre-foot of water used than does the conventional CP. The amount of feed grain produced per unit of ground water increased with the feed grain price because the SDI with lower pumping costs and higher application efficiency was able to make greater use of ground water pumped even as well yields declined.

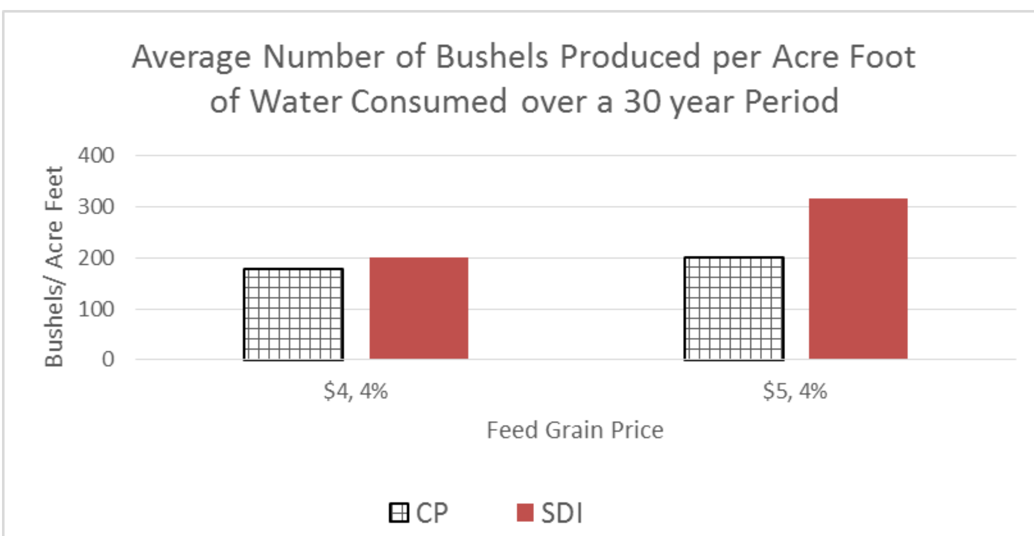


Figure 28. Comparison Potential Production of Grain Sorghum on a Quarter Section over a 30-year Planning Horizon at Two Feed Grain Prices and Four Percent Interest.

Effect of Holding Size on Irrigation Investments and Optimal Long Term Water Use

In this section the producer is assumed to control a 640 acre section of land developed for irrigation as shown below in Figure 29. It is assumed the producer has one well on each quarter section of land and that the wells have been interconnected by an underground pipe as shown in Figure 29.

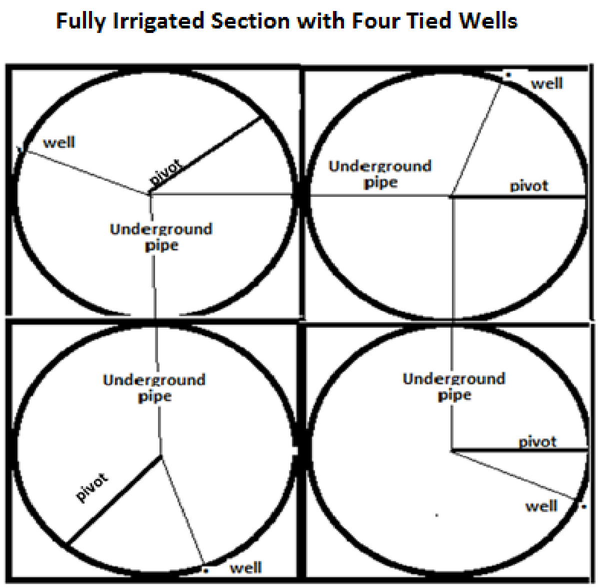


Figure 29. Diagram of 640 Acre Section with Four Connected Irrigation Wells.

It is assumed the producer must invest in either a CP or an SDI irrigation system to continue irrigation. The analysis is conducted first assuming the producer has only the 60 feet of water saturated sand under the 640 acre holding (6,720 acre feet) and second assuming the producer is in a location where only 50 percent of the surrounding land is irrigated (And has twice the supply (13,440 acre feet). The effects of two feed grain prices ($4.48/bus corn, $4.16/bus GS, $5.48/ bus corn and $5.09/bus GS) and two discount rates (four percent and seven percent) on the investment are considered with each water supply. The initial output of each well is assumed to be 600 GPM.

Irrigation Systems, Water Use with 640 Acres, Limited Water, and Four Dollar Feed Grain

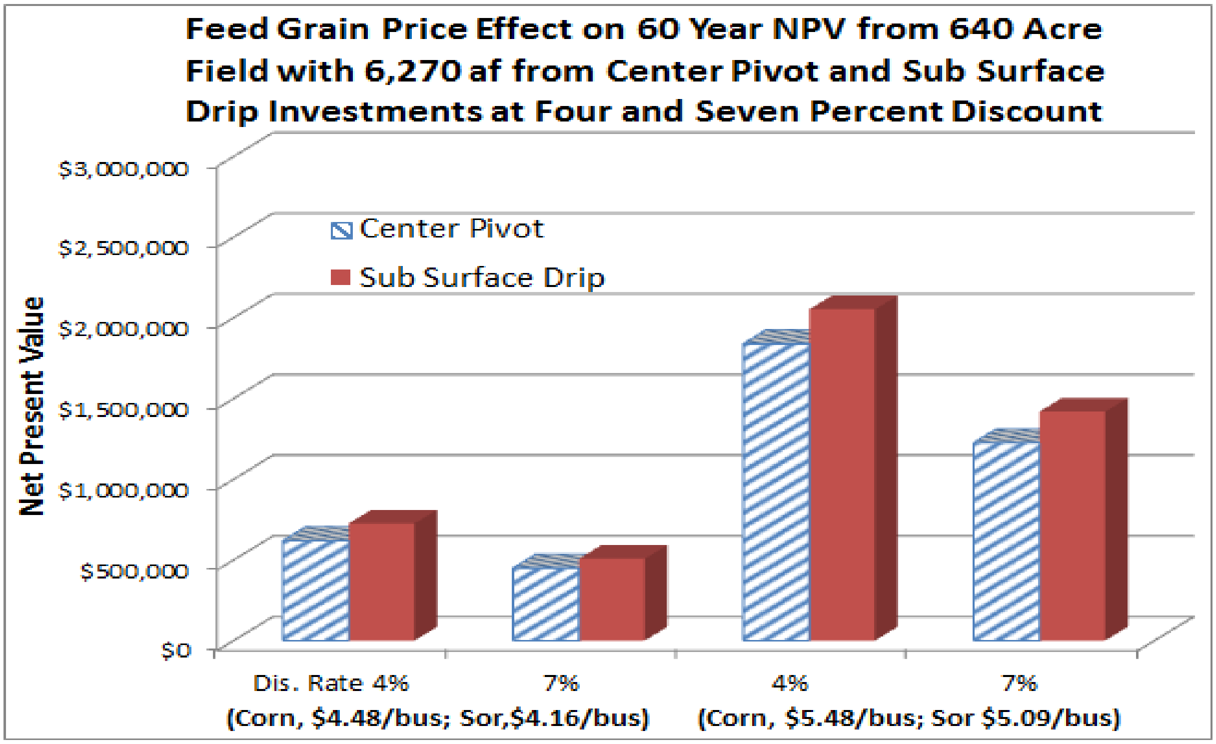
The 60-year results for the producer choosing either a CP or a SDI systems and continuing with that type of system until the aquifer is exhausted are compared in Table 26 . The producer with the 640 acre system of land has more flexibility than with a single quarter system because irrigation systems can be established on 0 to four quarters. If the producer establishes irrigation on one quarter section, then the producer may still draw from four wells to increase the GPM delivered to the irrigation system over the amount that could be delivered if an irrigation system were established on all four quarter sections.

CP(640a, $4, 4%, Lw) The results on the left side of Table 26 show the producer investing in the CP would purchase only two CP systems for the first 15 years (irrigating 240) acres. The price received for corn and GS over the 60 period is $4.48/bus and $4.16/bus respectively. The discount rate is four percent. The producer intensively irrigates corn (Irt = .9) and obtains estimated yields of 214 bus/acre for the first four years. Then the producer would switch to GS for years 5 through 15. In year 16, the producer would purchase only one 120 acre CP. As the supply of irrigated land becomes more limited and the supply of water delivered to the pivot is increased back to 800 GPM, the producer grows 213 bushel corn for three years. As the ground water table declines to where less than 400 GPM can be delivered to the irrigated area, the producer switches to GS for the remainder of the aquifer life. A third CP system purchased in year 31 would be used to produce 124 bushel GS until the aquifer is exhausted at the end of year 45. Only dryland GS would be produced in years 46-60.

Initial net cash receipts in years 1-4 are estimated to be $63,840 (machinery expenses are not deducted). These decline to $37,680 by year 15. Annual net cash receipts continue to decline with the water table to $17,760 in the last year of irrigation in year 45. Returns from dryland production are expected to average $3,840 in years 46-60. The cumulative NPV from 60 years of operating the 640 acre parcel with the pivot system are estimated to $618,708. Figure 30compares the sensitivity of the NPV to changes in the ground water supply, feed grain price, and discount rate.

SDI(640a, $4, 4%, Lw) Results for the producer investing in a series of SDI systems are shown on the right side of Table 26. Initially, the SDI system would provide irrigation to 450 acres (three, 150-acre SDI systems) of sorghum for the first 15 years. The GS would be intensively irrigated (IrT = .9) and the estimate GS yields would be 164 bus/acre. However as the aquifer declines, the IrT for irrigation of GS declines to .6 by year 15. In year 16, the producer replaces only 125 acres of the previous 450 acres. With the smaller systems and the ability to draw water from 4 wells, the producer grows three years of intensively irrigated corn

(Irt = .9, yields = 214 bus/acre). The producer then switches back to intensively (IrT=.9) irrigated GS for years 19-30. At the end of year 30, there was only 31 acre-feet of groundwater



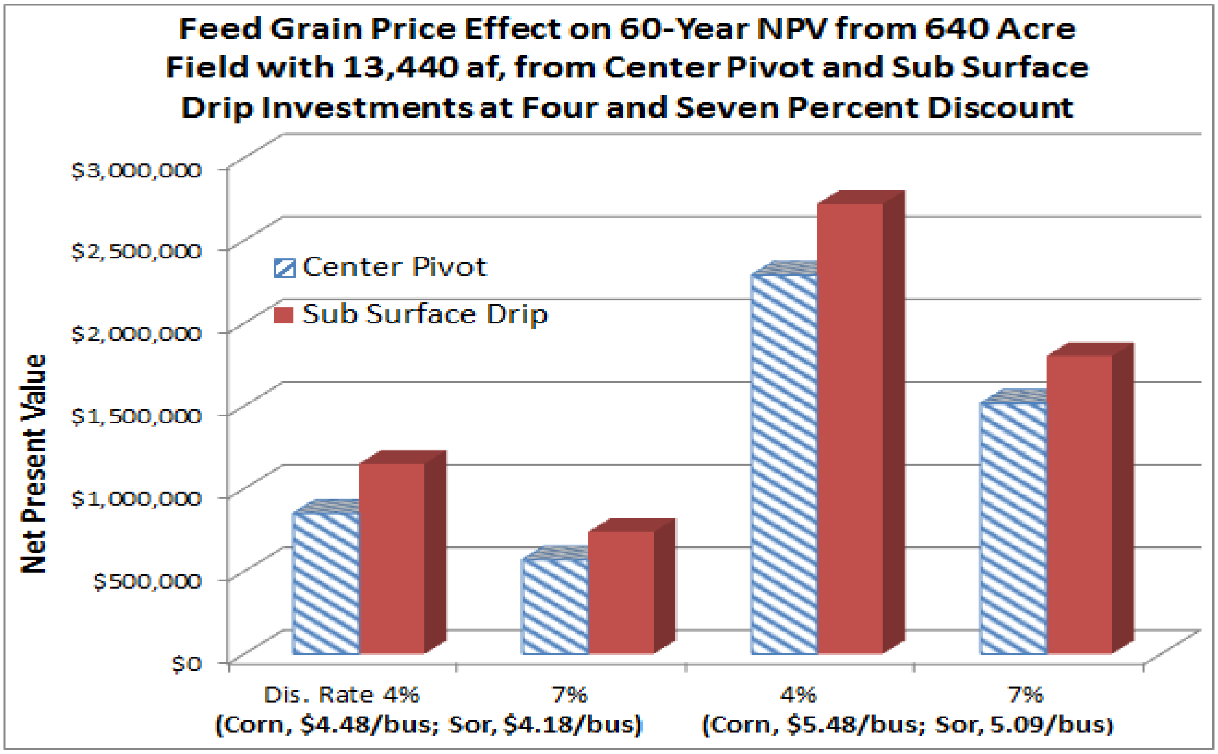


Figure 30. Comparison of NPV from Center Pivot and Subsurface Drip Investments on a 640 Acre Field with Initial Water Supplies of 6,240 and 13,440 Acre Feet Under Two Feed Grain Prices and Two Discount Rates.

Table 26. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 640 Acres with 6,720 Acre Feet of Groundwater in Texas County when Corn price is $4.48 and the Grain Sorghum Price is $4.16 per Bushel and the Discount Rate is Four Percent.

	Center Pivot							Sub Surface Drip						
Year	Crop IrT	Yield Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulative NPV 4	GW (aft) 6720	Crop IrT	Ir.Yield Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulative NPV 4	GW (aft) 6,720
1	C, .9	213	240	400	$ 63,840	$ (58,615)	6271	S,.9	164	450	515	$ 96,990	$(227,740)	6,265
2	C, .9	213	240	400	$ 63,840	$ 408	5822	S,.9	164	450	515	$ 96,990	$(138,068)	5,810
3	C, .9	213	240	400	$ 63,356	$ 56,731	5373	S,.9	160	450	515	$ 93,615	$ (54,845)	5,391
4	C, .9	213	240	400	$ 62,880	$ 110,481	4923	S,.9	155	450	515	$ 90,690	$ 22,678	5,004
5	S, .6	138	240	400	$ 59,438	$ 159,335	4525	S,.9	155	450	515	$ 90,690	$ 97,218	4,617
6	S, .6	138	240	400	$ 43,029	$ 193,342	4365	S,.9	152	450	515	$ 89,246	$ 167,751	4,260
7	S, .6	138	240	400	$ 42,960	$ 225,988	4205	S,.9	147	450	515	$ 88,440	$ 234,958	3,921
8	S, .6	138	240	400	$ 42,960	$ 257,378	4045	S,.9	135	450	515	$ 88,440	$ 299,580	3,582
9	S, .6	138	240	400	$ 42,960	$ 287,562	3885	S,.9	147	450	515	$ 83,350	$ 358,141	3,261
10	S, .6	138	240	400	$ 42,960	$ 316,584	3725	S,.9	140	450	515	$ 72,690	$ 407,247	2,978
11	S, .6	138	240	400	$ 42,960	$ 344,490	3565	S,.9	135	450	515	$ 72,690	$ 454,465	2,694
12	S, .6	138	240	400	$ 42,960	$ 371,322	3405	S,.8	135	450	515	$ 72,690	$ 499,867	2,411
13	S, .6	136	240	400	$ 39,019	$ 394,756	3238	S,.8	135	450	515	$ 57,937	$ 534,663	2,204
14	S, .6	134	240	400	$ 37,680	$ 416,515	3068	S,.6	115	450	515	$ 33,090	$ 553,771	2,126
15	S, .6	134	240	400	$ 37,680	$ 437,438	2899	S,.6	93	450	515	$ 33,090	$ 572,145	2,048
16	C, .9	213	120	510	$ 33,600	$ 423,343	2674	C, .9	214	125	515	$ 35,840	$ 542,855	1,812
17	C, .9	213	120	510	$ 33,600	$ 440,592	2450	C, .9	214	125	515	$ 35,840	$ 561,254	1,577
18	C, .9	213	120	510	$ 33,555	$ 457,156	2225	C, .9	214	125	515	$ 35,840	$ 578,946	1,341
19	S, .6	138	120	510	$ 23,400	$ 468,262	2145	S,.9	166	125	515	$ 35,779	$ 595,928	1,107
20	S, .6	138	120	510	$ 23,400	$ 478,942	2065	S,.9	166	125	515	$ 26,215	$ 607,892	1,012
21	S, .6	138	120	510	$ 23,400	$ 489,211	1985	S,.9	166	125	515	$ 26,215	$ 619,396	918
22	S, .6	138	120	510	$ 23,400	$ 499,084	1905	S,.9	155	125	515	$ 26,215	$ 630,458	824
23	S, .6	138	120	510	$ 23,400	$ 508,578	1825	S,.9	147	125	515	$ 26,215	$ 641,094	730
24	S, .6	138	120	510	$ 23,400	$ 517,707	1745	S,.9	147	125	515	$ 26,215	$ 651,321	636
25	S, .6	138	120	510	$ 23,400	$ 526,485	1665	S,.9	147	125	515	$ 26,215	$ 661,155	542
26	S, .6	138	120	510	$ 23,400	$ 534,925	1585	S,.9	147	125	515	$ 26,215	$ 670,610	447
27	S, .6	138	120	510	$ 23,400	$ 543,040	1505	S,.9	147	125	640	$ 26,215	$ 679,702	353
28	S, .6	138	120	510	$ 23,400	$ 550,844	1425	S,.9	147	125	640	$ 26,215	$ 688,444	259
29	S, .6	138	120	510	$ 23,400	$ 558,347	1345	S,.9	147	125	640	$ 26,215	$ 696,850	165
30	S, .6	138	120	510	$ 23,400	$ 565,562	1265	S,.9	147	125	640	$ 26,215	$ 704,932	71
31	S, .6	138	120	510	$ 23,400	$ 554,711	1185	-	-	-	640	$ 3,840	$ 706,071	71
32	S, .6	138	120	510	$ 21,520	$ 560,845	1104	-	-	-	640	$ 3,840	$ 707,165	71
33	S, .6	124	120	510	$ 17,760	$ 565,713	1019	-	-	-	640	$ 3,840	$ 708,218	71
34	S, .6	124	120	510	$ 17,760	$ 570,394	935	-	-	-	640	$ 3,840	$ 709,230	71
35	S, .6	124	120	510	$ 17,760	$ 574,895	851	-	-	-	640	$ 3,840	$ 710,203	71
36	S, .6	124	120	510	$ 17,760	$ 579,222	766	-	-	-	640	$ 3,840	$ 711,139	71
37	S, .6	124	120	510	$ 17,760	$ 583,383	682	-	-	-	640	$ 3,840	$ 712,039	71
38	S, .6	124	120	510	$ 17,760	$ 587,384	597	-	-	-	640	$ 3,840	$ 712,904	71
39	S, .6	124	120	510	$ 17,760	$ 591,231	513	-	-	-	640	$ 3,840	$ 713,735	71
40	S, .6	124	120	510	$ 17,760	$ 594,931	428	-	-	-	640	$ 3,840	$ 714,535	71
41	S, .6	124	120	510	$ 17,760	$ 598,488	344	-	-	-	640	$ 3,840	$ 715,304	71
42	S, .6	124	120	510	$ 17,760	$ 601,908	260	-	-	-	640	$ 3,840	$ 716,044	71
43	S, .6	124	120	510	$ 17,760	$ 605,196	175	-	-	-	640	$ 3,840	$ 716,755	71
44	S, .6	124	120	510	$ 17,760	$ 608,358	91	-	-	-	640	$ 3,840	$ 717,439	71
45	S, .6	124	120	510	$ 17,760	$ 611,399	6	-	-	-	640	$ 3,840	$ 718,096	71
46-59					$ 3,840	$ 618,343	6				640	$ 3,840	$ 725,040	71
60					$ 3,840	$ 618,708	6				640	$ 3,840	$ 725,405	71

Irt: Irrigation trigger: An irrigation is initiated when moisture level is at or below the indicated level

GW(aft): acre feet of ground water remaining at end of year

46-59: average acres, net revenue, cumulative NPV, GW remaining in year 59

remaining, so there was no further irrigation system investment. Dryland GS is produced from years 30 through 60. Compared to the CP system, the SDI used more water in the initial period and exhausted in 30 years as compared to 45 years for the CP system.

Net receipts, (no deduction for fixed machinery or irrigation system costs) reached $96,990 for the first three years, but declined to $35,840 by year 15. Net receipts in year 16 (with 125 acres of irrigated corn) are $35,779 but decline to $26,215 by year 30. Annual net receipts are $3,840 for years 31-60. The investment cost of the 450 acre system was not recovered until year 3 whereas the investment cost of the CP system was recovered by year 2. The 60-year cumulative NPV (at 4 percent) (with irrigation system costs deducted) reached $725,405. This compares to the cumulative NPV of the CP system which was $618,708.

An increase in the discount rate from four to seven percent (Table 27) lowers the NPV from each system but was also expected to increase the near term use of ground water and make capital investments more expensive. For the CP system, the producer still buys two pivots and irrigates 240 acres. However, the producer raises 240 acres of 213 bushel corn for six years rather than four years with the four percent discount. Grain Sorghum is grown in years 7-15. At the end of year 15 there is 2,243 acre feet of ground water remaining compared to 2,225 acre feet at the four percent discount rate.

It was profitable to drop to a 120 acre pivot in year 16 and to replace this system again in year 31. In year 16, the irrigated corn is grown, but then GS is grown for years 17 to 41. Under the seven percent discount rate, irrigation was terminated after year 41. Production was limited to dryland sorghum from years 42-60. The cumulative NPV at seven percent discount reached $448,906 by year 60.

Irrigation Systems, Water Use with 640 Acres, Limited Water, and Five Dollar Feed Grain

CP(640a, $5, 4%, Lw) If the price of corn increased from $4.48 to $5.49/bus, and the price of GS increased from $4.16 to $5.09/bus., it is anticipated all irrigation system investments would become more profitable. Table 28 shows that at the four percent discount rate, the producer would still invest in two, 120 acres pivots and then purchase one 120 acre pivot in year 16 and again in year 31.

With the higher corn price, long-term profits would be increased by growing seven years of 213 bushel irrigated corn (rather than four years with $4.48 corn) before switching to irrigated GS in year 7. Because there are four years of less intensively irrigated GS, the producer ends the first 15 year period with slightly more groundwater than was the case with four dollar feed grain.

In years 16-45, the production of five dollar GS with a single 120 acre pivot, (fed by four wells) gives similar results as with respect to water use and irrigation intensity as found with the four dollar GS. Irrigation terminated in year 45 and only dryland GS was grown in years 46-60.

Annual net returns were higher with the five dollar feed grain than with the four dollar feed grain. With the four percent discount rate, the 60-year cumulative NPV from the CP system was $1,839,290. The NPV is very sensitive to the price of feed grain. The 22 percent increase in price caused the NPV to increase by three times.

SDI(640a, $5, 4%, Lw) (Table 28) For the SDI system, higher feed grain prices made it profitable to install four, 150 SDI systems for the first 15 years. In contrast to the CP system, intensively irrigated GS was the crop of choice. The irrigation of 600 acres was not sustainable for the full 15 year period and the area of irrigated GS declined from 600 to 582 acres in year 15. There were 1818 acre feet of ground water remaining after the first 15 year period. In the second 15-year period, the irrigated area was limited to a single 125 acre system. The aquifer was exhausted by year 30 and dryland GS was grown from years 31-60.

Net receipts (no deduction of machinery fixed cost) were $208,000 in the first two years but declined to $73,600 by year 30. Dryland receipts were $41,600 over the 31-60 year period. The cumulative 60-year NPV at four percent was $2,052,066.

CP(640a, $5, 7%, Lw) Increasing the discount rate from four to seven percent naturally reduced the NPV of both investments. For the pivot system the investment pattern (240 acres in years 1-15 and 120 acres in years 16-30) remain unchanged from the four percent rate. There was more initial use of ground water as eight years of corn were produced rather than seven years with the four percent discount rate. There were seven years of corn production after the irrigated acreage was reduced from 240 to 120 acres in the second 15 year period. The rate of ground water extraction was

Table 27. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 640 Acres with 6,720 Acre Feet of Groundwater in Texas County when Corn price is $4.48 and the Grain Sorghum Price is $4.16 per Bushel and the Discount Rate is Seven Percent

	Center Pivot							Sub Surface Drip						
Year	Crop IrT	Yield Bus	Irrig. Year	Dry Acres	640Acre Net Rev.	Cumulative NPV 4	GW (aft) 6720	Crop IrT	Ir.Yield Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulative NPV	GW (aft) GPM
1	C, .9	213	240	400	$63,840	$ (60,336)	6271	S,.9	155	500	140	$104,840	$(264,819)	6,290
2	C, .9	213	240	400	$63,840	$ (4,576)	5822	S,.9	155	500	140	$104,840	$(173,247)	5,860
3	C, .9	213	240	400	$63,356	$ 47,141	5373	S,.9	161	500	140	$105,038	$ (87,505)	5,412
4	C, .9	213	240	400	$62,880	$ 95,112	4923	S,.9	161	500	140	$105,340	$ (7,142)	4,937
5	C, .9	213	240	400	$62,874	$ 139,940	4474	S,.9	161	500	140	$104,872	$ 67,630	4,466
6	C, .9	213	240	400	$62,160	$ 181,360	4025	S,.9	147	500	140	$ 92,840	$ 129,493	4,089
7	S, .6	139	240	400	$57,152	$ 216,951	3651	S,.9	147	500	140	$ 92,840	$ 187,309	3,713
8	S, .6	139	240	400	$42,960	$ 241,954	3491	S,.9	147	500	140	$ 92,205	$ 240,974	3,339
9	S, .6	139	240	400	$42,290	$ 264,957	3324	S,.9	135	500	140	$ 80,340	$ 284,673	3,024
10	S, .7	140	240	400	$39,120	$ 284,843	3123	S,.9	135	500	140	$ 80,340	$ 325,514	2,709
11	S, .7	140	240	400	$39,120	$ 303,429	2921	S,.9	135	500	140	$ 80,340	$ 363,683	2,394
12	S, .6	134	240	400	$37,680	$ 320,159	2752	S,.9	135	500	140	$ 65,978	$ 392,978	2,031
13	S, .6	134	240	400	$37,680	$ 335,795	2582	S,.9	97	500	140	$ 45,640	$ 411,917	1,758
14	S, .6	134	240	400	$37,680	$ 350,408	2413	S,.9	97	500	140	$ 39,340	$ 427,174	1,636
15	S, .6	134	240	400	$37,680	$ 364,065	2243	S,.9	93	500	140	$ 36,340	$ 440,345	1,550
16	C, .9	213	120	520	$33,120	$ 354,960	2019	S,.9	167	125	515	$ 30,465	$ 419,942	1,418
17	S, .6	139	120	520	$23,400	$ 362,368	1939	S,.9	167	125	515	$ 30,465	$ 429,586	1,286
18	S, .6	139	120	520	$23,400	$ 369,291	1859	S,.9	167	125	515	$ 30,465	$ 438,600	1,154
19	S, .6	139	120	520	$23,400	$ 375,761	1779	S,.9	167	125	515	$ 30,295	$ 446,977	1,024
20	S, .6	139	120	520	$23,400	$ 381,808	1699	S,.9	147	125	515	$ 26,215	$ 453,751	929
21	S, .6	139	120	520	$23,400	$ 387,460	1619	S,.9	147	125	515	$ 26,215	$ 460,082	835
22	S, .6	139	120	520	$23,400	$ 392,741	1539	S,.9	147	125	515	$ 26,215	$ 465,999	741
23	S, .6	139	120	520	$23,400	$ 397,678	1459	S,.9	147	125	515	$ 26,215	$ 471,529	647
24	S, .6	139	120	520	$23,400	$ 402,291	1379	S,.9	147	125	515	$ 26,215	$ 476,698	553
25	S, .6	139	120	520	$23,400	$ 406,602	1299	S,.9	147	125	515	$ 26,215	$ 481,528	459
26	S, .6	139	120	520	$23,400	$ 410,632	1219	S,.9	147	125	515	$ 26,215	$ 486,042	364
27	S, .6	139	120	520	$23,400	$ 414,397	1139	S,.9	147	125	515	$ 26,215	$ 490,261	270
28	S, .6	139	120	520	$18,546	$ 417,187	1055	S,.9	147	125	515	$ 26,215	$ 494,203	176
29	S, .6	125	120	520	$17,760	$ 419,683	971	S,.9	147	125	515	$ 26,215	$ 497,888	82
30	S, .6	125	120	520	$17,760	$ 422,016	886	S,.9	147	125	515	$ 26,215	$ 501,332	0
31	S, .6	125	120	520	$17,760	$ 431,563	802	-	-	-	640	$ 3,840	$ 501,803	0
32	S, .6	125	120	520	$17,760	$ 433,600	717	-	-	-	640	$ 3,840	$ 502,244	0
33	S, .6	125	120	520	$17,760	$ 435,505	633	-	-	-	640	$ 3,840	$ 502,656	0
34	S, .6	125	120	520	$17,760	$ 437,285	548	-	-	-	640	$ 3,840	$ 503,041	0
35	S, .6	125	120	520	$17,760	$ 438,948	464	-	-	-	640	$ 3,840	$ 503,400	0
36	S, .6	125	120	520	$17,760	$ 440,503	380	-	-	-	640	$ 3,840	$ 503,736	0
37	S, .5	122	120	520	$17,280	$ 441,917	300	-	-	-	640	$ 3,840	$ 504,051	0
38	S, .5	122	120	520	$17,280	$ 443,238	220	-	-	-	640	$ 3,840	$ 504,344	0
39	S, .5	122	120	520	$17,280	$ 444,472	140	-	-	-	640	$ 3,840	$ 504,619	0
40	S, .5	122	120	520	$17,280	$ 445,626	60	-	-	-	640	$ 3,840	$ 504,875	0
41	S, .5	122	80.7	559	$12,884	$ 446,431	6	-	-	-	640	$ 3,840	$ 505,115	0
42	-	-	-	640	$ 3,840	$ 446,655	6	-	-	-	640	$ 3,840	$ 505,339	0
43	-	-	-	640	$ 3,840	$ 446,864	6	-	-	-	640	$ 3,840	$ 505,548	0
44	-	-	-	640	$ 3,840	$ 447,059	6	-	-	-	640	$ 3,840	$ 505,744	0
45	-	-	-	640	$ 3,840	$ 447,242	6	-	-	-	640	$ 3,840	$ 505,926	0
46-59	-	-	-	640	$ 3,840	$ 448,841	6	-	-	-	640	$ 3,840	$ 507,525	0
60	-	-	-	640	$ 3,840	$ 448,908	6	-	-	-	640	$ 3,840	$ 507,592	0

Irt: Irrigation trigger: An irrigation is initiated when moisture level is at or below the indicated level
GW(aft): acre feet of ground water remaining at end of year
46-59: average acres, net revenue, cumulative NPV year 59, GW remaining in year 59

Table 28. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 640 Acres with 6,720 Acre Feet of Groundwater in Texas County when Corn price is $5.48 and the Grain Sorghum Price is $5.09 per Bushel and the Discount Rate is Four Percent

	Center Pivot							Sub Surface Drip						
Year	Crop IrT	Yield Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulative NPV	GW (aft) 6,720	Crop IrT	Ir.Yield Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulative NPV	GW (aft) 6,720
1	C,.9	213	240	400	$138,560	$ 13,231	6,271	S,.9	155	600	40	$ 208,400	$ (227,615)	6,204
2	C,.9	213	240	400	$138,560	$ 141,337	5,822	S,.9	155	600	40	$ 208,400	$ (34,938)	5,687
3	C,.9	213	240	400	$138,076	$ 264,086	5,373	S,.9	155	600	40	$ 201,433	$ 144,135	5,224
4	C,.9	213	240	400	$137,600	$ 381,707	4,923	S,.9	147	600	40	$ 200,000	$ 315,096	4,772
5	C,.9	213	240	400	$137,594	$ 494,799	4,474	S,.9	147	600	40	$ 191,009	$ 472,091	4,345
6	C,.9	213	240	400	$136,880	$ 602,977	4,025	S,.9	135	600	40	$ 173,600	$ 609,290	3,968
7	C,.9	213	240	400	$101,899	$ 680,412	3,833	S,.9	135	600	40	$ 173,600	$ 741,211	3,590
8	S,.6	139	240	400	$ 97,520	$ 751,669	3,673	S,.9	135	600	40	$ 162,045	$ 859,616	3,243
9	S,.6	139	240	400	$ 97,520	$ 820,185	3,513	S,.9	119	600	40	$ 143,000	$ 960,086	2,949
10	S,.6	139	240	400	$ 97,196	$ 885,847	3,353	S,.9	119	600	40	$ 143,000	$ 1,056,692	2,654
11	S,.6	139	240	400	$ 91,040	$ 944,985	3,183	S,.9	119	600	40	$ 143,000	$ 1,149,582	2,360
12	S,.6	134	240	400	$ 91,040	$ 1,001,848	3,014	S,.9	119	600	40	$ 117,095	$ 1,222,719	2,173
13	S,.6	134	240	400	$ 91,040	$ 1,056,525	2,844	S,.9	93	600	40	$ 97,400	$ 1,281,215	2,070
14	S,.6	134	240	400	$ 91,040	$ 1,109,098	2,675	S,.9	93	600	40	$ 97,400	$ 1,337,461	1,966
15	S,.6	134	240	400	$ 91,040	$ 1,159,649	2,505	S,.9	93	582	58	$ 102,016	$ 1,394,107	1,818
16	S,.6	134	120	520	$ 89,840	$ 1,175,581	2,281	C,.9	144	125	515	$ 93,100	$ 1,395,389	1,582
17	C,.9	213	120	520	$ 69,612	$ 1,211,318	2,201	C,.9	215	125	515	$ 93,100	$ 1,443,184	1,347
18	S,.6	139	120	520	$ 69,560	$ 1,245,655	2,121	C,.9	215	125	515	$ 93,100	$ 1,489,141	1,111
19	S,.6	139	120	520	$ 69,560	$ 1,278,671	2,041	C,.9	215	125	515	$ 73,953	$ 1,524,242	1,015
20	S,.6	139	120	520	$ 69,560	$ 1,310,418	1,961	S,.9	147	125	515	$ 73,600	$ 1,557,832	921
21	S,.6	139	120	520	$ 69,560	$ 1,340,943	1,881	S,.9	147	125	515	$ 73,600	$ 1,590,130	827
22	S,.6	139	120	520	$ 69,560	$ 1,370,294	1,801	S,.9	147	125	515	$ 73,600	$ 1,621,186	733
23	S,.6	139	120	520	$ 69,560	$ 1,398,516	1,721	S,.9	147	125	515	$ 73,600	$ 1,651,048	638
24	S,.6	139	120	520	$ 69,560	$ 1,425,653	1,641	S,.9	147	125	515	$ 73,600	$ 1,679,761	544
25	S,.6	139	120	520	$ 69,560	$ 1,451,746	1,561	S,.9	147	125	515	$ 73,600	$ 1,707,369	450
26	S,.6	139	120	520	$ 69,560	$ 1,476,836	1,481	S,.9	147	125	515	$ 73,600	$ 1,733,916	356
27	S,.6	139	120	520	$ 69,560	$ 1,500,960	1,401	S,.9	147	125	515	$ 73,600	$ 1,759,442	262
28	S,.6	139	120	520	$ 69,560	$ 1,524,157	1,321	S,.9	147	125	515	$ 73,600	$ 1,783,986	167
29	S,.6	139	120	520	$ 69,560	$ 1,546,461	1,241	S,.9	147	125	515	$ 73,600	$ 1,807,585	73
30	S,.6	139	120	520	$ 69,560	$ 1,567,908	1,161	S,.9	147	125	515	$ 73,600	$ 1,830,278	0
31	S,.6	139	120	520	$ 65,000	$ 1,569,390	1,078	S,.9	147	0	640	$ 41,600	$ 1,842,610	0
32	S,.6	139	120	520	$ 62,360	$ 1,587,166	994	-	-	0	640	$ 41,600	$ 1,854,469	0
33	S,.6	125	120	520	$ 62,360	$ 1,604,259	909	-	-	0	640	$ 41,600	$ 1,865,871	0
34	S,.6	125	120	520	$ 62,360	$ 1,620,694	825	-	-	0	640	$ 41,600	$ 1,876,835	0
35	S,.6	125	120	520	$ 62,360	$ 1,636,497	740	-	-	0	640	$ 41,600	$ 1,887,377	0
36	S,.6	125	120	520	$ 62,360	$ 1,651,692	656	-	-	0	640	$ 41,600	$ 1,897,514	0
37	S,.6	125	120	520	$ 62,360	$ 1,666,303	571	-	-	0	640	$ 41,600	$ 1,907,260	0
38	S,.6	125	120	520	$ 61,640	$ 1,680,189	491	-	-	0	640	$ 41,600	$ 1,916,632	0
39	S,.5	122	120	520	$ 61,640	$ 1,693,542	411	-	-	0	640	$ 41,600	$ 1,925,644	0
40	S,.5	122	120	520	$ 61,640	$ 1,706,381	331	-	-	0	640	$ 41,600	$ 1,934,308	0
41	S,.5	122	120	520	$ 61,640	$ 1,718,726	251	-	-	0	640	$ 41,600	$ 1,942,640	0
42	S,.5	122	120	520	$ 61,640	$ 1,730,596	171	-	-	0	640	$ 41,600	$ 1,950,651	0
43	S,.5	122	120	520	$ 61,640	$ 1,742,010	91	-	-	0	640	$ 41,600	$ 1,958,354	0
44	S,.5	122	120	520	$ 61,640	$ 1,752,985	11	-	-	0	640	$ 41,600	$ 1,965,761	0
45	S,.5	122	0	640	$ 41,600	$ 1,760,106	11	-	-	0	640	$ 41,600	$ 1,972,883	0
46-59	-	-	0	640	$ 41,600	$ 1,835,335	11	-	-	0	640	$ 41,600	$ 2,048,111	0
60	-	-	0	640	$ 41,600	$ 1,839,290	11	-	-	0	640	$ 41,600	$ 2,052,066	0

Irt: Irrigation trigger: An irrigation is initiated when moisture level is at or below the indicated level

GW(aft): acre feet of ground water remaining at end of year

46-59: average acres, net revenue, cumulative NPV year 59, GW remaining in year 59

increased and irrigation was terminated with aquifer exhaustion in year 30 as opposed to year 45 in the four percent discount case.

SDI(640a, $5, 7%, Lw) The increase in the discount rate from four to seven percent caused the initial irrigated area to decline from 600 to 500 acres (four 125-acres systems). This might be anticipated because the higher initial cost of the SDI system makes it more sensitive to increased discount rates. Irrigated GS was the crop of choice for the first 13 years. Irrigated corn was produced in years 14 and 15. This can occur when the model anticipates the scarcity of water may be reduced relative to the scarcity of irrigated land if the irrigated area will soon be reduced. The irrigated area was reduced to a single 125 acre drip system for years 16-30 but irrigation terminated with aquifer exhaustion in year 29. Dryland GS was produced for years 30-60.

In the limited water situation examined above, the SDI system was more profitable than the conventional CP system under both four dollar and five dollar feed grain prices. The SDI was also more profitable than the CP under both four and seven percent discount rates.

Table 29. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 640 Acres with 6,720 Acre Feet of Groundwater in Texas County when Corn price is $5.48 and the Grain Sorghum Price is $5.09 per Bushel and the Discount Rate is Seven Percent

	Center Pivot							Sub Surface Drip						
Year	Crop	Yield	Irrig.	Dry	640Acre	Cumulative	GW (aft)	Crop	Ir.Yield	Irrig.	Dry	640Acre	Cumulative	GW (aft)
	IrT	Bus	Acres	Acres	Net Rev.	NPV	6720	IrT	Bus	Acres	Acres	Net Rev.	NPV	6720
1	C,.9	213	240	400	$ 138,560	$ 9,495	6271	S,.9	161	500	140	$ 188,100	$ (187,006)	6245
2	C,.9	213	240	400	$ 138,560	$ 130,519	5822	S,.9	161	500	140	$ 188,100	$ (22,712)	5771
3	C,.9	213	240	400	$ 138,076	$ 243,230	5373	S,.9	161	500	140	$ 186,495	$ 129,524	5325
4	C,.9	213	240	400	$ 137,600	$ 348,204	4923	S,.9	155	500	140	$ 185,600	$ 271,117	4894
5	C,.9	213	240	400	$ 137,594	$ 446,307	4474	S,.9	155	500	140	$ 184,982	$ 403,006	4466
6	C,.9	213	240	400	$ 136,880	$ 537,516	4025	S,.9	147	500	140	$ 169,100	$ 515,685	4089
7	C,.9	213	240	400	$ 136,880	$ 622,758	3576	S,.9	147	500	140	$ 169,100	$ 620,992	3713
8	C,.9	213	240	400	$ 114,281	$ 689,270	3260	S,.9	147	500	140	$ 168,211	$ 718,892	3339
9	S,.6	134	240	400	$ 91,040	$ 738,790	3091	S,.9	135	500	140	$ 151,600	$ 801,353	3024
10	S,.6	134	240	400	$ 91,040	$ 785,070	2921	S,.9	135	500	140	$ 151,600	$ 878,418	2709
11	S,.6	134	240	400	$ 91,040	$ 828,323	2752	S,.9	135	500	140	$ 151,600	$ 950,443	2394
12	S,.6	134	240	400	$ 91,040	$ 868,746	2582	S,.9	135	500	140	$ 141,695	$ 1,013,357	2031
13	S,.6	134	240	400	$ 91,040	$ 906,524	2413	C, .9	144	500	140	$ 131,600	$ 1,067,966	1620
14	S,.6	134	240	400	$ 91,040	$ 941,831	2243	C, .9	144	500	140	$ 113,887	$ 1,112,134	1343
15	S,.6	134	240	400	$ 82,880	$ 971,870	2075	S,.6	90	500	140	$ 85,100	$ 1,142,978	1284
16	S,.6	125	120	520	$ 89,360	$ 981,816	1850	S,.9	167	125	515	$ 80,225	$ 1,139,430	1152
17	C,.9	213	120	520	$ 89,360	$ 1,010,105	1625	S,.9	167	125	515	$ 79,632	$ 1,164,639	1023
18	C,.9	213	120	520	$ 89,360	$ 1,036,543	1401	S,.9	147	125	515	$ 73,600	$ 1,186,415	929
19	C,.9	213	120	520	$ 89,360	$ 1,061,252	1176	S,.9	147	125	515	$ 73,600	$ 1,206,766	835
20	C,.9	213	120	520	$ 73,360	$ 1,080,209	988	S,.9	147	125	515	$ 73,600	$ 1,225,785	741
21	C,.9	213	120	520	$ 68,240	$ 1,096,690	812	S,.9	147	125	515	$ 73,600	$ 1,243,561	646
22	C,.9	164	120	520	$ 64,212	$ 1,111,184	701	S,.9	147	125	515	$ 73,600	$ 1,260,173	552
23	C,.9	164	120	520	$ 63,320	$ 1,124,541	605	S,.8	141	125	515	$ 71,475	$ 1,275,251	468
24	S,.7	129	120	520	$ 63,320	$ 1,137,024	508	S,.8	141	125	515	$ 71,475	$ 1,289,342	384
25	S,.7	129	120	520	$ 62,360	$ 1,148,514	424	S,.8	141	125	515	$ 71,475	$ 1,302,511	300
26	S,.6	125	120	520	$ 62,360	$ 1,159,252	339	S,.8	141	125	515	$ 71,475	$ 1,314,818	215
27	S,.6	125	120	520	$ 62,360	$ 1,169,288	255	S,.7	134	125	515	$ 68,600	$ 1,325,858	141
28	S,.6	125	120	520	$ 62,360	$ 1,178,667	170	S,.7	134	125	515	$ 68,600	$ 1,336,176	66
29	S,.6	125	120	520	$ 62,360	$ 1,187,432	86	S,.7	134	125	515	$ 68,600	$ 1,345,818	0
30	S,.6	125	120	520	$ 62,360	$ 1,195,624	1	-	-	-	640	$ 41,600	$ 1,351,283	0
31	S,.6	125	-	640	$ 41,600	$ 1,200,732	1	-	-	-	640	$ 41,600	$ 1,356,391	0
32	-	-	-	640	$ 41,600	$ 1,205,505	1	-	-	-	640	$ 41,600	$ 1,361,164	0
33	-	-	-	640	$ 41,600	$ 1,209,966	1	-	-	-	640	$ 41,600	$ 1,365,625	0
34	-	-	-	640	$ 41,600	$ 1,214,135	1	-	-	-	640	$ 41,600	$ 1,369,794	0
35	-	-	-	640	$ 41,600	$ 1,218,032	1	-	-	-	640	$ 41,600	$ 1,373,690	0
36	-	-	-	640	$ 41,600	$ 1,221,673	1	-	-	-	640	$ 41,600	$ 1,377,332	0
37	-	-	-	640	$ 41,600	$ 1,225,076	1	-	-	-	640	$ 41,600	$ 1,380,735	0
38	-	-	-	640	$ 41,600	$ 1,228,257	1	-	-	-	640	$ 41,600	$ 1,383,916	0
39	-	-	-	640	$ 41,600	$ 1,231,229	1	-	-	-	640	$ 41,600	$ 1,386,888	0
40	-	-	-	640	$ 41,600	$ 1,234,007	1	-	-	-	640	$ 41,600	$ 1,389,666	0
41	-	-	-	640	$ 41,600	$ 1,236,604	1	-	-	-	640	$ 41,600	$ 1,392,263	0
42	-	-	-	640	$ 41,600	$ 1,239,030	1	-	-	-	640	$ 41,600	$ 1,394,689	0
43	-	-	-	640	$ 41,600	$ 1,241,298	1	-	-	-	640	$ 41,600	$ 1,396,957	0
44	-	-	-	640	$ 41,600	$ 1,243,417	1	-	-	-	640	$ 41,600	$ 1,399,076	0
45	-	-	-	640	$ 41,600	$ 1,245,398	1	-	-	-	640	$ 41,600	$ 1,401,057	0
46-59	-	-	-	640	$ 41,600	$ 1,221,673		-	-	-	640	$ 41,600	$ 1,418,379	0
60	-	-	-	640	$ 41,600	$ 1,225,076		-	-	-	640	$ 41,600	$ 1,419,097	0

Irt: Irrigation trigger: An irrigation is initiated when moisture level is at or below the indicated level

GW(aft): acre feet of ground water remaining at end of year

46-59: average acres, net revenue, cumulative NPV year 59, GW remaining in year 59

Irrigation Systems, Water Use with 640 Acres, High Water, and Four Dollar Feed Grain

In the solution below, the results for the producer with 640 acres are repeated with the assumption that the producer is more isolated and can draw water from twice as much land (1,280 acres) as is farmed. The producer is assumed to have 4 tied wells with 60 feet of water saturated sand and can use up to 13,440 acre feet. The planning horizon is 60 years.

CP(640a, $4, 4%, Hw) (Table 30) The increased groundwater supply did not change to the optimal CP investment pattern (2, 120 acre pivots) from the limited water situation under the lower feed grain prices in the first 15 years. However, irrigated corn was grown for 13 years before the switch was made to irrigated sorghum. During the second 15 year period, two 120-acre pivots were used as opposed to one pivot under the low water situation. The irrigated acres declined to 120 acres during the 31-45 year period and 120 acres were irrigated during the 46-60 year period. A second 10-year period of irrigated corn production began when the irrigated area declined from 240 the 120 acres in year 31. Aquifer depletion occurred at the end of year 59.

As anticipated the increased water supply increased annual net returns for longer periods than was possible with the limited water case. The cumulative CP NPV at 4% reached $850,152 by year 60

SDI(640a, $4, 4%, Hw) The SDI system showed more sensitivity to the increased water supply than did the CP system. Six hundred of the 640 acres were developed for irrigation purchasing four 150 systems in years 1-15. In years 16-30, three 125 acre systems were used, and a single 125 acre systems were used during years 31-45 and years 46-60. Aquifer depletion occurred in year 60. (Table 30)

Intensively irrigated GS grown in the SDI system for the entire 60 year period. Initial annual returns were in excess of $100,000 for the 10 years because of the larger area irrigated. The 60-year cumulative NPV at 4% reached $1,120,173.

CP(640a, $4, 7%, Hw) An increase in the discount rate (Table 31) with other factors held constant is expected to encourage near term resource use and discourage capital intensive investments. The optimal investment pattern of 30 years with one 120 acre CP system used for years 31-45. Aquifer depletion occurred in year 45 and the last 15 years were dryland production. This was accomplished in part by a longer (15-year) period of intensively irrigated corn. (The period of corn production was limited to 13 years with the four percent discount rate). The second period of corn production (years 31-36) was limited to six years. Again, the corn production began when only one quarter section was irrigated and the pivot could be fed by three wells. The 60-year cumulative CP NPV was $569,682.

SDI(640a, $4, 7%, Hw) The optimal pattern of SDI investment (Table 31) was also unchanged, 600 acres (4 150-acre SDI systems) for the first 15 years. However only 2 125-acre systems were used in years 16-30 followed by single 125-acre systems in years 31-45 and years 46-60. Intensively irrigated grain sorghum was produced in most years. Three years of irrigated corn were produced following the acre reduction from 600 to 250 (when two wells could feed each system). Irrigated corn was again produced when further downsizing occurred in year 31 when four wells could tie into a single system. Aquifer depletion occurred in year 60. The cumulative 60-year NPV at seven percent reached $739,125.

