Oklahoma Water
Resources Center

2017 Annual Research Report

Research conducted March 1, 2017 – February 28, 2018

Published June 2018

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Introduction

Dr. Justin Moss served as interim director of the Oklahoma Water Resources Center December 2016-July 2017. The Center had a successful transition of leadership from Dr. Justin Moss to Dr. Kevin Wagner in August 2017, including their co-hosting the Summer Water Research Advisory Board meeting in August 2017.

Progress was made in 2017-2018 to address priority research, outreach, and education needs related to water in Oklahoma. Some of the major accomplishments are highlighted below:

1. Dr. Moss attended the NIWR annual meeting in Washington DC and educated the Oklahoma congressional delegation on the impacts and importance of the program to Oklahoma.

2. The Oklahoma Water Resources Center successfully administered two extended PY2016 USGS 104(b) grants and four PY2017 USGS 104(b) grants, including one faculty project at $25,000, and three student-led projects at $5,000 each. This funding was provided by the USGS 104(b) program and was matched 2:1 with funding from the PIs' universities.

3. For PY2018, the Oklahoma Water Resources Center selected four research grants of $25,000 each (for two faculty projects) and $5,000 each (for two student projects); these are still going through the approval process.

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

    - **Dr. Jason Warren**, Associate Professor of Plant and Soil Sciences – *On-Farm Subsurface Drip Irrigation: How does Soil Type Impact Efficiency and Management*

  b. 2016-2018
    - **Tyson E. Ochsner**, Associate Professor of Applied Soil Physics and Sarkeys Distinguished Professor in the Department of Plant and Soil Sciences -- *Improved seasonal streamflow forecasts to inform surface water management in Oklahoma*
    - **Jason R. Vogel**, Associate Professor and Stormwater Specialist in the Department of Biosystems and Agricultural Engineering -- *Using Oklahoma-sourced Biochar for Removal of Pesticides in Runoff*

5. The Oklahoma Water Resources Center hired a part-time staff writer, to assist in creating stories around successful water projects funded by our program. These stories were included in our newsletters and online.

6. Our two styles of newsletters continued to be published regularly. *The Aquahoman* and *Currents* have different content, lengths, and publication frequencies. *The Aquahoman* contains full-length articles and spotlights faculty and Advisory Board members. *Currents* is published more frequently to keep our constituents as current as possible. The newsletters are sent to approximately 1100 subscribers and our 80+ OSU faculty partners.

7. The Oklahoma Water Resources Center organized and hosted the 2017 Student Water Conference (http://water.okstate.edu/students/swc) held March 23-24, 2017. It followed the UN World Water Day theme: “Why Waste Water?”.

8. The Oklahoma Water Resources Center co-sponsored and co-hosted the 38th Annual Oklahoma Governor’s Water Conference and Research Symposium at the Embassy Suites Hotel and Conference Center in Norman, OK on October 31-Novemeber 1, 2017. The theme of this year’s meeting was “Liquid Assets: The Value of Water Investment in Oklahoma.” The meeting included over 400 attendees. The invited speaker of the Oklahoma Water Resources Center was Dr. Todd Halihan (Professor of Hydrogeophyics at Oklahoma State University and the National Ground Water Association 2018 McEllhiney Distinguished Lecturer)), whose talk “The Future of Water: Data or Instincts?” discussed the wisdom in using data, not instincts or past habits, to address future water management strategies. A special Café-Style Poster Session was held at the conference to encourage student participation and interaction with the registrants.

Research Program

The Oklahoma Water Resources Center successfully administered four research projects funded in 2017. Funding for these 2017 projects was delayed several months due to USGS delays and change in administration in the Water Center. Projects 1-3 have submitted interim project reports. Project #4 has been successfully completed and generated a final report. PY2017 projects are as follows:

1. *Utilizing native isopods to assess the connectivity and quality of Oklahoma groundwater* (Dr. Ronald Bonett and Alexander Hess)
2. *The Impact of Drought on Vegetation Water Use in Different Climatic Divisions across Oklahoma* (Kul Bikram Khand with Dr. Saleh Taghvaeian)
3. *Economics of Groundwater Interaction and Competing Crops* (Karthik Ramaswamy with Dr. Art Stoecker)
4. *Modeling soil moisture under various land cover types: using long-term grassland monitoring data to estimate soil moisture in Oklahoma forests* (Briana M. Wyatt with Drs. Tyson E. Ochsner and Chris B. Zou)

The Oklahoma Water Resources Center successfully administered two extended USGS 104(b) projects from 2016:

1. *Western Oklahoma Irrigation Water and Energy Audits: Findings, Recommendations and Educational Materials* (Scott Frazier, Saleh Taghvaeian, Jason Warren, Don Sternitzke, Cameron Murley)
2. *Evaluating the Reuse of Swine Lagoon Effluent and Recycled Municipal Water for Agricultural Production* (Hailin Zhang, Doug Hamilton, Saleh Taghvaeian, Scott Carter)

Reports are included in this document.

Selection of 2018 Projects:

Research pre-proposals were solicited from any Oklahoma research university starting in mid-June 2017. One-page pre-proposals were due in July 2017. The 24-member Water Research Advisory Board (Board) then reviewed and discussed the 41 pre-proposals at the summer Board meeting held in Stillwater, OK.

The Board selected ten projects (6 faculty and 4 students) to submit full proposals, which were reviewed by three reviewers, including the two Water Center staff and the USGS Water Science Center director. In December 2017 four faculty and 2 student researchers presented their proposals to the Board in Stillwater, OK. After the presentations, the Board deliberated and selected the top proposals. The following projects were selected for funding (learn more at http://water.okstate.edu/library/reports/project-reports/2018-projects):

1. Faculty Projects:
    a. *Developing Seasonal Streamflow Forecasts to Inform Surface Water Management in Oklahoma* (Dr. Tyson Ochsner, Dr. Erik Krueger, Briana Wyatt, and Eric Jones)
    b. *Control of Problematic Halanaerobiales that Limit the Reuse of Hydraulic Fracturing Fluids* (Drs. Joseph M. Suflita and Irene A. Davidova)
2. Student Projects:
    a. *Conserving Agricultural Water Resources in Oklahoma using Smart Technologies* (Sumon Datta with Dr. Saleh Taghvaeian)
    b. *Evaluating the Potential of Sentinel-2 and Landsat Images for Mapping Open Surface Water Body Areas and Water Quality in Oklahoma* (Zhenhua Zou with Dr. Xiangming Xiao)

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 2017, the Oklahoma Water Resources Center engaged in four primary efforts: (1) publication of a newsletter containing news stories of research being conducted by OSU researchers and others funded through the 104(b) program, (2) meetings with state agency personnel, (3) maintenance of an up-to-date website, and (4) holding conferences.

1. Newsletter:
    a. The Oklahoma Water Resources Center's quarterly newsletter is *The Aquahoman*. With a distribution list of nearly 1100, *The Aquahoman* not only provides a means of getting information to the public, but also informs researchers throughout the state about water research activities. *The Aquahoman* was distributed to state and federal legislators; to water managers throughout Oklahoma; to state, federal, and tribal agency personnel; to water researchers at every university in the State, to members of our Water Research Advisory Board, and to anyone who requests it. This project year the newsletter was published in April and September 2017.
    b. We continued distribution and strengthening of the Currents news update. *Currents* is published bimonthly in the months that *The Aquahoman* is not published. Like *The Aquahoman*, it is sent to approximately 1100 subscribers and was published February, March, May, July, October, and November in 2017 and January 2018.

   c. In addition to *The Aquahoman* and *Currents* newsletters, weekly to monthly "News & Notices Updates" were distributed to the Center's faculty and staff partners. This e-mail updates recipients on news, events, funding opportunities, new resources, and other important information.

2. Water Research Advisory Board: The Board consists of 24 water professionals representing state agencies, federal agencies, tribes, and non-governmental organizations. This advisory board was formed in 2006 to assist by setting funding priorities, recommending proposals for funding, and providing general advice on the direction of the Center. The Board members have found that they also benefit from their involvement in at least two ways. First, they profit from the opportunity to discuss water issues with other professionals. Second, the semi-annual meetings afford them the opportunity to stay informed about water research and water resource planning in Oklahoma. This is accomplished, in part, by having the investigators of the previous year's projects return and present their findings to the Board. Thus, the Board is an important part of the Oklahoma Water Resources Center's efforts to disseminate research findings to state agencies for use in problem-solving.

3. Website: The Oklahoma Water Resources Center continues to maintain an up-to-date website to convey news and research findings to anyone interested. Site visitors can obtain interim and final reports from any research project (all reports from 1965 to the previous project year are available for immediate download). Also available are current and past issues of our newsletters and information about the annual grants competition, including the RFP and guidelines for applying. The website is also a major source of information for upcoming events, including the annual Water Research Symposium.

4. Conferences:
   a. Oklahoma Water Research Symposium: The Oklahoma Water Resources Center has held an annual Water Research Symposium since 2003. The purpose of this event is to bring together water researchers and water professionals from across the state to discuss their projects and network with others. Again in 2017, the Symposium was integrated with the Oklahoma Water Resources Board's annual Governor's Water Conference. The two-day event in Norman, OK drew over 400 water professionals, agency staff, politicians, members of the press, researchers, and interested citizens. This combination of events affords a unique opportunity for interchange between those interested in water policy (who traditionally

attend the Governor's Water Conference) and those interested in water research (who traditionally attend the Research Symposium).

Specific to information transfer from a research perspective, the Oklahoma Water Resources Center invited Dr. Todd Halihan (Professor of Hydrogeophyics at Oklahoma State University), who discussed the wisdom in using data rather than instincts or past habits to address future water management strategies. The 2017 Symposium included a unique Café-style poster session, where 20 students from universities across Oklahoma and 5 professionals orally presented a two-minute overview of their poster, followed by the designated poster session. These factors in concert promoted interaction between the students and the conference participants. Awards were given to those students at the end of the day in a joint session between the Oklahoma Water Resources Center and the Oklahoma Water Resources Board. Undergraduate and graduate students were eligible for outstanding poster awards. Three outstanding poster awards were presented with funds from the USGS 104(b) program. The program funds also supported free student registration at the symposium.

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

b. Student Water Conference: The Oklahoma Water Resources Center organized and hosted the 2017 Student Water Conference held March 23-24, 2017. Its theme of "Why Waste Water" (following the UN World Water Day theme). The event featured a Water Expo sponsored and supported by the Biosystems and Agricultural Engineering Graduate Student Organization working with the Oklahoma Water Resources Center.

   This event brought together several student groups, and invited students from all disciplines to learn about various water topics (streams, fisheries, run-off, etc.) 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. In 2017, 62 students presented (25 oral presentations, 37 poster presentations) with 15 presentations by students visiting from outside universities. Two students not from Oklahoma State University received travel assistantship grants supported through the USGS 104(b) program.

c. Oklahoma Grows Green Industry Water Conference: This multi-state, triennial conference was held in cooperation with the Oklahoma Nursery and Landscape Association and the Oklahoma Turfgrass Research Foundation on November 8-9, 2017 at the Winstar Convention Center, Thackerville, OK.

Student Support

Student Status	Number	Disciplines
Undergraduate	3	NIMFFAB-EPP
M.S.	1 1 1	Biosystems & Ag Engineering NIMFFAB-EPP Plant and Soil Sciences
Ph.D.	1 1 3 1 2.2	Agricultural Economics Biological Science Biosystems & Ag Engineering NIMFFAB-EPP Plant and Soil Sciences
Post Doc	1	Plant and Soil Sciences
Total	15.2	

Notable Awards and Achievements

None

Publications and Presentations from Prior Projects

1. 2014OK307B: *Estimating Groundwater Recharge Using the Oklahoma Mesonet*
   Wyatt, B.M., **T.E. Ochsner**, C.A. Fiebrich, C.R. Neel and D.S. Wallace. 2017. Useful Drainage Estimates Obtained from a Large-Scale Soil Moisture Monitoring Network by Applying the Unit-Gradient Assumption. Vadose Zone J. 16. doi:10.2136/vzj2017.01.0016.
2. 2014OK311B: *Increasing water yield and quality through redcedar removal and establishment of herbaceous biofuel feedstock production systems*
   a. Acharya, B. S., T. Halihan, **C. B. Zou**, and R. E. Will. 2017. Vegetation Controls on the Spatio-Temporal Heterogeneity of Deep Moisture in the Unsaturated Zone: A Hydrogeophysical Evaluation. Scientific Reports 7.
   b. Acharya, B. S., Y. H. Hao, T. E. Ochsner, and **C. B. Zou**. 2017. Woody plant encroachment alters soil hydrological properties and reduces downward flux of water in tallgrass prairie. Plant and Soil 414:379-391.
   c. Acharya, B. S., E. Stebler, and **C. B. Zou**. 2017. Monitoring litter interception of rainfall using leaf wetness sensor under controlled and field conditions. Hydrological Processes 31:240-249.
   d. **Zou, C. B.**, G. L. Caterina, R. E. Will, E. Stebler, and D. Turton. 2015. Canopy Interception for a Tallgrass Prairie under Juniper Encroachment. Plos One 10.
3. 2015OK318B: *Quantifying Streambank Erosion and Phosphorus Load for Watershed Assessment and Planning*
   a. Mittelstet, A.R., **D.E. Storm**, G.A. Fox and P.M. Allen, 2017. Modeling streambank erosion on composite streambanks on a watershed scale. Transactions of the ASABE. 60(3): 753-767.
   b. Mittelstet, A.R., **D.E. Storm** and G.A. Fox, 2017. Testing of the modified streambank erosion and in-stream phosphorus routines for the SWAT model. Journal of the American Water Resource Association. 53(1): 101-114.
4. 2016OK325B: *Algal Remediation of Waste Water Produced during Hydraulic Fracturing*
   a. Giovanni Antonio Lutzu and **Nurhan Turgut Dunford**. 2017. Algal Treatment of Wastewater Generated during Oil and Gas Production Using Hydraulic Fracturing Technology. Environmental Technology. https://doi.org/10.1080/09593330.2017.1415983
   b. Nan Zhou and **Nurhan Turgut Dunford**. 2017. Characterization of Green Microalgae and Cyanobacteria Isolated from Great Salt Plains. Trans. ASABE, 60(2):283-290.
5. 2016OK326B: *Western Oklahoma Irrigation Water and Energy Audits: Findings, Recommendations and Educational Materials*

    a. Blessing, Masasi, **R. Scott Frazier**, Saleh Taghvaeian. May 2017. Review and Operational Guidelines for Portable Ultrasonic Flowmeters. BAE-1535. 7 Pages
    b. **R. Scott Frazier**, Saleh Taghvaeian, Divya Handa. November 2017. Measuring Depth to Groundwater in Irrigation Wells. BAE-1538. 4 Pages
    c. Saleh Taghvaeian, **R. Scott Frazier**, Garey Fox. 2016. The Ogallala Aquifer. BAE-1531. 3 Pages
    d. **R. Scott Frazier**, Carol Jones. 2016. Irrigation Pump System Testing. BAE1525. 4 Pages
    e. **R. Scott Frazier**. Energy and Water Efficiency of Center Pivot Irrigation (with updates), 2018 Oklahoma Irrigation Conference. Weatherford.
    f. **R. Scott Frazier.** Energy and Water Efficiency of Center Pivot Irrigation (with updates). 2017 Oklahoma Irrigation Conference, Altus.
    g. **R. Scott Frazier.** Energy and Water Efficiency of Center Pivot Irrigation. 2016 Oklahoma Irrigation Conference, Caddo County.
    h. **R. Scott Frazier**, Saleh Taghvaeian, Dustin Livingston). Irrigation Efficiency Tests in the Oklahoma Panhandle. ASABE Annual International Meeting. July 17-20, 2016; Orlando, FL.
    i. Blessing Masasi, Saleh Taghvaeian, **R. Scott Frazier**. Performance Evaluation of Irrigation Systems in Western Oklahoma. 9th International Conference on Irrigation and Drainage. Oct. 11-14, 2016; Fort Collins, CO.
    j. Blessing Masasi, Saleh Taghvaeian, **R. Scott Frazier**. Benchmarking Performance of Irrigation Systems in Western Oklahoma. OSU Student Water Conference. Mar. 22-24, 2017; Stillwater, OK.
    k. Divya Handa, **R. Scott Frazier**, Saleh Taghvaeian. Assessing the Energy Consumption Efficiency of Center-Pivot Irrigation Systems. 38th Annual Oklahoma Governor's Water Conference & Research Symposium. Oct. 31-Nov. 1st, 2017; Norman, OK.

