Oklahoma Water Resources Center

2014 Annual Research Report

Research conducted March 1, 2014 – February 28, 2015

Published May 2015

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Introduction

The Oklahoma Water Resources Center transitioned leadership from the direction of Dr. Dave Engle (March 1, 2014-June 30, 2014) to Dr. Garey Fox (July 1, 2014-February 28, 2015). Significant progress was made in 2014 to address priority research, outreach, and education needs related to water in Oklahoma. Some of the major accomplishments are highlighted below:

1. The Water Center successfully administered an extended USGS 104(b) grant from 2013 and three USGS 104(b) grants of $25,000 each funded in 2014. Funding from the USGS 104(b) program provided $25,000, which was matched 2:1 with funding from the PI's university.

2. The Water Center awarded three research grants of $25,000 each that will start March 1, 2015. The selection process for these projects was improved to more effectively account for external reviews in the selection process. The selection process began with one-page pre-proposals due in July 2014. The 22-member Water Resources Advisory Board (WRAB) then selected six projects to submit full proposals. Five full proposals were submitted. Full proposals were externally reviewed by three reviewers including 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. Then the researchers presented their proposals to the WRAB. A grading/ranking scheme was developed and provided to the WRAB members that summarized the external reviews. Projects that were funded included the following: Quantifying Streambank Erosion and Phosphorus Load for Watershed Assessment and Planning (PI: Dr. Dan Storm, Oklahoma State University); Threats to the Lugert-Altus Irrigation District: Untangling the Effects of Drought, Land Use Change, and Groundwater Development (PI: Dr. Tyson Ochsner, Oklahoma State University); and Optimizing the Economic Value Water from Ogallala Aquifer used for Irrigation (PI: Dr. Jason Warren, Oklahoma State University).

3. The Oklahoma Water Resources Center co-sponsored and co-hosted the 35th Annual Oklahoma Governor's Water Conference and Research Symposium at the Cox Convention Center in Oklahoma City, OK on October 22-23, 2014. The meeting included over 400 attendees. Keynote speakers included Pat Mulroy (Senior Fellow, Climate Adaptation and Environmental Policy, Brookings Mountain West and Maki Distinguished

Faculty Associate, Desert Research Institute) who presented on “The Las Vegas Story: Adapting a New Normal”; and Dr. Francois Birgand (Associate Professor, North Carolina State University) who presented on “High Frequency Water Quality Data: Is this Really Necessary?” A special Café Style Poster Session was held at the conference to support student participation and interaction with the registrants. Four outstanding poster awards were awarded to two undergraduate students and two graduate students.

4. The Oklahoma Water Resources Center assisted in hosting the 2014 Student Water held April 10-11, 2014. The conference consisted 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 2014, 49 students presented (22 oral presentations, 27 poster presentations) with 15 presentations by students visiting from outside universities. The Water Center is currently organizing the 4th Annual Student Water Conference to be held on March 26-27, 2015. The Water Center under Dr. Fox’s leadership is now the primary organizer of this unique conference, supported through the Buchanan Family Trust through the Buchanan Endowed Chair and USDA NIFA through a National Integrated Water Quality grant. Planned activities include a water trivia and social will be hosted for students studying about water across campus, more than 60 presentations by students from 16 universities.

5. The Water Center hired part-time staff writer as part of funding through the Division of Agricultural Sciences and Natural Resources (DASNR) at Oklahoma State University (OSU) 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.

6. Many of these stories were part of our newsletter, the *Aquahoman*, published at a much higher frequency this past year (June 2014, August 2014, November 2014, and February 2015). We also began to highlight one member of our Water Resources Advisory Board (WRAB) in each of the issues of the *Aquahoman*.

7. A special student section of the newsletter was created to highlight student-related events such as the Student Water Conference and opportunities for undergraduate research through a funded National Science Foundation (NSF) Research Experience for Undergraduates (REU).

8. The Water Center created a video series called the *Foundations of Oklahoma Water*, accessible at www.youtube.com/user/OkstateWaterCenter. The video series includes an introduction to the Water 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. Funding for the video series was provided to the Water Center through the Renewable Resources Extension Act monies ($10,000), administered by Dr. Dwayne Elmore (participating Water Center faculty member). The *Foundations of Oklahoma Water* video series was submitted for Educational Aids Blue Ribbon Award through ASABE (pending).

Research Program

Progress on 2013 and 2014 Projects:

The Water Center successfully administered one extended project that was funded in 2013 and three research projects funded in 2014 (all of which have been extended until August 2015):

- FY 2013 - *Remote Sensing of Water Quality and Harmful Algae in Oklahoma's Lakes* (PI: Dr. David Hambright, University of Oklahoma) – The project used satellite imagery and handheld remote sensing devices to test the detection of potential harmful algae blooms. Preliminary results were extremely promising. Both satellite- and spectroradiometer-measured reflectance were strongly related to chlorophyll, phycocyanin, and turbidity, indicating that all three water quality parameters could be accurately predicted remotely in both Lake Texoma and Grand Lake. Despite some problems with obtaining simultaneous ground and satellite data, the project was able to collect water quality and reflectance data from a wide range of conditions, from low to moderate turbidities and concentrations of chlorophyll and phycocyanin. There was also a moderate degree of overlap in water quality values between the two lakes, suggesting that observed relationships may be robust across a wider range of lakes and lake types. This is particularly true for LANDSAT-based water quality estimation. However, the in-situ reflectance measures (ASD spectroradiometers, digital camera), while very accurate at estimating water quality parameters in Lake Texoma, where much less capable of such for Grand Lake. The project team has discussed these issues with researchers at Grand Lake and is considering options for additional measurements and parameters necessary to improve their models. The project partially supported nine students: four undergraduates in biology, geography, and professional writing; one Master of Science student in zoology, and three Ph.D. students in biology and microbiology. Results were presented at the 2014 Oklahoma Governor's Water Conference and Oklahoma Water

Resources Research Symposium in Oklahoma City in October 2014 and are currently being prepared for publication. The final technical report for this project is included in this 2014 Annual Research Report.

- FY 2014 - *Estimating Groundwater Recharge using the Oklahoma Mesonet* (PI: Dr. Tyson Ochsner, Oklahoma State University) – This project built upon the team's previous projects sponsored by the USGS 104(b) program that developed plant available moisture capabilities for the Oklahoma Mesonet. The objective was to provide estimates of recharge to groundwater using Oklahoma Mesonet-based data and specifically addressed the priority of developing methods of monitoring groundwater established by the WRAB. The project has supported one undergraduate student in Environmental Science and one M.S. student in Plant and Soil Science. The interim technical report for this project is included in this 2014 Annual Research Report.

- FY 2014 - *Comparison of Grain Sorghum and Corn Productivity under Limited Irrigation with Subsurface Drip* (PI: Dr. Jason Warren, Oklahoma State University) – This project investigated the production advantage of grain sorghum over corn when irrigation water was in limited supply. The project also served as a demonstration for the use of subsurface drip irrigation for grain sorghum. The project specifically addressed funding priorities of conservation in the sensitive Ogallala aquifer region of Oklahoma. The project has supported one undergraduate student in Plant and Soil Science and three M.S. students (two in Plant and Soil Science and one in Agricultural Economics). The interim technical report for this project is included in this 2014 Annual Research Report.

- FY 2014 - *Increasing water yield and quality through redcedar removal and establishment of herbaceous biofuel feedstock production systems* (PI: Chris Zou, Oklahoma State University) – Most studies of land conversion to bioenergy production have focused solely on surface water and not groundwater. 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. The overall objective was to quantitatively assess the effects of vegetation types on groundwater recharge in upland ecosystems. The proposed project was a field-based experiment conducted at the Oklahoma State University Range Research Station (OSURRS). Understanding rooting zone soil water and groundwater are critical for adapting land management to increasing climate variability and drought frequency for water resource management and long-term planning, and therefore the project directly addressed priority topics of groundwater/surface water interactions and climate change established by the WRAB. The project supported one Ph.D. student in the Department of Natural Resource Ecology and Management. The interim technical report for this project is included in this 2014 Annual Research Report.

Selection of 2015 Projects:

Research pre-proposals were solicited from all Oklahoma universities starting in late May 2014. One-page pre-proposals were due in July 2014. The 22-member Water Resources Advisory Board (WRAB) then reviewed and discussed these pre-proposals at the summer WRAB meeting held in Stillwater, OK. The WRAB selected six projects to submit full proposals. Five full proposals were submitted. Full proposals were externally reviewed by three reviewers solicited by Dr. Garey Fox, Director of the Oklahoma Water Resources Center. 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. Then the researchers presented their proposals to the WRAB in 45-minute presentations at the winter WRAB meeting held at the first of January 2015 in Stillwater, OK. After the presentations, the WRAB deliberated on the selection of the top three proposals. The Water Center provided a ranking/classification scheme that summarized the external reviews. This input assisted the WRAB in incorporating the feedback from experts in each of the fields. The following three projects were selected for funding:

- *Quantifying Streambank Erosion and Phosphorus Load for Watershed Assessment and Planning* (PIs: Dr. Dan Storm and Mr. Aaron Mittelstet, Oklahoma State University) – The Illinois River watershed in eastern Oklahoma is a designated scenic river and a highly valued system visited by many Oklahomans every year. The Illinois River along with the Barren Fork Creek is on the 303(d) list of impaired waters due to elevated phosphorus (P), which is caused in part from historic poultry litter application and wastewater treatment discharges. Since over 80% of the litter produced within the watershed is now exported outside the watershed and wastewater treatment plant discharges have improved dramatically, they are no longer the largest P sources in the watershed. Current Soil and Water Assessment Tool (SWAT) modeling has shown that pasture and elevated soil test P are now the largest P sources. Recent research on the Barren Fork Creek, a major tributary of the Illinois River and also a designated scenic river, has shown that streambank erosion is also a significant P source in the watershed (Miller et al., 2014). Past SWAT modeling efforts of the Illinois River watershed have ignored the contribution of stream banks as a P source due to lack of field data and model limitations. With recent modifications to the SWAT model and data collected by Miller et al. (2014), it is now possible to estimate P contributions from stream banks in the Barren Fork Creek watershed. This will not only improve our understanding of the Barren Fork Creek watershed and other streams in the Ozarks, but also contribute and improve the well-known and widely used SWAT model. The first objective of this research is to estimate streambank erosion at the ten reaches from the Miller et al. (2014) study using the SWAT model, and compare the simulated eroded volume of sediment to the observed erosion. The second objective addresses the 2015 Water Research Funding Priority 3f by extending the streambank erosion estimates to the entire Barren Fork Creek watershed. After obtaining satisfactory results from the 10 reaches, we will extend the streambank parameters to each of the reaches on the Barren Fork based on the aerial images and their current riparian protection. This SWAT simulation will provide annual and event based erosion estimates on the Barren Fork. After modifying the SWAT code, the quantity of P from the eroded stream banks will be added to the benthic P in the in-stream P subroutine and the model will be re-calibrated for P. We expect the inclusion of P from stream banks to improve the simulation results and therefore give us a defendable estimate of sediment and P added to the Barren Fork Creek each year from streambank erosion.

- *Threats to the Lugert-Altus Irrigation District: Untangling the Effects of Drought, Land Use Change, and Groundwater Development* (PIs: Dr. Tyson Ochsner, Dr. Yohannes Yimam, Dr. Eric Krueger, Oklahoma State University) – 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 has not contained enough water to produce an irrigated cotton crop since 2010. Severe drought in 2011 and 2012 played a major role in the demise of the lake, but local residents suspect 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 already 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 is unknown, and the future of the lake, the irrigation district, and the Altus community which depends on both is highly uncertain. There is a pressing need for research to better understand the drivers of change in this regionally-significant watershed. 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 is to evaluate the effects of drought, land use change, and groundwater development on streamflow into Lake Altus-Lugert.

- *Optimizing the Economic Value Water from Ogallala Aquifer used for Irrigation* (PIs: Dr. Jason Warren, Dr. Jody Campiche, Dr. Rodney Jones, and Dr. Art Stoecker) - During the 2013 and 2014 crop years, efforts have been made to compare yield potential for sorghum and corn when irrigated at a range of irrigation capacities that represent the pumping capacities found in the Oklahoma Panhandle. This effort was to determine the irrigation capacity at which sorghum becomes more productive and profitable than corn. This research is currently utilizing this data to calibrate the EPIC crop model to allow us to simulate long term average yields as well as variability in yields for these crops. This will allow for determination of profitability and risk. While our current efforts will be fruitful in allowing us to understand the value of water when used to produce corn versus sorghum, it does fall short from providing a complete assessment of possible crop production options. Specifically, irrigation wheat production must also be included in our analysis because of its prevalence in the area. In fact, the National Agriculture Statistics Service reports that in 2012 there were approximately 80,000, 13,000, and 45,000 acres of corn, sorghum and wheat respectively. The decision to grow wheat under irrigation is generally based on the need to rotation out of corn to control pest pressures and therefor our current efforts have focused on comparing corn and sorghum in order to assist producers in deciding which is more economically advantageous. However, we must include wheat in our analysis to insure a holistic understanding of the irrigated production system. The objectives are to evaluate the yield and water use efficiency of corn, sorghum and corn under a range of irrigation capacities. The second objective is to evaluate the profitability and production risks of these crops such that producers can make sound decisions on the utilization of their water resources.

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 2014, the Oklahoma Water 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 OWRRI's quarterly newsletter is the *Aquahoman*. With a distribution list of nearly 1500, the *Aquahoman* not only provides a means of getting information to the general public, but also informs researchers throughout the state about water research activities. This project year the newsletter was published in June 2014, August 2014, November 2014, and February 2015. 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 one. All issues of the *Aquahoman* are also 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 water issues in the state of Oklahoma by members of the Water Resources Advisory Board. Grant impact statements were developed on projects funded from 2007-2008 through the USGS 104(b) program and included articles on a project by Dr. Garey Fox on *Subsurface Transport of Phosphorus to Streams: A Potential Source of Phosphorus not Alleviated by Best Management Practices* and on a project by Dr. Tracy Boyer on *Decision Support Model for Optimal Water Pricing Protocol for Oklahoma Water Planning: Lake Tenkiller Case Study.* Examples of these WRAB member articles included "Protecting State Water is Vital" by Mr. Ed Fite, Oklahoma Scenic Rivers Commission, and "Ground Water Protection Council: Purpose and Projects" by Mr. Dan Yates, Groundwater Protection Council.

Water Research Advisory Board: The WRAB consists of 22 water professionals representing state agencies, federal agencies, tribes, and non-governmental organizations. This advisory board was formed in 2006 to assist the OWRRI by setting funding priorities, recommending proposals for funding, and providing general advice on the direction of the Institute. The Board members have found that they also benefit from their involvement in at least two ways. First, they profit from the opportunity to discuss water issues with other professionals. Second, the 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.

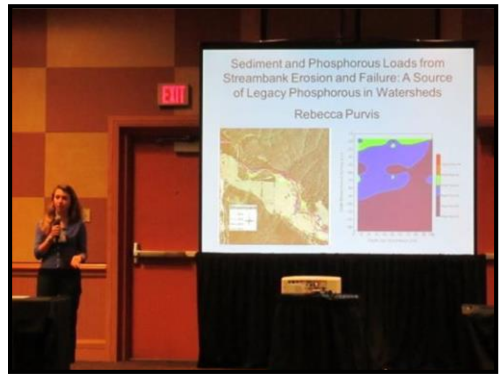
Thus, the WRAB is an important part of the Water Center's efforts to disseminate research findings to state agencies for use in problem solving. This project year the WRAB met during the summer to hear presentations of findings from previous year's projects and to select from among the pre-proposals submitted for the 2014 grants competition those that will continue in the competition as full proposals. They also received copies of all the final reports from 2014. In January, they met to review and select proposals for FY 2015 funding.