Table 30. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 640 Acres with 13,440 Acre Feet of Groundwater in Texas County when Corn price is $4.48 and the Grain Sorghum Price is $4.16 per Bushel and the Discount Rate is Four Percent

Year	Center Pivot							Sub Surface Drip						
	Crop IrT	Yiel Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulative NPV 4	GW (af 13440	Crop IrT	Yiel Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulative NPV @4%	GW (aft) 13440
1	C,.9	213	240	400	$ 63,840	$ (58,615)	12991	S,.9	155	600	40	$ 119,040	$ (313,538)	12924
2	C,.9	213	240	400	$ 63,840	$ 408	12542	S,.9	155	600	40	$ 119,040	$ (203,479)	12407
3	C,.9	213	240	400	$ 63,840	$ 57,162	12093	S,.9	155	600	40	$ 119,040	$ (97,653)	11891
4	C,.9	213	240	400	$ 63,840	$ 111,732	11643	S,.9	155	600	40	$ 119,040	$ 4,103	11375
5	C,.9	213	240	400	$ 63,831	$ 164,197	11194	S,.9	155	600	40	$ 117,063	$ 100,320	10901
6	C,.9	213	240	400	$ 62,880	$ 213,892	10745	S,.9	147	600	40	$ 116,040	$ 192,028	10449
7	C,.9	213	240	400	$ 62,880	$ 261,676	10296	S,.9	147	600	40	$ 116,040	$ 280,209	9997
8	C,.9	213	240	400	$ 62,880	$ 307,622	9847	S,.9	147	600	40	$ 116,040	$ 364,998	9545
9	C,.9	213	240	400	$ 62,880	$ 351,800	9398	S,.9	147	600	40	$ 116,040	$ 446,526	9093
10	C,.9	213	240	400	$ 62,867	$ 394,271	8949	S,.9	147	600	40	$ 102,145	$ 515,532	8691
11	C,.9	213	240	400	$ 62,160	$ 434,649	8500	S,.9	135	600	40	$ 95,640	$ 577,658	8313
12	C,.9	213	240	400	$ 62,160	$ 473,474	8050	S,.9	135	600	40	$ 95,640	$ 637,394	7935
13	C,.9	213	240	400	$ 62,160	$ 510,806	7601	S,.9	135	600	40	$ 95,640	$ 694,833	7557
14	S,.6	139	240	400	$ 55,462	$ 542,833	7253	S,.9	135	600	40	$ 95,640	$ 750,063	7179
15	S,.6	139	240	400	$ 42,960	$ 566,687	7093	S,.9	135	600	40	$ 95,640	$ 803,168	6801
16	S,.6	139	240	400	$ 42,960	$ 525,555	6933	S,.9	155	375	265	$ 73,547	$ 697,160	6507
17	S,.6	139	240	400	$ 42,960	$ 547,610	6773	S,.9	147	375	265	$ 70,965	$ 733,591	6225
18	S,.6	139	240	400	$ 40,430	$ 567,567	6586	S,.9	147	375	265	$ 70,965	$ 768,621	5942
19	S,.7	140	240	400	$ 39,120	$ 586,135	6384	S,.9	147	375	265	$ 70,965	$ 802,304	5659
20	S,.7	140	240	400	$ 39,120	$ 603,989	6182	S,.9	147	375	265	$ 70,965	$ 834,692	5377
21	S,.6	134	240	400	$ 37,680	$ 620,524	6013	S,.9	147	375	265	$ 70,965	$ 865,834	5094
22	S,.6	134	240	400	$ 37,680	$ 636,424	5844	S,.9	147	375	265	$ 70,965	$ 895,778	4812
23	S,.6	134	240	400	$ 37,680	$ 651,711	5674	S,.9	147	375	265	$ 70,965	$ 924,570	4529
24	S,.6	134	240	400	$ 37,680	$ 666,411	5505	S,.9	147	375	265	$ 47,664	$ 943,165	4227
25	S,.6	134	240	400	$ 37,680	$ 680,546	5335	C,.9	144	375	265	$ 39,840	$ 958,109	3919
26	S,.6	134	240	400	$ 37,680	$ 694,136	5166	C,.9	144	375	265	$ 39,840	$ 972,479	3610
27	S,.6	134	240	400	$ 37,680	$ 707,204	4996	S,.9	97	375	265	$ 35,769	$ 984,885	3396
28	S,.6	134	240	400	$ 37,680	$ 719,770	4827	S,.9	97	375	265	$ 30,465	$ 995,044	3305
29	S,.6	134	240	400	$ 37,680	$ 731,852	4657	S,.9	97	375	265	$ 30,465	$ 1,004,813	3214
30	S,.6	134	240	400	$ 37,680	$ 743,469	4488	S,.9	93	375	265	$ 28,215	$ 1,013,512	3149
31	C,.9	213	120	520	$ 33,120	$ 735,500	4263	C,.9	215	125	515	$ 35,840	$ 997,248	2913
32	C,.9	213	120	520	$ 33,120	$ 744,941	4039	S,.9	167	125	515	$ 30,465	$ 1,005,932	2781
33	C,.9	213	120	520	$ 33,120	$ 754,019	3814	S,.9	167	125	515	$ 30,465	$ 1,014,282	2649
34	C,.9	213	120	520	$ 33,120	$ 762,748	3590	S,.9	167	125	515	$ 30,465	$ 1,022,312	2517
35	C,.9	213	120	520	$ 33,120	$ 771,141	3365	S,.9	167	125	515	$ 30,465	$ 1,030,032	2386
36	C,.9	213	120	520	$ 33,120	$ 779,211	3141	S,.9	167	125	515	$ 30,465	$ 1,037,455	2254
37	C,.9	213	120	520	$ 33,120	$ 786,971	2916	S,.9	167	125	515	$ 29,558	$ 1,044,381	2130
38	C,.9	213	120	520	$ 33,120	$ 794,433	2691	S,.9	147	125	515	$ 26,215	$ 1,050,286	2036
39	C,.9	213	120	520	$ 33,120	$ 801,607	2467	S,.9	147	125	515	$ 26,215	$ 1,055,965	1941
40	C,.9	213	120	520	$ 32,863	$ 808,452	2244	S,.9	147	125	515	$ 26,215	$ 1,061,425	1847
41	S,.9	134	120	520	$ 18,720	$ 812,201	2129	S,.9	147	125	515	$ 26,215	$ 1,066,676	1753
42	S,.9	134	120	520	$ 18,720	$ 815,806	2014	S,.9	147	125	515	$ 26,215	$ 1,071,724	1659
43	S,.9	134	120	520	$ 18,720	$ 819,273	1899	S,.9	147	125	515	$ 26,215	$ 1,076,578	1565
44	S,.9	134	120	520	$ 18,720	$ 822,606	1784	S,.9	147	125	515	$ 26,215	$ 1,081,246	1471
45	S,.9	134	120	520	$ 18,720	$ 825,811	1669	S,.9	147	125	515	$ 26,215	$ 1,085,734	1376
46-59	S,.9	134	120	520	$ 18,720	$ 849,787	60	S,.9	147	125	515	$ 26,215	$ 1,118,211	58
60	-	-	0	640	$ 3,840	$ 850,152	60	S,.9	147	125	515	$ 26,215	$ 1,120,703	0

Irt: Irrigation trigger: An irrigation is initiated when moisture level is at or below the indicated level

GW(aft): acre feet of ground water remaining at end of year

46-59: average acres, net revenue, cumulative NPV, GW remaining in year 59

Table 31. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 640 Acres with 13,440 Acre Feet of Groundwater in Texas County when Corn price is $4.48 and the Grain Sorghum Price is $4.16 per Bushel and the Discount Rate is Seven Percent

	Center Pivot							Sub Surface Drip						
Year	Crop IrT	Yielc Bus	Irrig. Acres	Dry Acre	640Acre Net Rev.	Cumulative NPV 4	GW (aft) 13440	Crop IrT	Yield Bus	Irrig Acre	Dry Acres	640Acre Net Rev.	Cumulative NPV @4%	GW (aft) 13440
1	C,.9	213	240	400	$ 63,840	$ (60,336)	12,991	S,.9	155	600	40	$119,040	$(316,748)	12,924
2	C,.9	213	240	400	$ 63,840	$ (4,576)	12,542	S,.9	155	600	40	$119,040	$(212,774)	12,407
3	C,.9	213	240	400	$ 63,840	$ 47,536	12,093	S,.9	155	600	40	$119,040	$(115,601)	11,891
4	C,.9	213	240	400	$ 63,840	$ 96,240	11,643	S,.9	155	600	40	$119,040	$ (24,786)	11,375
5	C,.9	213	240	400	$ 63,831	$141,751	11,194	S,.9	155	600	40	$117,063	$ 58,678	10,901
6	C,.9	213	240	400	$ 62,880	$183,650	10,745	S,.9	147	600	40	$116,040	$ 136,000	10,449
7	C,.9	213	240	400	$ 62,880	$222,809	10,296	S,.9	147	600	40	$116,040	$ 208,264	9,997
8	C,.9	213	240	400	$ 62,880	$259,405	9,847	S,.9	147	600	40	$116,040	$ 275,801	9,545
9	C,.9	213	240	400	$ 62,880	$293,608	9,398	S,.9	147	600	40	$116,040	$ 338,919	9,093
10	C,.9	213	240	400	$ 62,867	$325,566	8,949	S,.9	147	600	40	$102,145	$ 390,844	8,691
11	C,.9	213	240	400	$ 62,160	$355,098	8,500	S,.9	135	600	40	$ 95,640	$ 436,282	8,313
12	C,.9	213	240	400	$ 62,160	$382,698	8,050	S,.9	135	600	40	$ 95,640	$ 478,747	7,935
13	C,.9	213	240	400	$ 62,160	$408,492	7,601	S,.9	135	600	40	$ 95,640	$ 518,434	7,557
14	C,.9	213	240	400	$ 62,160	$432,599	7,152	S,.9	135	600	40	$ 95,640	$ 555,525	7,179
15	C,.9	213	240	400	$ 61,595	$454,924	6,708	S,.9	135	600	40	$ 95,640	$ 590,189	6,801
16	S,.9	148	240	400	$ 41,040	$428,177	6,449	C,.9	215	250	390	$ 62,169	$ 549,802	6,373
17	S,.7	140	240	400	$ 39,120	$440,562	6,248	C,.9	202	250	390	$ 60,840	$ 569,063	5,956
18	S,.7	140	240	400	$ 39,120	$452,136	6,046	C,.9	202	250	390	$ 57,077	$ 585,950	5,656
19	S,.7	140	240	400	$ 39,120	$462,953	5,844	S,.9	161	250	390	$ 55,090	$ 601,182	5,419
20	S,.7	140	240	400	$ 39,120	$473,062	5,643	S,.9	161	250	390	$ 55,090	$ 615,419	5,182
21	S,.7	140	240	400	$ 39,120	$482,510	5,441	S,.9	161	250	390	$ 55,090	$ 628,724	4,944
22	S,.7	140	240	400	$ 39,120	$491,340	5,240	S,.9	161	250	390	$ 55,090	$ 641,158	4,707
23	S,.6	134	240	400	$ 37,680	$499,289	5,070	S,.9	161	250	390	$ 55,090	$ 652,779	4,470
24	S,.6	134	240	400	$ 37,680	$506,717	4,901	S,.9	147	250	390	$ 48,590	$ 662,359	4,281
25	S,.6	134	240	400	$ 37,680	$513,660	4,731	S,.9	147	250	390	$ 48,590	$ 671,311	4,093
26	S,.6	134	240	400	$ 37,680	$520,148	4,562	S,.9	147	250	390	$ 48,590	$ 679,678	3,905
27	S,.6	134	240	400	$ 35,085	$525,794	4,380	S,.9	147	250	390	$ 48,590	$ 687,498	3,716
28	S,.7	129	240	400	$ 32,640	$530,703	4,187	S,.9	147	250	390	$ 48,590	$ 694,806	3,528
29	S,.7	129	240	400	$ 31,440	$535,123	4,018	S,.9	147	250	390	$ 48,590	$ 701,636	3,340
30	S,.6	125	240	400	$ 31,440	$539,253	3,849	S,.9	147	250	390	$ 48,590	$ 708,019	3,151
31	S,.6	125	120	520	$ 33,120	$535,953	3,625	C,.9	215	125	515	$ 35,840	$ 701,283	2,916
32	C,.9	213	120	520	$ 33,120	$539,753	3,400	C,.9	215	125	515	$ 35,840	$ 705,395	2,680
33	C,.9	213	120	520	$ 33,120	$543,305	3,175	C,.9	215	125	515	$ 31,017	$ 708,722	2,538
34	C,.9	213	120	520	$ 33,120	$546,624	2,951	S,.9	167	125	515	$ 30,465	$ 711,775	2,406
35	C,.9	213	120	520	$ 33,120	$549,726	2,726	S,.9	167	125	515	$ 30,465	$ 714,628	2,274
36	C,.9	213	120	520	$ 33,120	$552,626	2,502	S,.9	167	125	515	$ 27,802	$ 717,062	2,165
37	C,.9	213	120	520	$ 30,306	$555,105	2,319	S,.9	147	125	515	$ 26,215	$ 719,206	2,071
38	S,.6	139	120	520	$ 23,400	$556,894	2,239	S,.9	147	125	515	$ 26,215	$ 721,211	1,977
39	S,.6	139	120	520	$ 18,720	$558,232	2,124	S,.9	147	125	515	$ 26,215	$ 723,084	1,883
40	S,.9	134	120	520	$ 18,720	$559,482	2,009	S,.9	147	125	515	$ 26,215	$ 724,835	1,789
41	S,.9	134	120	520	$ 18,720	$560,650	1,894	S,.9	147	125	515	$ 26,215	$ 726,471	1,695
42	S,.9	134	120	520	$ 18,720	$561,742	1,779	S,.9	147	125	515	$ 26,215	$ 728,000	1,600
43	S,.9	134	120	520	$ 18,720	$562,762	1,664	S,.9	147	125	515	$ 26,215	$ 729,429	1,506
44	S,.9	134	120	520	$ 18,720	$563,716	1,549	S,.9	147	125	515	$ 26,215	$ 730,764	1,412
45	S,.9	134	120	520	$ 18,720	$564,607	1,434	S,.9	147	125	515	$ 26,215	$ 732,013	1,318
46-59	S, .7	131	120	520	$ 18,360	$569,616	4	S, .8	145	125	515	$ 25,679	$ 738,733	49
60	S, .6	125	0	640	$ 3,840	$569,682	4	S ,.7	133.7	125	515	$ 22,715	$ 739,125	-

Irt: Irrigation trigger: An irrigation is initiated when moisture level is at or below the indicated level
GW(aft): acre feet of ground water remaining at end of year
46-59: average acres, net revenue, cumulative NPV, GW remaining in year 59

Irrigation Systems, Water Use with 640 Acres, High Water, and Five Dollar Feed Grain

CP(640a, $5, 4%, Hw) (Table 32) An increase in the feed grain price from $4 to $5 did not change the optimal CP investment pattern (2, 120 acre pivots) from the limited water situation under the lower feed grain prices in the first 15 years. Until year 15, the CP system produces corn at full irrigation (IrT.90) then it switches to grain sorghum at .7 stress during the transformation period (year 16), however, grain sorghum continues until the pivot is replaced (year 30) at IrT .6. From year 31-44, corn is grown with full irrigation on a 120-acre field, leaving the rest of the land for dryland practices. The changes between irrigated corn and sorghum are determined by the relative area of land with equipment for irrigation and the remaining groundwater supply. Corn is grown when the supply of groundwater is large relative to the land under irrigation. In Table 32 in year 30, the producer has 240 acres under two pivots. In year 31, there is only one pivot so land that can be irrigated becomes scarce relative to the supply of groundwater. However as the ground water supply becomes more depleted and limiting, it is optimal to switch back to grain sorghum. One pivot is purchased at the year 46 to irrigated sorghum till year 59 leaving 456 acre feet of water in the aquifer.

Table 32. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 640 Acres with 13,440 Acre Feet of Groundwater in Texas County when Corn price is $5.48 and the Grain Sorghum Price is $5.09 per Bushel and the Discount Rate is Four Percent

	Center Pivot							Sub Surface Drip						
Year	Crop IrT	Yield Bus	Irrig. Acre:	Dry Acres	640Acre Net Rev.	Cumulative NPV	GW (aft) 13,440	Crop IrT	Yield Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulative NPV	GW (aft) 13,440
1	C,.9	213	240	400	$ 138,560	$ 13,231	12,991	S,.9	155	600	40	$ 208,400	$ (227,615)	12,924
2	C,.9	213	240	400	$ 138,560	$ 141,337	12,542	S,.9	155	600	40	$ 208,400	$ (34,938)	12,407
3	C,.9	213	240	400	$ 138,560	$ 264,517	12,093	S,.9	155	600	40	$ 208,400	$ 150,329	11,891
4	C,.9	213	240	400	$ 138,560	$ 382,958	11,643	S,.9	155	600	40	$ 208,400	$ 328,470	11,375
5	C,.9	213	240	400	$ 138,551	$ 496,837	11,194	S,.9	155	600	40	$ 202,865	$ 495,210	10,901
6	C,.9	213	240	400	$ 137,600	$ 605,585	10,745	S,.9	147	600	40	$ 200,000	$ 653,273	10,449
7	C,.9	213	240	400	$ 137,600	$ 710,149	10,296	S,.9	147	600	40	$ 200,000	$ 805,257	9,997
8	C,.9	213	240	400	$ 137,600	$ 810,692	9,847	S,.9	147	600	40	$ 200,000	$ 951,395	9,545
9	C,.9	213	240	400	$ 137,600	$ 907,368	9,398	S,.9	147	600	40	$ 200,000	$ 1,091,912	9,093
10	C,.9	213	240	400	$ 137,587	$ 1,000,317	8,949	S,.9	147	600	40	$ 182,018	$ 1,214,877	8,691
11	C,.9	213	240	400	$ 136,880	$ 1,089,232	8,500	S,.9	135	600	40	$ 173,600	$ 1,327,644	8,313
12	C,.9	213	240	400	$ 136,880	$ 1,174,727	8,050	S,.9	135	600	40	$ 173,600	$ 1,436,074	7,935
13	C,.9	213	240	400	$ 136,880	$ 1,256,933	7,601	S,.9	135	600	40	$ 173,600	$ 1,540,334	7,557
14	C,.9	213	240	400	$ 136,880	$ 1,335,978	7,152	S,.9	135	600	40	$ 173,600	$ 1,640,583	7,179
15	C,.9	213	240	400	$ 135,731	$ 1,411,345	6,703	S,.9	135	600	40	$ 173,600	$ 1,736,977	6,801
16	S,.7	140	120	520	$ 93,920	$ 1,397,420	6,479	C,.9	215	250	390	$ 136,520	$ 1,713,015	6,373
17	S,.7	140	120	520	$ 93,920	$ 1,445,636	6,254	C,.9	202	250	390	$ 134,600	$ 1,782,115	5,956
18	S,.6	134	120	520	$ 91,040	$ 1,490,576	6,030	C,.9	202	250	390	$ 134,600	$ 1,848,558	5,539
19	S,.6	134	120	520	$ 91,040	$ 1,533,788	5,805	C,.9	202	250	390	$ 134,600	$ 1,912,444	5,121
20	S,.6	134	120	520	$ 91,040	$ 1,575,337	5,581	C,.9	202	250	390	$ 134,600	$ 1,973,874	4,704
21	S,.6	134	120	520	$ 91,040	$ 1,615,288	5,356	S,.9	161	250	390	$ 115,235	$ 2,024,443	4,467
22	S,.6	134	120	520	$ 91,040	$ 1,653,703	5,131	S,.9	147	250	390	$ 105,600	$ 2,069,001	4,279
23	S,.6	134	120	520	$ 91,040	$ 1,690,640	4,907	S,.9	147	250	390	$ 105,600	$ 2,111,846	4,090
24	S,.6	134	120	520	$ 91,040	$ 1,726,157	4,682	S,.9	147	250	390	$ 105,600	$ 2,153,043	3,902
25	S,.6	134	120	520	$ 91,040	$ 1,760,308	4,458	S,.9	147	250	390	$ 105,600	$ 2,192,655	3,714
26	S,.6	134	120	520	$ 91,040	$ 1,793,145	4,233	S,.9	147	250	390	$ 105,600	$ 2,230,744	3,525
27	S,.6	134	120	520	$ 91,040	$ 1,824,719	4,009	S,.9	147	250	390	$ 105,600	$ 2,267,368	3,337
28	S,.6	134	120	520	$ 88,981	$ 1,854,392	3,784	S,.9	147	250	390	$ 105,600	$ 2,302,583	3,149
29	S,.6	125	120	520	$ 82,880	$ 1,880,968	3,560	S,.9	147	250	390	$ 105,600	$ 2,336,444	2,960
30	S,.6	125	120	520	$ 82,880	$ 1,906,521	3,335	S,.9	147	250	390	$ 105,600	$ 2,369,002	2,772
31	C,.9	213	120	520	$ 89,360	$ 1,925,647	3,110	C,.9	215	125	515	$ 82,773	$ 2,366,652	2,619
32	C,.9	213	120	520	$ 89,360	$ 1,951,120	2,886	S,.9	167	125	515	$ 80,225	$ 2,389,521	2,487
33	C,.9	213	120	520	$ 89,360	$ 1,975,613	2,661	S,.9	167	125	515	$ 80,225	$ 2,411,510	2,356
34	C,.9	213	120	520	$ 89,360	$ 1,999,164	2,437	S,.9	167	125	515	$ 80,225	$ 2,432,653	2,224
35	C,.9	213	120	520	$ 89,360	$ 2,021,809	2,216	S,.9	147	125	515	$ 73,600	$ 2,451,305	2,129
36	C,.9	213	120	520	$ 89,360	$ 2,043,583	2,040	S,.9	147	125	515	$ 73,600	$ 2,469,239	2,035
37	C,.9	213	120	520	$ 89,360	$ 2,064,520	1,864	S,.9	147	125	515	$ 73,600	$ 2,486,483	1,941
38	C,.9	213	120	520	$ 89,360	$ 2,084,651	1,688	S,.9	147	125	515	$ 73,600	$ 2,503,064	1,847
39	C,.9	213	120	520	$ 74,491	$ 2,100,787	1,512	S,.9	147	125	515	$ 73,600	$ 2,519,007	1,753
40	C,.9	164	120	520	$ 68,240	$ 2,115,001	1,336	S,.9	147	125	515	$ 73,600	$ 2,534,337	1,659
41	C,.9	164	120	520	$ 68,240	$ 2,128,668	1,160	S,.9	147	125	515	$ 73,600	$ 2,549,078	1,564
42	C,.9	164	120	520	$ 68,240	$ 2,141,809	984	S,.9	147	125	515	$ 73,600	$ 2,563,251	1,470
43	C,.9	164	120	520	$ 68,240	$ 2,154,445	808	S,.9	147	125	515	$ 73,600	$ 2,576,879	1,376
44	C,.9	164	120	520	$ 63,333	$ 2,165,721	632	S,.9	147	125	515	$ 73,600	$ 2,589,984	1,282
45	S,.7	129	120	520	$ 63,320	$ 2,176,562	456	S,.9	147	125	515	$ 73,600	$ 2,602,584	1,188
46-59	-	-	-	640	$ 41,600	$ 2,287,119	456	S,.7	141	250	390	$ 71,314	$ 2,710,249	82
60	-	-	-	640	$ 41,600	$ 2,291,073	456	S,.7	134	54.17	586	$ 53,300	$ 2,722,097	-

Irt: Irrigation trigger: An irrigation is initiated when moisture level is at or below the indicated level

GW(aft): acre feet of ground water remaining at end of year

46-59: average acres, net revenue, cumulative NPV, GW remaining in year 59

Table 33. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 640 Acres with 13,440 Acre Feet of Groundwater in Texas County when Corn price is $5.48 and the Grain Sorghum Price is $5.09 per Bushel and the Discount Rate is Seven Percent

	Center Pivot							Sub Surface Drip						
Year	Crop IrT	Yield Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulat NPV	GW (aft) 13440	Crop IrT	Yield Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulative NPV	GW (aft) 13440
1	C,.9	213	240	400	138560	9495	12991	C,.8	184	600	40	$ 230,600	$ (212,486)	12640
2	C,.9	213	240	400	138560	130519	12542	S,.9	155	600	40	$ 208,400	$ (30,461)	12124
3	C,.9	213	240	400	138560	243625	12093	S,.9	155	600	40	$ 208,400	$ 139,655	11607
4	C,.9	213	240	400	138560	349332	11643	S,.9	155	600	40	$ 206,674	$ 297,326	11104
5	C,.9	213	240	400	138551	448117	11194	S,.9	147	600	40	$ 200,000	$ 439,923	10652
6	C,.9	213	240	400	137600	539806	10745	S,.9	147	600	40	$ 200,000	$ 573,192	10200
7	C,.9	213	240	400	137600	625496	10296	S,.9	147	600	40	$ 200,000	$ 697,742	9748
8	C,.9	213	240	400	137600	705581	9847	S,.9	147	600	40	$ 200,000	$ 814,143	9296
9	C,.9	213	240	400	137600	780426	9398	S,.9	147	600	40	$ 193,990	$ 919,661	8861
10	C,.9	213	240	400	137587	850368	8949	S,.9	135	600	40	$ 173,600	$ 1,007,911	8483
11	C,.9	213	240	400	136880	915399	8500	S,.9	135	600	40	$ 173,600	$ 1,090,387	8105
12	C,.9	213	240	400	136880	976175	8050	S,.9	135	600	40	$ 173,600	$ 1,167,467	7727
13	C,.9	213	240	400	136880	1032976	7601	S,.9	135	600	40	$ 173,600	$ 1,239,505	7349
14	C,.9	213	240	400	136880	1086060	7152	S,.9	135	600	40	$ 173,600	$ 1,306,830	6971
15	C,.9	213	240	400	136206	1135428	6703	S,.9	135	564	76	$ 165,635	$ 1,366,864	6616
16	C,.9	213	120	520	89840	1145535	6479	C,.9	202	250	390	$ 134,600	$ 1,351,011	6198
17	C,.9	213	120	520	89840	1173976	6254	C,.9	202	250	390	$ 134,600	$ 1,393,622	5781
18	C,.9	213	120	520	89840	1200557	6030	C,.9	202	250	390	$ 134,600	$ 1,433,446	5364
19	C,.9	213	120	520	89840	1225398	5805	C,.9	202	250	390	$ 134,600	$ 1,470,664	4946
20	C,.9	213	120	520	89840	1248615	5581	C,.9	202	250	390	$ 134,600	$ 1,505,447	4529
21	C,.9	213	120	520	89840	1270312	5356	C,.9	202	250	390	$ 118,601	$ 1,534,090	4191
22	C,.9	213	120	520	89840	1290590	5131	C,.9	179	250	390	$ 115,850	$ 1,560,239	3866
23	C,.9	213	120	520	89840	1309542	4907	C,.9	179	250	390	$ 115,850	$ 1,584,678	3541
24	C,.9	213	120	520	89840	1327253	4682	C,.9	179	250	390	$ 105,614	$ 1,605,499	3352
25	C,.9	213	120	520	89807	1343800	4458	S,.9	147	250	390	$ 105,600	$ 1,624,956	3164
26	C,.9	213	120	520	89360	1359188	4233	S,.9	147	250	390	$ 105,600	$ 1,643,139	2975
27	C,.9	213	120	520	89360	1373568	4009	S,.9	147	250	390	$ 105,600	$ 1,660,134	2787
28	C,.9	213	120	520	89360	1387008	3784	S,.9	147	250	390	$ 105,600	$ 1,676,016	2599
29	C,.9	213	120	520	89360	1399569	3560	S,.9	147	250	390	$ 105,600	$ 1,690,860	2410
30	C,.9	213	120	520	89360	1411308	3335	S,.9	147	250	390	$ 105,600	$ 1,704,732	2222
31	C,.9	213	120	520	89360	1414913	3110	C,.9	179	125	515	$ 78,725	$ 1,703,261	2059
32	C,.9	213	120	520	89360	1425166	2886	C,.9	179	125	515	$ 78,725	$ 1,712,294	1897
33	C,.9	213	120	520	89360	1434749	2661	C,.9	179	125	515	$ 78,725	$ 1,720,736	1734
34	C,.9	213	120	520	89360	1443704	2437	C,.9	179	125	515	$ 78,725	$ 1,728,626	1572
35	C,.9	213	120	520	87520	1451902	2216	C,.9	179	125	515	$ 78,725	$ 1,736,000	1409
36	C,.9	164	120	520	68240	1457875	2040	C,.9	179	125	515	$ 78,725	$ 1,742,891	1247
37	C,.9	164	120	520	68240	1463458	1864	C,.9	179	125	515	$ 78,725	$ 1,749,331	1084
38	C,.9	164	120	520	68240	1468675	1688	C,.9	179	125	515	$ 78,725	$ 1,755,350	922
39	C,.9	164	120	520	68240	1473551	1512	C,.9	179	125	515	$ 78,725	$ 1,760,976	759
40	C,.9	164	120	520	68240	1478108	1336	C,.9	179	125	515	$ 78,725	$ 1,766,233	597
41	C,.9	164	120	520	68240	1482367	1160	C,.9	179	125	515	$ 78,725	$ 1,771,146	434
42	C,.9	164	120	520	68240	1486348	984	C,.9	179	125	515	$ 78,725	$ 1,775,738	272
43	C,.9	164	120	520	68240	1490068	808	C,.9	179	125	515	$ 74,252	$ 1,779,786	169
44	C,.9	164	120	520	68240	1493544	632	S,.9	147	125	515	$ 73,600	$ 1,783,536	75
45	C,.9	164	120	520	68240	1496793	456	S,.9	147	125	515	$ 73,600	$ 1,787,040	0
46-59	-	-	-	640	41600	1514116	456	S,.9	179	-	640	$ 41,600	$ 1,800,952	-
60	-	-	-	640	41600	1514834	456	-	-	-	640	$ 41,600	$ 1,801,893	-

Irt: Irrigation trigger: An irrigation is initiated when moisture level is at or below the indicated level

GW(aft): acre feet of ground water remaining at end of year

46-59: average acres, net revenue, cumulative NPV, GW remaining in year 59

Summary and Conclusions.

The study began by using the EPIC simulation model to estimate irrigated corn and sorghum yields in Texas County under alternative irrigation well capacities and soil moisture levels (irrigation trigger) to initiate an irrigation with central pivot and subsurface drip irrigation systems. The EPIC simulation model was calibrated against the limited irrigation data available from research and variety trials at the Oklahoma Panhandle Research and Extension Center at Goodwell, Oklahoma. Data from irrigation research and variety trials from Kansas Stations at Garden City and Tribune and from the ARS station at Bushland, Texas and variety trials from the Texas Panhandle were also used as reference points for the EPIC simulated yields in Texas County, Oklahoma.

Before the simulation could begin, considerable effort was made to construct a daily weather data base covering a 50 year period from 1965 through 2014 to represent long-term weather conditions in the Oklahoma Panhandle. The fifty year daily weather series was used to estimate the mean yield for corn and grain sorghum under full and deficit irrigation.

In the center pivot simulation, the minimum irrigation frequency was determined by the number of days it would take to complete one revolution of the pivot while applying 1.2 acre inches. The 50-year daily simulation was used to estimate the mean yield, given an irrigation trigger and minimum irrigation frequency. No attempt was made to estimate a continuous response function of irrigated corn or grain sorghum to various levels of irrigation because values of water stress also changed along with the level of irrigation. Rather, the estimated yields from different irrigation levels and water stress values were used as discrete opportunities.

Enterprise budgets were constructed to determine the static profitability of the alternative irrigation levels and irrigation triggers (moisture levels to initiate an irrigation). These budgets themselves provide starting points for determining the long term use of groundwater. The net returns over variable costs and the quantity of groundwater used were used directly in developing programming models.

Several scenarios were examined to determine their effect on the optimal value and long-term use of ground water. The first scenario examined was the different producer's decision objectives. The difference in multiyear earnings between producers who followed a series of BSYC (Best Single Year Choices) or always selected the enterprise that gave the highest immediate return without considering the quantity of ground water required. This was contrasted with the producer who followed a crop selection and an irrigation level that maximized the long-term discounted profits (MNPV). This was done for a producer with a 160 acre and with a 640 acre section. Center pivot irrigation systems were used in the comparison. Returns in initial years favored the BSYC producers but after 3 to 4 years, the higher annual returns and increased groundwater levels favored the MNPV producer. This was because the MNPV producer selected grain sorghum (which used less water than corn) the resulting NPV of the planning period always favored the MNPV producer.

The main focus of the report is on a comparison between net returns from conventional center pivot (CP) systems and sub surface drip (SDI) systems. The SDI system has higher water use efficiency because it was assumed there was 10 percent less water lost to evaporation and runoff. The sensitivity of returns and water use rates to changes in feed grain prices, interest rates, holding size, and initial groundwater supplies was analyzed. The feed grain prices used were (low with $4.48 corn and $4.16 grains sorghum) and high (with $5.48/bus. corn and $5.09/bus. grain sorghum). The discount rates used were four and seven percent. The holding sizes used were 160 acres and 640 acres. In the case of the 640 acre holding, two supplies of groundwater were considered.

The optimal MNPV investment for CP and SDI systems on the 160 acre field size were analyzed with a 30-year planning horizon. The SDI was found to be more profitable than the CP systems. The 30-year MNPV values for the four cases analyzed were,

	CP		SDI	
Discount Rate	4%	7%	4%	7%
Feed Grain Price				
Low (C, $4.18; S,4.16)	$106,607	$78,286	$160,861	$115,296
High (C, $548; S, $5,09)	$344,489	$260,312	$436,103	$313,318

Adoption of the SDI system did not always extend the life of the aquifer. However, more grain was produced from the amount of groundwater used with the SDI system than with the CP system.

The 640 acre field with four existing wells offers a conservation possibility to the producer not presented by the 160 acre case. The producer may leave one or more 160 acre subfields unirrigated and increase the quantity of water supplied to the one or more 160 acre fields that are irrigated. This may also reduce the drawn down to in each pumping well. The emphasis however, was on the comparison between the CP and SDI systems. Two water supplies were considered. The low water supply considered only the water under 640 field. This amount with 60 feet of water saturated sand was estimated to be 6,280 acre feet. The larger amount was for a producer located where only 50 percent of the surrounding area was irrigated. The water supply in the second case was 13,440 acre feet. A 60-year planning horizon was used in the second case in order to determine the optimal use of the larger groundwater supply. The Cumulative NPV from CP and SDI investments for the 640 acre field were,

	CP		SDI	
Discount Rate	4%	7%	4%	7%
Limited Water				
Feed Grain Price				
Low (C, $4.18; S,4.16)	$ 618,708	$ 448,998	$ 725,405	$ 507,592
High (C, $548; S, $5,09)	$1,839,290	$1,225,076	$2,052016	$1,419,097
High Water				
Feed Grain Price				
Low (C, $4.18; S,4.16)	$ 850152	$ 569,682	$1,120,703	$ 739,125
High (C, $548; S, $5,09)	$2,291,073	$1,514,834	$2,722,097	$1,801,893

The MNPV results indicated that even with the higher feed grain prices, it was optimal for the CP producer to leave two quarter sections unirrigated and use the wells from those quarters to increase the GPM to pivots on the irrigated quarter sections. By contrast, the SDI producer would develop 600 acres (4- 150 acre SDI systems) for irrigation in the first 15 years with the five dollar feed grain prices. As shown above, the NPV from the SDI system was always more profitable than the CP for the 640 acre field.

Limitations

The study shows the advantage of MNPV from the remaining groundwater. This would be optimal if followed by all producers. We did not have the resources in this study to address the rate of groundwater flow from under one producer's field to that of another producer. If one producer follows the BSYC while the neighbor follows the MNPV strategy, there would be a difference in ground water levels which would flow toward the BSYC producer. Hopefully, the implications of this interaction can be addressed through the use of groundwater models in future studies.

The heavy reliance on simulated data is another limitation but is unavoidable. The authors have used tested simulation models and attempted to calibrate them against observed data where possible.

References

Almas, L. K. and W. A. Colette, 2008. Economic Optimization of Groundwater Resources: A Case of Texas County in the Oklahoma Panhandle. World Environmental and Water Resources Congress, 2008, Ahupua'a.

Ciriacy-Wantrup, S.V. (1963). *Resource Conservation: Economics and Policy*. Univ. Rev. Ed., Ca. Div. Ag. Sciences, Ag. Exp. Stat., Berkley, Ca.

Guru, M. V., & Horne, J. E. (2000). The Ogallala aquifer. Retrieved from. www.kerrcenter.com/publications/ogallala_aquifer.pdf.

Israelsen, O.W. and V.E. Hansen, (1962). *Irrigation Principles and Practices*, J. Wiley and Sons Inc., New York.

Karassik, I. J., J.P. Messina, P. Cooper, C. C. Heald, (2001). *Pump Handbook*, McGraw-Hill, 3'rd Ed., New York.

Luckey, R.R, N.I. Osborn, M.F. Becker, and W.J. Williams. 2000. Water flow in the High Plains Aquifer in northwestern Oklahoma. USGS Fact Sheet 081-00. Oklahoma City, Ok.: United States Geological Survey.

Dhuyvetter, K. C. and T. J. Dumler, (2011). KSU Irrigation Energy Costs: A Spreadsheet Program to Compare the Costs of Irrigation Energy Options. Agricultural Extension Service, Kansas State University,

Schwab, G. O.;Fangmeier, D. D.;Elliot, W. J.;Frevert, R. K. *Soil and water conservation engineering.* Thomas Learning, 1993 pp. xiv + 507 pp.

Qi, S.L. and Christenson, S. 2010. Assessing groundwater availability the the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, Texas and Wyoming. U.S. Geological Survey Fact Sheet 2010-3008

USDA-Natural Resources Conservation Service (2014). Geospatial Data Gateway, USDA, NRCS, https://gdg.sc.egov.usda.gov, Accessed during 2014.

Appendix A Structure of Mixed Integer Programming Model for Subsurface Drip.

The SDI offers the producers more choices than the CP on a 160 acre field in that any part of the field (given suitable soil conditions) can be developed. In the study, the possible sizes of the SDI were given in 25 acre increments from 50 to 150 acres. An outline of a mixed integer programming model where the producer considers the purchase of a 50 acre, a 75 acre, a 100 acre, a 125 acre, or a 150 acre system is shown in Figure A1 below over a 15 year planning horizon. If the producer purchases the 50 acre system unit, then the producer is allowed to grow 50 acres of irrigated sorghum for each of the 15 years over the expected life of the system. The producer has 160 acres of land available each year and 280 acre feet for ground water available in each of six aquifer layers under the 160 acres. Any irrigation water not used in year 1 in each layer is transferred to the same layer for use in the following year. When the water at the top of the aquifer (layer 6) is exhausted, the producer begins pumping from the next lower layer in the aquifer.

Figure A1. Illustration of Programming Model with Alternative Sizes and Irrigation Strategies and Non-irrigated Crop Choices for a Quarter Section and a 15 Year Planning Horizon.

		RHS	Integer Variables					Year one Crop Choices									Year 3 crop				Year 15 Crop Choices							
			IP101	IP201	IP301	IP401																						
	Year		-60000	-120000	-180000	-240000		Sf30116	..	Sf90116	..	Sa30111	..	Sa90111	szo0100							Sf31516	..	Sf91516	..	Sa31511	..	szo0100
Irg.Size	1	1	1	1	1	1	1																					
IP01	1	0	-50	-75	-100	-125	-150	1	..	1	..	1	..	1														
IP02	2	0	-50	-75	-100	-125	-150																					
IP03	3	0	-50	-75	-100	-125	-150										1	..	1									
IP14	14	0	-50	-75	-360	-125	-150																					
IP15	15	0	-50	-75	-360	-125	-150															1	..	1		1	..	
TA01	1	160						1	..	1	..	1	..	1	1													
W601	1	280						0.6	..	1.1	..																	
W501	1	280																										
W102	1	280										0.18	..	0.2														
TA03	3	160															1	..	1									
																	..	..	..									
TA15	15	160																				1	..	1		1	..	1
W615	15	0																				0.6	..	1	..			
W515	15	0																										
W115	15	0																								0.2	..	0

The problem is for the Producer to choose the profit maximizing size of system and also choose the crops to be grown (only sorghum is shown in Figure A1) and the irrigation intensity each year over the planning horizon.

For a producer with a 640 acre section, the acreages and the costs of the SDI systems are scaled up. For a longer planning horizon, (in 15 year increments), the system purchase costs are discounted and repeated.

Final Report – Ochsner et al. OWRRI Project FY2014

Title: Estimating Groundwater Recharge Using the Oklahoma Mesonet

Start Date: 03/01/14

Original End Date: 02/28/15 **No-Cost Extension Until:** 12/31/15

Congressional District: 3rd

Focus Category: GW, WQN, MET

Descriptors: groundwater, recharge, soil moisture

Students:

Student Status	Number	Disciplines
Undergraduate	1	Environmental Science
M.S.	1	Plant and Soil Sciences
Ph.D.		
Post Doc		
Total	2	

Principal Investigators:

Tyson Ochsner, Assoc. Prof., Plant and Soil Sciences, Oklahoma State University
Chris Fiebrich, Assoc. Director, Oklahoma Climatological Survey, University of Oklahoma
Chris Neel, Water Resources Geologist, Oklahoma Water Resources Board

Publications:

Wyatt, B.M., T.E. Ochsner, C.A. Fiebrich, C.R. Neel, and D.S.Wallace. *in review*. A simple method for estimating drainage through long-term soil moisture monitoring. Vadose Zone J.

"Drainage Mapping." soilmoisture.okstate.edu. Oklahoma State University Soil Physics Group, Accessed Feb. 25, 2016. http://soilmoisture.okstate.edu/

Presentations:

1. Ochsner, T.E., B.M. Sallee, C. Fiebrich and C. Neel. 2014. Estimating Groundwater Recharge Using the Oklahoma Mesonet. Oklahoma Water Research Symposium, Oklahoma City, Oklahoma. Oct. 22-23, 2014. Invited.
2. Sallee, B.M. and T.E. Ochsner. 2013. Estimating Groundwater Recharge Using the Oklahoma Mesonet. Oklahoma Water Resources Research Symposium, Midwest City, Oklahoma. Oct. 22-23, 2013.

3. Sallee, B.M. and T.E. Ochsner. 2014. Estimating Groundwater Recharge Using the Oklahoma Mesonet. 3rd Annual Student Water Conference, Stillwater, Oklahoma. Apr. 10-11, 2014.
4. Sallee, B.M., T.E. Ochsner, C. Fiebrich and C. Neel. 2014. Estimating Groundwater Recharge Using the Oklahoma Mesonet. Oklahoma Water Research Symposium, Oklahoma City, Oklahoma. Oct. 22-23, 2014.
5. Sallee, B.M., T.E. Ochsner, C. Fiebrich and C. Neel. 2014. Estimating Groundwater Recharge Using the Oklahoma Mesonet. ASA-CSSA-SSSA International Annual Meeting, Long Beach, California. November 2-5, 2014.
6. Wyatt, B.M., T.E. Ochsner, C. Fiebrich and C. Neel. 2015. Estimating groundwater recharge using the Oklahoma Mesonet. Soil Science Society of America Annual Meeting, Minneapolis, MN. Nov. 15-18, 2015.
7. Wyatt, B.M., T.E. Ochsner, C. Fiebrich and C. Neel. 2015. Estimating groundwater recharge using the Oklahoma Mesonet. Oklahoma Water Resources Advisory Board, Ada, OK.
8. Wyatt, B.M., T.E. Ochsner, C. Fiebrich and C. Neel. 2015. Estimating groundwater recharge using the Oklahoma Mesonet. Oklahoma Water Research Symposium, Norman, OK. Dec. 2-3, 2015.
9. Wyatt, B.M., T.E. Ochsner, C. Fiebrich and C. Neel. 2015. Estimating groundwater recharge using the Oklahoma Mesonet. The 2015 Workshop at Marena, Oklahoma, In Situ Sensor Testbed (MOISST), Stillwater, OK. Jun. 2-3, 2015.

Problem and Research Objectives:

Statement of critical regional or State water problem

Oklahoma water resource managers need accurate information on groundwater recharge rates to allow more effective water management and planning and to reduce groundwater related conflicts, but *no functional recharge monitoring network exists in Oklahoma, or anywhere else to our knowledge.* The statewide Oklahoma Mesonet provides a uniquely rich set of long-term data on hydro-meteorological variables which are relevant for recharge estimation, most notably soil moisture. When soil moisture, hydraulic conductivity, and hydraulic gradient are known, drainage from the soil profile can be calculated based on unsaturated flow theory (Nolan et al., 2007). Groundwater withdrawals that exceed the rate of drainage from the soil profile are not sustainable in the long term, unless the aquifer receives inflows from adjacent aquifers or surface water bodies. We have recently completed an intensive measurement campaign in which we estimated soil hydraulic conductivity functions for the stations of the Oklahoma Mesonet. These new data have enabled us, for the first time, to calculate drainage rates using Mesonet data. In our preliminary work for this proposal, we calculated Mesonet-based drainage rates for five sites in Oklahoma and discovered a remarkable level of agreement between the average annual drainage rates at those sites and previously published groundwater recharge estimates for the corresponding aquifers. This exciting discovery suggested that the Mesonet had real potential as a tool for estimating groundwater recharge across Oklahoma. However, we lacked any independent estimates of groundwater recharge directly co-located with Mesonet sites, so the site-specific level of agreement between recharge and Mesonet-based drainage rate is unknown. Also, we had no knowledge about the extent to which regional scale spatial variability in groundwater recharge is reflected in Mesonet-based drainage rates. There was a critical need for both site-specific and regional scale research to fill these two knowledge gaps.

Nature, scope, and objectives of the project

The *long-term goal* for this team of collaborators is to improve scientific understanding about and inform sustainable management of Oklahoma's groundwater resources by creating powerful new tools for recharge estimation and mapping. The *objective of this proposal* was to clarify the relationship between Mesonet-based drainage rates and groundwater recharge rates in western Oklahoma. To accomplish our objective we proposed two specific aims, to be completed over two years:

1. **Determine the site-specific level of agreement between Mesonet-based drainage rates and independent estimates of recharge in selected aquifers.** Site-specific, independent recharge estimates were obtained for selected locations in the Rush Springs aquifer and in the Ogallala aquifer. The unsaturated zone chloride mass balance method was applied to core samples collected from these locations to determine recharge for comparison with drainage estimates from co-located Mesonet stations.

2. **Determine the regional level of agreement between Mesonet-based drainage rates and independent regional recharge estimates for western Oklahoma.** Drainage was calculated for the decade from 1998-2014 for all Mesonet stations in Oklahoma having the necessary soil moisture data. An average annual soil drainage rate map was created for Oklahoma and compared with a pre-existing recharge map based on the stream baseflow separation method.

Methodology:

Specific aim #1: Determine the site-specific level of agreement between Mesonet-based drainage rates and independent estimates of recharge in selected aquifers.

Research design: Drainage at the 60 cm depth was calculated on a daily time step for the ~15-yr period of record for Mesonet sites above the Ogallala aquifer and the Rush Springs aquifer. We followed previous studies (Keese et al., 2005; Nolan et al., 2007; Wang et al., 2009) in using hydraulic conductivity functions estimated by the Rosetta pedotransfer function (Schaap et al., 2001), but <u>we improved on these studies in two important ways</u>. First, we used daily measurements of soil moisture as the independent variable in the hydraulic conductivity functions rather than modeled soil moisture values or infrequent measurements of soil moisture as employed in prior studies. Soil moisture was calculated from the output of the Mesonet's Campbell Scientific 229-L heat dissipation sensors (Illston et al., 2008) using newly developed soil water retention curves which improve the accuracy of the resulting soil moisture values by >30% relative to the pre-existing curves (Scott et al., 2013). Drainage events can be highly episodic and the importance of having daily soil moisture measurements should not be underestimated. Second, we used the H5 model within Rosetta which requires more input data (i.e., water retention at -33 and -1500 kPa) and is known to produce more accurate results than the H3 model within Rosetta (Schaap et al., 2001), the one used in previous recharge studies.

The unsaturated zone chloride mass balance approach (uz-CMB) was used to obtain site-specific recharge estimates at the Arnett, Boise City, Freedom, Goodwell, Hooker, Slapout, and Woodward Mesonet sites in northwest Oklahoma and the Fort Cobb Mesonet site above the Rush Springs aquifer following the methods of Scanlon et al. (2010). Core samples were collected from the surface to maximum depths ranging from 1 to 8 m. Cores were divided into

~0.5 m segments and sealed to prevent water loss during transport. In the laboratory the water content and bulk density of the segments was determined, and the segments were leached with double-deionized water and the extracts analyzed for chloride concentrations using flow injection analysis colorimetry by the mercuric thiocyanate method (e.g. Zalesny et al., 2008). Extract chloride concentrations were converted to pore water concentrations, which were then be used in the uz-CMB calculations to estimate the site-specific recharge rate corresponding to each core following Scanlon et al. (2010). Chloride concentrations in precipitation, required in the CMB method, will be obtained from the National Atmospheric Deposition Program (http://nadp.sws.uiuc.edu/).

Specific aim #2: Determine the regional level of agreement between Mesonet-based drainage rates and independent regional recharge estimates for western Oklahoma.

2.1 Research design: Daily drainage was calculated for 1998-2014 for all Mesonet stations in Oklahoma which have 60 cm soil moisture data. Calculation procedures were described under specific aim #1. Annual drainage totals and average annual drainage rate were calculated for each station. Ordinary kriging (Ahmadi and Sedghamiz, 2007) was applied to create a drainage map for Oklahoma using the station latitude and longitude coordinates together with the average annual drainage rates. Groundwater samples from existing OWRB monitoring wells in western Oklahoma were collected in conjunction with the startup of the new OWRB groundwater monitoring and assessment program. These groundwater samples were analyzed for chloride and sulfate as in the work of Scanlon et al. (2010). While the unsaturated zone soil samples indicate site-specific recharge conditions, groundwater samples indicate recharge conditions for the local region up-gradient of the sampling site with spatial scales up to several kilometers (Scanlon et al., 2002). Therefore, the chloride concentrations in the groundwater samples were used in the saturated zone CMB approach (sz-CMB) to estimate regional recharge rates for aquifers in western Oklahoma. Spatial patterns in the Mesonet-based drainage map were also qualitatively compared with those in a pre-existing statewide recharge map (Pettyjohn et al., 1983), and the magnitudes of the mapped variables were compared in order to determine the regional level of agreement between Mesonet-based drainage rates and independent regional recharge estimates for western Oklahoma.

Principal Findings and Significance:

Mean annual soil moisture-based drainage rates across the state ranged from 6 mm yr^{-1} at Boise City, OK to 266 mm yr^{-1} at Bristow for the period from 1998-2014 (Figure 1). A similar range of recharge values has been found by prior studies in Oklahoma, with reported recharge rates ranging from 0.8 to 333 mm yr^{-1}. The state-wide median value of the mean annual soil moisture-based drainage rate for the years 1998-2014 was found to be 67 mm yr^{-1} (2.6 in yr^{-1}), which is approximately 7.7% of the median state-wide rainfall of 870 mm yr^{-1} for the same period. A similar percentage was found by Kim and Jackson (2012), who observed that an average of 8% of rainfall became recharge under grassland systems in their global analysis. Soil moisture-based drainage rates generally followed the precipitation gradient of the state, as expected, decreasing from east to west (Figure 1).

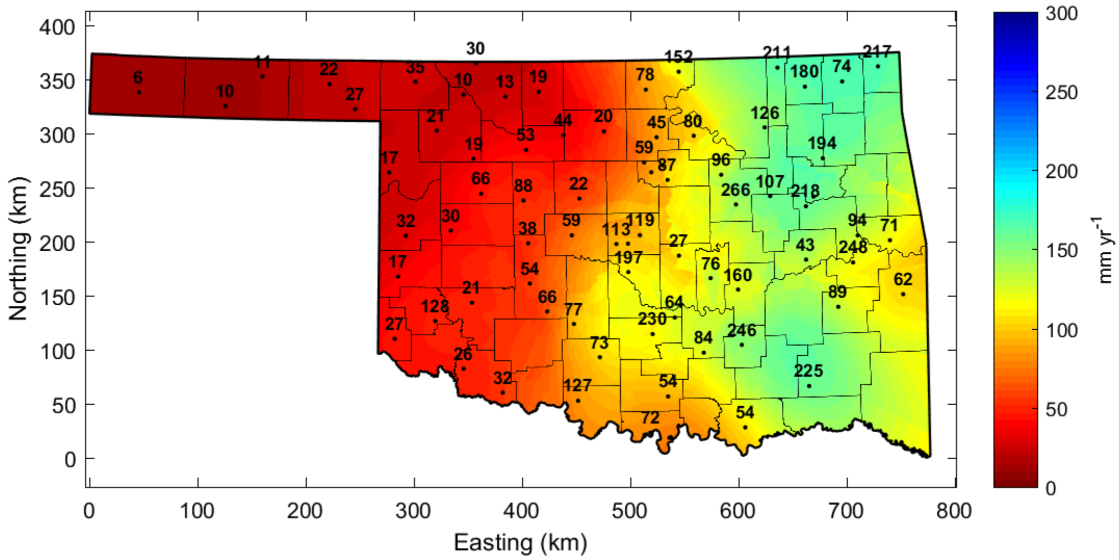


Figure 1. Statewide mean annual soil moisture-based drainage rates for the years 1998-2014 in mm per year. Drainage rate labels for the Stillwater, Oklahoma City East, Porter, and Marena sites were excluded for clarity, but were 214, 82, 166, and 66 mm yr^{-1}, respectively.

The most recent prior state-wide recharge rate map for Oklahoma (Fig. 2), published by Pettyjohn et al. (1983), corresponds fairly well with the map of soil moisture-based drainage rates. Although Pettyjohn et al. (1983) used the baseflow separation method and data from the 1970's, the maps are similar in several ways, including the trend that drainage and recharge rates decrease from east to west. Additionally, the maximum soil moisture-based drainage rate (266 mm yr^{-1}) and maximum Pettyjohn et al. (1983) recharge rate (254 mm yr^{-1}) are comparable. However, there are also some differences between the two maps. For instance, our calculated drainage rates in the Oklahoma Panhandle range from 6 to 27 mm yr^{-1} and are higher than the recharge rate of 2.5 mm yr^{-1} or less estimated for this region by Pettyjohn et al (1983). This difference is reasonable, given that the baseflow method used by Pettyjohn et al. (1983) underestimates recharge when there are upstream water losses due to groundwater evapotranspiration in riparian areas or groundwater pumping, both of which likely influence streamflow in the semi-arid, groundwater-irrigated Panhandle region (Scanlon et al., 2002). Also, there is a difference in the location of the maximum estimated drainage and recharge rates between the two studies. Pettyjohn et al. (1983) estimated that the greatest rates of groundwater recharge occur in the southeast portion of the state, near the Oklahoma-Arkansas border (Figure 3), while the maximum soil moisture-based drainage rates occurred in two areas: one in the northeast and one in the southeast (Figure 2). This may be caused, in part, by a relative lack of soil moisture sensors at the 60-cm depth in the far southeastern part of the state due to shallow bedrock, which leads to a lack of drainage rate estimates in that region.