6. 2017OK334B: *Utilizing native isopods to assess the connectivity and quality of Oklahoma groundwater*

    Utilizing native isopods to assess the connectivity and quality of Oklahoma groundwater. Hess, A.J. and **Bonett, R.M.** 2018. NSF EPSCoR Annual State Conference. Poster presentation.

7. 2017OK336B: *Modeling soil moisture under various land cover types: using long-term grassland monitoring data to estimate soil moisture in Oklahoma forests*
    a. Wyatt, B.M., **T.E. Ochsner**, and C.B. Zou. 2017. Integration of remote sensing and in-situ data to estimate soil moisture across mixed land cover types. Oklahoma Governor's Water Conference and Research Symposium. Norman, OK.

   - b. Wyatt, B.M., **T.E. Ochsner**, and C.B. Zou. 2017. Integration of remote sensing and in-situ data to estimate soil moisture across mixed land cover types. ASA-CSSA-SSSA Annual International Meeting. Tampa, FL.
   - c. Wyatt, B.M., **T.E. Ochsner**, and C.B. Zou. 2017. Integration of remote sensing and in-situ data to estimate soil moisture across mixed land cover types. Marena, Oklahoma In-Situ Sensor Testbed (MOISST) annual meeting. Stillwater, OK.
   - d. Wyatt, B.M., **T. E. Ochsner**, and C.B. Zou. 2017. Combining remote sensing and in-situ data to estimate soil moisture across mixed land cover types. Oklahoma State University Plant and Soil Sciences Department Research Symposium.

8. 2017OK337B: *The Impact of Drought on Vegetation Water Use in Different Climatic Divisions across Oklahoma*
   - a. Khand, Kul; **Saleh Taghvaeian**; Ali Ajaz; Prasanna Gowda, 2018, Evapotranspiration responses to droughts from croplands and grasslands in semi-arid and humid climates of Oklahoma, USA (manuscript in preparation).
   - b. Ajaz, Ali; **Saleh Taghvaeian**; Kul Khand, 2018, Development of agricultural drought indices by effective harnessing of soil moisture and weather data (manuscript in preparation).
   - c. Khand, Kul; **Saleh Taghvaeian**; Ali Ajaz, 2017, Drought and its impact on agricultural water resources in Oklahoma. (Available in: http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Document-10705/BAE-1533web.pdf), Oklahoma Cooperative Extension Service, BAE-1533.
9. 2017OK338B: *Economics of Groundwater Interaction and Competing Crops*
   - a. Ramaswamy K., **A. Stoecker**, J. Warren, R. Jones, S. Taghvaeian. 2017. “Choice of Irrigated Corn or Sorghum and Center Pivot or Sub Surface Drip in Oklahoma Panhandle” AAEA conference proceedings, Chicago, IL
   - b. Ramaswamy K., **A. Stoecker**, J. Warren, R. Jones, S. Taghvaeian. 2017. “Irrigation System Choice in Oklahoma Panhandle: Center Pivot versus Subsurface Drip” Oklahoma Governor’s Water Conference, Norman, OK
   - c. Ramaswamy K., **A. Stoecker**, J. Warren, R. Jones, S. Taghvaeian. 2018. “Economics of a Potential Groundwater Management Area in Oklahoma Panhandle” Oklahoma Clean Lakes and Watershed Association, Stillwater, OK

Funding

Funding for the projects reported herein was provided by the U.S. Geological Survey and the Division of Agricultural Sciences and Natural Resources at Oklahoma State University. Additional support was provided by private donations to the Thomas E. Berry Endowed Professorship in Integrated Water Resources and Management. Research projects through the USGS 104(b) program included in-kind services made available by the researchers’ institutions. The Oklahoma Water Resources Center is grateful for their support.

Title: Utilizing native isopods to assess the connectivity and quality of Oklahoma groundwater

Authors' Names and Affiliations:

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Ron Bonett, Associate Professor, ron-bonett@utulsa.edu, 918-631-3328, University of Tulsa, Department of Biological Science, 800 South Tucker Drive, Tulsa OK 74194

Start Date: 03/01/2017

End Date: 02/28/2019 (One year extension from 02/28/2018).

Congressional District: 1 (University of Tulsa), 2 (Oklahoma Ozarks)

Focus Category:

GW, HYDROL, ECL, NC, SW, WL

Descriptors: Isopods, Biodiversity, Water Quality

Students:

Student Status	Number	Disciplines
Undergraduate	0	
M.S.	0	
Ph.D.	1	Biodiversity, Biogeography, Ecology
Post Doc	0	
Total	1	

Principal Investigators:

Ron Bonett, Associate Professor, University of Tulsa

Alex Hess, PhD Student, University of Tulsa

Publications:

Utilizing native isopods to assess the connectivity and quality of Oklahoma groundwater. Hess, A.J. and Bonett, R.M. 2018. NSF EPSCoR Annual State Conference. Poster presentation.

Problem and Research Objectives:

This study aims to assess native groundwater isopod distributions as a method to delineate watershed boundaries, as a tool to identify surface-groundwater interactions, and as a possible indicator of water quality.

Understanding the distribution and connectivity of groundwater and its relationship to surface flow is critical for the management and conservation of this invaluable resource. The Ozark aquifer system occurs in parts of four states and is subject to range-wide extraction. Therefore aquifer border delimitation is essential to accurately measure rates of recharge and sustainable withdrawal limits. Aquifer borders typically follow the extent of drainage basins, but subterranean karstic boundaries like those of the Ozark Plateau are not necessarily correlated with surface relief and can change with fluctuating water tables. Regional declines in Ozark groundwater have been noted repeatedly since the turn of the century and local depressions have been observed around major pumping centers (reviewed Pope et al. 2009).

Receding well levels increase concerns about the sustainability of the water supply and the risk of declining water quality. With the reduction in regional water levels the risk of saline water migration from western regions of the aquifer or upwelling from lower geologic strata increases (Pope et al. 2009). Furthermore, as surface disturbance grows concurrent with population, agricultural contaminants present a growing risk. Runoff can rapidly enter groundwater due to the thin soil and extensive network of near surface karstic faults and fractures (Imes and Emmett 1994). Degrading regional water quality presents risks to human health and ecosystem integrity.

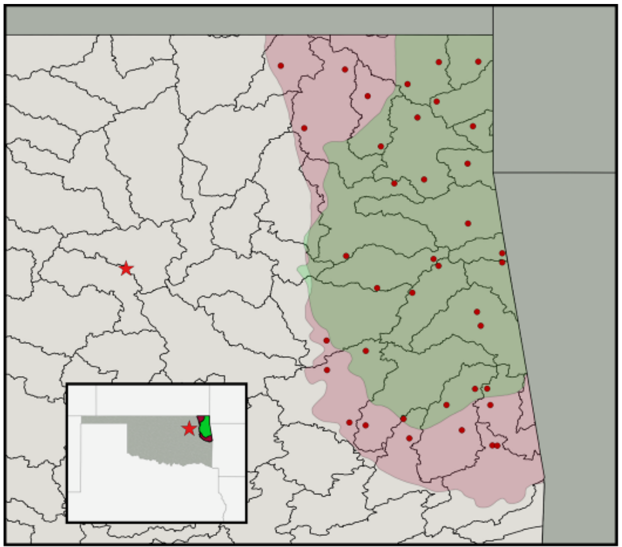
Due to their abundance and the ease of distinction between surface and subterranean species, isopods present a potentially powerful tool for assessing watershed connectivity and quality. The geographic genetic distribution of isopod diversity will likely mirror the hydrologic connectivity and discontinuity within the region. By developing distributional maps of both surface and subterranean species throughout the Oklahoma Ozarks, the limits of surface and sub-surface drainage systems can be delineated. In conjunction with water quality data, identification of species-level environmental limits can be identified to evaluate their use as a tool for understanding water quality. Continued monitoring of isopod species composition and density could serve as an indicator of changing groundwater quality.

Methodology:

Genetic Distributions of Native of Ozark Isopods: Isopods were collected from more than 50 Ozark streams. So far, thirteen sets of expressed genes (transcriptomes) and the mitochondrial gene *cytochrome oxidase 1* (*Co1*) have been sequenced for Ozark isopods to identify variable and conserved genomic regions (7 *Lirceus*, 6 *Caecidotea*). These regions will be targeted for analyzing the distribution of genetic diversity across the Oklahoma Ozarks. This will allow us to build a robust map of relationships between isopod populations of different watersheds using 100-200 genomic regions. Concurrent with measuring abundance, all isopods found at each sampling locality have been collected and stored for genetic analyses, providing sampling resolution across both aquifers and all watersheds within the Oklahoma Ozarks.

Species: Sequenced species include *Caecidotea ancyla, Caecidotea steevesi, Caecidotea stiladactyla Lirceus garmani, Lirceus hoppinae*

Isopod Abundance: To examine isopod abundance in relation to various water chemistry features we surveyed 38 Ozark streams for isopods and water chemistry. The Oklahoma Ozarks were divided into Hydrologic Unit Codes for Watersheds (HUC10) watersheds using Quantum Geographical Information Systems (QGIS). To maintain consistency of habitat type, low order streams were chosen in each watershed for sampling. At each sampling locality, bottle traps outfitted with iButton dataloggers were deployed to measure both temperature and isopod abundance during the sampling periods. All sites were checked for abundance a minimum of 2x during October – December 2017. Concurrent with isopod collection, a water quality meter (YSI proDSS) was used to measure water chemistry parameters. These include pH, conductivity, pressure, nitrates, dissolved oxygen, and total dissolved solids. These measurements were collected during each isopod sampling period. We analyzed the data using multivariate statistics in the program R to determine which environmental features were significant predictors of isopod abundance.

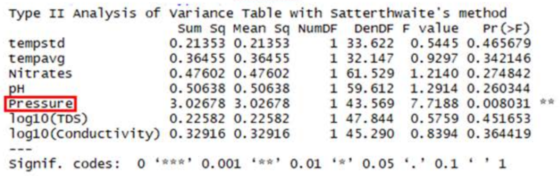


Map of isopod sampling localities (red circles). Green and pink layers represent the two aquifers of the Oklahoma Ozarks (green – Boone, red – Roubidoux). Polygons represent the HUC10 watersheds.

Principal Findings and Significance:

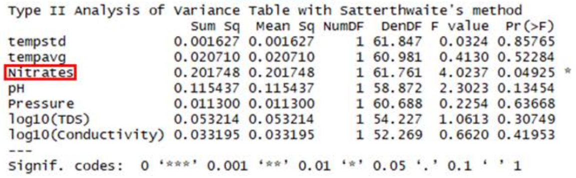
There are clearly identifiable ecological and body size differences among the Ozark isopods these include cave-dwelling *Caecidotea*, swamp-dwelling *Caecidotea*, and surface-dwelling *Lirceus*. There is also significant size variation within these groups. Genetic data thus far indicate geographic structure and described species may contain multiple cryptic lineages.

Lirceus



```
Type II Analysis of Variance Table with Satterthwaite's method
                     Sum Sq Mean Sq NumDF  DenDF F value   Pr(>F)
tempstd             0.21353 0.21353     1 33.622  0.5445 0.465679
tempavg             0.36455 0.36455     1 32.147  0.9297 0.342146
Nitrates            0.47602 0.47602     1 61.529  1.2140 0.274842
pH                  0.50638 0.50638     1 59.612  1.2914 0.260344
Pressure            3.02678 3.02678     1 43.569  7.7188 0.008031 **
log10(TDS)          0.22582 0.22582     1 47.844  0.5759 0.451653
log10(Conductivity) 0.32916 0.32916     1 45.290  0.8394 0.364419
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Caecidotea



```
Type II Analysis of Variance Table with Satterthwaite's method
                      Sum Sq  Mean Sq NumDF  DenDF F value  Pr(>F)
tempstd             0.001627 0.001627     1 61.847  0.0324 0.85765
tempavg             0.020710 0.020710     1 60.981  0.4130 0.52284
Nitrates            0.201748 0.201748     1 61.761  4.0237 0.04925 *
pH                  0.115437 0.115437     1 58.872  2.3023 0.13454
Pressure            0.011300 0.011300     1 60.688  0.2254 0.63668
log10(TDS)          0.053214 0.053214     1 54.227  1.0613 0.30749
log10(Conductivity) 0.033195 0.033195     1 52.269  0.6620 0.41953
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

The isopods collected in our abundance analyses were identified to genus as either *Lirceus* (surface) or *Caecidotea* (groundwater). Analyses were then run separately on each group to identify which environmental parameters were most relevant to their abundance while controlling for site specific effects. Based on our analyses so far, *Caecidotea* isopods are abundant when nitrates are high ($p = 0.049$). In contrast, *Lirceus* is more abundant at higher elevation sites, which may be associated with increased oxygen content. We will further assess these parameters across a second sampling round (May – June 2018).

References

Imes, J.L., and Emmett, L.F. 1994. Geohydrology of the Ozark Plateaus aquifer system in parts of Missouri, Arkansas, Oklahoma, and Kansas. U.S. Geological Survey Professional Paper 1414D. 127 p.

Pope, L.M., Mehl, H.E., and Coiner, R.L. 2009. Quality characteristics of ground water in the Ozark aquifer of northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma. 2006-07: U.S. Geological Survey Scientific Investigations Report 2009-5093. 60 p.

Title: The Impact of Drought on Vegetation Water Use in Different Climatic Divisions across Oklahoma

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Start Date: 03/01/2017

End Date: 02/28/2019

Congressional District: 3

Focus Category: AG, DROU, GW, HYDROL, IG, M&P, MET, MOD, SW, WU

Descriptors: Evapotranspiration, irrigation, drought, remote sensing

Students: Kul Khand

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

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Publications:

Khand, Kul; Saleh Taghvaeian; Ali Ajaz, 2017, Drought and its impact on agricultural water resources in Oklahoma. (Available in: http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Document-10705/BAE-1533web.pdf), Oklahoma Cooperative Extension Service, BAE-1533.

Khand, Kul; Saleh Taghvaeian; Ali Ajaz; Prasanna Gowda, 2018, Evapotranspiration responses to droughts from croplands and grasslands in semi-arid and humid climates of Oklahoma, USA (manuscript in preparation).

Ajaz, Ali; Saleh Taghvaeian; Kul Khand, 2018, Development of agricultural drought indices by effective harnessing of soil moisture and weather data (manuscript in preparation).

Problem and Research Objectives:

Water use by vegetation is one of the major components of water budget, having a significant impact on water availability at variable scales. The state of Oklahoma lies in a transitional zone between eastern humid and western semi-arid climates. These climatic variations lead to differences in vegetation water use (also termed evapotranspiration) across the state. At the same time, the vegetation water use behavior is impacted by frequent droughts. Therefore, capturing water use variations in relation to climatic conditions and droughts can provide critical information for decision makers to optimize water management plans and conserve the finite water resources of Oklahoma. The main objective of this study was to analyze in-situ and remotely sensed data to study the interrelations between evapotranspiration (ET), droughts and climatic conditions, as well as their impacts on water resources.

Methodology:

The study has been conducted in three phases. At first, an initial study was conducted to synthesize the drought impacts on water resources in western Oklahoma. Three different sites were selected based on water resources: the Oklahoma Panhandle (Ogallala aquifer region), southwest region (Lugert-Altus Irrigation District), and central (the Rush-Springs aquifer) region. Groundwater level data from the USGS monitoring wells and the surface water level data were collected and analyzed to assess the impact of droughts on water resources.

In the second phase, meteorological and soil moisture data from Mesonet stations were used to develop drought indices. Daily meteorological data such as solar radiation, air temperature, wind speed and relative humidity were used to compute daily reference ET (ASCE-EWRI, 2005). These daily reference ET values were integrated with soil moisture data to develop two new drought indices: Soil Moisture Evaporation Index (SMEI) and Drought Duration Index (DDI). Five sites were selected in this study to capture climatic conditions across Oklahoma (Figure 1). SMEI and DDI were computed for the period of 2000 to 2017 and compared with previously developed drought indices and the US Drought Monitor.

