ASSESSING THE ENERGY CONSUMPTION EFFICIENCY, IRRIGATION APPLICATION UNIFORMITY AND LIFE CYCLE ASSESSMENT OF GROUNDWATER-BASED IRRIGATION SYSTEMS IN OKLAHOMA

By

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Abstract: Irrigation systems across Oklahoma were tested from 2015 to 2018 with the aim of determining their energy consumption efficiencies, irrigation uniformities, and application efficiencies. The actual Overall Pumping Efficiency (OPE) of the pumping plants were evaluated and compared against two widely used standards: The Nebraska Pumping Plant Performance Criteria (NPPPC) (Krantz, 2010) and the efficiency classification developed by the Center for Irrigation Technology (CIT) at California State University-Fresno. Life cycle assessment (LCA) was also performed to quantify the environmental burdens of operating the pumping plants. For uniformity evaluations, two parameters Christiansen's coefficient of uniformity (CU) and Distribution uniformity (DU) were evaluated. Catch can method was used. Based on the audits results, three different irrigation treatments (different levels of uniformities) were chosen. The DayCent ecosystem model was used to simulate the impact of non-uniform irrigation on evaporation, transpiration, percolation, nutrient losses, leaching, crop yield etc.

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INTRODUCTION

Water is essential to sustain human life (Siegel, 2008). Water is needed for the production of economically viable crops, industrial, and domestic purposes. Worldwide, irrigated agriculture is the largest consumer of water, withdrawing nearly 70% or 2663 cubic kilometers of freshwater per year (Km3/yr) (Plappally et al., 2012; Mora et al., 2013). In the U.S., irrigation is the second largest consumer of water, accounting for 34% of all water withdrawals (Griffiths et al., 2009). In Oklahoma, growers applied more than 170 billion gallons of water for irrigating 426,602 acres of farm land (Taghvaeian, 2014).

Water and energy are interlinked in many ways. Water is needed for the production of energy and energy is required for water extraction, distribution, disposal etc. (Siddiqi et al., 2011). This inter dependency is also called water-energy nexus (Griffiths et al., 2009; Rothausen et al., 2011). Irrigated agriculture relies on energy resources to extract freshwater and to convey it to application sites. In Oklahoma, electricity was the main source of pumping energy, supplying water to 46% of all irrigated acres in state. This was followed by natural gas which powered pumps to irrigate 42% of all irrigated acres (Taghvaeian, 2014). Both water and energy are finite natural resources. As such, strategies to improve the performance of irrigation systems should look at both water and energy resources especially at field level.

Studies have shown that pumping of groundwater is an energy intensive process. In the U.S., Sloggett et al. (1979; 1992) reported that pumping groundwater required 23% of total on farm energy use. According to Hodges et al. (1994), 15% of total energy used for crop production was used to pump irrigation water. The amount of energy consumed for groundwater pumping and conveyance depends on number of factors like depth to groundwater, efficiency of the system, crop water requirement etc. Energy consumption has major environmental consequences (Khan et al., 2014; Pradeleix et al., 2015). In China, Wang et al. (2012) reported that pumping groundwater for irrigation accounted for 3% of total emissions from agriculture. A similar study in Iran found that groundwater pumping was responsible for 3.6% of total carbon emissions in the country (Karimi et al., 2012). In India, groundwater pumping lead to emission of nearly 6% of India's total GHG emissions (Shah, 2009). In the US, carbon emissions due to pumping irrigation water were reported to be about 3 million metric tons of carbon per year (MMTC/yr) (Follett, 2001).

The rapidly increasing population, climate change, increased per capita water consumption, declining groundwater levels have influenced the water and energy demand (Griffiths et al., 2009; Alvaro et al., 2010; Plappally et al., 2012; Qui et al., 2018). As a result, there is increased pressure on available freshwater resources (Gracia et al., 2011). Additionally, growers are under pressure to produce more yield with less inputs (Howes et al., 2014; Mora et al., 2013; Levidow et al., 2014). Improving the overall efficiency and application uniformity of irrigation systems is essential for rational and efficient use of irrigation water and energy. Which in turn is essential for sustainable development (Moreno et al., 2007). Optimizing water management is also crucial for maintaining environmental quality (Leung et al., 2000). Apart from enhancing the environmental quality, optimizing the efficiency of the irrigation system can augment the economic returns of the growers in terms of energy, fuel and costs of inputs like fuel, fertilizers etc.

CHAPTER II

THE EFFICIENCIES, COSTS AND ENVIRONMENTAL IMPACTS OF ENERGY CONSUMPTION FOR GROUNDWATER-BASED IRRIGATION IN OKLAHOMA

Abstract

Irrigation systems in the central and north west Oklahoma were tested with the aim of determining their energy consumption efficiencies. The pumping plants tested were broadly divided into two categories: electricity powered pumping plant and natural gas powered pumping plants. The energy consumption efficiency is a function of overall pumping efficiency (OPE). The actual Overall Pumping Efficiency (OPE) of the pumping plants were evaluated and compared against two widely used standards: The Nebraska Pumping Plant Performance Criteria (NPPPC) (Krantz, 2010) and the efficiency classification developed by the Center for Irrigation Technology (CIT) at California State University-Fresno. The average OPE was found to be 43.3% and 13.6% for electricity powered irrigation pumps and natural gas powered irrigation pumps respectively. These averages were much lower than the recommended NPPC standards. Life cycle assessment (LCA) was also performed to quantify the environmental burdens of operating the pumping plants.