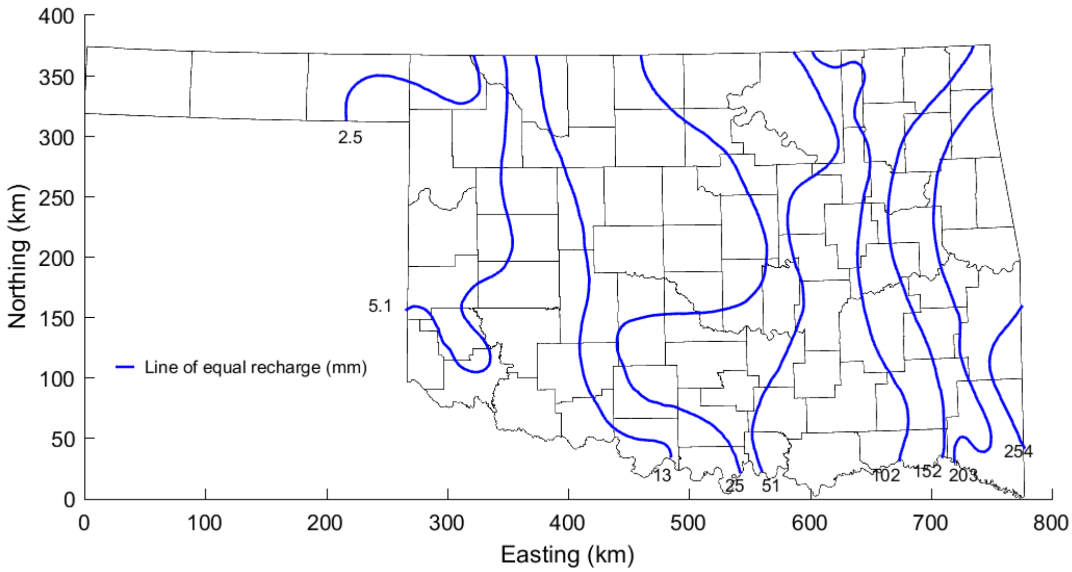


Figure 2. Previously published state-wide recharge map made using the stream baseflow method of recharge estimation. Adapted from original publication by Pettyjohn et al. (1983).

Soil moisture-based drainage estimates summarized by aquifer compare well with previous recharge estimates for major Oklahoma aquifers (Table 1). These drainage values were found by computing the median value of the mean annual drainage rate for aquifers with a minimum of three Mesonet sites above them, resulting in aquifer-scale drainage rate estimates for six Oklahoma aquifers. All aquifer-scale median soil moisture-based drainage rates fall within the range of previous recharge estimates, with the exception of the Arkansas River alluvial aquifer, which has only one prior recharge estimate. Though only one other study has estimated recharge for the Arkansas River alluvial aquifer, the soil moisture-based drainage estimate is within 30% of the estimated recharge rate found by that study. These results provide evidence that drainage estimates from a large-scale soil moisture monitoring network can be indicative of potential recharge rates at the spatial scales of an individual aquifer and an entire state.

Table 1. Summary of soil moisture-based drainage rates by aquifer. Aquifer name, number of Mesonet sites located above the aquifer, median value of the mean annual soil moisture-based drainage rate, a range of previous recharge estimates, and the number of publications contributing to that range.

Aquifer	Sites	Drainage	Recharge	Sources
		mm yr^{-1}	mm yr^{-1}	
Boone	3	74	2.3-267	4
Arkansas River	5	165	127	1
Garber-Wellington	3	113	0.8-211	4
Rush Springs	5	66	5.1-89	4
Antlers	4	63	7.6-76	3
Ogallala	8	19	1.5-56	4

Measured mean chloride concentrations found by CMB_{uz} analysis of soil cores taken at the eight focus sites ranged from 39 mg L^{-1} at the Goodwell site to 1529 mg L^{-1} at the Freedom site (Table 2). These chloride concentrations led to estimated recharge rates ranging from 0.12 mm yr^{-1} at Boise City to 2.5 mm yr^{-1} at the Arnett site. CMB_{uz} analysis of soil cores taken at the eight focus sites gave a median recharge rate of 0.3 mm yr^{-1}, a significantly lower value than the 19 mm yr^{-1} median estimate made from Mesonet soil moisture data. The reasons for this discrepancy between Mesonet drainage rates and CMB_{uz} recharge values are not clear. One possibility is that the unit-gradient assumption made in our analysis of Mesonet drainage rates does not reflect actual conditions at these sites. Another possibility is that chloride inputs not reflected in the NADP data could have affected chloride concentrations in the soil, leading to an underestimation of recharge from the CMB_{uz} analyses. A third possibility is that significant root water uptake may occur beneath the 60 cm depth such that the Mesonet-based drainage rates overestimate recharge.

Table 2. Site name, mean annual precipitation, mean chloride concentrations in precipitation, depth-weighted mean chloride concentration beneath the root zone from soil cores, and CMB_{uz} recharge estimates for the eight Mesonet focus sites.

Mesonet Site	Precipitation	Cl_P	Chloride	Recharge
	mm yr^{-1}	mg L^{-1}	mg L^{-1}	mm yr^{-1}
Arnett	561	0.19	81	2.5
Boise City	386	0.1	624	0.12
Fort Cobb	712	0.19	961	0.27
Freedom	655	0.19	1529	0.16
Goodwell	410	0.1	39	2.0
Hooker	436	0.1	687	0.13
Slapout	530	0.1	516/76	0.20/1.4
Woodward	630	0.19	127	1.8

Analysis of groundwater data from the OWRB's GMAP program by the CMB_{sz} method yielded aquifer-scale recharge rates for five Oklahoma reservoirs (Table 3). A total of 54 groundwater samples from the GMAP program had chloride concentrations below the detection limit of 10 mg L^{-1}, while 19 samples had sulfate concentrations beneath this limit. These samples were assumed to have chloride and sulfate concentrations of 5 mg L^{-1}, which would also create an upper limit on recharge rates. For the Ogallala aquifer, this assumed concentration results in the highest recharge rate possible being 18.9 mm yr^{-1}. The removal of samples with a $Cl:SO_4$ ratio greater than one led to the exclusion of 32 of the 155 groundwater samples taken. Recharge rates from this analysis ranged from 4.8 mm yr^{-1} for the Canadian River alluvial aquifer to 25.4 mm yr^{-1} for both the Elk City and Gerty Sand aquifers. Because groundwater samples are representative of a large area and not specific to a certain location, recharge estimates found by the CMB_{sz} method are only comparable to Mesonet-based drainage rates summarized by aquifer (Table 3). The only aquifers that were tested under the GMAP program which also have an adequate number of Mesonet sites located above them to produce a reliable aquifer- scale median drainage rate are the Ogallala and Rush Springs aquifers. Aquifer-scale median Mesonet estimates of drainage and recharge estimated by CMB_{sz} show a high level agreement for the Ogallala aquifer, with rates of 21 and 17.8 mm yr^{-1}, respectively. However, the median Mesonet-based drainage rate and CMB_{sz} -estimated recharge rate for the Rush Springs aquifer vary by an order of magnitude, with rates of 74 mm yr^{-1} and 7.6 mm yr^{-1}, respectively. The cause of this discrepancy between the CMB_{sz} and Mesonet-based estimates for the Rush Springs aquifer is unclear. One reason could be that groundwater samples used in the CMB_{sz} calculations reflect chloride concentrations over only one year of sampling, while drainage estimates calculated using Mesonet data are given as the median of mean drainage rates for sites above the aquifer for the years 1996-2012. Recharge estimates from this analysis of groundwater chloride seem to be intermediate between the Mesonet-based drainage rates, which are slightly higher, and the CMB_{uz} recharge rates, which are much lower.

Table 3. Mean annual precipitation, number of samples, mean groundwater chloride concentrations, and recharge estimates calculated by the CMB_{sz} method for select Oklahoma aquifers sampled in the 2013 portion of the GMAP program.

Aquifer	Precipitation	No. Samples	GW chloride	Recharge
	mm yr^{-1}		ppm	mm yr^{-1}
Gerty Sand	894	5	11	25.4
Canadian River	770	34	52	4.8
Rush Springs	714	64	31	7.6
Elk City	683	13	9	25.4
Ogallala NW	587	39	11	17.8

We have written and submitted a manuscript describing these results for peer-reviewed publication in Vadose Zone Journal, a high quality journal in hydrologic sciences. That manuscript is designed to disseminate the result of the project to the international scientific community. We have also created a new web portal to deliver annual drainage maps to the public and end users such as the Oklahoma Water Resource Board. These annual and long-term mean drainage maps are at http://soilmoisture.okstate.edu/. Thus, this project has leveraged the existing Mesonet infrastructure to provide a continual flow of valuable new information relevant for understanding and managing groundwater resources in Oklahoma. Furthermore, the methods developed and demonstrated in this project can be applied to a number of other large-scale soil moisture monitoring networks around the world. Doing so is likely to produce new information about potential groundwater recharge rates that will be valuable for advancing hydrologic understanding with the ultimate goal of improving management of groundwater resources, resources that are increasingly critical for societies worldwide.

References:

Ahmadi, S. and A. Sedghamiz. 2007. Geostatistical Analysis of Spatial and Temporal Variations of Groundwater Level. Environ. Monit. Assess. 129: 277-294. doi:10.1007/s10661-006-9361-z.

Illston, B.G., J.B. Basara, D.K. Fisher, R. Elliot, C.A. Fiebrich, K.C. Crawford, K. Humes and E. Hunt. 2008. Mesoscale monitoring of soil moisture across a statewide network. J. Atmos. Ocean. Tech. 25: 167-182. doi:10.1175/2007JTECHA993.1.

Keese, K.E., B.R. Scanlon and R.C. Reedy. 2005. Assessing controls on diffuse groundwater recharge using unsaturated flow modeling. Water Resour. Res. 41: W06010. doi:10.1029/2004wr003841.

Kim, J.H. and R.B. Jackson. 2012. A Global Analysis of Groundwater Recharge for Vegetation, Climate, and Soils. Vadose Zone J. 11. doi:10.2136/vzj2011.0021RA.

Nolan, B.T., R.W. Healy, P.E. Taber, K. Perkins, K.J. Hitt and D.M. Wolock. 2007. Factors influencing ground-water recharge in the eastern United States. J. Hydrol. 332: 187-205. doi:10.1016/j.jhydrol.2006.06.029.

Pettyjohn, W.A., H. White and S. Dunn. 1983. Water Atlas of OklahomaUniversity Center for Water Research, Oklahoma State University, Stillwater, OK.

Scanlon, B., R. Healy and P. Cook. 2002. Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeol. J. 10: 18-39. doi:10.1007/s10040-001-0176-2.

Scanlon, B.R., R.C. Reedy, J.B. Gates and P.H. Gowda. 2010. Impact of agroecosystems on groundwater resources in the Central High Plains, USA. Agr. Ecosyst. Environ. 139: 700-713.

Schaap, M.G., F.J. Leij and M.T. van Genuchten. 2001. ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. J. Hydrol. 251: 163-176.

Scott, B.L., T.E. Ochsner, B.G. Illston, C.A. Fiebrich, J.B. Basara and A.J. Sutherland. 2013. New Soil Property Database Improves Oklahoma Mesonet Soil Moisture Estimates. J. Atmos. Ocean. Tech. 30: 2585-2595. doi:10.1175/JTECH-D-13-00084.1.

Wang, T., V.A. Zlotnik, J. Simunek and M.G. Schaap. 2009. Using pedotransfer functions in vadose zone models for estimating groundwater recharge in semiarid regions. Water Resour. Res. 45: W04412. doi:10.1029/2008wr006903.

Zalesny, J.A., R.S. Zalesny Jr, A.H. Wiese, B. Sexton and R.B. Hall. 2008. Sodium and chloride accumulation in leaf, woody, and root tissue of Populus after irrigation with landfill leachate. Environ. Pollut. 155: 72-80. doi:10.1016/j.envpol.2007.10.032.

Title: Comparison of Grain Sorghum and Corn Productivity under Limited Irrigation with Subsurface Drip

Start Date: 3/1/2014

End Date: 8/28/15.

Congressional District: 3rd Oklahoma Congressional district

Focus Category: AG, ECON, WS, WU

Descriptors: Irrigation, Corn, Sorghum, Ogallala

Student Status	Number	Disciplines
Undergraduate	1	Plant and Soil Sciences
M.S.	3	Plant and Soil Sciences, Agricultural Economics
Ph.D.		
Post Doc		
Total	4	

Principal Investigators: Jason Warren, Art Stoecker, Jordan Gatlin, Karthik Ramaswamy, Rodney Jones, Jody Campiche, and Andrew Paul; Oklahoma State University

Publications:

Abstracts:

1. Gatlin, J., and J.G. Warren. 2014. Comparison of grain sorghum and corn productivity under limited irrigation with subsurface drip. *In* ASA-CSSA and SSSA abstracts. Available online at: https://scisoc.confex.com/scisoc/2014am/webprogram/Paper86030.html

Thesis:

1. Gatlin, Jordan. 2015. Corn and Sorghum yield response to limited irrigation supplied by sub-surface drip. MS Thesis. Department of Plant and Soil Sciences, Collage of Agricultural Sciences and Natural Resources, Oklahoma State University, Stillwater, OK, 40p

Extension Presentations:

1. Warren, J., D. Sims, and C. Murley. 2015. Alternative planting strategies for sub-surface drip. Presented at the Fall Crops Tour. Goodwell, OK. 21 Aug.
2. Warren, J. 2015. Economics of Irrigated Corn vs. Grain Sorghum. Presented at the Winter Crops Clinic. Goodwell, OK. 10 Apr.
3. Gatlin, J., and J. Warren. 2014. Subsurface Drip Technology & Research. Fall Crops Tour. Goodwell, OK 13 Aug.
4. Warren, J. 2014. Subsurface Drip Irrigation. Sorghum Tour. Goodwell, OK 25 July.

Grant Proposals Written:

1. Schipanski, M., J. Warren, et al. 2015. Sustaining Agriculture through Adaptive Management Resilient to a Declining Ogallala Aquifer and Changing Climate. Submitted to AFRI Coordinated Agricultural Project Program for $10,000,000. Pending.

Agronomic Report

INTRODUCTION

The Ogallala aquifer is a vital resource for the entire economy of the Oklahoma Panhandle. Agricultural irrigation is the primary use of water in the region overlaying the Ogallala aquifer, representing 86% of water used (OWRB, 2012). This water is used to produce a variety of crops, however much of the irrigation water is used for the production of corn grain. In fact, the 2007 National Agricultural Statistic Survey shows that approximately 84,000 acres of corn were irrigated, producing approximately 18.4 million bushels of corn to be fed at regional animal production facilities (NASS, 2007). Recent production estimates show that corn production in the region has increased to as high as 26.8 million bushels in 2010 (NASS, 2010). Additional value, for the State of Oklahoma and the broader Southern High Plains Region, is added to this corn as a component of feed for cattle and hogs produced in the region.

The loss of pumping capacity resulting from drawdown of the Ogallala aquifer and/or future restrictions on withdrawal for irrigation poses a significant risk to the future of irrigated crop production and the animal production systems in the region which depend on this local source of grain. Numerous studies have been published in the past 20 years showing that the water levels in this aquifer are declining. For example, the USGS found that water levels declined by as much as 100 ft under Texas County, OK between the 1940s and 1990s. The report went on to suggest that if withdrawal continued at the same rate as in 1996, the water level would decrease by an additional 20-25 ft under Texas County, OK by 2020 (Luckey, et al. 2000).

The effects of these aquifer drawdowns are being felt by an increasing number of crop producers in the Panhandle region. Specifically, irrigation well pumping capacities are declining to levels insufficient to irrigate corn for optimum yields. Historically, various strategies have been used to overcome these declines in well pumping capacity. First, the drilling of additional wells can maintain production potential. Another option is to decrease irrigated acreage by using a smaller portion of the center pivot or combine wells to increase the capacity on a specific field. The cost of drilling a new well combined with the uncertainty of its pumping capacity has made this option less attractive to many producers. Combining wells or otherwise decreasing the acreage irrigated per well will allow for effective use of available water for corn production but in time will cause a net decrease in the feed grain production capacity of the region. This will have a negative impact on the regional animal production complex and the overall economy of the Oklahoma panhandle because of reduced availability of local feed grain.

The producers are now left with very serious decisions about water use and management. One proven technology to increase water use efficiency is subsurface drip irrigation. Subsurface drip irrigation delivers water at low pressure through plastic tape buried below ground. This eliminates evaporative water losses during application thereby resulting in 100% application efficiency. This is a significant improvement in the efficiency of water application when compared to common pivot irrigation systems that apply water at 70 to 90% efficiency. Water use efficiency is additionally improved by the fact that in a subsurface drip system, the soil surface is dry, which allows for improved infiltration of precipitation. The dry soil surface also minimizes evaporative water loss, which further improves efficiency. Interception of irrigation water by the crop canopy is nonexistent in a drip irrigation system, resulting in additional improvements in water use efficiency.

Various research projects have demonstrated the utility of subsurface drip irrigation to improve water use efficiency for crops in the U.S. High Plains. Lamm and Trooien (2003) summarized 10 years of research in Kansas and concluded that irrigation water use for corn can be reduced by 35-55% using subsurface drip irrigation compared to commonly used irrigation systems in the region. The pool of knowledge demonstrating the efficiency of drip irrigation negates the need for further comparison of drip to center pivot irrigation. This project does not seek to do so, but rather this project will be utilized to demonstrate drip irrigation and to develop local knowledge in the successful utilization of this irrigation practice.

Irrigated grain producers also have the option of growing alternative crops with lower water requirements than corn. Grain sorghum provides an ideal alternative crop. It is well adapted to the region and can serve as a replacement for corn in the animal production systems in the region. Historically, grain sorghum has not been competitive with corn as a component of animal feed due to the perception of lower feed quality and milling characteristics. However, modern sorghum varieties have equivalent feed quality characteristics to corn and feed mills are becoming more accepting of sorghum as a feed ingredient. This along with the use of grain sorghum as a feedstock for ethanol production has caused sorghum prices (currently $4.44/bushel) to be competitive with corn prices ($4.44/bushel). This makes sorghum an ideal alternative to corn for irrigation in the Panhandle.

Irrigated grain sorghum has not been given the attention that corn has received due to the historic popularity and profitability of corn. Therefore, irrigation requirements for sorghum have yet to be fully evaluated in the Panhandle region of Oklahoma. Previous research clearly shows that sorghum can be produced with dramatically less irrigation water than corn. For example, the NRCS irrigation guide (NRCS, 2010) suggests that at Goodwell, OK, optimum production of corn requires 20 inches of supplemental water, while grain sorghum only requires 15.5 inches. A preliminary report by Rees and Anderson (2010) confirmed the lower water requirements of sorghum by showing that evapotranspiration (ET) by sorghum was 30% less than that of corn in south central Nebraska. A study conducted at Garden City, KS showed that maximum sorghum yields of 120 bushels/acre could be achieved with an average of 4 inches of irrigation water. In comparison, maximum corn yields of 205 bushels required 12 inches of irrigation (Klocke and Curri, 2009). Additionally, average yields in Oklahoma State University sorghum variety trials conducted in the Oklahoma Panhandle between 2009-2012 were 150 bushels/acre with an average annual irrigation rate of 9.4 inches/acre. In contrast, corn yields in variety trials conducted in the Panhandle produced an average of 190 bushels/acre with an average irrigation rate of 22 inches of water/acre. These data demonstrate the lower water requirement for grain sorghum in the growing environment presented in the Panhandle region of Oklahoma. Similar data collected in the Southern High Plains of Texas near Lubbock on producer’s fields were combined with economic analysis to show that grain sorghum yields of 115 bushels/acre produced more value/inch of water ($31.4/inch) than corn yields of 214 bushels/acre which provided a value of $27.6/inch of water. In this research, the sorghum received an average of 7.9 inches compared to 17.4 inches of water for the corn. It should be noted that corn was more profitable/acre ($479/acre) than sorghum ($248/acre) (Texas Alliance for Water Conservation, 2011). Of course, as water becomes more scarce, returns per unit of water will become a more important driver of the decision making process.

Despite this limited data, there has not yet been a comprehensive economic analysis of irrigated sorghum that encompasses both profitability and risk at a wide range of irrigation application rates. This study is expected to show that producers who follow long-term profit maximization principles in the choice of crops, irrigation water use, and equipment selection will be able to gain more grain production and greater discounted profits from current water supplies than producers who choose maximization of immediate profits.

Commercially available irrigation scheduling technologies provide opportunity to improve irrigation water use efficiency by providing producers with science based recommendations for daily irrigation requirements. Technologies which estimate water requirements based on estimates of evapotranspiration, combined with short-term weather forecasts, provide the most promise for the region. These tools use meteorological data to estimate evapotranspiration and irrigation rates scheduled to replace the daily loss of water from the soil system. The proposed project will evaluate one such scheduling tool as well as provide valuable water use data for high yielding sorghum that will be useful in improving the accuracy of such technologies for irrigated sorghum.

The **OBJECTIVES** of this project are to compare the yield potential and water use efficiency of sorghum and corn under limited irrigation with subsurface drip. This data will serve to validate estimates used in the economic analysis to evaluate the profitability of irrigated grain sorghum and its risk relative to that of corn production under limited water availability.

The funding of this project will also be used to demonstrate a number of technologies proven to improve water use efficiency of irrigated crop production. Specifically, this project will demonstrate the use of subsurface drip irrigation and a commercially available irrigation scheduling product. This will increase the knowledge levels of producers in the region and improve the adoption of these technologies.

METHODOLOGIES

Irrigation system and plot layout

This research utilized the subsurface drip irrigation system located at the Oklahoma Panhandle Research and Extension center. This system provided 48 individually plumbed experimental units that could be irrigated independently. These plots are 15.24 m long and 4.57 m wide. The drip tapes are located at a depth of 0.35 m below the soil surface and 1.52 m apart such that one tape irrigates two crop rows spaced 0.76 m apart. The plots are six rows wide (4.6 m), which means there are three tapes located in each plot, and 15.3 m long. The emitters on the tape are located every 0.30 m and were set to emit 4.5 L/min each. This resulted in a target application rate of 4mm/ha/hour. Flow meters with analog totalizers were installed during the 2013 growing season on each plot to assess instantaneous flow and to monitor cumulative irrigation applied to each plot during the growing season.

Experimental Design

The experimental design is a randomized complete block with split plot design. Main plots were crop (corn or sorghum), and subplots were irrigation rate. The four sorghum treatments and the four corn treatments simulated application rates achievable with well pumping capacities shown in Table 1 when applied to a 50.6 ha center pivot. The sorghum treatments included all pumping capacities included in the table except for the 3028 L min^{-1} because this rate exceeds water requirements for sorghum. The corn treatments included all pumping capacities listed except for the 379 L min^{-1} rate because this is well below the required water for irrigated corn. In 2013 the target irrigation depth was 38.1 mm per irrigation event which resulted in return intervals and application rates shown in Table 1.

Table 1: 2013 Irrigation Treatments.

Treatment		Well Capacity	Application per Interval	Minimum Irrigation Interval	Application Rate
Corn	Sorghum	L $min^{-1}ha^{-1}$	mm	days	L $min^{-1}ha^{-1}$
C1	--	3028	38.1	4.24	60
C2	S1	2271	38.1	5.66	45
C3	S2	1514	38.1	8.49	30
C4	S3	757	38.1	16.94	15
--	S4	379	38.1	29.02	7.5

Treatments are meant to simulate a center pivot system irrigating a 50.6 ha circle with specific well pumping capacities.

In 2014, the target irrigation depth was 25.4 mm per irrigation event which resulted in return intervals and application rates shown in Table 2.

Table 2: 2014 Irrigation Treatments.

Treatment		Well Capacity	Application per Interval	Minimum Irrigation Interval	Application Rate
Corn	Sorghum	L $min^{-1}ha^{-1}$	mm	days	L $min^{-1}ha^{-1}$
C1	--	3028	25.4	2.9	60
C2	S1	2271	25.4	3.7	45
C3	S2	1514	25.4	5.9	30
C4	S3	757	25.4	11.8	15
--	S4	379	25.4	23.1	7.5

Treatments are meant to simulate a center pivot system irrigating a 50.6 ha circle with specific well pumping capacities.

Crop Management

Prior to planting corn and sorghum in 2013 and 2014, plots were fertilized using a strip-till fertilizer applicator. Corn plots received 225 kg N ha^{-1} as liquid UAN (28-0-0) and sorghum plots received 140 kg N ha^{-1} as liquid UAN (28-0-0). Strip tillage was conducted April 5, 2013 and April 15th, 2014. At planting, 19 L of 10-34-0 liquid fertilizer were applied as starter fertilizer. In 2013, corn was planted on April 15th and sorghum was planted June 17th. Inaccurate row placement of the corn rows relative to the drip tape caused unacceptable distribution of water to the corn rows in the April planting; therefore this crop was terminated and corn was replanted on June 4th. In 2014, corn was planted on April 16th and sorghum was planted June 3rd. In each year, dry conditions in April (Table 3) presented stand establishment challenges. Specifically, the strip tillage appeared to reduce capillary movement of water from the drip tape to the corn crop row. Therefore, in order to initiate emergence the corn rows were hand watered. In 2013, the June planted corn did not require hand watering, nor did the sorghum in either year.

Table 3: In-Season Rainfall, Goodwell, OK (mm)

			Month				Total
Year	April	May	June	July	August	September	
2013	8	4	49	26	103	50	240
2014	12	87	95	74	25	41	334

Corn hybrids utilized in both years were Pioneer 1768AMX, planted at 81,500 seeds ha^{-1} on treatments receiving 60 and 45 LPM ha^{-1}, and Pioneer 1151YXR4, planted at 43,200 seeds ha^{-1} on treatments receiving 30 and 15 LPM ha^{-1}. Sorghum hybrids used were Pioneer 84G62, planted at 154,400 seeds ha^{-1} for treatments receiving 45 and 30 LPM ha^{-1}, and DeKalb 3707, planted at 74,100 seeds per ha^{-1} on treatments receiving 15 and 7.5 LPM ha^{-1}. The practice of planting shorter season hybrids on the treatments with lower well capacities is common in this region. The earlier maturing varieties are better suited to limited irrigation systems because they do not require as much water throughout the season as the longer full season varieties. They also are planted at lower populations than the full-season hybrids to ensure better plant survival with limited water. Using these different planting populations also allows the data to be more realistic when utilized for future economic analyses evaluating economic returns from the range of irrigation treatments imposed in this study. In 2013, corn was harvested on October 16th and sorghum was harvested on October 24th with a small plot combine. In 2014, corn was harvested on October 8th and sorghum was harvested on October 15th. The center two rows from each plot were harvested to determine plot weight, test weight and moisture with a harvest master weighing system. Yields presented were corrected to 15.5% moisture for corn and 14% moisture for grain sorghum and 25 kg test weight.

<u>Soil Sampling</u>

Soil cores (4.4 cm diameter) were collected on June 11, 2013 prior to planting of sorghum. The cores were also collected from the corn plots on this date after the second planting. These cores were taken to a target depth of 2.4 m or resistance with a tractor-mounted hydraulic probe. One core per plot was collected in October 2013 post-harvest to assess residual soil moisture to the target depth of 2.4 m. Due to dry subsurface conditions, this target depth was not attainable in all plots, and so the target depth was adjusted to 1.2 m.

In 2014, soil cores were taken from the corn plots on May 7 and from the sorghum plots on June 4 with a hydraulic probe to determine soil water content. One core per plot was collected October 22, 2014 to assess residual soil moisture post-harvest to a target depth of 1.2 m. One core per plot was collected and cut into 0.3 m sections before being weighed, dried at 100°C for 24 hours, and then weighed again to determine gravimetric water content and bulk density. These values were used to determine volumetric water content of the soil. This was then used to calculate the depth of water per depth of soil ($m\ m^{-1}$).

Irrigation Management

In 2013, approximately 76 mm of pre-season irrigation was applied to the corn plots prior to the first planting. Between the first planting and the collection of soil samples on June 11th an additional 100 mm was applied to the corn plots in an effort to germinate the first planting. During this time 38 mm was applied to the sorghum plots. The in-season irrigation was initiated on June 15th for the corn plots and June 28th for the sorghum plots as advised by the Aquaplanner program.

In 2014, 81 mm of irrigation was applied prior to planting the corn and collection of initial soil samples. However, no pre-plant irrigation was applied to the sorghum plots because 85 mm of rainfall was received during the 2 weeks prior to sorghum planting. In season irrigation initiated on May 9th for the corn crop and on June 24th for the sorghum crop.

After initiation, irrigation was applied to treatments at the frequencies presented in Tables 1 and 2. When rainfall was experienced irrigation was postponed if the Aquaplanner program calculated that the soil profile was at or near field capacity.

An irrigation log was maintained which consisted of irrigation duration and volume of water applied to each plot. Water volumes were measured with flow meters attached to the valves on each of the 32 plots to confirm actual flow applied to each plot. This flow meter data was collected throughout the growing season. This flow meter data allowed for the discovery of leaks and incorrect flow rates within the system, and so application times were adjusted accordingly. It was found that in 2013, flow rates were estimated incorrectly, and so the target application of 38.1 mm per event was not realized; instead, the application per event was closer to 22.9 mm. This discrepancy was caused by a difference in the instantaneous flow and the time weighted average flow which was caused by reduced flow during filter flush events. The flows were corrected in 2014 by reducing the frequency of filter flush events and by using the average flow instead of instantaneous flow rate to schedule irrigation event duration such that actual applications were much closer to the target application of 25.4 mm per application event in 2014.

Water Balance

The fallowing water balance equation (Eq. 1) adapted from Kanemasu, et al (1983) was used in this study

Eq 1 $$SM_c = SM_{ini} + I_{eff} + P_{eff} - D - RO - E - T$$

Where:

SM_c	current soil moisture content
SM_{ini}	initial soil moisture content
I_{eff}	effective irrigation
P_{eff}	effective precipitation
D	drainage from the root zone
RO	runoff
E	evaporation
T	transpiration

The soil texture and bulk density as measured on soil samples collection in April and June of 2013, were input into the ROSETTA software program to estimate hydraulic parameters of water held at field capacity (FC, -33 kPa) and permanent wilting point (PWP, -1500 kPa). A soil water characteristic curve (SWC) was used to describe the amount of water retained in a soil at a given matric potential (Tuller et al, 2003). The curve can be constructed using a known volumetric water content (θ) of a soil and relating it to the matric potential, as shown in eq. 2 (van Genuchten, 1980).

Eq. 2

$$\frac{\theta - \theta r}{\theta s - \theta r} = \frac{1}{[1-(-\alpha \times MP)^n]^m}$$

Where:

θ water content

θ_r residual water content

θ_s saturated water content

α

n parameters dependent on the matric potential

m

MP matric potential

The pedotransfer functions utilized in the Rosetta software allow users to input limited physical data such as texture to provide estimates for hydraulic parameters (Schaap et al, 2001). The values given by the Rosetta software using the van Genuchten Eq. 2 allow for SMC curves to be extrapolated, calculating the θ_v at various matric potentials. The water contents at the matric potentials of FC and PWP can be used to calculate how much water can be stored in the profile, and how much of that water is plant available water (PAW).

Initial and Ending Soil Moisture Collection

The volumetric water content calculated from the soil cores collected prior to planting was used to determine SM_{ini} for each treatment. These pre-plant soil moisture values were used as the starting point of the water balance, and the postharvest data was used to validate the water budget ending soil moisture.

Rainfall Data Collection

Precipitation data was collected from the Mesonet (2015) and it was not adjusted, due to the fact that there was no hourly rainfall data available. Also, the crop coefficient (Kcmid) of 1.2 used for the middle of the growing season was selected to account for increased evaporation due to interception. This meant that an efficiency of 100% was assumed to achieve the P_{eff} factor for the water balance.

Irrigation Data Collection

As previously mentioned, irrigation data was collected using flowmeters on each plot. Irrigation data was modified, to assume an efficiency of 95% for SDI (Lamm,) to achieve the I_{eff} value for the water balance.

Calculation of RO and D

Runoff was assumed to be zero, because of the lack of hourly rainfall data needed to determine if its intensity was in excess of infiltration rate. Furthermore, due to the low average seasonal rainfall at this location and the dry nears surface soil conditions presented by the use of subsurface drip irrigation, it was assumed that runoff would be negligible. Drainage was assumed to occur under saturated conditions, when the profile moisture content exceeded FC.

Calculation of ETc

Crop ET (ET_c) was calculated from a reference ET (ET_o) using the single-crop coefficient method outlined in FAO-56 (eq. 3).

Eq.3 $$ET_c = ET_o + K_c$$

Where:

ET_c crop evapotranspiration
ET_o reference evapotranspiration
K_c crop coefficient

This equation adjusts the ET_o based on the crop coefficient (K_c), and the reference ET (ET_o). The K_c can be derived using a single-crop coefficient or a dual-crop coefficient. The single-crop method is recommended for irrigation planning, design, and management utilizing basic irrigation schedules, through computing a daily water balance using the ET_c .In the single-crop coefficient, the calculations are much simpler, because they combine crop transpiration and soil evaporation into one Kc coefficient. This gives only time-averaged effects of ETc (FAO-56).

The ET_o comes from the Penman-Monteith (ASCE-PM) equation from ASCE Manual 70 (Jensen et al, 1990) for calculating a standardized reference ET, or ET_{sz} (eq.4). According to the Task Committee on Standardization of Reference Evapotranspiration, the equation for ET_{sz} uses meteorological data and characteristics of a defined vegetative surface to create a standard reference for calculating ET_c (2005). This defined vegetative surface is defined as “a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of the same vegetation” (ASCE, 2005). The short crop used for reference (ET_{os}) is clipped cool-season grass, and the tall crop reference (ET_{rs}) used is alfalfa. For the this study the following equation was used in combination with data from the Mesonet to calculate the ET_{rs},

Eq. 4 $$ET_{sz} = \frac{0.408\,\Delta(R_n\text{-}G) + \Upsilon(C_n/T+273)u_2(e_s\text{-}e_a)}{\Delta + \Upsilon(1 + C_d u_2)}$$

Where:

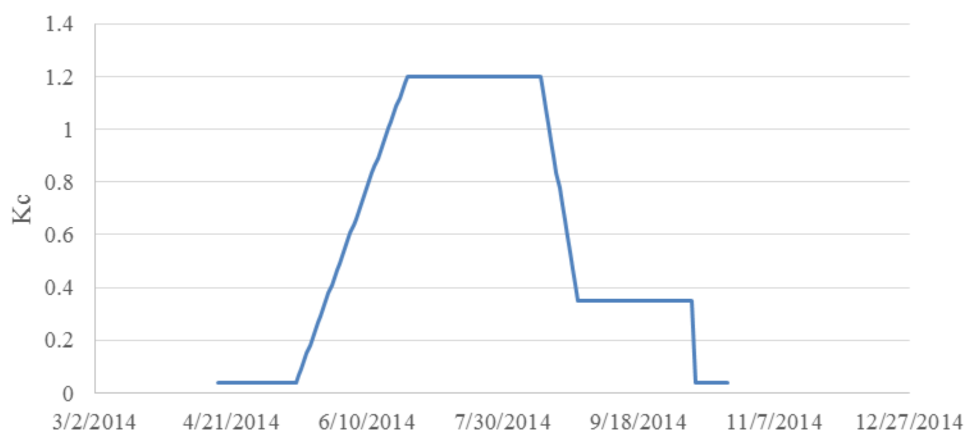
ET_{sz} standardized reference crop evapotranspiration for short (Et_{os}) or tall (Et_{rs}) surfaces (mm d^{-1} for daily time steps or mm h^{-1} for hourly time steps)
R_n calculated net radiation at the crop surface ($MJm^{-2}d^{-1}$ for daily time steps or $MJm^{-1}h^{-1}$ for hourly time steps)

G	soil heat flux density at the soil surface (MJ m^{-2} d^{-1} for daily time steps or MJ m^{-2} h^{-1} for hourly time steps)
T	mean daily or hourly air temperature at 1.5 to 2.5-m height (°C)
u_2	mean daily or hourly wind speed at 2-m height (m s^{-1})
e_s	saturation vapor pressure at 1.5 to 2.5-m height (kPa), calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperature
e_a	mean actual vapor pressure at 1.5 to 2.5-m height (kPa)
Δ	slope of the saturation vapor pressure-temperature curve (kPa $°C^{-1}$)
Υ	psychrometric constant (kPa $°C^{-1}$)
C_n	numerator constant that changes with reference type and calculation time step (K mm s3 Mg $^{-1}$ d^{-1} or K mm s^3 Mg^{-1} h^{-1})
C_d	denominator constant that changes with reference type and calculation time step (s m^{-1})

Corn Crop Coefficients

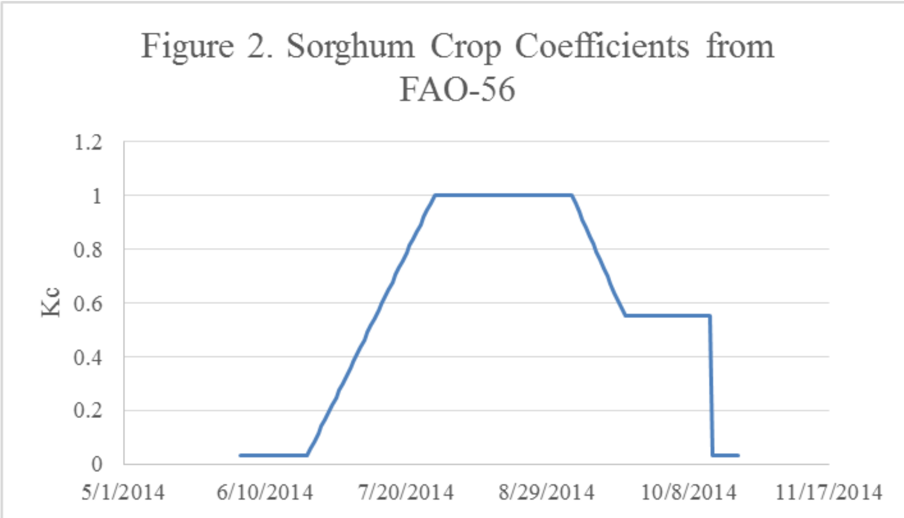
For this study, the crop coefficient was found using the single-crop coefficient method from FAO-56. The K_{cini} was adjusted for wetting, using the average rainfall events during the 30-day period after the 2014 planting date from 2011-2014. This meant that during the initial period, the K_c was very low, only 0.0325. The K_{cmid} used was 1.2. A linear increase was used to determine the K_c during the K_{cdev} stage. For corn, a 15-day period was used for the decline from the K_{cmid} of 1.2 to the K_{cend} of 0.35. After harvest in October, the K_c drops back to 0.0325.

Figure 1. Corn Crop Coefficients from FAO-56



Sorghum Crop Coefficients

For sorghum, the Kcini was determined using the rainfall data from 2011-2014 using the average rainfall for the 30-day period following a June 4 planting. The Kcmid was selected from Table 12 and was 1. The Kcend was 0.55, and the curve decreased linearly over a fifteen-day period just as with the corn. The Kcend remained 0.55 until harvest, and then it was assumed to return to 0.0375.



RESULTS:

Yield and Irrigation Data

In 2013, corn yields were maximized at 11173 kg ha^{-1}, reached in the highest irrigation treatment (60 LPM ha^{-1}). There were 32.8 cm of water applied to this treatment. There were no significant differences in corn yield between the 60, 45, and 30 LPM ha^{-1} treatments. Sorghum yields were maximized in the highest irrigation treatment (45 LPM ha^{-1}), with 9478 kg ha^{-1} produced with 25.9 cm irrigation water applied. Furthermore there were no differences in sorghum yields among the irrigation capacity treatments 45, 30, and 15 LPM ha^{-1}. Comparison of corn and sorghum yields found that at the 45, 30, and 15 LPM ha^{-1} irrigation capacities the corn and sorghum yields were not significantly different. In fact, sorghum yields produced with the 15 LPM ha^{-1} treatment were not significantly different from the corn yields produced with 30 LPM ha^{-1}.

As is generally observed, water use efficiency increased with decreasing irrigation water applied in 2013. The with in a irrigation treatment water use efficiency was significantly higher for sorghum compared to corn only in the 15 LPM ha^{-1} treatment.

In 2014, Grain yields were again maximized when corn was irrigated at the 60 LPM ha-1 irrigation capacity. However these yields were not significantly greater than those achieved with 45 LPM ha-1. At the 45 LPM ha-1 irrigation capacity sorghum yields were significantly lower than corn yields. At irrigation capacities below this level there were no differences between corn and sorghum. However, it must be noted that corn yields were numerically higher than sorghum yields at each irrigation capacity treatment.

Because of lower irrigation water application to sorghum under each irrigation capacity treatment, the water use efficiency was higher for sorghum than for corn. In fact, it was significantly higher at the 30, and 15 LPM ha-1 treatments. this is similar to previous research suggesting that irrigation water use efficiency for sorghum is higher than for corn.

Table 4. In season Irrigation applied, resulting yield and irrigation water use efficiency (WUE_{irr}) in 2013

Irrigation Capacity	Irrigation		Yield		Irrigation WUE	
	Corn	**Sorghum**	**Corn**	**Sorghum**	**Corn**	**Sorghum**
LPM† ha^{-1}	-----------cm----------		----------Kg ha^{-1}---------		--------Kg ha^{-1} cm^{-1}-------	
60	32.8		11173a‡		341e	
45	29.0	25.9	10482ab	9478bc	362e	366e
30	21.8	19.6	9980abc	8787cd	457cd	449cd
15	15.5	14.7	7532d	8599cd	486c	584b
7.5		9.9		7218d		729a

†LPM, liters per minute

‡ Means followed by the same letter are not statistically different. Corn and sorghum data were analyzed together to allow comparison between species.

Table 5. In season Irrigation applied, resulting yield and irrigation water use efficiency (WUE_{irr}) in 2014

Irrigation Capacity	Irrigation		Yield		Irrigation WUE	
	Corn	**Sorghum**	**Corn**	**Sorghum**	**Corn**	**Sorghum**
LPM† ha^{-1}	-----------cm----------		----------Kg ha^{-1}---------		--------Kg ha^{-1} cm^{-1}------	
60	55.1		12123a		194d	
45	45.0	33.8	11496ab	9365c	224d	273cd
30	37.3	30.0	10046bc	8789cd	218d	352b
15	22.1	18.5	6985de	5806e	213d	331bc
7.5		13.5		6446e		629a

†LPM, liters per minute

‡ Means followed by the same letter are not statistically different. Corn and sorghum data were analyzed together to allow comparison between species.

Water Use Efficiency

Tables 4 and 5 present the irrigation water use efficiency (WUE_{irr}), which does not take into account any other source of water besides irrigation. The WUE_{irr} is simply yield divided by in-season irrigation water applied, without taking into account precipitation or soil water used by the crop during the season. This number served to provide a comparison between not only treatments within each crop, but also between the two crops. When other variables are taken into account using the water balance, which accounts for all water that moves into and out of the system, the total water use efficiency (WUE_{total}) can be estimated.

Table 6 shows the pre-plant and post-harvest soil profile moisture content to a depth of 120 cm. Data shows that soil water use ranged from as high as 17 cm for treatment C2 in 2013 to as little as 2 cm for the same treatment in 2014. The elevated soil water use for the corn treatments in 2013 was result of the inadvertent under irrigation of the corn treatments in 2014 due to a error in estimating flow rates. This also explains the similarities in irrigation water use efficiency between corn and sorghum presented in table 4.

Table 6. Total cm of water in the top 120 cm of the profile averaged across reps for each treatment.

Treatment	2013 Soil Moisture		In-Season Soil Water Use	2014 Soil Moisture		In-Season Soil Water Use
	Pre-plant	Post harvest		Pre-plant	Post-harvest	
	--cm--					
C1	46	31	15	39	36	3
C2	46	29	17	37	35	2
C3	44	29	16	40	33	8
C4	44	30	15	39	32	7
S1	42	33	12	38	34	4
S2	40	36	4	34	30	4
S3	42	35	7	35	29	6
S4	42	38	4	35	25	10

†Means followed by the same letter are not statistically different.

Table 7 shows the total water use and water use efficiency for each crop in 2013 and 2014. This presentation of data demonstrates that the water use efficiency of sorghum is higher than that found for corn at each irrigation treatment. This is in agreement with prior research presented above. This suggests that sorghum with produce more grain per cm of water at all irrigation capacities evaluated in this study.

Table 7: The total water used (irrigation, rainfall, and soil water) during the 2013 and 2014 crop years and the resulting water use efficiency for corn and sorghum.

Irrigation Capacity	------Total Water Used-------				---------Water Use Efficiency------			
	------2013------		------2014------		------2013------		------2014------	
	Corn	Sorghum	Corn	Sorghum	Corn	Sorghum	Corn	Sorghum
LPM† ha^{-1}	----------------------cm---------------------				----------------Kg ha^{-1} cm^{-1} --------------			
60	76		95		146		128	
45	75	66	84	65	141	143	137	145
30	66	52	82	61	151	169	123	144
15	59	50	66	52	128	171	106	113
7.5		42		51		170		128

Water Balance

The water balance was initiated at the time of initial soil sample collection. The effective irrigation (I_{eff}), the effective precipitation (P_{eff}) were added to this value on a daily time step. The Crop ET (Etc) was subtracted from this value on a daily time step. When the soil water content to a depth of 120 cm was found to be able field capacity the difference between the current soil water content and field capacity was assumed to be equal to drainage for that day and was subtracted from the soil water. The resulting cumulative values for these variables for the 2014 crop year are presented in table 8 for each corn treatment and table 9 for each sorghum. The measured post-harvest soil moisture (Sm_{final}) is also presented for comparison to the estimated to allow for assessment of the accuracy of the the water balance. The measured value was generally 2cm larger than the estimated value in the corn treatments. In contrast, the measure value for the sorghum was 6.5 cm greater than the estimate in the S1 treatment but 0.3 cm less than the estimated value for S4. This suggests that at fully irrigated conditions our estimate of ETc was in excess of the true ET. This suggests that the ETc estimated by the aquaplanner program (Table 10) may have been closer than that used in our water balance. These findings certainly tell us that that the crop coefficicients provided by the FOA are in sufficient to provide accurate estimates of ETc from a fully irrigated sorghum crop. The similarities between the estimated and measured ETc for the S4 treatment were likely achieved despite the apparently flawed crop coefficients because of the stress coefficients prevented the estimated soil water content from approaching the permanent wilting point of the soil profile which was 23.4 cm. Prior the submission of the final report efforts will be made to find alternative crop coefficients for sorghum in an effort to improve these ET estimates. Given the similarities between the estimated and measured final soil moisture in the corn water balance we it appears that the coefficients used in this water balance were generally accurate. This is not surprising given the extent of research conducted on corn with provides improved estimates of these coefficients from the FAO.

Table 8: Individual components of the Water Balance for each Corn treatment in 2014

							Sm_{final}	
Treatment	Sm_{ini}	I_{eff}	P_{eff}	D	RO	Etc	Estimate	Measured
	--------------------------------------				cm		--------------------------------------	
C1	39	55	37	4.5	0	93	34	36
C2	37	45	37	1.8	0	84	33	35
C3	40	37	37	7.2	0	77	30	33
C4	39	22	37	4.1	0	63	30	32

Table 9: Individual components of the Water Balance for each sorghum treatment in 2014.

Treatment	Sm_{ini}	I_{eff}	P_{eff}	D	RO	Etc	Sm_{final} Estimate	Sm_{final} Measured
	---------------	-------	-------	-------	cm	-------	-------	---------------
S1	38	34	27	6.3	0	65	28	34
S2	34	30	27	2.3	0	61	28	30
S3	35	19	27	3.5	0	51	26	29
S4	35	14	27	3.4	0	47	25	25

Table 10: ETc from the Aquaplanner, mesonet, and FAO

	Cumulative Etc (cm)		
Treatment	Aquaplanner	Mesonet	FAO
Corn	--	105.4	--
C1	89.9	--	92.7
C2	87.9	--	83.8
C3	68.8	--	77.5
C4	62.7		63.3
Sorghum	--	57.90	--
S1	56.3	--	64.8
S2	55.5	--	61.0
S3	47.1	--	51.3
S4	41.4	--	47.0

SUMMARY:

Corn provides the yield potential to allow for the maximization of grain production at irrigation capacities equal to or greater than 45 LPM ha^{-1}. At the remaining irrigation capacities corn and sorghum yields were similar, suggesting that this is the irrigation capacity where it becomes advantageous to grow sorghum instead of corn due to the lower production costs. Furthermore, the water use efficiency was higher for sorghum at irrigation well capacities less than 45 LPM ha^{-1}. This shows that the production of sorghum will result in more grain produced per L of water.

Assessment of the water budgets shows that the 3 different estimates of ETc were within 15% of each other. Specifically, under full irrigation conditions, the mesonet estimate was 15 cm greater than the aquaplanner estimate and the FAO estimate was 3 cm greater than the aquaplanner. In contrast, FAO estimate for sorghum was 8.5 cm greater than the aquaplanner estimate and the mesonet estimate was only 1.6 cm greater. The soil water budget for corn using the FAO ETc estimate showed good agreement between measured and estimated final soil moisture. In each treatment the measured profile moisture was greater than the estimated value, and the greatest difference was in the C3 treatment where the measured value was 3 cm greater than the estimate. The sorghum water budget analysis again showed that the measure values were equal to or greater than estimates with the greatest differences observed in the S1 treatment. This data suggests that our water budget is either over estimating losses such as ET, drainage or underestimate water inputs such as effective rainfall or irrigation. The water balance assumed an irrigation efficiency of 95% and a rainfall efficiency of 100%. Therefore, it is more likely that drainage or ET were over estimated. Future efforts will focus on these estimates. The ET estimates used in this study were based on empirical data collected from surface irrigation and may in fact work well for center pivot irrigation scheduling. However, they are likely over estimating ET from drip irrigation because of reduced canopy and residue interception as well as reduced soil surface wetting when using drip irrigation compared to sprinkler irrigation. Finally, the weather data used to calculate the reference ET was not collected from within the corn field but rather in an adjacent grass field; therefore the atmospheric conditions such as humidity are not accurately representing the irrigated crop. This must be corrected for through adjustments of the reference ET values.

This work has highlighted the improved water use efficiency of irrigated sorghum as compared to corn and that sorghum can be a viable alternative as well capacity declines. Furthermore, the water balance data suggests that current irrigation scheduling tools based on water budgets consistently under estimate soil water availability for subsurface drip irrigation.

Works Cited

Carreira, R.I. (2004) Economic Study of Alternative Best Management Practices for Swine Effluent Application to Corn in a Semiarid Climate, Ph.D. Dissertation, Edmond Low Library, Oklahoma State University.

Carreira, R.I., A.L. Stoecker, F.M. Epplin, J.A. Hattey, and M.A. Kizer, (2006) Subsurface Drip Irrigation Verus Center-Pivot Sprinkler for Applying Swine Effluent to Corn. Journal of Agriculture and Applied Economics. Vol. 38(3), PP 645-648.

Harris, T.R. and H.P. Mapp. 1988. A Stochastic Dominance Comparison of Water-Conserving Irrigation Strategies. Amer. J. Agricultural Economics, 68:298-305.

Klocke, N, and R. S. Curri. 2009. Corn and Grain Sorghum Production with Limited Irrigation. In the Southwest Research-Extension Center, Field Day 2009 Report. pgs 35-38. Kansas State University Agricultural Experiment Station and Cooperative Extension Service, Manhattan, KS. Available online at: http://www.ksre.k-state.edu/library/crpsl2/SRP1014.pdf. Verified on Oct. 24, 2011.