Website: The Water 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 sponsored by the OWRRI (all reports from 1965 to the previous project year are available for immediate download). Also available are current and past issues of the *Aquahoman*, information about the annual grants competition including the RFP and guidelines for applying, and details about the OWRRI's effort to gather public input for the state's revision of the State's comprehensive water plan. The website 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 Water Center significantly expanded the video content on the website this past year. As part of Dr. Fox's leadership, the Water Center organized and participated in water video series called ***Foundations of Oklahoma Water*** (www.youtube.com/user/OkstateWaterCenter.) The Water 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 Dwayne Elmore through the Renewable Resources Extension Act ($10,000). We recently released 10 videos. This list includes the title, participating Extension expert, release date, and # of views as of April 1, 2015:

- *Introduction to the Water Center* – Dr. Garey Fox (11/17; 223 views)
- *Surface Water Hydrology* – Dr. Garey Fox (11/17; 99 views)
- *Groundwater Hydrology* – Dr. Garey Fox (11/24; 57 views)
- *Oklahoma Mesonet* – Dr. Garey Fox and Mr. Al Sutherland (12/5; 27 views)
- *Flood Irrigation* – Dr. Saleh Taghvaeian (11/24; 146 views)
- *Sprinkler Irrigation* – Dr. Saleh Taghaveian (11/17; 68 views)
- *Subsurface Irrigation* – Dr. Saleh Taghaveian (11/17; 56 views)
- *Outdoor Urban Irrigation* – Dr. Justin Moss (11/17; 60 views)
- *Water Law* – Dr. Shannon Ferrell (12/5; 87 views)
- An additional video was produced 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 (11/24; 157 views).

Oklahoma Research Symposium and Student Water Conference: The Water 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 this year, the Symposium was integrated with the Oklahoma Water Resources Board's annual Governor's Water Conference. The two-day event in Oklahoma City 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 Water Center invited Dr. Francois Birgand (Associate Professor, North Carolina State University) as a keynote presentation. He presented a talk titled "High Frequency Water Quality Data: Is this Really Necessary?" His presentation challenged the way in which water quality data are being collected across the state of Oklahoma.

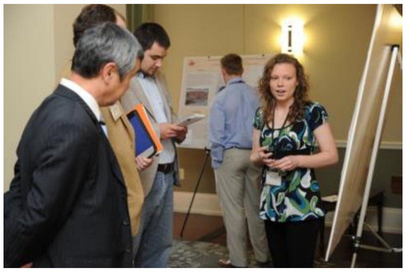
This year the symposium included a unique Café style poster session, where 26 students from universities across Oklahoma orally presented a two-minute overview of their poster followed by the designated poster session. This session significantly improved interaction between the students and the conference participants because of the posters were in a designated session and a brief introduction was also provided to the audience in their two-minute overview.

Undergraduate and graduate students were eligible for outstanding poster awards: $250 awards were given to two undergraduate students and two graduate students (total of $1000).

In this project year, the OWRRI will again host the Symposium in conjunction with the Governor's Water Conference. As previously, the OWRRI will assist 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 assisted in hosting the 2014 Student Water to be held April 10-11, 2014. The conference consists entirely of student presentations to be judged by a panel of faculty members for providing constructive feedback to students in regard to their research presentation skills. Awards are given for outstanding student presentations. Also, student activities will promote interaction among students of all disciplines and professional development. In 2014, 49 students presented (22 oral presentations, 27 poster presentations) with 15 presentations by students visiting from outside universities, including Kansas State University, University of Kentucky, University of Arkansas, Iowa State University, University of Florida, University of Minnesota, Western Kentucky University, Texas A&M University. A keynote presentation was given by Dr. Russell Persyn of the San Antonio River Authority as part of the annual Buchanan Lecture. Also, Mr. Greg Kloxin (OSU alumnus, Oklahoma Conservation Commission), Mr. Chris Neel (OSU alumnus, Oklahoma Water Resources Board), and Mr. Chris Stoner (USDA-NRCS) participated in a roundtable discussion on water careers. Mrs. Rachel Felice (OSU alumnus, US Army Corps of Engineers) also presented her early career experiences as part of an awards reception to end the conference.

The Water Center is currently organizing the 4th Annual Student Water Conference to be held on March 26-27, 2015. The Water Center under Dr. Fox's leadership is now the primary organizer of this unique conference, supported through the Buchanan Family Trust through the Buchanan Endowed Chair and USDA NIFA through a National Integrated Water Quality grant. Planned activities include a water trivia and social will be hosted for students studying about water across campus, more than 60 presentations by students from 16 universities, the Buchanan Keynote Lecture to be given by J.D. Strong, OSU alumnus and Executive Director of the Oklahoma Water Resources Board, and a career perceptions lecture by Dr. Maria Chu, Assistant Professor at the University of Illinois and Ph.D. graduate of Oklahoma State University.



Illinois River Watershed Symposium: The Water Center organized the first Illinois River Watershed Symposium in cooperation with the Arkansas Water Resources Center. The meeting was attended by 75 academic, nonprofit, state and federal agency representatives from Arkansas and Oklahoma. The event was attended and completely funded by the Cherokee Nation Environmental Programs. The meeting was highly successful in generating research and Extension needs in a priority watershed in Oklahoma. A new webpage was created to transfer information on the Illinois River Watershed (http://water.okstate.edu/IRW). The Center's future vision is to expand this symposium to other watersheds and groundwater aquifers in Oklahoma.

USGS Summer Intern Program

None.

Student Support

Category	Section 104 Base Grant	Section 104 NCGP Award	NIWR-USGS Internship	Supplemental Awards	Total
Undergraduate	6	0	0	0	6
Masters	5	0	0	0	5
Ph.D.	4	0	0	0	4
Post-Doc.	1	0	0	0	1
Total	1	0	0	0	16

Notable Awards and Achievements

The Oklahoma Water Resources Center co-sponsored and co-hosted the 35th Annual Oklahoma Governor's Water Conference and Research Symposium at the Cox Convention Center in Oklahoma City, OK on October 22-23, 2014. The meeting included over 400 attendees. Keynote speakers included Pat Mulroy (Senior Fellow, Climate Adaptation and Environmental Policy, Brookings Mountain West and Maki Distinguished Faculty Associate, Desert Research Institute) who presented on "The Las Vegas Story: Adapting a New Normal"; and Dr. Francois Birgand

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Publications from Prior Projects

2010OK192G, "Scale Dependent Phosphorus Leaching in Alluvial Floodplains"

1. 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): DOI 10.13031/trans.58.11056.

2. Miller, R.B., D.M. Heeren, G.A. Fox, T. Halihan, and D.E. Storm. 2015. Heterogeneity influences on stream water–groundwater interactions in a gravel-dominated floodplain. Hydrological Sciences Journal doi: 10.1080/02626667.2014.992790 (In Press, Accepted on November 24, 2014).

3. Heeren, D.M., G.A. Fox, A.K. Fox, D.E. Storm, R.B. Miller, and A.R. Mittelstet. 2014. Divergence and flow direction as indicators of subsurface heterogeneity and stage-dependent storage in alluvial floodplains. Hydrological Processes 28(3): 1307-1317, doi: 10.1002/hyp.9674.

4. Heeren, D.M., G.A. Fox, and D.E. Storm. 2014. A berm infiltration method for conducting leaching tests at various spatial scales. Journal of Hydrologic Engineering 19(2): 457-461, doi: 10.1061/(ASCE)HE.1943-5584.0000802.

5. Miller, R.B., D.M. Heeren, G.A. Fox, T. Halihan, D.E. Storm, and A.R. Mittelstet. 2014. The hydraulic conductivity structure of gravel-dominated vadose zones within alluvial floodplains. Journal of Hydrology 513: 229-240, doi: 10.1016/j.jhydrol.2014.03.046.

6. Freiberger, R., D.M. Heeren, G.A. Fox, C.J. Penn, and D.E. Eisenhauer. 2014. Finite element modeling of long-term phosphorus leaching through macropores in the Ozark ecoregion. ASABE Paper No. 141897543. St. Joseph, Mich.: ASABE.

2012OK248B, Identifying Nutrient Pathways to Streams, Fox

1. Daly, E., R.B. Miller, 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 (In Press, Accepted January 4, 2015), doi: 10.1016/j.advwatres.2015.01.004.

2. Daly, E.R., R.B. Miller, and G.A. Fox. 2014. Bank Stability and Toe Erosion (BSTEM) modeling of bank retreat and riparian tree root protection in composite streambanks. ASABE Paper No. 141895637. St. Joseph, Mich.: ASABE.

3. 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.

2010OK184B, Drought Monitoring, Ochsner

1. 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.

2011OK207B, Incorporating Ecological Costs and Benefits into Environmental Flow Recommendations, Vaughn

1. Vaughn, Caryn C., Carla L. Atkinson and Jason P. Julian. 2015. Drought-induced changes in flow regimes lead to long-term losses in mussel-provided ecosystem services. Ecology and Evolution 5:1291-1305.

2. Gates, Kiza K., Caryn C. Vaughn and Jason P. Julian. 2015. Incorporating species traits in a guild approach to develop environmental flow recommendations for freshwater mussels. Freshwater Biology 60:620-635.

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2014OK310B, Comparison of Grain Sorghum and Corn Productivity, Warren

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Funding

Funding for the projects reported herein was provided by the U.S. Geological Survey and the Division of Agricultural Sciences and Natural Resources (DASNR) at Oklahoma State University. Additional support was provided by grant funding from the NSF and 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: DASNR at Oklahoma State University and the University of Oklahoma. The Water Center is grateful for their support.

Final Technical Report

Title: Remote Sensing of WQ and harmful algae in OK Lakes

Authors' Names and Affiliations:
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Start Date: 1 March 2013

End Date: 30 July 2014

Congressional District: 3, 4

Focus Category: WQL; SW; CP

Descriptors: Grand Lake, Lake Texoma, satellite imagery, GPS digital camera, water quality

Principal Investigators: K.D. Hambright (University of Oklahoma); X. Xiao (University of Oklahoma); A.R. Dzialowski (Oklahoma State University)

Publications: in progress

Students and Postdocs salaried through this project

Student Status	Number	Disciplines
Undergraduate	4	2-Biology; 1-Geography; 1-Biology/Professional Writing
M.S.	1	Zoology
Ph.D.	3	2-Biology/EEB; 1-Microbiology/EEB
Post Doc	1	Remote sensing
Total	9	

Problem and Research Objectives:

The many lakes (reservoirs) of Oklahoma provide rich fisheries, abundant recreational activities, and a general, high-value aesthetic quality to the state. Larger lakes, such as Lake Texoma, Lake Eufaula, and Grand Lake, also serve as critical economic engines for surrounding communities. Agriculture and continued urban and rural development have generated excessive nutrient inputs to many of our lakes, leading to increased frequency and magnitude of harmful algal blooms (HABs), particularly of toxic cyanobacteria (blue-green algae). Blooms of cyanobacteria, which can produce a variety of harmful toxins including: hepatotoxins, neurotoxins, or dermatoxins that may be harmful or lethal to animals and humans, have been exacerbated by recent drought and heat conditions. In 2006, a pet died from cyanotoxin exposure in Lake Texoma, in 2011, Sen. James Inhofe fell gravely ill after swimming in Grand Lake during a *Microcysitis* bloom, and in 2012, two dogs died from exposure to cyanobacterial toxins in Lake Ellsworth (Lawton). Many humans have experienced sub-lethal adverse acute effects from cyanobacteria, particularly in recent years (R. Lynch, OUHSC, College of Public Health), but we have little understanding of the consequences of chronic exposures. Fortunately, no human fatalities in Oklahoma have yet been linked to cyanobacteria.

Following the 2011 HAB outbreak season, the Oklahoma Secretary of the Environment convened a committee of experts from across the state to provide recommendations for the state's HAB monitoring needs. That committee concluded that just to monitor the largest 100 lakes once monthly for a year, $3.5 million would be required (Smithee et al. 2012). A program designed to provide the necessary coverage of Oklahoma's lakes sufficient for safeguarding public health would require more frequent monitoring at higher spatial resolutions and therefore would require much more funding. More importantly, experience gained from other states faced with similar HAB problems, indicates that even the most basic (= insufficient) statewide monitoring program for HABs is not economically sustainable (K. Loftin, USGS, Lawrence, KS, pers. comm.). At present, Oklahoma does not have a sufficient monitoring program in place for protecting the health of the public who visit and swim, boat, and fish in the state's many large lakes. With little effort and monies being directed to mitigation of nutrient pollution, HAB issues are forecast to worsen with time. As such, Oklahoma is in dire need of a solution for dealing with the threat of HABs – one that is low in cost, is sustainable, and offers real-time public protection.

This project represents an initial phase of a long-term strategic plan between the Xiao, Hambright, and Dzialowski labs and other collaborating scientists, engineers, and agencies in the region (C. Armstrong and J. Wright, Oklahoma Department of Environmental Quality-DEQ; T. Clyde, US Army Corps of Engineers-USACE; J. Chambers and D. Martin, Oklahoma Water Resources Board-OWRB; D. Townsend, Grand River Dam Authority-GRDA). Our long-term goal is twofold: 1) to improve our knowledge and capacity of remote sensing of water quality and harmful algal blooms using chlorophyll-a, plus the accessory pigments phycocyanin (unique to cyanobacteria) and carotenoids (found in golden algae, another group of HAB species important in Oklahoma and the region), and 2) to develop a monitoring program for water quality and harmful algal blooms in Oklahoma lakes based on traditional approaches coupled to remote sensing and digital photography. In short, we aim to provide the State of Oklahoma a comprehensive program for monitoring surface water quality and HABs that will greatly enhance current risk management capabilities with respect to public health and the state's recreational water bodies.

This two-lake pilot study was designed to provide proof-of-concept across a range of water body types and water qualities and will provide a foundation for multiple future projects. For example, because LANDSAT images extend back to the 1970s, it may be possible to examine long-term trends in Lake Texoma (and other lakes) water quality (from LANDSAT images) as related to both land-use and climate change. Further, we are planning to expand our data collection and analyses to more lakes around the state, and because LANDSAT images have resolutions of 30 m and are available only at 16-day intervals, we have been pursuing increased collaboration with USGS and USACE to develop a near real-time, satellite-based, water quality and HAB monitoring model for all large lakes in the state using daily images from satellites such as MERIS (15 bands, 300-m resolution) and RapidEye (5 bands, 6.5-m resolution), as well as DoD satellite imagery available through the USACE. Such a monitoring tool could provide efficient, near-real time, low-cost remote monitoring for targeting limited resources for *in-situ* monitoring while allowing greater coverage of lakes for public health protection.