1. Introduction

Irrigated agriculture around the world relies heavily on energy resources to extract freshwater and to convey it to application sites. This is especially the case in arid/semi-arid regions, where large amounts of irrigation supplies are required to sustain crop production. As a result, the availability and cost of energy are among major factors impacting the economic viability of irrigated agriculture in these regions. In addition, energy consumption for irrigation has major environmental consequences, mainly due to the emission of greenhouse gasses (Khan et al., 2014; Pradeleix et al., 2015). Wang et al., 2012 reported that pumping groundwater for irrigation accounted for 3% of total emissions from agriculture in China. A similar study in Iran found that groundwater pumping was responsible for 3.6% of total carbon emissions in the country (Karimi et al., 2012). In India, groundwater pumping lead to emission of nearly 6% of India's total GHG emissions(Shah, 2009). In the US, carbon emissions due to pumping irrigation water were reported to be about 3 MMTC/yr (Follett, 2001).

Energy consumption and its associated energy/maintenance costs and greenhouse gas emissions can be reduced by improving pumping efficiency (Patle et al., 2016). In a study in central Tunisia, Luc et al. (2006) found that improving pumping efficiency could result in 33% cost reduction on average. An average cost saving of 17% following efficiency improvement was also reported by Mora et al. (2013) for an irrigated area in southeastern Spain. Pump efficiency is primarily dependent on the operating conditions such as the total dynamic head (TDH) and the condition of the pump. Any deviation from the optimum conditions can lead to reduced efficiency and increased expenditure and emissions.

One deviation from the optimum conditions is the change in the TDH, caused by declines in groundwater levels. This is especially the case in irrigated areas that rely primarily on deep groundwater resources. In these areas, depth to groundwater accounts for a significant portion of the TDH. In the North China Plain, Qui et al. (2018) estimated that groundwater declines from 1996 to 2013 has led to 22% increase in energy consumption and 42% increase in greenhouse gas emissions. Increases in the groundwater depth will not only increase the TDH and consequently energy use (Griffiths et al., 2009), but will also result in a gradual deviation from design parameters used in selecting the most efficient pump and hence a reduction in system efficiency.

Irrigated agriculture in Oklahoma has been facing similar energy-related challenges. In 2013, Oklahoma producers spent over USD 22 million to power more than 5,300 pumps (Taghvaeian, 2014). Electricity was the main source of pumping energy, supplying water to 46 percent of all irrigated areas in the state. This was closely followed by natural gas, which powers pumps to irrigate 42 percent of all irrigated lands (Taghvaeian, 2014). Thus, identifying energy consumption efficiencies and practices that can improve them will have a considerable impact on the profitability of agricultural production in Oklahoma. In addition, Oklahoma producers who rely on groundwater resources have been experiencing a decline in water availability, reflected in a reduction in average well capacities from 0.032 m^3 sec^{-1} in 2008 to 0.026 m^3 sec^{-1} in 2013 (Taghvaeian, 2014). The groundwater decline has been more significant in the Panhandle region and during drought periods.

The overarching goal of this study was to identify the efficiency of irrigation pumping plants in agricultural regions of central and western Oklahoma that rely on groundwater resources. The more specific objectives included: i) to conduct energy audits and estimate the overall pumping efficiency for a representative number of plants in Oklahoma; ii) to study greenhouse gas emissions and other associated environmental impacts of energy consumption for irrigation; and, iii) to investigate the impacts of variable depth to groundwater on the efficiencies, economics, and environmental footprint of pumping plants.

2. Materials and Methods

2.1 Study Area

A total of 24 irrigation pumping plants in central and north western Oklahoma were tested between 2015 and 2018 with the aim of determining their energy consumption efficiencies. Of the pumping plants evaluated, fourteen were located within the Ogallala aquifer and ten within the Rush Spring bedrock aquifers (Fig. 1). The Ogallala sites were all natural gas internal combustion powered and the Rush Spring sites were electricity powered pumping plants. The Ogallala aquifer is one of the most important aquifers in Oklahoma, supplying more than 98% of the total water demand in the Panhandle regions (Taghvaeian et al., 2016). The Rush Spring is another important bedrock aquifer in the state and provides irrigation water to numerous fields in central Oklahoma. The depth to groundwater is much larger in Ogallala and it has experienced a steady decline over the past several decades, while the Rush Spring is shallower and more sensitive to inter-annual variations in precipitation (Taghvaeian, 2014).