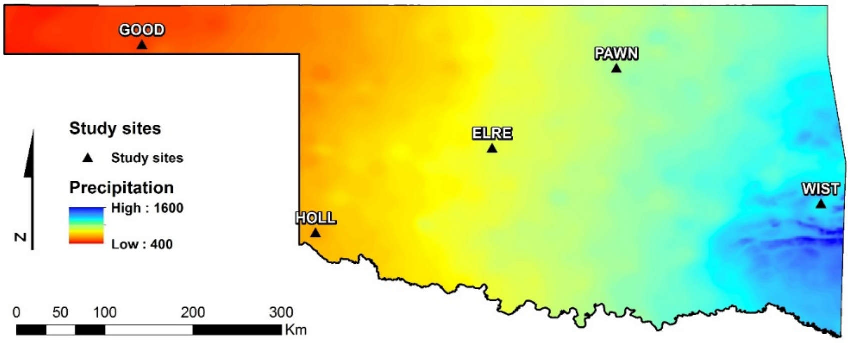

Figure 1. Location of five Mesonet study sites across Oklahoma

In the third phase, daily ET maps were generated using MODIS (Moderate Resolution Imaging Spectroradiometer) imagery. The Surface Energy Balance System (SEBS) model (Su, 2002) was implemented to compute daily ET maps with meteorological inputs from Mesonet stations. The ET results from croplands and grasslands were compared for different climate divisions across the state for the period of 2001 to 2014. The NLCD landcover (Homer et al., 2015) was used as a reference for distinguishing the different landcover types. Results from all three phases were integrated to analyze the impact of drought on water resources and vegetation water use across different climatic conditions.

Principal Findings and Significance:

Drought impacts on water resources: The Ogallala aquifer in the Panhandle regions is a major source of irrigation water and has been diminishing during the past few decades. Based on water level data collected from 42 monitoring wells across the Panhandle, water levels in the Ogallala aquifer declined 19 feet from 2001 to 2017 (Figure 2). About 50 percent of decline (9 ft) occurred in the recent drought between 2011 and 2015. The average decline rate during the drought period was 2.2 feet per year, which is 2.75 times greater than during non-drought years (0.8 feet per year).

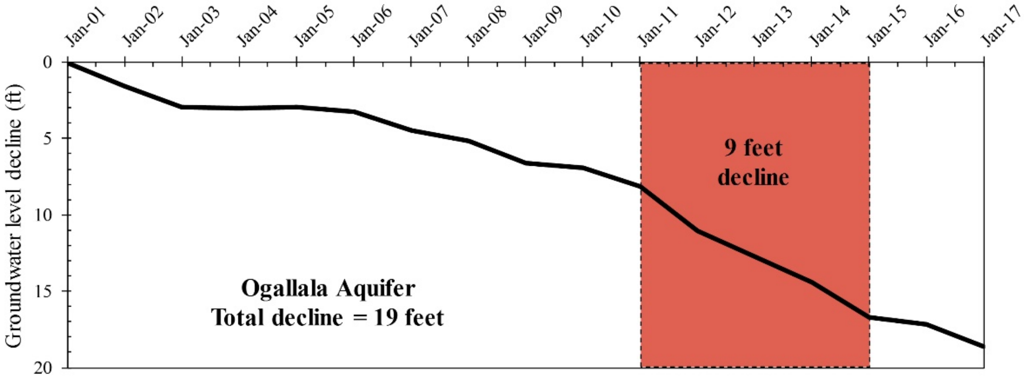

Figure 2. Groundwater level decline in the Ogallala aquifer of Oklahoma Panhandle

Rush Springs is the second most important aquifer within the state and provides irrigation water to several counties in western Oklahoma. This aquifer also experienced groundwater level depletion during droughts. The water level data from 12 monitoring wells showed that the water level in the Rush Springs aquifer dropped 10 feet during 2001 to 2017. About 70 percent of that decline was observed in recent drought between 2011 and 2015 (Figure 3). The average rate of water level decline during drought years was 1.8 feet per year, nine times the average decline rate in non-drought years (0.2 feet per year). Unlike Ogallala, the Rush Springs aquifer showed increases in groundwater level after rainy periods in 2005, 2007 to 2009 and 2015 to 2017.

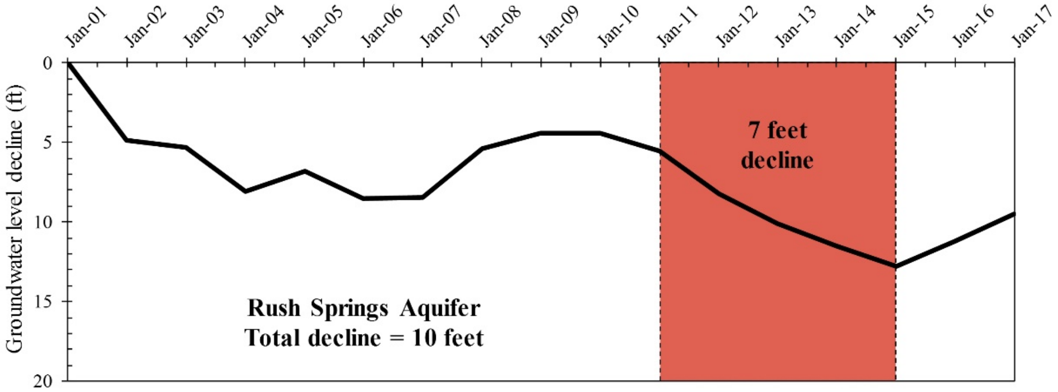

Figure 3. Groundwater level decline in the Rush Springs aquifer

Similar to groundwater resources, surface water resources were impacted by droughts. Lake Altus in southwest Oklahoma is a primary source of irrigation water for the Lugert-Altus Irrigation District (LAID). The lake was significantly impacted by the drought of 2011. Water storage in the lake was declined by about 70 percent in July 2011 compared to July 2010. Due to this decline, irrigation water was restricted to LAID, which ultimately decreased the irrigated area to near zero in 2011 (figure 4). In July 2014, water storage in Lake Altus was about 85 percent less than that in July 2010. After receiving rainfall in early 2015, the water level in July 2015 in Lake Altus overpassed the water level of that in July 2010 (Khand et al., 2017).

The study documented the vulnerability and resilience of water resources in response to recent drought. The Rush Springs aquifer, which is hydrologically connected to surface water resources showed a quicker response to the rainfall (Figure 3), indicating greater resilience to drought. However, the Ogallala aquifer did not show any response even after rainy periods, indicating sustainability issues for the long term.

The report on these results is published by the Oklahoma Cooperative Extension Service and is available online (http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Document-10705/BAE-1533web2018.pdf).

Development of drought indices: Drought indices were developed to incorporate two components of drought severity: magnitude and duration. SMEI (soil moisture evapotranspiration index) to measure magnitude and DDI (drought duration index) to capture drought duration component. The SMEI and DDI results from 2000 to 2017 indicated the successful detection of droughts across different climates of Oklahoma. Comparison with existing soil moisture-based and meteorological drought indices showed good correlations.

The performance of the new indices for temporal and spatial tracking of drought was also studied. For temporal analysis, a Mesonet site (Goodwell) from Oklahoma Panhandle was selected for a drought period of 2011 to 2014. The SMEI and DDI were able to capture the magnitude and duration components of drought episodes as indicated by the US Drought Monitor and other indices (Figure 4).

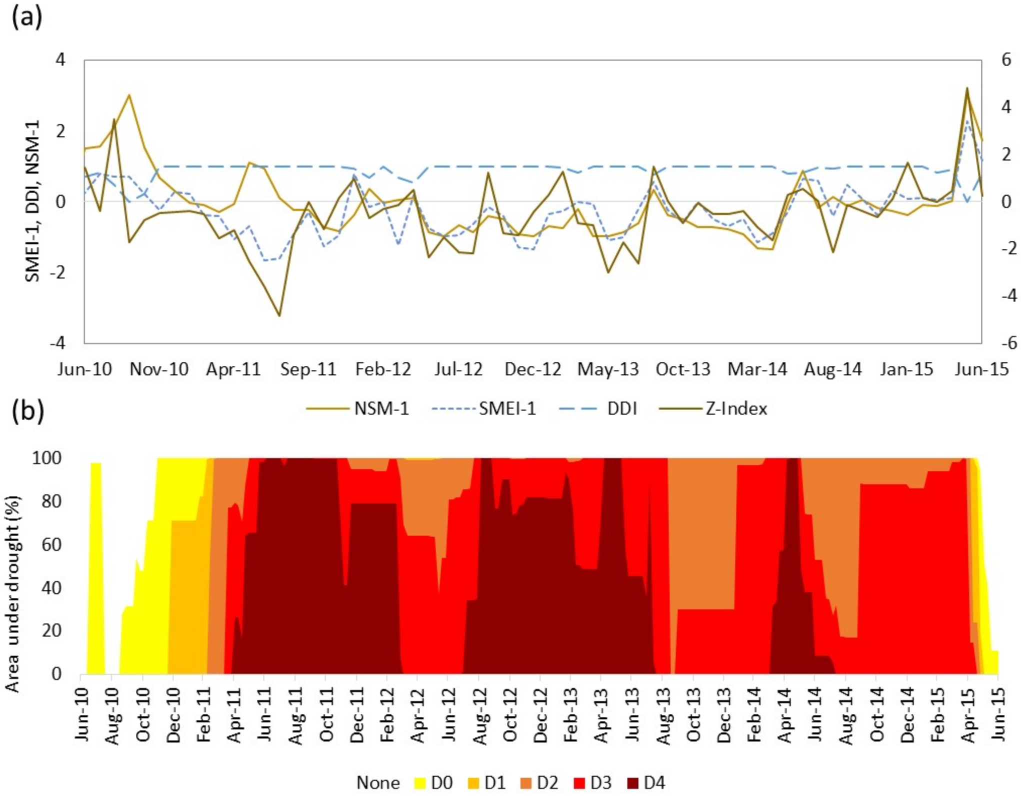

Figure 4. Comparison of SMEI and DDI with (a) soil moisture-based (NSM) and meteorological drought index (z-index), and (b) US drought monitor.

The spatial pattern of drought indicated by SMEI was similar to the US drought monitor, indicating successful incorporation of spatial variation of drought across the state. Application of soil moisture and meteorological data from Mesonet stations across the state was useful for tracking drought and for developing indices suitable for the climates of Oklahoma. The soil moisture and reference ET data could be further explored for predicting droughts and making timely decisions to minimize losses from droughts. The manuscript on this study is ready for submission.

Drought impacts on vegetation water use: The comparison of water use (ET) maps between July 2010 (no-drought) and July 2011 (drought) is shown in Figure 5. The results indicated the greater impact of drought on western parts of the state compared to the eastern parts. In the western parts of the state, grasslands and croplands are the dominant land covers. However, eastern part is mostly covered by forests. Based on these two months, forest indicated greater resilience to drought compared to croplands and grasslands.

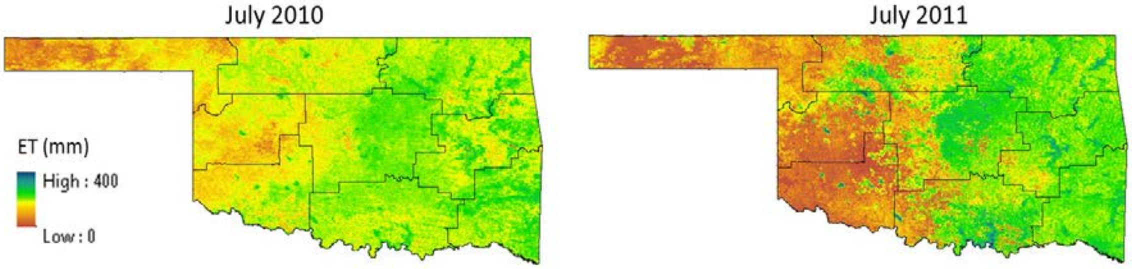

Figure 5. Monthly ET for July 2010 and 2011 across Oklahoma

Further analysis is being conducted and the results will be presented in upcoming meetings and reports. The final results and findings will be included in a manuscript that is expected to be submitted for publication by Summer 2018.

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Environmental and Water Resources Institute of the American Society of Civil Engineers (ASCE-EWRI). The ASCE Standardized Reference Evapotranspiration Equation; Report of the ASCE-EWRI Task Committee on Standardization of Reference Evapotranspiration; ASCE: Reston, VA, USA, 2005.

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Khand, Kul; Saleh Taghvaeian; Ali Ajaz, 2017, Drought and its impact on agricultural water resources in Oklahoma. (Available in: http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Document-10705/BAE-1533web.pdf), Oklahoma Cooperative Extension Service, BAE-1533.

Title: Economics of Groundwater Interaction and Competing Crops

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Start Date: 03/01/17

End Date: 02/28/19

Congressional District: 3

Focus Category: AG, COV, ECON, GW, IG, LIP, MOD, WU

Descriptors: Aquifer Life, Corn, Sorghum, Center Pivot, Long-Term Profit Maximization, Annual Profit Maximization, Limited Groundwater.

Students:

Student Status	Number	Disciplines
Undergraduate		
M.S.		
Ph.D.	1	Agricultural Economics
Post Doc		
Total	1	

Principal Investigators: Dr. Art Stoecker, Associate Professor, Department of Agricultural Economics, Oklahoma State University, 312 Ag Hall, Stillwater, OK 74078

Publications:
Ramaswamy K., A. Stoecker, J. Warren, R. Jones, S. Taghvaeian. 2017. “Choice of Irrigated Corn or Sorghum and Center Pivot or Sub Surface Drip in Oklahoma Panhandle” AAEA conference proceedings, Chicago, IL

Ramaswamy K., A. Stoecker, J. Warren, R. Jones, S. Taghvaeian. 2017. “Irrigation System Choice in Oklahoma Panhandle: Center Pivot versus Subsurface Drip” Oklahoma Governor’s Water Conference, Norman, OK

Ramaswamy K., A. Stoecker, J. Warren, R. Jones, S. Taghvaeian. 2018. “Economics of a Potential Groundwater Management Area in Oklahoma Panhandle” Oklahoma Clean Lakes and Watershed Association, Stillwater, OK

Problem and Research Objectives:

The major irrigated crops in Oklahoma Panhandle area (OPA) are corn, sorghum, and winter wheat. Irrigated corn gives greater net returns than sorghum when well capacities are above 5 GPM per acre, but irrigated sorghum gives greater net returns than corn if well capacities decline below 5 GPM per acre. Completed studies show that it is more profitable to follow a long-term profit maximizing strategy by replacing irrigated corn with grain sorghum (uses less water) and conventional pivot irrigation with subsurface drip (SDI) when well capacity declines below 5 GPM per acre. Past conservation efforts to slow down the aquifer decline and establish the economic viability of the region have been mostly unsuccessful (Golden, 2017).

Economic valuation of irrigation research shows that producers gain the highest discounted benefits from limited groundwater by following a long-term profit maximizing (LPM) strategy (Ramaswamy, 2016). In this strategy, an LPM producer would use less water than the annual profit maximizing (APM) but irrigate for more years if the discounted net profit from using the saved water is higher in the future. However, it is argued that producers will not adopt the more profitable LPM strategy because they fear that any water saved for the future use will migrate toward and be used by an adjoining APM neighbor. However, it is expected the proportion of lateral groundwater loss from a contiguous group of LPM producers would be less than from a single LPM producer.

The project will determine the recommended optimal contiguous size of the land area that must be controlled or agreed upon to form a cooperative irrigation district (CID) to follow LPM strategies. Increasingly larger CIDs will be evaluated until a size is found where CID producers can utilize at least 90% of their expected groundwater.

Objectives

The overall objective of this research is to determine groundwater migration and observe the benefits of constructing a CID for planning periods of 30 or more years.

Specific objectives test hypothesis

1. To estimate well interference through lateral flows for different sized groups (1, 4, 9, 16, etc., 640-acre sections) of LPM in a CID surrounded by APM producers.

2. To quantify the effect of different hydraulic conductivities on the lateral movement of groundwater from each size of CID defined above surrounded by APM producers.

3. Determine the optimal contiguous size of land area that must be controlled or agreed upon by the producers to follow LPM strategies.

Methodology:

In this study, two groups of producers are assumed to compete for a common pool of groundwater. The APM group chooses crops (grain sorghum or corn) and irrigation levels that give maximum annual profits. The LPM group chooses crops and irrigation levels that maximize the net present value (NPV) from the remaining groundwater for 30 or more years. This is determined by a mathematical programming model assuming a single cell aquifer. Each individual producer is assumed to have a 640-acre field with four wells. Initially, the producer could irrigate up to four 120-acre pivot circles. A representative section of land is shown below in Figure 1.