Methodology:

We have sampled 12 and 11 sites each in Lake Texoma and Grand Lake, respectively, based on previous monitoring programs of the PEL lab (Texoma) and the BUMP program of OWRB (Grand) (OWRB 2010). Grand Lake was visited five times; Texoma four. Many other lake visits were planned and cancelled due to overcast skies and other weather-related conditions. During lake visits, samples were collected for chlorophyll (total algae), phycocyanin (blue-green algae), golden algae, total organic carbon (TOC), colored dissolved organic matter (CDOM), and turbidity. We also measured reflectance of the water at each sample site, using ASD FieldSpec@3 and ASD Handheld-2 spectroradiometers. Ten measurements were recorded from each side of the boat, and the mean, median, and standard deviation of these twenty measurements constitute the reflectance for each site. White-surface calibration of the instrument was done every 30 minutes or more frequently if sky conditions changed. In addition to NADIR angle measurements, we carried out measurements at several viewing angles, and the resultant data will be used for radiative transfer models and the study of the effect of viewing angles on *in-situ* water reflectance. We also used a GPS-enabled digital camera (Casio Exilim EX-H20G) and an iPhone to take photos of the water at each site.

Temperature, pH, dissolved oxygen (DO), conductivity, chlorophyll a (a proxy for total algal biomass), and phycocyanin (a proxy for cyanobacterial biomass) were measured in situ with a Hydrolab DS5x sonde (Texoma) or a YSI 6600 V2-4 sonde (Grand). The sondes were deployed at 1-m intervals from the surface to the thermocline or lake bottom (depending on season and site). Light extinction was measured using a Li-Cor 2π PAR sensor deployed at 1-m intervals from the surface to 1% surface light. Secchi depth was measured using a standard 20-cm Secchi disk. Depth-integrated (upper 10 m or to 1% surface light) water samples (250 mL) were collected in sterile Nalgene bottles, stored on ice in the field, and refrigerated in the laboratory for subsequent sub-sampling for CDOM, extracted chlorophyll, and turbidity. Golden algae densities were measured using qPCR (Zamor et al. 2012). CDOM was measured by fluorometry (American Public Health Association 2012).

The spectral characteristics of water in lakes are functions of hydrological, biological and chemical characteristics of water and other interference factors (Seyhan and Dekker, 1986). We have conducted preliminary statistical data analyses of water constituents (algal pigments, turbidity, Secchi depth transparency), light penetrance and extinction, water hyperspectral reflectance from ASD spectroradiometers, and reflectance data for LANDSAT and digital camera sensors representing red, green, and blue wavelengths.

Principal Findings and Significance:

We completed five trips on Grand Lake and four on Lake Texoma for a total of 88 water samples. Due to partial cloud cover on some lake trips, we have 44 usable site-specific satellite images for Grand lake and 32 usable site-specific satellite images for Texoma.

Preliminary results are extremely promising. Both satellite- and spectroradiometer-measured reflectance were strongly related to chlorophyll, phycocyanin, and turbidity, indicating that all three water quality parameters could be accurately predicted remotely in both Lake Texoma and Grand Lake. Despite some problems with obtaining simultaneous ground and satellite data, we were able to collect water quality and reflectance data from a wide range of conditions, from low to moderate turbidities and concentrations of chlorophyll and phycocyanin. There was also a moderate degree of overlap in water quality values between the two lakes, suggesting that observed relationships may be robust across a wider range of lakes and lake types. This is particularly true for LANDSAT-based water quality estimation. However, the in-situ reflectance measures (ASD spectroradiometers, digital camera), while very accurate at estimating water quality parameters in Lake Texoma, where much less capable of such for Grand Lake. We have discussed these issues with researchers at Grand Lake and are considering options for additional measurements and parameters necessary to improve our models.

Overall, this study has provided a firm foundation for ongoing and future research aimed at developing a state-of-the-art remote sensing-based tool for providing affordable, efficient, near-real time water quality and HAB assessment, that will allow for more focused targeting of limited resources, while simultaneously allowing for greater coverage of monitored lakes across the state, particularly isolated and difficult to sample lakes, thus maximizing public health protection.

These and other results were presented at the 2014 Oklahoma Governor's Eater Conference and Oklahoma Water Resources Research Institute symposium in Oklahoma City and are currently being prepared for publication. However, because online posting of our results in this report could potentially jeopardize future publication of the student projects associated with this research, we are not presenting any details of our analyses, nor any data, in this report. Of course, we will be happy to discuss any aspect of this project in person, should anyone within the WRAB, OWRRI, USGS, or OWRB wish. Copies of all publications arising from this project will be forwarded to the OWRRI.

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Interim 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

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/Presentations:

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.

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.

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.

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.

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.

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 suggests that the Mesonet has real potential as a tool for estimating groundwater recharge across Oklahoma. However, we currently lack 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 have no knowledge about the extent to which regional scale spatial variability in groundwater recharge is reflected in Mesonet-based drainage rates. There is 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* is to clarify the relationship between Mesonet-based drainage rates and groundwater recharge rates in western Oklahoma. To accomplish our objective we propose 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 will be obtained for three locations in the Rush Springs aquifer and four in the Ogallala aquifer. The unsaturated zone chloride mass balance method will be 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 will be calculated for the decade from 2000-2009 for all Mesonet stations in western Oklahoma having the necessary soil moisture data. An average annual soil drainage rate map will be created for western Oklahoma and compared with a new regional recharge map based on chloride concentrations in groundwater sampled from existing OWRB monitoring wells.

Methodology:

Specific aim #1: Determine the site-specific level of agreement between Mesonet-based drainage rates and independent estimates of recharge in selected aquifers.

1.1 Research design: Drainage at the 60 cm depth will be calculated on a daily time step for the ~15-yr period of record for four Mesonet sites above the Ogallala aquifer (Boise City, Goodwell, Hooker, and Slapout) in the Oklahoma Panhandle and three Mesonet sites above the Rush Springs aquifer (Putnam, Hinton, and Ft. Cobb). We will follow 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 we will improve on these studies in two important ways. First, we will use 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 will be 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 (unpublished data). Drainage events can be highly episodic and the importance of having daily soil moisture measurements should not be underestimated. Second, we will use 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) will be used to obtain site-specific recharge estimates at the seven Mesonet sites listed in the first paragraph of this section following the methods of Scanlon et al. (2010b). Core samples from the surface to a depth of ~15 m will be collected using a direct-push drill rig (e.g., Model 6620DT or similar, Geoprobe, Salina, KS) or by direct-rotary drilling (Shuter and Teasdale, 1989) at sites with consolidated subsurface materials impenetrable by the direct push system. Cores will be 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 will be determined, and the segments will be 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 will be converted to pore water concentrations, which will then be used in the uz-CMB calculations to estimate the site-specific recharge rate corresponding to each core following Scanlon et al. (2010b). Chloride concentrations in precipitation, required in the CMB method, will be obtained from the National Atmospheric Deposition Program (http://nadp.sws.uiuc.edu/).

1.2 Expected outcomes: The research proposed under specific aim #1 is expected to result in new knowledge about site-specific recharge rates in two significant aquifers in Oklahoma, the Ogallala and the Rush Springs, which serve regions facing the prospects of serious water supply shortfalls. This research is also expected to provide the foundation for a Mesonet-based, statewide groundwater recharge estimation system by revealing new insights into the relationship between Mesonet drainage rates and site-specific groundwater recharge values.

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 will be calculated for 2000-2009 for the ~50 Mesonet stations in western Oklahoma which have 60 cm soil moisture data throughout that time period. Calculation procedures were described under specific aim #1. Annual drainage totals and average annual drainage rate for the decade will be calculated for each station. Ordinary kriging (Ahmadi and Sedghamiz, 2007) will be applied to create a drainage map for western 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 will be collected in conjunction with the startup of the new OWRB groundwater monitoring and assessment program. These groundwater samples will be analyzed for chloride and sulfate as in the work of Scanlon et al. (2010b). Existing groundwater chloride and sulfate data for Oklahoma will also be obtained from the USGS National Water Information System database (waterdata.usgs.gov/nwis). 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 will be used in the saturated zone CMB approach (sz-CMB) to estimate regional recharge rates across western Oklahoma. Ordinary kriging will be used to interpolate these estimates and create a regional recharge map for western Oklahoma similar to the one recently produced for the Texas Panhandle (Scanlon et al., 2010b). Spatial patterns in the Mesonet-based drainage map will be qualitatively compared with those in the sz-CMB recharge map, and the magnitudes of the mapped variables will be compared in order to determine the regional level of agreement between Mesonet-based drainage rates and independent regional recharge estimates for western Oklahoma.

2.2 Expected outcomes: The research proposed under specific aim 2 will result in important new knowledge about spatial patterns of groundwater recharge across western Oklahoma, a region heavily dependent on groundwater. The western Oklahoma recharge map produced here will be the first large-scale recharge map produced for Oklahoma in thirty years. This research will provide a key first indication of the Mesonet's ability to represent spatial variability in groundwater recharge at the regional scale, thus this work is an important step toward an operational statewide groundwater recharge estimation system based on the Oklahoma Mesonet.

Principal Findings and Significance:

Through two previous OWRRI projects (2010-2011) we created a comprehensive database of soil hydraulic properties at the Mesonet stations. Using funds from our 2013-2014 OWRRI projects, we have merged these soil properties with daily soil moisture measurements and the Buckingham-Darcy equation for unsaturated flow to calculate drainage below 60 cm, which is the standard depth of the deepest Mesonet soil moisture sensors. For the aquifers in which drainage estimates from three or more Mesonet stations are available, median annual drainage at 60 cm falls within the range of previously published recharge rates (Table 1). Calculated mean drainage rates across the state ranged from 4 mm yr^{-1} at the Hinton, OK Mesonet site to 275 mm yr^{-1} at Bristow (Figure 2). The state-wide median Mesonet-based drainage rate was found to be 61 mm yr^{-1}, which is approximately 7% of the median state-wide rainfall. A similar percentage was found by Kim and Jackson (2011), who observed that 8% of rainfall became recharge under grassland systems in their global analysis. Generally, Mesonet drainage rates decrease from the southeastern portion of Oklahoma to the panhandle, following the precipitation gradient of the state. In the remaining months of the project, we plan to create interpolated maps showing the spatial patterns of drainage across Oklahoma. We also plan to submit the results of our research for publication in a peer-reviewed journal and to present our results to researchers, government agency personnel, and public citizens at the Oklahoma Water Research Symposium in the fall of 2015.

Table 1. Summary of median annual precipitation and drainage at 60 cm for Mesonet sites above selected Oklahoma aquifers from 1996 through 2012. For comparison, prior published estimates of groundwater recharge for these aquifers are also shown.

Aquifer	Sites	Precipitation	Drainage	Recharge	No. Sources
		mm yr^{-1}	mm yr^{-1}	mm yr^{-1}	
Boone	3	1076	235	2.3-254	4
Arkansas River	5	1006	171	127	1
Garber-Wellington	3	893	121	7.6-203	4
Rush Springs	5	735	74	4.9-99	4
Antlers	4	936	70	8.1-152	4
Ogallala	8	497	21	1.5-54	4

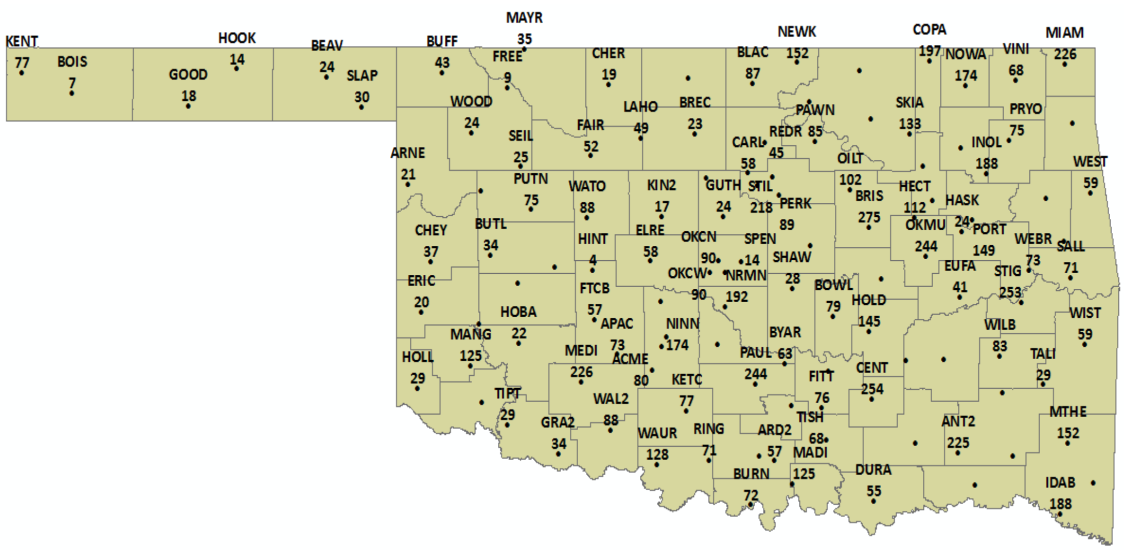


Figure 2. Calculated mean annual drainage rates (mm yr^{-1}) and four-character site ID codes at Mesonet sites across Oklahoma for the years 1996-2012. For sites where no information is given, the corresponding Mesonet station did not have adequate soil moisture data to yield a reliable drainage rate.

Student Status	Number	Disciplines
Undergraduate	1	Environmental Science
M.S.	1	Plant and Soil Sciences
Ph.D.		
Post Doc		
Total	2	

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

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. Gatlin, J., and J. Warren. 2014. Subsurface Drip Technology & Research. Fall Crops Tour. Goodwell, OK 13 Aug.
2. Warren, J. Subsurface Drip Irrigation. Sorghum Tour. Goodwell, OK 25 July.

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	

This report has been split into 2 separate reports. The first provides a interim report on the agronomic component and the other provides an interim report on the economic components of this project.

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.

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.

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. This meant that an efficiency of 100% was assumed to achieve the P_{eff} factor for the water balance. Prior to completion of this project effort will be made to use estimates of leaf area index (LAI) to determine rainfall interception by the crop canopy during different points in the growing season. Interception by residue on the soil surface will also be estimated and used to adjust P_{eff}.

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. 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})

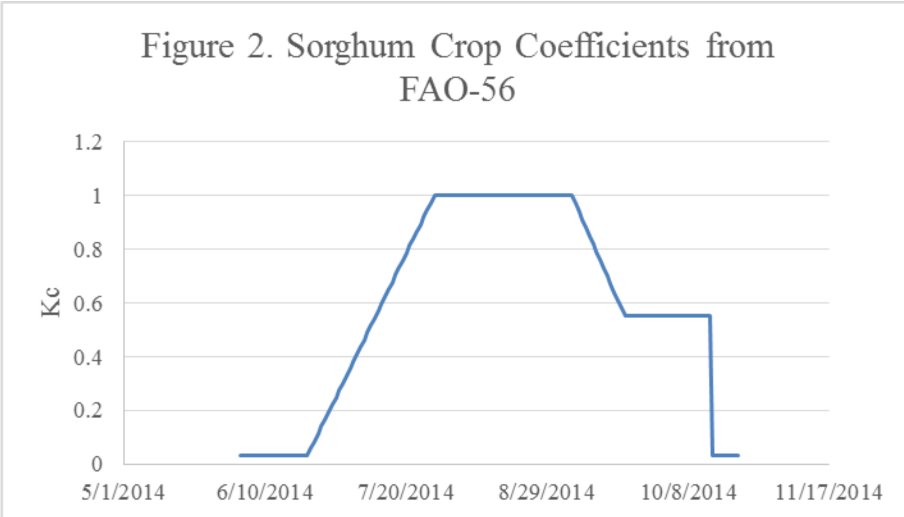
Corn Crop Coefficients

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:

<u>Yield and Irrigation Data</u>

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 and 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 and 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 (Smfinal) 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: Indiviual components of the Water Balance for each Corn treatment in 2014

Irrigation Capacity	Sm_{ini}	I_{eff}	P_{eff}	D	RO	Etc	Sm_{final} Estimate	Sm_{final} Measured
LPM ha^{-1}	---cm---							
C1	39.0	55.1	36.7	4.5	0	92.8	33.5	36
C2	36.6	44.9	36.7	1.8	0	83.8	32.6	35
C3	40.4	37.3	36.7	7.2	0	77.4	29.9	33
C4	38.7	22.1	36.7	4.1	0	63.3	30.1	32

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

Irrigation Capacity	Sm_{ini}	I_{eff}	P_{eff}	D	RO	Etc	Sm_{final} Estimate	Sm_{final} Measured
LPM ha^{-1}	---------------------------------------cm---------------------------------------							
S1	37.8	33.8	27.0	6.3	0	64.8	27.5	34
S2	34.2	30.0	27.0	2.3	0	61.0	27.8	30
S3	35.3	18.5	27.0	3.5	0	51.2	26.1	29
S4	35.3	13.5	27.0	3.4	0	47.0	25.3	25

Table 10: ETc from the Aquaplanner, mesonet, and FAO

	Cumulative Etc (cm)		
Treatment	Aquaplanner	Mesonet	Water Budget
Corn	--	105.41	--
C1	89.916	--	92.71
C2	87.884	--	83.82
C3	68.7578	--	77.47
C4	62.738		63.246
Sorghum	--	57.912	--
S1	56.3372	--	64.77
S2	55.4482	--	60.96
S3	47.0662	--	51.308
S4	41.4274	--	46.99

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. This shows that the production of sorghum will result in more grain produced per L of water.