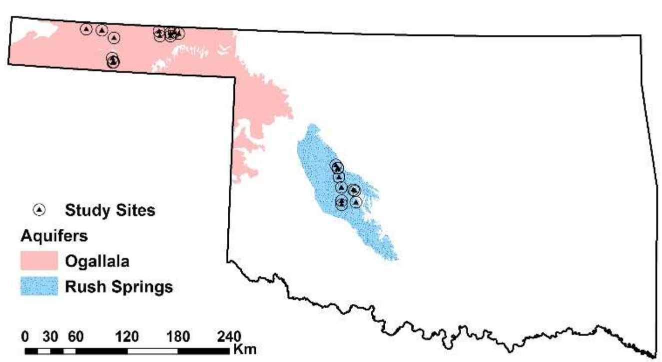

Figure 1. Location of tested systems across western Oklahoma

2.2 Energy audit

The energy audits included determining several basic irrigation well and pump parameters such as depth to groundwater, water pressure, and discharge rate. These parameters were then used to estimate the Overall Pumping Efficiency (OPE), a widely used metric for assessing the efficiency of irrigation systems. The OPE is the ratio of the output work the pump exerts on the water at the pump outlet, known as water power (WP), to the required energy input or energy horsepower (EHP) of the driving unit required to pump the measured water output (Brar et al., 2017) and is calculated as:

$$OPE = \frac{Water\ output\ (WHP)}{Energy\ input\ (EHP)} \times 100 \tag{1}$$

The WHP (kW) can be determined as:

$$WHP = \frac{Q \times TDH}{F} \tag{2}$$

where Q is the discharge rate ($m^3\ sec^{-1}$), TDH is the total dynamic head (m) and F is a conversion factor equal to 0.102 ($m^4\ sec^{-1}\ kW^{-1}$). In this study Q was measured using an ultrasonic flow meter (Portaflow-C, Fuji Electric Co., Japan) on the discharge pipe from the pump. The accuracy of the ultrasonic flow meter was tested previously against a calibrated flow device and found to be acceptable (Masasi et al., 2017).

The TDH is the total equivalent pressure that must be applied to the water column being pumped while also taking into account the losses due to friction (Brar et al., 2017). In this study the friction losses in the pipe have been estimated and added to the measured lift term:

$$TDH = pumping\ lift + pressure\ head \tag{3}$$

where, pumping lift is the vertical distance between the pumping water level and center of the pump outlet (m) and pressure head is the pressure required at the pump outlet (m). The pumping lift was measured by lowering a water level meter (model 102, Solinst Canada Ltd., Canada) probe 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 (Frazier et al., 2017).

The estimation procedure for EHP depends on the type of energy used and differs among electric motor in the Rush Spring aquifer region and natural gas engine driven pumps in the Ogallala aquifer region.

2.2.1. Electric motors

Electric motor driven irrigation pumps tend to be used where the ground water depth is less than 80 meters and three-phase power is available. These pumps usually require less maintenance and operational activity than internal combustion engines. For electric motors the energy input (kW) is the electrical power supplied to the motor and can be calculated using the following equation for a three phase motor:

$$EHP = \frac{V \times I \times PF \times 1.732}{1000} \tag{4}$$

where V is voltage (V), I is current (A), PF is power factor, and 1.732 is a conversion factor. In this study V, I and PF were measured using 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.

2.2.2. Natural gas engines

The natural gas consumption of the internal combustion engines was measured by a rotary gas meter (Dresser Roots® Series B, General Electric, Boston, MA, USA). The gas meter was installed by turning off the gas supply to the engine at the gas meter. The main fuel line running to the intake manifold was disconnected and the rotary meter was installed in-line with this gas line which was then reconnected to the engine. The engine was allowed to run until in steady state operating temperature. The irrigation water pump was also allowed to bring the entire irrigation system up to operating pressure (water delivery from all nozzles). The engine and pump system were allowed to run for 30-45 minutes at which time average fuel consumption readings and correction factors were recorded. Removing the rotary meter was the reverse of installation procedure.

The meter auto-corrects for gas pressure, density, and temperature. The display gives readings of cubic feet per minute, which were converted to Btu per hour which is converted to mechanical power MJ/hr. This is a measure of the input "fuel power".

The estimated OPE of the audited pumping plants was compared against two widely used benchmarks: the Nebraska Pumping Plant Performance Criteria (NPPPC) and the efficiency classification developed by the Center for Irrigation Technology (CIT) at California State University-Fresno (Hanson, 2002). According to NPPPC, the OPE of accurately designed and appropriately maintained electricity- and natural gas-driven pumping plants should be 66% and 17%, respectively (Ross and Hardy 1997).

2.3. Life cycle assessment

The greenhouse gas (GHG) emissions for the pumping sites were calculated using the GREET® (GREET.NET version 2017, Argonne National Laboratory, Argonne, IL, USA) and the U.S. Environmental Protection Agency (EPA) Greenhouse Gas Inventory Guidance (Greenhouse Gas Inventory Guidance, United States Environmental Protection Agency (EPA), 2016). While the GREET model is basically a transportation Life Cycle Assessment (LCA) analysis tool, it can provide an accepted approximation for examining fuels and energy production from extraction and processing (well) to end-use (pump). This technique in GREET is called "Well to Pump"

(WTP). The WTP approach calculates GHG emissions during the production, transmission and distribution stages of electricity.