Lamm, F.R., D.M. O'Brien, D.H. Rogers, and T.J. Dumler. 2012. Comparison of SDI and Center Pivot Sprinkler Economics. Proceedings of the 2012 Irrigation Association Technical

Conference, Orlando, Florida, Nov. 2-6. Available from the Irrigation Association, Falls Church, VA

Lamm, F.R., and T.P. Tooien. 2003. Subsurface drip irrigation for corn production: a review of 10 years of research in Kansas. Irrigation Science. 22: 195-200.

Luckey, R.R., N.L.Osborn, M.F. Beker, and W. J. Andrews. 2000. Water Flow in the High Plains Aquifer in Northwestern Oklahoma. USGS Fact Sheet 081-00.

NASS. 2007. Census of Agriculture: Oklahoma. State and County Data. Volume 1. Geographic Area Series. Part 36. Available online at: http://www.agcensus.usda.gov/Publications/2007/Full_Report/Volume_1,_Chapter_1_State_Level/Oklahoma/ Verified on Oct. 8, 2012.

NASS. 2010. Oklahoma Corn County Estimates. Available online at: http://www.nass.usda.gov/Statistics_by_State/Oklahoma/Publications/County_Estimates/2011/ok_corn_county_estimates_2011.pdf Verified on Oct. 8, 2012.

NRCS. 2010. National Engineering Handbook - Part 652, National Irrigation Guide and Oklahoma Supplements. Available online at: http://www.ok.nrcs.usda.gov/technical/Manuals/ig.html. Verified on Oct. 01, 2012.

OWRB 2012. Oklahoma Comprehensive Water Plan, Panhandle Watershed Planning Region Report. Available online at: https://www.owrb.ok.gov/supply/ocwp/pdf_ocwp/WaterPlanUpdate/regionalreports/OCWP_Panhandle_Region_Report.pdf Verified on Oct. 8, 2012

Prescott, E.C. (1972) The multi-period control problem under uncertainity, Econometrica, vol 72, 1972

Rees, J., and D. Anderson 2009. Comparison of Crop Water Consumptive Use of Sorghum, Corn, and Soybeans. Annual Report, available online at: http://water.unl.edu/c/document_library/get_file?folderId=1242079&name=DLFE-14668.pdf. Verified on Oct. 08, 2012.

Sick, G.A. (1986) A Certainty-Equivalent Approach to Capital Budgeting, *Financial Management* Vol. 15, pp 23-32

Stoecker, A.L., A. Siedman, and G.S. Lloyd. 1985. A Linear Dynamic Programming Approach to Irrigation System Management with Depleting Groundwater. Management Science, 31(4)422-434.

Texas Alliance for Water Conservation. 2011. When Water Determines your Success. Observed Cotton, Grain Sorghum and Grain Corn Fields in the Texas High Plains, 2005-2011. Available online at: http://www.depts.ttu.edu/tawc/documents/Water_determines%20success.pdf Verified on Oct. 08, 2012.

Economic Modeling of Irrigated Corn vs. Grain Sorghum Using Center Pivot or Subsurface Drip Systems

Final Report to OWRRI at Oklahoma State University

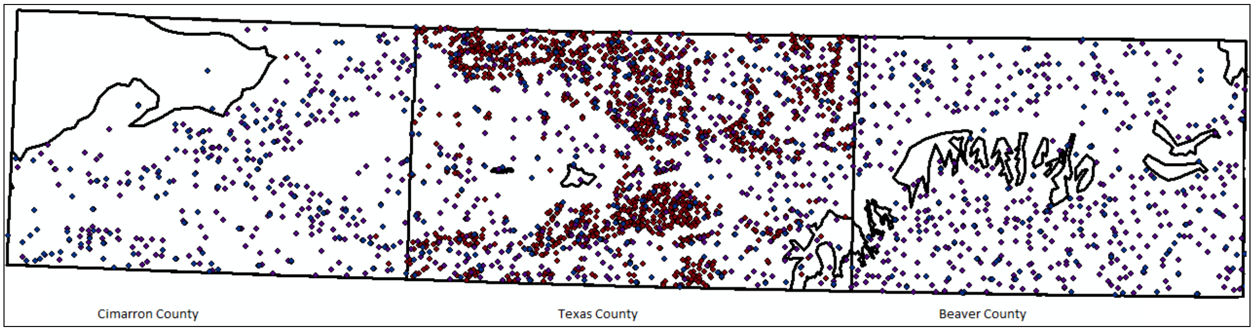
August 31, 2015

By

Dr. Art Stoecker, Associate Professor, Department of Agricultural Economics, Oklahoma State University, Stillwater, OK 74078
Karthik Ramaswamy, Graduate Research Assistant, Department of Agricultural Economics, Oklahoma State University, Stillwater, OK 74078
Dr. Jason Warren, Associate Professor, Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK 74078
Dr. Rodney Jones, Professor, Department of Agricultural Economics, Oklahoma State University, Stillwater, OK 74078
Dr. Jody Campiche, Professor, Department of Agricultural Economics, Oklahoma State University, Stillwater, OK 74078
Andrew Paul, Graduate Research Assistant, Department of Agricultural Economics, Oklahoma State University, Stillwater, OK 74078
Brooke Lane, Undergraduate Assistant, Department of Agricultural Economics, Oklahoma State University, Stillwater, OK, 74078

Introduction

The study area concerns the Ogallala Aquifer that underlies parts of Cimarron, Texas, and Beaver counties in the Oklahoma Panhandle. This area is intensively irrigated and there has been state and national concern over the fate of the Ogallala or Great Plains Aquifer (USGS). Figure 1 below shows the three county study area with the underlying Ogallala Aquifer and the location of wells in Cimarron, Texas, and Beaver counties.



Source: Geospatial Data Gateway and USGS website

Figure 1. Cimarron, Texas, and Beaver County Study Area with Wells and an Outline of the Ogallala Aquifer under the Oklahoma Panhandle

Both the USGS and the Oklahoma Department of Water Resources conduct measurements on water tables in wells. The USGS began publishing an annual series of water levels in wells in the High Plains Aquifer (Ogallala) across Colorado, Kansas, Nebraska, Oklahoma, Texas, and Wyoming in 1994. A simple average of the water levels measured in Beaver, Cimarron, and Texas counties is shown in Figure 2 below. The graph shows the trend is downward with considerable variation between years. A simple trend analysis shows the following water table declines in Beaver, Cimarron, and Texas counties were;

Beaver, County: 92.7 + 2.59 Yr, r^2 = .68,
Cimarron, County: 180.7 + 0.94 Yr, r^2 = .28, and
Texas, County: 178.4 + 1.87 Yr, r^2 = .65

The trend analysis shows that while the depth to the static water table was smaller in Beaver County, they have a greater rate of decline (2.59 feet per year) than do the deeper wells in Texas and Cimarron counties. The year to year variability is due in part to weather and in part to the fact that the location of all wells sampled changes from year to year.

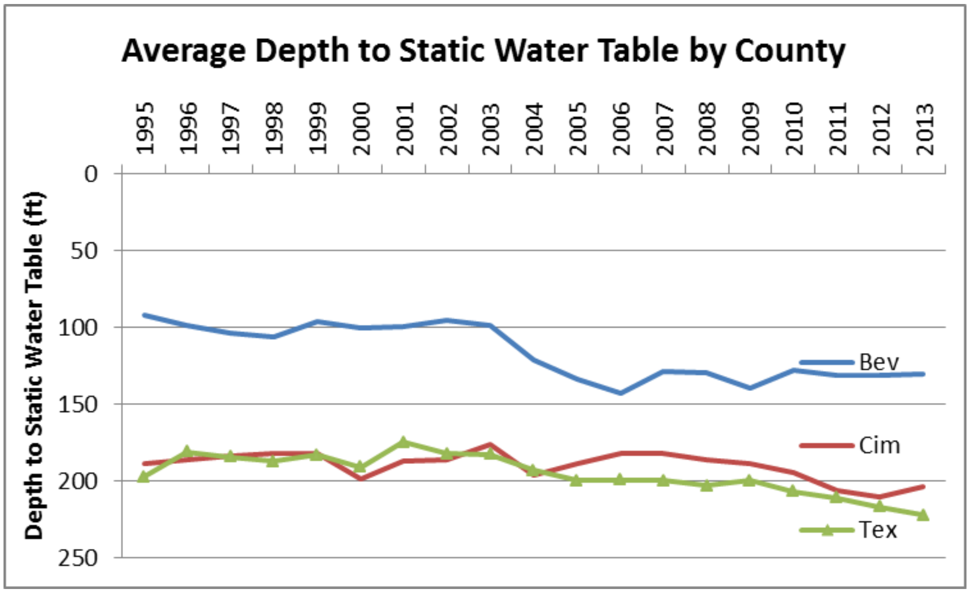


Figure 2. Average Depth to the Static Water Table in Wells in Beaver, Cimarron, Texas Counties from 1994 through 2013 as reported by the USGS.

Tex Co 178.4 + 1.87 Yr, R^2 = .65, Cim. Co. 180.7 + 0.94 Yr, R^2 = .28
Bev. Co. 92.7 + 2.59 Yr, R^2 = .68

A longer trend from 1950 would show greater declines in the level of the Ogallala in the Oklahoma Panhandle. The recharge rate to the aquifer in the Panhandle is dependent upon percolation of limited rainfall and has been estimated to be between 0.25 and 0.5 inches per year (Guru, 2000).

Luckey and others suggested that if withdrawal continued at the same rate as in 1996, the water level would decrease by an additional 20-25 feet under the Oklahoma Panhandle by 2020 (Luckey, et al. 2000). USGS found that water levels declined by as much as 100 feet under the Oklahoma Panhandle between the 1940s and the 1990s.

A primary problem for producers in the Oklahoma Panhandle is depleting ground water and ravaging droughts. The source of the irrigation water in Oklahoma Panhandle is the Ogallala aquifer. In Oklahoma, irrigation accounts for 86% of the withdrawal from the Ogallala aquifer (OWRB, 2012). It is in a state of disequilibrium, as the natural recharge to the aquifer is much less than the annual withdrawals. The continued decline in the water table causes the cost of pumping to increase. By 1989, Lacewell and Lee noted the cost of pumping irrigation water had increased from $5.98 per acre-foot in 1969 to $63.96 per acre-foot in 1988 for sprinkler irrigation (Lacewell and Lee, 1989). In response, many producers in the panhandle adopted advanced irrigation systems such as Pivot Systems and low energy precision application (LEPA) systems.

The panhandle's saturated stratum has relatively low permeability, which is the ultimate reason for the rapid water table decline. The Ogallala aquifer is an unconfined aquifer, under normal conditions in an unconfined aquifer the water percolation from the land surface is expected to freely join the saturated zone. However, due to poor permeability in the Ogallala aquifer and clay-soil characteristics the recharge rate is negligible or none. The recharge rate has been estimated to be between 0.25 to 0.5 inches per year (Guru, 2000).

Study Objectives

The overall objective of the economic portion of this study was to determine comparative advantages of irrigated corn relative to sorghum and the comparative advantages of center pivot irrigations systems relative to subsurface drip irrigation to aid producers to gain the maximum value from their remaining groundwater reserves.   More specifically the objectives are to compare,

a. Long-term values and aquifer life with center pivot irrigated corn.
b. Long-term values and aquifer life with subsurface drip irrigated corn.
c. Long-terms values and aquifer life with center pivot irrigated grain sorghum.
d. Long-term values and aquifer life with subsurface drip irrigated grain sorghum.

Study Methods

The remaining ground water reserve could last from a few years to more than 50 years. The weather in the Oklahoma Panhandle is also highly variable. The analysis required estimates of crop yields and water use under a wide range of weather conditions. Actual observed and measured data relating to crop yields and water use are available for only limited periods of time. In addition future weather patterns are uncertain. Data sets reflecting alternative climate change values for the regions like the Oklahoma Panhandle are just becoming available. The approach followed was to use the EPIC (Environmental Policy Impact Calculator) simulation model to generate yields using a 50 year historical weather set for Goodwell, Oklahoma.

Construction of a 50 year daily weather set for Goodwell, Oklahoma

EPIC can utilize daily weather variables such as minimum temperature, maximum temperature, precipitation, relative humidity, solar radiation, and wind speed. EPIC will operate on daily precipitation, minimum daily temperature and maximum daily temperature. In this case, the remaining values are simulated. It was assumed a better data set could be obtained by using as much actual available weather data as possible from the area.

Two daily weather data sets were constructed for Goodwell, Oklahoma. A twenty-one year data set was constructed for the period from 1/1/1994 – 11/30/2014. This data set was based on the Oklahoma MESONET data for Goodwell, Oklahoma which can provide all of the variables listed above. Unfortunately the MESONET temperature values were not reported until February of 1997. In addition, there were many missing values for the remaining variables. Missing values were estimated by multiple regressions from the surrounding weather stations and MESONET stations with MESONET data from Hooker (in Texas County) and Boise City (in Cimarron County).

Construction of the 50 year daily weather file was more problematic. During the 50 year period from 1/1/1965 to 11/30/2014 there were many changes in weather stations and in the data collected. Variables like relative humidity, wind speed, were only reported by larger federal weather stations like Dodge City and Garden City Kansas, Amarillo, Texas, and from the airport at Liberal, Kansas. Solar Radiation data were not available outside the 1994-2014 period from the MESONET sites. Completion of the data set for the individual weather variables was done on a case by case basis.

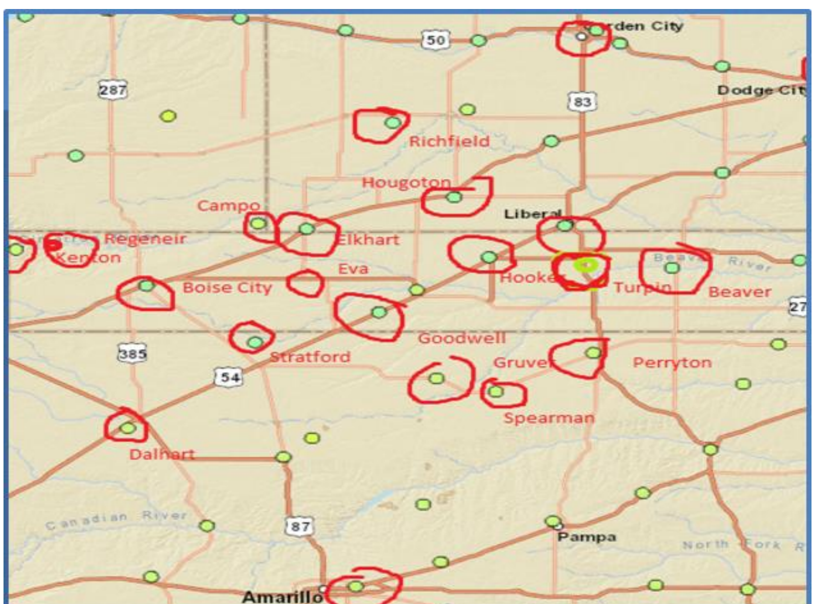


Figure 3. Locations of sites around Goodwell where Weather Variables were Obtained to Estimate Missing Goodwell Values

A common approach is to use inverse distance weighting of values from surrounding reporting sites to fill in data gaps. However this approach only uses the information in the weather values on a given day and does not use any statistically estimated relationships between sites where all data are present. A multiple regression was used in this study. Figure 3 above shows the locations of sites around Goodwell, Oklahoma where one or more weather values are reported. In order to estimate a missing temperature value for Goodwell, temperature values were obtained from Hooker, and Boise City in Oklahoma, and Liberal and Elkhart in Kansas, and Amarillo, and Perryton Texas. An OLS regression of the reported Goodwell temperature was regressed against the reported daily values (independent variables) as follows;

$$GW_t = a\ Hk_t + b\ BC_t + e\ Li_t + d\ Ek_t + ePy_t + f\ Am_t,$$

where the respective variables GW, Hk, BC, Li, Ek, Py andAm represent observations form Goodwell, Hooker, Boise City, Liberal, Perryton and Amarillo respectivelyThe estimated regression was then used to predict missing Goodwell temperature values. The limitation of the process is that the reported weather series from other locations also contain data gaps. If one of the independent sites has a missing value on the same day as Goodwell, then the regression cannot be used to estimate the Goodwell temperature. This problem was solved by estimating additional regression equations by omitting one of the independent variable. In some cases it was necessary to omit more than two variables. The equations were then ranked in order of decreasing r-square values. On days where the equation with all independent variables could not be used because one or more of the independent weather values was missing, the next best equation with no missing values was used. The estimation and predictions were carried out using SAS 9.1. SAS will not make a prediction on days when the values for one or more of the independent variables are missing.

Minimum Daily Temperature:

Goodwell was the dependent variable. The independent variables were Hooker, Boise City, Elkhart, Gruver, and Stratford. The estimated regression equations were,

$GWm_t = -.54 + .057\ Hk_t + .279\ Elk_t + .242\ BC_t + .184\ Gru_t + .254\ Str_t, \quad r^2 = .96$
$GWm_t = .003 + .292\ Elk_t + .247\ BC_t + .196\ Gru_t + .280\ Str_t, \quad r^2 = .96$
$GWmt = .033 + .086Hk_t + .266BC_t + .266\ Gru_t + .318\ Str_t, \quad r^2 = .96$
$GWmt = -.154 + .044\ Hk_t + .389Elk_t + .244Gru_t + .329\ Str, \quad r^2 = .96$
$GWmt = .047 + .070Hk_t + .336Elk_t + .286BC_t + .326\ Str_t, \quad r^2 = .96$
$GWmt = -.193 + .107Hk_t + .324Elk_t + .310BC_t + .273Gru_t, \quad r^2 = .96$
All coefficients were significant at the 10 percent level or better.

Maximum Daily Temperature:

The stations used as independent variables in the estimation of missing Goodwell maximum daily temperature values were the same as above for the minimum temperature. The estimated equations were,

$GWmx_t = -.043 + .383Hk_t + .021\ Elk_t + .096\ BC_t + .017\ Gru_t + .487\ Str_t, \quad r^2 = .95$
$GWmx_t = -.319 + ,111\ Elk_t + ,130\ BC_t + .208\ Gru_t + ,567\ Str_t, \quad r^2 = .94$
$GWmx_t = -.066 + ,393\ Hk_t + .100\ BC_t + .015\ Gru_t + .496\ Str_t, \quad r^2 = .95$
$GWmx_t = .142 + 396\ Hk_t + .060\ Elk_t + .037Gru_t{}^* + .504\ Str_t, \quad r^2 = .95$
$GWmx_t = -.026 + .392\ Hk_t + .025\ Elk_t + .099\ BC_t + .489\ Str_t, \quad r^2 = .95$
$GWmx_t = .720 + .403\ Hk_t + .336\ Elk_t + .033\ BC_t + .185\ Gru_t, \quad r^2 = .90$
Unless indicated (*) all coefficients are significant at the 10% level or better.

Precipitation:

Daily precipitation was the hardest variable to estimate because of the unevenness of the rainfall over the High Plains area. The stations used as independent and dependent variables are listed below. Thirty-minute rainfall was reported by the Goodwell station for some of the dates. On some days when the daily total was missing, and there were two or more periods of 15 minute rainfall reported, an estimate for the day's rainfall, based on the reported 15 minute rainfall and the time of year, during the missing period could be made. However, there were still

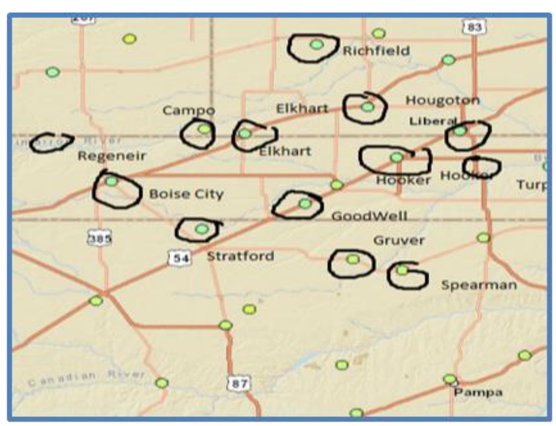


Figure 4. Location of Daily Rainfall Values used in the Regression Equations

many gaps in the precipitation values from the independent sites used in the regression. The approach was to collect all reported daily rainfall values between 1965 and the present from locations as near Goodwell as possible. Data were used from the stations circled on the map in Figure 3. The estimated regression equations were,

$GWp_t = .352\ Str_t + .110\ Elk_t + .071 Gru_t + .198\ Eva_t - .030\ Hug + .112 Spr + .062\ Rch + .09 DwtWrn_t*$, r2 = .59
$GWp_t = .189 Str_t + .051\ Elk_t + .100\ Gru_t + .095 Eva_t + .030 Hug + .030 Spr + .029\ Rch + .371 DwtWrn_t$, r2 = .59
$GWp_t = .031\ Elk_t + .045\ Hug - .169\ Rch + .799\ DwtWrn_t$, r2 = .46
$GWp_t = .029 Elk_t + .051 Hug + .016 Spr + .776\ DwtWrn_t$, r2 = .44

The respective sites used were Stratford, Texas (Str), Elkhart, Kansas (Elk), Gruver, Texas (Gru), Eva, Oklahoma (Eva), Hugoton, Kansas (Hug), Spearman, Texas (Spr), and Richfield, Kansas (Rch). All coefficients are significant at the 10 percent level or better unless indicated (*).

The variable DwtWrn (inverse distance weighted rainfall) was not significant in the first equation, but was significant in the remaining three equations. The r-square values are in the .4-.5 range. It is notable that on days when all stations were reporting observations, the inverse distance weighting method was not significant. When only a few stations were available, the values of those stations were significant along with the inverse weighted distance value.

Relative Humidity:

Weather stations in the Central High Plains with long reported records of relative humidity (or dewpoint temperature) were limited. The regressions below utilize data from Liberal, Kansas, Elkhart, Kansas, Dalhart, Texas, and Clayton, New Mexico. Relative humidity data were only estimated from 1973-2014.

The regressions obtained were,

$GWh_t = 6.92 + .313\ Li_t + .116\ Am_t + .062\ Da_t + .314\ Elk_t + .255 Cy_t$, $r^2 = .81$
$GWh_t = 8.53 + .321\ Li_t + .174\ Am_t + .491\ Da_t$, $r^2 = .74$
$GWh_t = 10.23 + .423\ Li_t + .501 Am_t$, $r^2 = .69$

Wind Speed:

Prior to the establishment of the MESONET in 1994, the Goodwell Research station was one of the few places in the study area reporting wind speeds. Unfortunately, there were many gaps in this data. Wind speed was recorded by the airport at Liberal, Kansas but the data were not electronically available before 1973. Amarillo, Texas, Dodge City and Garden City, Kansas (Figure 5) had wind

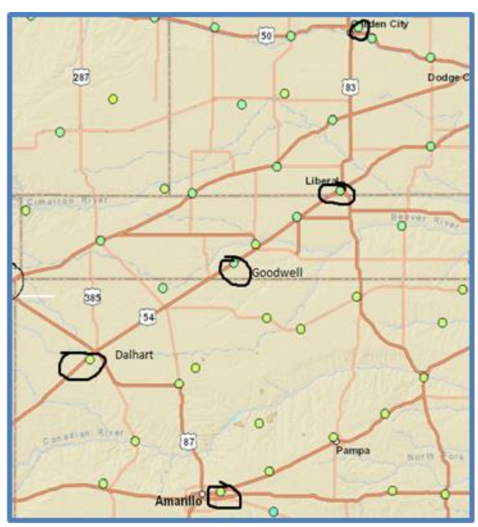


Figure 5. Location of Stations Reporting Windspeeds used in the Regression Analysis

speed records dating back to 1965. The estimated regression equations were,

$GWWt = -0.226 + 0.236\ Gc_t + 0.313\ Cy_t + -0.003\ Am_t + 0.183\ Dh_t + 1.196\ DC_t + 0.085\ Li_t,\ r^2=0.41$

$GWW_t = -0.104 + 0.361\ Cy_t + -0.003\ Am_t + 0.187\ Dh_t + 1.325\ DC_t + 0.109\ Li_t,\ r^2= 0.41$

$GWW_t = -0.150 + 0.303\ Gc_t + 0.000\ Am_t + 0.399\ Dh_t + 1.169\ DC_t + 0.076\ Li_t,\ r^2= 0.37$

$GWW_t = -0.226 + 0.236\ Gc_t + 0.314\ Cy_t + 0.182\ Dht + 1.197DC_t + 0.086\ Li_t,\ r^2= 0.41$

$GWW_t = -1.01 + 0.252\ Gc + 0.419\ Cy_t -0.0003\ Am_t + 1.202\ DC_t + 0.115Li_t,\ r^2= 0.41$

$GWW_t = 0.790 + 1.070\ Gc_t + 0.287\ Cy_t -0.005\ Am_t + 0.276\ Dh_t + 0.266\ Li_t,\ r^2= 0.36$

$GWW_t = -0.396 + 0.273\ Gc_t + 0.320\ Cy_t -0.004\ Am_t + 0.218\ Dh_t + 1.235\ DC_t,\ r^2= 0.41$

$GWW_t = -2.80 + 0.004\ Am_t + 1.852\ Dct\ r^2= 0.40$

The respective cities were Garden City (GC), Clayton, New Mexico (Cy), Amrillo, Texas (Am), Dalhart, Texas (Dh), Dodge City, Kansas (DC), and Liberal, Kansas (Li).

Solar Radiation:

Solar Radiation data covers only the period from 1994 through the present and was found only at the more recent MESONET sites. The missing Goodwell MESONET solar radiation values were estimated by the following regressions based on data at Beaver and Boise City. The regression equations estimated were,

$GWS_t = -0.182 + 0.450\ BV_t + 0.561\ BCt,\ r^2= 0.961$

$GWS_t = 1.660 + 0.939\ BV_t,\ r^2= 0.908$

$GWS_t = -0.126 +0.985\ BC_t,\ r^2= 0.923.$

All coefficients significant at the 10 percent level or better.

The monthly mean values along with their standard deviations, maximum observed value, and maximum observed values for each month are shown below in Table 1.

Table 1. Fifty Year Averages of Monthly Means and Standard Deviations of the Daily Goodwell Weather set.

Item and Unit	Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Max. Daily Tmp Celsius	Mean	9.1	11.3	15.9	21.1	25.9	31.4	34.1	32.8	28.5	22.4	15.0	9.6	21.5
	Sdev	8.1	8.3	7.9	6.8	6.0	5.0	3.9	4.2	5.7	6.7	7.3	7.9	11.0
	MinObs	-13.3	-16.7	-12.5	-6.1	4.4	12.2	17.2	15.0	4.4	-6.1	-12.2	-17.2	-17.2
	MaxObs	27.2	30.6	34.4	37.8	39.6	43.9	42.1	42.2	42.8	35.8	31.7	32.7	43.9
Min. Daily Tmp. Celsius	Mean	-7.0	-5.3	-1.2	4.0	9.5	15.2	18.0	17.1	12.4	5.3	-1.3	-5.9	5.1
	Sdev	5.3	5.3	5.1	4.6	4.2	3.4	2.4	2.5	4.2	4.5	4.8	5.3	9.9
	MinObs	-25.6	-23.9	-19.0	-12.8	-4.3	4.4	8.3	7.2	-2.2	-11.7	-20.6	-25.0	-25.6
	MaxObs	17.8	9.4	22.2	23.3	32.8	33.9	24.5	23.4	23.3	20.6	10.7	10.4	33.9
Monthly Precp mm	Mean	7.6	10.3	25.4	34.1	67.8	64.2	58.8	58.4	36.9	32.4	14.8	11.3	34.7
	Sdev	1.2	1.7	3.2	4.3	7.6	6.1	6.2	6.1	5.1	5.0	2.4	2.0	4.8
	MinObs	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	MaxObs	17.8	23.6	38.4	46.0	91.4	49.8	76.7	80.3	74.7	86.9	28.7	53.3	91.4
Daily Rel. Hum. proportion	Mean	0.6	0.6	0.6	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
	Sdev	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
	MinObs	0.2	0.2	0.1	0.1	0.1	0.1	0.2	0.3	0.1	0.2	0.2	0.1	0.1
	MaxObs	1.0	1.0	1.0	1.0	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Daily Wind Speed m/sec	Mean	9.1	9.5	10.6	11.1	9.9	9.7	8.9	8.4	8.9	9.1	9.1	9.2	9.5
	Sdev	2.8	3.1	3.5	4.1	4.0	3.8	3.3	3.8	3.8	3.9	3.2	2.8	3.6
	MinObs	2.4	2.1	3.2	1.2	0.3	0.1	0.1	0.5	1.0	0.8	0.1	2.3	0.1
	MaxObs	26.3	25.5	25.2	30.7	27.4	31.3	28.6	75.5	27.3	33.3	26.2	22.1	75.5
Daily Solar Rad. Wats/m^2	Mean	10.8	13.7	17.8	24.5	26.4	25.4	22.2	19.3	15.2	11.6	9.9	18.3	22.2
	Sdev	3.0	4.2	5.5	6.5	5.2	4.9	5.0	4.6	4.4	3.3	3.0	7.4	6.1
	MinObs	1.3	1.3	1.8	2.0	3.1	3.4	4.2	2.3	1.1	1.2	0.5	0.5	2.3
	MaxObs	15.8	21.1	26.1	33.4	32.7	32.1	30.1	26.4	21.7	17.1	20.2	33.4	31.3

Simulated Yields

In this section, the Environmental Policy Impact Calculator (EPIC) yield responses using historical 50-year daily weather data at Goodwell are compared with experimental results from the Oklahoma Panhandle, Southwest Kansas, and the Texas Panhandle. The EPIC simulated yields were averaged over the 50 year weather period (1965-2014). The planting date and the harvesting date for both corn and grain sorghum was held constant for each year. For grain sorghum, the previous studies and experiments from Bushland, Texas, Goodwell, Oklahoma, Guymon, Oklahoma, Tribune, Kansas, and Garden City, Kansas suggests that the reasonable planting date (end of May or Beginning of June) is May 28, and harvested (end of October) on October 31. The plant population for corn and sorghum was 52,000 plants ac^{-1} and 32,000 plants ac^{-1} respectively, also held constant each year. The corn and grain sorghum yields under the center pivot were obtained from the EPIC simulations results where a 36 mm application could be applied any time after the minimum number of days since the previous application if the soil moisture was also below an irrigation stress level. The irrigation triggers (1- stress level) were .9, .8, .7, .6, .5, .4, and .3. The purpose of the irrigation triggers was to test if less than full irrigation would be profitable in the long run. The minimum days between irrigations for each size of well and the application levels when an irrigation did occur are shown in Table 2.

Table 2. Center Pivot System Irrigation Frequency and Application Rates

Well Capacity	**Frequency**		
GPM	**DAYS**	**inches**	**mm**
800	4	1.42	36.00
700	5	1.42	36.00
600	6	1.42	36.00
500	7	1.42	36.00
400	8	1.42	36.00
300	11	1.42	36.00
200	16	1.42	36.00
100	32	1.42	36.00

The subsurface drip was simulated under the assumption of a constant amount per acre being applied every day if the water depletion level was below the allowable limit. The amount per day was determined by spreading the output per well across fields of 50, 75, 100, 125, or 150 acres. As field size is increased, the amount applied per day declines. The yields can be expected to decline with an increase in field size. The amounts applied per day are shown in Table 3.

Table 3. Subsurface Drip System Irrigation Frequency and Application Rates

	Field Size	Maximum Daily Application									
		50 acres		75 acres		100 acres		125 acres		150 acre	
GPM	**DAYS to apply**	**inches**	**mm**	**inches**	**mm**	**inches**	**mm**	**inches**	**mm**	**inches**	**mm**
800	1	0.87	22	0.59	15	0.43	11	0.35	9	0.31	8
700	1	0.75	19	0.51	13	0.39	10	0.31	8	0.28	7
600	1	0.67	17	0.43	11	0.35	9	0.28	7	0.24	6
500	1	0.55	14	0.35	9	0.28	7	0.24	6	0.20	5
400	1	0.43	11	0.31	8	0.24	6	0.20	5	0.16	4
300	1	0.35	9	0.24	6	0.16	4	0.16	4	0.12	3
200	1	0.24	6	0.16	4	0.12	3	0.12	3	0.08	2
100	1	0.12	3	0.08	2	0.08	2	0.08	2	0.04	1

Results of Yield Simulation for Center Pivot System (CPS):

Actual irrigation research experiments with current corn and grain sorghum varieties are limited to a few locations over relatively short time periods. For the Panhandle research and extension site, this period was 2005-2014. Weather occurring during the 2005-2014 period will not have the same mean and variability as might be expected over the next 50 years. The purpose of the simulation was to extend and estimate yields of irrigated corn and grain sorghum that would occur under weather patterns of the past 50 years in the Oklahoma Panhandle counties and under irrigation levels not directly tested by budget limited experiments. The 50 year mean yields and irrigation water use by irrigated corn and grain sorghum using CPS are shown respectively in Tables 4 and 5 below. Mean yields of irrigated grain sorghum varied from 162.8 bushels (800 GPM well, irrigation trigger of .9) to 87.5 bushels per acre (100 GPM well, irrigation trigger of .3). The respective average annual irrigation amounts varied from 15.6 to 2.2 acre inches. It must be remembered that the yields present a static annual view but producers face a dynamic situation as the water table, and consequently the well capacity, declines annually.

Table 4. Results from EPIC Simulation of Irrigated Sorghum Yields and Irrigation rates Using Center Pivot System on a 120 acre Quarter Section

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**	**0.30**	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**
800	122.1	124.9	129.0	138.6	148.7	156.5	162.8	8.3	8.6	9.2	9.2	12.6	14.2	15.6
700	122.4	125.3	129.1	137.3	145.3	150.9	155.7	8.2	8.5	9.1	10.3	11.8	13.0	14.1
600	122.3	125.2	128.5	134.0	139.6	144.6	148.4	8.2	8.5	9.0	10.0	10.7	11.9	12.6
500	120.5	123.5	126.0	129.6	134.1	137.5	141.1	8.0	8.3	8.8	9.3	9.8	10.8	11.3
400	116.9	119.7	122.4	124.6	128.6	131.4	133.8	7.7	8.0	8.3	8.6	9.4	9.9	10.4
300	104.8	107.0	108.7	110.4	112.3	115.0	117.2	6.5	6.8	7.1	7.3	7.6	7.8	8.3
200	88.4	89.1	89.6	90.1	90.5	91.1	92.0	2.9	3.1	3.2	3.3	3.4	3.6	4.1
100	87.5	87.8	87.9	88.1	88.2	88.3	88.5	2.2	2.3	2.4	2.4	2.5	2.6	2.8

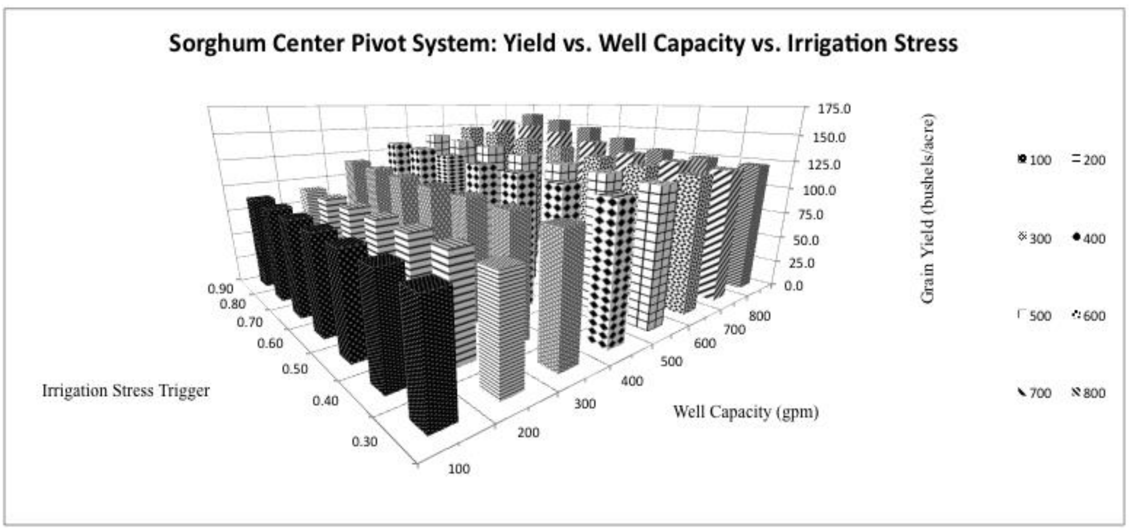


Figure 6. Simulated EPIC Grain Sorghum Yields with a 120 Acre Center Pivot Irrigation by Well Capacity when Irrigation Occurs if Soil Moisture Level Reach Specified Levels

The 50 year mean irrigated corn yields simulated by EPIC varied from 213.4 bushels (800 GPM well and a .9 irrigation trigger) to 96.8 bushels simulated with a 100 GPM well and a .3 irrigation trigger. With low GPM wells, the irrigation trigger had little effect with the center pivot simulation because the moisture level was usually below the trigger by the time the pivot could complete the revolution. That is the pivot system was usually in motion.

Table 5. Results from EPIC Simulation of Irrigated Corn Yields and Irrigation rates Using Center Pivot System on a 120 acre quarter section

	Irrigation Trigger													
GPM	**Yields (bushels/acre)**							**Gross Irrigation (acre-inches)**						
	0.30	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**	**0.30**	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**
800	159.3	163.4	166.9	180.8	193.9	206.3	213.4	14.6	15.3	16.2	18.8	21.5	22.5	22.5
700	158.4	161.9	165.1	176.0	186.3	194.6	198.9	14.6	15.3	16.1	18.0	20.4	22.1	23.1
600	156.9	159.8	163.0	170.7	177.2	182.9	186.9	14.6	15.0	15.9	17.2	19.0	20.4	21.6
500	153.8	156.1	158.3	162.2	168.4	172.4	175.0	14.1	14.6	15.3	16.0	17.4	18.6	19.5
400	148.5	150.1	152.1	154.7	157.7	161.2	164.4	13.5	13.9	14.4	15.0	15.9	17.0	17.6
300	133.7	134.9	136.9	138.4	139.3	141.2	142.6	11.0	11.3	11.8	12.3	12.8	13.4	13.9
200	117.5	117.7	118.9	119.2	120.1	121.2	122.2	8.7	8.8	9.1	9.4	9.7	10.1	10.3
100	96.8	97.7	98.1	98.1	98.4	98.9	99.1	5.4	5.5	5.7	5.8	5.9	6.0	6.1

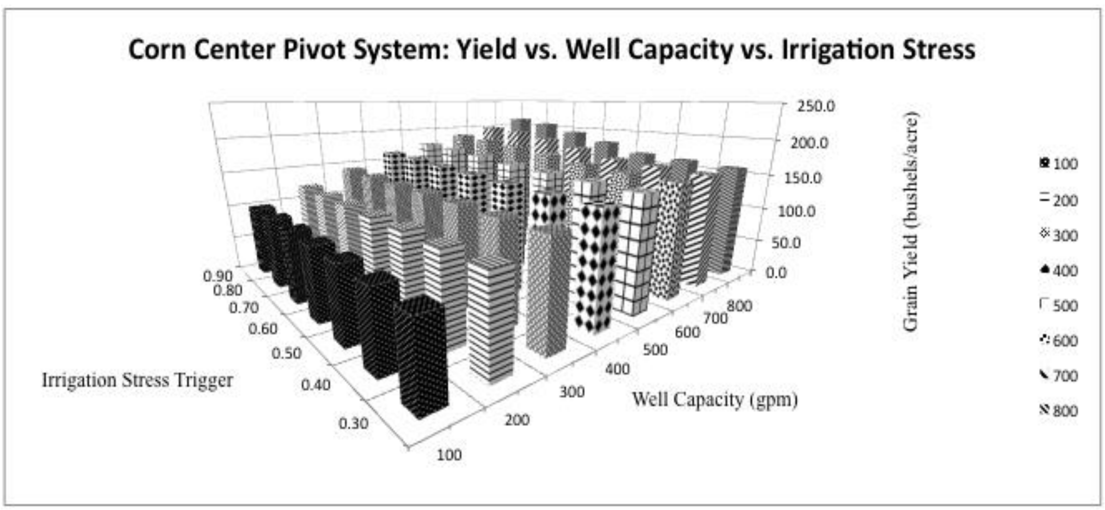


Figure 7. Simulated EPIC Corn Yields with 120 Acre Center Pivot Irrigation by Well Capacity when Irrigation occurs when Soil Moisture Levels fall below the Indicated levels.

Comparison of Simulated Yields and Water Use with Existing Experimental and Variety Trial Results

The general objective of variety trials is often to compare maximum yields among varieties. The averages of irrigated variety trials conducted at Goodwell, Oklahoma, Hereford, Texas, and Garden City, Kansas were used to check the simulated full irrigation yields of corn and grain sorghum. This was done by comparing the EPIC yields for the specific years when variety trials were conducted at the various locations. Variety trial results were available at Goodwell from 2005 through 2014. In Figure 8 below, the EPIC yields for each year from 2005-2014 are compared with the variety trial yields for those years. The simulated yields assume continuous irrigated production whereas crop rotations are often involved with the variety trials. The EPIC simulated corn yields followed the variety trial results reasonably well and caught the 2011 downturn but not the 2014 decline.

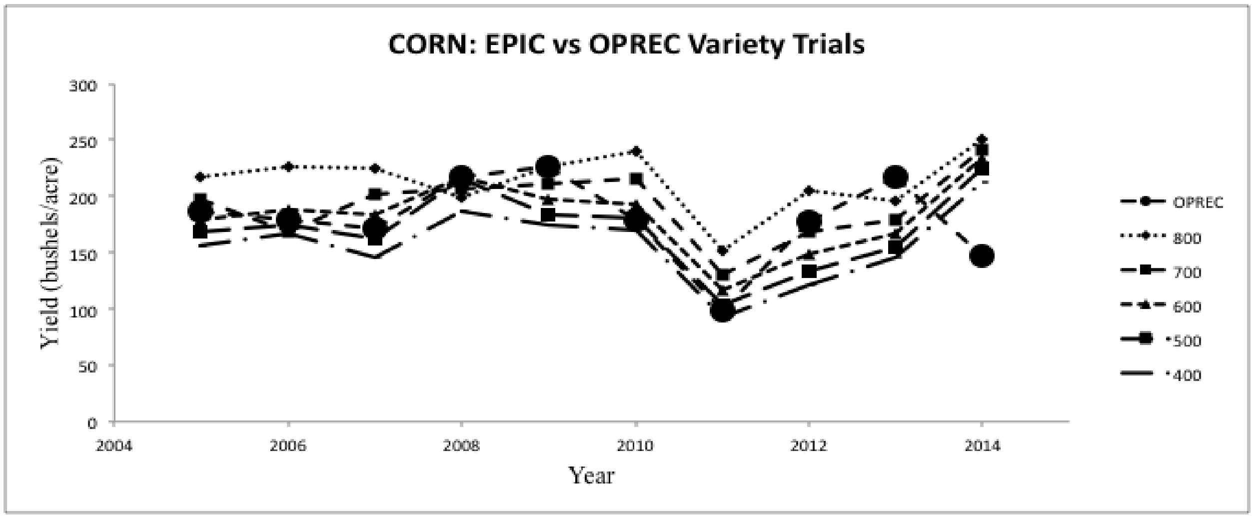


Figure 8. Results from EPIC corn simulation full irrigation comparing with OPREC Variety Trials

The simulated sorghum yields miss the downturn in 2011 but match the upturn in sorghum yields in 2013 and 2014. There are items related to planting dates and soil moisture conditions involved in the trial that cannot readily be simulated.

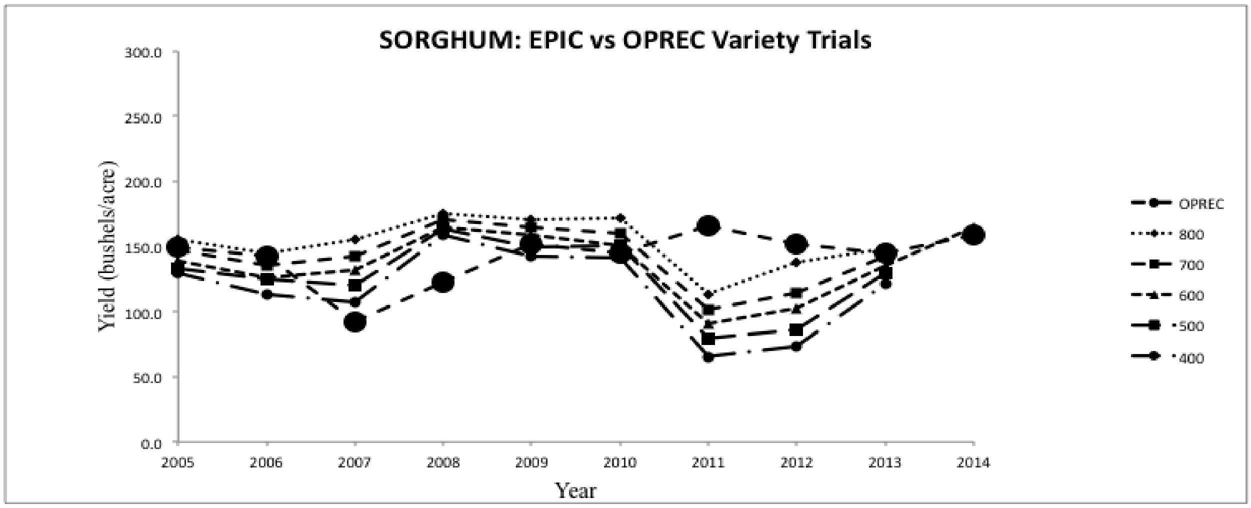


Figure 9. Results from EPIC sorghum simulation full irrigation comparing with OPREC Variety Trials

Water Use Efficiency

The simulated full (.9 trigger) yields and irrigation quantities by well capacity for corn and sorghum are shown below in Figure 10. As expected the corn yields and irrigation requirements for corn are greater than for sorghum.

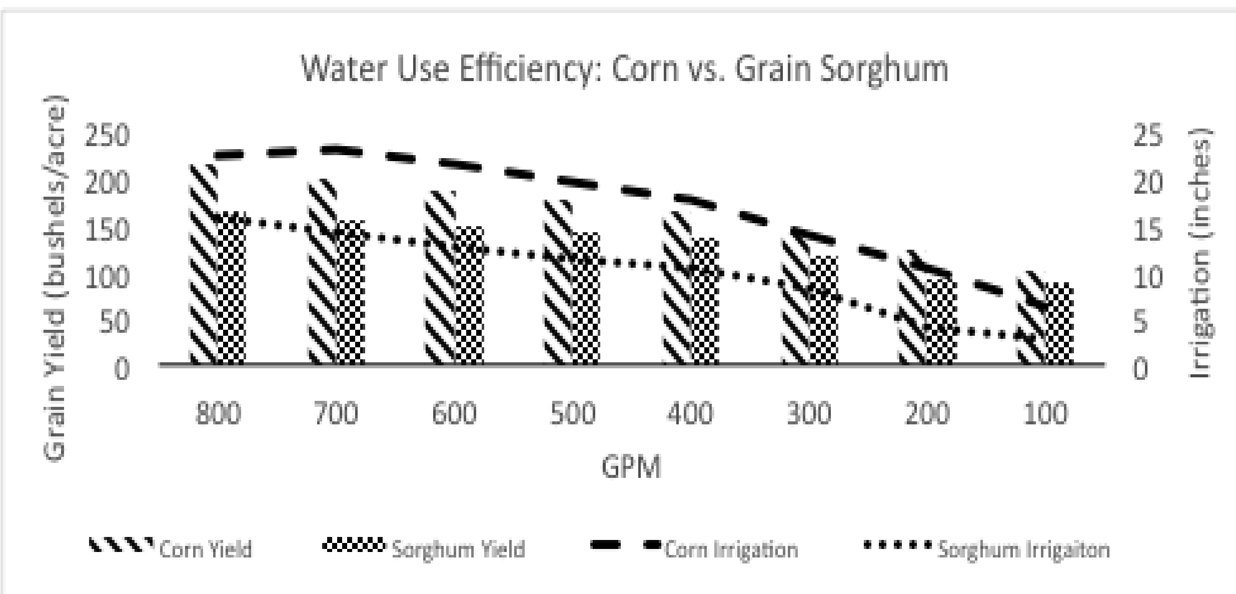


Figure 10. Results from EPIC Corn and Sorghum simulation full irrigation showing its water use efficiency.

The relative grain sorghum yields with irrigation plus rainfall from the simulation are compared with similar results in Garden City, Kansas (Figure 11a) and with an experiment at

Bushland, Texas (Figure 11b) below. The EPIC simulated yields are below those at Garden City where it is assumed there would less evapotranspiration than at Goodwell but approximately equal to those at Bushland where the expected transpiration would be somewhat higher than for Goodwell.

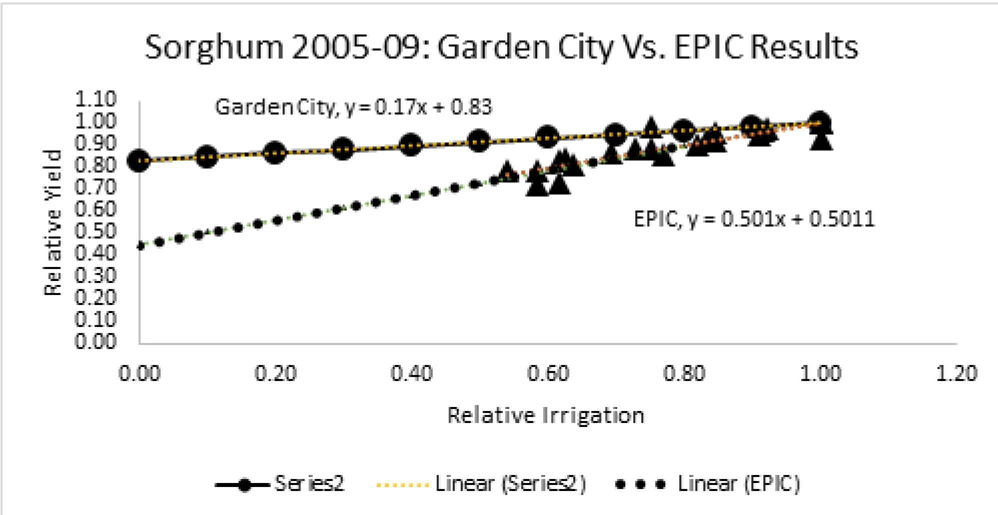


Figure 11a. Results from EPIC Sorghum Simulation as compared to Experimental Data from Garden City, Kansas

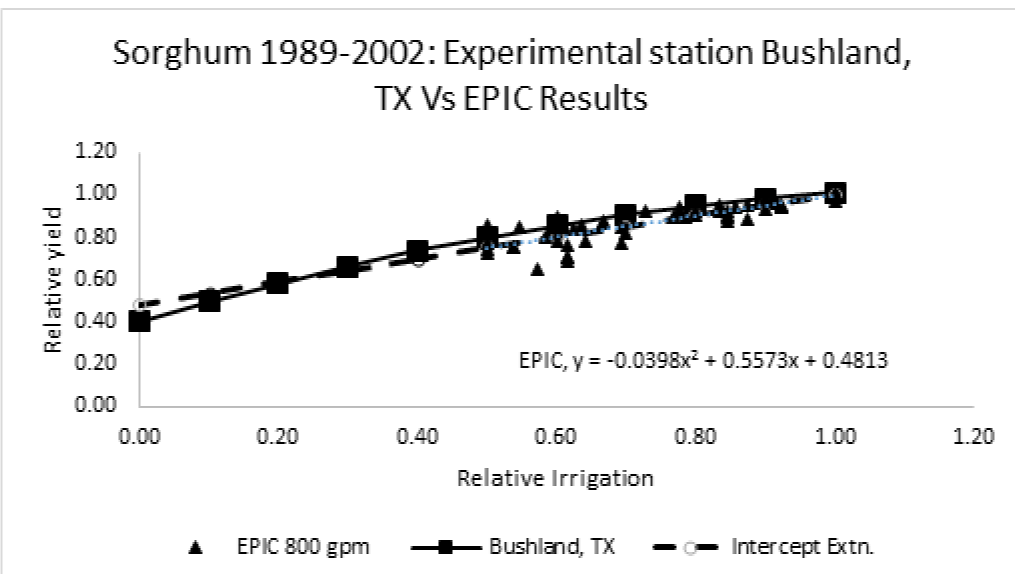


Figure 11b. Results from EPIC Sorghum Simulation as compared to Experimental Data from Bushland, Texas.