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Economic Modeling of Irrigated Corn vs. Grain Sorghum Using Center Pivot or Subsurface Drip Systems

Preliminary Report to OWRRI at Oklahoma State University

May 1, 2015

By

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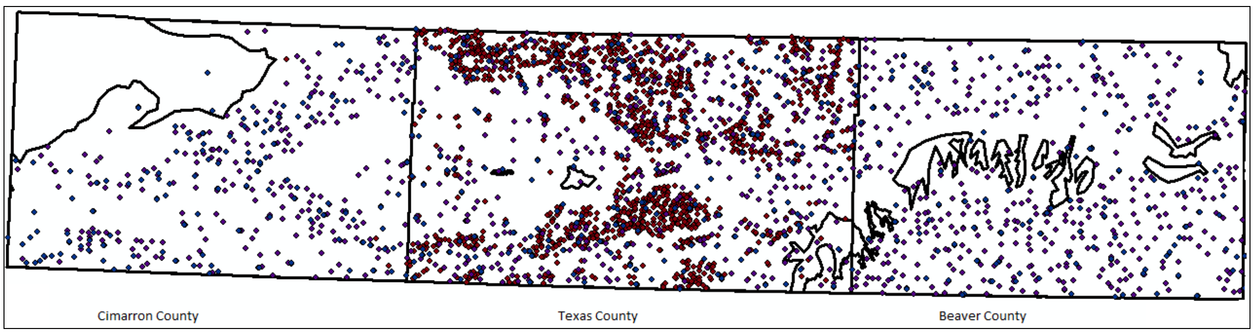
Introduction

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, Coounty: 92.7 + 2.59 Yr, $r^2 = .68$,
Cimarron, County: 180.7 + 0.94 Yr, $r^2 = .28$, and
Texas, Country: 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.

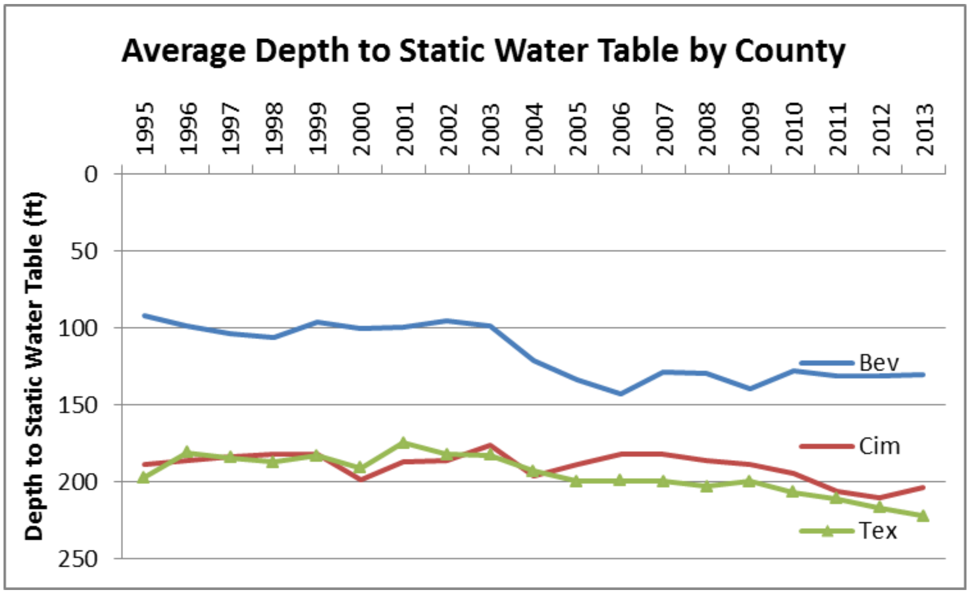


Figure 2. Average Depth to the Static Water Table in Wells in Beaver, Cimarron, Texas Counties from 1994 through 2013 as reported by the USGS.

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 to 0.5 inches per year (Manjula, 2000).

Luckey 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 (Delmar et al, limited rainfall and has been estimated to be between 0.25 to 0.5 inches per year (Manjula, 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) 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 provides 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 regression from the surrounding weather stations and MESONET stations from 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.

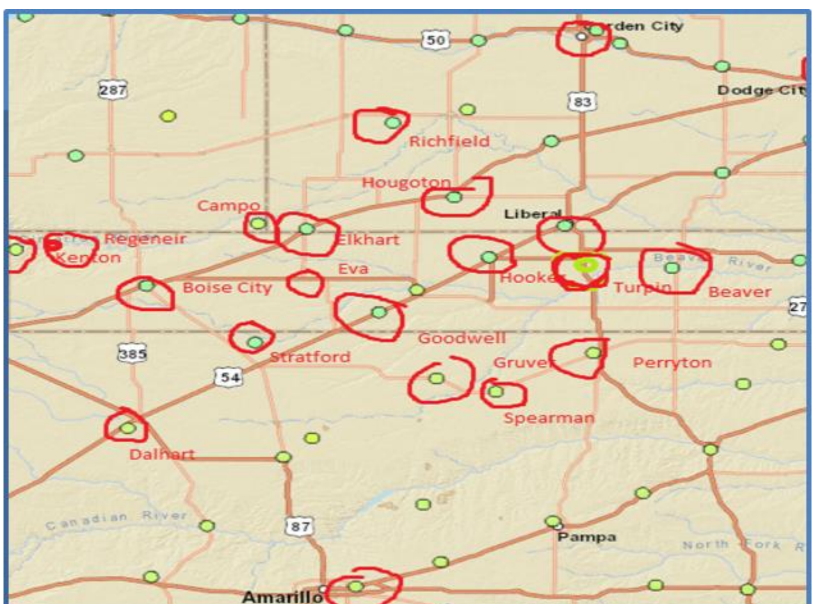


Figure 3. Locations of sites around Goodwell where Weather Variables were Obtained to Estimate Missing Goodwell Values

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 below 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, Am represent observations form Goodwell, Hooker, Boise Cit;y, Liberal, Perryton and Amarillo respectively.

The 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 is based on the reported 15 minute rainfall and the time of year, rainfall during the missing period could be made. However, there were still

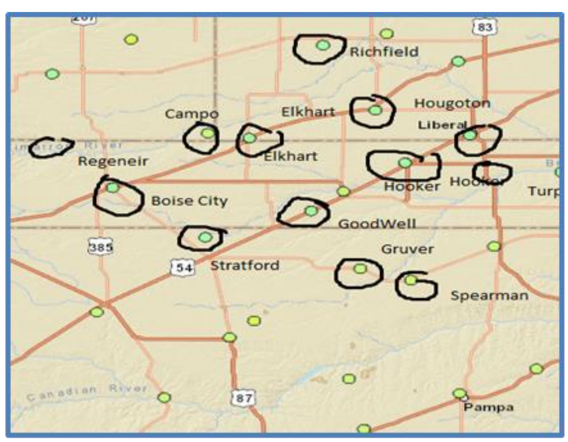


Figure 4. Location of Daily Rainfall Values used in the Regression Equations

many gaps and the precipitation values from the independent sites were 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 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

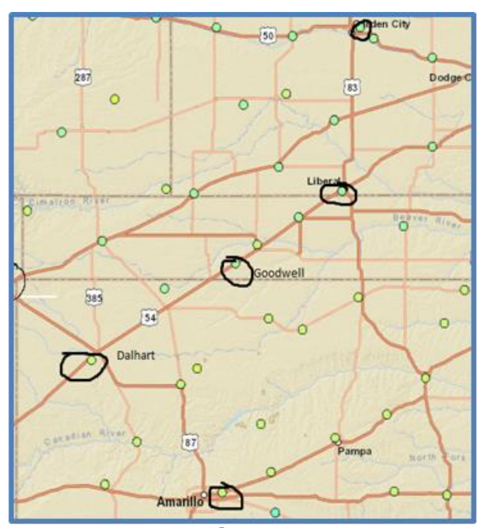


Figure 5. Location of Stations Reporting Windspeeds used in the Regression Analysis

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	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
Celsius	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.	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
Celsius	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	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
mm	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.	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
proportion	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	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
m/sec	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.	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
Wats/m^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 dates and harvesting dates for both corn and grain sorghum were 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} (32,000 plants ac^{-1}) was 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 anytime 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

	Frequency	Application per Revolution	
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

		Maximum Daily Application									
Field Size		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:

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 at 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 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

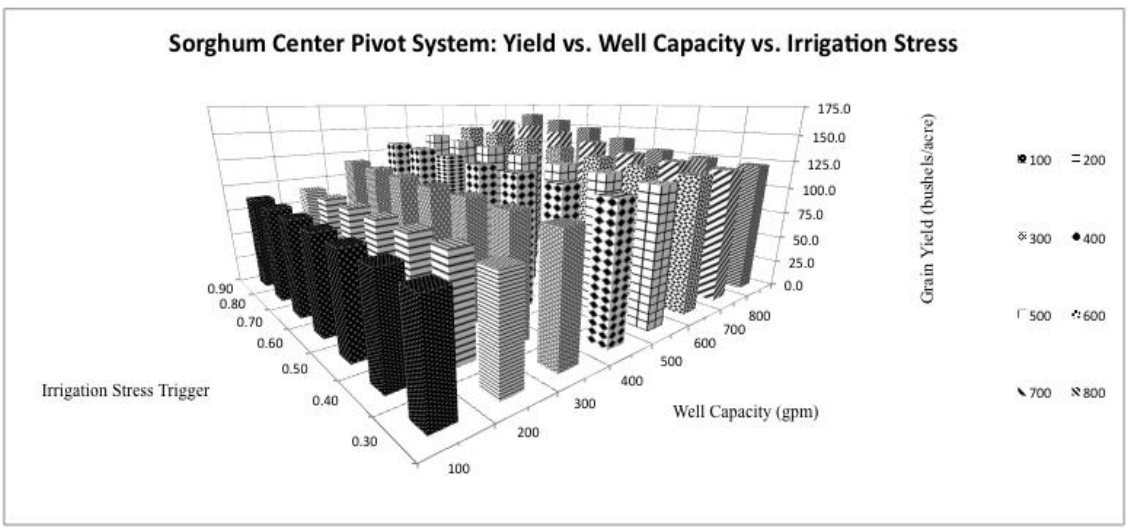


Figure 6. Simulated EPIC Grain Sorghum Yields with a 120 Acre Center Pivot Irrigation by Well Capacity when Irrigation Occurs if Soil Moisture Level Reach Specified Levels

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 central 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 Sorghum 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

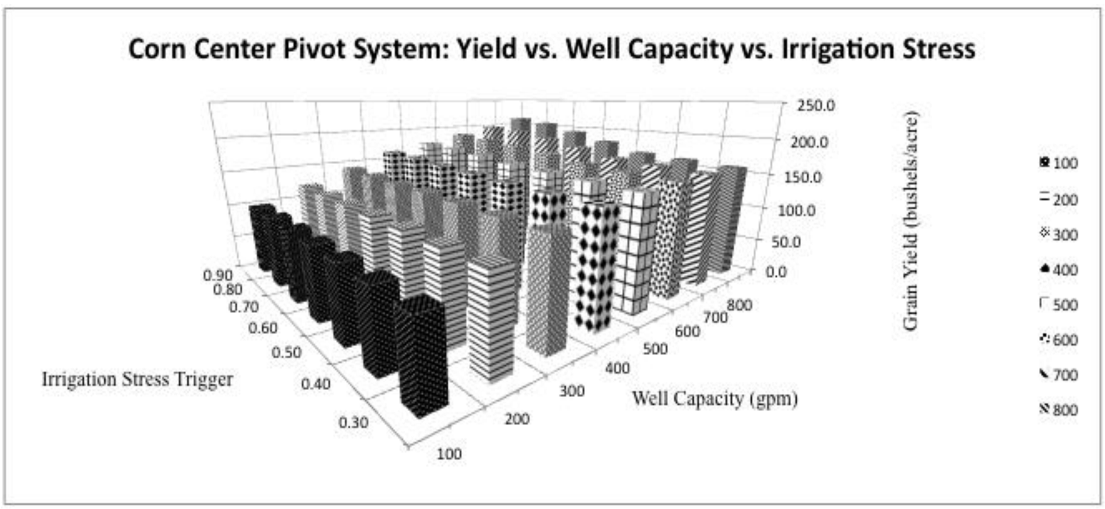


Figure 7. Simulated EPIC Corn Yields with a 120 Acre Center Pivot Irrigation by Well Capacity when Irrigation occurs when Soil Moisture Levels fall below the Indicated levels.

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, Herford, 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 2007 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.

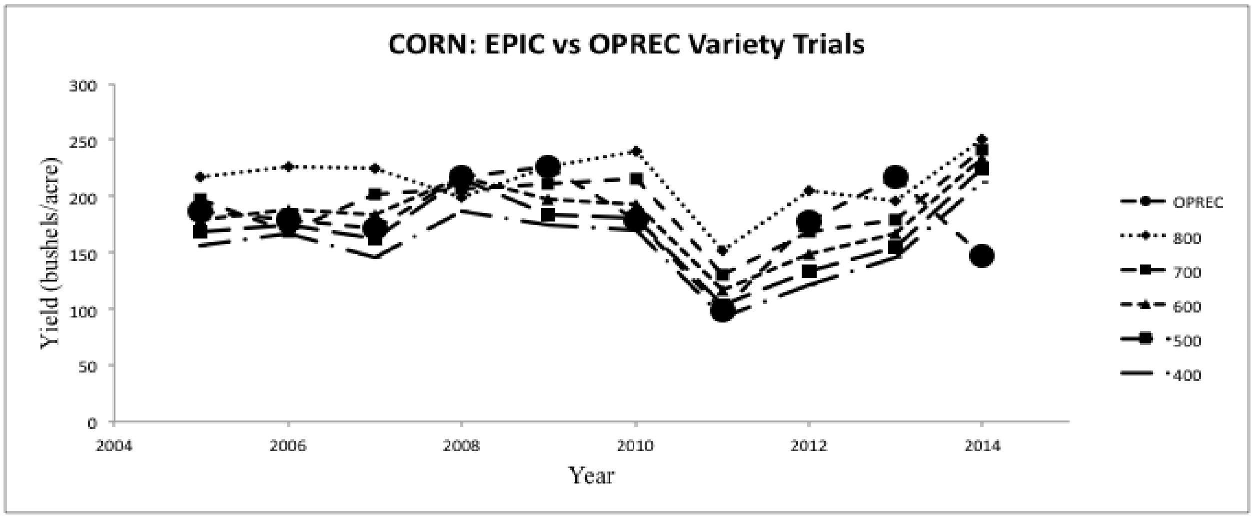


Figure 8. Results from EPIC corn simulation full irrigation comparing with OPREC Variety Trials

The simulated sorghum yields miss 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.