In the case of electricity where end-use is essentially emission free for both stationary and vehicle uses, the WTP model can be used for stationary irrigation pumping plants without the need for any modification. The U.S. Central and Southern Pains Utility Mix category was chosen to best represent grid electricity composition for Oklahoma. The emissions were calculated for 1,000 hours of irrigation system operation. In the case of natural gas, GREET "Well to Pump" (WTP) greenhouse gas analysis (extraction, transmission through pipes, distribution) is added to an EPA stationary engine emissions calculation technique to give an approximation of the total GHG emissions for stationary engines.

The EPA end-use GHG estimation for natural gas methodology employed was based on using the natural gas volume consumed and measured during the field tests with the gas flow meter. The methodology is as follows:

$$Em = Fuel \times HHV \times EF \tag{5}$$

where Em is the mass of CO_2, CH_4 , or N_2O emitted, Fuel is the mass or volume of fuel combusted, HHV is the fuel heat content (higher heating value) in units of energy per mass of fuel, and EF is the emission factor of CO_2, CH_4, or N_2O per energy unit. The HHV and EF values reported in (Greenhouse Gas Inventory Guidance, United States EPA, 2016) for natural gas combustion were used in this study. For the total GHG emissions from combustion, the CO_2 equivalence factors of 25 for CH_4 and 298 for N_2O were applied. Similar to electric motors, the emissions were reported for 1,000 hours of irrigation system operation.

2.4. Long-term trends

Since irrigated agriculture in the study area relies heavily on groundwater, it is of great importance to investigate the impacts of long-term fluctuations in groundwater levels on efficiencies, emissions, and economics of irrigation pumping. The first step to conduct this analysis was to estimate variations in energy requirement in response to changes in groundwater depth for each of the studied aquifers (Ogallala and Rush Spring). Several previous studies have investigated energy required for pumping groundwater as a function of depth to groundwater (Rothausen et al. 2011, Karimi et al. 2012, Patle et al. 2016, and Shahdany et al. 2018). These studies have used the following equation or a variation of it, which was also selected in the present study and applied to estimate annual energy requirement over the 17-year period from 2001 to 2017:

$$Energy = \frac{TDH \times M \times g}{3.62 \times 10^{6} \times OPE} \tag{6}$$

where energy is in kWh, M is the total mass of groundwater pumped for irrigation (kg), g is the gravitational acceleration (9.8 m sec^{-2}), and other parameters have been defined before.

Since actual long-term TDH data for audited systems were not available, this parameter was approximated through developing a linear regression model to predict TDH from groundwater depth (GWD) based on the data collected during energy audits. The assumption was that GWD is by far the largest portion of TDH, especially since all tested center pivot systems were mid-elevation spray application type and thus required significantly lower operating pressures compared to traditional center pivots. The close proximity of irrigation wells to irrigation systems meant that pressure losses during water conveyance were fairly small too. Once this relationship was developed it was applied to the average annual GWD, estimated during the 2001-2017 period based on the readings reported by the Oklahoma Water Resources Board (OWRB) at 42 and 22 observation wells in the Ogallala and Rush Spring aquifers, respectively.

The discharge rates obtained during the energy audits were averaged for each studied aquifer and used in obtaining M, assuming 1,000 hours of system operation per year. The OPE was estimated in a similar fashion, assuming that the average OPE of audited systems in each region is a reasonable representative of the average OPE of all systems in that region. In addition, this average OPE was assumed to remain constant over the studied long-term period (2001-2017). For natural gas powered pumping plants the energy use rate was converted from kWh to MJ. Variations in groundwater depths also influences the energy use and the GHG emissions.

3. Results and Discussion

3.1. Energy audits

The measurements made at audited sites showed significant differences among Rush Spring (RS) and Ogallala (OG) aquifers. The average static groundwater depths (GWD), for instance, was 24.4 and 79.7 m for RS and OG, respectively. Barefoot (1980) tested 13 natural gas irrigation pumping plants in the Oklahoma Panhandle region (OG) and reported a similar average pumping lift of 80.4 m. The average dynamic GWD, measured 15 minutes after starting the pump, was 30.7 and 89.1 m for the same aquifers, respectively. The measured water pressure was larger for irrigation systems in RS, resulting in a smaller difference in TDH compared to GWD. The average TDH was 67.8 and 105.9 m for the RS and OG aquifers, respectively.

The difference in TDH was accompanied by a corresponding difference in input energy. With an average value of 270 kW (362 Hp), the input power requirement in OG was nearly five times larger than the RS region with an average 56 kW (75 Hp). This probably explains the preference of natural gas engines over electric motors as an energy source for powering OG pumping plants since large electric motors have specific wiring and utility constraints. The water discharge rates were similar in the two study regions, with average values of 36.2 and 36.0 l sec^{-1}

for RS and OG aquifers, respectively. The average discharge reported by Barefoot (1980) was 47.9 in the OG aquifer region, about 33% larger than the value found in the present study.