SUBSURFACE DRIP SIMULATION RESULTS

Simulations of Subsurface Drip Irrigated Grain Sorghum

There are large economies of size with the center pivot system so only one size was simulated. There are economies of size with the subsurface drip system but of a smaller magnitude than with the pivot system, thus the producer is more likely to consider the capacity of the well in selecting the size of the area to be irrigated by a subsurface drip system. Field sizes of 50, 75, 100, 125, and 150 acres were assumed. The EPIC simulations were based on the assumption of a constant amount per day per acre if soil moisture was below the irrigation trigger. As the field size covered by a given well is increased, the amount applied per day declines. The highest yields would be expected from the smaller fields.

The average simulated yields and average annual water use are shown in Tables 5 to 9 below. The simulated subsurface irrigated corn yields varied from 222.9 bushels (slightly higher than with the pivot) for the fifty acre field with an 800 GPM well down to 93.3 bushels for the 150 acre field with a 100 GPM well and a .3 irrigation trigger. Again the irrigation trigger had little effect when well capacity dropped below 300 GPM because the field moisture was usually below the trigger level.

Table 6. Results from EPIC Simulation of Irrigated Sorghum Yields and Irrigation Rates Using a Subsurface System on a 50 Acre field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	141.3	144.7	149.4	154.1	158.0	163.4	172.1	9.3	9.8	10.4	11.3	11.9	12.9	14.9
700	137.1	142.0	146.6	151.1	155.6	162.6	170.7	8.6	9.2	9.8	10.6	11.2	12.6	14.3
600	134.3	139.8	144.5	149.4	154.5	161.2	168.7	8.1	8.8	9.4	10.2	10.9	12.1	13.7
500	129.3	134.4	141.4	145.3	150.4	156.6	166.4	7.3	8.0	8.8	9.3	10.1	11.2	13.1
400	122.8	128.6	134.0	138.8	142.9	149.5	168.3	6.4	7.1	7.7	8.3	8.9	9.9	13.2
300	115.6	121.1	125.7	130.7	137.1	150.6	166.6	5.7	6.2	6.7	7.2	8.0	9.9	12.7
200	89.3	91.0	92.2	93.6	95.5	97.9	100.9	1.4	1.7	2.0	2.2	2.7	3.2	4.1
100	87.1	88.5	90.5	92.3	93.7	95.1	96.6	0.9	1.1	1.5	1.8	2.1	2.5	2.9

Table 7. Results from EPIC Simulation of Irrigated Sorghum Yields and Irrigation Rates Using a Subsurface System on a 75 Acre field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	131.6	136.5	142.2	147.2	151.9	158.5	166.1	7.6	8.3	9.0	9.7	10.4	11.5	13.0
700	128.2	133.7	138.6	143.4	148.6	154.1	167.8	7.1	7.8	8.3	9.0	9.8	10.7	13.2
600	122.8	128.6	134.0	138.8	142.9	149.5	168.3	6.4	7.1	7.7	8.3	8.9	9.9	13.2
500	115.6	121.1	125.7	130.7	137.1	150.6	166.6	5.7	6.2	6.7	7.2	8.0	9.9	12.7
400	110.2	115.8	120.8	127.6	136.8	152.9	164.5	5.2	5.7	6.2	6.8	7.9	10.1	12.1
300	96.7	103.1	112.7	124.8	137.7	147.4	155.2	4.1	4.6	5.3	6.4	7.7	9.0	10.3
200	87.9	89.3	90.8	92.8	94.9	96.9	99.1	1.1	1.3	1.6	2.0	2.4	2.9	3.6
100	86.4	88.1	89.4	90.3	91.1	91.9	93.0	0.7	1.0	1.2	1.4	1.6	1.8	2.1

Table 8. Results from EPIC Simulation of Irrigated Sorghum Yields and Irrigation Rates Using a Subsurface System on a 100 Acre Field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	122.8	128.6	134.0	138.8	142.9	149.5	168.3	6.4	7.1	7.7	8.3	8.9	9.9	13.2
700	119.9	125.2	130.3	135.0	140.0	149.2	167.8	6.1	6.7	7.2	7.8	8.4	9.7	13.0
600	115.6	121.1	125.7	130.7	137.1	150.6	166.6	5.7	6.2	6.7	7.2	8.0	9.9	12.7
500	104.3	109.5	116.2	124.7	137.9	150.7	161.0	4.7	5.1	5.7	6.5	7.9	9.7	11.4
400	96.7	103.1	112.7	124.8	137.7	147.4	155.2	4.1	4.6	5.3	6.4	7.7	9.0	10.3
300	83.4	95.9	108.8	118.1	124.5	130.1	135.4	3.1	3.9	4.8	5.6	6.2	6.8	7.6
200	87.1	88.5	90.5	92.3	93.7	95.1	96.6	0.9	1.1	1.5	1.8	2.1	2.5	2.9
100	86.4	88.1	89.4	90.3	91.1	91.9	93.0	0.7	1.0	1.2	1.4	1.6	1.8	2.1

Table 9. Results from EPIC Simulation of Irrigated Sorghum Yields and Irrigation Rates Using a Subsurface System on a 125 Acre Field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	115.6	121.1	125.7	130.7	137.1	150.6	166.6	5.7	6.2	6.7	7.2	8.0	9.9	12.7
700	110.2	115.8	120.8	127.6	136.8	152.9	164.5	5.2	5.7	6.2	6.8	7.9	10.1	12.1
600	104.3	109.5	116.2	124.7	137.9	150.7	161.0	4.7	5.1	5.7	6.5	7.9	9.7	11.4
500	96.7	103.1	112.7	124.8	137.7	147.4	155.2	4.1	4.6	5.3	6.4	7.7	9.0	10.3
400	89.5	98.4	111.0	124.1	133.7	140.8	147.0	3.6	4.1	5.1	6.2	7.2	8.1	9.0
300	83.4	95.9	108.8	118.1	124.5	130.1	135.4	3.1	3.9	4.8	5.6	6.2	6.8	7.6
200	87.1	88.5	90.5	92.3	93.7	95.1	96.6	0.9	1.1	1.5	1.8	2.1	2.5	2.9
100	86.4	88.1	89.4	90.3	91.1	91.9	93.0	0.7	1.0	1.2	1.4	1.6	1.8	2.1

Table 10. Results from EPIC Simulation of Irrigated Sorghum Yields and Irrigation Rates Using a Subsurface System on a 150 Acre Field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	110.2	115.8	120.8	127.6	136.8	152.9	164.5	5.2	5.7	6.2	6.8	7.9	10.1	12.1
700	104.3	109.5	116.2	124.7	137.9	150.7	161.0	4.7	5.1	5.7	6.5	7.9	9.7	11.4
600	96.7	103.1	112.7	124.8	137.7	147.4	155.2	4.1	4.6	5.3	6.4	7.7	9.0	10.3
500	89.5	98.4	111.0	124.1	133.7	140.8	147.0	3.6	4.1	5.1	6.2	7.2	8.1	9.0
400	83.4	95.9	108.8	118.1	124.5	130.1	135.4	3.1	3.9	4.8	5.6	6.2	6.8	7.6
300	80.3	91.0	99.8	104.9	109.6	114.7	119.1	2.8	3.5	4.1	4.5	4.9	5.4	5.9
200	86.4	88.1	89.4	90.3	91.1	91.9	93.0	0.7	1.0	1.2	1.4	1.6	1.8	2.1
100	85.2	85.7	86.2	86.6	87.0	87.5	88.2	0.5	0.6	0.7	0.8	0.9	1.0	1.1

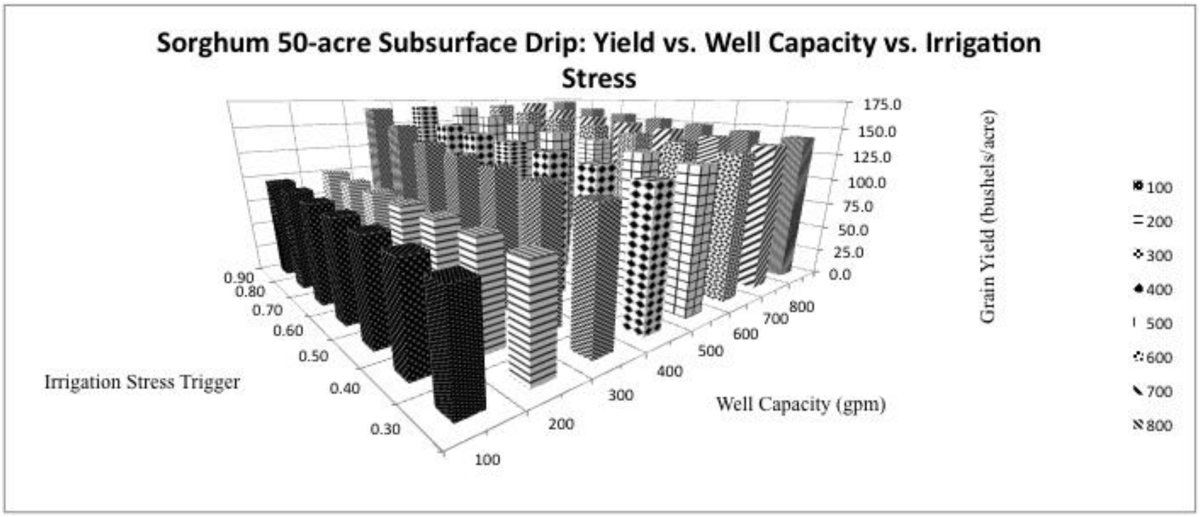


Figure 12. Results from EPIC Sorghum Subsurface Simulation showing Yields and Irrigation along with the Well Capacity for a 50 Acre Field.

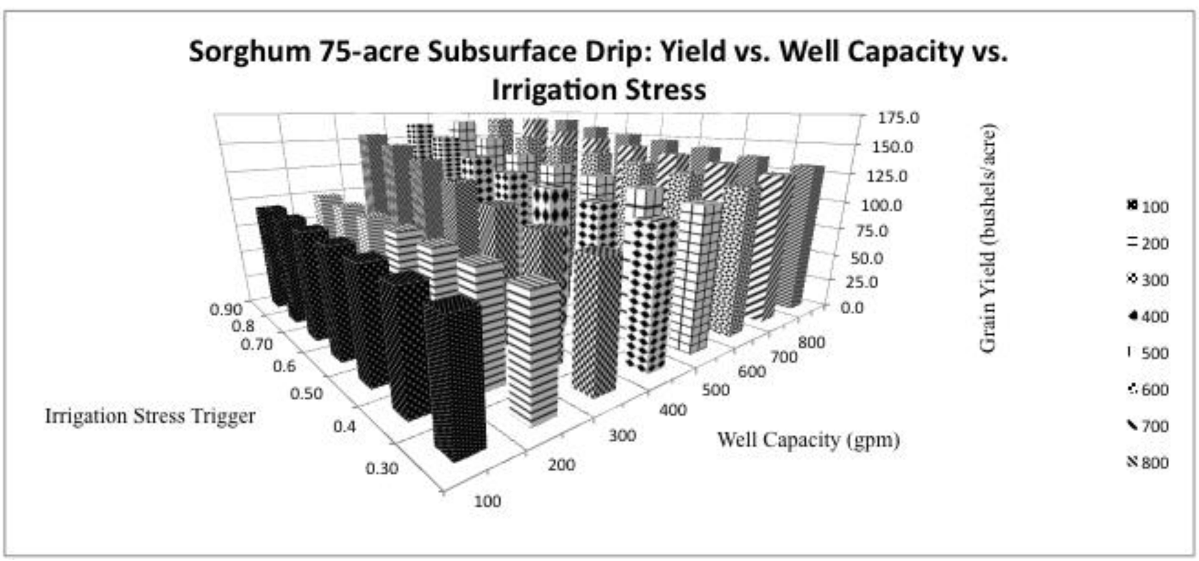


Figure 13. Results from EPIC Sorghum Subsurface Simulation showing Yields and Irrigation along with the Well Capacity for a 75 Acre Field.

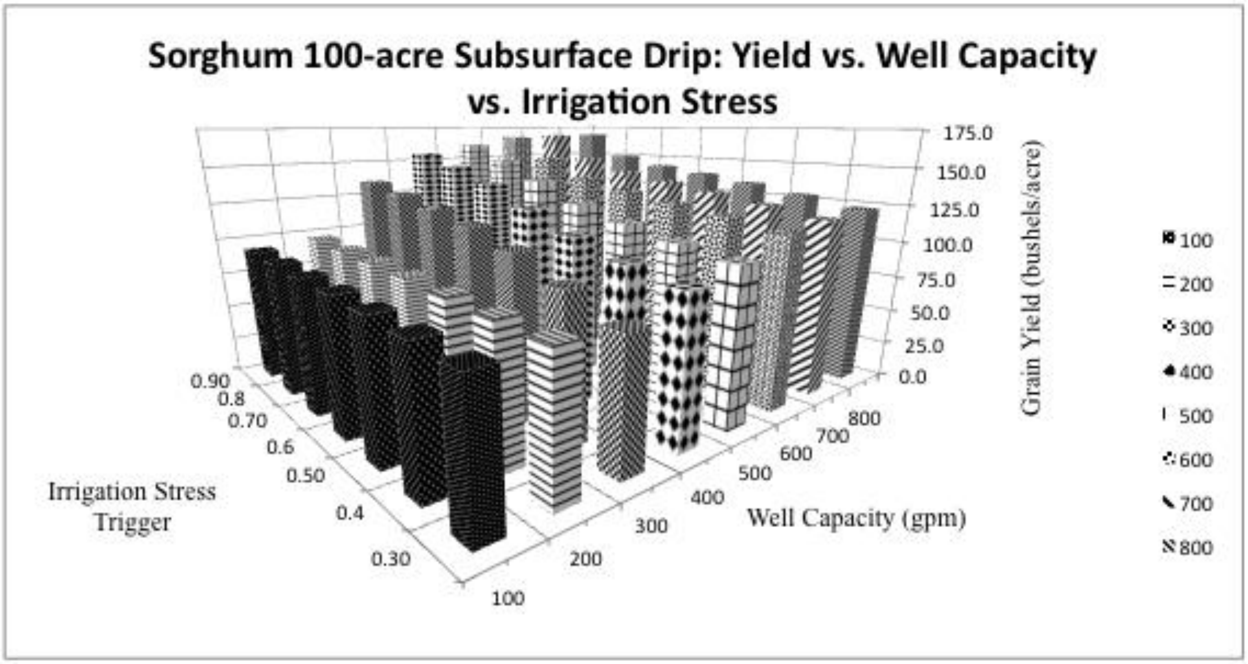


Figure 14. Results from EPIC Sorghum Subsurface Simulation showing Yields and Irrigation along with the Well Capacity for a 100 Acre Field.

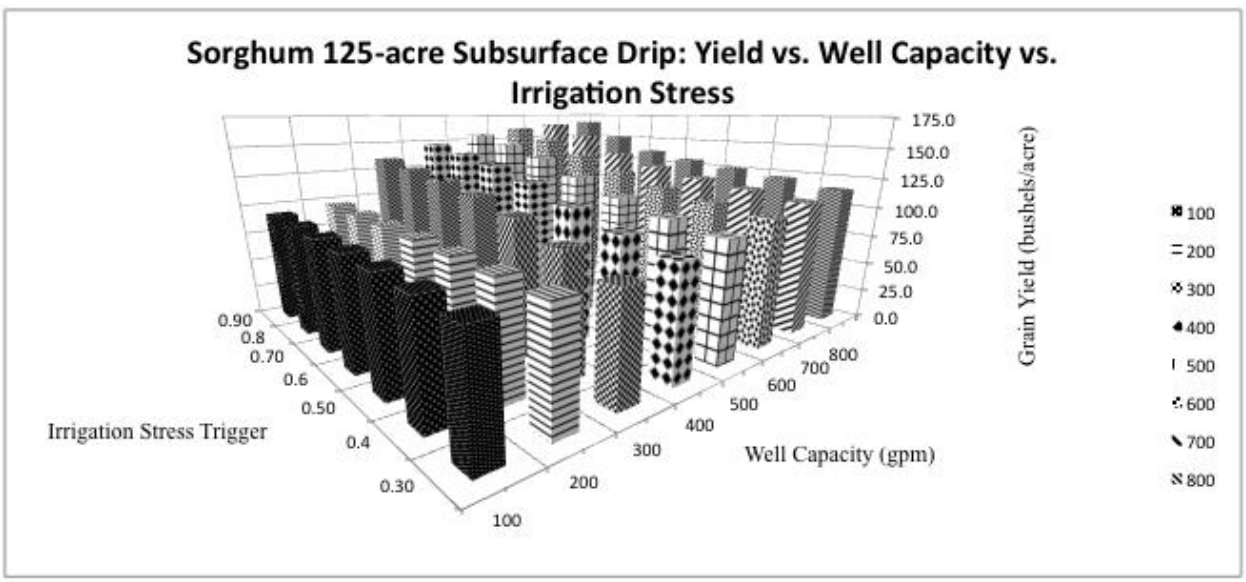


Figure 15. Results from EPIC Sorghum Subsurface Simulation showing Yields and Irrigation along with the Well Capacity for a 125 Acre field.

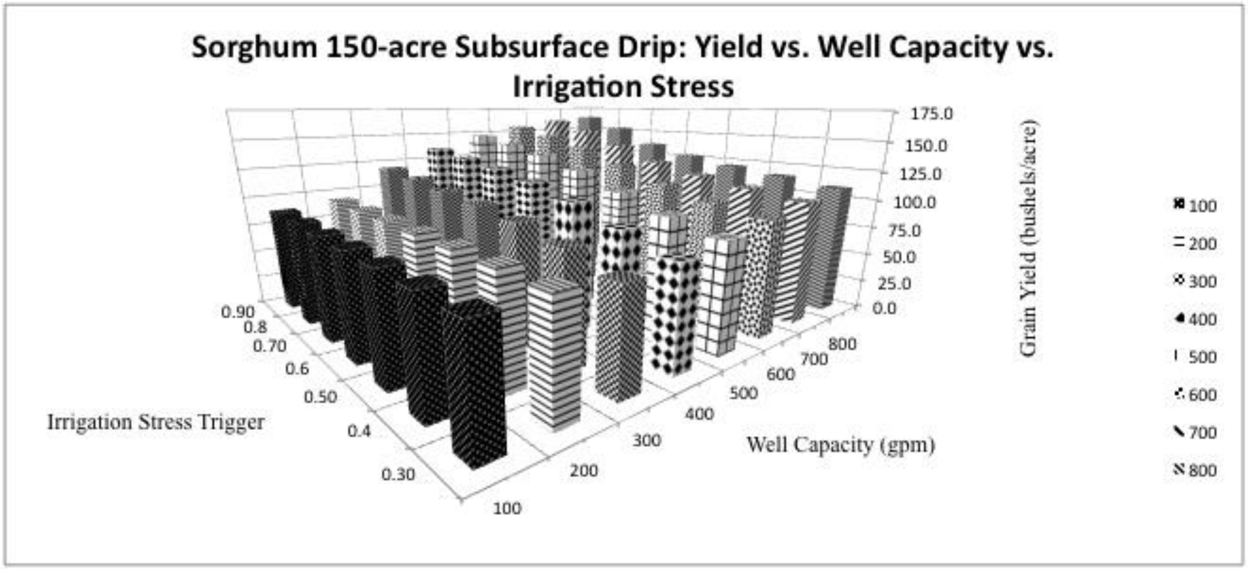


Figure 16. Results from EPIC Sorghum Subsurface Simulation showing Yields and Irrigation along with the Well Capacity for a 150 Acre field.

Simulation of Drip Irrigated Corn

The same field sizes, daily application rates, and irrigation triggers that were used in simulating irrigated grain sorghum were used in simulating subsurface drip irrigated corn. The simulated yields ranged from 222.9 bushels for the 50 acre field with an 800 GPM well, (.9 irrigation trigger) to 93.9 bushels per acre for the 150 acre field with a 100 GPM well (.3 irrigation trigger). The respective gross per acre application rates varied from 26.8 acre inches to 2.4 acre inches. The respective maximum CP yields and water use for the 120 acre pivot were 213.4 bushes and 22.5 acre inches. The maximum yield and related water use for the 125 acre drip field were 214.9 and 22.6 acre inches.

Table 11. Results from EPIC Simulation of Irrigated Corn Yields and Irrigation rates using a Subsurface Drip System on a 50 acre field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.40**	**0.50**	**0.60**	**0.70**	**0.80**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	179.6	184.9	190.7	196.1	201.5	209.4	222.9	17.1	18.1	19.3	20.3	21.7	23.5	26.8
700	174.3	179.9	185.2	191.2	197.0	205.6	218.5	16.0	17.0	18.1	19.2	20.5	22.4	25.6
600	169.8	175.0	181.0	186.8	192.9	202.2	213.0	15.1	16.1	17.3	18.3	19.7	21.7	24.4
500	161.8	167.0	173.6	179.0	185.9	193.6	210.0	13.6	14.6	15.8	16.7	18.1	19.8	23.7
400	152.3	157.6	162.7	168.6	174.5	182.3	208.4	11.8	12.8	13.6	14.7	15.9	17.5	23.2
300	143.3	147.4	152.6	158.0	164.9	182.7	202.3	10.3	11.0	12.0	12.9	14.3	17.7	22.0
200	125.4	130.2	137.8	149.0	162.7	173.2	182.0	7.4	8.2	9.5	11.3	13.6	15.6	17.6
100	110.4	119.0	125.5	129.7	133.4	137.2	140.6	5.1	6.3	7.2	7.8	8.4	9.0	9.8

Table 12. Results from EPIC Simulation of Irrigated Corn Yields and Irrigation rates using a Subsurface Drip System on a 75 acre field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	168.2	173.9	180.3	186.1	193.2	201.7	214.3	14.2	15.3	16.5	17.6	18.9	20.7	23.7
700	162.6	168.8	174.3	180.4	186.8	194.3	216.2	13.2	14.2	15.3	16.3	17.6	19.2	24.1
600	156.0	161.3	166.4	172.8	178.9	187.1	214.2	12.0	12.9	13.8	14.9	16.1	17.8	23.6
500	147.4	151.5	157.0	162.7	169.8	188.4	208.9	10.5	11.1	12.1	13.1	14.5	18.0	22.3
400	141.0	144.8	150.1	157.1	166.3	186.9	202.4	9.5	10.1	11.1	12.3	12.8	17.8	21.2
300	127.8	132.8	140.5	152.3	165.9	177.1	185.9	7.4	8.3	9.6	11.5	13.7	15.7	17.7
200	115.3	124.4	135.6	143.4	150.0	154.7	159.5	5.7	7.0	8.6	9.7	10.8	11.7	12.7
100	105.4	110.0	112.5	115.1	117.6	120.0	122.1	4.2	4.8	5.1	5.5	5.9	6.3	6.7

Table 13. Results from EPIC Simulation of Irrigated Corn Yields and Irrigation rates using a Subsurface Drip System on a 100 acre field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	158.3	164.0	169.2	175.6	181.6	190.0	217.9	12.1	13.0	13.9	15.0	16.2	17.9	23.8
700	153.7	159.2	164.3	169.9	176.3	188.0	215.5	11.3	12.2	13.0	14.1	15.3	17.6	23.3
600	148.8	153.4	158.4	164.3	171.5	190.7	211.4	10.5	11.2	12.1	13.2	14.6	18.1	22.5
500	137.6	141.1	148.4	156.0	171.2	186.8	199.8	8.6	9.2	10.5	11.7	14.2	17.1	19.9
400	129.9	134.9	142.8	154.8	168.6	179.9	189.1	7.5	8.3	9.7	11.6	13.8	15.8	17.9
300	117.6	126.8	138.3	146.3	152.7	157.8	162.9	5.7	7.1	8.7	9.9	10.9	11.8	12.9
200	117.6	121.7	128.5	132.9	136.7	140.6	144.1	5.2	6.4	7.3	7.9	8.5	9.2	9.9
100	105.4	110.0	112.5	115.1	117.6	120.0	122.1	4.2	4.8	5.1	5.5	5.9	6.3	6.7

Table 14. Results from EPIC Simulation of Irrigated Corn Yields and Irrigation rates using a Subsurface Drip System on a 125 acre field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	150.9	156.1	161.1	167.0	174.5	193.9	214.9	10.5	11.4	12.2	13.3	14.7	18.2	22.6
700	145.5	149.8	154.9	162.0	173.4	193.3	209.8	9.7	10.3	11.3	12.5	14.5	18.0	21.5
600	138.8	142.6	150.1	157.8	173.0	188.8	202.1	8.6	9.3	10.5	11.8	14.3	17.2	20.0
500	131.5	136.4	144.7	156.9	171.1	182.3	191.7	7.5	8.3	9.7	11.6	13.9	15.9	18.0
400	124.1	130.9	141.2	154.7	164.1	171.9	178.7	6.5	7.6	9.2	11.2	12.7	14.1	15.6
300	117.6	126.8	138.3	146.3	152.7	157.8	162.9	5.7	7.1	8.7	9.9	10.9	11.8	12.9
200	112.9	121.7	128.5	132.9	136.7	140.6	144.1	5.2	6.4	7.3	7.9	8.5	9.2	9.9
100	105.4	110.0	112.5	115.1	117.6	120.0	122.1	4.2	4.8	5.1	5.5	5.9	6.3	6.7

Table 15. Results from EPIC Simulation of Irrigated Corn Yields and Irrigation Rates Using a Subsurface Drip System on a 150 acre field

	Yields (bushels/acre)							Gross Irrigation (acre-inches)						
	Stress Levels							Stress Levels						
GPM	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**	**0.30**	**0.4**	**0.50**	**0.6**	**0.70**	**0.8**	**0.90**
800	146.5	150.6	156.0	163.3	174.6	194.8	211.3	9.7	10.4	11.3	12.6	14.5	18.1	21.6
700	140.1	143.8	151.2	159.1	174.7	190.6	204.1	8.7	9.3	10.6	11.9	14.4	17.3	20.1
600	132.8	137.8	146.3	158.6	172.8	184.3	140.1	7.6	8.4	9.8	11.7	14.0	16.0	8.7
500	125.5	132.3	143.0	156.7	166.3	174.2	181.1	6.6	7.6	9.3	11.2	12.8	14.2	15.7
400	119.4	128.8	140.5	148.6	155.1	160.4	165.6	5.8	7.1	8.8	9.9	10.9	11.9	13.0
300	115.1	124.0	131.0	135.5	139.3	143.4	147.0	5.2	6.4	7.4	8.0	8.6	9.3	10.0
200	107.8	112.5	115.1	117.7	120.4	122.8	125.0	4.2	4.8	5.2	5.6	6.0	6.3	6.8
100	93.9	94.7	96.1	97.4	98.6	99.7	100.8	2.4	2.5	2.7	2.9	3.1	3.2	3.4

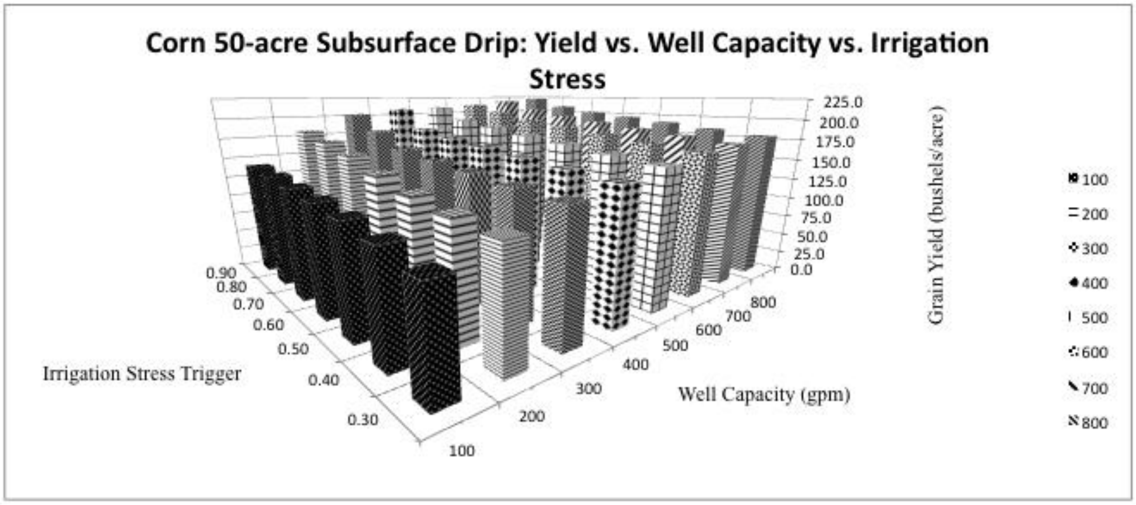


Figure 17. Results from EPIC Corn Subsurface Simulation showing Yields and Irrigation along the Well Capacity for a 50 Acre Field

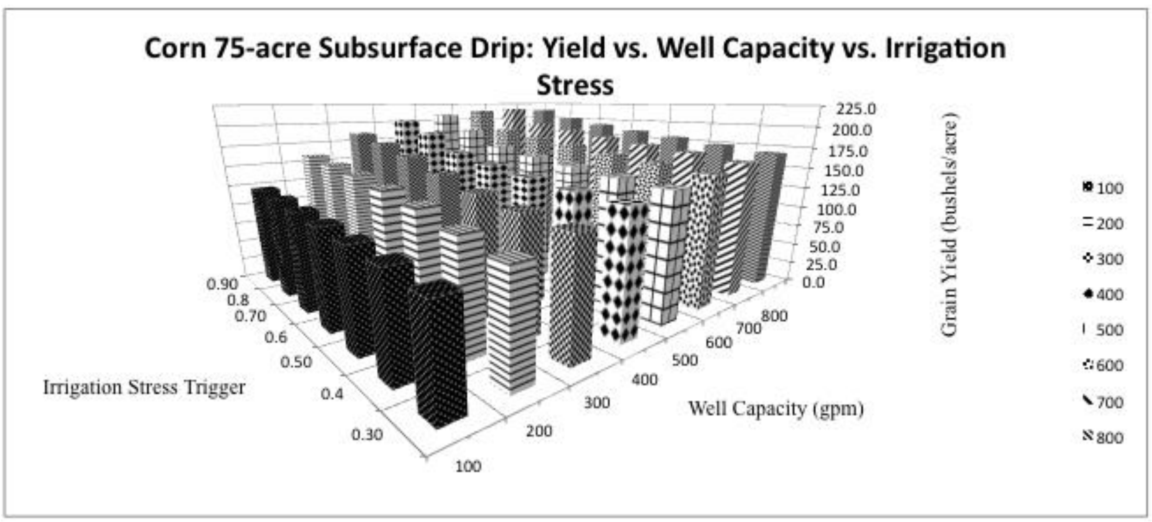


Figure 18. Results from EPIC Corn Subsurface Simulation showing Yields and Irrigation along the Well Capacity for a 75 Acre Field

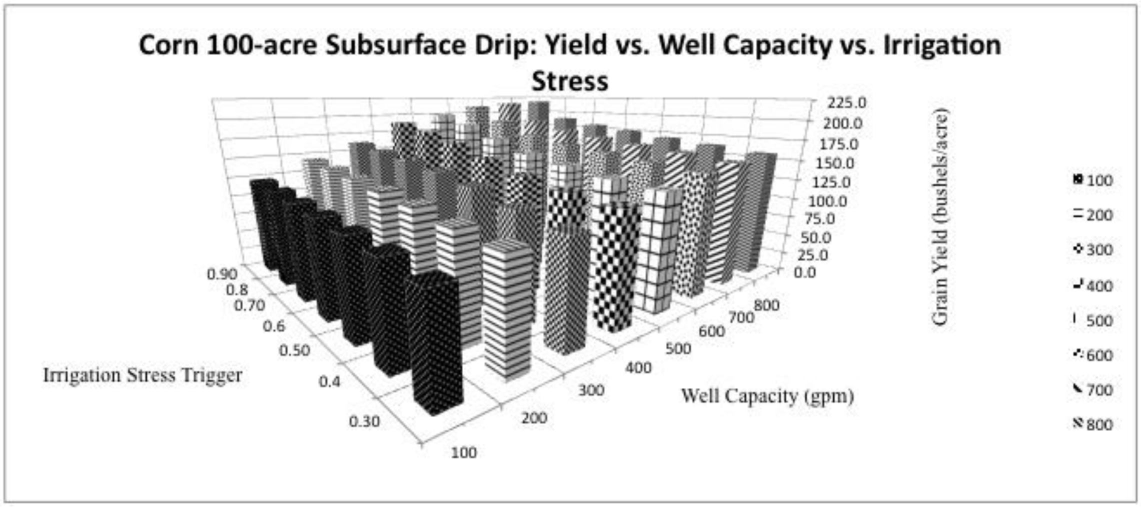


Figure 19. Simulated Yields Results from EPIC Corn Subsurface Simulation showing Yields and Irrigation along with the Well Capacity for a 100 Acre Field

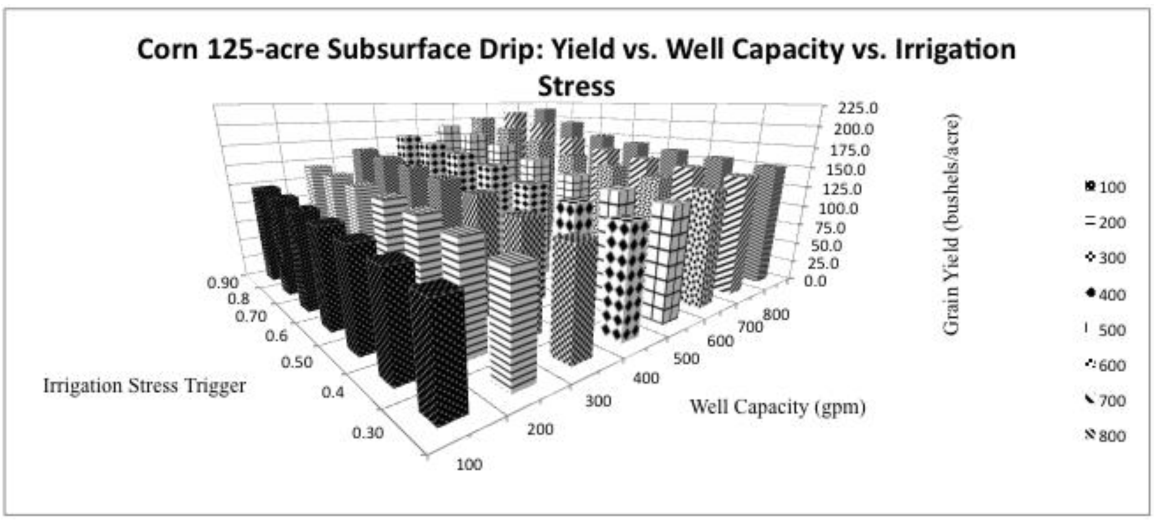


Figure 20. Results from EPIC Corn Subsurface Simulation showing Yields and Irrigation along the Well Capacity for a 125 Acre Field

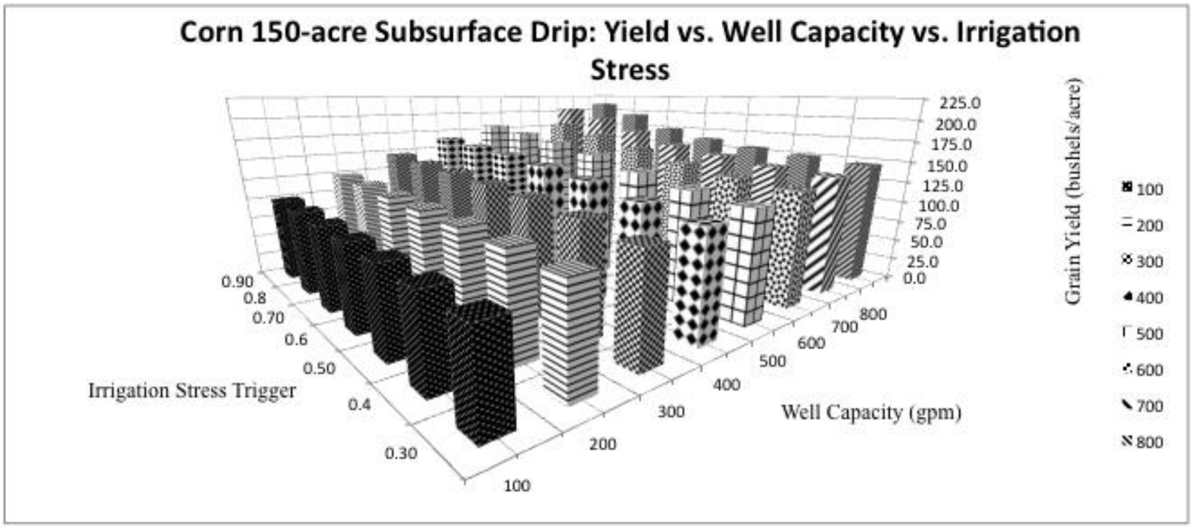


Figure 21. Results from EPIC Corn Subsurface Simulation showing yields and Irrigation along the Well Capacity for a 150 Acre Field.

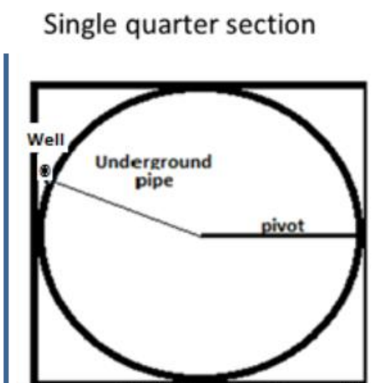


Figure 22. Illustration of a Single One-fourth Section with a 120 acre pivot

Static Budget Analysis

Pumping Cost:

Pumping cost for the case of a producer with a single 160 quarter section field with a 120 acre pivot irrigation system were based on the diagram in Figure 22. The well was assumed located outside the irrigated area.

It was assumed the maximum well capacity would be 800 GPM and that with 10 feet of drawn down per 100 GPM, the bowl height would be 5 feet, and the top of the safety zone would be 35 feet above the pump bowls. The static water table would be 140 feet above the base of

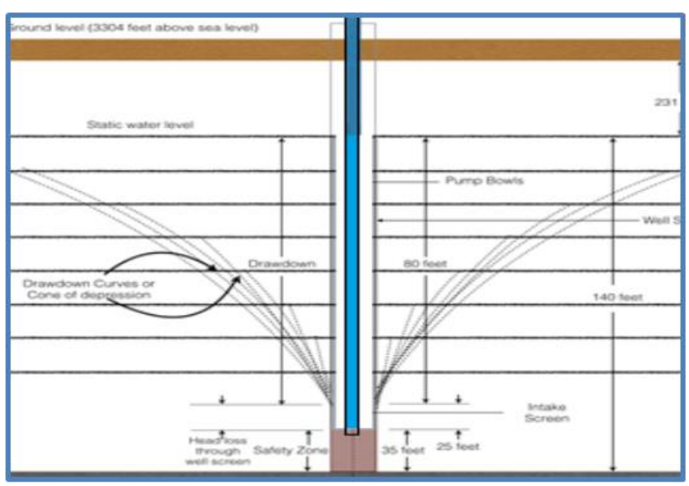


Figure 23. Illustration of well depth and water table level used in Pumping Cost Calculations

the aquifer. The land surface was assumed to be 200 feet above the 800 GPM water table.

Pumping cost calculations were based on the assumption of natural gas at $6 per thousand MCF. Pump efficiency was assumed to be 70 percent, the motor efficiency 17.7 percent, and the drive efficiency was 95 percent. The overall efficiency was 11.8 percent. The pressure at the pivot head was 35 PSI.

The cost of pumping an acre foot of water from each of the well sizes used in the Center Pivot Analysis are shown below in Table 15. It should be noted that because the bottom of the pumping draw down cone is always at the maximium depth (top of the safety zone), that the power required and cost decreases slightly as well capacity declines. This is because the total pumping height does not change. As the water table declines, the depth of the drawdown cone declines to match the increased height above the static water table. The water horse power (WHP) requirements decline with the water table because the volume of water being pumped each minute declines with the water table.

Table 16. Parameters used to Estimate the Cost of Pumping an Acre Foot of Water by Well Size for the Center Pivot Irrigation System.

Parameters and Pumping Costs used for Center Pivot							
800 GPM Well			700 GPM Well			600 GPM Well	
L8 S.W.T (ft)	200		L7 S.W.T. (ft)	210		L6 S.W.T. (ft)	220
Tot. Head (ft)	390		Tot. Head (ft)	381		Tot. Head (ft)	376
WHP	79		WHP	67		WHP	57
Cost/af	$ 69.46		Cost/af	$ 67.86		Cost/af	$ 66.97
500 GPM Well			400 GPM Well			300 GPM Well	
L5 S.W.T. (ft)	230		L4 S.W.T. (ft)	240		L3 S.W.T. (ft)	250
Tot. Head (ft)	372		Tot. Head (ft)	368		Tot. Head (ft)	365
WHP	47		WHP	37		WHP	28
Cost/af	$ 66.21		Cost/af	$ 65.53		Cost/af	$ 65.02
200 GPM Well			100 GPM Well				
L5 S.W.T. (ft)	260		L5 S.W.T. (ft)	270			
Tot. Head (ft)	363		Tot. Head (ft)	362			
WHP	18		WHP	9			
Cost/af	$ 64.71		Cost/af	$ 64.24			

Abbreviations used: S.W.T. is static water table, Tot. head is total dynamic head in feet, af is acre foot, WHP is water horse power.

Effect of System Choice on Pumping Cost and Annual Fixed Cost:

The first step in the economic analysis is the construction of standard static enterprise budgets for irrigated corn and sorghum with center pivot and subsurface drip irrigation. Static budgets are quite common but can also be deceiving in dynamic situations. In this study, the water table and well capacity are declining over time. Tables 17 and 18 provide estimates of returns over irrigation fixed costs for grain sorghum under CP and SDI. Similarly, Tables 19 and 20 provide estimates of returns over irrigation fixed costs for corn under CP and SDI. The budgets are based on the simulated crop yields and water use. The requirements for nitrogen and phosphorus are also given by the simulation model. The budgets assume the irrigation trigger is .9 or that the producer is essentially practicing full irrigation. The pivot and subsurface drip irrigation budgets are most closely comparable at the 120-125 acre sizes. At this size, the CP shows slightly lower profits per acre with the four dollar feed grain prices.

Table 17. Estimated Net Revenue over Variable Cost for Grain Sorghum Irrigated by Central Pivot when Irrigation Occurs with a 10 Percent or Greater Moisture Deficit by Well Capacity for a 120 Acre Pivot

Well Capacity	GPM	800	700	600	500	400	300	200	100
Yield	bu/ac	162.8	155.7	148.4	141.1	133.8	117.2	92.0	88.5
Nitrogen	lbs/ac	181.6	173.6	165.5	157.3	149.2	130.7	102.5	98.7
Phosphorous	lbs/ac	29.4	28.1	26.8	25.4	24.1	21.1	16.6	16.0
Irrigation	acre-inch	15.6	14.1	12.6	11.3	10.4	8.3	4.1	2.8
Net Revenue ($4.16/bu)	$	677.4	647.7	617.3	586.8	556.5	487.6	382.6	368.2
Fertilizer-Nitrogen	$	99.9	95.5	91.0	86.5	82.0	71.9	56.4	54.3
Fertilizer-Phosphorous	$	15.3	14.6	13.9	13.2	12.5	11.0	8.6	8.3
Seed Cost	$	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1
Herbicide Cost	$	52.4	52.4	52.4	52.4	52.4	52.4	52.4	52.4
Insecticide Cost	$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Crop Consulting	$	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
Drying	$	21.2	20.2	19.3	18.3	17.4	15.2	12.0	11.5
Miscelleneous	$	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Custom Hire	$	132.5	129.4	126.2	122.9	119.7	112.5	101.3	99.8
Non Machinery Labor	$	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Interest	$	15.7	15.1	14.4	13.8	13.1	11.7	9.5	9.2
Irrigation Cost	$	90.4	79.8	70.3	62.6	56.8	44.9	21.9	14.8
Sub Total	$	477.7	457.3	437.9	420.1	404.4	369.9	312.5	300.7
Crop Insurance	$	22.9	22.0	21.0	20.2	19.4	17.8	15.0	14.4
Total Varible Cost	$	500.6	479.3	458.9	440.3	423.8	387.7	327.5	315.1
Net Revenue-Var Cost	$	176.8	168.4	158.4	146.5	132.7	100.0	55.1	53.1
Annual System Cost[a]	$	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
Net Ret-system Cost	$	131.8	123.5	113.4	101.6	87.7	55.0	10.2	8.1

[a] Initial system cost of $60,000 over 15 years at four percent.

Table 18. Estimated net revenue over Irrigation Cost for Grain Sorghum Irrigated by Subsurface Drip if Irrigation Occurs with a Ten Percent or Greater Moisture Deficit by Well Capacity for a 125 Acre Field.

GPM		800	700	600	500	400	300	200	100
Yield (bu/acre)		166.6	164.5	161.0	155.2	147.0	135.4	96.6	93.0
N (lbs/a)		185.7	183.4	179.5	173.0	163.9	151.0	107.7	103.7
P (lbs/a)		30.0	29.7	29.0	28.0	26.5	24.4	17.4	16.8
Irrigation (inches)		12.7	12.1	11.4	10.3	9.0	7.6	2.9	2.1
Net Revenue ($4.48/bu)	$	693.0	684.3	669.7	645.4	611.6	563.3	401.9	387.0
Fertilizer-nitrogen	$	102.2	100.9	98.7	95.2	90.2	83.1	59.2	57.0
Fertilizer-phosphorus	$	15.6	15.4	15.1	14.6	13.8	12.7	9.1	8.7
Seed cost	$	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1
herbicide Cost	$	52.4	52.4	52.4	52.4	52.4	52.4	52.4	52.4
Insecticide Cost	$	-	-	-	-	-	-	-	-
Crop Consulting	$	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
Drying	$	21.7	21.4	20.9	20.2	19.1	17.6	12.6	12.1
Miscellaneous	$	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Custom Hire	$	134.2	133.3	131.7	129.2	125.6	120.5	103.4	101.8
Non Machinery Labor	$	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Interest	$	16.0	15.8	15.5	15.0	14.3	13.3	9.9	9.6
Irrigation Cost	$	66.7	62.3	57.6	51.6	44.7	30.7	14.2	10.1
Sub Total ($)	$	459.1	389.5	384.7	376.8	365.7	349.9	296.9	292.0
Crop Insurance	$	22.0	18.7	18.5	18.1	17.6	16.8	14.3	14.0
Total Variable Cost	$	481.1	473.6	463.6	449.0	430.1	398.9	326.0	316.6
Net Returns - Var. Cost	$	211.9	210.7	206.1	196.4	181.5	164.5	75.9	70.5
Annual System Cost* $/a	$	65.3	65.3	65.3	65.3	65.3	65.3	65.3	65.3
Net Returns - Syst. Cost	$	146.6	145.5	140.8	131.2	116.3	99.2	10.6	5.2

[a] Annual cost for 125 acre subsurface drip system costing 90,700 for a 125 acre field over 15 years at four percent interest.

Table 19. Detailed Costs and Returns for Center Pivot irrigated Corn by Well Capacity when irrigation occurs when the soil moisture depletion is 10 percent of capacity or less.

GPM		800	700	600	500	400	300	200	100
Yield	bu/ac	213.41	198.86	186.90	174.99	164.37	142.64	122.23	99.08
N	lbs/ac	196.8	183.0	171.9	160.9	151.0	130.9	112.1	90.9
P	lbs/ac	28.5	26.5	25.0	23.4	21.9	19.0	16.3	13.2
Irrigation (inches)	acre-inch	22.5	23.1	21.6	19.5	17.6	13.9	10.3	6.1
Net Revenue ($4.48/bu)	$	956.1	890.9	837.3	784.0	736.4	639.0	547.6	443.9
Fertilizer-Nitrogen	$	108.2	100.7	94.6	88.5	83.0	72.0	61.7	50.0
Fertilizer-Phosphorous	$	14.8	13.8	13.0	12.1	11.4	9.9	8.5	6.9
Seed Cost	$	112.6	112.6	112.6	112.6	112.6	112.6	112.6	112.6
Herbicide Cost	$	61.0	61.0	61.0	61.0	61.0	61.0	61.0	61.0
Insecticide Cost	$	16.0	15.7	15.5	15.2	15.0	14.6	14.1	13.6
Crop Consulting	$	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Drying	$	27.7	25.9	24.3	22.7	21.4	18.5	15.9	12.9
Miscelleneous	$	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Custom Hire	$	161.5	155.1	149.9	144.7	140.0	130.5	121.5	111.4
Non Machinery Labor	$	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Interest	$	20.0	19.0	18.1	17.3	16.5	14.9	13.4	11.8
Irrigation Cost	$	130.0	130.5	120.4	107.4	96.1	75.3	55.5	32.7
Sub Total	$	686.5	668.8	643.9	616.0	591.6	543.8	498.8	447.4
Crop Insurance	$	33.0	32.1	30.9	29.6	28.4	26.1	23.9	21.5
Total Varible Cost	$	719.4	700.9	674.8	645.6	620.0	569.9	522.7	468.8
Net Returns-Var Cost	$	236.6	190.0	162.5	138.4	116.4	69.1	24.9	-25.0
Annual System Cost[a]	$	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
Net Ret-system Cost	$	191.7	145.0	117.6	93.4	71.4	24.2	-20.1	-69.9

a Initial system cost of $60,000 over 15 years at four percent.

Table 20. Costs and Returns over Irrigation Costs for Subsurface Drip Irrigated Corn by Well Capacity on a 125 Acre Field if Irrigation Occurs when Soil Moisture is 10 Percent of Capacity or Less.

GPM		800	700	600	500	400	300	200	100
Yield (bu/acre)		214.9	209.8	202.1	191.7	178.7	162.9	144.1	122.1
N (lbs/a)		204.4	199.5	192.1	191.7	169.6	154.6	136.6	115.8
P (lbs/a)		29.5	28.8	27.7	26.3	24.5	22.3	19.7	16.7
Irrigation (inches)		22.6	21.5	20.0	18.0	15.6	12.9	9.9	6.7
Net Revenue ($4.48/bu)	$	962.9	939.9	905.5	859.0	800.5	729.8	645.4	547.2
Fertilizer-nitrogen	$	112.4	109.7	105.6	105.5	93.3	85.0	75.1	63.7
Fertilizer-phosphorus	$	15.3	15.0	14.4	13.7	12.7	11.6	10.3	8.7
Seed cost	$	112.6	112.6	112.6	112.6	112.6	112.6	112.6	112.6
herbicide Cost	$	61.0	61.0	61.0	61.0	61.0	61.0	61.0	61.0
Insecticide Cost	$	16.1	16.0	15.8	15.6	15.3	15.0	14.6	14.1
Crop Consulting	$	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
Drying	$	27.9	27.3	26.3	24.9	23.2	21.2	18.7	15.9
Miscellaneous	$	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Custom Hire	$	162.2	159.9	156.6	152.0	146.3	139.4	131.1	121.5
Non Machinery Labor	$	18.0	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Interest	$	20.1	19.8	19.2	18.5	17.5	16.4	15.0	13.4
Irrigation Cost	$	119.1	110.6	101.4	90.0	77.1	52.3	48.0	32.3
Sub Total ($)	$	681.3	666.3	647.4	628.2	593.6	548.9	521.0	477.7
Crop Insurance	$	32.7	32.0	31.1	30.2	28.5	26.4	25.0	22.9
Total Variable Cost	$	714.0	698.3	678.5	658.4	622.1	575.3	546.0	500.7
Net Returns - Var. Cost	$	248.9	241.6	227.0	200.6	178.4	154.5	99.4	46.6
Annual System Cost*	$	65.3	65.3	65.3	65.3	65.3	65.3	65.3	65.3
Net Returns - Syst. Cost	$	183.7	176.4	161.8	135.3	113.1	89.3	34.2	-18.7

a Annual cost for an SDI system for a 125 acre field with initial cost of $90,700 over 15 years at four percent interest.