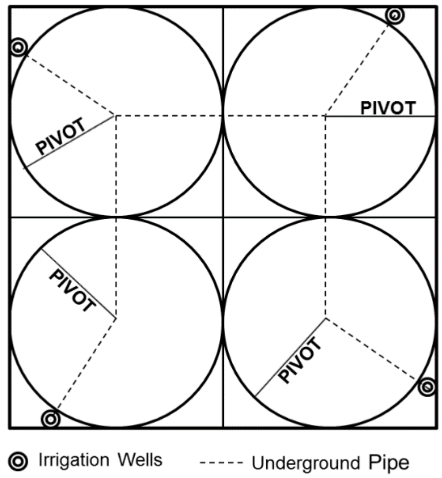


Figure 1. Representative farm with a discharge wells of 600 GPM that are interconnected using underground pipe.

The annual pumping rates for all producers are entered into a MODFLOW model which is used to simulate the combined pumping on aquifer levels over the planning period. The LPM water-level declines at a slower rate than APM level because the LPM uses less water annually. Therefore, LPM water table is expected to be at a higher level than that of an adjoining APM producer as shown in Table 1.

Table 1. Expected Annual Water Use of LPM and APM producers with four wells on a 640 acre for 30 years

	Acre-feet per year																
Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17-30
LPM	461	461	321	185	185	185	185	185	217	238	238	213	209	209	209	230	104
APM	462	462	462	462	457	431	405	352	352	284	206	206	206	206	206	104	104

Various sizes of contiguous CID areas are tested for the LPM group. These are a single 640-acre irrigated section surrounded by eight APM sections, four 640-acre LPM producers surrounded by 12 APM sections, and a block of nine 640-acre LPM producers surrounded by 40 sections of APM producers. This continues until the block of LPM producers can retain at least 90 percent net benefits they would gain if all producers followed the LPM strategy. Representative CIDs surrounded by APM producers are shown in Figure 2a, 2b and 2c.

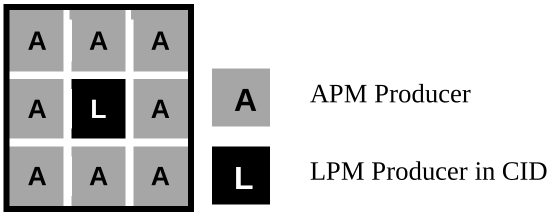


Figure 2a. One LPM section surrounded by Eight APM sections

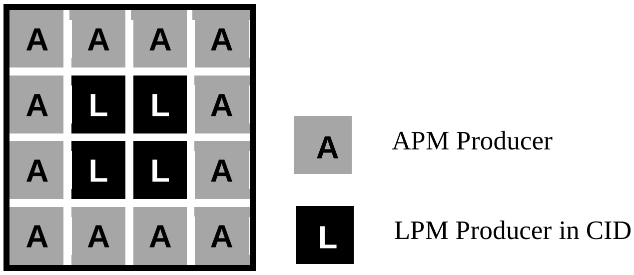


Figure 2b. Four LPM sections surrounded by 12 APM sections

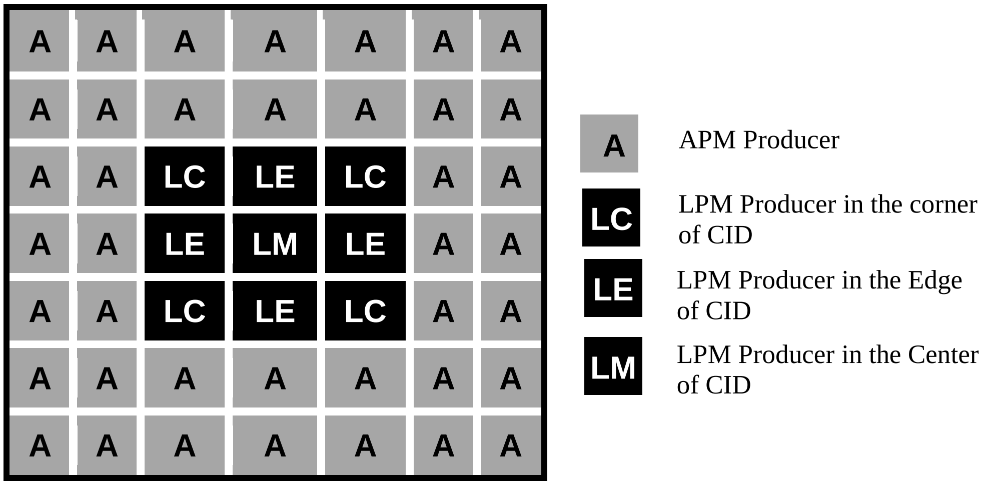


Figure 2c. Nine LPM sections surrounded by 40 APM sections

For each size of LPM group and surrounding APM, the hydrology parameters from United States Geological Survey (USGS) and Oklahoma Water Resources Board (OWRB) were collected and entered into the MODLOW model. The hydraulic conductivity in OPA ranges between 25 and 100 feet per day, and specific yield ranges between 0.12 and 0.24.

The optimal water use strategy (crop choice and water use given the current groundwater level) is determined by a multi-period mixed integer programming (MIP) model and the APM optimal water use strategy is determined by Recursive Linear Programming. Following each year the amount of groundwater flow from the CID producers to the surrounding APM producers is calculated. Groundwater interaction analysis are done in MODFLOW for contiguous land sizes and well locations. Drawdown effects on well interference and dewatering for a given saturated thickness are noted. The results for each size of CIDs lateral flow to the surrounding APM producers is compared to potential returns if all producers adopted the LPM strategy.

Principal Findings and Significance:

Preliminary results presented in this sections assume that the LPM producers in CID maximize the value of groundwater over a period of 30 years. The annual pumping rates are less than or equal to those in Table 1. The hydraulic conductivity for the current results is 25 feet per day. The specific yield is 0.175.

In the principal findings, three CID sizes were assessed using MODFLOW. In all the three scenarios, LPM producers in CID and surrounding APM producers start with 48 feet of saturated thickness. The maximum well capacity for LPM and APM producers is 600 GPM.

Scenario 1: One LPM producer surrounded by Eight APM Producers

In this scenario, the LPM producer's water table declined from 48 to 25.1 in year 10 as shown in Figure 3a. The water table in the CID declined to 13.7 in the year 20 as shown in Figure 3b. Figure 3c shows that the water table of LPM producer declined to 7.1 feet by year 30.

The annual groundwater migration from the LPM producer in CID is shown in Figure 3d. Expected total groundwater migration from the LPM producer in CID to the surrounding APM producers over 30 years is 852 acre-feet. Results show that LPM producer in the CID can retain up to 77% of potential groundwater saved. The water table and levels and lateral flow rates one LPM producer CID are compared to results of all producers following LPM. Summary of the scenario one results are provided in Table 2.

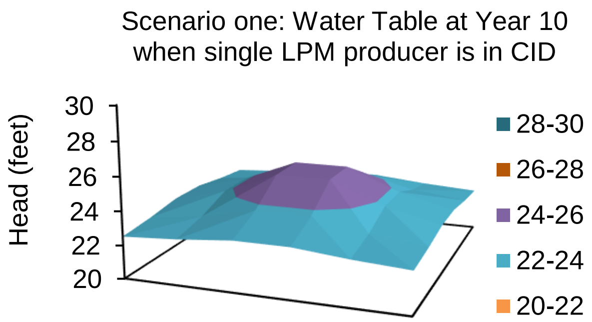


Figure 3a. Water table level of one single LPM producer in CID surrounded by 8 APM producers at year 10

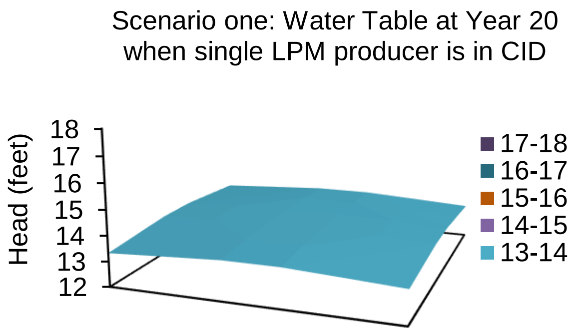
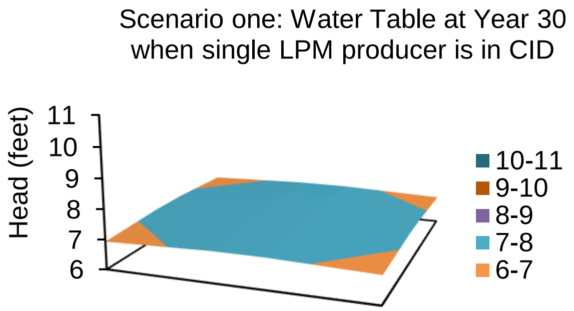


Figure 3b. Water table level of one single LPM producer in CID surrounded by 8 APM producers at year 20



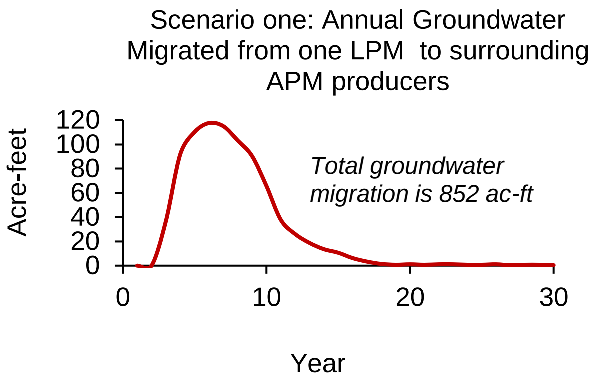


Figure 3c. Water table level of one single LPM producer in CID surrounded by 8 APM producers at year 30

Figure 3d. Annual groudwater migrated from the LPM producer in CID to surrounding APM producers

<u>Scenario two</u>: Four LPM producers surrounded by 12 APM Producers

In the case of four LPM producers in CID are surrounded by 12 APM producers, the results of groundwater levels are shown in Figure 4a, 4b, and 4c. The water table of the CID producers declined to 27.4 in year 10 as shown in Figure 4a. In year 20, the water table declined to 15.4 feet as shown in Figure 4b. As shown in Figure 4c, the water table reached 8.6 feet in year 30.

The total groundwater migration from each LPM producer in the CID to the surrounding APM producers over 30 years is 659 acre-feet. Amount of annual groundwater migration from each LPM producers was shown in Figure 6d. Results show that LPM producers in this CID can retain up to 82% of potential groundwater saved. The results of groundwater levels and lateral flow rates are compared with results if all producers were following LPM use in Table 3.

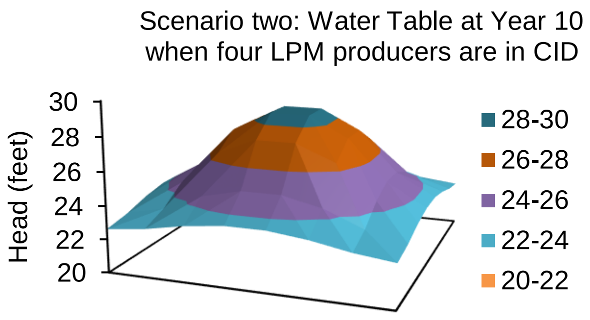


Figure 4a. Water table level of four LPM producers in CID surrounded by 12 APM producers at year 10

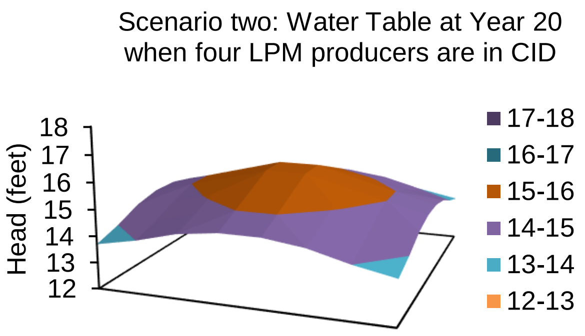


Figure 4b. Water table level of four LPM producers surrounded by 12 APM producers in CID at year 20

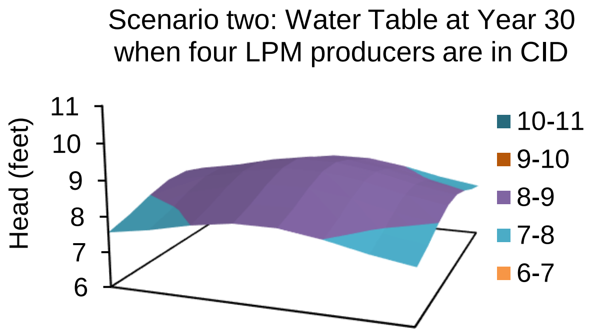


Figure 4c. Water table level of four LPM producers in CID surrounded by 12 APM producers at year 30

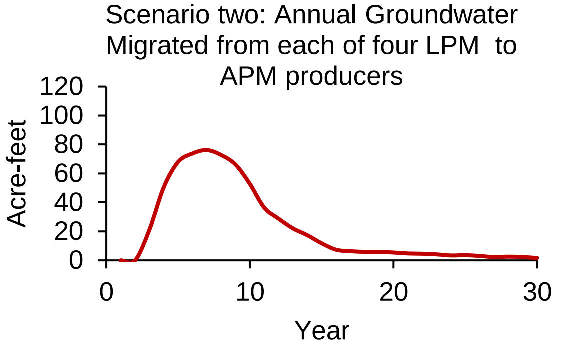


Figure 4d. Annual grodwater migrated from each of four LPM producers in CID to surrounding APM producers

<u>Scenario three</u>: Nine LPM producers surrounded by 40 APM Producers

If nine LPM producers in a CID are surrounded by 40 APM producers, the LPM producer in the corners and edges will save less water than the LPM producer in the center of CID. The water table for this scenario in year 10, 20, and 30 are shown in Figure 5a, 5b, and 5c respectively.

Groundwater level of the LPM producers on corners of the CID declined to 28.1 feet in year 10, by year 20 the water table declined to 16.2 feet, and by the end of year 30 water table reached to 9.3 feet. Results show that LPM producers in the corners of CID can retain up to 84% of potential groundwater saved. The water table and lateral flow results of this scenario is compared with the results of all producers are following LPM in Table 4.

LPM producers' groundwater level on edges of the CID decline to 29.2 feet in year 10, water table declined to 17.0 feet by year 20, and by end of year 30 the water table reached to 9.9 feet. LPM producers on edges of the CID can retain up to 86% of potential groundwater saved. The results of this scenario results are compared with the results of all producers are following LPM in Table 5.

In this scenario, the water table level of LPM producer in the center of CID declined from 30.6 in year 10, the water table declined to 17.9 in year 20, and by end of year 30 the water table reached to 10.5 feet. LPM producer in the center of CID can retain up to 88% of potential groundwater saved compared to results of all producers are following LPM. A summary of the scenario three results are provided in Table 6.

The corner LPM producers in scenario three are expected to lose 582 acre-feet over 30 years. The amount of groundwater migrated over 30 years from LPM producers on edges CID is 519 acre-feet and from the center LPM producers is 448 acre-feet. Amount of annual groundwater migration from each corner, edge, and center LPM producer are shown in Figure 5d.