The overall pumping efficiency (OPE) of the sites in the RS aquifer region (electricity powered) varied from 24.9% to 62.6%. Of the ten pumping plants evaluated, nine had an OPE below 56% and fell under the low rating category according to the CIT classification. Seven plants had OPE less than 50%, which was proposed by Hanson (2002) as the threshold below which repairing or replacing the plant should be considered. All of the systems had efficiencies smaller than the recommended OPE of 66% by the NPPPC standard. The average OPE for the RS region was 43.3%. The difference between estimated OPE and NPPPC standard implies that nearly 23% of electrical energy is wasted on average due to poor efficiency of the pumping plant in the RS region. The average OPE in this study compares well with the average OPE of 42.6% reported by Fipps et al. (1995) and 47.0% reported by New and Schneider (1988) for pumping plants in the High Plains and Trans-Pecos areas of Texas. The range of efficiencies in New and Schneider (1988) was also similar to this study with values varying from 16.8% to 70.6%. However, DeBoer et al. (1983) reported larger average OPE of 58% in for electricity-driven pumping plants in west central Minnesota, North Dakota and South Dakota. The plants tested in DeBoer's study were fairly new, with 74% being less than six year old, which could be the cause of relatively higher efficiency.

The OPE of the natural gas powered pumping plants in the OG aquifer region ranged from 5.7% to 21.4%. Out of 14 audited pumping plants, ten had an OPE less than the NPPPC recommended standard of 17% for natural gas internal combustion engines. The average OPE for the OG region was 13.6%, close to average OPE of 13.2%, 11.7%, and 13.1% reported for natural gas powered pumping plants in Oklahoma and Texas by Barefoot (1980), New and Schneider (1988), and Fipps et al. (1995), respectively. The range of OPE in New and Schneider (1988) was 2.2-21.6%, similar to the range of OPE estimated in the present study.

Linear regression analysis conducted on data collected at each site and combined revealed that there was no significant relationship between OPE and the two aquifer parameters of TDH and discharge rate (p values larger than 0.37). This suggest that the performance of audited systems was impacted by other factors such as the age and condition of the pumping plants. Small sample sizes of systems tested may have also contributed to the lack of correlation.

Table 1. Average values of main characteristics of studied irrigation pumping plants in the Rush Spring (RS) and Ogallala (OG) study areas

Parameter	RS	OG
Static groundwater depth (m)	24.4	79.7
Dynamic groundwater depth (m)	30.7	89.1
Total dynamic head (m)	67.8	105.9
Discharge (l sec^{-1})	36.2	36.0
Overall pumping efficiency (%)	43.3	13.6

3.2. Life Cycle Assessment

The LCA of electric motor pumps examined the emissions at the electric generation stations The total GHG emissions for these pumping plants ranged from 29 to 54 metric tons of CO_2 (t CO_2-eq) and averaged 41 t CO_2-eq for 1,000 hours of pump operation.

The LCA of natural gas driven pumps examined the emissions from natural gas extraction, processing, storage, transportation and end-use at the irrigation site. As mentioned before, a two-part analysis that used GREET WTP and EPA emissions calculations for stationary engines was carried out. The energy required by natural gas powered pumping sites for pumping groundwater ranged from 527,528 MJ to 1,543,969 MJ for 1,000 hours of pump operation. The total GHG emissions from these sites averaged 79.25 (tons) CO_2-eq and ranged from 68.1 t to 112 t CO_2-eq. Compared to electricity powered pumping sites, the energy required and total GHG emissions of natural gas powered pumping sites were considerably higher. Part of this is due to the fact that natural gas engine irrigation pumps are used for deeper wells (higher TDH). In China, GHG emissions from groundwater pumping were reported to be 8.72 million metric tons of CO_2 -eq (Qiu et al., 2018). Zou et al. (2013) evaluated GHG emissions from groundwater pumping and surface water pumping in China. The researchers calculated the GHG emissions as a product of energy consumption and emission factor (3.3 t CO_2/ t for diesel and 0.9738 t CO_2/MWh for electric pumps). Groundwater pumping using sprinkler irrigation accounted for 172.63x 10^4 t of CO_2- eq. In Iran, pumping groundwater for irrigation accounted for 3.6% of total carbon emissions of the country (nearly 4.945 million metric tons of carbon) (Karimi et al., 2012). Compared to the US, the OPE in China and Iran is low. This affects the energy consumption and subsequently the GHG emissions. Variation in depth to groundwater also influences the energy use and hence the GHG emissions. Patle et al. (2016) investigated the GHG emissions from groundwater pumping for a variety of crops in Haryana state of India. The TDH of 12m, OPE of 34.7% and emission factor of 0.94 kg CO_2/kWh was used for estimating energy use and CO_2 emissions respectively.