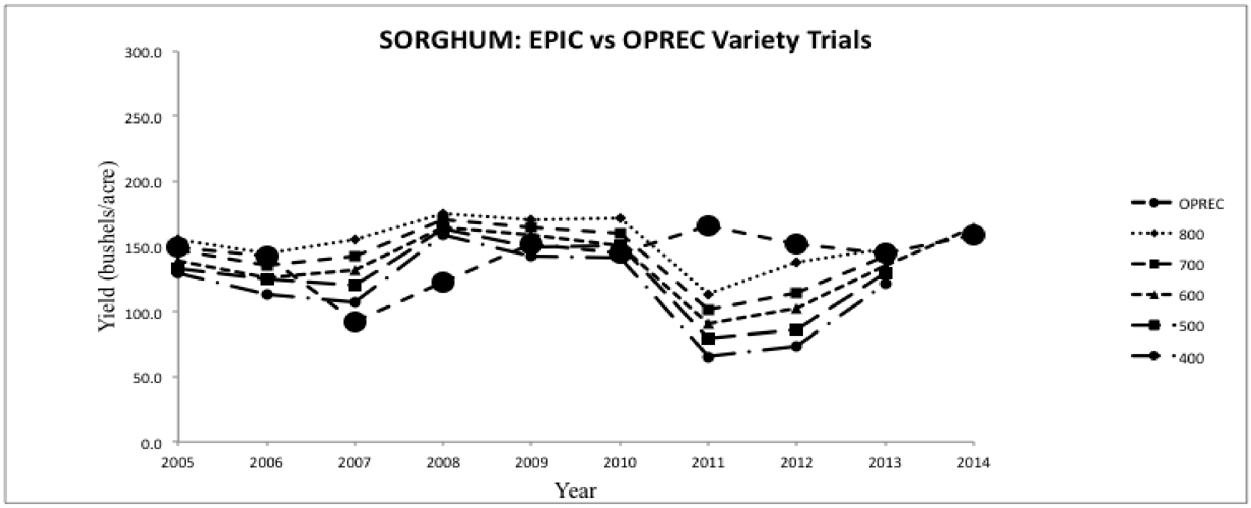


Figure 9. Results from EPIC sorghum simulation full irrigation comparing with OPREC Variety Trials Water Use Efficiency

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.

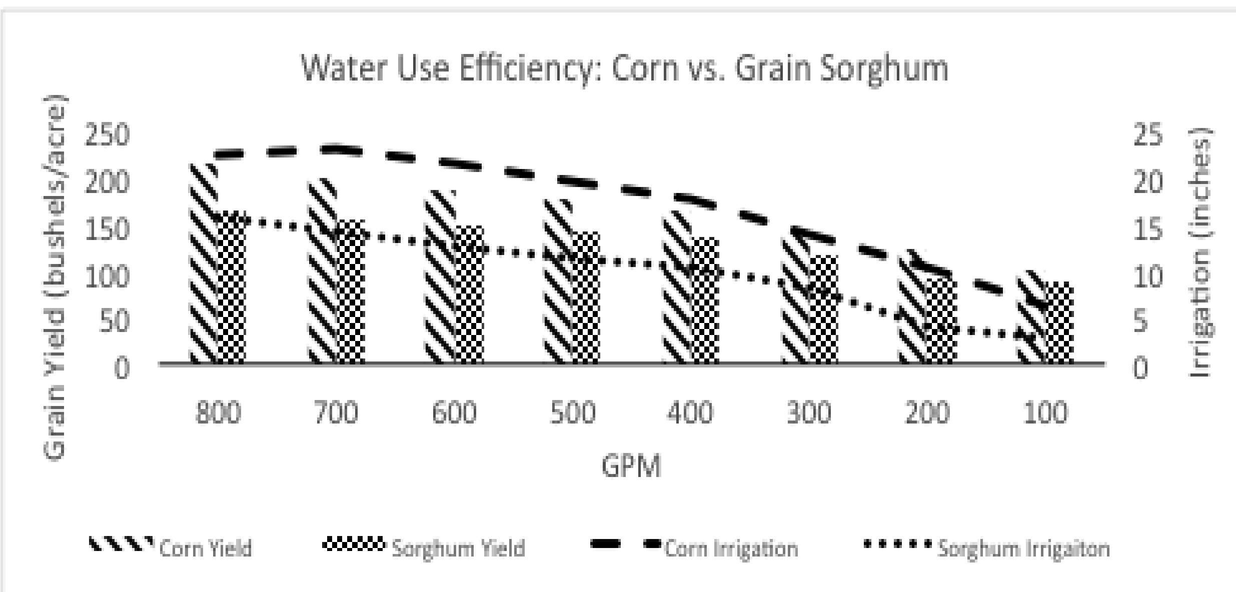
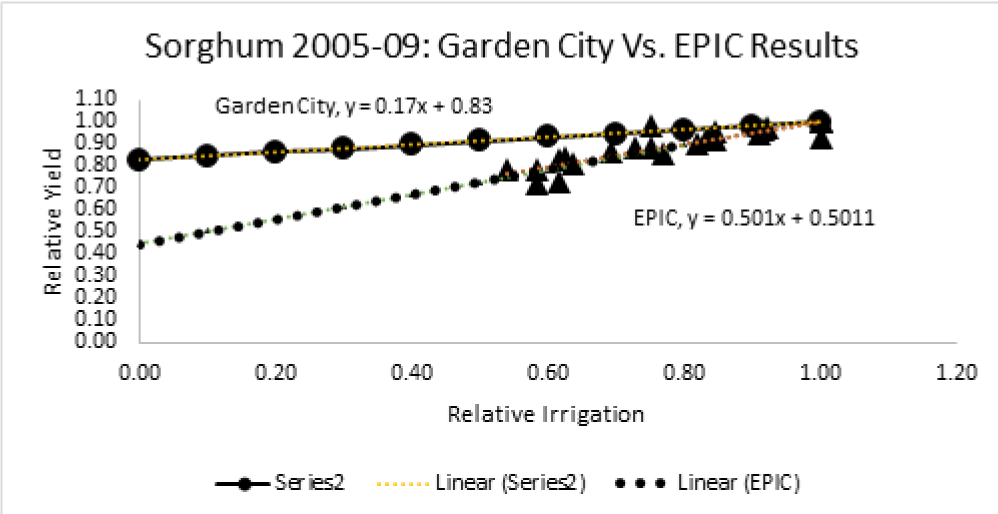


Figure 10. Results from EPIC Corn and Sorghum simulation full irrigation showing its water use efficiency.

The relative grain sorghum yields with irrigation plus rainfall from simulation are compared with similar results a 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.



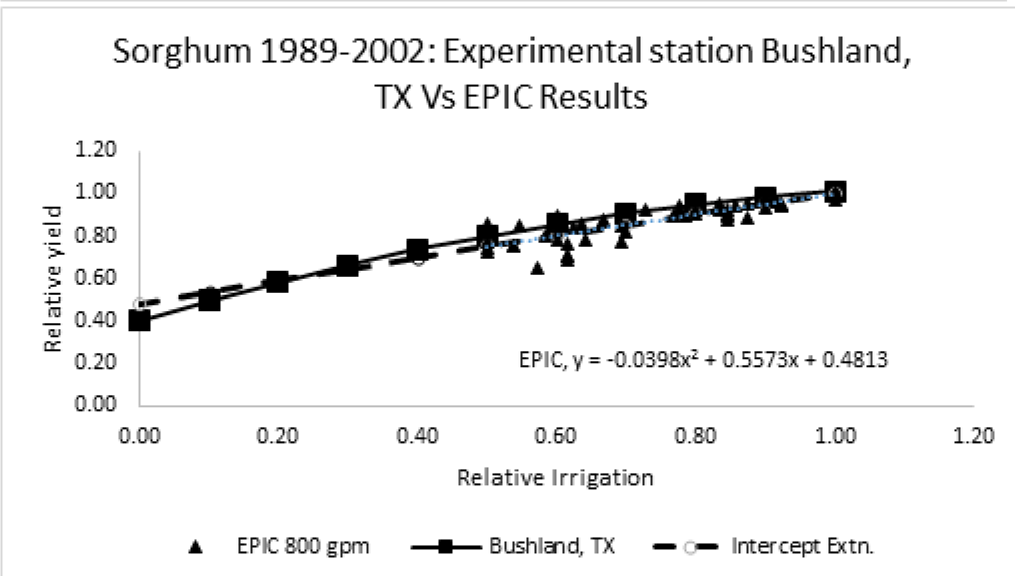


Figure 11. Results from EPIC Corn and Sorghum Simulation as compared to Experimental Data from Bushland, Texas.

SUBSURFACE DRIP SIMULATION RESULTS

Subsurface Drip 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 that with the pivot system. Thus the producer is more likely to consider the capacity of the well in selecting the size of 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

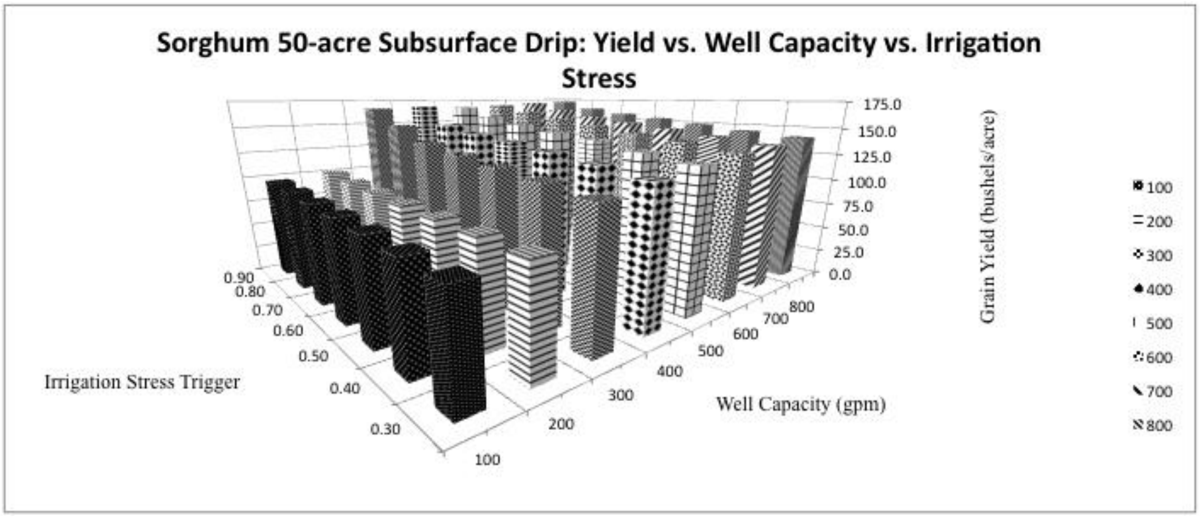


Figure 12. Results from EPIC Sorghum Subsurface Simulation showing Yields and Irrigation along with the Well Capacity for a 50 Acre Field.

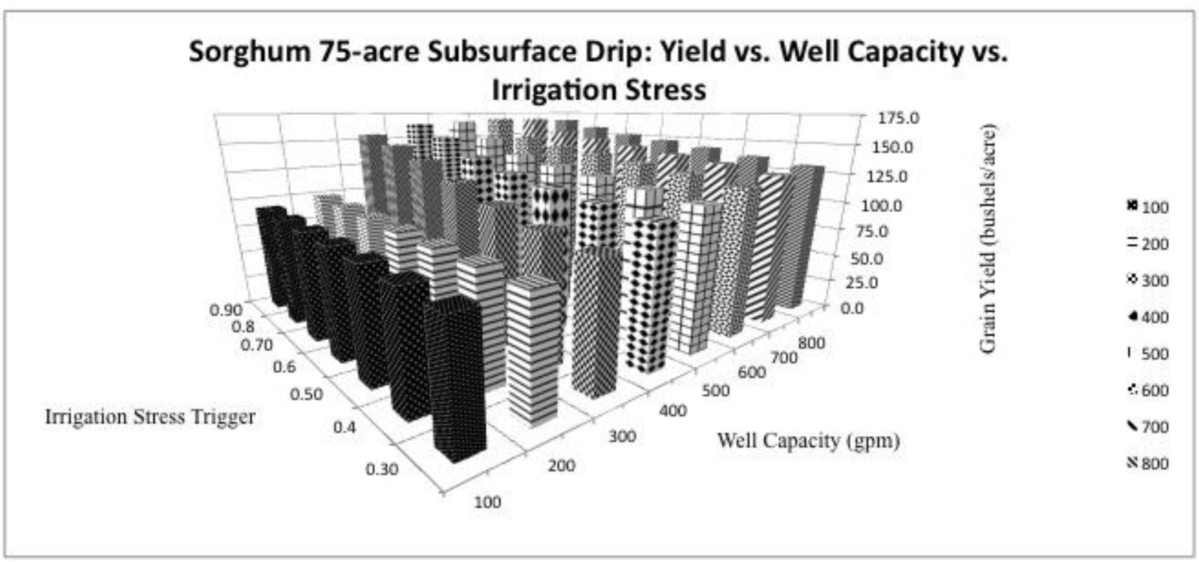


Figure 13. Results from EPIC Sorghum Subsurface Simulation showing Yields and Irrigation along with the Well Capacity for a 75 Acre Field.

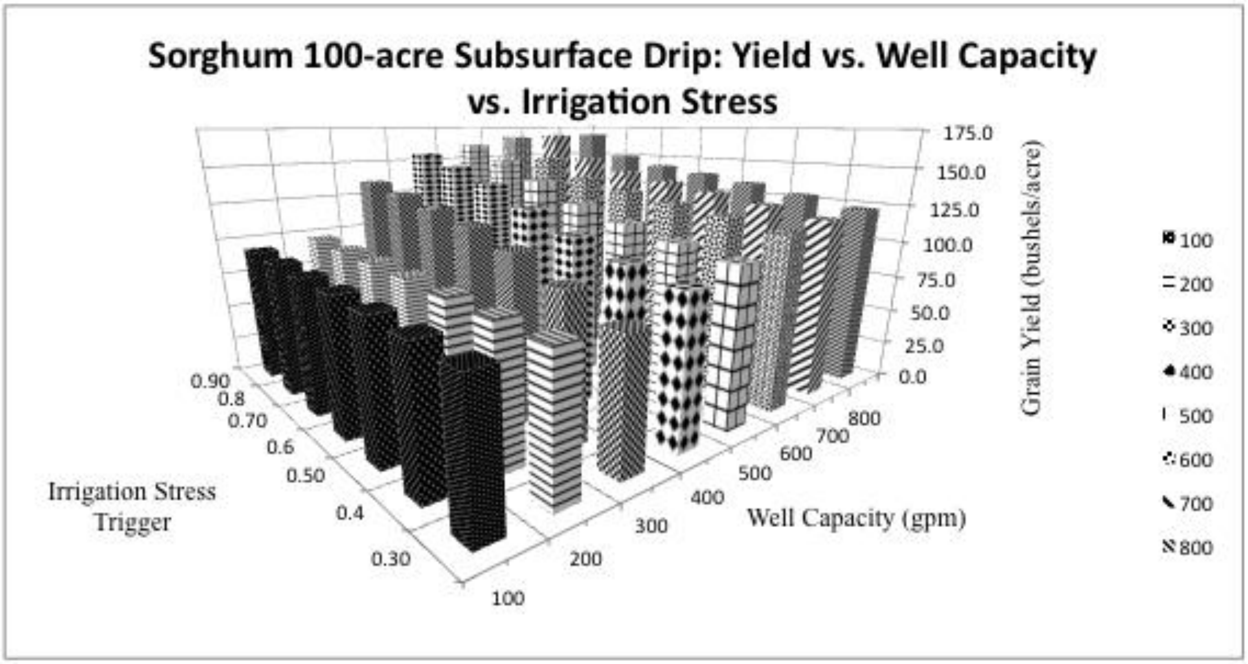


Figure 14. Results from EPIC Sorghum Subsurface Simulation showing Yields and Irrigation along with the Well Capacity for a 100 Acre Field.