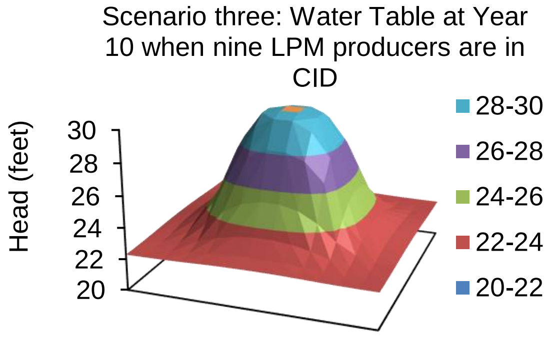


Figure 5a. Water table level of nine LPM producers in CID surrounded by 40 APM producers at year 10

Figure 5b. Water table level of nine LPM producers in CID surrounded by 40 APM producers at year 20

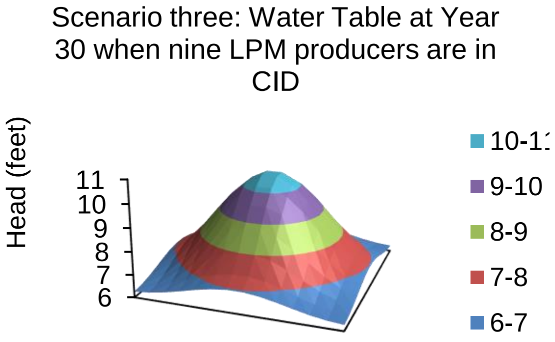


Figure 5c. Water table level of nine LPM producers in CID surrounded by 40 APM producers at year 30

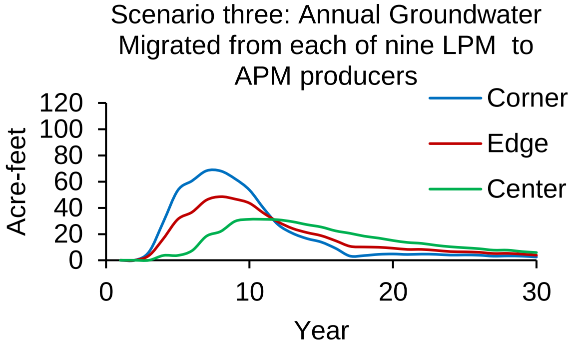


Figure 5d. Annual groudwater migrated from each of nine LPM producers in CID to surrounding APM producers

The water table decline rates for cases where all producers in the area were LTM and when all producers were APM producers are shown by the upper and lower lines in Figure 6. When there are 4 LPM or 9 LPM producers in a CID, the water table will be between the upper and lower levels in Figure 6. The LPM producers in nine section CID will retain between 84 and 88 % of the water supply they would have in all producers were LPM.

Results show that LPM can reduce the water migration to APM if the CID size is increased from one LPM section to four LPM sections. This research will continue until a size of CID is reached where 90% of the potential groundwater is saved (or only 10 % is lost by lateral flow) to surrounding APM producers. The research will be repeated with 50 feet per day hydraulic conductivity.

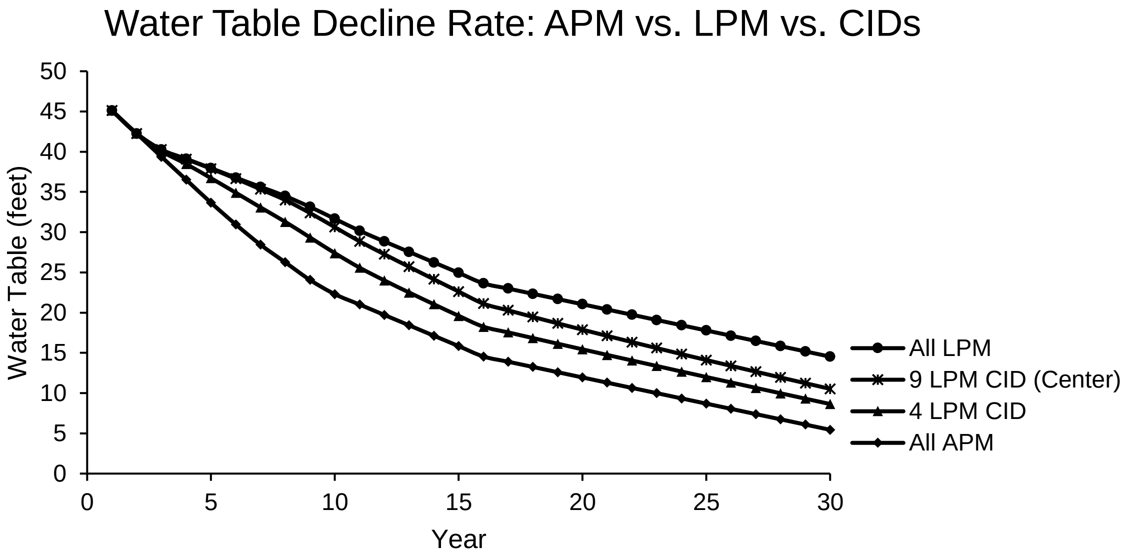


Figure 6. Water table decline rate for a group of four and nine LPM producers in CID as compared to decline rates if all irrigators were LPM producers, and if all irrigators were APM producers.

Table 2. MODFLOW results for Scenario one – One LPM producer surrounded by Eight APM producers compared with results of all producers following LPM

	If all producers follow LPM					One LPM producer in CID surrounded by Eight APM producers					
Year	Beg Head (ft)	End Head (ft)	Change in Head (ft)	Water Used (ac-ft/Q.sec)	Water Used (ac-ft/sec)	Beg Head (ft)	End Head (ft)	Change in Head (ft)	Water Used (ac-ft/Q.sec)	Water Used (ac-ft/sec)	Water Lost by LPM to APM (ac-ft)
1	48.0	45.1	2.9	80.8	323.4	48.00	45.11	2.9	80.8	323.4	0.0
2	45.1	42.3	2.9	79.9	319.7	45.11	42.26	2.9	79.9	319.7	0.0
3	42.3	40.3	2.0	56.0	224.1	42.26	39.93	2.3	65.2	260.9	36.7
4	40.3	39.1	1.1	32.2	128.6	39.93	37.96	2.0	55.1	220.5	91.9
5	39.1	38.0	1.1	32.2	128.6	37.96	35.83	2.1	59.7	238.8	110.2
6	38.0	36.8	1.2	33.1	132.3	35.83	33.60	2.2	62.5	249.9	117.6
7	36.8	35.6	1.1	32.2	128.6	33.60	31.42	2.2	60.9	243.6	115.0
8	35.6	34.5	1.1	32.2	128.6	31.42	29.35	2.1	58.0	231.9	103.3
9	34.5	33.1	1.3	37.7	150.7	29.35	27.20	2.2	60.3	241.0	90.4
10	33.1	31.7	1.5	41.3	165.4	27.20	25.13	2.1	57.8	231.1	65.8
11	31.7	30.2	1.5	41.5	166.1	25.13	23.31	1.8	51.0	203.9	37.8
12	30.2	28.8	1.3	37.2	148.8	23.31	21.75	1.6	43.7	174.9	26.1
13	28.8	27.5	1.3	36.5	145.9	21.75	20.28	1.5	41.2	164.6	18.7
14	27.5	26.2	1.3	36.5	145.9	20.28	18.86	1.4	39.9	159.5	13.6
15	26.2	24.9	1.3	36.4	145.5	18.86	17.46	1.4	39.0	156.2	10.7
16	24.9	23.6	1.3	36.5	139.6	17.46	16.22	1.2	34.9	145.9	6.3
17	23.6	23.0	0.6	18.2	72.8	16.22	15.66	0.6	15.6	73.7	0.9
18	23.0	22.3	0.7	18.3	73.1	15.66	15.02	0.6	17.9	73.7	0.6
19	22.3	21.7	0.6	18.2	72.8	15.02	14.36	0.7	18.4	73.5	0.7
20	21.7	21.0	0.6	18.2	72.8	14.36	13.70	0.7	18.5	73.4	0.6
21	21.0	20.4	0.7	18.3	73.1	13.70	13.04	0.7	18.5	73.9	0.7
22	20.4	19.7	0.6	18.2	72.8	13.04	12.39	0.7	18.5	73.1	0.3
23	19.7	19.1	0.6	18.2	72.8	12.39	11.73	0.7	18.5	73.9	1.1
24	19.1	18.4	0.7	18.3	73.1	11.73	11.07	0.7	18.5	73.9	0.7
25	18.4	17.8	0.6	18.2	72.8	11.07	10.41	0.7	18.4	73.5	0.7
26	17.8	17.1	0.6	18.2	72.8	10.41	9.75	0.7	18.5	73.9	1.1
27	17.1	16.5	0.7	18.3	73.1	9.75	9.09	0.7	18.4	73.5	0.4
28	16.5	15.8	0.6	18.2	72.8	9.09	8.44	0.7	18.4	73.5	0.7
29	15.8	15.2	0.6	18.2	72.8	8.44	7.78	0.7	18.4	73.5	0.7
30	15.2	14.5	0.7	18.3	73.1	7.78	7.13	0.7	18.4	73.5	0.4

Table 3. MODFLOW results for Scenario Two – Four LPM producers surrounded by 12 APM producers compared with results of all producers following LPM

	If all producers follow LPM					Four LPM producers in CID surrounded by 12 APM producers					
Year	Beg Head (ft)	End Head (ft)	Change in Head (ft)	Water Used (ac-ft/Q.sec)	Water Used (ac-ft/sec)	Beg Head (ft)	End Head (ft)	Change in Head (ft)	Water Used (ac-ft/Q.sec)	Water Used (ac-ft/sec)	Water Lost by LPM to APM (ac-ft)
1	48.0	45.1	2.9	80.8	323.4	48.0	45.1	2.9	80.8	323.4	0.0
2	45.1	42.3	2.9	79.9	319.7	45.1	42.3	2.9	79.9	319.7	0.0
3	42.3	40.3	2.0	56.0	224.1	42.3	40.1	2.2	61.3	245.3	21.1
4	40.3	39.1	1.1	32.2	128.6	40.1	38.5	1.6	44.8	179.1	50.5
5	39.1	38.0	1.1	32.2	128.6	38.5	36.7	1.8	49.1	196.6	68.0
6	38.0	36.8	1.2	33.1	132.3	36.7	34.9	1.8	50.5	202.1	69.8
7	36.8	35.6	1.1	32.2	128.6	34.9	33.1	1.8	51.2	204.8	76.2
8	35.6	34.5	1.1	32.2	128.6	33.1	31.3	1.8	50.3	201.4	72.8
9	34.5	33.1	1.3	37.7	150.7	31.3	29.3	1.9	54.2	216.8	66.1
10	33.1	31.7	1.5	41.3	165.4	29.3	27.4	1.9	54.5	218.1	52.7
11	31.7	30.2	1.5	41.5	166.1	27.4	25.6	1.8	50.6	202.5	36.4
12	30.2	28.8	1.3	37.2	148.8	25.6	24.0	1.6	44.4	177.6	28.8
13	28.8	27.5	1.3	36.5	145.9	24.0	22.5	1.5	42.0	167.9	22.0
14	27.5	26.2	1.3	36.5	145.9	22.5	21.0	1.5	41.0	164.1	18.2
15	26.2	24.9	1.3	36.4	145.5	21.0	19.6	1.4	40.2	160.8	15.2
16	24.9	23.6	1.3	36.5	139.6	19.6	18.3	1.4	37.9	151.6	5.7
17	23.6	23.0	0.6	18.2	72.8	18.3	17.5	0.7	19.8	79.1	6.3
18	23.0	22.3	0.7	18.3	73.1	17.5	16.8	0.7	19.8	79.0	5.9
19	22.3	21.7	0.6	18.2	72.8	16.8	16.1	0.7	19.7	78.6	5.9
20	21.7	21.0	0.6	18.2	72.8	16.1	15.4	0.7	19.5	78.2	5.4
21	21.0	20.4	0.7	18.3	73.1	15.4	14.7	0.7	19.5	77.9	4.8
22	20.4	19.7	0.6	18.2	72.8	14.7	14.1	0.7	19.3	77.3	4.6
23	19.7	19.1	0.6	18.2	72.8	14.1	13.4	0.7	19.2	76.9	4.1
24	19.1	18.4	0.7	18.3	73.1	13.4	12.7	0.7	19.1	76.5	3.4
25	18.4	17.8	0.6	18.2	72.8	12.7	12.0	0.7	19.1	76.3	3.6
26	17.8	17.1	0.6	18.2	72.8	12.0	11.3	0.7	18.9	75.8	3.0
27	17.1	16.5	0.7	18.3	73.1	11.3	10.7	0.7	18.9	75.4	2.3
28	16.5	15.8	0.6	18.2	72.8	10.7	10.0	0.7	18.8	75.3	2.6
29	15.8	15.2	0.6	18.2	72.8	10.0	9.3	0.7	18.8	75.1	2.3
30	15.2	14.5	0.7	18.3	73.1	9.3	8.6	0.7	18.7	74.8	1.7

Table 4. MODFLOW results for Scenario Three (Corner Wells)- Nine LPM sections surrounded by 40 APM sections compared with results of all producers following LPM

	If all producers follow LPM					Four LPM producers in CID surrounded by 40 APM producers					
Year	Beg Head (ft)	End Head (ft)	Change in Head (ft)	Water Used (ac-ft/Q.sec)	Water Used (ac-ft/sec)	Beg Head (ft)	End Head (ft)	Change in Head (ft)	Water Used (ac-ft/Q.sec)	Water Used (ac-ft/sec)	Water Lost by LPM to APM (ac-ft)
1	48.0	45.1	2.9	80.8	323.4	48.0	45.1	2.9	80.8	323.4	0.0
2	45.1	42.3	2.9	79.9	319.7	45.1	42.3	2.9	79.9	319.7	0.0
3	42.3	40.3	2.0	56.0	224.1	42.3	40.2	2.1	57.6	230.6	6.4
4	40.3	39.1	1.1	32.2	128.6	40.2	38.8	1.4	39.5	158.0	29.4
5	39.1	38.0	1.1	32.2	128.6	38.8	37.2	1.6	45.5	181.9	53.3
6	38.0	36.8	1.2	33.1	132.3	37.2	35.4	1.7	48.2	192.9	60.6
7	36.8	35.6	1.1	32.2	128.6	35.4	33.7	1.8	49.2	196.9	68.3
8	35.6	34.5	1.1	32.2	128.6	33.7	31.9	1.8	49.2	196.7	68.1
9	34.5	33.1	1.3	37.7	150.7	31.9	30.0	1.9	53.2	212.8	62.1
10	33.1	31.7	1.5	41.3	165.4	30.0	28.1	2.0	54.7	218.9	53.6
11	31.7	30.2	1.5	41.5	166.1	28.1	26.2	1.8	51.4	205.5	39.4
12	30.2	28.8	1.3	37.2	148.8	26.2	24.7	1.6	44.0	175.9	27.1
13	28.8	27.5	1.3	36.5	145.9	24.7	23.2	1.5	41.6	166.5	20.6
14	27.5	26.2	1.3	36.5	145.9	23.2	21.7	1.5	40.6	162.4	16.5
15	26.2	24.9	1.3	36.4	145.5	21.7	20.3	1.4	39.8	159.4	13.9
16	24.9	23.6	1.3	36.5	139.6	20.3	18.9	1.4	38.7	155.0	9.1
17	23.6	23.0	0.6	18.2	72.8	18.9	18.2	0.7	19.0	76.0	3.2
18	23.0	22.3	0.7	18.3	73.1	18.2	17.6	0.7	19.2	76.7	3.6
19	22.3	21.7	0.6	18.2	72.8	17.6	16.9	0.7	19.3	77.3	4.5
20	21.7	21.0	0.6	18.2	72.8	16.9	16.2	0.7	19.4	77.5	4.8
21	21.0	20.4	0.7	18.3	73.1	16.2	15.5	0.7	19.4	77.5	4.4
22	20.4	19.7	0.6	18.2	72.8	15.5	14.8	0.7	19.4	77.4	4.7
23	19.7	19.1	0.6	18.2	72.8	14.8	14.1	0.7	19.3	77.3	4.5
24	19.1	18.4	0.7	18.3	73.1	14.1	13.4	0.7	19.3	77.1	4.0
25	18.4	17.8	0.6	18.2	72.8	13.4	12.7	0.7	19.2	76.8	4.0
26	17.8	17.1	0.6	18.2	72.8	12.7	12.0	0.7	19.2	76.6	3.9
27	17.1	16.5	0.7	18.3	73.1	12.0	11.4	0.7	19.1	76.2	3.1
28	16.5	15.8	0.6	18.2	72.8	11.4	10.7	0.7	19.0	76.1	3.3
29	15.8	15.2	0.6	18.2	72.8	10.7	10.0	0.7	19.0	75.9	3.1
30	15.2	14.5	0.7	18.3	73.1	10.0	9.3	0.7	18.9	75.6	2.5

Table 5. MODFLOW results for Scenario Three (Edge Wells)- Nine LPM sections surrounded by 40 APM sections