3.3. Long-term trends

Examination of the groundwater depth (GWD) data showed that the Rush Springs (RS) aquifer levels varied between 18.2 and 21.0 m from ground surface over the 17-year period, with a net decline of 1.5 m (Fig 2a). On the other hand, the Ogallala (OG) aquifer GWD experienced a steady decline from 56.6 to 62.3 m (Fig 2b). This is due to the fact that OG is deeper than the RS and has significantly smaller recharge rates. As a result the RS aquifer experienced an increase in groundwater level during wet periods in 2005, 2007 to 2009 and 2015-2017, while no rise in water level was observed in OG. The rate of decline in water level was much greater during the drought years of 2011-2014 compared to wet and normal years for both aquifers.

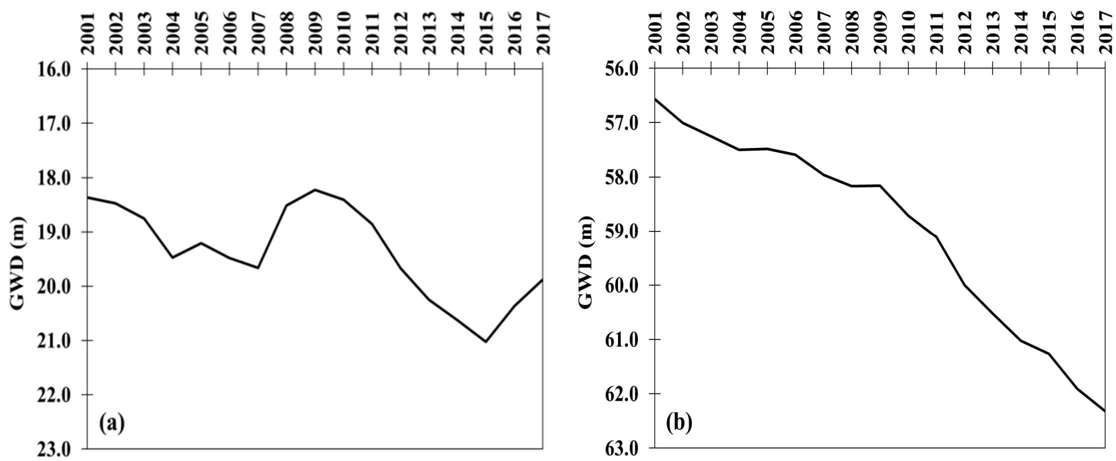

Figure 2. Annual average groundwater depth (GWD) for the Rush Spring (a) and Ogallala (b) aquifers.

The linear relationship developed based on TDH and GWD measurements at audited sites is presented below:

$$TDH = 0.67 \times GWD + 53.76 \tag{7}$$

The relationship was statistically significant and had a large coefficient of determination ($R^2 = 0.78$), suggesting that over three-fourth of variability in TDH could be explained by changes in GWD. A similar approach was employed by Wang et al. (2012), where the slope, intercept, and R^2 were 0.91, 21.75, and 0.62 for a linear relationship between pump lift and GWD.

As expected, the variations in energy requirement during the 2001-2017 period had a pattern similar to that of GWD in each aquifer region. In case of RS, energy requirement for 1,000 hours of system operation per year varied from 53,721 to 55,247 kWh during the 17 years considered and had an average of 54,344 kWh. The energy requirement was much larger at OG and increased over time, with a range of 233,175-242,980 kWh and average of 237,277 kWh (more than four times larger than the average in RS). When considering energy requirements per unit volume (1.0 m^3) of pumped water, RS and OG regions had average rates of 0.42 and 1.84 kWh, respectively. These values are similar to energy use rates of 0.21 to 0.64 kWh m^{-3} reported by Wang et al. (2012) for eleven surveyed provinces in China.

In OG, the increase in energy requirement due to the increase in GWD over the 17-year period was 4% of the initial (2001) amount. Qiu et al. (2018) reported a significantly larger increase of 22% in energy use in China between 1996 and 2013. However, the rate of groundwater level decline in their study was 0.6 m yr^{-1}, two times larger than the drop rate of 0.3 m yr^{-1} observed in the present study. The results also revealed that improving the OPE at each region to achievable levels recommended by NPPPC would result in 34% and 19% reductions in average energy requirement in the RS and OG regions, respectively.

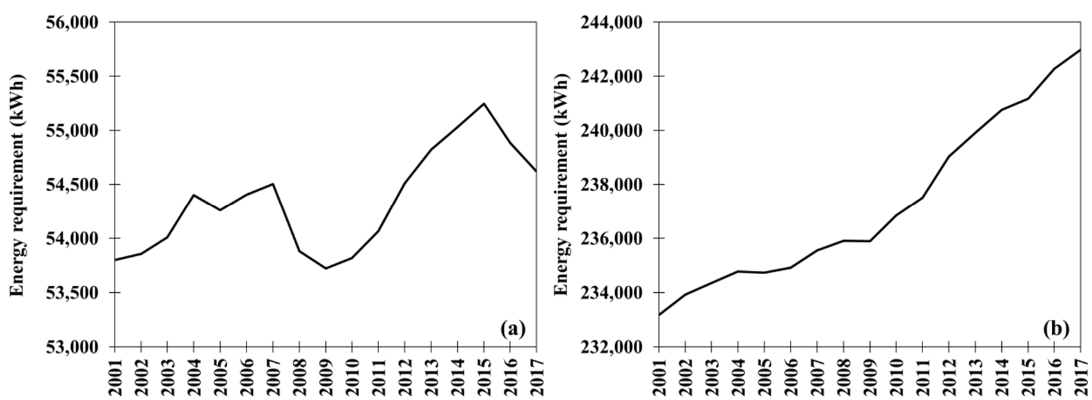

Figure 3. Variations in annual energy requirement for 1,000 hours of operation per year in the RS (a) and OG (b) regions.