Crop and Irrigation Choices with Limited Groundwater Supplies

Two long term scenarios are examined in this analysis. The first is when the producer makes a series of "Best Single Year Choices" (BSYC). The second is when the producer makes a series of choices that "Maximize the Net Present Value" of returns (MNPV) over the life of a limited resource. The major objective of this research was to determine how producers could gain the maximum value from the remaining water supply. One factor affecting the value of the remaining water supply is the objective of the producers. Researchers have long known that optimal long term rates, MNPV of extracting a non-renewable resource differ from that which would be received by a series of BSYC annual rates of extraction. Analysis of the difference in expected returns from following a BSYC VS. a MNVP path are examined below.

Annual net crop returns over fixed costs are presented in an enterprise budget for a representative acre. The budget represents returns to land which is usually the producer's most limiting resource. Other choices may be made when labor or capital are limiting. This is also true when groundwater resources are limiting. The BSYC case is followed by always selecting the crop that has the highest single year return per acre. In the budget tables listed above, irrigated corn (if the producer's well supplies 500 GPM or more per quarter section), provides higher net returns over variable costs than grain sorghum. Under high feed grain prices, the annual profit advantage of corn over sorghum is even more pronounced than in the budgets shown in Tables 17 to 20 above. However the fact that corn requires more groundwater than sorghum, has long-term implications that may easily be overlooked when making a crop choice based only on expected one-year returns.

Consider a producer who has one quarter section with one 600 GPM irrigation well. We assume that to continue irrigation, the producer must purchase a new pivot that will irrigate 120 acres at a cost of $60,000. The producer will choose between irrigated corn and grain sorghum based on the data shown above in Tables 17 and 19. Based on annual profits (Table 19), with a 600 GPM well, irrigated corn yielding approximately 187 bushels per acre provides the highest expected net return over variable cost at $165 per acre. The net return for the 160 acre field would be $20,443. An acre of irrigated corn is expected to require 1.79 acre feet of groundwater. The 120 acre field would use approximately 215 acre feet of ground water per year.

The results depend on the availability of groundwater to the producer's well. A 600 GPM well would mean the producer has about 60 feet of water saturated sand above a safety zone 35 feet above the aquifer base and pump bowls. The output of the well would decline about 100 GPM for each 10 feet of decline in water saturated sand. For this example, assume the producer has 1,680 acre feet of groundwater that can be extracted or about 280 acre feet in each 10 foot layer of saturated sand. This example represents the case for a producer with a single quarter section that is surrounded by irrigated fields so that the producer has access only to the water that underlies the 160 acre parcel.

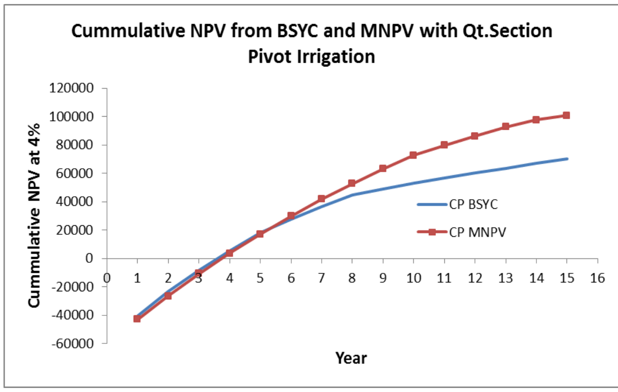
Table 21 shows that the 15 year returns for the MNPV strategy begin to exceed annual returns from the BSYC strategy by year 3 and Cumulative NPV (at four percent) after year 6. The Cumulative 15 year NPV for the BSYC is $69,959 as compared to the $100,681 for the MNPV strategy.

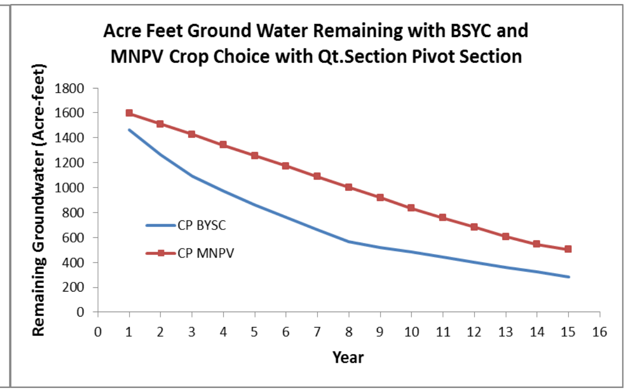
One reason for the lower eventual returns from the BSYC strategy is that the initial choice of irrigated corn draws down the aquifer at a faster rate (Figure 24, upper left). The returns from the MNPV strategy eventually begin to exceed returns from BSYC strategy because the higher groundwater level reduced pumping cost. The BYSC producer produces nearly three years of irrigated corn which draws down the aquifer. In contrast, the MNPV producer begins with stressed (IrT is .6) irrigated sorghum and uses less water per acre. The MNPV producer is still obtaining 300 GPM from the well by year 13 whereas the BYSC producer is pumping from the 100 GPM level of the aquifer.

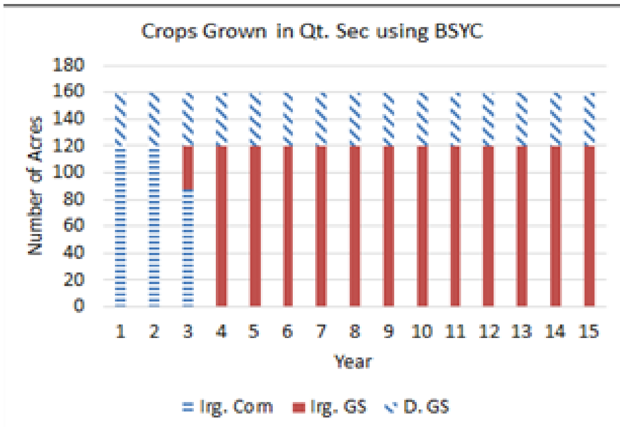
The BSYC was also compared with the MNPV strategy on a 640 acre field (section) where the available water supply (6,720 acre feet) was limited to that under the producer's field and where the producer had twice the water supply (13,440 acre feet). Center pivot irrigation was assumed in this analysis. The results shown in Figures 25 and 26 below again indicate the MNPV strategy yields the higher cumulative NPV in all of the situations.

Table 21. Importance of Considering Long-Returns from Crop Choice of Irrigated Corn or Grain Sorghum when Initial Groundwater Supplies are 1680 Acre Feet

BSYC Qt. Section Pivot Irrigation								MNPV Qt. Section Pivot Irrigation							
	Crop,	Well				Cumulative GW			Crop,	Well				Cumulative GW	
Year	Irt	GPM	Ir Yield	Dac	Net Ret.	NPV	(aft)	Year	Irt	GPM	Ir Yield	Dac	Net Ret.	NPV	(aft)
1	C, .9	600	187	20	20422	$ (40,363)	1464	1	S, .6	600	120	40	17760	$ (42,923)	1595
2	C, .9	500	187	20	18334	$ (23,413)	1263	2	S, .6	600	120	40	17760	$ (26,503)	1511
3	C,.9,S.9	400	182	20	17005	$ (8,295)	1090	3	S, .6	600	120	40	17760	$ (10,714)	1426
4	S, .9	400	133	20	15767	$ 5,182	975	4	S, .6	500	120	40	16732	$ 3,589	1341
5	S, .9	400	133	20	15767	$ 18,142	860	5	S, .6	500	120	40	16320	$ 17,002	1256
6	S, .9	300	94	20	12239	$ 27,814	759	6	S, .6	500	120	40	16320	$ 29,900	1172
7	S, .9	200	89	20	11506	$ 36,558	662	7	S, .6	400	120	40	15654	$ 41,796	1087
8	S, .9	200	89	20	11506	$ 44,966	564	8	S, .6	400	120	40	14760	$ 52,581	1003
9	S, .4	200	89	20	5894	$ 49,106	522	9	S, .6	400	120	40	14760	$ 62,951	918
10	S, .4	200	89	20	5662	$ 52,931	482	10	S, .6	300	120	40	14377	$ 72,663	835
11	S, .4	100	88	20	5662	$ 56,609	442	11	S, .6	300	120	40	10680	$ 79,601	758
12	S, .4	100	88	20	5662	$ 60,145	402	12	S, .6	300	120	40	10680	$ 86,272	682
13	S, .4	100	88	20	5662	$ 63,545	362	13	S, .6	300	120	40	10680	$ 92,686	605
14	S, .4	100	88	20	5662	$ 66,815	322	14	S, .5	200	120	40	8422	$ 97,549	545
15	S, .4	100	88	20	5662	$ 69,959	282	15	S, .5	200	120	40	5640	$100,681	504


Cummulative NPV from BSYC and MNPV with Qt.Section Pivot Irrigation
Cummulative NPV at 4%
Year
CP BSYC
CP MNPV
120000
100000
80000
60000
40000
20000
0
-20000
-40000
-60000
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16


Acre Feet Ground Water Remaining with BSYC and MNPV Crop Choice with Qt.Section Pivot Section
Remaining Groundwater (Acre-feet)
Year
CP BYSC
CP MNPV
1800
1600
1400
1200
1000
800
600
400
200
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16


Crops Grown in Qt. Sec using BSYC
Number of Acres
Year
Irg. Com
Irg. GS
D. GS
180
160
140
120
100
80
60
40
20
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

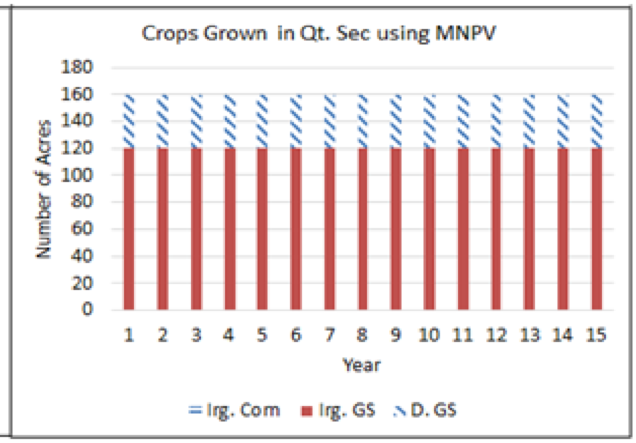

Crops Grown in Qt. Sec using MNPV
Number of Acres
Year
Irg. Com
Irg. GS
D. GS
180
160
140
120
100
80
60
40
20
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

Figure 24. BSYC and MNPV strategies from a 120 Acre Pivot with Limited Groundwater.

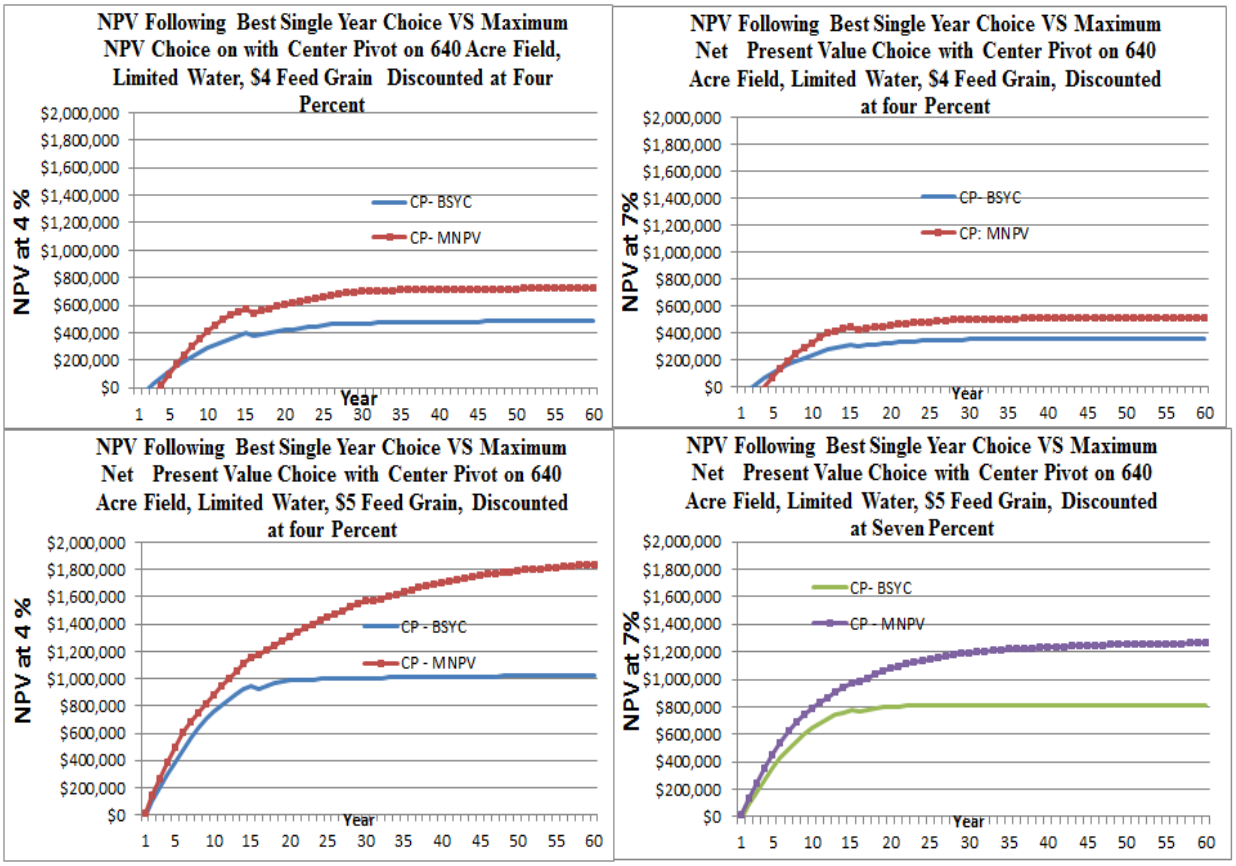


Figure 25. Comparison of BSYC VS MNPV Paths on Cumulative NPV from 640 Acre Field with a CP system with 6720 Acre Feet, Four and Five Dollar Feed Grain, Discounted at Four and Seven Percent

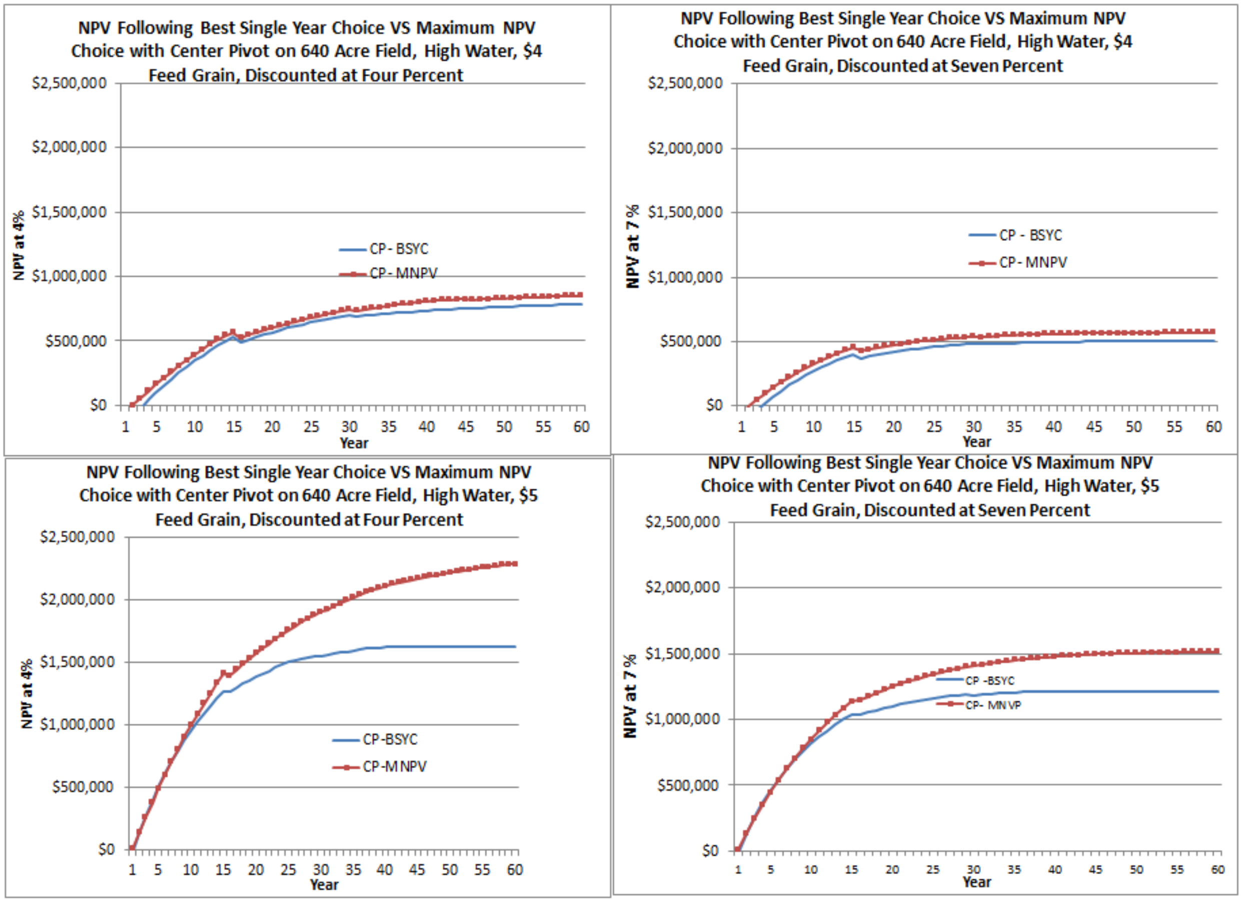


Figure 26. Comparison of BSYC VS MNPV Paths on Cumulative NPV from 640 Acre Field with a CP system with 13,440 Acre Feet, Four and Five Dollar Feed Grain, Discounted at Four and Seven Percent

Determination of Maximum Net Present Value for Center Pivot and Sub Surface Drip Systems

The MNPV optimal investment and groundwater use paths are compared over a 30 year planning horizon for the 160 acre field and over a 60 year planning horizon for the 640 acre field. Two initial water supplies are considered for the 640 acre field. The sensitivity of discounted returns and economic length of irrigation for the SDI and CP were compared with two crop prices for producers with a quarter section of land and with a full section of land. The returns for a producer with 160 acres of land and 60 feet of water saturated sand were estimated with SDI and CP over a 30 year period. For the quarter section case, it was assumed that 100 percent of the surrounding land was irrigated. Then, returns were estimated for producers with a 640 acre section of land with 60 feet of water saturated sand over a 60 year period. Two water supply cases were considered. In one case, it was assumed 100 percent of the surrounding land was irrigated and in the second case that only 50 percent of the surrounding land was irrigated. The 60 year period was used for the 640 acre producer because it was desirable to test whether the producer would leave one or more quarters unirrigated but would increase the supply of water to the irrigated portion by drawing water from all four wells.

One size of CP system was considered while five alternative sizes of SDI systems were budgeted. The irrigation system costs used for the CP and SDI systems were,

CP		SDI	
Acres	Cost	Acres	Cost
120	$60,000	50	$ 43,000
		75	$ 58,000
		100	$ 74,300
		125	$ 90,700
		150	$ 107,000.

The feed grain prices used were,

	Four Dollar Feed Grain	Five Dollar Feed Grain
Corn	$4.48/bus	$5.48/bus
Grain Sorghum	$4.16/bus	$5.09/bus.

MNPV Quarter Section Results with Pivot Irrigation and Sub Surface Drip Irrigation

This part of the analysis compares producer returns from CP and SDI systems. Each system is assumed to have a 15 year life. The initial cost of the center pivot is $60,000. The five sizes of SDI systems range from 50 to 150 acres in 25 acre increments. The planning horizon is 30 years and it was assumed the producer has only 60 feet of water saturated sand underlying the 160 acre parcel. Based on the specific yield of .175, (USGS, 2012) for much of Texas County, it is assumed the producer has 1,680 acre feet of ground water that can be extracted from under the 160 acre field. The results are examined under two feed grain prices and two discount rates.

The optimal results were determined by solving a MIP model for each type of system with GAMS-CPLEX. The subheadings below are in the form of System (acres, Feed Grain Price, Discount Rate) and are used indicate which system and parameters are being discussed.

CP(160a, $4, 4%) The left side of Table 22 compares the NPV and water use over a 30 year period with the four dollar feed grain prices (Corn price = $4.48/bus, GS price = $4.16/bus.) with a four percent discount rate. If the producer chose the pivot system, the results indicate the crop choice would be GS (not corn) for the first 15 years and then the 160 acres would be converted to dryland with 504 acre feet of groundwater remaining. The optimal solution has the CP producer irrigating GS with some stress (irrigate when the IrT is .6 or less). The 30-year NPV from both irrigated and dry GS production over the 30 year period is $106,607.

Figure 27 compares the NPV from the quarter section CP and SDI investments under the four dollar feed grain prices (Corn price = $4.48/bus, GS price = $4.16/bus.) with four and seven percent discount rates and under the five dollar feed grain prices (Corn price = $5.48, GS price=$5.09) discounted at four and seven percent. As shown in Figure 27, the SDI system always had the higher NPV.

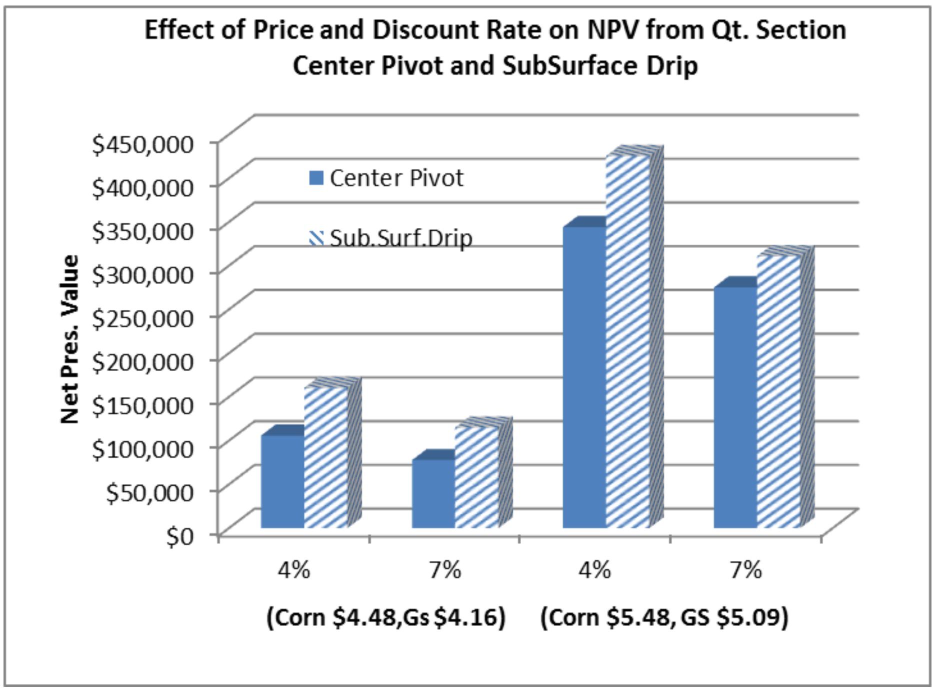


Figure 27. NPV of Center Pivot and Sub Surface Drip Systems with Feed Grain Prices at Four Dollars/bushel and Five Dollars/bushel when Discounted at Four and Seven Percent Interest

SDI(160a, $4, 4%) The right side of Table 22 presents the NPV and optimal groundwater use from an SDI system. The results indicate that for the first 15 years, the 125 acre SDI would be used which would be followed by a smaller 50 acre SDI system for years 16-30. During the first 15 years, it fully irrigated GS (irrigation initiated when soil moisture reaches the .9 level or less). The SDI system used slightly more water during the first 15 years (1,194 VS 1176 remaining) than did the CP. During years 16-21, with the smaller 50 acre SDI, water becomes relatively less limiting than the irrigated area and irrigated corn is produced. In years 22-30, the producer switches back to fully irrigated GS. The 1,680 acre feet of groundwater is exhausted by year 30. The NPV from the SDI system plus dryland GS production is estimated to be $160,861 or 50 percent higher than for the CP system.

CP(160a, $4, 7%) Table 23 (left side) shows effects of the higher discount rate on 30-year CP are shown in Table 23 with the same feed grain prices as in Table 22. In the case of the single quarter section producer with 1,680 acre feet of groundwater, the increase in the interest rate from four to seven percent did not affect either the level of investment or the rate of groundwater use. It was still optimal for the CP producer to buy a pivot only for the first 15 years.

SDI(160a, $4, 7%) For the SDI producer, (Table 23, right side), the optimal size was still 125 acres for the first 15 years and 50 acres for the second 15 years. The NPV for both systems were greatly reduced (NPV CP = $78,286 VS NPV SDI= $115,296). The NPV of the SDI system over the NPV of the CP system was reduced to 47 percent and the SDI has higher capital costs and is more sensitive to higher discount rates.

Table 22. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 160 Acres in Texas County when Corn price is $4.48 and the Grain Sorghum Price is $4.16 per Bushel and the Discount Rate is Four Percent

	Center Pivot Irrigation							Subsurface Drip Irrigation						
Year	Crop, IrT[a]	Yield bus	Irrig. Acres	Dry Acres	160acre Net.Rev.	Cumulative NPV $	GW(aft) 1680	Crop, IrT	Yield Bus	Irrig. Acres	Dry Acres	160 acre Net Rev.	Cumulative NPV $	GW(aft) 1680
1	S, .6	134	120	40	$17,760	$ (42,923)	1595	S, .9	155	125	35	$ 26,210	$(65,498)	1572
2	S, .6	134	120	40	$17,760	$ (26,503)	1511	S, .9	155	125	35	$ 26,210	$(41,265)	1465
3	S, .6	134	120	40	$17,760	$ (10,714)	1426	S, .9	160	125	35	$ 26,259	$(17,921)	1353
4	S, .6	132	120	40	$16,732	$ 3,589	1341	S, .9	147	125	35	$ 26,335	$ 4,590	1234
5	S, .6	130	120	40	$16,320	$ 17,002	1256	S, .9	147	125	35	$ 26,223	$ 26,143	1117
6	S, .6	130	120	40	$16,320	$ 29,900	1172	S, .9	147	125	35	$ 23,335	$ 44,585	1023
7	S, .6	128	120	40	$15,654	$ 41,796	1087	S, .9	141	125	35	$ 23,335	$ 62,318	929
8	S, .6	124	120	40	$14,760	$ 52,581	1003	S, .9	134	125	35	$ 23,170	$ 79,248	836
9	S, .6	124	120	40	$14,760	$ 62,951	918	S, .9	134	125	35	$ 20,085	$ 93,360	757
10	S, .6	124	120	40	$14,377	$ 72,663	835	S, .9	134	125	35	$ 20,085	$ 106,928	679
11	S, .6	105	120	40	$10,680	$ 79,601	758	S, .9	134	125	35	$ 20,085	$ 119,975	600
12	S, .6	87	120	40	$10,680	$ 86,272	682	S, .9	114	125	35	$ 14,637	$ 129,118	550
13	S, .6	87	120	40	$10,680	$ 92,686	605	S, .9	93	125	35	$ 9,085	$ 134,574	528
14	S, .5	87	120	40	$ 8,422	$ 97,549	545	S, .9	93	125	35	$ 9,085	$ 139,820	507
15	S, .5	87	120	40	$ 5,640	$ 100,681	504	S, .9	93	125	35	$ 9,085	$ 144,865	486
16	-	-	-	160	$ 960	$ 101,193	504	C, .9	182	50	110	$ 9,810	$ 127,144	413
17	-	-	-	160	$ 960	$ 101,686	504	C, .9	182	50	110	$ 9,810	$ 132,181	339
18	-	-	-	160	$ 960	$ 102,160	504	C, .9	161	50	110	$ 9,810	$ 137,023	266
19	-	-	-	160	$ 960	$ 102,616	504	C, .9	141	50	110	$ 9,062	$ 141,324	198
20	-	-	-	160	$ 960	$ 103,054	504	C, .9	141	50	110	$ 5,260	$ 143,725	158
21	-	-	-	160	$ 960	$ 103,475	504	C, .9	141	50	110	$ 5,260	$ 146,033	117
22	-	-	-	160	$ 960	$ 103,880	504	S, .9	96	50	110	$ 4,775	$ 148,048	95
23	-	-	-	160	$ 960	$ 104,270	504	S, .9	96	50	110	$ 4,510	$ 149,878	83
24	-	-	-	160	$ 960	$ 104,644	504	S, .9	96	50	110	$ 4,510	$ 151,637	71
25	-	-	-	160	$ 960	$ 105,004	504	S, .9	96	50	110	$ 4,510	$ 153,329	59
26	-	-	-	160	$ 960	$ 105,351	504	S, .9	96	50	110	$ 4,510	$ 154,956	47
27	-	-	-	160	$ 960	$ 105,684	504	S, .9	96	50	110	$ 4,510	$ 156,520	35
28	-	-	-	160	$ 960	$ 106,004	504	S, .9	96	50	110	$ 4,510	$ 158,024	23
29	-	-	-	160	$ 960	$ 106,311	504	S, .9	96	50	110	$ 4,510	$ 159,470	11
30	-	-	-	160	$ 960	$ 106,607	504	S, .9	96	50	110	$ 4,510	$ 160,861	0

IrT: Irrigation Trigger, Soil Moisture Content to trigger an irrigation

GW(aft): Acre feet of groundwater remaining at end of year

Table 23. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 160 Acres in Texas County when Corn price is $4.48 and the Grain Sorghum Price is $4.16 per Bushel and the Discount Rate is Seven Percent

Year	Center Pivot Irrigation							Sub Surface Drip Irrigation						
	Crop, IrT	Yield bus	Irrig. Acres	Dry Acres	160 acre N.Rev	Cumulative NPV $	GW (aft) 1680	Crop, IrT	Yield bus	Irrig. Acres	Dry Acre	160 acre Net Rev.	Cumulative NPV $	GW (aft) 1680
1	S, .6	134	120	40	$ 17,760	$ (43,402)	1595	S, .9	155	125	35	$26,210	-$66,205	1572
2	S, .6	134	120	40	$ 17,760	$ (27,890)	1511	S, .9	155	125	35	$26,210	-$43,312	1465
3	S, .6	134	120	40	$ 17,760	$ (13,392)	1426	S, .9	160	125	35	$26,259	-$21,876	1353
4	S, .6	132	120	40	$ 16,732	$ (627)	1341	S, .9	160	125	35	$26,335	-$1,785	1234
5	S, .6	130	120	40	$ 16,320	$ 11,009	1256	S, .9	147	125	35	$26,223	$16,911	1117
6	S, .6	130	120	40	$ 16,320	$ 21,884	1172	S, .9	147	125	35	$23,335	$32,460	1023
7	S, .6	128	120	40	$ 15,654	$ 31,632	1087	S, .9	147	125	35	$23,335	$46,992	929
8	S, .6	124	120	40	$ 14,760	$ 40,222	1003	S, .9	147	125	35	$23,170	$60,477	836
9	S, .6	124	120	40	$ 14,760	$ 48,251	918	S, .9	135	125	35	$20,085	$71,402	757
10	S, .6	124	120	40	$ 14,377	$ 55,559	835	S, .9	135	125	35	$20,085	$81,612	679
11	S, .6	105	120	40	$ 10,680	$ 60,633	758	S, .9	135	125	35	$20,085	$91,154	600
12	S, .6	87	120	40	$ 10,680	$ 65,375	682	S, .9	135	125	35	$14,637	$97,653	550
13	S, .6	87	120	40	$ 10,680	$ 69,807	605	S, .9	93	125	35	$9,085	$101,423	528
14	S, .5	87	120	40	$ 8,422	$ 73,073	545	S, .9	93	125	35	$9,085	$104,947	507
15	S, .5	87	120	40	$ 5,640	$ 75,117	504	S, .9	93	125	35	$9,085	$108,240	486
16	-	-	-	160	$ 960	$ 75,443	504	C, .9	182	50	110	$9,810	$96,997	413
17	-	-	-	160	$ 960	$ 75,746	504	C, .9	182	50	110	$9,810	$100,102	339
18	-	-	-	160	$ 960	$ 76,030	504	C, .9	182	50	110	$9,810	$103,005	266
19	-	-	-	160	$ 960	$ 76,296	504	C, .9	182	50	110	$9,062	$105,510	198
20	-	-	-	160	$ 960	$ 76,544	504	C, .9	141	50	110	$5,260	$106,870	158
21	-	-	-	160	$ 960	$ 76,776	504	C, .9	141	50	110	$5,260	$108,140	117
22	-	-	-	160	$ 960	$ 76,993	504	S, .9	141	50	110	$4,775	$109,218	95
23	-	-	-	160	$ 960	$ 77,195	504	S, .9	97	50	110	$4,510	$110,169	83
24	-	-	-	160	$ 960	$ 77,384	504	S, .9	97	50	110	$4,510	$111,058	71
25	-	-	-	160	$ 960	$ 77,561	504	S, .9	97	50	110	$4,510	$111,889	59
26	-	-	-	160	$ 960	$ 77,726	504	S, .9	97	50	110	$4,510	$112,666	47
27	-	-	-	160	$ 960	$ 77,881	504	S, .9	97	50	110	$4,510	$113,392	35
28	-	-	-	160	$ 960	$ 78,025	504	S, .9	97	50	110	$4,510	$114,070	23
29	-	-	-	160	$ 960	$ 78,160	504	S, .9	97	50	110	$4,510	$114,704	11
30	-	-	-	160	$ 960	$ 78,286	504	S, .9	97	50	110	$4,510	$115,296	0

Irt: Irrigation Trigger, moisture level to trigger an irrigation
GW(aft): Acre feet of remaining ground water at end of year

CP(160a, $5, 4%) The optimal 30-year investments (Table 24) and ground water use with the higher feed grain prices (corn price = $5.48/bus, GS price = $5.09/bus) with the discount rate at four percent are shown in Table 24. For the CP choice, the crop selection and rate of groundwater use over the first 15 years increased irrigation intensity slightly in the first 15 years ending with 442 acre feet rather than 540 shown in Table 22. The higher price did make it slightly profitable to purchase a replacement pivot and irrigate 120 acres in years 16-24. The irrigation ended in year 24 when the aquifer was exhausted. The 30 year NPV for the CP system was $344,489.

SDI(160a, $5, 4%) With the higher feed grain price, the SDI systems size was increased to 150 acres for the entire thirty year period. The crop choice is GS except for year 13 when corn was grown. (This is likely an anomaly in the budgets). The initial net revenue over variable costs was $52,100 (with 155 bushel GS) in year 1 and declined to $22,400 (with 88 bushel GS) by year 30. The 30-year cumulative NPV at seven percent reached $436,103 as compared to $344,489 for the above CP example.

CP(160a, $5, 7%) In general an increased discount discourages investments. However in this study, the irrigation investments are a lumpy yes or no choice. In this example, (Table 25), the profitability of the CP investment is reduced but it was still optimal to purchase a 120 acre system for use in years 1-15 and replace the system in year 16. Irrigation continued through 28 years of the 30 year planning horizon. The 30-year cumulative NPV, at a seven percent discount rate, was $260,312.

SDI(160a, $5, 7%) The 150 acre SDI was purchased for the first 15-year period and replaced in year 16 for the 16-30 year period. Intensively irrigated GS was the selected crop except for years 13 and 14. Irrigation continued for the 30 year period. The 30-year cumulative NPV, at a seven percent discount rate, reached $318,318 in year 30.

Table 24. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 160 Acres in Texas County when Corn price is $5.48 and the Grain Sorghum Price is $5.09 per Bushel and the Discount Rate is Four Percent

Year	Center Pivot Irrigation							Sub Surface Drip Irrigation						
	Crop, IrT	Yield bus	Irrig. Acres	Dry Acres	160 acre N.Rev	Cumulative NPV $	GW (aft) 1680	Crop, IrT	Yield bus	Irrig. Acres	Dry Acre	160 acre Net Rev.	Cumulativ NPV $	GW (aft) 1680
1	S, .6	134	120	40	$ 35,000	$(26,346)	1595	S, .9	155	150	10	$52,100	-$56,904	1551
2	S, .6	134	120	40	$ 35,000	$ 6,013	1511	S, .9	155	150	10	$52,100	-$8,734	1422
3	S, .6	134	120	40	$ 35,000	$ 37,128	1426	S, .9	155	150	10	$50,358	$36,034	1306
4	S, .6	132	120	40	$ 33,715	$ 65,948	1341	S, .9	147	150	10	$50,000	$78,774	1193
5	S, .6	130	120	40	$ 33,200	$ 93,236	1256	S, .9	147	150	10	$47,752	$118,023	1086
6	S, .6	130	120	40	$ 33,200	$119,475	1172	S, .9	135	150	10	$43,400	$152,322	992
7	S, .6	128	120	40	$ 32,277	$144,003	1087	S, .9	135	150	10	$43,400	$185,303	897
8	S, .6	124	120	40	$ 31,040	$166,683	1003	S, .9	135	150	10	$40,511	$214,904	811
9	S, .6	124	120	40	$ 31,040	$188,492	918	S, .9	119	150	10	$35,750	$240,022	737
10	S, .6	124	120	40	$ 30,058	$208,798	838	S, .9	119	150	10	$35,750	$264,173	664
11	S, .6	110	120	40	$ 25,400	$225,297	762	S, .9	119	150	10	$35,750	$287,395	590
12	S, .6	108	120	40	$ 25,400	$241,162	685	S, .9	119	150	10	$31,234	$306,904	511
13	S, .5	108	120	40	$ 24,800	$256,056	612	C, .9	125	150	10	$27,800	$323,600	426
14	S, .5	108	120	40	$ 23,141	$269,419	533	S, .9	93	150	10	$24,350	$337,661	401
15	C, .5	108	120	40	$ 19,760	$280,391	442	S, .9	93	150	10	$24,350	$351,182	375
16	C, .5	118	120	40	$ 19,760	$258,907	351	S, .9	93	150	10	$24,350	$307,055	350
17	C, .5	118	120	40	$ 19,263	$268,796	274	S, .9	93	150	10	$24,350	$319,555	324
18	S, .4	88	120	40	$ 17,840	$277,602	234	S, .9	93	150	10	$24,350	$331,575	299
19	S, .4	88	120	40	$ 17,840	$286,070	194	S, .9	88	150	10	$23,989	$342,962	275
20	S, .4	88	120	40	$ 17,840	$294,212	154	S, .9	88	150	10	$22,400	$353,185	262
21	S, .4	88	120	40	$ 17,840	$302,041	114	S, .9	88	150	10	$22,400	$363,014	248
22	S, .4	88	120	40	$ 17,840	$309,569	74	S, .9	88	150	10	$22,400	$372,466	235
23	S, .4	88	120	40	$ 17,840	$316,807	34	S, .9	88	150	10	$22,400	$381,554	221
24	S, .4	88	120	40	$ 16,439	$323,220	1	S, .9	88	150	10	$22,400	$390,293	208
25	-	-	-	160	$ 10,400	$327,121	1	S, .9	88	150	10	$22,400	$398,696	194
26	-	-	-	160	$ 10,400	$330,872	1	S, .9	88	150	10	$22,400	$406,775	181
27	-	-	-	160	$ 10,400	$334,479	1	S, .9	88	150	10	$22,400	$414,544	167
28	-	-	-	160	$ 10,400	$337,947	1	S, .9	88	150	10	$22,400	$422,014	154
29	-	-	-	160	$ 10,400	$341,282	1	S, .9	88	150	10	$22,400	$429,196	140
30	-	-	-	160	$ 10,400	$344,489	1	S, .9	88	150	10	$22,400	$436,103	127

Irt: Irrigation Trigger, moisture level to trigger an irrigation
GW(aft): Acre feet of remaining ground water at end of year

Table 25. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 160 Acres in Texas County when Corn price is $5.48 and the Grain Sorghum Price is $5.09 per Bushel and the Discount Rate is Seven Percent

Year	Center Pivot Irrigation							Sub Surface Drip Irrigation						
	Crop, IrT	Yield bus	Irrig. Acres	Dry Acres	160 acre N.Rev	Cumulative NPV $	GW (aft) 1680	Crop, IrT	Yield bus	Irrig. Acres	Dry Acre	160 acre Net Rev	Cumulati NPV $	GW (aft) 1680
1	S,.6	134	120	40	$35,000	$ (27,290)	1595	S, .9	155	150	10	$52,100	-$58,308	1551
2	S,.6	134	120	40	$35,000	$ 3,281	1511	S, .9	155	150	10	$52,100	-$12,802	1422
3	S,.6	134	120	40	$35,000	$ 31,851	1426	S, .9	155	150	10	$50,358	$28,305	1306
4	S,.6	134	120	40	$33,715	$ 57,572	1341	S, .9	147	150	10	$50,000	$66,450	1193
5	S,.6	130	120	40	$33,200	$ 81,244	1256	S, .9	147	150	10	$47,752	$100,496	1086
6	S,.6	130	120	40	$33,200	$ 103,366	1172	S, .9	135	150	10	$43,400	$129,416	992
7	S,.6	130	120	40	$32,277	$ 123,467	1087	S, .9	135	150	10	$43,400	$156,443	897
8	S,.6	125	120	40	$31,040	$ 141,532	1003	S, .9	135	150	10	$40,511	$180,021	811
9	S,.6	125	120	40	$31,040	$ 158,416	918	S, .9	119	150	10	$35,750	$199,467	737
10	S,.6	125	120	40	$30,510	$ 173,926	835	S, .9	119	150	10	$35,750	$217,640	664
11	S,.6	110	120	40	$25,400	$ 185,993	758	S, .9	119	150	10	$35,750	$234,625	590
12	S,.6	110	120	40	$25,400	$ 197,271	682	S, .9	119	150	10	$31,234	$248,493	511
13	S,.6	110	120	40	$25,400	$ 207,811	605	C, .9	125	150	10	$27,800	$260,029	426
14	S,.6	110	120	40	$22,335	$ 216,473	544	C, .9	125	150	10	$27,800	$270,810	342
15	S,.5	90	120	40	$18,560	$ 223,200	503	S, .9	93	150	10	$24,350	$279,636	316
16	S,.5	90	120	40	$18,560	$ 209,163	461	S, .9	93	150	10	$24,350	$251,639	291
17	S,.5	90	120	40	$18,560	$ 215,039	420	S, .9	93	150	10	$23,416	$259,052	271
18	S,.5	90	120	40	$18,560	$ 220,530	379	S, .9	88	150	10	$22,400	$265,679	257
19	S,.5	90	120	40	$18,560	$ 225,662	337	S, .9	88	150	10	$22,400	$271,873	244
20	S,.5	90	120	40	$18,560	$ 230,458	296	S, .9	88	150	10	$22,400	$277,661	230
21	S,.5	90	120	40	$18,139	$ 234,839	255	S, .9	88	150	10	$22,400	$283,071	217
22	S,.5	90	120	40	$17,840	$ 238,866	215	S, .9	88	150	10	$22,400	$288,127	203
23	S,.4	88	120	40	$17,840	$ 242,629	175	S, .9	88	150	10	$22,400	$292,852	190
24	S,.4	88	120	40	$17,840	$ 246,146	135	S, .9	88	150	10	$22,400	$297,269	176
25	S,.4	88	120	40	$17,840	$ 249,433	95	S, .9	88	150	10	$22,400	$301,396	163
26	S,.4	88	120	40	$17,840	$ 252,505	55	S, .9	88	150	10	$22,400	$305,253	149
27	S,.4	88	120	40	$17,840	$ 255,376	15	S, .9	88	150	10	$22,400	$308,858	136
28	S,.4	88	58	102	$14,011	$ 257,483	0	S, .9	88	150	10	$22,400	$312,227	122
29	S,.4	88	-	160	$10,400	$ 258,945	0	S, .9	88	150	10	$22,400	$315,375	109
30	-	-	-	160	$10,400	$ 260,312	0	S, .9	88	150	10	$22,400	$318,318	95

Irt: Irrigation Trigger, moisture level to trigger an irrigation

GW(aft): Acre feet of remaining ground water at end of year

In the one fourth section examples addressed above, investment is the SDI system always provided higher discounted net returns than did the CP system. In the four cases above, aquifer life was prolonged. However, there are periods where the SDI producer would irrigate a larger area than the CP producer and use more water in a given year. There are cases in the next section where the economic life of the aquifer was not prolonged by choosing the SDI over the CP.

One question is the the relation between adoption of the SDI system and "Conservation of Groundwater" of the Ogallala Aquifer. The definition of conservation given by Ciriacy-Wantrup (1963) can help answer this question. S. V. Ciriacy -Wantrup (1963) defined conservation as the wise use of resources over time. He went on to describe "the optimal state of conservation as that time distribution of use rates that maximizes the present value of the flow of expected net revenues". The total bushels of irrigated corn and sorghum produced over the 30-year period divided by the total acre-feet of groundwater used in Tables 22 and 24 above are presented below in Figure 28. The results show the SDI system would allow producers to produce more feed grain per acre-foot of water used than does the conventional CP. The amount of feed grain produced per unit of ground water increased with the feed grain price because the SDI with lower pumping costs and higher application efficiency was able to make greater use of ground water pumped even as well yields declined.

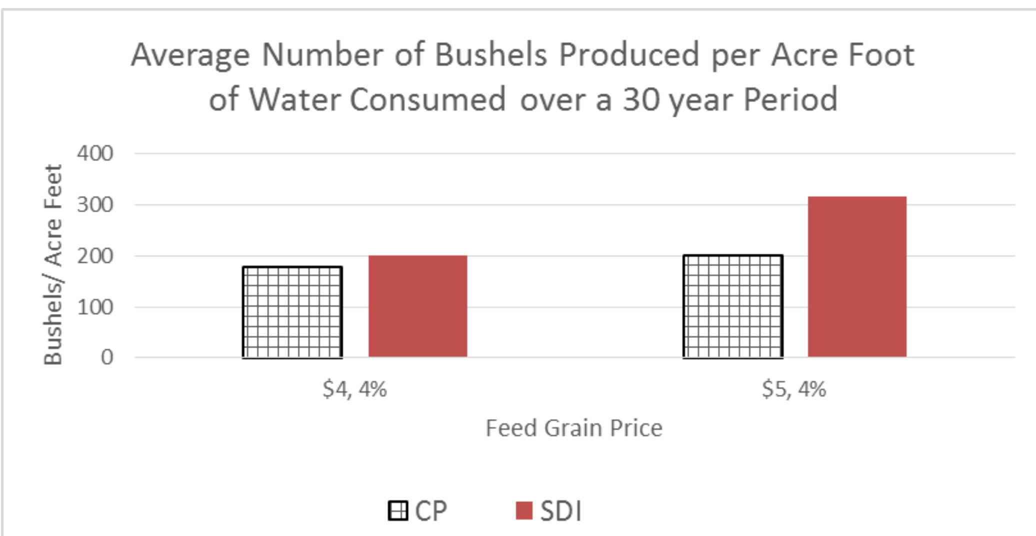


Figure 28. Comparison Potential Production of Grain Sorghum on a Quarter Section over a 30-year Planning Horizon at Two Feed Grain Prices and Four Percent Interest.

Effect of Holding Size on Irrigation Investments and Optimal Long Term Water Use

In this section the producer is assumed to control a 640 acre section of land developed for irrigation (Figure 29). It is assumed the producer has one well on each quarter section of land and that the wells have been interconnected by an underground pipe (Figure 29).

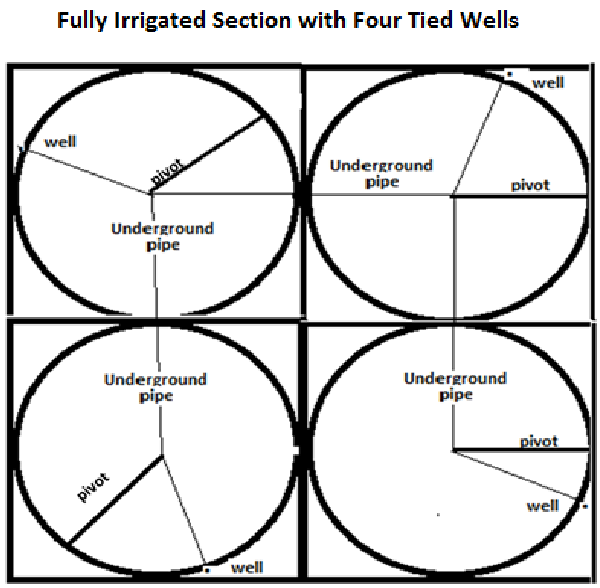


Figure 29. Diagram of 640 Acre Section with Four Connected Irrigation Wells.

It is assumed the producer must invest in either a CP or an SDI irrigation system to continue irrigation. The analysis is conducted first assuming the producer has only the 60 feet of water saturated sand under the 640 acre holding (6,720 acre feet) and second assuming the producer is in a location where only 50 percent of the surrounding land is irrigated (And has twice the supply (13,440 acre feet). The effects of two feed grain prices ($4.48/bus corn, $4.16/bus GS, $5.48/ bus corn and $5.09/bus GS) and two discount rates (four percent and seven percent) on the investment are considered with each water supply. The initial output of each well is assumed to be 600 GPM.

Irrigation Systems, Water Use with 640 Acres, Limited Water, and Four Dollar Feed Grain

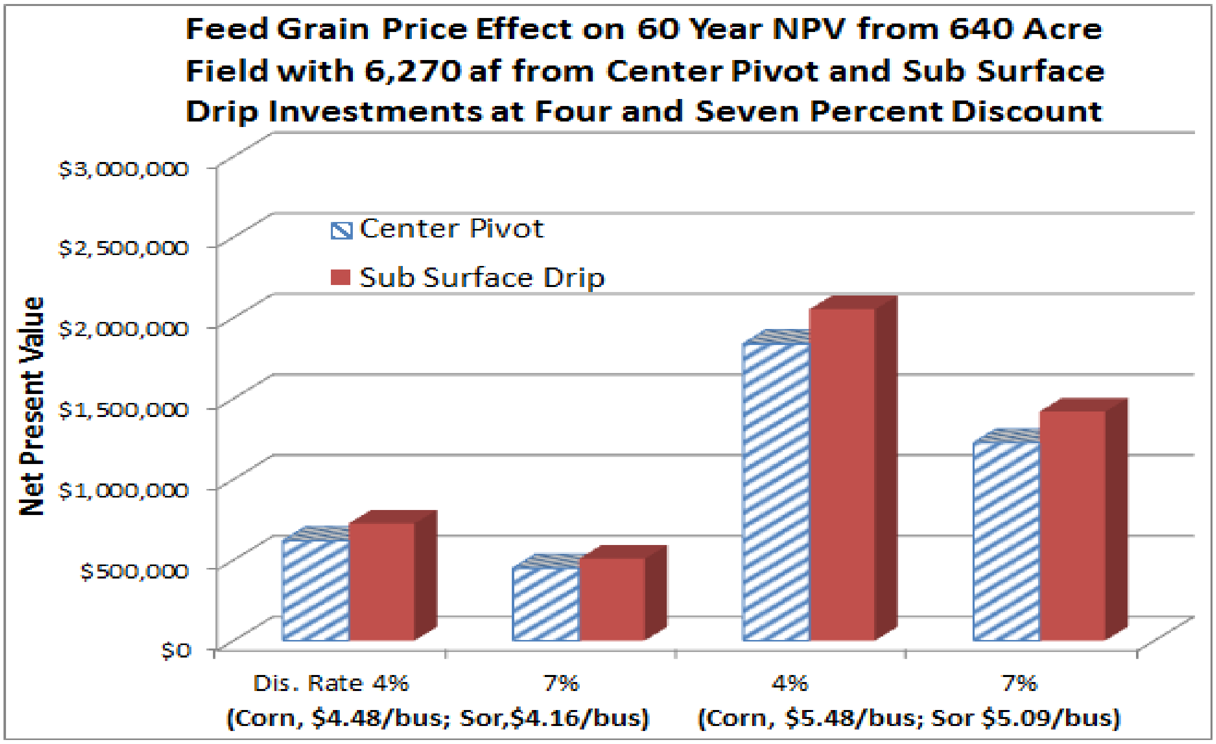
The 60-year results for the producer choosing either a CP or a SDI systems and continuing with that type of system until the aquifer is exhausted are compared in Table 26 . The producer with the 640 acre system of land has more flexibility than with a single quarter system because irrigation systems can be established on 0 to four quarters. If the producer establishes irrigation on one quarter section, then the producer may still draw from four wells to increase the

GPM delivered to the irrigation system over the amount that could be delivered if an irrigation system were established on all four quarter sections.