	Independent LPM section					Four LPM sections in CID					
Year	Beg Head (ft)	End Head (ft)	Change in Head (ft)	Water Used (ac-ft/Q.sec)	Water Used (ac-ft/sec)	Beg Head (ft)	End Head (ft)	Change in Head (ft)	Water Used (ac-ft/Q.sec)	Water Used (ac-ft/sec)	Water Lost by LPM to APM (ac-ft)
1	48.0	45.1	2.9	80.8	323.4	48.0	45.1	2.9	80.8	323.4	0.0
2	45.1	42.3	2.9	79.9	319.7	45.1	42.3	2.9	79.9	319.7	0.0
3	42.3	40.3	2.0	56.0	224.1	42.3	40.2	2.0	57.0	227.8	3.7
4	40.3	39.1	1.1	32.2	128.6	40.2	38.9	1.3	36.3	145.1	16.5
5	39.1	38.0	1.1	32.2	128.6	38.9	37.5	1.4	40.0	159.8	31.2
6	38.0	36.8	1.2	33.1	132.3	37.5	36.0	1.5	42.3	169.0	36.7
7	36.8	35.6	1.1	32.2	128.6	36.0	34.4	1.6	43.6	174.5	45.9
8	35.6	34.5	1.1	32.2	128.6	34.4	32.9	1.6	44.3	177.1	48.5
9	34.5	33.1	1.3	37.7	150.7	32.9	31.1	1.8	49.3	197.3	46.7
10	33.1	31.7	1.5	41.3	165.4	31.1	29.2	1.9	52.2	208.9	43.5
11	31.7	30.2	1.5	41.5	166.1	29.2	27.4	1.8	50.5	201.9	35.8
12	30.2	28.8	1.3	37.2	148.8	27.4	25.8	1.6	44.5	178.0	29.2
13	28.8	27.5	1.3	36.5	145.9	25.8	24.3	1.5	42.5	170.1	24.3
14	27.5	26.2	1.3	36.5	145.9	24.3	22.8	1.5	41.8	167.0	21.1
15	26.2	24.9	1.3	36.4	145.5	22.8	21.4	1.5	41.1	164.3	18.7
16	24.9	23.6	1.3	36.5	139.6	21.4	19.9	1.4	40.2	160.8	14.9
17	23.6	23.0	0.6	18.2	72.8	19.9	19.2	0.7	20.9	83.4	10.7
18	23.0	22.3	0.7	18.3	73.1	19.2	18.4	0.7	20.8	83.2	10.1
19	22.3	21.7	0.6	18.2	72.8	18.4	17.7	0.7	20.7	82.7	9.9
20	21.7	21.0	0.6	18.2	72.8	17.7	17.0	0.7	20.5	81.9	9.2
21	21.0	20.4	0.7	18.3	73.1	17.0	16.2	0.7	20.3	81.4	8.3
22	20.4	19.7	0.6	18.2	72.8	16.2	15.5	0.7	20.3	81.0	8.3
23	19.7	19.1	0.6	18.2	72.8	15.5	14.8	0.7	20.1	80.3	7.5
24	19.1	18.4	0.7	18.3	73.1	14.8	14.1	0.7	19.9	79.7	6.6
25	18.4	17.8	0.6	18.2	72.8	14.1	13.4	0.7	19.8	79.2	6.4
26	17.8	17.1	0.6	18.2	72.8	13.4	12.7	0.7	19.7	78.8	6.1
27	17.1	16.5	0.7	18.3	73.1	12.7	12.0	0.7	19.6	78.3	5.1
28	16.5	15.8	0.6	18.2	72.8	12.0	11.3	0.7	19.5	78.0	5.2
29	15.8	15.2	0.6	18.2	72.8	11.3	10.6	0.7	19.4	77.4	4.7
30	15.2	14.5	0.7	18.3	73.1	10.6	9.9	0.7	19.2	77.0	3.9

Table 6. MODFLOW results for Scenario Three (Center Well)- Nine LPM sections surrounded by 40 APM sections

	Independent LPM section					Four LPM sections in CID					
Year	Beg Head (ft)	End Head (ft)	Change in Head (ft)	Water Used (ac-ft/Q.sec)	Water Used (ac-ft/sec)	Beg Head (ft)	End Head (ft)	Change in Head (ft)	Water Used (ac-ft/Q.sec)	Water Used (ac-ft/sec)	Water Lost by LPM to APM (ac-ft)
1	48.0	45.1	2.9	80.8	323.4	48.0	45.1	2.9	80.8	323.4	0.0
2	45.1	42.3	2.9	79.9	319.7	45.1	42.3	2.9	79.9	319.7	0.0
3	42.3	40.3	2.0	56.0	224.1	42.3	40.3	2.0	56.0	224.1	0.0
4	40.3	39.1	1.1	32.2	128.6	40.3	39.1	1.2	33.1	132.3	3.7
5	39.1	38.0	1.1	32.2	128.6	39.1	37.9	1.2	33.1	132.3	3.7
6	38.0	36.8	1.2	33.1	132.3	37.9	36.6	1.2	34.9	139.6	7.3
7	36.8	35.6	1.1	32.2	128.6	36.6	35.3	1.3	36.7	147.0	18.4
8	35.6	34.5	1.1	32.2	128.6	35.3	34.0	1.3	37.7	150.7	22.0
9	34.5	33.1	1.3	37.7	150.7	34.0	32.4	1.6	45.1	180.4	29.8
10	33.1	31.7	1.5	41.3	165.4	32.4	30.6	1.8	49.1	196.6	31.2
11	31.7	30.2	1.5	41.5	166.1	30.6	28.9	1.8	49.3	197.3	31.2
12	30.2	28.8	1.3	37.2	148.8	28.9	27.3	1.6	44.9	179.7	30.9
13	28.8	27.5	1.3	36.5	145.9	27.3	25.7	1.6	43.8	175.3	29.4
14	27.5	26.2	1.3	36.5	145.9	25.7	24.1	1.5	43.3	173.1	27.2
15	26.2	24.9	1.3	36.4	145.5	24.1	22.6	1.5	42.7	170.9	25.4
16	24.9	23.6	1.3	36.5	139.6	22.6	21.1	1.5	42.1	168.3	22.4
17	23.6	23.0	0.6	18.2	72.8	21.1	20.3	0.8	23.3	93.3	20.6
18	23.0	22.3	0.7	18.3	73.1	20.3	19.5	0.8	22.9	91.5	18.4
19	22.3	21.7	0.6	18.2	72.8	19.5	18.7	0.8	22.4	89.7	16.9
20	21.7	21.0	0.6	18.2	72.8	18.7	17.9	0.8	22.0	87.8	15.1
21	21.0	20.4	0.7	18.3	73.1	17.9	17.1	0.8	21.7	86.7	13.6
22	20.4	19.7	0.6	18.2	72.8	17.1	16.3	0.8	21.4	85.6	12.9
23	19.7	19.1	0.6	18.2	72.8	16.3	15.6	0.8	21.0	84.1	11.4
24	19.1	18.4	0.7	18.3	73.1	15.6	14.8	0.7	20.9	83.4	10.3
25	18.4	17.8	0.6	18.2	72.8	14.8	14.1	0.7	20.6	82.3	9.6
26	17.8	17.1	0.6	18.2	72.8	14.1	13.4	0.7	20.4	81.6	8.8
27	17.1	16.5	0.7	18.3	73.1	13.4	12.7	0.7	20.2	80.8	7.7
28	16.5	15.8	0.6	18.2	72.8	12.7	11.9	0.7	20.1	80.5	7.7
29	15.8	15.2	0.6	18.2	72.8	11.9	11.2	0.7	19.8	79.4	6.6
30	15.2	14.5	0.7	18.3	73.1	11.2	10.5	0.7	19.8	79.0	5.9

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Title: Combining remote sensing and in-situ data to estimate soil moisture across mixed land cover types

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Start Date: 03/01/2017

End Date: 02/28/2018

Congressional District: OK 3

Focus Category: WQN, HYDROL

Descriptors: soil moisture estimation, MODIS, remote sensing

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Student Status	Number	Disciplines
Undergraduate		
M.S.		
Ph.D.	1	Soil Science
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Wyatt, B.M., T.E. Ochsner, and C.B. Zou. 2017. Integration of remote sensing and in-situ data to estimate soil moisture across mixed land cover types. Oklahoma Governor's Water Conference and Research Symposium. Norman, OK.

Wyatt, B.M., T.E. Ochsner, and C.B. Zou. 2017. Integration of remote sensing and in-situ data to estimate soil moisture across mixed land cover types. ASA-CSSA-SSSA Annual International Meeting. Tampa, FL.

Wyatt, B.M., T.E. Ochsner, and C.B. Zou. 2017. Integration of remote sensing and in-situ data to estimate soil moisture across mixed land cover types. Marena, Oklahoma In-Situ Sensor Testbed (MOISST) annual meeting. Stillwater, OK.

Wyatt, B.M., T. E. Ochsner, and C.B. Zou. 2017. Combining remote sensing and in-situ data to estimate soil moisture across mixed land cover types. Oklahoma State University Plant and Soil Sciences Department Research Symposium.

Problem and Research Objectives:

While the current long-term soil moisture record is useful for a number of applications in many research areas, a major limitation of the current data is that it has been collected exclusively in grassland ecosystems and does not reflect soil moisture conditions under other land covers. However, remote sensing by satellites has led to the availability of high-resolution vegetation indices data, and we hypothesize that these data, along with in-situ meteorological data from the Oklahoma Mesonet, may be incorporated into a simple water balance model to effectively estimate root-zone soil moisture at sites throughout Oklahoma. These estimates may then be used to train a computational model to estimate soil moisture across the entire state, regardless of land cover.

The *long-term goal* of this project is to increase scientific understanding of the variability of soil moisture under the many cover types found throughout Oklahoma and to create a new, general method of large-scale soil moisture estimation and mapping. We will reach this goal by 1) incorporating vegetation indices (e.g., normalized difference vegetation index [NDVI] or enhanced vegetation index [EVI]) data collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensors aboard NASA's Aqua and Terra Satellites and Mesonet meteorological data in a water balance model capable of estimating soil moisture under various land cover types found in Oklahoma, and 2) validating estimated soil moisture values using in-situ soil moisture monitoring in multiple vegetation types throughout Oklahoma.

Methodology:

Objective #1: The MODIS instruments report global high-resolution (250 m^2) vegetation index data every 8 days (Huete et al,. 1999). Daily vegetation index values will be found using a simple linear interpolation between observations (Glenn et al., 2011). These vegetation index values, along with meteorological data from the Oklahoma Mesonet, will be used in a water balance model capable of estimating soil moisture for each remote sensing pixel. Initially, we had planned to create our own model to complete this objective, but upon further research we found that a suitable model had already been developed. This model, HidroMORE, will be used to produce gridded soil moisture estimates across Oklahoma, including areas where there are no in-situ monitoring data (Sanchez et al., 2010). Model inputs include remote sensing vegetation index data and land cover type data, meteorological data, soil type data, and several other inputs.

Objective #2: In-situ soil moisture sensors will be used to validate vegetation index-estimated soil moisture in various land cover types throughout the state. Funding for this project was used to purchase sensors that will be installed under 5 vegetation types in order for a robust validation of model results across land cover types. Due to funding delays, soil moisture sensors were not able to be purchased until late 2017 and have not yet been installed in the field.

Current Progress:

The HidroMORE model was developed in Spain, and as such the model itself is in Spanish. A significant amount of time was spent translating the model into English and ensuring the translation was as correct as possible. Satellite images for the HidroMORE model have been gathered, organized, and prepared for inclusion in the model for the years 2000-2016. Meteorological data from the Oklahoma Mesonet are readily available, and SSURGO soils data are currently being collected and prepared for input into the model.

Currently we are working on an initial model run for Payne County, OK at a 250 m^2 resolution. Work is ongoing for the installation of field monitoring equipment and is expected to be completed in Summer 2018 under grassland, winter crops, summer crops, deciduous forest, and oak forest. Soil moisture data from these in-situ monitoring stations will be used to validate the model results within Payne County and expansion of the model to the entire state of Oklahoma will be done after this initial modeling stage.

Principal Findings and Significance:

While HidroMORE model simulations have not been completed yet, the water balance method used by the model has been used to estimate soil moisture at sites under native grass at the Marena, OK Mesonet station as well as under oak forest at the Cross Timbers Experimental Range station from April 2015-April 2016. Early results indicate that this method is well-suited for estimating soil moisture (shown here as plant available water, or PAW) under different vegetation types (Figure 1).

Future work on this project includes completing HidroMORE model simulations, installing soil moisture sensors under various land cover types, and validating model results using in-situ soil moisture data. The final goal of this research is to estimate daily soil moisture at a 250 m^2 resolution for the state of Oklahoma.

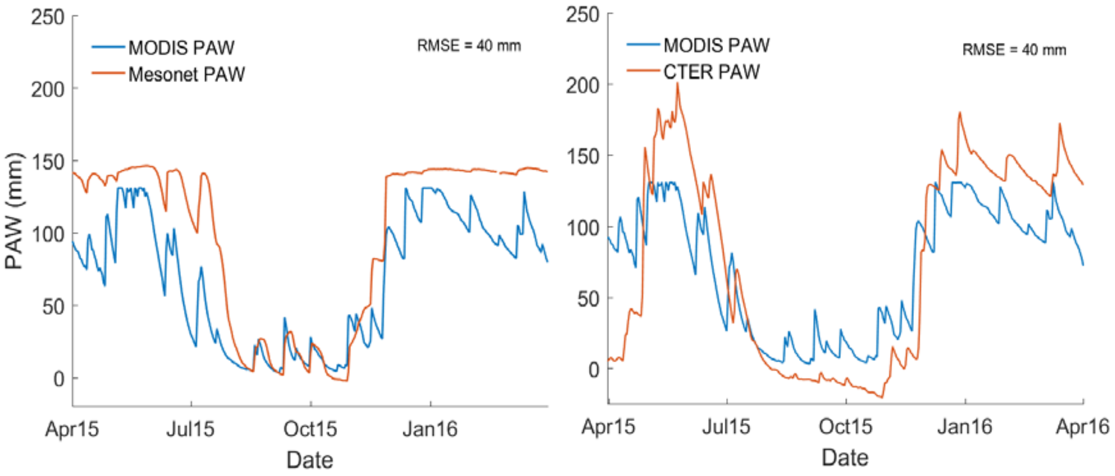

Figure 1. MODIS-estimated versus measured plant available water (PAW) for the Marena Mesonet site under grassland (left) and an oak forest site (right).

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Western Oklahoma Irrigation Water and Energy Audits: Findings, Recommendations and Educational Materials

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Start Date: 03/01/2016

End Date: 02/28/2018

Congressional District: 3

Focus Category:

IG, WU, DROU

Descriptors: Irrigation, Energy Management, Irrigation Efficiency, Groundwater, Sustainability, Aquifer Management

Students:

Student Status	Number	Disciplines
Undergraduate		
M.S.	1	
Ph.D.		
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Publications:

OSU DASNR Factsheets (USGS support acknowledged in Fact Sheets)

(Blessing, Masasi, R, Scott Frazier, Saleh Taghvaeian), May 2017, Review and Operational Guidelines for Portable Ultrasonic Flowmeters, BAE-1535, 7 Pages

(R, Scott Frazier, Saleh Taghvaeian, Divya Handa), November 2017, Measuring Depth to Groundwater in Irrigation Wells, BAE-1538, 4 Pages

(Saleh Taghvaeian, R. Scott Frazier, Garey Fox), 2016, The Ogallala Aquifer, BAE-1531, 3 Pages

(R. Scott Frazier, Carol Jones), 2016, Irrigation Pump System Testing, BAE1525, 4 Pages

Conference Presentations using 104b Grant Project Data (USGS support acknowledged in Presentations)

(R. Scott Frazier), Energy and Water Efficiency of Center Pivot Irrigation (with updates), 2018 Oklahoma Irrigation Conference, Weatherford.

(R. Scott Frazier), Energy and Water Efficiency of Center Pivot Irrigation (with updates), 2017 Oklahoma Irrigation Conference, Altus.

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(R. Scott Frazier, Saleh Taghvaeian, Dustin Livingston), Irrigation Efficiency Tests in the Oklahoma Panhandle. ASABE Annual International Meeting. July 17-20, 2016; Orlando, FL.

(Blessing Masasi, Saleh Taghvaeian, R. Scott Frazier), Performance Evaluation of Irrigation Systems in Western Oklahoma. 9th International Conference on Irrigation and Drainage. Oct. 11-14, 2016; Fort Collins, CO.

(Blessing Masasi, Saleh Taghvaeian, R. Scott Frazier), Benchmarking Performance of Irrigation Systems in Western Oklahoma. OSU Student Water Conference. Mar. 22-24, 2017; Stillwater, OK.