The increase in energy use would be directly responsible for an associated increase in total GHG emissions over the study period. A 4.6% increase in energy use rate in the OG aquifer region led to a predicted 14.3% increase in total GHG emissions for every 1,000 hours of operation. In the RS aquifer region, the total GHG emissions and energy use rate would increase by nearly the same amount (i.e. 1.72 %). The total GHG emissions were found to be higher in the OG aquifer region than RS aquifer region due to lower water depths and observed state of tune of many of the natural gas engines (Figure 21). Apart from the groundwater level of the aquifer, the OPE of the system has large influence on the energy use rate and emissions. Improving the OPE of electricity powered pumping sites in the RS aquifer region to NPPPC recommended standard of 66% could on an average reduce total GHG emissions by nearly 52%. Similarly, improving the OPE of natural gas powered pumping sites from an average of 13.75% to NPPPC recommended 17% in the OG aquifer region could potentially reduce emissions by 20%. In India, Patle et al. (2016) reported that improving electric pumping system efficiency (OPE) to 51% from existing 34.7% could lead to a decline in CO_2 emissions by 32%.

3.4. Economic analysis

The economic implications for improving Oklahoma center pivot irrigation system energy efficiencies was also investigated. Irrigation energy costs can be one of the largest categories of costs a producer in Oklahoma will incur over a season (Taghvaeian, 2014). Improving the efficiency of the Oklahoma pumping plants to the NPPPC recommended standards could therefore decrease the current irrigation operating costs.

Based on the audit data, growers in Oklahoma, on an average, spent \$6,194 and \$4,609 for every 1,000 hours of operation of electricity and natural gas-powered pumping sites respectively. Depending on crop rotations etc., many producers will run longer than 1,000 hours.

A significant potential for reduction in the operating costs of pumping plants was predicted if producers could meet the NPPPC standards from their current efficiencies. An average saving based on the 24 irrigation systems tested to date would be, for every 1,000 hours of operation, \$2,190 and \$1,195 for electricity and natural gas powered pumping plants respectively. This is consistent with the findings of Hardin and Lacewell (1979) who reported dramatic decrease in fuel costs and increase in farm profits if OPE of center pivot systems was improved to achievable levels in the Texas High Plains.

Extrapolating a similar trend for the total 3,456 electricity powered and 1,354 natural gas powered pumping plants in Oklahoma and assuming they had similar efficiencies to what the study observed, leads to estimated average savings amounting to approximately $7,600,000 per year for electrical irrigation systems in the state. The total extrapolated savings for natural gas irrigation statewide would be $1,160,000 for every 1,000 hours of operation. Over 20 years this could amount to over $150,000,000 and $22,000,000 in savings for electricity and natural gas powered pumping plants. Again, this is per 1,000 hours of operation and the sample size is limited but the implications are for significant energy cost savings.

Also, the cost of a unit of electricity and natural gas varies over the years. In general, the cost of electricity in Oklahoma has been on a rise. Increasing from $0.061 per kWh in 2001 to $0.078 per kWh in 2017 (U.S. Energy Information Administration (EIA)). Higher variations have been observed in terms of costs of natural gas. The cost ranged from $6.27 to $13.03 per 1,000 cubic feet of natural gas ($/MCF) (U.S. EIA). However, the cost of natural gas has decreased from $7.37/MCF in 2001 to $6.27/MCF in 2017. Considering the depth to groundwater of the pumping sites and the unit cost of electricity, the users in Oklahoma on an average spent nearly 28% more in costs for 1,000 hours of pump operations in 2017 as compared to 2001. The cost increased from $3,464 in 2001 to $4,447 in 2017. The increasing cost of unit of energy and declining depth to groundwater could be the major cause of the incremental costs incurred. In the case of natural gas, a reverse trend was observed in the operating costs from 2001 to 2017. The cost decreased from $5,479 in 2001 to $4,661 in 2017 for every 1,000 hours of pump operations. The rapidly decreasing cost of natural gas was largely responsible for declining operating costs of pumping sites. The effect of declining costs of source of energy was dominant as compared to lowering groundwater levels.

4. Conclusion

Prior to the study, the relative energy efficiency of Oklahoma center pivot irrigation systems over the two main western aquifers (Ogallala and Rush Springs) was unknown. Studies in Texas, Minnesota, North Dakota and South Dakota had shown considerable potential for energy efficiency improvement in these types of systems (New et al., 1988, DeBoer et al., 1983). After three years of testing Oklahoma systems over these aquifers, it appears the potential for improvement is also significant. Improving the efficiency of the Oklahoma pumping plants to the NPPC recommended standards would (on average) decrease the current energy use of these systems.