CP(640a, $4, 4%, Lw) The results on the left side of Table 26 show the producer investing in the CP would purchase only two CP systems for the first 15 years (irrigating 240) acres. The price received for corn and GS over the 60 period is $4.48/bus and $4.16/bus respectively. The discount rate is four percent. The producer intensively irrigates corn (Irt = .9) and obtains estimated yields of 214 bus/acre for the first four years. Then the producer would switch to GS for years 5 through 15. In year 16, the producer would purchase only one 120 acre CP. As the supply of irrigated land becomes more limited and the supply of water delivered to the pivot is increased back to 800 GPM, the producer grows 213 bushel corn for three years. As the ground water table declines to where less than 400 GPM can be delivered to the irrigated area, the producer switches to GS for the remainder of the aquifer life. A third CP system purchased in year 31 would be used to produce 124 bushel GS until the aquifer is exhausted at the end of year 45. Only dryland GS would be produced in years 46-60.

Initial net cash receipts in years 1-4 are estimated to be $63,840 (machinery expenses are not deducted). These decline to $37,680 by year 15. Annual net cash receipts continue to decline with the water table to $17,760 in the last year of irrigation in year 45. Returns from dryland production are expected to average $3,840 in years 46-60. The cumulative NPV from 60 years of operating the 640 acre parcel with the pivot system are estimated to $618,708. Figure 30compares the sensitivity of the NPV to changes in the ground water supply, feed grain price, and discount rate.

SDI(640a, $4, 4%, Lw) Results for the producer investing in a series of SDI systems are shown on the right side of Table 26. Initially, the SDI system would provide irrigation to 450 acres (three, 150-acre SDI systems) of sorghum for the first 15 years. The GS would be intensively irrigated (IrT = .9) and the estimate GS yields would be 164 bus/acre. However as the aquifer declines, the IrT for irrigation of GS declines to .6 by year 15. In year 16, the producer replaces only 125 acres of the previous 450 acres. With the smaller systems and the ability to draw water from 4 wells, the producer grows three years of intensively irrigated corn (Irt = .9, yields = 214 bus/acre). The producer then switches back to intensively (IrT=.9) irrigated GS for years 19-30. At the end of year 30, there was only 31 acre-feet of groundwater



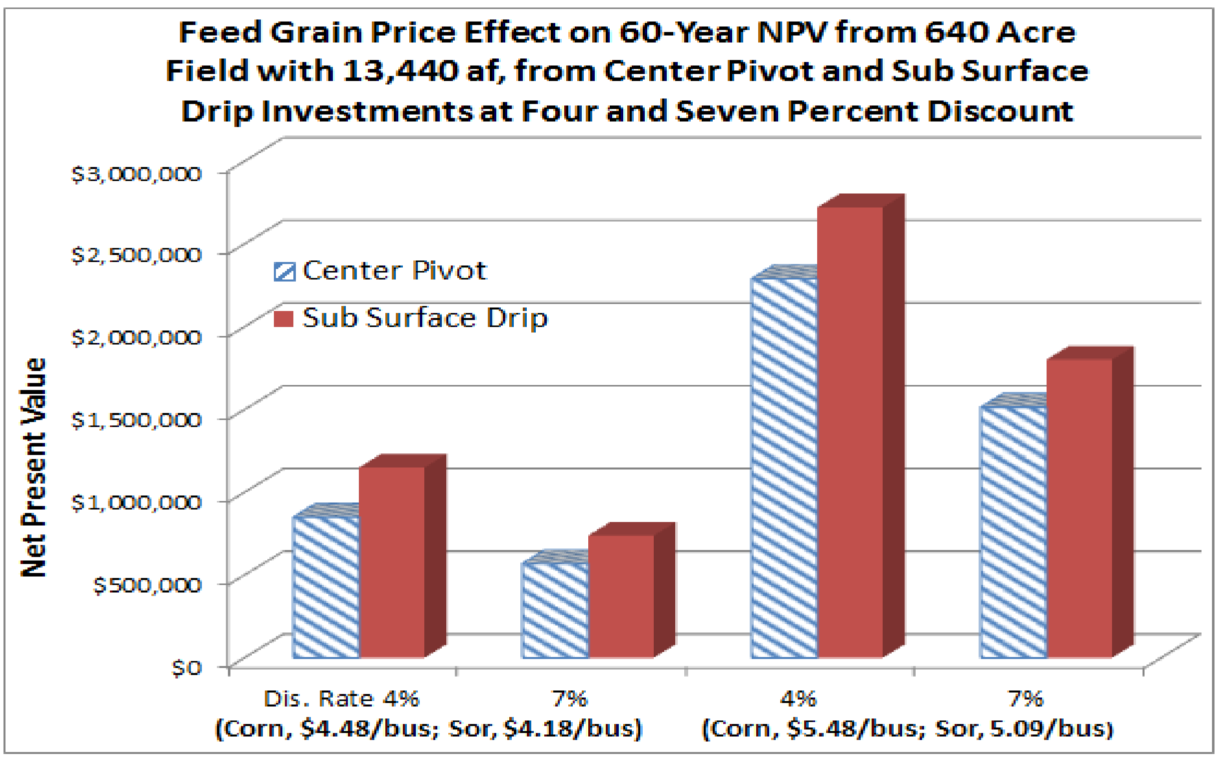


Figure 30. Comparison of NPV from Center Pivot and Subsurface Drip Investments on a 640 Acre Field with Initial Water Supplies of 6,240 and 13,440 Acre Feet Under Two Feed Grain Prices and Two Discount Rates.

Table 26. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 640 Acres with 6,720 Acre Feet of Groundwater in Texas County when Corn price is $4.48 and the Grain Sorghum Price is $4.16 per Bushel and the Discount Rate is Four Percent.

	Center Pivot							Sub Surface Drip						
Year	Crop IrT	Yield Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulative NPV 4	GW (aft) 6720	Crop IrT	Ir.Yield Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulative NPV 4	GW (aft) 6,720
1	C, .9	213	240	400	$ 63,840	$ (58,615)	6271	S,.9	164	450	515	$ 96,990	$(227,740)	6,265
2	C, .9	213	240	400	$ 63,840	$ 408	5822	S,.9	164	450	515	$ 96,990	$(138,068)	5,810
3	C, .9	213	240	400	$ 63,356	$ 56,731	5373	S,.9	160	450	515	$ 93,615	$ (54,845)	5,391
4	C, .9	213	240	400	$ 62,880	$ 110,481	4923	S,.9	155	450	515	$ 90,690	$ 22,678	5,004
5	S, .6	138	240	400	$ 59,438	$ 159,335	4525	S,.9	155	450	515	$ 90,690	$ 97,218	4,617
6	S, .6	138	240	400	$ 43,029	$ 193,342	4365	S,.9	152	450	515	$ 89,246	$ 167,751	4,260
7	S, .6	138	240	400	$ 42,960	$ 225,988	4205	S,.9	147	450	515	$ 88,440	$ 234,958	3,921
8	S, .6	138	240	400	$ 42,960	$ 257,378	4045	S,.9	135	450	515	$ 88,440	$ 299,580	3,582
9	S, .6	138	240	400	$ 42,960	$ 287,562	3885	S,.9	147	450	515	$ 83,350	$ 358,141	3,261
10	S, .6	138	240	400	$ 42,960	$ 316,584	3725	S,.9	140	450	515	$ 72,690	$ 407,247	2,978
11	S, .6	138	240	400	$ 42,960	$ 344,490	3565	S,.9	135	450	515	$ 72,690	$ 454,465	2,694
12	S, .6	138	240	400	$ 42,960	$ 371,322	3405	S,.8	135	450	515	$ 72,690	$ 499,867	2,411
13	S, .6	136	240	400	$ 39,019	$ 394,756	3238	S,.8	135	450	515	$ 57,937	$ 534,663	2,204
14	S, .6	134	240	400	$ 37,680	$ 416,515	3068	S,.6	115	450	515	$ 33,090	$ 553,771	2,126
15	S, .6	134	240	400	$ 37,680	$ 437,438	2899	S,.6	93	450	515	$ 33,090	$ 572,145	2,048
16	C, .9	213	120	510	$ 33,600	$ 423,343	2674	C, .9	214	125	515	$ 35,840	$ 542,855	1,812
17	C, .9	213	120	510	$ 33,600	$ 440,592	2450	C, .9	214	125	515	$ 35,840	$ 561,254	1,577
18	C, .9	213	120	510	$ 33,555	$ 457,156	2225	C, .9	214	125	515	$ 35,840	$ 578,946	1,341
19	S, .6	138	120	510	$ 23,400	$ 468,262	2145	S,.9	166	125	515	$ 35,779	$ 595,928	1,107
20	S, .6	138	120	510	$ 23,400	$ 478,942	2065	S,.9	166	125	515	$ 26,215	$ 607,892	1,012
21	S, .6	138	120	510	$ 23,400	$ 489,211	1985	S,.9	166	125	515	$ 26,215	$ 619,396	918
22	S, .6	138	120	510	$ 23,400	$ 499,084	1905	S,.9	155	125	515	$ 26,215	$ 630,458	824
23	S, .6	138	120	510	$ 23,400	$ 508,578	1825	S,.9	147	125	515	$ 26,215	$ 641,094	730
24	S, .6	138	120	510	$ 23,400	$ 517,707	1745	S,.9	147	125	515	$ 26,215	$ 651,321	636
25	S, .6	138	120	510	$ 23,400	$ 526,485	1665	S,.9	147	125	515	$ 26,215	$ 661,155	542
26	S, .6	138	120	510	$ 23,400	$ 534,925	1585	S,.9	147	125	515	$ 26,215	$ 670,610	447
27	S, .6	138	120	510	$ 23,400	$ 543,040	1505	S,.9	147	125	640	$ 26,215	$ 679,702	353
28	S, .6	138	120	510	$ 23,400	$ 550,844	1425	S,.9	147	125	640	$ 26,215	$ 688,444	259
29	S, .6	138	120	510	$ 23,400	$ 558,347	1345	S,.9	147	125	640	$ 26,215	$ 696,850	165
30	S, .6	138	120	510	$ 23,400	$ 565,562	1265	S,.9	147	125	640	$ 26,215	$ 704,932	71
31	S, .6	138	120	510	$ 23,400	$ 554,711	1185	-	-	-	640	$ 3,840	$ 706,071	71
32	S, .6	138	120	510	$ 21,520	$ 560,845	1104	-	-	-	640	$ 3,840	$ 707,165	71
33	S, .6	124	120	510	$ 17,760	$ 565,713	1019	-	-	-	640	$ 3,840	$ 708,218	71
34	S, .6	124	120	510	$ 17,760	$ 570,394	935	-	-	-	640	$ 3,840	$ 709,230	71
35	S, .6	124	120	510	$ 17,760	$ 574,895	851	-	-	-	640	$ 3,840	$ 710,203	71
36	S, .6	124	120	510	$ 17,760	$ 579,222	766	-	-	-	640	$ 3,840	$ 711,139	71
37	S, .6	124	120	510	$ 17,760	$ 583,383	682	-	-	-	640	$ 3,840	$ 712,039	71
38	S, .6	124	120	510	$ 17,760	$ 587,384	597	-	-	-	640	$ 3,840	$ 712,904	71
39	S, .6	124	120	510	$ 17,760	$ 591,231	513	-	-	-	640	$ 3,840	$ 713,735	71
40	S, .6	124	120	510	$ 17,760	$ 594,931	428	-	-	-	640	$ 3,840	$ 714,535	71
41	S, .6	124	120	510	$ 17,760	$ 598,488	344	-	-	-	640	$ 3,840	$ 715,304	71
42	S, .6	124	120	510	$ 17,760	$ 601,908	260	-	-	-	640	$ 3,840	$ 716,044	71
43	S, .6	124	120	510	$ 17,760	$ 605,196	175	-	-	-	640	$ 3,840	$ 716,755	71
44	S, .6	124	120	510	$ 17,760	$ 608,358	91	-	-	-	640	$ 3,840	$ 717,439	71
45	S, .6	124	120	510	$ 17,760	$ 611,399	6	-	-	-	640	$ 3,840	$ 718,096	71
46-59					$ 3,840	$ 618,343	6				640	$ 3,840	$ 725,040	71
60					$ 3,840	$ 618,708	6				640	$ 3,840	$ 725,405	71

Irt: Irrigation trigger: An irrigation is initiated when moisture level is at or below the indicated level

GW(aft): acre feet of ground water remaining at end of year

46-59: average acres, net revenue, cumulative NPV, GW remaining in year 59

remaining, so there was no further irrigation system investment. Dryland GS is produced from years 30 through 60. Compared to the CP system, the SDI used more water in the initial period and exhausted in 30 years as compared to 45 years for the CP system.

Net receipts, (no deduction for fixed machinery or irrigation system costs) reached $96,990 for the first three years, but declined to $35,840 by year 15. Net receipts in year 16 (with 125 acres of irrigated corn) are $35,779 but decline to $26,215 by year 30. Annual net receipts are $3,840 for years 31-60. The investment cost of the 450 acre system was not recovered until year 3 whereas the investment cost of the CP system was recovered by year 2. The 60-year cumulative NPV (at 4 percent) (with irrigation system costs deducted) reached $725,405. This compares to the cumulative NPV of the CP system which was $618,708.

An increase in the discount rate from four to seven percent (Table 27) lowers the NPV from each system but was also expected to increase the near term use of ground water and make capital investments more expensive. For the CP system, the producer still buys two pivots and irrigates 240 acres. However, the producer raises 240 acres of 213 bushel corn for six years rather than four years with the four percent discount. Grain Sorghum is grown in years 7-15. At the end of year 15 there is 2,243 acre feet of ground water remaining compared to 2,225 acre feet at the four percent discount rate.

It was profitable to drop to a 120 acre pivot in year 16 and to replace this system again in year 31. In year 16, the irrigated corn is grown, but then GS is grown for years 17 to 41. Under the seven percent discount rate, irrigation was terminated after year 41. Production was limited to dryland sorghum from years 42-60. The cumulative NPV at seven percent discount reached $448,906 by year 60.

Irrigation Systems, Water Use with 640 Acres, Limited Water, and Five Dollar Feed Grain

CP(640a, $5, 4%, Lw) If the price of corn increased from $4.48 to $5.49/bus, and the price of GS increased from $4.16 to $5.09/bus., it is anticipated all irrigation system investments would become more profitable. Table 28 shows that at the four percent discount rate, the producer would still invest in two, 120 acres pivots and then purchase one 120 acre pivot in year 16 and again in year 31.

With the higher corn price, long-term profits would be increased by growing seven years of 213 bushel irrigated corn (rather than four years with $4.48 corn) before switching to irrigated GS in year 7. Because there are four years of less intensively irrigated GS, the producer ends the first 15 year period with slightly more groundwater than was the case with four dollar feed grain.

In years 16-45, the production of five dollar GS with a single 120 acre pivot, (fed by four wells) gives similar results as with respect to water use and irrigation intensity as found with the four dollar GS. Irrigation terminated in year 45 and only dryland GS was grown in years 46-60.

Annual net returns were higher with the five dollar feed grain than with the four dollar feed grain. With the four percent discount rate, the 60-year cumulative NPV from the CP system was $1,839,290. The NPV is very sensitive to the price of feed grain. The 22 percent increase in price caused the NPV to increase by three times.

SDI(640a, $5, 4%, Lw) (Table 28) For the SDI system, higher feed grain prices made it profitable to install four, 150 SDI systems for the first 15 years. In contrast to the CP system, intensively irrigated GS was the crop of choice. The irrigation of 600 acres was not sustainable for the full 15 year period and the area of irrigated GS declined from 600 to 582 acres in year 15. There were 1818 acre feet of ground water remaining after the first 15 year period. In the second 15-year period, the irrigated area was limited to a single 125 acre system. The aquifer was exhausted by year 30 and dryland GS was grown from years 31-60.

Net receipts (no deduction of machinery fixed cost) were $208,000 in the first two years but declined to $73,600 by year 30. Dryland receipts were $41,600 over the 31-60 year period. The cumulative 60-year NPV at four percent was $2,052,066.

CP(640a, $5, 7%, Lw) Increasing the discount rate from four to seven percent naturally reduced the NPV of both investments. For the pivot system the investment pattern (240 acres in years 1-15 and 120 acres in years 16-30) remain unchanged from the four percent rate. There was more initial use of ground water as eight years of corn were produced rather than seven years with the four percent discount rate. There were seven years of corn production after the irrigated acreage was reduced from 240 to 120 acres in the second 15 year period. The rate of ground water extraction was

Table 27. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 640 Acres with 6,720 Acre Feet of Groundwater in Texas County when Corn price is $4.48 and the Grain Sorghum Price is $4.16 per Bushel and the Discount Rate is Seven Percent

	Center Pivot							Sub Surface Drip						
Year	Crop IrT	Yielc Bus	Irrig. Year	Dry Acres	640Acre Net Rev.	Cumulative NPV 4	GW (aft 6720	Crop IrT	Ir.Yielc Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulative NPV	GW (aft) GPM
1	C, .9	213	240	400	$63,840	$ (60,336)	6271	S,.9	155	500	140	$104,840	$(264,819)	6,290
2	C, .9	213	240	400	$63,840	$ (4,576)	5822	S,.9	155	500	140	$104,840	$(173,247)	5,860
3	C, .9	213	240	400	$63,356	$ 47,141	5373	S,.9	161	500	140	$105,038	$ (87,505)	5,412
4	C, .9	213	240	400	$62,880	$ 95,112	4923	S,.9	161	500	140	$105,340	$ (7,142)	4,937
5	C, .9	213	240	400	$62,874	$ 139,940	4474	S,.9	161	500	140	$104,872	$ 67,630	4,466
6	C, .9	213	240	400	$62,160	$ 181,360	4025	S,.9	147	500	140	$ 92,840	$ 129,493	4,089
7	S, .6	139	240	400	$57,152	$ 216,951	3651	S,.9	147	500	140	$ 92,840	$ 187,309	3,713
8	S, .6	139	240	400	$42,960	$ 241,954	3491	S,.9	147	500	140	$ 92,205	$ 240,974	3,339
9	S, .6	139	240	400	$42,290	$ 264,957	3324	S,.9	135	500	140	$ 80,340	$ 284,673	3,024
10	S, .7	140	240	400	$39,120	$ 284,843	3123	S,.9	135	500	140	$ 80,340	$ 325,514	2,709
11	S, .7	140	240	400	$39,120	$ 303,429	2921	S,.9	135	500	140	$ 80,340	$ 363,683	2,394
12	S, .6	134	240	400	$37,680	$ 320,159	2752	S,.9	135	500	140	$ 65,978	$ 392,978	2,031
13	S, .6	134	240	400	$37,680	$ 335,795	2582	S,.9	97	500	140	$ 45,640	$ 411,917	1,758
14	S, .6	134	240	400	$37,680	$ 350,408	2413	S,.9	97	500	140	$ 39,340	$ 427,174	1,636
15	S, .6	134	240	400	$37,680	$ 364,065	2243	S,.9	93	500	140	$ 36,340	$ 440,345	1,550
16	C, .9	213	120	520	$33,120	$ 354,960	2019	S,.9	167	125	515	$ 30,465	$ 419,942	1,418
17	S, .6	139	120	520	$23,400	$ 362,368	1939	S,.9	167	125	515	$ 30,465	$ 429,586	1,286
18	S, .6	139	120	520	$23,400	$ 369,291	1859	S,.9	167	125	515	$ 30,465	$ 438,600	1,154
19	S, .6	139	120	520	$23,400	$ 375,761	1779	S,.9	167	125	515	$ 30,295	$ 446,977	1,024
20	S, .6	139	120	520	$23,400	$ 381,808	1699	S,.9	147	125	515	$ 26,215	$ 453,751	929
21	S, .6	139	120	520	$23,400	$ 387,460	1619	S,.9	147	125	515	$ 26,215	$ 460,082	835
22	S, .6	139	120	520	$23,400	$ 392,741	1539	S,.9	147	125	515	$ 26,215	$ 465,999	741
23	S, .6	139	120	520	$23,400	$ 397,678	1459	S,.9	147	125	515	$ 26,215	$ 471,529	647
24	S, .6	139	120	520	$23,400	$ 402,291	1379	S,.9	147	125	515	$ 26,215	$ 476,698	553
25	S, .6	139	120	520	$23,400	$ 406,602	1299	S,.9	147	125	515	$ 26,215	$ 481,528	459
26	S, .6	139	120	520	$23,400	$ 410,632	1219	S,.9	147	125	515	$ 26,215	$ 486,042	364
27	S, .6	139	120	520	$23,400	$ 414,397	1139	S,.9	147	125	515	$ 26,215	$ 490,261	270
28	S, .6	139	120	520	$18,546	$ 417,187	1055	S,.9	147	125	515	$ 26,215	$ 494,203	176
29	S, .6	125	120	520	$17,760	$ 419,683	971	S,.9	147	125	515	$ 26,215	$ 497,888	82
30	S, .6	125	120	520	$17,760	$ 422,016	886	S,.9	147	125	515	$ 26,215	$ 501,332	0
31	S, .6	125	120	520	$17,760	$ 431,563	802	-	-	-	640	$ 3,840	$ 501,803	0
32	S, .6	125	120	520	$17,760	$ 433,600	717	-	-	-	640	$ 3,840	$ 502,244	0
33	S, .6	125	120	520	$17,760	$ 435,505	633	-	-	-	640	$ 3,840	$ 502,656	0
34	S, .6	125	120	520	$17,760	$ 437,285	548	-	-	-	640	$ 3,840	$ 503,041	0
35	S, .6	125	120	520	$17,760	$ 438,948	464	-	-	-	640	$ 3,840	$ 503,400	0
36	S, .6	125	120	520	$17,760	$ 440,503	380	-	-	-	640	$ 3,840	$ 503,736	0
37	S, .5	122	120	520	$17,280	$ 441,917	300	-	-	-	640	$ 3,840	$ 504,051	0
38	S, .5	122	120	520	$17,280	$ 443,238	220	-	-	-	640	$ 3,840	$ 504,344	0
39	S, .5	122	120	520	$17,280	$ 444,472	140	-	-	-	640	$ 3,840	$ 504,619	0
40	S, .5	122	120	520	$17,280	$ 445,626	60	-	-	-	640	$ 3,840	$ 504,875	0
41	S, .5	122	80.7	559	$12,884	$ 446,431	6	-	-	-	640	$ 3,840	$ 505,115	0
42	-	-	-	640	$ 3,840	$ 446,655	6	-	-	-	640	$ 3,840	$ 505,339	0
43	-	-	-	640	$ 3,840	$ 446,864	6	-	-	-	640	$ 3,840	$ 505,548	0
44	-	-	-	640	$ 3,840	$ 447,059	6	-	-	-	640	$ 3,840	$ 505,744	0
45	-	-	-	640	$ 3,840	$ 447,242	6	-	-	-	640	$ 3,840	$ 505,926	0
46-5!	-	-	-	640	$ 3,840	$ 448,841	6	-	-	-	640	$ 3,840	$ 507,525	0
60	-	-	-	640	$ 3,840	$ 448,908	6	-	-	-	640	$ 3,840	$ 507,592	0

Irt: Irrigation trigger: An irrigation is initiated when moisture level is at or below the indicated level

GW(aft): acre feet of ground water remaining at end of year

46-59: average acres, net revenue, cumulative NPV year 59, GW remaining in year 59

Table 28. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 640 Acres with 6,720 Acre Feet of Groundwater in Texas County when Corn price is $5.48 and the Grain Sorghum Price is $5.09 per Bushel and the Discount Rate is Four Percent

	Center Pivot							Sub Surface Drip						
Year	Crop IrT	Yield Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulative NPV	GW (aft) 6,720	Crop IrT	Ir.Yield Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulative NPV	GW (aft) 6,720
1	C,.9	213	240	400	$138,560	$ 13,231	6,271	S,.9	155	600	40	$ 208,400	$ (227,615)	6,204
2	C,.9	213	240	400	$138,560	$ 141,337	5,822	S,.9	155	600	40	$ 208,400	$ (34,938)	5,687
3	C,.9	213	240	400	$138,076	$ 264,086	5,373	S,.9	155	600	40	$ 201,433	$ 144,135	5,224
4	C,.9	213	240	400	$137,600	$ 381,707	4,923	S,.9	147	600	40	$ 200,000	$ 315,096	4,772
5	C,.9	213	240	400	$137,594	$ 494,799	4,474	S,.9	147	600	40	$ 191,009	$ 472,091	4,345
6	C,.9	213	240	400	$136,880	$ 602,977	4,025	S,.9	135	600	40	$ 173,600	$ 609,290	3,968
7	C,.9	213	240	400	$101,899	$ 680,412	3,833	S,.9	135	600	40	$ 173,600	$ 741,211	3,590
8	S,.6	139	240	400	$ 97,520	$ 751,669	3,673	S,.9	135	600	40	$ 162,045	$ 859,616	3,243
9	S,.6	139	240	400	$ 97,520	$ 820,185	3,513	S,.9	119	600	40	$ 143,000	$ 960,086	2,949
10	S,.6	139	240	400	$ 97,196	$ 885,847	3,353	S,.9	119	600	40	$ 143,000	$ 1,056,692	2,654
11	S,.6	139	240	400	$ 91,040	$ 944,985	3,183	S,.9	119	600	40	$ 143,000	$ 1,149,582	2,360
12	S,.6	134	240	400	$ 91,040	$ 1,001,848	3,014	S,.9	119	600	40	$ 117,095	$ 1,222,719	2,173
13	S,.6	134	240	400	$ 91,040	$ 1,056,525	2,844	S,.9	93	600	40	$ 97,400	$ 1,281,215	2,070
14	S,.6	134	240	400	$ 91,040	$ 1,109,098	2,675	S,.9	93	600	40	$ 97,400	$ 1,337,461	1,966
15	S,.6	134	240	400	$ 91,040	$ 1,159,649	2,505	S,.9	93	582	58	$ 102,016	$ 1,394,107	1,818
16	S,.6	134	120	520	$ 89,840	$ 1,175,581	2,281	C,.9	144	125	515	$ 93,100	$ 1,395,389	1,582
17	C,.9	213	120	520	$ 69,612	$ 1,211,318	2,201	C,.9	215	125	515	$ 93,100	$ 1,443,184	1,347
18	S,.6	139	120	520	$ 69,560	$ 1,245,655	2,121	C,.9	215	125	515	$ 93,100	$ 1,489,141	1,111
19	S,.6	139	120	520	$ 69,560	$ 1,278,671	2,041	C,.9	215	125	515	$ 73,953	$ 1,524,242	1,015
20	S,.6	139	120	520	$ 69,560	$ 1,310,418	1,961	S,.9	147	125	515	$ 73,600	$ 1,557,832	921
21	S,.6	139	120	520	$ 69,560	$ 1,340,943	1,881	S,.9	147	125	515	$ 73,600	$ 1,590,130	827
22	S,.6	139	120	520	$ 69,560	$ 1,370,294	1,801	S,.9	147	125	515	$ 73,600	$ 1,621,186	733
23	S,.6	139	120	520	$ 69,560	$ 1,398,516	1,721	S,.9	147	125	515	$ 73,600	$ 1,651,048	638
24	S,.6	139	120	520	$ 69,560	$ 1,425,653	1,641	S,.9	147	125	515	$ 73,600	$ 1,679,761	544
25	S,.6	139	120	520	$ 69,560	$ 1,451,746	1,561	S,.9	147	125	515	$ 73,600	$ 1,707,369	450
26	S,.6	139	120	520	$ 69,560	$ 1,476,836	1,481	S,.9	147	125	515	$ 73,600	$ 1,733,916	356
27	S,.6	139	120	520	$ 69,560	$ 1,500,960	1,401	S,.9	147	125	515	$ 73,600	$ 1,759,442	262
28	S,.6	139	120	520	$ 69,560	$ 1,524,157	1,321	S,.9	147	125	515	$ 73,600	$ 1,783,986	167
29	S,.6	139	120	520	$ 69,560	$ 1,546,461	1,241	S,.9	147	125	515	$ 73,600	$ 1,807,585	73
30	S,.6	139	120	520	$ 69,560	$ 1,567,908	1,161	S,.9	147	125	515	$ 73,600	$ 1,830,278	0
31	S,.6	139	120	520	$ 65,000	$ 1,569,390	1,078	S,.9	147	0	640	$ 41,600	$ 1,842,610	0
32	S,.6	139	120	520	$ 62,360	$ 1,587,166	994	-	-	0	640	$ 41,600	$ 1,854,469	0
33	S,.6	125	120	520	$ 62,360	$ 1,604,259	909	-	-	0	640	$ 41,600	$ 1,865,871	0
34	S,.6	125	120	520	$ 62,360	$ 1,620,694	825	-	-	0	640	$ 41,600	$ 1,876,835	0
35	S,.6	125	120	520	$ 62,360	$ 1,636,497	740	-	-	0	640	$ 41,600	$ 1,887,377	0
36	S,.6	125	120	520	$ 62,360	$ 1,651,692	656	-	-	0	640	$ 41,600	$ 1,897,514	0
37	S,.6	125	120	520	$ 62,360	$ 1,666,303	571	-	-	0	640	$ 41,600	$ 1,907,260	0
38	S,.6	125	120	520	$ 61,640	$ 1,680,189	491	-	-	0	640	$ 41,600	$ 1,916,632	0
39	S,.5	122	120	520	$ 61,640	$ 1,693,542	411	-	-	0	640	$ 41,600	$ 1,925,644	0
40	S,.5	122	120	520	$ 61,640	$ 1,706,381	331	-	-	0	640	$ 41,600	$ 1,934,308	0
41	S,.5	122	120	520	$ 61,640	$ 1,718,726	251	-	-	0	640	$ 41,600	$ 1,942,640	0
42	S,.5	122	120	520	$ 61,640	$ 1,730,596	171	-	-	0	640	$ 41,600	$ 1,950,651	0
43	S,.5	122	120	520	$ 61,640	$ 1,742,010	91	-	-	0	640	$ 41,600	$ 1,958,354	0
44	S,.5	122	120	520	$ 61,640	$ 1,752,985	11	-	-	0	640	$ 41,600	$ 1,965,761	0
45	S,.5	122	0	640	$ 41,600	$ 1,760,106	11	-	-	0	640	$ 41,600	$ 1,972,883	0
46-59	-	-	0	640	$ 41,600	$ 1,835,335	11	-	-	0	640	$ 41,600	$ 2,048,111	0
60	-	-	0	640	$ 41,600	$ 1,839,290	11	-	-	0	640	$ 41,600	$ 2,052,066	0

Irt: Irrigation trigger: An irrigation is initiated when moisture level is at or below the indicated level

GW(aft): acre feet of ground water remaining at end of year

46-59: average acres, net revenue, cumulative NPV year 59, GW remaining in year 59

increased and irrigation was terminated with aquifer exhaustion in year 30 as opposed to year 45 in the four percent discount case.

SDI(640a, $5, 7%, Lw) The increase in the discount rate from four to seven percent caused the initial irrigated area to decline from 600 to 500 acres (four 125-acres systems). This might be anticipated because the higher initial cost of the SDI system makes it more sensitive to increased discount rates. Irrigated GS was the crop of choice for the first 13 years. Irrigated corn was produced in years 14 and 15. This can occur when the model anticipates the scarcity of water may be reduced relative to the scarcity of irrigated land if the irrigated area will soon be reduced. The irrigated area was reduced to a single 125 acre drip system for years 16-30 but irrigation terminated with aquifer exhaustion in year 29. Dryland GS was produced for years 30-60.

In the limited water situation examined above, the SDI system was more profitable than the conventional CP system under both four dollar and five dollar feed grain prices. The SDI was also more profitable than the CP under both four and seven percent discount rates.

Table 29. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 640 Acres with 6,720 Acre Feet of Groundwater in Texas County when Corn price is $5.48 and the Grain Sorghum Price is $5.09 per Bushel and the Discount Rate is Seven Percent

	Center Pivot							Sub Surface Drip						
Year	Crop IrT	Yield Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulative NPV	GW (aft) 6720	Crop IrT	Ir.Yield Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulative NPV	GW (aft) 6720
1	C,.9	213	240	400	$ 138,560	$ 9,495	6271	S,.9	161	500	140	$ 188,100	$ (187,006)	6245
2	C,.9	213	240	400	$ 138,560	$ 130,519	5822	S,.9	161	500	140	$ 188,100	$ (22,712)	5771
3	C,.9	213	240	400	$ 138,076	$ 243,230	5373	S,.9	161	500	140	$ 186,495	$ 129,524	5325
4	C,.9	213	240	400	$ 137,600	$ 348,204	4923	S,.9	155	500	140	$ 185,600	$ 271,117	4894
5	C,.9	213	240	400	$ 137,594	$ 446,307	4474	S,.9	155	500	140	$ 184,982	$ 403,006	4466
6	C,.9	213	240	400	$ 136,880	$ 537,516	4025	S,.9	147	500	140	$ 169,100	$ 515,685	4089
7	C,.9	213	240	400	$ 136,880	$ 622,758	3576	S,.9	147	500	140	$ 169,100	$ 620,992	3713
8	C,.9	213	240	400	$ 114,281	$ 689,270	3260	S,.9	147	500	140	$ 168,211	$ 718,892	3339
9	S,.6	134	240	400	$ 91,040	$ 738,790	3091	S,.9	135	500	140	$ 151,600	$ 801,353	3024
10	S,.6	134	240	400	$ 91,040	$ 785,070	2921	S,.9	135	500	140	$ 151,600	$ 878,418	2709
11	S,.6	134	240	400	$ 91,040	$ 828,323	2752	S,.9	135	500	140	$ 151,600	$ 950,443	2394
12	S,.6	134	240	400	$ 91,040	$ 868,746	2582	S,.9	135	500	140	$ 141,695	$ 1,013,357	2031
13	S,.6	134	240	400	$ 91,040	$ 906,524	2413	C, .9	144	500	140	$ 131,600	$ 1,067,966	1620
14	S,.6	134	240	400	$ 91,040	$ 941,831	2243	C, .9	144	500	140	$ 113,887	$ 1,112,134	1343
15	S,.6	134	240	400	$ 82,880	$ 971,870	2075	S,.6	90	500	140	$ 85,100	$ 1,142,978	1284
16	S,.6	125	120	520	$ 89,360	$ 981,816	1850	S,.9	167	125	515	$ 80,225	$ 1,139,430	1152
17	C,.9	213	120	520	$ 89,360	$ 1,010,105	1625	S,.9	167	125	515	$ 79,632	$ 1,164,639	1023
18	C,.9	213	120	520	$ 89,360	$ 1,036,543	1401	S,.9	147	125	515	$ 73,600	$ 1,186,415	929
19	C,.9	213	120	520	$ 89,360	$ 1,061,252	1176	S,.9	147	125	515	$ 73,600	$ 1,206,766	835
20	C,.9	213	120	520	$ 73,360	$ 1,080,209	988	S,.9	147	125	515	$ 73,600	$ 1,225,785	741
21	C,.9	213	120	520	$ 68,240	$ 1,096,690	812	S,.9	147	125	515	$ 73,600	$ 1,243,561	646
22	C,.9	164	120	520	$ 64,212	$ 1,111,184	701	S,.9	147	125	515	$ 73,600	$ 1,260,173	552
23	C,.9	164	120	520	$ 63,320	$ 1,124,541	605	S,.8	141	125	515	$ 71,475	$ 1,275,251	468
24	S,.7	129	120	520	$ 63,320	$ 1,137,024	508	S,.8	141	125	515	$ 71,475	$ 1,289,342	384
25	S,.7	129	120	520	$ 62,360	$ 1,148,514	424	S,.8	141	125	515	$ 71,475	$ 1,302,511	300
26	S,.6	125	120	520	$ 62,360	$ 1,159,252	339	S,.8	141	125	515	$ 71,475	$ 1,314,818	215
27	S,.6	125	120	520	$ 62,360	$ 1,169,288	255	S,.7	134	125	515	$ 68,600	$ 1,325,858	141
28	S,.6	125	120	520	$ 62,360	$ 1,178,667	170	S,.7	134	125	515	$ 68,600	$ 1,336,176	66
29	S,.6	125	120	520	$ 62,360	$ 1,187,432	86	S,.7	134	125	515	$ 68,600	$ 1,345,818	0
30	S,.6	125	120	520	$ 62,360	$ 1,195,624	1	-	-	-	640	$ 41,600	$ 1,351,283	0
31	S,.6	125	-	640	$ 41,600	$ 1,200,732	1	-	-	-	640	$ 41,600	$ 1,356,391	0
32	-	-	-	640	$ 41,600	$ 1,205,505	1	-	-	-	640	$ 41,600	$ 1,361,164	0
33	-	-	-	640	$ 41,600	$ 1,209,966	1	-	-	-	640	$ 41,600	$ 1,365,625	0
34	-	-	-	640	$ 41,600	$ 1,214,135	1	-	-	-	640	$ 41,600	$ 1,369,794	0
35	-	-	-	640	$ 41,600	$ 1,218,032	1	-	-	-	640	$ 41,600	$ 1,373,690	0
36	-	-	-	640	$ 41,600	$ 1,221,673	1	-	-	-	640	$ 41,600	$ 1,377,332	0
37	-	-	-	640	$ 41,600	$ 1,225,076	1	-	-	-	640	$ 41,600	$ 1,380,735	0
38	-	-	-	640	$ 41,600	$ 1,228,257	1	-	-	-	640	$ 41,600	$ 1,383,916	0
39	-	-	-	640	$ 41,600	$ 1,231,229	1	-	-	-	640	$ 41,600	$ 1,386,888	0
40	-	-	-	640	$ 41,600	$ 1,234,007	1	-	-	-	640	$ 41,600	$ 1,389,666	0
41	-	-	-	640	$ 41,600	$ 1,236,604	1	-	-	-	640	$ 41,600	$ 1,392,263	0
42	-	-	-	640	$ 41,600	$ 1,239,030	1	-	-	-	640	$ 41,600	$ 1,394,689	0
43	-	-	-	640	$ 41,600	$ 1,241,298	1	-	-	-	640	$ 41,600	$ 1,396,957	0
44	-	-	-	640	$ 41,600	$ 1,243,417	1	-	-	-	640	$ 41,600	$ 1,399,076	0
45	-	-	-	640	$ 41,600	$ 1,245,398	1	-	-	-	640	$ 41,600	$ 1,401,057	0
46-59	-	-	-	640	$ 41,600	$ 1,221,673		-	-	-	640	$ 41,600	$ 1,418,379	0
60	-	-	-	640	$ 41,600	$ 1,225,076		-	-	-	640	$ 41,600	$ 1,419,097	0

Irt: Irrigation trigger: An irrigation is initiated when moisture level is at or below the indicated level

GW(aft): acre feet of ground water remaining at end of year

46-59: average acres, net revenue, cumulative NPV year 59, GW remaining in year 59

Irrigation Systems, Water Use with 640 Acres, High Water, and Four Dollar Feed Grain

In the solution below, the results for the producer with 640 acres are repeated with the assumption that the producer is more isolated and can draw water from twice as much land (1,280 acres) as is farmed. The producer is assumed to have 4 tied wells with 60 feet of water saturated sand and can use up to 13,440 acre feet. The planning horizon is 60 years.

CP(640a, $4, 4%, Hw) (Table 30) The increased groundwater supply did not change to the optimal CP investment pattern (2, 120 acre pivots) from the limited water situation under the lower feed grain prices in the first 15 years. However, irrigated corn was grown for 13 years before the switch was made to irrigated sorghum. During the second 15 year period, two 120-acre pivots were used as opposed to one pivot under the low water situation. The irrigated acres declined to 120 acres during the 31-45 year period and 120 acres were irrigated during the 46-60 year period. A second 10-year period of irrigated corn production began when the irrigated area declined from 240 the 120 acres in year 31. Aquifer depletion occurred at the end of year 59.

As anticipated the increased water supply increased annual net returns for longer periods than was possible with the limited water case. The cumulative CP NPV at 4% reached $850,152 by year 60

SDI(640a, $4, 4%, Hw) The SDI system showed more sensitivity to the increased water supply than did the CP system. Six hundred of the 640 acres were developed for irrigation purchasing four 150 systems in years 1-15. In years 16-30, three 125 acre systems were used, and a single 125 acre systems were used during years 31-45 and years 46-60. Aquifer depletion occurred in year 60. (Table 30)

Intensively irrigated GS grown in the SDI system for the entire 60 year period. Initial annual returns were in excess of $100,000 for the 10 years because of the larger area irrigated. The 60-year cumulative NPV at 4% reached $1,120,173.

CP(640a, $4, 7%, Hw) An increase in the discount rate (Table 31) with other factors held constant is expected to encourage near term resource use and discourage capital intensive investments. The optimal investment pattern of 30 years with one 120 acre CP system used for years 31-45. Aquifer depletion occurred in year 45 and the last 15 years were dryland production. This was accomplished in part by a longer (15-year) period of intensively irrigated corn. (The period of corn production was limited to 13 years with the four percent discount rate). The second period of corn production (years 31-36) was limited to six years. Again, the corn production began when only one quarter section was irrigated and the pivot could be fed by three wells. The 60-year cumulative CP NPV was $569,682.

SDI(640a, $4, 7%, Hw) The optimal pattern of SDI investment (Table 31) was also unchanged, 600 acres (4 150-acre SDI systems) for the first 15 years. However only 2 125-acre systems were used in years 16-30 followed by single 125-acre systems in years 31-45 and years 46-60. Intensively irrigated grain sorghum was produced in most years. Three years of irrigated corn were produced following the acre reduction from 600 to 250 (when two wells could feed each system). Irrigated corn was again produced when further downsizing occurred in year 31 when four wells could tie into a single system. Aquifer depletion occurred in year 60. The cumulative 60-year NPV at seven percent reached $739,125.

Table 30. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 640 Acres with 13,440 Acre Feet of Groundwater in Texas County when Corn price is $4.48 and the Grain Sorghum Price is $4.16 per Bushel and the Discount Rate is Four Percent

	Center Pivot							Sub Surface Drip						
Year	Crop IrT	Yiel Bus	Irrig. Acre:	Dry Acre:	640Acre Net Rev.	Cumulative NPV 4	GW (af 13440	Crop IrT	Yiel Bus	Irrig. Acres	Dry Acre:	640Acre Net Rev.	Cumulative NPV @4%	GW (aft) 13440
1	C,.9	213	240	400	$ 63,840	$ (58,615)	12991	S,.9	155	600	40	$ 119,040	$ (313,538)	12924
2	C,.9	213	240	400	$ 63,840	$ 408	12542	S,.9	155	600	40	$ 119,040	$ (203,479)	12407
3	C,.9	213	240	400	$ 63,840	$ 57,162	12093	S,.9	155	600	40	$ 119,040	$ (97,653)	11891
4	C,.9	213	240	400	$ 63,840	$ 111,732	11643	S,.9	155	600	40	$ 119,040	$ 4,103	11375
5	C,.9	213	240	400	$ 63,831	$ 164,197	11194	S,.9	155	600	40	$ 117,063	$ 100,320	10901
6	C,.9	213	240	400	$ 62,880	$ 213,892	10745	S,.9	147	600	40	$ 116,040	$ 192,028	10449
7	C,.9	213	240	400	$ 62,880	$ 261,676	10296	S,.9	147	600	40	$ 116,040	$ 280,209	9997
8	C,.9	213	240	400	$ 62,880	$ 307,622	9847	S,.9	147	600	40	$ 116,040	$ 364,998	9545
9	C,.9	213	240	400	$ 62,880	$ 351,800	9398	S,.9	147	600	40	$ 116,040	$ 446,526	9093
10	C,.9	213	240	400	$ 62,867	$ 394,271	8949	S,.9	147	600	40	$ 102,145	$ 515,532	8691
11	C,.9	213	240	400	$ 62,160	$ 434,649	8500	S,.9	135	600	40	$ 95,640	$ 577,658	8313
12	C,.9	213	240	400	$ 62,160	$ 473,474	8050	S,.9	135	600	40	$ 95,640	$ 637,394	7935
13	C,.9	213	240	400	$ 62,160	$ 510,806	7601	S,.9	135	600	40	$ 95,640	$ 694,833	7557
14	S,.6	139	240	400	$ 55,462	$ 542,833	7253	S,.9	135	600	40	$ 95,640	$ 750,063	7179
15	S,.6	139	240	400	$ 42,960	$ 566,687	7093	S,.9	135	600	40	$ 95,640	$ 803,168	6801
16	S,.6	139	240	400	$ 42,960	$ 525,555	6933	S,.9	155	375	265	$ 73,547	$ 697,160	6507
17	S,.6	139	240	400	$ 42,960	$ 547,610	6773	S,.9	147	375	265	$ 70,965	$ 733,591	6225
18	S,.6	139	240	400	$ 40,430	$ 567,567	6586	S,.9	147	375	265	$ 70,965	$ 768,621	5942
19	S,.7	140	240	400	$ 39,120	$ 586,135	6384	S,.9	147	375	265	$ 70,965	$ 802,304	5659
20	S,.7	140	240	400	$ 39,120	$ 603,989	6182	S,.9	147	375	265	$ 70,965	$ 834,692	5377
21	S,.6	134	240	400	$ 37,680	$ 620,524	6013	S,.9	147	375	265	$ 70,965	$ 865,834	5094
22	S,.6	134	240	400	$ 37,680	$ 636,424	5844	S,.9	147	375	265	$ 70,965	$ 895,778	4812
23	S,.6	134	240	400	$ 37,680	$ 651,711	5674	S,.9	147	375	265	$ 70,965	$ 924,570	4529
24	S,.6	134	240	400	$ 37,680	$ 666,411	5505	S,.9	147	375	265	$ 47,664	$ 943,165	4227
25	S,.6	134	240	400	$ 37,680	$ 680,546	5335	C,.9	144	375	265	$ 39,840	$ 958,109	3919
26	S,.6	134	240	400	$ 37,680	$ 694,136	5166	C,.9	144	375	265	$ 39,840	$ 972,479	3610
27	S,.6	134	240	400	$ 37,680	$ 707,204	4996	S,.9	97	375	265	$ 35,769	$ 984,885	3396
28	S,.6	134	240	400	$ 37,680	$ 719,770	4827	S,.9	97	375	265	$ 30,465	$ 995,044	3305
29	S,.6	134	240	400	$ 37,680	$ 731,852	4657	S,.9	97	375	265	$ 30,465	$ 1,004,813	3214
30	S,.6	134	240	400	$ 37,680	$ 743,469	4488	S,.9	93	375	265	$ 28,215	$ 1,013,512	3149
31	C,.9	213	120	520	$ 33,120	$ 735,500	4263	C,.9	215	125	515	$ 35,840	$ 997,248	2913
32	C,.9	213	120	520	$ 33,120	$ 744,941	4039	S,.9	167	125	515	$ 30,465	$ 1,005,932	2781
33	C,.9	213	120	520	$ 33,120	$ 754,019	3814	S,.9	167	125	515	$ 30,465	$ 1,014,282	2649
34	C,.9	213	120	520	$ 33,120	$ 762,748	3590	S,.9	167	125	515	$ 30,465	$ 1,022,312	2517
35	C,.9	213	120	520	$ 33,120	$ 771,141	3365	S,.9	167	125	515	$ 30,465	$ 1,030,032	2386
36	C,.9	213	120	520	$ 33,120	$ 779,211	3141	S,.9	167	125	515	$ 30,465	$ 1,037,455	2254
37	C,.9	213	120	520	$ 33,120	$ 786,971	2916	S,.9	167	125	515	$ 29,558	$ 1,044,381	2130
38	C,.9	213	120	520	$ 33,120	$ 794,433	2691	S,.9	147	125	515	$ 26,215	$ 1,050,286	2036
39	C,.9	213	120	520	$ 33,120	$ 801,607	2467	S,.9	147	125	515	$ 26,215	$ 1,055,965	1941
40	C,.9	213	120	520	$ 32,863	$ 808,452	2244	S,.9	147	125	515	$ 26,215	$ 1,061,425	1847
41	S,.9	134	120	520	$ 18,720	$ 812,201	2129	S,.9	147	125	515	$ 26,215	$ 1,066,676	1753
42	S,.9	134	120	520	$ 18,720	$ 815,806	2014	S,.9	147	125	515	$ 26,215	$ 1,071,724	1659
43	S,.9	134	120	520	$ 18,720	$ 819,273	1899	S,.9	147	125	515	$ 26,215	$ 1,076,578	1565
44	S,.9	134	120	520	$ 18,720	$ 822,606	1784	S,.9	147	125	515	$ 26,215	$ 1,081,246	1471
45	S,.9	134	120	520	$ 18,720	$ 825,811	1669	S,.9	147	125	515	$ 26,215	$ 1,085,734	1376
46-59	S,.9	134	120	520	$ 18,720	$ 849,787	60	S,.9	147	125	515	$ 26,215	$ 1,118,211	58
60	-	-	0	640	$ 3,840	$ 850,152	60	S,.9	147	125	515	$ 26,215	$ 1,120,703	0

Irt: Irrigation trigger: An irrigation is initiated when moisture level is at or below the indicated level

GW(aft): acre feet of ground water remaining at end of year

46-59: average acres, net revenue, cumulative NPV, GW remaining in year 59

Table 31. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 640 Acres with 13,440 Acre Feet of Groundwater in Texas County when Corn price is $4.48 and the Grain Sorghum Price is $4.16 per Bushel and the Discount Rate is Seven Percent

	Center Pivot							Sub Surface Drip						
Year	Crop IrT	Yielc Bus	Irrig. Acre:	Dry Acre	640Acre Net Rev.	Cumulative NPV 4	GW (aft) 13440	Crop IrT	Yield Bus	Irrig Acre	Dry Acres	640Acre Net Rev.	Cumulative NPV @4%	GW (aft) 13440
1	C,.9	213	240	400	$ 63,840	$ (60,336)	12,991	S,.9	155	600	40	$119,040	$(316,748)	12,924
2	C,.9	213	240	400	$ 63,840	$ (4,576)	12,542	S,.9	155	600	40	$119,040	$(212,774)	12,407
3	C,.9	213	240	400	$ 63,840	$ 47,536	12,093	S,.9	155	600	40	$119,040	$(115,601)	11,891
4	C,.9	213	240	400	$ 63,840	$ 96,240	11,643	S,.9	155	600	40	$119,040	$ (24,786)	11,375
5	C,.9	213	240	400	$ 63,831	$ 141,751	11,194	S,.9	155	600	40	$117,063	$ 58,678	10,901
6	C,.9	213	240	400	$ 62,880	$ 183,650	10,745	S,.9	147	600	40	$116,040	$ 136,000	10,449
7	C,.9	213	240	400	$ 62,880	$ 222,809	10,296	S,.9	147	600	40	$116,040	$ 208,264	9,997
8	C,.9	213	240	400	$ 62,880	$ 259,405	9,847	S,.9	147	600	40	$116,040	$ 275,801	9,545
9	C,.9	213	240	400	$ 62,880	$ 293,608	9,398	S,.9	147	600	40	$116,040	$ 338,919	9,093
10	C,.9	213	240	400	$ 62,867	$ 325,566	8,949	S,.9	147	600	40	$102,145	$ 390,844	8,691
11	C,.9	213	240	400	$ 62,160	$ 355,098	8,500	S,.9	135	600	40	$ 95,640	$ 436,282	8,313
12	C,.9	213	240	400	$ 62,160	$ 382,698	8,050	S,.9	135	600	40	$ 95,640	$ 478,747	7,935
13	C,.9	213	240	400	$ 62,160	$ 408,492	7,601	S,.9	135	600	40	$ 95,640	$ 518,434	7,557
14	C,.9	213	240	400	$ 62,160	$ 432,599	7,152	S,.9	135	600	40	$ 95,640	$ 555,525	7,179
15	C,.9	213	240	400	$ 61,595	$ 454,924	6,708	S,.9	135	600	40	$ 95,640	$ 590,189	6,801
16	S,.9	148	240	400	$ 41,040	$ 428,177	6,449	C,.9	215	250	390	$ 62,169	$ 549,802	6,373
17	S,.7	140	240	400	$ 39,120	$ 440,562	6,248	C,.9	202	250	390	$ 60,840	$ 569,063	5,956
18	S,.7	140	240	400	$ 39,120	$ 452,136	6,046	C,.9	202	250	390	$ 57,077	$ 585,950	5,656
19	S,.7	140	240	400	$ 39,120	$ 462,953	5,844	S,.9	161	250	390	$ 55,090	$ 601,182	5,419
20	S,.7	140	240	400	$ 39,120	$ 473,062	5,643	S,.9	161	250	390	$ 55,090	$ 615,419	5,182
21	S,.7	140	240	400	$ 39,120	$ 482,510	5,441	S,.9	161	250	390	$ 55,090	$ 628,724	4,944
22	S,.7	140	240	400	$ 39,120	$ 491,340	5,240	S,.9	161	250	390	$ 55,090	$ 641,158	4,707
23	S,.6	134	240	400	$ 37,680	$ 499,289	5,070	S,.9	161	250	390	$ 55,090	$ 652,779	4,470
24	S,.6	134	240	400	$ 37,680	$ 506,717	4,901	S,.9	147	250	390	$ 48,590	$ 662,359	4,281
25	S,.6	134	240	400	$ 37,680	$ 513,660	4,731	S,.9	147	250	390	$ 48,590	$ 671,311	4,093
26	S,.6	134	240	400	$ 37,680	$ 520,148	4,562	S,.9	147	250	390	$ 48,590	$ 679,678	3,905
27	S,.6	134	240	400	$ 35,085	$ 525,794	4,380	S,.9	147	250	390	$ 48,590	$ 687,498	3,716
28	S,.7	129	240	400	$ 32,640	$ 530,703	4,187	S,.9	147	250	390	$ 48,590	$ 694,806	3,528
29	S,.7	129	240	400	$ 31,440	$ 535,123	4,018	S,.9	147	250	390	$ 48,590	$ 701,636	3,340
30	S,.6	125	240	400	$ 31,440	$ 539,253	3,849	S,.9	147	250	390	$ 48,590	$ 708,019	3,151
31	S,.6	125	120	520	$ 33,120	$ 535,953	3,625	C,.9	215	125	515	$ 35,840	$ 701,283	2,916
32	C,.9	213	120	520	$ 33,120	$ 539,753	3,400	C,.9	215	125	515	$ 35,840	$ 705,395	2,680
33	C,.9	213	120	520	$ 33,120	$ 543,305	3,175	C,.9	215	125	515	$ 31,017	$ 708,722	2,538
34	C,.9	213	120	520	$ 33,120	$ 546,624	2,951	S,.9	167	125	515	$ 30,465	$ 711,775	2,406
35	C,.9	213	120	520	$ 33,120	$ 549,726	2,726	S,.9	167	125	515	$ 30,465	$ 714,628	2,274
36	C,.9	213	120	520	$ 33,120	$ 552,626	2,502	S,.9	167	125	515	$ 27,802	$ 717,062	2,165
37	C,.9	213	120	520	$ 30,306	$ 555,105	2,319	S,.9	147	125	515	$ 26,215	$ 719,206	2,071
38	S,.6	139	120	520	$ 23,400	$ 556,894	2,239	S,.9	147	125	515	$ 26,215	$ 721,211	1,977
39	S,.6	139	120	520	$ 18,720	$ 558,232	2,124	S,.9	147	125	515	$ 26,215	$ 723,084	1,883
40	S,.9	134	120	520	$ 18,720	$ 559,482	2,009	S,.9	147	125	515	$ 26,215	$ 724,835	1,789
41	S,.9	134	120	520	$ 18,720	$ 560,650	1,894	S,.9	147	125	515	$ 26,215	$ 726,471	1,695
42	S,.9	134	120	520	$ 18,720	$ 561,742	1,779	S,.9	147	125	515	$ 26,215	$ 728,000	1,600
43	S,.9	134	120	520	$ 18,720	$ 562,762	1,664	S,.9	147	125	515	$ 26,215	$ 729,429	1,506
44	S,.9	134	120	520	$ 18,720	$ 563,716	1,549	S,.9	147	125	515	$ 26,215	$ 730,764	1,412
45	S,.9	134	120	520	$ 18,720	$ 564,607	1,434	S,.9	147	125	515	$ 26,215	$ 732,013	1,318
46-59	S, .7	131	120	520	$ 18,360	$ 569,616	4	S, .8	145	125	515	$ 25,679	$ 738,733	49
60	S, .6	125	0	640	$ 3,840	$ 569,682	4	S ,.7	133.7	125	515	$ 22,715	$ 739,125	-

Irt: Irrigation trigger: An irrigation is initiated when moisture level is at or below the indicated level
GW(aft): acre feet of ground water remaining at end of year
46-59: average acres, net revenue, cumulative NPV, GW remaining in year 59

Irrigation Systems, Water Use with 640 Acres, High Water, and Five Dollar Feed Grain

CP(640a, $5, 4%, Hw) (Table 32) An increase in the feed grain price from $4 to $5 did not change the optimal CP investment pattern (2, 120 acre pivots) from the limited water situation under the lower feed grain prices in the first 15 years. Until year 15, the CP system produces corn at full irrigation (IrT.90) then it switches to grain sorghum at .7 stress during the transformation period (year 16), however, grain sorghum continues until the pivot is replaced (year 30) at IrT .6. From year 31-44, corn is grown with full irrigation on a 120-acre field, leaving the rest of the land for dryland practices. The changes between irrigated corn and sorghum are determined by the relative area of land with equipment for irrigation and the remaining groundwater supply. Corn is grown when the supply of groundwater is large relative to the land under irrigation. In Table 32 in year 30, the producer has 240 acres under two pivots. In year 31, there is only one pivot so land that can be irrigated becomes scarce relative to the supply of groundwater. However as the ground water supply becomes more depleted and limiting, it is optimal to switch back to grain sorghum. One pivot is purchased at the year 46 to irrigated sorghum till year 59 leaving 456 acre feet of water in the aquifer.