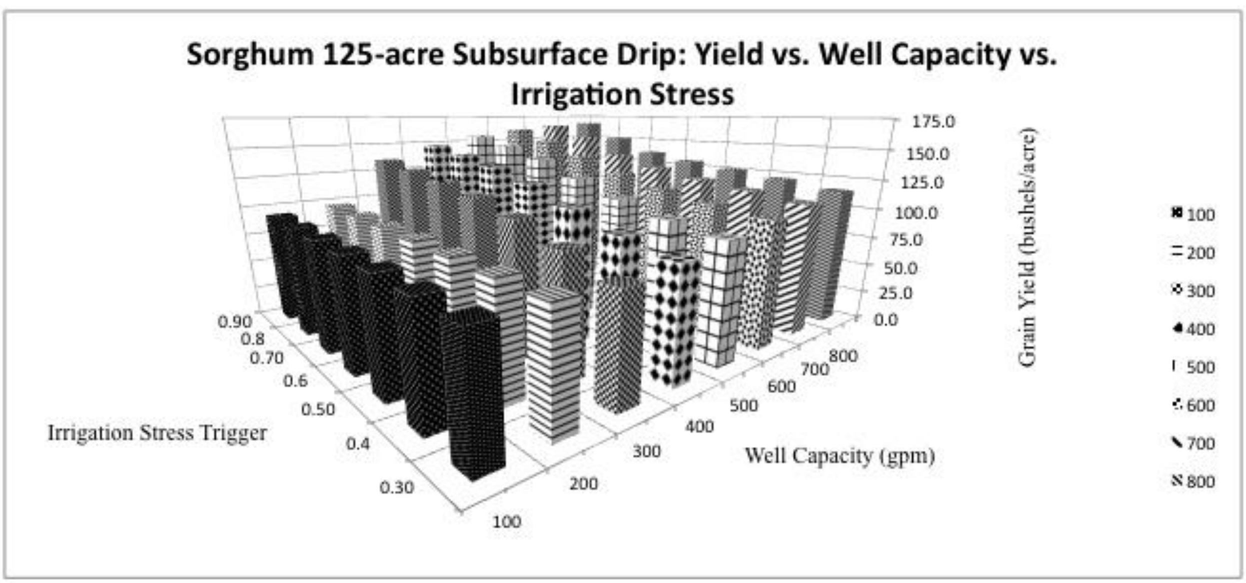


Figure 15. Results from EPIC Sorghum Subsurface Simulation showing Yields and Irrigation along with the Well Capacity for a 125 Acre field.

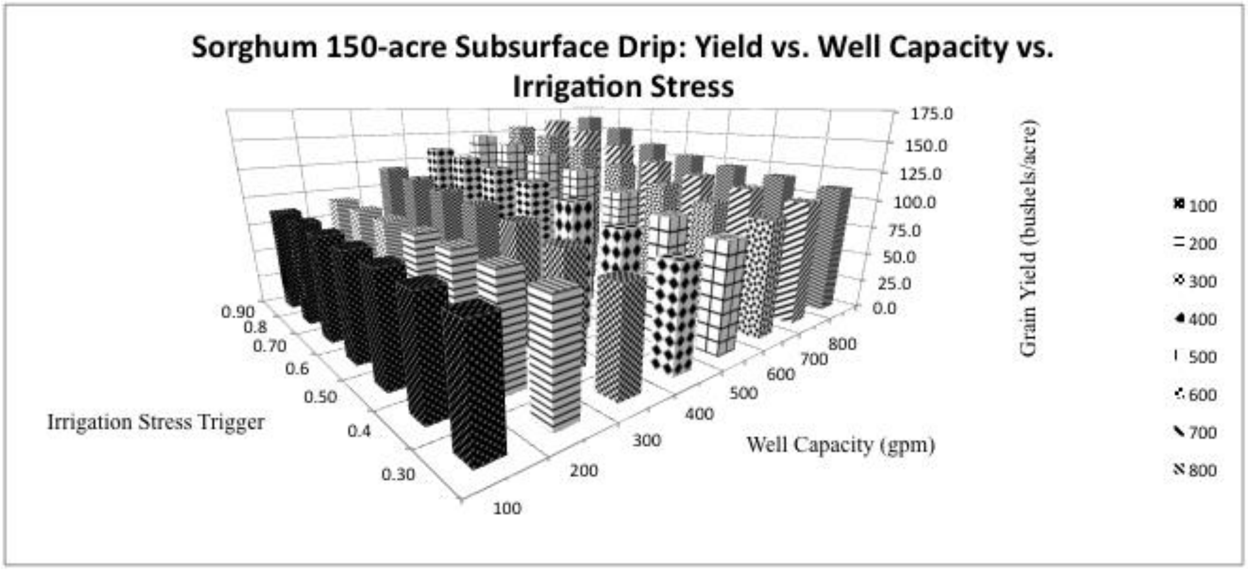


Figure 16. Results from EPIC Sorghum Subsurface Simulation showing Yields and Irrigation along with the Well Capacity for a 150 Acre field.

Simulations 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

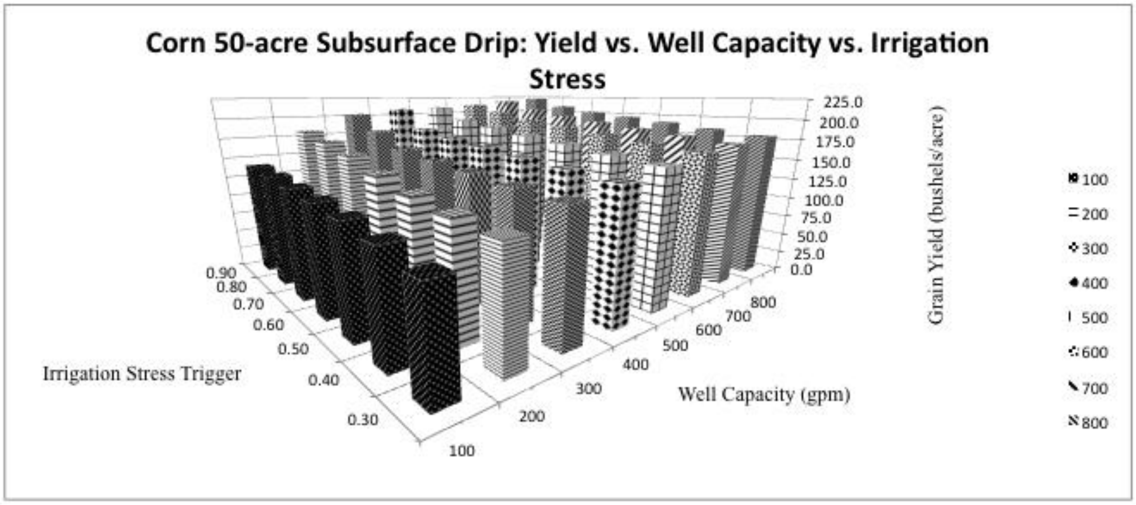


Figure 17. Results from EPIC Corn Subsurface Simulation showing Yields and Irrigation along the Well Capacity for a 50 Acre Field

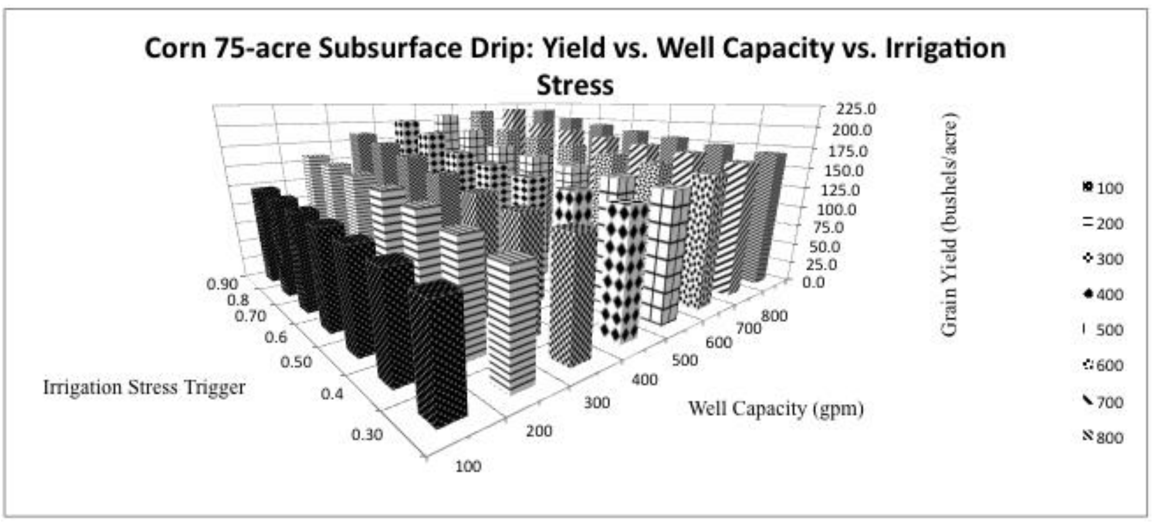


Figure 18. Results from EPIC Corn Subsurface Simulation showing Yields and Irrigation along the Well Capacity for a 75 Acre Field

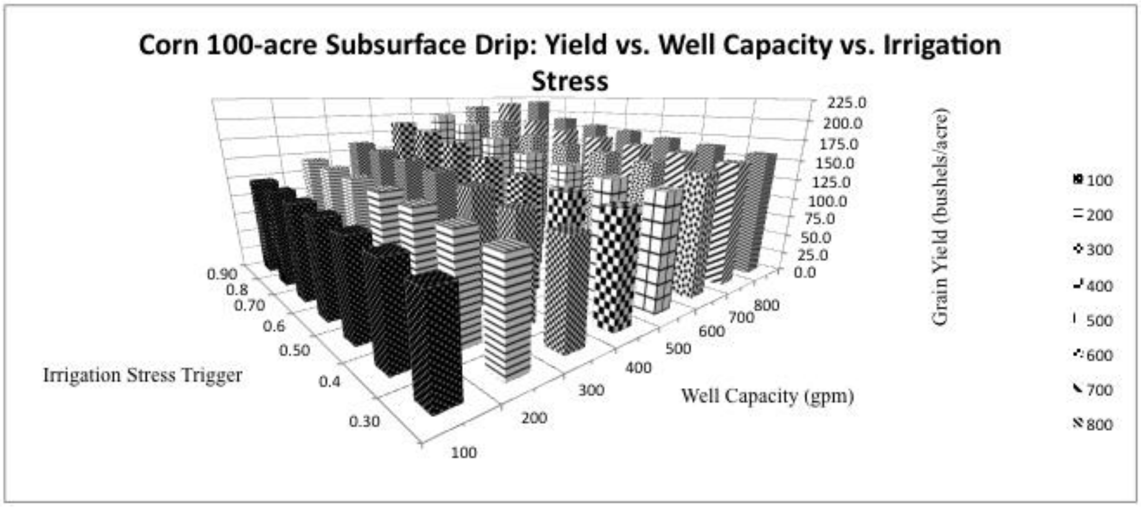


Figure 19. Simulated Yields Results from EPIC Corn Subsurface Simulation showing Yields and Irrigation along with the Well Capacity for a 100 Acre Field

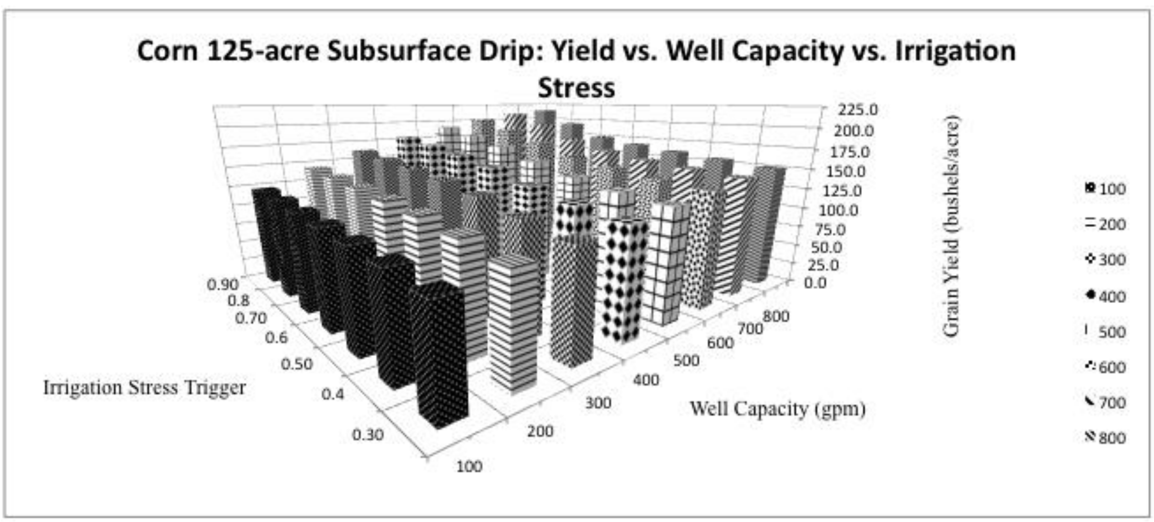


Figure 20. Results from EPIC Corn Subsurface Simulation showing Yields and Irrigation along the Well Capacity for a 125 Acre Field

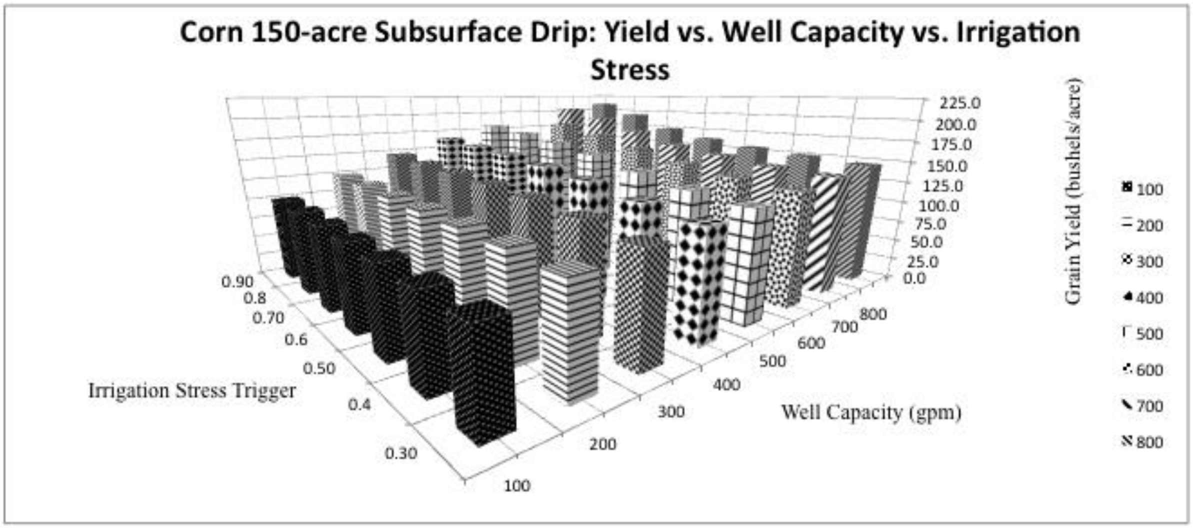


Figure 21. Results from EPIC Corn Subsurface Simulation showing yields and Irrigation along the Well Capacity for a 150 Acre Field.