(Divya Handa, R. Scott Frazier, Saleh Taghvaeian), Assessing the Energy Consumption Efficiency of Center-Pivot Irrigation Systems. 38th Annual Oklahoma Governor's Water Conference & Research Symposium. Oct. 31-Nov. 1st, 2017; Norman, OK.

Problem and Research Objectives:

The western portion of Oklahoma is in a precarious water supply situation. Recent record rains may prove to be an anomaly with a rapid return to widespread drought. The groundwater levels in this part of the state have been lowering significantly every year due to high use and lack of recharge rainwater. The largest user of water in this portion of the state is agricultural irrigation. Competition with municipal water demands will only exacerbate the irrigation water needs. Given that this precious resource of water is threatened, we should make all attempts to assure that irrigation operations in this area are as effective and efficient (sustainable) as possible.

Methodology:

A total of 26 center-pivot irrigation systems in western Oklahoma were tested between 2015 and 2017 with the aim of determining their energy consumption efficiencies (OPE) and irrigation (water) conveyance efficiencies and application uniformities. The energy consumption efficiency is a function of overall pumping efficiency and application uniformity is expressed in terms of coefficient of uniformity (CU) and distribution uniformity (DU). The irrigation systems were all located within the three western climatic divisions in Oklahoma, namely the Panhandle, the West Central, and the Southwest (Figure1). The long-term average annual precipitation of these divisions range from 498 mm in the Panhandle to 705 mm in the southwest. The water demand of dominant agricultural crops in this region is significantly larger than these precipitation values (ref). Hence, irrigation water needs to be applied in most years to sustain an economically viable food production system. While the Rush Spring’s aquifer is a major source of irrigation for the counties in South West and Central Oklahoma, the Ogallala aquifer is the major source of irrigation for the counties in North Western Oklahoma. Of the pumping plants evaluated, eighteen were electricity powered pumping plants and eight were natural gas internal combustion powered pumping plants.

Energy Auditing of Irrigation Systems

The actual (energy) Overall Pumping Efficiency (OPE) of the pumping plants were evaluated and compared against two widely used standards: The Nebraska Pumping Plant Performance Criteria (NPPPC) and the efficiency classification developed by the Center for Irrigation Technology (CIT) at California State University-Fresno.

Overall Pumping Efficiency (OPE)

The Overall Pumping Efficiency (equation 1) is the ratio of the output work (water horsepower) the pump exerts to the water at the pump outlet in relation to the required input power of the driving unit (Chavez J.L., et al).

$$OPE = \frac{Water\ horsepower}{Input\ power} \times 100$$

The major parameters required to determine the overall pumping efficiency of the electrical powered pumping plants were: water horsepower (equation 2) and electric power demand of the plant.

Water Horsepower

Water horsepower (WHP) is the power required to pump the measured water output. The water horsepower can be determined if the flow rate of the water and the force (pressure) required to produce that flow is known (total dynamic head). The WHP is rated in horsepower and can be calculated using the following equation:

$$Water\ Horsepower = \frac{TDH \times Q}{3960}$$

where, Q represents the flow rate of water in gallons per minute and total dynamic head (TDH) is pressure in “feet”. The flow rate can be measured using an ultrasonic flow meter on the discharge pipe from the pump. The ultrasonic flow meter was installed per recommendations on straight sections of the discharge pipe to ensure proper reading. Additional details about the proper use of ultrasonic flow meter can be found in Review and Operational Guidelines for Portable Ultrasonic Flowmeters by Masasi et al., (2017).

Total Dynamic Head

The total dynamic head (TDH) is the total equivalent (pressurethat must be applied to the water column being pumped while also taking into account the losses due to friction. In this study the friction losses in the pipe have been estimated and added to the measured lift term:

$$TDH = Elevation\ head + Friction\ head\ + Pressure\ head$$

where, TDH is the total dynamic head (feet), Pumping lift is the vertical distance between the pumping water level and center of the pump outlet (m), and Pressure head is the pressure at the pump outlet.

The pumping lift was measured by lowering an electric water level meter through an access hole in the pump base-plate whilst a pressure gauge close to the pump outlet was used to measure the pressure head.

Electric Motors

Input kilowatts (KW) is the electrical power supplied to the electric motor. The input kW for a three phase motor can be estimated as:

$$Input\ Kilowatts = \frac{V \times I \times P.F \times 1.732}{1000}$$

The voltage (V), the current (I) and, the power factor (P.F.), were measured using an electric power meter. Measurements were obtained from a three phase electric meter. The current of each of the three legs was first measured individually and then averaged, the voltage was measured across all three legs and also averaged.

If the measured three phase voltage was unbalanced greater than 10% (Max voltage difference phase to phase)/Average voltage, then this was reported as an additional problem needing attention in the customer report.

In order to convert horsepower (hp) to kilowatts (kW) (electrical units of power) the following equation can be used:

$$1\ hp = 0.746\ KW$$

Natural Gas Engines

The natural gas consumption of the internal combustion engines used to drive the well pumps was measured by a Dresser Roots® Series B rotary gas meter. The meter auto-corrects for gas pressure, density, and temperature. The display gives readings of cubic feet per minute which can be converted to Btu/hour. This in turn, can be converted to mechanical horsepower.

1 Mechanical Horsepower = 2,544.43 Btu per hour

The Btu value of natural gas can be estimated by the correction factors that the meter outputs based on temperature and pressure. This is roughly 1,037 Btu per cubic foot (0.0283 cubic meters at 101.325 kPa and 15 degrees Celsius standard conditions).

The rotary gas meter is installed by turning off the gas supply to the engine at the gas meter. The main fuel line running to the intake manifold is disconnected and the rotary meter is installed in-line with this gas line which is then reconnected to the engine.

The engine is allowed to run until in steady state operating temperature. The water pump is also allowed to bring the entire irrigation system up to operating pressure (water delivery from all nozzles).

The engine and pump system is allowed to run for 30-45 minutes at which time average fuel consumption readings and correction factors are recorded. Removing the rotary meter is the reverse of installation.

The general condition of the natural gas engine, any identifying model and serial numbers, estimated date of manufacture and installation and peripheral systems are noted at the time of the audit and recorded.

Water audit

A total of 11 center pivot irrigation systems were evaluated for water efficiencies and uniformities in Western Oklahoma over a period of 3 years. The systems analyzed varied in size, with the shortest center pivot having 3 spans and the longest having 10 spans. The selection of center pivot systems of different sizes was done in order to get a good representation of the different types of irrigation systems in the study area.

Water Application Uniformity

Water application uniformity is a measure of the consistency of water distribution over the entire irrigated area. Irrigation systems should apply the water uniformly in sufficient quantities without over-watering or generating runoff (Irrigation energy audit manual, 2012).

The global standardized catch-can method (Zhang et al., 2011) was used to estimate water application uniformity. For each evaluation, numerous catch-cans were placed on a radius of the irrigated circle at equal distances (10 feet to 20 feet) in the path of the center pivot. The area covered by the sprinklers increases with the increase in distance from the pivot center. Thus, each catch-can represents a different area. The catch-cans were graduated both in inches and millimeters to ensure direct measurement.

The irrigation system span was allowed to pass completely over the catch-cans while applying water. The quantity of water output supplied by the irrigation pump for each tested system (span) was also measured using the ultrasonic flowmeter (conveyance efficiency mentioned below). Therefore, span water input and output are compared. Location coordinates of each system were noted, amount of water in the can, wind speed and temperature were also measured during the tests. The amount of water collected in each evaluation was used to estimate water application uniformity and efficiency. The water application uniformity parameters that were used to characterize the performance of the center pivot systems were the Coefficient of Uniformity (CU) and Distribution Uniformity (DU).

Coefficient of Uniformity (CU)

CU was estimated based on the Heermann and Hein formula (ANSI/ASAE S436.1):

$$\mathrm{CU} = 100\% \times \left[1- \frac{\frac{1}{n}\sum_{i=1}^{n} S_i|V_i-\overline{V}_p|}{\sum_{i=1}^{n} V_i S_i}\right]$$

where n is the number of catch cans used in the data analysis, CU is the Heermann and Hein uniformity coefficient, j is the number assigned to identify a particular catch can beginning with i = n for the most remote catch can from the pivot point, V_i is the volume of water collected in the ith catch can, Sj represents distance of the ith collector from the pivot point, and Vp is the weighted average of the volume of water caught.

Based on Merriam et al. (1978), CU values lying in the range of 90%-95% were classified as excellent, 85%-90% as good, 80-85% as fair and less than 80% as poor - with a recommendation of full maintenance of the entire irrigation system.

Distribution Uniformity (DU)

The DU indicates the uniformity of application throughout the field and is computed by:

$$DU = \frac{average\ low\ quarter\ depth\ of\ water\ recieved}{average\ depth\ of\ water\ recieved} \times 100$$

The average low-quarter depth of water received was calculated by measuring the average depth of water collected in the low one-quarter the total catch cans. DU was then calculated by dividing the average low-quarter depth of water received by the average depth of water received by the entire field.

Based on Merriam and Keller (1978) DU ratings were classified into five categories. The DU ratings were classified as excellent, very good, good, fair, poor and unacceptable ratings for the range greater than 85%, 80%, 75%, 70%, and less than 65% respectively.

Conveyance Efficiency

Conveyance efficiency (CE) is typically defined as the ratio between the amount of water that reaches a farm or field, and the amount diverted from the irrigation water source (well). It is defined as:

$$E_c = \frac{V_f}{V_t} \times 100$$

where E_c is the conveyance efficiency (%), V_f is the volume of water that reaches the farm or field (m^3), and V_t is the volume of water diverted (m^3) from the source (Howell, 2003).

In general, conveyance losses are typically negligible for center pivot irrigation systems as compared to flood or other simpler irrigation methods. However, the conveyance losses for center pivot irrigation can become significant in the event of broken or leaking water lines and sprinklers.

Principal Findings and Significance:

Energy Audits

OPE of Electricity powered pumping plants

Table (1) represents the calculated values of OPE of the electricity powered pumping plants for the observed values of discharge, TDH, WHP, and Input power. Each site was allotted a unique pumping I.D. The average OPE of the pumping plants was found to be 46.9%, much lower than the recommended NPPC standard of 66%. A possible explanation for the poor performance could be: aging electrical motors, wiring issues, pump malfunctions or significant changes in the operating conditions (lowering water levels – TDH).

Table 1. Pump Pressure, Head and Efficiency

Pump I.D.	Discharge Pressure (psi)	TDH (feet)	OPE (%)
P.1.	19	91.3	50.3
P.2	28	100.2	48.9
P.3	32	109	44.7
P.4	39	130	56.6
P.5	58	186.4	46.3
P.6	49	177.5	66.7
P.7	44	278	55.2
P.8	34	183	41.8
P.9	70	301	50.7
P.10	32	160	36.3
P.11	56	216.4	62.6
P.12	38	187.8	24.9
P.13	47	202	50.2
P.14	40	210.5	41.9
P.15	63	247.9	41.3
P.16	59	221.3	40.3
P.17	32	196.8	40.9
P.18	92	279.5	44

OPE of natural gas powered pumping plants

The average OPE of the natural gas powered pumping plant was estimated to be 13.75 percent which is below the recommended NPPC standard value of 17 percent. The majority of the pumping plants had an OPE lower than the NPPC standard. Only one pumping plant showed an OPE value (21.4%) higher than the NPPC standard (Figure 1).

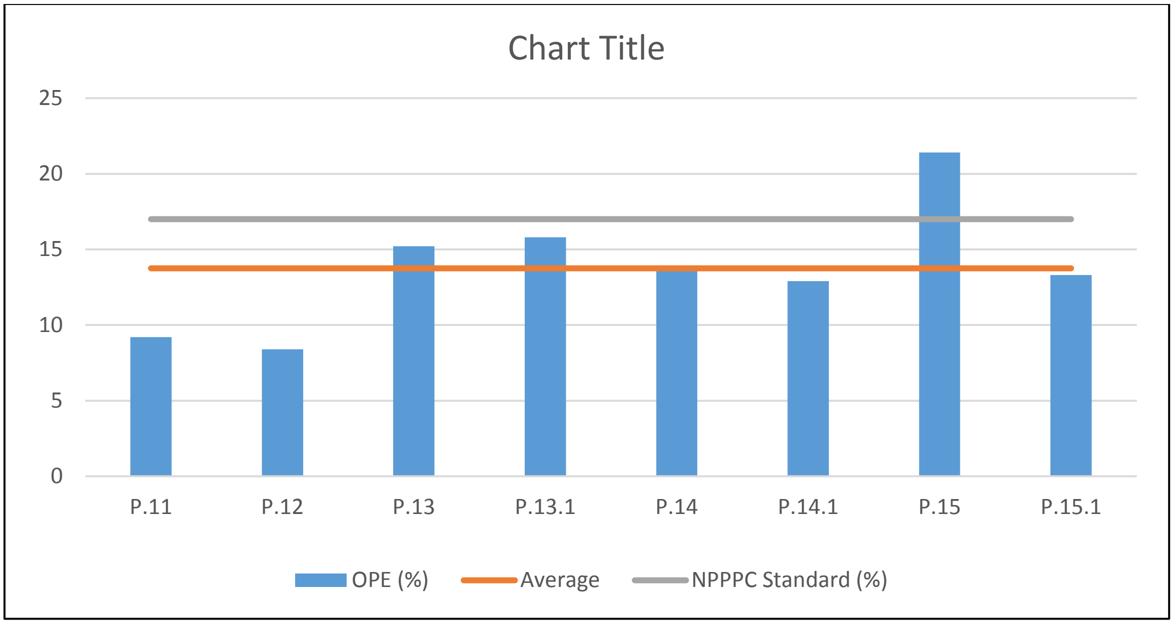

Figure 1. Actual OPE of natural gas (IC Engine) powered pumping plants as compared to NPPPC standards.

According to the Farm and Ranch Irrigation Survey (2013) there are total 1,345 natural gas powered pumps in Oklahoma. If the results from these tests were to be extrapolated to all of these pumps it would imply that 87.5%, i.e. nearly 1,176 pumps, might operate below the recommended efficiency. The sample size of the pumps in this test (8 ea.) is not large enough to make this a statistically valid assumption, however (see Table 2).

Table 2. Pump Pressure, Head and OPE

Pump I.D.	Discharge Pressure (PSI)	TDH (feet)	OPE (%)
P.19	8	328.6	9.2
P.20	30	321	8.4
P.21	22	304.5	15.2
P.22	32	289.7	15.8
P.23	26	274.1	13.8
P.24	27	309.7	12.9
P.25	21	430	21.4
P.26	35	412.3	13.3

Water Audits

The water audits were performed by calculating the two uniformity indicators: CU and DU. Calculated values of CU and DU were then compared against the recommended standards. The average CU was found to be 79.6%, which according to the classification falls under the poor category. Of the eleven plants evaluated only three pumps had excellent performance, i.e. had a CU rating in the 90%-95% range.

Similarly, the average DU was estimated to be 70.9%, which is much below the recommended standards. However, the distribution uniformity performance fared slightly better than coefficient of uniformity performance, with only two pumps falling in the poor performance category.

The water conveyance efficiency of most pumps ranged from 90%- 100%. Even though the percentage loss might look insignificant, reducing or eliminating this amount of water loss will not only result in supplying more water to the field, but will also result in potential reductions in energy costs since less number of hours of pump operation is required to deliver the same amount of water.

Table 3. Pump Uniformity and Water Efficiency

Pump ID	DU (%)	CU (%)	WCE (%)
P.1	69	75	93
P.7	73	84	100
P.8	62	76	89
P.9	69	79	95
P.10	86	92	96
P.11	82	87	100
P.12	77	87	93
P.15	82	85	91
P.17	81	90	90
P.19	14	31	89
P.20	85	90	100

Conclusions

Based on the results of the audits conducted, we suspect there is significant potential for reduction in the operating costs of similar pumping plants in the state. Improving the efficiency of the Oklahoma pumping plants to the NPPC recommended standards could (on average) decrease the current irrigation operating costs. An average saving based on the 26 irrigation systems tested to date would be, for every one thousand hours of operation, \$1,517 (+/- \$262 s.d.) and \$1,176 (+/- \$480 s.d.) for electricity and natural gas powered pumping plants respectively. Assuming a similar trend for the total 3,456 electricity powered and 1,354 natural gas powered pumping plants in Oklahoma could lead to significant average savings amounting to approximately \$5,240,000 per year for electrical irrigation systems in the state. The total extrapolated savings for natural gas irrigation statewide would be \$1,590,000 for every one thousand hours of operation. Over 20 years this could amount to over \$136,000,000 in savings.