Table 32. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 640 Acres with 13,440 Acre Feet of Groundwater in Texas County when Corn price is $5.48 and the Grain Sorghum Price is $5.09 per Bushel and the Discount Rate is Four Percent

	Center Pivot							Sub Surface Drip						
Year	Crop IrT	Yield Bus	Irrig. Acre:	Dry Acres	640Acre Net Rev.	Cumulative NPV	GW (aft) 13,440	Crop IrT	Yield Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulative NPV	GW (aft) 13,440
1	C,.9	213	240	400	$ 138,560	$ 13,231	12,991	S,.9	155	600	40	$ 208,400	$ (227,615)	12,924
2	C,.9	213	240	400	$ 138,560	$ 141,337	12,542	S,.9	155	600	40	$ 208,400	$ (34,938)	12,407
3	C,.9	213	240	400	$ 138,560	$ 264,517	12,093	S,.9	155	600	40	$ 208,400	$ 150,329	11,891
4	C,.9	213	240	400	$ 138,560	$ 382,958	11,643	S,.9	155	600	40	$ 208,400	$ 328,470	11,375
5	C,.9	213	240	400	$ 138,551	$ 496,837	11,194	S,.9	155	600	40	$ 202,865	$ 495,210	10,901
6	C,.9	213	240	400	$ 137,600	$ 605,585	10,745	S,.9	147	600	40	$ 200,000	$ 653,273	10,449
7	C,.9	213	240	400	$ 137,600	$ 710,149	10,296	S,.9	147	600	40	$ 200,000	$ 805,257	9,997
8	C,.9	213	240	400	$ 137,600	$ 810,692	9,847	S,.9	147	600	40	$ 200,000	$ 951,395	9,545
9	C,.9	213	240	400	$ 137,600	$ 907,368	9,398	S,.9	147	600	40	$ 200,000	$ 1,091,912	9,093
10	C,.9	213	240	400	$ 137,587	$ 1,000,317	8,949	S,.9	147	600	40	$ 182,018	$ 1,214,877	8,691
11	C,.9	213	240	400	$ 136,880	$ 1,089,232	8,500	S,.9	135	600	40	$ 173,600	$ 1,327,644	8,313
12	C,.9	213	240	400	$ 136,880	$ 1,174,727	8,050	S,.9	135	600	40	$ 173,600	$ 1,436,074	7,935
13	C,.9	213	240	400	$ 136,880	$ 1,256,933	7,601	S,.9	135	600	40	$ 173,600	$ 1,540,334	7,557
14	C,.9	213	240	400	$ 136,880	$ 1,335,978	7,152	S,.9	135	600	40	$ 173,600	$ 1,640,583	7,179
15	C,.9	213	240	400	$ 135,731	$ 1,411,345	6,703	S,.9	135	600	40	$ 173,600	$ 1,736,977	6,801
16	S,.7	140	120	520	$ 93,920	$ 1,397,420	6,479	C,.9	215	250	390	$ 136,520	$ 1,713,015	6,373
17	S,.7	140	120	520	$ 93,920	$ 1,445,636	6,254	C,.9	202	250	390	$ 134,600	$ 1,782,115	5,956
18	S,.6	134	120	520	$ 91,040	$ 1,490,576	6,030	C,.9	202	250	390	$ 134,600	$ 1,848,558	5,539
19	S,.6	134	120	520	$ 91,040	$ 1,533,788	5,805	C,.9	202	250	390	$ 134,600	$ 1,912,444	5,121
20	S,.6	134	120	520	$ 91,040	$ 1,575,337	5,581	C,.9	202	250	390	$ 134,600	$ 1,973,874	4,704
21	S,.6	134	120	520	$ 91,040	$ 1,615,288	5,356	S,.9	161	250	390	$ 115,235	$ 2,024,443	4,467
22	S,.6	134	120	520	$ 91,040	$ 1,653,703	5,131	S,.9	147	250	390	$ 105,600	$ 2,069,001	4,279
23	S,.6	134	120	520	$ 91,040	$ 1,690,640	4,907	S,.9	147	250	390	$ 105,600	$ 2,111,846	4,090
24	S,.6	134	120	520	$ 91,040	$ 1,726,157	4,682	S,.9	147	250	390	$ 105,600	$ 2,153,043	3,902
25	S,.6	134	120	520	$ 91,040	$ 1,760,308	4,458	S,.9	147	250	390	$ 105,600	$ 2,192,655	3,714
26	S,.6	134	120	520	$ 91,040	$ 1,793,145	4,233	S,.9	147	250	390	$ 105,600	$ 2,230,744	3,525
27	S,.6	134	120	520	$ 91,040	$ 1,824,719	4,009	S,.9	147	250	390	$ 105,600	$ 2,267,368	3,337
28	S,.6	134	120	520	$ 88,981	$ 1,854,392	3,784	S,.9	147	250	390	$ 105,600	$ 2,302,583	3,149
29	S,.6	125	120	520	$ 82,880	$ 1,880,968	3,560	S,.9	147	250	390	$ 105,600	$ 2,336,444	2,960
30	S,.6	125	120	520	$ 82,880	$ 1,906,521	3,335	S,.9	147	250	390	$ 105,600	$ 2,369,002	2,772
31	C,.9	213	120	520	$ 89,360	$ 1,925,647	3,110	C,.9	215	125	515	$ 82,773	$ 2,366,652	2,619
32	C,.9	213	120	520	$ 89,360	$ 1,951,120	2,886	S,.9	167	125	515	$ 80,225	$ 2,389,521	2,487
33	C,.9	213	120	520	$ 89,360	$ 1,975,613	2,661	S,.9	167	125	515	$ 80,225	$ 2,411,510	2,356
34	C,.9	213	120	520	$ 89,360	$ 1,999,164	2,437	S,.9	167	125	515	$ 80,225	$ 2,432,653	2,224
35	C,.9	213	120	520	$ 89,360	$ 2,021,809	2,216	S,.9	147	125	515	$ 73,600	$ 2,451,305	2,129
36	C,.9	213	120	520	$ 89,360	$ 2,043,583	2,040	S,.9	147	125	515	$ 73,600	$ 2,469,239	2,035
37	C,.9	213	120	520	$ 89,360	$ 2,064,520	1,864	S,.9	147	125	515	$ 73,600	$ 2,486,483	1,941
38	C,.9	213	120	520	$ 89,360	$ 2,084,651	1,688	S,.9	147	125	515	$ 73,600	$ 2,503,064	1,847
39	C,.9	213	120	520	$ 74,491	$ 2,100,787	1,512	S,.9	147	125	515	$ 73,600	$ 2,519,007	1,753
40	C,.9	164	120	520	$ 68,240	$ 2,115,001	1,336	S,.9	147	125	515	$ 73,600	$ 2,534,337	1,659
41	C,.9	164	120	520	$ 68,240	$ 2,128,668	1,160	S,.9	147	125	515	$ 73,600	$ 2,549,078	1,564
42	C,.9	164	120	520	$ 68,240	$ 2,141,809	984	S,.9	147	125	515	$ 73,600	$ 2,563,251	1,470
43	C,.9	164	120	520	$ 68,240	$ 2,154,445	808	S,.9	147	125	515	$ 73,600	$ 2,576,879	1,376
44	C,.9	164	120	520	$ 63,333	$ 2,165,721	632	S,.9	147	125	515	$ 73,600	$ 2,589,984	1,282
45	S,.7	129	120	520	$ 63,320	$ 2,176,562	456	S,.9	147	125	515	$ 73,600	$ 2,602,584	1,188
46-59	-	-	-	640	$ 41,600	$ 2,287,119	456	S,.7	141	250	390	$ 71,314	$ 2,710,249	82
60	-	-	-	640	$ 41,600	$ 2,291,073	456	S,.7	134	54.17	586	$ 53,300	$ 2,722,097	-

Irt: Irrigation trigger: An irrigation is initiated when moisture level is at or below the indicated level

GW(aft): acre feet of ground water remaining at end of year

46-59: average acres, net revenue, cumulative NPV, GW remaining in year 59

Table 33. Comparison of Optimal Irrigation Strategies with Center Pivot and Sub Surface Drip Irrigation on 640 Acres with 13,440 Acre Feet of Groundwater in Texas County when Corn price is $5.48 and the Grain Sorghum Price is $5.09 per Bushel and the Discount Rate is Seven Percent

	Center Pivot							Sub Surface Drip						
Year	Crop IrT	Yield Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulat NPV	GW (aft) 13440	Crop IrT	Yield Bus	Irrig. Acres	Dry Acres	640Acre Net Rev.	Cumulative NPV	GW (aft) 13440
1	C,.9	213	240	400	138560	9495	12991	C,.8	184	600	40	$ 230,600	$ (212,486)	12640
2	C,.9	213	240	400	138560	130519	12542	S,.9	155	600	40	$ 208,400	$ (30,461)	12124
3	C,.9	213	240	400	138560	243625	12093	S,.9	155	600	40	$ 208,400	$ 139,655	11607
4	C,.9	213	240	400	138560	349332	11643	S,.9	155	600	40	$ 206,674	$ 297,326	11104
5	C,.9	213	240	400	138551	448117	11194	S,.9	147	600	40	$ 200,000	$ 439,923	10652
6	C,.9	213	240	400	137600	539806	10745	S,.9	147	600	40	$ 200,000	$ 573,192	10200
7	C,.9	213	240	400	137600	625496	10296	S,.9	147	600	40	$ 200,000	$ 697,742	9748
8	C,.9	213	240	400	137600	705581	9847	S,.9	147	600	40	$ 200,000	$ 814,143	9296
9	C,.9	213	240	400	137600	780426	9398	S,.9	147	600	40	$ 193,990	$ 919,661	8861
10	C,.9	213	240	400	137587	850368	8949	S,.9	135	600	40	$ 173,600	$ 1,007,911	8483
11	C,.9	213	240	400	136880	915399	8500	S,.9	135	600	40	$ 173,600	$ 1,090,387	8105
12	C,.9	213	240	400	136880	976175	8050	S,.9	135	600	40	$ 173,600	$ 1,167,467	7727
13	C,.9	213	240	400	136880	1032976	7601	S,.9	135	600	40	$ 173,600	$ 1,239,505	7349
14	C,.9	213	240	400	136880	1086060	7152	S,.9	135	600	40	$ 173,600	$ 1,306,830	6971
15	C,.9	213	240	400	136206	1135428	6703	S,.9	135	564	76	$ 165,635	$ 1,366,864	6616
16	C,.9	213	120	520	89840	1145535	6479	C,.9	202	250	390	$ 134,600	$ 1,351,011	6198
17	C,.9	213	120	520	89840	1173976	6254	C,.9	202	250	390	$ 134,600	$ 1,393,622	5781
18	C,.9	213	120	520	89840	1200557	6030	C,.9	202	250	390	$ 134,600	$ 1,433,446	5364
19	C,.9	213	120	520	89840	1225398	5805	C,.9	202	250	390	$ 134,600	$ 1,470,664	4946
20	C,.9	213	120	520	89840	1248615	5581	C,.9	202	250	390	$ 134,600	$ 1,505,447	4529
21	C,.9	213	120	520	89840	1270312	5356	C,.9	202	250	390	$ 118,601	$ 1,534,090	4191
22	C,.9	213	120	520	89840	1290590	5131	C,.9	179	250	390	$ 115,850	$ 1,560,239	3866
23	C,.9	213	120	520	89840	1309542	4907	C,.9	179	250	390	$ 115,850	$ 1,584,678	3541
24	C,.9	213	120	520	89840	1327253	4682	C,.9	179	250	390	$ 105,614	$ 1,605,499	3352
25	C,.9	213	120	520	89807	1343800	4458	S,.9	147	250	390	$ 105,600	$ 1,624,956	3164
26	C,.9	213	120	520	89360	1359188	4233	S,.9	147	250	390	$ 105,600	$ 1,643,139	2975
27	C,.9	213	120	520	89360	1373568	4009	S,.9	147	250	390	$ 105,600	$ 1,660,134	2787
28	C,.9	213	120	520	89360	1387008	3784	S,.9	147	250	390	$ 105,600	$ 1,676,016	2599
29	C,.9	213	120	520	89360	1399569	3560	S,.9	147	250	390	$ 105,600	$ 1,690,860	2410
30	C,.9	213	120	520	89360	1411308	3335	S,.9	147	250	390	$ 105,600	$ 1,704,732	2222
31	C,.9	213	120	520	89360	1414913	3110	C,.9	179	125	515	$ 78,725	$ 1,703,261	2059
32	C,.9	213	120	520	89360	1425166	2886	C,.9	179	125	515	$ 78,725	$ 1,712,294	1897
33	C,.9	213	120	520	89360	1434749	2661	C,.9	179	125	515	$ 78,725	$ 1,720,736	1734
34	C,.9	213	120	520	89360	1443704	2437	C,.9	179	125	515	$ 78,725	$ 1,728,626	1572
35	C,.9	213	120	520	87520	1451902	2216	C,.9	179	125	515	$ 78,725	$ 1,736,000	1409
36	C,.9	164	120	520	68240	1457875	2040	C,.9	179	125	515	$ 78,725	$ 1,742,891	1247
37	C,.9	164	120	520	68240	1463458	1864	C,.9	179	125	515	$ 78,725	$ 1,749,331	1084
38	C,.9	164	120	520	68240	1468675	1688	C,.9	179	125	515	$ 78,725	$ 1,755,350	922
39	C,.9	164	120	520	68240	1473551	1512	C,.9	179	125	515	$ 78,725	$ 1,760,976	759
40	C,.9	164	120	520	68240	1478108	1336	C,.9	179	125	515	$ 78,725	$ 1,766,233	597
41	C,.9	164	120	520	68240	1482367	1160	C,.9	179	125	515	$ 78,725	$ 1,771,146	434
42	C,.9	164	120	520	68240	1486348	984	C,.9	179	125	515	$ 78,725	$ 1,775,738	272
43	C,.9	164	120	520	68240	1490068	808	C,.9	179	125	515	$ 74,252	$ 1,779,786	169
44	C,.9	164	120	520	68240	1493544	632	S,.9	147	125	515	$ 73,600	$ 1,783,536	75
45	C,.9	164	120	520	68240	1496793	456	S,.9	147	125	515	$ 73,600	$ 1,787,040	0
46-59	-	-	-	640	41600	1514116	456	S,.9	179	-	640	$ 41,600	$ 1,800,952	-
60	-	-	-	640	41600	1514834	456	-	-	-	640	$ 41,600	$ 1,801,893	-

Irt: Irrigation trigger: An irrigation is initiated when moisture level is at or below the indicated level

GW(aft): acre feet of ground water remaining at end of year

46-59: average acres, net revenue, cumulative NPV, GW remaining in year 59

Summary and Conclusions.

The study began by using the EPIC simulation model to estimate irrigated corn and sorghum yields in Texas County under alternative irrigation well capacities and soil moisture levels (irrigation trigger) to initiate an irrigation with central pivot and subsurface drip irrigation systems. The EPIC simulation model was calibrated against the limited irrigation data available from research and variety trials at the Oklahoma Panhandle Research and Extension Center at Goodwell, Oklahoma. Data from irrigation research and variety trials from Kansas Stations at Garden City and Tribune and from the ARS station at Bushland, Texas and variety trials from the Texas Panhandle were also used as reference points for the EPIC simulated yields in Texas County, Oklahoma.

Before the simulation could begin, considerable effort was made to construct a daily weather data base covering a 50 year period from 1965 through 2014 to represent long-term weather conditions in the Oklahoma Panhandle. The fifty year daily weather series was used to estimate the mean yield for corn and grain sorghum under full and deficit irrigation.

In the center pivot simulation, the minimum irrigation frequency was determined by the number of days it would take to complete one revolution of the pivot while applying 1.2 acre inches. The 50-year daily simulation was used to estimate the mean yield, given an irrigation trigger and minimum irrigation frequency. No attempt was made to estimate a continuous response function of irrigated corn or grain sorghum to various levels of irrigation because values of water stress also changed along with the level of irrigation. Rather, the estimated yields from different irrigation levels and water stress values were used as discrete opportunities.

Enterprise budgets were constructed to determine the static profitability of the alternative irrigation levels and irrigation triggers (moisture levels to initiate an irrigation). These budgets themselves provide starting points for determining the long term use of groundwater. The net returns over variable costs and the quantity of groundwater used were used directly in developing programming models.

Several scenarios were examined to determine their effect on the optimal value and long-term use of ground water. The first scenario examined was the different producer's decision objectives. The difference in multiyear earnings between producers who followed a series of BSYC (Best Single Year Choices) or always selected the enterprise that gave the highest immediate return without considering the quantity of ground water required. This was contrasted with the producer who followed a crop selection and an irrigation level that maximized the long-term discounted profits (MNPV). This was done for a producer with a 160 acre and with a 640 acre section. Center pivot irrigation systems were used in the comparison. Returns in initial years favored the BSYC producers but after 3 to 4 years, the higher annual returns and increased groundwater levels favored the MNPV producer. This was because the MNPV producer selected grain sorghum (which used less water than corn) the resulting NPV of the planning period always favored the MNPV producer.

The main focus of the report is on a comparison between net returns from conventional center pivot (CP) systems and sub surface drip (SDI) systems. The SDI system has higher water use efficiency because it was assumed there was 10 percent less water lost to evaporation and runoff. The sensitivity of returns and water use rates to changes in feed grain prices, interest rates, holding size, and initial groundwater supplies was analyzed. The feed grain prices used were (low with $4.48 corn and $4.16 grains sorghum) and high (with $5.48/bus. corn and $5.09/bus. grain sorghum). The discount rates used were four and seven percent. The holding sizes used were 160 acres and 640 acres. In the case of the 640 acre holding, two supplies of groundwater were considered.

The optimal MNPV investment for CP and SDI systems on the 160 acre field size were analyzed with a 30-year planning horizon. The SDI was found to be more profitable than the CP systems. The 30-year MNPV values for the four cases analyzed were,

	CP		SDI	
Discount Rate	4%	7%	4%	7%
Feed Grain Price				
Low (C, $4.18; S,4.16)	$106,607	$78,286	$160,861	$115,296
High (C, $548; S, $5,09)	$344,489	$260,312	$436,103	$313,318

Adoption of the SDI system did not always extend the life of the aquifer. However, more grain was produced from the amount of groundwater used with the SDI system than with the CP system.

The 640 acre field with four existing wells offers a conservation possibility to the producer not presented by the 160 acre case. The producer may leave one or more 160 acre subfields unirrigated and increase the quantity of water supplied to the one or more 160 acre fields that are irrigated. This may also reduce the drawn down to in each pumping well. The emphasis however, was on the comparison between the CP and SDI systems. Two water supplies were considered. The low water supply considered only the water under 640 field. This amount with 60 feet of water saturated sand was estimated to be 6,280 acre feet. The larger amount was for a producer located where only 50 percent of the surrounding area was irrigated. The water supply in the second case was 13,440 acre feet. A 60-year planning horizon was used in the second case in order to determine the optimal use of the larger groundwater supply. The Cumulative NPV from CP and SDI investments for the 640 acre field were,

	CP		SDI	
Discount Rate	4%	7%	4%	7%
Limited Water				
Feed Grain Price				
Low (C, $4.18; S,4.16)	$ 618,708	$ 448,998	$ 725,405	$ 507,592
High (C, $548; S, $5,09)	$1,839,290	$1,225,076	$2,052016	$1,419,097
High Water				
Feed Grain Price				
Low (C, $4.18; S,4.16)	$ 850152	$ 569,682	$1,120,703	$ 739,125
High (C, $548; S, $5,09)	$2,291,073	$1,514,834	$2,722,097	$1,801,893

The MNPV results indicated that even with the higher feed grain prices, it was optimal for the CP producer to leave two quarter sections unirrigated and use the wells from those quarters to increase the GPM to pivots on the irrigated quarter sections. By contrast, the SDI producer would develop 600 acres (4- 150 acre SDI systems) for irrigation in the first 15 years with the five dollar feed grain prices. As shown above, the NPV from the SDI system was always more profitable than the CP for the 640 acre field.

Limitations

The study shows the advantage of MNPV from the remaining groundwater. This would be optimal if followed by all producers. We did not have the resources in this study to address the rate of groundwater flow from under one producer's field to that of another producer. If one producer follows the BSYC while the neighbor follows the MNPV strategy, there would be a difference in ground water levels which would flow toward the BSYC producer. Hopefully, the implications of this interaction can be addressed through the use of groundwater models in future studies.

The heavy reliance on simulated data is another limitation but is unavoidable. The authors have used tested simulation models and attempted to calibrate them against observed data where possible.

References

Almas, L. K. and W. A. Colette, 2008. Economic Optimization of Groundwater Resources: A Case of Texas County in the Oklahoma Panhandle. World Environmental and Water Resources Congress, 2008, Ahupua'a.

Ciriacy-Wantrup, S.V. (1963). *Resource Conservation: Economics and Policy*. Univ. Rev. Ed., Ca. Div. Ag. Sciences, Ag. Exp. Stat., Berkley, Ca.

Guru, M. V., & Horne, J. E. (2000). The Ogallala aquifer. Retrieved from. www.kerrcenter.com/publications/ogallala_aquifer.pdf.

Israelsen, O.W. and V.E. Hansen, (1962). *Irrigation Principles and Practices*, J. Wiley and Sons Inc., New York.

Karassik, I. J., J.P. Messina, P. Cooper, C. C. Heald, (2001). *Pump Handbook*, McGraw-Hill, 3'rd Ed., New York.

Luckey, R.R, N.I. Osborn, M.F. Becker, and W.J. Williams. 2000. Water flow in the High Plains Aquifer in northwestern Oklahoma. USGS Fact Sheet 081-00. Oklahoma City, Ok.: United States Geological Survey.

Dhuyvetter, K. C. and T. J. Dumler, (2011). KSU Irrigation Energy Costs: A Spreadsheet Program to Compare the Costs of Irrigation Energy Options. Agricultural Extension Service, Kansas State University,

Schwab, G. O.;Fangmeier, D. D.;Elliot, W. J.;Frevert, R. K. *Soil and water conservation engineering.* Thomas Learning, 1993 pp. xiv + 507 pp.

Qi, S.L. and Christenson, S. 2010. Assessing groundwater availability the the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, Texas and Wyoming. U.S. Geological Survey Fact Sheet 2010-3008

USDA-Natural Resources Conservation Service (2014). Geospatial Data Gateway, USDA, NRCS, https://gdg.sc.egov.usda.gov, Accessed during 2014.

Appendix A Structure of Mixed Integer Programming Model for Subsurface Drip.

The SDI offers the producers more choices than the CP on a 160 acre field in that any part of the field (given suitable soil conditions) can be developed. In the study, the possible sizes of the SDI were given in 25 acre increments from 50 to 150 acres. An outline of a mixed integer programming model where the producer considers the purchase of a 50 acre, a 75 acre, a 100 acre, a 125 acre, or a 150 acre system is shown in Figure A1 below over a 15 year planning horizon. If the producer purchases the 50 acre system unit, then the producer is allowed to grow 50 acres of irrigated sorghum for each of the 15 years over the expected life of the system. The producer has 160 acres of land available each year and 280 acre feet for ground water available in each of six aquifer layers under the 160 acres. Any irrigation water not used in year 1 in each layer is transferred to the same layer for use in the following year. When the water at the top of the aquifer (layer 6) is exhausted, the producer begins pumping from the next lower layer in the aquifer.

Figure A1. Illustration of Programming Model with Alternative Sizes and Irrigation Strategies and Non-irrigated Crop Choices for a Quarter Section and a 15 Year Planning Horizon.

		RHS	Integer Variables					Year one Crop Choices									Year 3 crop					Year 15 Crop Choices						
			IP101	IP201	IP301	IP401																						
	Year		-60000	-120000	-180000	-240000		Sf30116	..	Sf90116	..	Sa30111	..	Sa90111	szo0100							Sf31516	..	Sf91516	..	Sa31511	..	szo0100
Irg.Size	1	1	1	1	1	1	1																					
IP01	1	0	-50	-75	-100	-125	-150	1	..	1	..	1	..	1														
IP02	2	0	-50	-75	-100	-125	-150																					
IP03	3	0	-50	-75	-100	-125	-150										1	..	1									
IP14	14	0	-50	-75	-360	-125	-150																					
IP15	15	0	-50	-75	-360	-125	-150															1	..	1		1	..	
TA01	1	160						1	..	1	..	1	..	1	1													
W601	1	280						0.6	..	1.1	..																	
W501	1	280																										
W102	1	280										0.18	..	0.2														
TA03	3	160															1	..	1									
																	..	..	..									
TA15	15	160																				1	..	1		1	..	1
W615	15	0																				0.6	..	1	..			
W515	15	0																										
W115	15	0																								0.2	..	0

The problem is for the Producer to choose the profit maximizing size of system and also choose the crops to be grown (only sorghum is shown in Figure A1) and the irrigation intensity each year over the planning horizon.

For a producer with a 640 acre section, the acreages and the costs of the SDI systems are scaled up. For a longer planning horizon, (in 15 year increments), the system purchase costs are discounted and repeated.

Title: Increasing water yield and quality through redcedar removal and establishment of herbaceous biofuel feedstock production systems: Effect of vegetation on groundwater recharge in upland ecosystems

Start Date: 03/01/2014

End Date: 08/30/2015

Congressional District: OK-3

Focus Category: Groundwater, invasive species, drought

Descriptors: Groundwater, redcedar, biofuel

Students:

Student Status	Number	Disciplines
Undergraduate		
M.S.		
Ph.D.	1	Natural resource ecology and management
Post Doc		
Total		

Principal Investigators: Chris Zou, Associate Professor, NREM, Oklahoma State University chris.zou@okstate.edu

Publications:

Peer reviewed articles

Zou CB, Caterina GL, Will RE, Stebler E, Turton D. 2015. Canopy interception for a tallgrass prairie under juniper encroachment. PLOS One. doi:10.1371/journal.pone.0141422.

Zou CB, Turton DJ, Will RE, Engle DM, Fuhlendorf SD (2014). Alteration of hydrological processes and streamflow with juniper (Juniperus virginiana) encroachment in a mesic grassland catchment. Hydrological Processes, 28(26), 6173-6182.

Presentations and abstracts

Acharya BS, Halihan T, Zou CB. 2015. Temporal variability in water level in a tallgrass prairie and juniper woodland indicate vegetation controls on deep drainage. NSF EPSCoR Annual State Conference, Norman, OK, USA, December 3, 2015.

Acharya BS, Halihan T, Zou CB, Fox G, Will RE. 2015. Hydrogeophysical evaluation of vadose zone moisture, subsurface flow and deep drainage in grassland, woodlands and oak forest, Oklahoma, USA. Oklahoma Governors Water Conference and Research Symposium, Norman, OK, USA, December 1-2, 2015.

Acharya BS, Halihan T, Zou CB, Will RE, Fox G. 2015. Detection of vadose zone moisture in a Oak forest using Electrical Resistivity. The 2015 workshop at MOISST: The dawn of the soil moisture information age? Stillwater, OK, USA, June 2-3, 2015.

Acharya BS, Halihan T, Zou CB, Will RE, Fox G. 2015. Time-lapse Electrical Resistivity Imaging (ERI) for spatio-temporal monitoring of vadose zone moisture. 24th Annual Clean Lakes and Watershed Association Confrence, Stillwater, OK, USA, April 8-9, 2015.

Acharya BS, Zou CB, Will RE, Fox G, Halihan T. 2014. Application of Electrical ResistivityImaging (ERI) in detecting vadose zone soil moisture dynamics. 3rd Annual Student Water Confrence (SWC), Stillwater, OK, USA, April 10-11, 2014.

Problem and Research Objectives:

Changes in land use and vegetation cover can directly alter groundwater recharge processes, especially in water limited semi-arid and subhumid regions. Vegetation reduces groundwater recharge by either extracting groundwater from the saturated zone or reducing rainfall reaching the groundwater table. Research so far has focused mainly on the riparian zone where connectivity between the surface and the alluvial aquifer is intuitive and the interaction can be rapid. However, over 90% of land surface is upland, and the effect on groundwater of changes in upland vegetation cover such as conversion from redcedar woodland to herbaceous biofuel feedstock production is poorly understood.

Objective 1: Quantify soil moisture for the rooting zone under three contrasting vegetation types – grassland, post oak forest and redcedar woodland with the same precipitation input.

Objective 2: Directly evaluate the water table and interflow under different vegetation types and its seasonable variation.

Objective 3: Directly assess long-term water efflux out of rooting zone using chloride mass balance - proximity for recharge potential.

Methodology:

We estimated soil moisture for the entire rooting zone and below up to a depth of 9 m using transient multi-electrode surface resistivity. For each vegetation cover type, we installed a permanent latitudinal transect of 42 m oriented along the contour lines and another permanent orthogonal transect of 21 m which run through the center of the latitudinal line. A total of 56 and 28 electrodes were permanently deployed on the surface across latitudinal and orthogonal transect, respectively with 0.75 m inter-electrode spacing. Electrode is 19.2 inch in length made up of copper coated steel lightning rods and was permanently installed to soil at a depth of 6 to 12 inch in June 2014. Apparent resistivity data was collected using SuperSting 8-channel resistivity instrument in an automated mode following OSU proprietary method (the Halihan-Fenstemaker method). A total of 277 apparent resistivity data were collected from an orthogonal transect and 1194 apparent resistivity from a latitudinal transect during one ERI data acquisition. A base station was established in both sites near ERI lines, and a rover and a TOPCON Hyperlite Plus Global Positioning System was set to record latitude, longitude and elevation for each electrode with 1 cm of accuracy. Data from Topcon GPS was downloaded to a computer and base data was sent to Online Positioning User Service (OPUS). The easting, northing and elevation of base station obtained from OPUS were used to correct location data of each electrode. Apparent resistivity data collected in field were inverted and images were developed using EarthImager 2D Software 1.6.8 (Advanced Geosciences, Inc., 2004), AestusRPT under a range of precipitation and soil moisture conditions and presented with consistent color scheme. Two groundwater observation wells were installed in the experimental site; one in grassland and the other in redcedar encroached site. The depth of the wells is 3 meter, which is the maximum depth we were able to reach using solid-stem auger mounted in Geoprobe 6300. EC-5 soil moisture sensor (Decagon Devices, Utah, USA) were also installed at 3 meter and 1.5-meter depth. Bentonite clay was packed around the well bore about 1 meter to guarantee that water and solutes are not traveling laterally through the topsoil and then vertically down the well hole. Prepacked wells were installed to limit clogging due to fine-grained aquifer sediments. Each observation well was instrumented with CTD-10 sensor (Decagon Devices, Inc., Pullman WA) to automatically monitor water level ($accuracy \pm$ 0.05%), electrical conductivity (accuracy ± 0.01 dS/m) and temperature (accuracy ±1°C) at 15-minute intervals.

In April 2015, we cored and collected soil samples at 25-cm interval and the maximum soil depth ranging from 125-cm to 275-cm using auger manually. Six locations in grassland and 6 locations in encroached site were randomly selected for sampling. A total of 90 samples were analyzed for chloride concentration. Chloride anion in the soil was determined by Lachat QuikChem 8500 flow injection analyzer by mercury thiocynate method. Cl content in the pore water was estimated by dividing soil Cl by gravimetric water. Deep drainage was estimated by using a steady-state equation which assumes that Cl deposited by rainfall is largely removed by drainage from the unsaturated zone and can be used as a surrogate for deep drainage or recharge

$$PCl_p = RCl_s$$

Where, P is the average annual precipitation (mm/yr), Cl_p is the average Cl input from all sources (mg/L); National atmospheric deposition program data was used to get Cl deposition (http://nadp.sws.uiuc.edu/), Cl_s is the average Cl concentration of pore water below root zone (mg/L), and R is the average annual deep drainage rate (mm/yr). Wet deposition of chloride was obtained from National Atmospheric Deposition Program (NADP) as weighted mean concentration in precipitation from Kessler Farm Field Laboratory, OK during 1983 -2014. Mean chloride concentration in precipitation was doubled to account for dry deposition.

Principal Findings and Significance:

We collected and archived a range of time-lapse electrical resistivity images (ERI) to track moisture change to a depth of 9 m in grassland and juniper (*Juniperus virginiana*, eastern redcedar) encroached, and oak forest catchments under different precipitation and soil moisture conditions. Analysis based on those images showed a two-layer moisture migration profile: non-wetted and wetted in grassland, juniper-encroached catchments, and oak forest after rainfall event. Percent change in conductivity was lower in the top 3-m and higher below 3-m depth in the electrical resistivity data across vegetation. However, the eastern redcedar-encroached catchment showed higher spatial-temporal variability in the root zone electrical conductivity and reduced deep drainage and recharge potential compared with grassland catchment (Fig. 1).

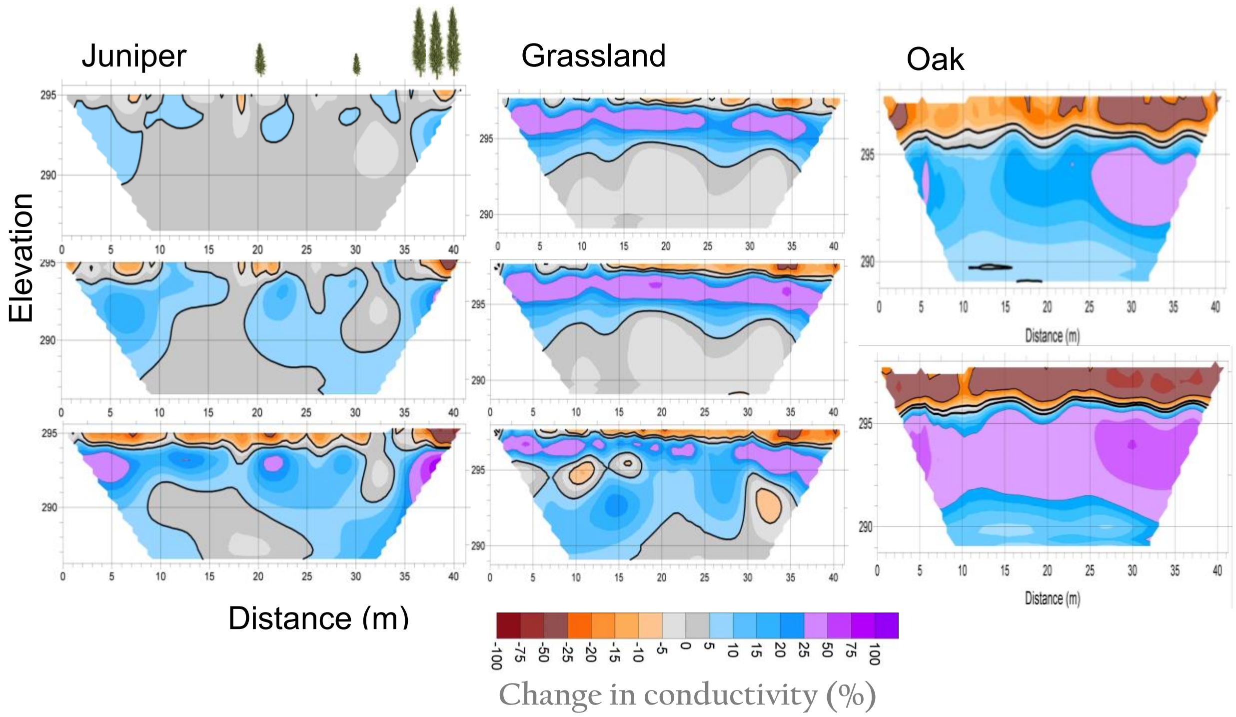


Fig. 1. Electrical resistivity images from the juniper-encroached (left panel) and grassland (middle panel) and oak forest (right panel) catchment. Images were taken during June-August, 2014 in juniper-encroached and grassland and during June-July, 2014 in oak forest from latitudinal transect deployed with 56 electrodes and are illustrated as pseudosections with percent change in conductivity to a depth of 9 m.

Direct observation of subsurface hydrologic flow pathways using point measurements is relatively difficult in soils underlying porous bedrock. Passive seasonal temporal ERI thus provided clues of lateral flow in tallgrass prairie. The flow was largely controlled by differences in lithologic properties with depth (Fig. 2).

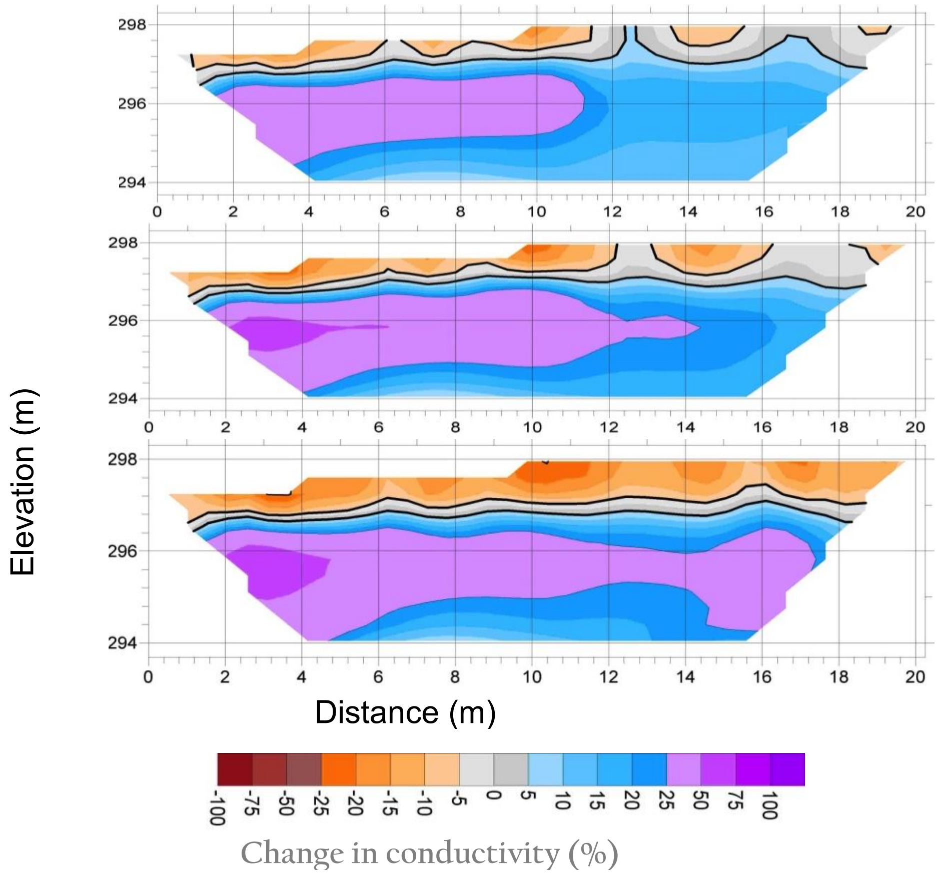


Fig. 2. Electrical resistivity images indicating lateral flow in the grassland catchment. Images were taken during June-August, 2014 from an orthogonal transect deployed with 28 electrodes, and are illustrated as pseudosections with percent change in conductivity to a depth of 4 m.

Based on drilling and ERI images, the groundwater table is deeper than 9 meters at the grassland, eastern redcedar encroached and oak woodland sites. This suggests that vegetation impact on groundwater at these upland sites is mainly through reducing net rainfall reaching the groundwater table. This limits our ability to quantify vegetation cover on groundwater through mentoring groundwater table fluctuation at these upland sites. This suggests that ERI method is a necessary approach to explore recharge process in order to further detect change in moisture content below different vegetation rooting zone in these heterogeneous sites.

Monitoring wells show temporal variability in water level in a tallgrass prairie and juniper catchment. Water level was higher under grassland than under juniper woodland for all times. Peak water level of 2485 mm was recorded during 16-May 2015 (Fig. 3). In contrast, the water level in woodland peaked up to 10 mm during 20-May 2015. Results indicate that vegetation can modulate deep drainage of water, and woody plants can decrease water level in a perched aquifer by a significant amount.

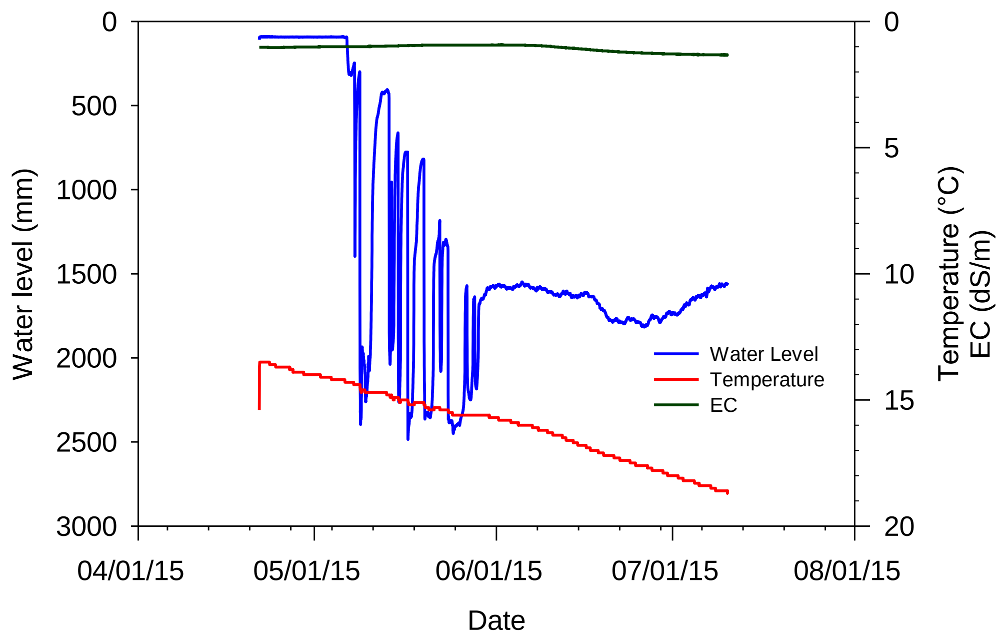
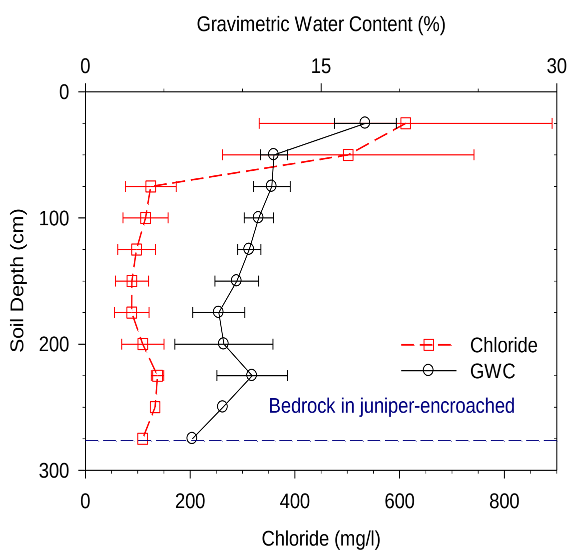


Fig. 3. Water level (mm), temperature (°C) and electrical conductivity (dS/m) recorded in a 3 m deep monitoring well in a grassland catchment at 15-minutes interval

Evaluation of soil chloride concentration indicates different chloride profiles under grassland catchment and redcedar encroached site. Soil chloride content varied between 5 to 162 mg/l in grassland (Fig. 4) and 88 to 612 mg/l in juniper encroached prairie (Fig. 5) across depths with greater Cl near the surface. Steady State flux indicates greater recharge potential in the grassland catchment. High soil chloride accumulation under redcedar indicates reduced percolation and potentially subsurface interflow flow and groundwater recharge potential associated with redcedar encroachment.



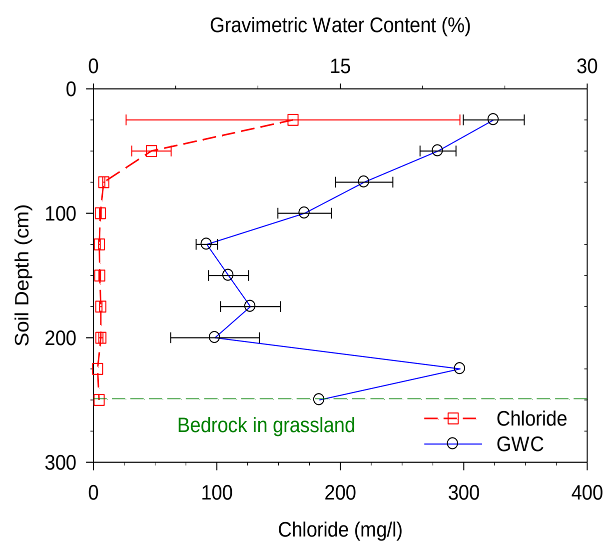


Fig. 4. Distribution of soil chloride (mg L^{-1}) and gravimetric water content (%) across different soil depth as measured in juniper-encroached and grassland catchments. Values are mean ± SE

In conclusion, different vegetation types control vadose zone soil moisture dynamics in the upland. ERI data confirms the existence of horizontal soil water migration (interflow) at the interface of soil and sandstone bedrock under grass cover, however, Juniper encroachment results in increased spatial and temporal variability of soil moisture in rooting zone, reducing both horizontal subsurface soil water movement (interflow) and vertical subsurface soil water movement (groundwater recharge). The results are consistent to the chloride data showing higher chloride concentration therefore less soil water percolation through the upper 100 cm soil profile for juniper encroached site in comparison with grassland.