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.

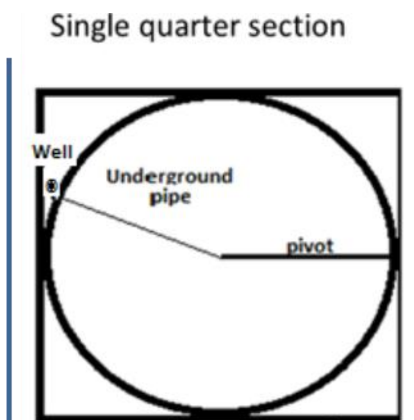


Figure 22. Illustration of a Single One-fourth Section with a 120 acre pivot

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

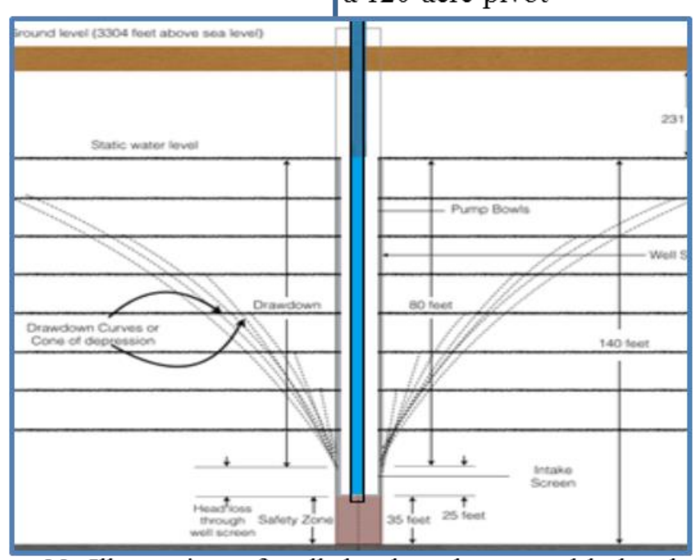


Figure 23. Illustration of well depth and water table level used in Pumping Cost Calculations

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 15 and 16 provide estimates of returns over irrigation fixed costs for grain sorghum 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

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

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	25.0	23.6	20.6	16.6	16.0
Irrigation (acre inches)	13.6	12.0	10.6	9.6	8.7	6.9	3.4	2.3
Net Revenue (@ $4.16/bu)	$ 676.10	$ 642.19	$ 607.75	$ 576.59	$ 544.36	$ 475.09	$ 383.76	$ 370.03
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
Sub Total	$ 465.70	$ 443.71	$ 423.75	$ 407.06	$ 390.93	$ 358.31	$ 309.33	$ 298.80
Crop Insurance	$ 22.35	$ 21.30	$ 20.34	$ 19.54	$ 18.76	$ 17.20	$ 14.85	$ 14.34
Total Variable Cost	$ 488.06	$ 465.01	$ 444.09	$ 426.60	$ 409.70	$ 375.51	$ 324.18	$ 313.14
Returns -Var. Cost	$ 188.04	$ 177.19	$ 163.66	$ 149.98	$ 134.66	$ 99.58	$ 59.58	$ 56.89
Annual System Cost	$ 44.97	$ 44.97	$ 44.97	$ 44.97	$ 44.97	$ 44.97	$ 44.97	$ 44.97
Return-Irg.Sys.Cost	$ 143.07	$ 132.22	$ 118.69	$ 105.01	$ 89.69	$ 54.61	$ 14.61	$ 11.92

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/a)	166.6	164.5	161.0	155.2	147.0	135.4	96.6	93.0
Nitrogen (lbs/a)	185.7	183.4	179.5	173.0	163.9	151.0	107.7	103.7
Phosphorus (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($4.16/bu)	$ 692.99	$ 684.30	$ 669.66	$ 645.44	$ 611.60	$ 563.34	$ 401.90	$ 387.00
Fertilizer-nitrogen	$ 102.15	$ 100.87	$ 98.72	$ 95.15	$ 90.16	$ 83.05	$ 59.24	$ 57.04
Fertilizer-Phosphorus	$ 15.62	$ 15.43	$ 15.09	$ 14.55	$ 13.79	$ 12.70	$ 9.06	$ 8.72
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	$ 21.66	$ 21.38	$ 20.93	$ 20.17	$ 19.11	$ 17.60	$ 12.56	$ 12.09
Miscellaneous	$ 10.00	$ 10.00	$ 10.00	$ 10.00	$ 10.00	$ 10.00	$ 10.00	$ 10.00
Custom Hire	$ 134.18	$ 133.26	$ 131.71	$ 129.15	$ 125.57	$ 120.46	$ 103.39	$ 101.81
Non Machinery Labor	$ 18.00	$ 18.00	$ 18.00	$ 18.00	$ 18.00	$ 18.00	$ 18.00	$ 18.00
Interest Cost	$ 16.01	$ 15.82	$ 15.52	$ 15.00	$ 14.29	$ 13.27	$ 9.87	$ 9.55
Irrigation Cost	$ 66.66	$ 62.33	$ 57.64	$ 51.64	$ 44.70	$ 30.72	$ 14.19	$ 10.06
Sub Total	$ 459.05	$ 389.54	$ 384.73	$ 376.79	$ 365.69	$ 349.86	$ 296.88	$ 292.00
Crop Insurance	$ 22.03	$ 18.70	$ 18.47	$ 18.09	$ 17.55	$ 16.79	$ 14.25	$ 14.02
Total Variable Cost	$ 481.08	$ 473.56	$ 463.60	$ 449.00	$ 430.09	$ 398.85	$ 326.00	$ 316.56
Net Revenue - Var. Cost	$ 211.90	$ 210.74	$ 206.06	$ 196.44	$ 181.51	$ 164.49	$ 75.90	$ 70.45
Annual System Cost $/a	$ 65.26	$ 65.26	$ 65.26	$ 65.26	$ 65.26	$ 65.26	$ 65.26	$ 65.26
Net Ret-Irrigation Cost[a]	$ 146.64	$ 145.48	$ 140.80	$ 131.18	$ 116.25	$ 99.23	$ 10.64	$ 5.19

[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/acre)	210.8	194.5	181.7	169.8	158.9	138.6	119.3	97.5
N (lbs/a)	194.3	179.1	167.1	156.0	145.9	127.2	109.4	89.5
P (lbs/a)	28.2	26.0	24.2	22.6	21.2	18.5	15.9	13.0
Irrigation (inches)	20.4	20.3	18.3	16.5	14.9	11.7	8.6	5.1
Net Revenue ($4.48/bu)	$ 944.41	$ 871.41	$ 814.03	$ 760.76	$ 712.02	$ 621.02	$ 534.55	$ 436.89
Fertilizer-nitrogen	$ 106.87	$ 98.48	$ 91.88	$ 85.78	$ 80.24	$ 69.97	$ 60.19	$ 49.22
Fertilizer-phosphorus	$ 14.65	$ 13.51	$ 12.61	$ 11.78	$ 11.02	$ 9.61	$ 8.27	$ 6.76
Seed cost	$ 112.64	$ 112.64	$ 112.64	$ 112.64	$ 112.64	$ 112.64	$ 112.64	$ 112.64
Herbicide Cost	$ 61.00	$ 61.00	$ 61.00	$ 61.00	$ 61.00	$ 61.00	$ 61.00	$ 61.00
Insecticide Cost	$ 15.99	$ 15.65	$ 15.38	$ 15.13	$ 14.90	$ 14.47	$ 14.06	$ 13.60
Crop Consulting	$ 6.50	$ 6.50	$ 6.50	$ 6.50	$ 6.50	$ 6.50	$ 6.50	$ 6.50
Drying	$ 27.40	$ 25.29	$ 23.62	$ 22.08	$ 20.66	$ 18.02	$ 15.51	$ 12.68
Miscellaneous	$ 10.00	$ 10.00	$ 10.00	$ 10.00	$ 10.00	$ 10.00	$ 10.00	$ 10.00
Custom Hire	$ 160.36	$ 153.22	$ 147.60	$ 142.38	$ 137.61	$ 128.70	$ 120.24	$ 110.67
Non Machinery Labor	$ 18.00	$ 18.00	$ 18.00	$ 18.00	$ 18.00	$ 18.00	$ 18.00	$ 18.00
Interest	$ 19.84	$ 18.66	$ 17.74	$ 16.88	$ 16.09	$ 14.62	$ 13.23	$ 11.65
Irrigation Cost	$ 117.89	$ 114.88	$ 102.39	$ 91.09	$ 81.55	$ 63.14	$ 46.42	$ 27.26
Sub Total	$ 671.16	$ 647.83	$ 619.35	$ 593.25	$ 570.21	$ 526.67	$ 486.06	$ 439.99
Crop Insurance	$ 32.22	$ 31.10	$ 29.73	$ 28.48	$ 27.37	$ 25.28	$ 23.33	$ 21.12
Total Variable Cost	$ 703.37	$ 678.92	$ 649.08	$ 621.73	$ 597.58	$ 551.96	$ 509.39	$ 461.10
Net Returns - Var. Cost	$ 241.03	$ 192.49	$ 164.95	$ 139.03	$ 114.44	$ 69.07	$ 25.16	$ (24.21)
Annual System Cost[a]	$44.97	$44.97	$44.97	$44.97	$44.97	$44.97	$44.97	$44.97
Net Ret. - System Cost	$ 196.06	$ 147.52	$ 119.98	$ 94.06	$ 69.47	$ 24.10	$ (19.81)	$ (69.18)

a Initial system cost of $60,100 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)	$962.86	$ 939.89	$ 905.47	$ 858.99	$ 800.45	$ 729.80	$ 645.41	$ 547.22
Fertilizer-nitrogen	$112.40	$ 109.70	$ 105.64	$ 105.46	$ 93.30	$ 85.02	$ 75.14	$ 63.67
Fertilizer-phosphorus	$ 15.32	$ 14.96	$ 14.40	$ 13.66	$ 12.73	$ 11.60	$ 10.26	$ 8.69
Seed cost	$112.64	$ 112.64	$ 112.64	$ 112.64	$ 112.64	$ 112.64	$ 112.64	$ 112.64
herbicide Cost	$ 61.00	$ 61.00	$ 61.00	$ 61.00	$ 61.00	$ 61.00	$ 61.00	$ 61.00
Insecticide Cost	$ 16.08	$ 15.97	$ 15.81	$ 15.59	$ 15.31	$ 14.98	$ 14.58	$ 14.12
Crop Consulting	$ 6.50	$ 6.50	$ 6.50	$ 6.50	$ 6.50	$ 6.50	$ 6.50	$ 6.50
Drying	$ 27.94	$ 27.27	$ 26.27	$ 24.93	$ 23.23	$ 21.18	$ 18.73	$ 15.88
Miscellaneous	$ 10.00	$ 10.00	$ 10.00	$ 10.00	$ 10.00	$ 10.00	$ 10.00	$ 10.00
Custom Hire	$ 162.17	$ 159.92	$ 156.55	$ 152.00	$ 146.27	$ 139.35	$ 131.09	$ 121.48
Non Machinery Labor	$ 18.00	$ 18.00	$ 18.00	$ 18.00	$ 18.00	$ 18.00	$ 18.00	$ 18.00
Interest	$ 20.14	$ 19.77	$ 19.21	$ 18.46	$ 17.52	$ 16.38	$ 15.02	$ 13.43
Irrigation Cost	$ 119.06	$ 110.57	$ 101.36	$ 90.00	$ 77.11	$ 52.28	$ 48.04	$ 32.33
Sub Total ($)	$ 681.25	$ 666.30	$ 647.39	$ 628.24	$ 593.61	$ 548.93	$ 520.99	$ 477.74
Crop Insurance	$ 32.70	$ 31.98	$ 31.07	$ 30.16	$ 28.49	$ 26.35	$ 25.01	$ 22.93
Total Variable Cost	$ 713.95	$ 698.28	$ 678.46	$ 658.40	$ 622.10	$ 575.28	$ 545.99	$ 500.67
Net Returns - Var. Cost	$ 248.91	$ 241.61	$ 227.01	$ 200.60	$ 178.35	$ 154.52	$ 99.41	$ 46.55
Annual System Cost*	$ 65.26	$ 65.26	$ 65.26	$ 65.26	$ 65.26	$ 65.26	$ 65.26	$ 65.26
Net Returns - Syst. Cost	$ 83.65	$ 176.35	$ 161.75	$ 135.34	$ 113.09	$ 89.26	$ 34.15	$ (18.71)

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 Choice when Groundwater Supplies are Limiting.

A major factor in selecting the crop to be grown is the expected annual net returns over fixed cost which usually formulated as an enterprise for a representative acre. Thus 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. In the budget tables listed above, irrigated corn commonly provided higher net returns over variable costs than grain sorghum. Under high feed grain prices, the annual profit advantage to corn over sorghum is more pronounced than in the budgets shown in Tables – and – 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 a quarter section with an irrigation well. 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 in Tables 15 and 17. Based on annual profits, with a 600 GPM well, irrigated corn yielding approximately 182 bushels per acre provides the highest expected net return over variable cost or $165 per acre. The net return for the 120 acre field would be $19,900. An acre of irrigated corn is expected to require 1.53 acre feet of groundwater. The 120 acre field would use approximately 184 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. 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 4800 acre feet of water groundwater that can be extracted or about 800 acre feet in each 10 foot layer of saturated sand.