In a similar study by McDougall at University of Arkansas (2015), the average OPE of electricity powered pumping plants was estimated to be 74%. The results obtained showed that improving OPE to NPPPC recommended standards in state of Arkansas could result in annual savings of 264.4 million kWh of electricity (considering 47.4% of 53,829 irrigation pumping plants are powered by electricity). Energy costs of \$0.10 USD/kWh were assumed. Thus, on an average 26.44 million USD could be saved annually. Mora et al. in their study in South East of Spain estimated that improving the efficiency by almost 13% increased the energy saving cost by 17%. The increase in efficiency was attributed to maintenance works. Therefore, we believe the need to improve irrigation energy and water efficiency to be fairly widespread and estimating savings over large aggregate numbers of irrigation systems may not be unreasonable.

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Title: Evaluating the Reuse of Swine Lagoon Effluent and Reclaimed Municipal Water for Agricultural Production

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End Date: February 28, 2018

Congressional District: Oklahoma 3rd

Focus Category: WQL

Descriptors: Swine effluent, treated wastewater, irrigation, alternative water sources, nutrient buildup and losses, soil health, water quality, crop production

Students: (Include number of students supported by the project during the project period in the table below.)

Student Status	Number	Disciplines
Undergraduate		
M.S.		
Ph.D.	0.2	Soil Science
Post Doc		
Total		

Principal Investigators:

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Publications: None

Problem and Research Objectives:

Significant amount of water in Oklahoma is used for crop irrigation. Water shortage in Oklahoma and the Southern Great Plains has become a major limitation for crop production and other uses, which will have a major impact on local economy. Therefore, alternative sources of irrigation water need to be explored. Treated municipal wastewater (TWW) is one of the most readily available alternative water sources, although infrastructures to use TWW for crop irrigation are lacking in most places and public acceptance is probably low because of the lack of field evaluations in the state. Currently, most TWW in the state is directly discharged to steams and rivers rather than recycled for crop production. Treated swine lagoon effluent is also available in west Oklahoma and other regions. Although swine effluent has been used to irrigate crops, more water use efficient application techniques need to be evaluated and promoted.

The objectives of this project were to 1.) evaluate the impact of continuous subsurface drip irrigation of swine effluent on salt and nutrient buildup and movement in soils; 2.) establish an environmental and agricultural baseline in a newly constructed treated municipal wastewater recycling site.

Methodology:

For the first objective, grid soil samples (grid size was about 2 acres) up to 1 m deep was collected the field where the subsurface drip irrigation of swine effluent was installed. The profile samples were separated into 0-6", 6-12", 12-24" and 24-36" segments. Soil samples were analyzed for pH, plant available N, P, K and electrical conductivity (EC). Five pairs of lysimeters were installed at selected locations at 2 and 4 feet deep to monitor nitrate leaching potential to groundwater but no leachate was collected due draught during the study period. Nutrient and EC maps were generated using GIS software and plotted vertically with soil depth. Effluent application quantity and timing were obtained to calculate the nutrient input. The conditions and effectiveness of the irrigation tape after 11 years in operation was evaluated as well.

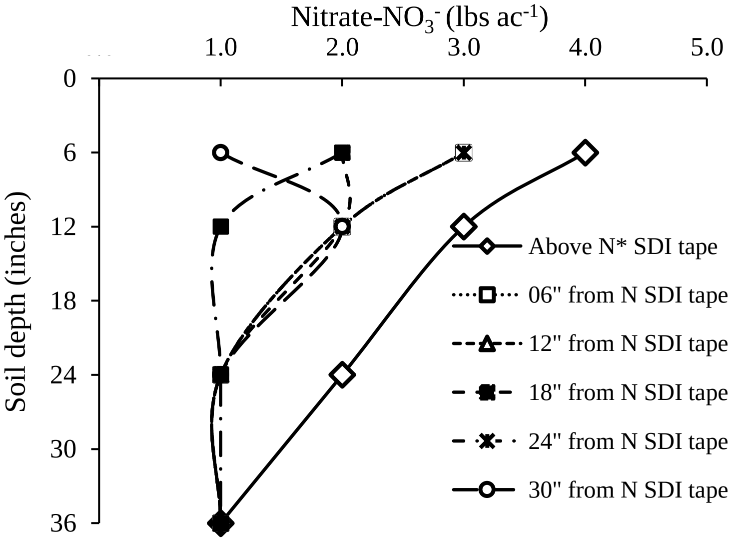
For the second objective, similar soil and plant health monitoring was conducted at the South Central Research Station in Chickasha where the reclaimed municipal wastewater was used for irrigation. Soil Samples were collected to 1 m deep at the beginning of the project. Treated wastewater was analyzed for irrigation water quality several times. Groundwater monitoring wells were installed at the beginning of the project at 6 strategic locations. Water samples from the monitoring well were collected and analyzed for common nutrients and salts.

Principal Findings and Significance:

1. Swine lagoon effluent is a good source of water and plant nutrients. It should be land applied when possible.

Figure 1. Bermudagrass in the field with subsurface drip irrigation system to distribute anaerobically digested lagoon effluent. The strips of grass reflect the orientation of drip tapes. The effluent supplied nutrients and water and resulted in good growth.

2. Subsurface drip irrigation is an efficient method of delivery the effluent to the parenial bermudagrass pasture. At the rates applied for 12 years, there was no evidence of nutrient and salt buildup in the soil, and movement to the groundwater. The drip tape was in good condition 12 years since installation and similar evaluations should be conducted about 5 years in the future.



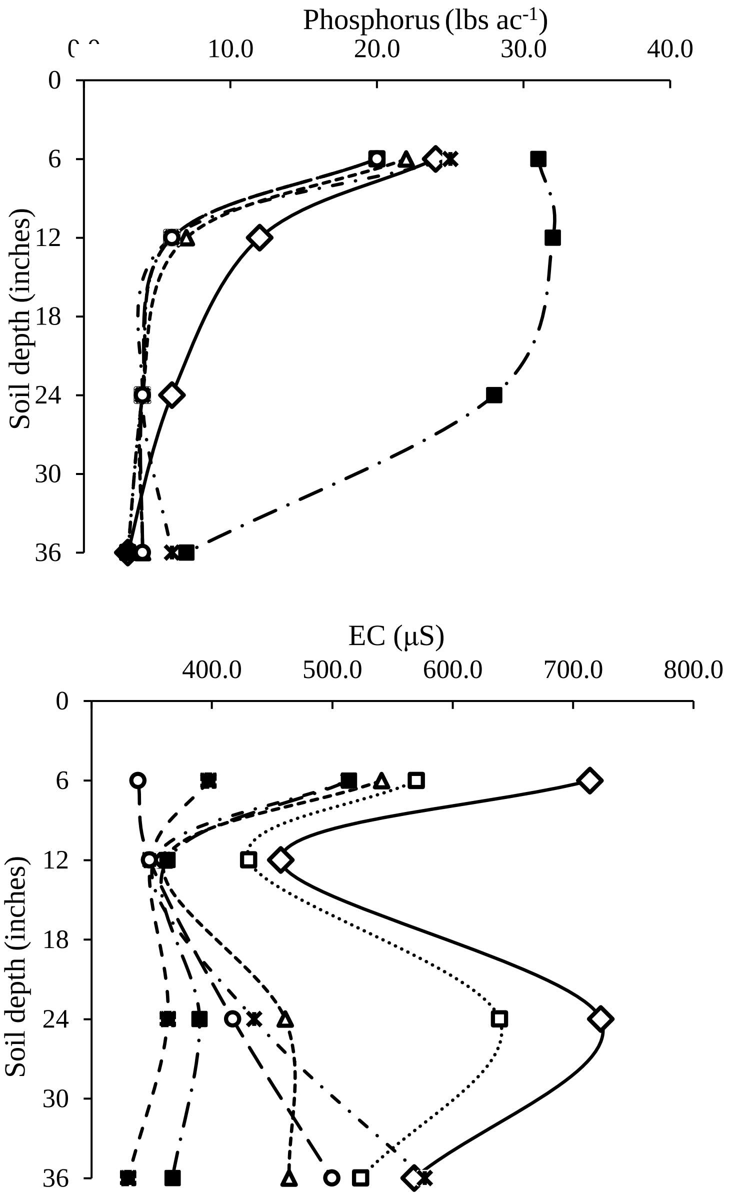


Figure 2. Representative nitrate-N, soil test P and EC distribution in soil profile between 2 drip tapes. All 3 analytes are typical of most agricultural soils. The soil test P is still below the 100% sufficiency level in Oklahoma.

3. The quality of the treated manuciple wastewater from Chickasha is considered acceptable irrigation water for most crops based on the analytes tested. It does contain some nitrogen and other beneficial nutrients. Therefore, it is recommended to give credits to those nutrients when deciding the amount of fertilizers to be applied to avoid over application.

Table 1. The quality of the treated municipal wastewater used for irrigation in Chickasha, OK.

Sampling dates	pH	EC	TDS	Nitrate-N	ICP-P	B	Sulfate	SAR	Na%
		uS/cm	---------------------ppm---------------------------						
3/15/2016*	7.8	1218	824	11.6	1.12	0.3	183	1.8	32
5/15/2016	8.0	1210	823	11.3	1.12	0.3	182	1.9	32
3/16/2017	8.4	1113	735	18.1	1.64	0.3	159	2.2	38

*sampled at the pump by the treatment plant. The rest of the samples were collected at the discharge point.

4. The baseline of soil properties in the 2 fields designed to receive treated wastewater has been established, and will serve as a comparison for future evaluations.

Table 2. Soil samples (0-6”) from the field with center pivot irrigation systems in Chickasha.

Grid	pH	NO$_3$-N	K	P	Ca	Mg	SO$_4$-S	Cu	Fe	Zn	B	OM	EC
Number		lbs A^{-1}	….Mehlich-3 (lbs A^{-1})…				lbs A^{-1}	..DTPA-sorbitol (ppm)..				%	(µS)
1	6.2	50	311	49	3141	1072	11.5	0.6	16.5	0.5	0.15	1.93	1356
2	6.5	23	467	52	3875	1599	12.6	0.8	17.5	0.4	0.19	2.42	1062
3	5.8	14	284	59	2507	1017	11.4	0.7	20	0.3	0.14	1.94	520
4	5.9	54	471	62	3503	1414	10.7	0.9	36.4	0.3	0.16	2.31	1245
5	6.3	20	521	75	4122	1718	8.8	1	34.7	0.4	0.21	2.56	900
6	6.1	36	322	45	2856	1129	10.9	0.7	18.6	0.3	0.17	2.1	924
7	6.2	8	382	28	3875	1205	12.3	0.7	17.3	0.3	0.23	2.64	738
8	6.6	6	606	30	4767	2067	12.9	1.2	29.2	0.4	0.34	2.95	681
9	6.4	3	287	26	3239	1032	9.9	0.5	12.9	0.2	0.16	2.02	513
10	6.1	6	287	26	2968	983	13.3	0.7	19.9	0.3	0.20	1.95	624
11	6.1	17	383	36	3658	1286	16.1	0.8	25.9	0.3	0.22	2.61	801
12	6.5	13	510	40	4165	1587	10.5	0.8	24.6	0.3	0.29	2.72	816

5. Six groundwater monitoring wells were installed at strategic locations and water samples were taken and analyzed. This first set of data will serve as the baseline for future references.

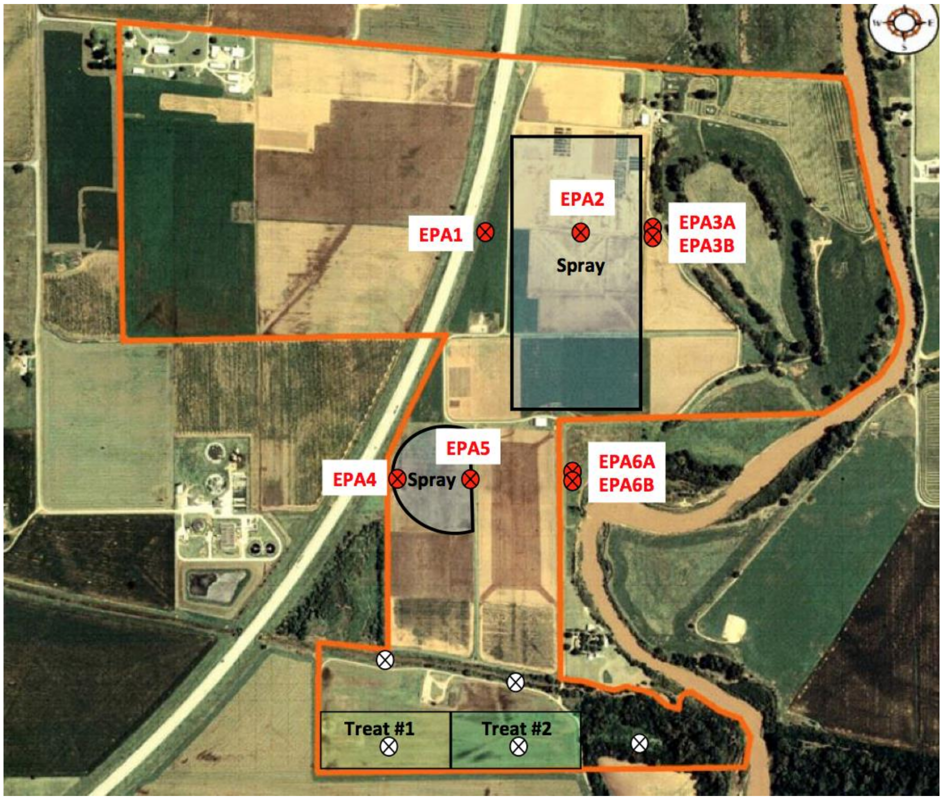


Figure 4. The locations of groundwater monitoring wells located above, inside and below the groundwater gradient under the irrigated area.

Table 3. Analysis from samples collected from the monitoring wells.

Well Number	pH	EC (µS)	Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	NO_3-N (ppm)	Cl (ppm)	SO_4 (ppm)	HCO_3 (ppm)	B (ppm)	TDS (ppm)	PAR (%)	SAR (%)	EPP (%)	ESP (%)	Hardness (ppm)	Alkalinity (ppm)	Zn (ppm)	Cu (ppm)	Mn (ppm)	Fe (ppm)	$NH_{4\text{-}N}$ (ppm)	P (ppm)
EPA1	7.6	1663	41	4.0	84	166	2.5	145	38	835	0.4	1316	0.03	0.6	3.8	< DL	892	685	0.01	< DL	0.12	0.46	0.06	0.26
EPA2	7.6	5690	1042	6.0	202	109	0.2	615	1762	626	3.1	4363	0.05	14.7	4	16.8	954	513	0.01	< DL	0.36	0.35	0.3	0.19
EPA3A	7.6	1824	102	3.0	106	151	8	82	133	927	0.8	1511	0.03	1.5	3.7	0.9	884	760	< DL	< DL	0.14	0.14	0.02	0.06
EPA3B	7.6	2600	291	3.0	107	152	4.5	253	413	821	1.2	2045	0.03	4.2	3.7	4.7	894	673	< DL	< DL	0.02	0.07	0.02	0.41
EPA4	7.7	1499	33	2.0	77	152	4.1	98	39	791	0.3	1195	0.02	0.5	3.6	< DL	819	648	< DL	< DL	< DL	0.05	0.01	0.28
EPA5	7.6	1522	82	3.0	92	127	0.2	68	134	791	0.7	1297	0.03	1.3	3.7	0.6	754	649	0.01	0.02	0.85	0.06	0.14	0.21
EPA6B	7.8	2430	335	2.0	90	120	1.1	190	446	813	1.5	1997	0.02	5.4	3.7	6.3	719	666	0.01	< DL	0.02	0.27	0.02	0.29
Ave.	7.6	2461	275	3.3	108	140	2.9	207	424	800	1.1	1961	0.03	4.0	3.7	5.9	845	656	0.01	0.02	0.25	0.20	0.08	0.24

6. This priliminary work laid a foundation for more studies on how treated wastewater affecting soil health and crop production in the future.