Table 19 illustrates the nature on long term returns over fixed costs over a 37 year planning horizon. The producer growing continuous irrigated corn would be expected with a supply of 800 acre feet of water per 10 foot layer could expect the water table to decline by 2.5

Table 21. Importance of Considering Long-Returns in Crop Choice When Groundwater Supplies are Limiting: Case of Corn VS Grain Sorghum

Year	Grow Continuous Irrigated Corn					Grow Continuous Irrigated Grain Sorghum				
	AcFt. Left	Remain Depth	Well GPM	Corn Yield	Nr. Rev.	Ac.Ft. Left	Remain Depth	Well GPM	Sorghum Yield	Nt. Rev.
					$(60,000)					$(60,000)
1	4800	60	600	182	$ 19,800	4800	60	600	161	$ 19,639
2	4616	58	600	182	$ 19,800	4694	59	600	161	$ 19,639
3	4433	55	600	182	$ 19,800	4588	57	600	161	$ 19,639
4	4249	53	600	182	$ 19,800	4482	56	600	161	$ 19,639
5	4066	51	550	176	$ 17,795	4376	55	600	161	$ 19,639
6	3894	49	500	170	$ 16,680	4270	53	600	161	$ 19,639
7	3729	47	500	170	$ 16,680	4164	52	600	161	$ 19,639
8	3564	45	500	170	$ 16,680	4058	51	550	158	$ 18,896
9	3399	42	500	170	$ 16,680	3957	49	500	155	$ 17,998
10	3234	40	450	165	$ 14,339	3861	48	500	155	$ 17,998
11	3082	39	400	159	$ 13,733	3765	47	500	155	$ 17,998
12	2933	37	400	159	$ 13,733	3669	46	500	155	$ 17,998
13	2784	35	400	159	$ 13,733	3573	45	500	155	$ 17,998
14	2635	33	400	159	$ 13,733	3477	43	500	155	$ 17,998
15	2486	31	350	149	$ 11,418	3381	42	500	155	$ 17,998
16	2350	29	300	139	$(51,712)	3285	41	450	151	$(42,222)
17	2233	28	300	139	$ 8,288	3190	40	400	147	$ 16,159
18	2116	26	300	139	$ 8,288	3103	39	400	147	$ 16,159
19	1999	25	300	139	$ 8,288	3016	38	400	147	$ 16,159
20	1882	24	300	139	$ 8,288	2929	37	400	147	$ 16,159
21	1765	22	300	139	$ 8,288	2842	36	400	147	$ 16,159
22						2755	34	400	147	$ 16,159
23						2668	33	400	147	$ 16,159
24						2581	32	400	147	$ 16,159
25						2494	31	400	147	$ 16,159
26						2407	30	350	141	$ 12,269
27						2336	29	300	137	$ 11,950
28						2267	28	300	135	$ 11,950
29						2198	27	300	135	$ 11,950
30						2129	27	300	135	$ 11,950
31						2060	26	300	135	$(48,050)
32						1991	25	300	135	$ 11,950
33						1922	24	300	135	$ 11,950
34						1853	23	300	135	$ 11,950
35						1784	22	300	135	$ 11,950
36						1715	21	300	135	$ 11,950
37						1646	21	300	135	$ 8,008
			NPV: Yrs 0-21		$118,057	NPV Irg Yrs 0-37				$215,692

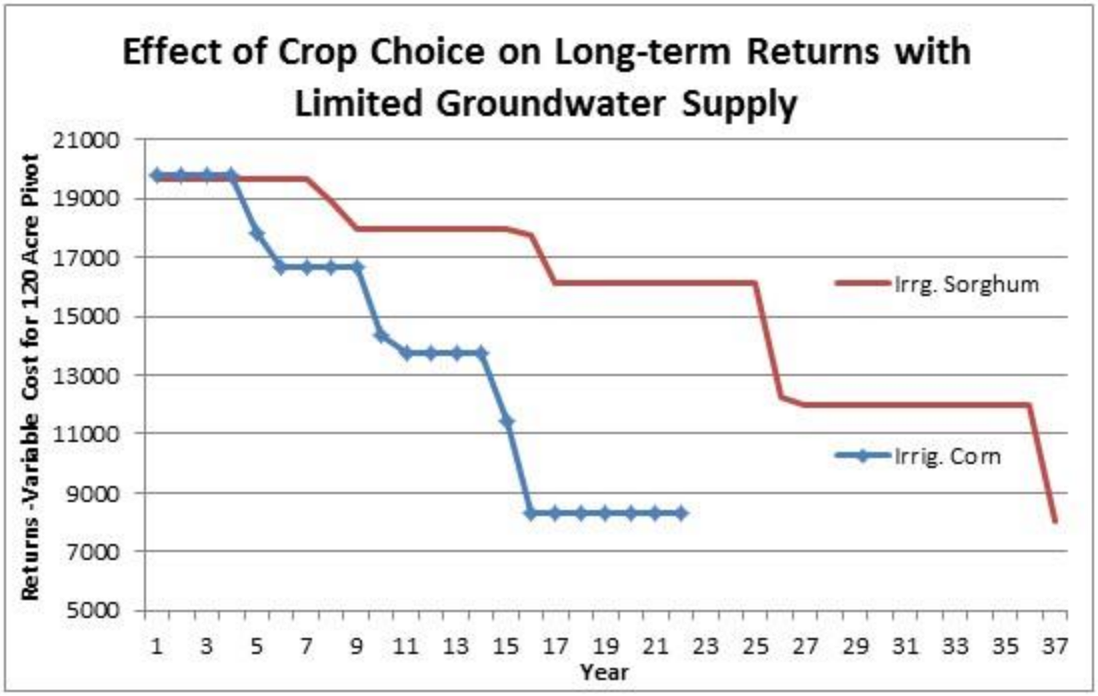
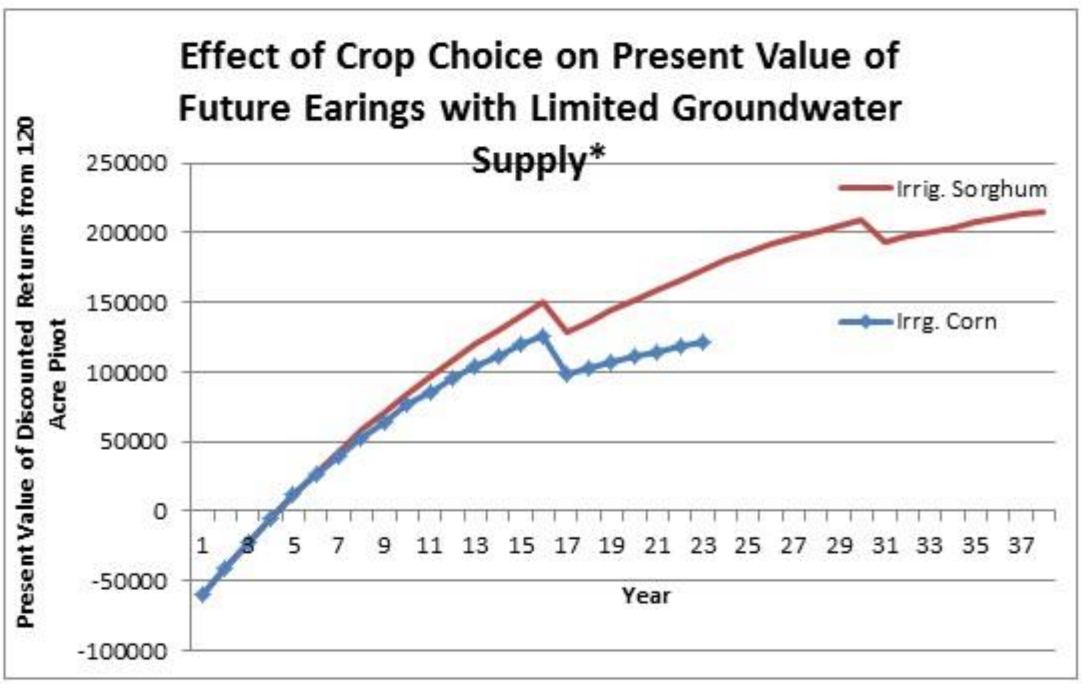


Figure 24. Effect of Crop Choice on Long-term Annual Returns from a 120 Acre Pivot with a Limited Groundwater Supply



* Returns discounted at four percent.

Figure 25. Effect of Crop Choice on Present Value of Future Earning with a Limited Groundwater Supply from a 120 Acre Pivot

feet per year and that well yields would decline to 500 GPM by year 5. This is faster than the average 1994-2014 average for Texas county but about the same as for Beaver county.
At 500 GPM, corn yields decline to approximately 170 bushels per acre and net returns decline to $139 per acre. Annual returns decline to approximately $16,700 for the 120 acre field.

The water table would be expected to decline to the 40 foot or 400 GPM level by year 10. Annual yields decline to 160 bushels and net returns decline to $114 per acre. In year 14 the water table declines to the 30 foot level and GPM declines to 300 GPM. The system is replaced in year 16 and irrigation can continue through the 300 GPM range until year 22. The total discounted returns over non-irrigation fixed cost are approximately $118,000.

The results for irrigated grain sorghum are shown on the right half of Table 19. The initial returns from grain sorghum are initially less than for corn. Because grain sorghum uses less water per acre than corn, the water table and annual returns for the sorghum producer decline more slowly than for the corn producer. In this example, the annual returns for the grain sorghum producer surpass the annual returns for the corn producer after five years. The difference increases over time. The sorghum producer is able to extend production through year 37 before the 200 GPM well capacity is reached. The two hundred well capacity level was reached for the corn producer in year 21. The discounted returns from the same water supply were $118,000 for the corn producer and approximately $215,700 for the sorghum producer.

Optimization Results:

One 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 known for a long time that optimal long term rates of extracting a non-renewable resource differ from that would be received by a series of annual rates of extraction.

Quarter Section Results with Subsurface Drip:

This part of the analysis considers returns to the producer who invests in a subsurface drip system over the same 30 year planning horizon as above. The producer has a choice of field sizes that can be developed for subsurface drip irrigation. The sizes and investment costs for the drip system are assumed to be,

Size (Acres)	Capital Cost
50	$ 43,000
75	$ 58,000
100	$ 74,300
125	$ 90,700
150	$ 107,000

The net present value derived from the 30 year optimization was 264,

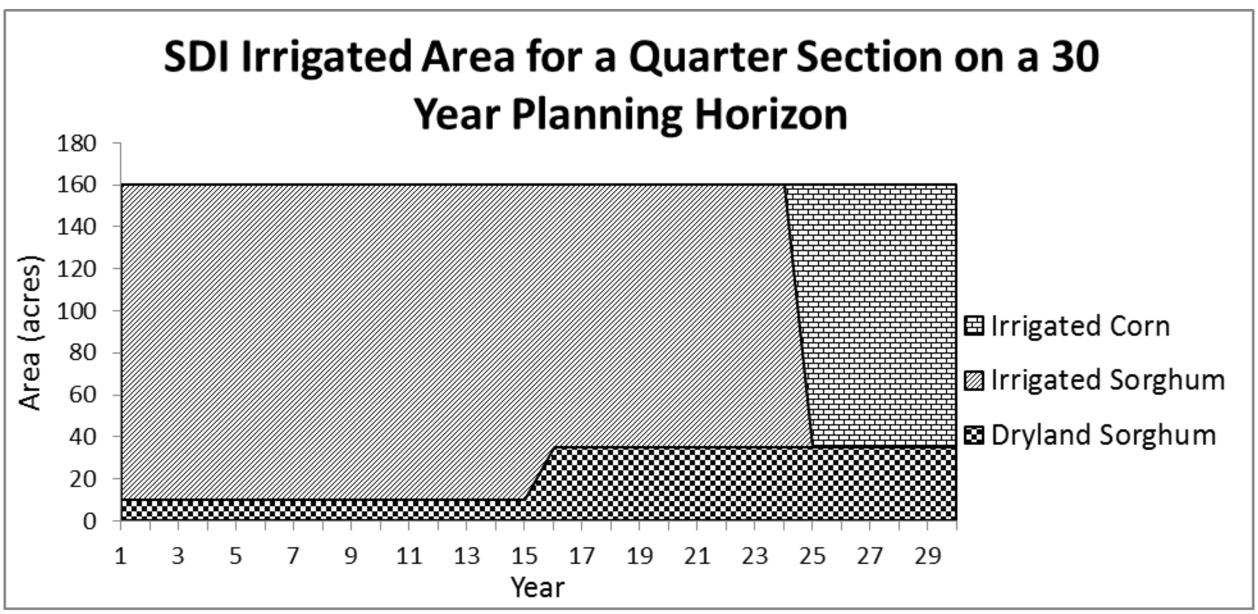


Figure 26. Graph showing the Optimal Annual Area Planted to Irrigated Corn, Irrigated Grain Sorghum, and Dryland Grain Sorghum Over a 30 Year Planning Horizon.

Table 22. Optimal Crop Selection and Land Use for the Producer with a Quarter Section, a 30 Year Planning Horizon who is Considering Subsurface Drip Irrigation System

	CROP		AREA					
Year	**Irrigated**	**Dryland**	**Irrigated Sorghum**	**Irrigated Corn**	**Dryland Sorghum**	**GPM**	**Aquifer Lvl**	**Stress**
1	sorghum	sorghum	150	0	10	600	6	0.9
2	sorghum	sorghum	150	0	10	600	6	0.9
3	sorghum	sorghum	150	0	10	600	6	0.9
4	sorghum	sorghum	150	0	10	600	6	0.9
5	sorghum	sorghum	150	0	10	500	5	0.9
6	sorghum	sorghum	150	0	10	500	5	0.9
7	sorghum	sorghum	150	0	10	500	5	0.9
8	sorghum	sorghum	150	0	10	500	5	0.9
9	sorghum	sorghum	150	0	10	500	5	0.9
10	sorghum	sorghum	150	0	10	400	4	0.9
11	sorghum	sorghum	150	0	10	400	4	0.9
12	sorghum	sorghum	150	0	10	400	4	0.9
13	sorghum	sorghum	150	0	10	400	4	0.9
14	sorghum	sorghum	150	0	10	400	4	0.9
15	sorghum	sorghum	150	0	10	400	4	0.9
16	sorghum	sorghum	125	0	35	400	4	0.9
17	sorghum	sorghum	125	0	35	300	3	0.9
18	sorghum	sorghum	125	0	35	300	3	0.9
19	sorghum	sorghum	125	0	35	300	3	0.9
20	sorghum	sorghum	125	0	35	300	3	0.9
21	sorghum	sorghum	125	0	35	300	3	0.9
22	sorghum	sorghum	125	0	35	300	3	0.9
23	sorghum	sorghum	125	0	35	300	3	0.9
24	sorghum	sorghum	125	0	35	300	3	0.9
25	Corn	sorghum	0	125	35	200	2	0.9
26	Corn	sorghum	0	125	35	200	2	0.9
27	Corn	sorghum	0	125	35	200	2	0.9
28	Corn	sorghum	0	125	35	200	2	0.9
29	Corn	sorghum	0	125	35	200	2	0.9
30	Corn	sorghum	0	125	35	200	2	0.9

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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

Principal Investigators: Chris Zou, Associate Professor, NREM, Oklahoma State University
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Publications:

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.

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. We have collected ERI images under a range of precipitation and soil moisture conditions.

We have installed two groundwater observation wells, one in grassland and the other in redcedar encroached site. The depth of the wells is 3 meter in depth, which is the maximum depth we were able to reach using geoprobe hydraulic drilling machine. We installed soil moisture EC-5 sensor (Decagon Devices, Utah, USA) 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. We installed prepacked wells to limit clogging due to fine-grained aquifer sediments. Each observation well was instrumented with water level loggers to automatically monitor water table elevation and temperature at 1-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 and organic carbon concentration.

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. Primary analysis based on those images showed a two-layer moisture migration profile: non-wetted and wetted in both grassland and encroached catchments 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 from both sites. 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.

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 detects change in moisture content below different vegetation rooting zone in these heterogeneous sites.

A preliminary evaluation of soil chloride concentration indicates different chloride profiles under grassland catchment and redcedar encroached site and further analysis is under way to understand how historic land use and vegetation change are related to this different chloride profiles through altering water percolation and recharge process. These findings demonstrated the coupling process between vegetation, moisture content and groundwater resources in Oklahoma.

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