Hand in hand with decreased energy use is the reduction in irrigation related emissions to air, land and water. In order to determine the approximate emissions savings, Life Cycle Assessments using the GREET® LCA software were performed on each irrigation test and the results shown above. Of particular interest are the greenhouse gas emissions at both fuel or energy production and at the end use (irrigation site).

The economic consequences for irrigation energy efficiency improvement are also shown. The potential savings are significant for producers who operate on small margins. The study also examines the energy, emissions and economic effects of lowering ground water levels in the Ogallala and Rush Springs aquifers over a 16 year span from 2001 to 2017. Because water pumping height is a primary variable in the pumping power relationship, lowering of these aquifers over short time spans produces corresponding higher energy requirements.

Acknowledgment

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CHAPTER III

THE UNIFORMITIES OF GROUNDWATER-BASED IRRIGATION SYSTEMS IN OKLAHOMA AND THEIR ENVIRONMENTAL IMPACTS

Abstract

Keywords: Center pivots; uniformity; catch can; DayCent model, plant production, evapotranspiration, nutrient cycling, and trace gas fluxes

Center pivot sprinkler systems are widely used in the US. Approximately 80% of irrigated farms used center pivots for irrigation in the US. However, sprinkler systems are associated with a degree of water application non-uniformity. This non-uniformity can impact crop yield, evaporation, percolation, transpiration, leaching etc. Irrigation audits were performed in the panhandle and west central Oklahoma from 2015 to 2017 in order to evaluate the uniformities and water application efficiencies of center pivot systems in Oklahoma. The "catch can" method was used to estimate application efficiencies of the systems. Based on the audit's results, three different irrigation treatments (different levels of uniformities- full irrigation (FI), under irrigation (UI), and over irrigation (OI)) were chosen. The DayCent ecosystem model was then used to simulate the impact of non-uniform irrigation on evaporation, transpiration, percolation, nutrient losses, leaching, crop yield etc. for the three different scenarios. The results demonstrate that while over irrigation lead to significant loss of water due to increased evaporation and nutrient loss. Under irrigation lead to reduced crop yield. Based on the modeling

results, we conclude that improving system efficiency is essential to reduce water losses, nutrient leaching, production of greenhouse gases and enhanced crop production.

1. Introduction

Center pivot sprinkler systems were invented over 60 years ago to reduce labor requirements, enhance agricultural production, and optimize water use (Martin, 2011). Today, center pivot systems are the most popular mode of irrigation in the United States of America. Analysis from the USDA farm and ranch irrigation survey show that in 2013, approximately 80% of the irrigated farms used center pivots for applying irrigation water. In Oklahoma, center pivot systems were used on nearly 96% of the irrigated farms. The growers applied more than 170 billion gallons of water for irrigation in Oklahoma (Taghvaeian, 2014).

Center pivots are capable of efficiently and effectively applying controlled amounts of water on different types of soil (Martin, 2011). However, sprinkler irrigation systems are associated with a degree of non-uniformity (Leung et al., 2000). Operation parameters (moving speed, head pressure, etc.), configuration parameters (type of nozzle, pressure regulator etc.) and the condition of the system at the time of operation influence the uniformity of sprinkler irrigation system (Lianhao et al., 2016). Water application uniformity is a measure of the consistency of water distribution over the entire irrigated area. With the rising population and associated crop production, increasing costs of farm inputs such as water, fertilizers, fuel etc. irrigators are under pressure to produce more yield with less water and thus, improve the efficiency of water application uniformity (Howes et al., 2014; Mora et al., 2013; Levidow et al., 2014). Irrigation systems should apply the water uniformly in sufficient quantities without over-watering or generating runoff (Irrigation energy audit manual, 2012). Optimizing water management is also crucial for maintaining environmental quality (Leung et al., 2000). In China, Li et al. (2005) conducted field experiments to study the effect of non- uniform irrigation on crop yield and percolation. Kassem et al. (2009) pioneered research to evaluate the impact of non-uniformities on evaporation, deep percolation, and yield. Previous studies also looked at impact of non-uniform irrigation on transpiration, yield etc. (Doorenbos et al., 1979; Solomon, 1983; Ayars et al., 1990; Asher et al., 1990; Montazar et al., 2008).

1.1 Model Description

DayCent is a daily time step ecosystem model developed from the monthly time step CENTURY model. The model simulates plant production, actual evapotranspiration, nutrient cycling, and trace gas fluxes like CO_2, N_2O, NOx and CH_4 (Parton et al., 1998). It has been widely used to estimate trace gas emissions from irrigated agricultural soils. Del Grosso et al (2008) used the model to predict Nitrous oxide emissions in irrigated tillage systems in Colorado. Cheng et al (2013) and Weiler et al (2018) used DayCent to estimate daily CH4 fluxes from rice cropping system in China and Brazil respectively. In the United States, simulations for nitrous oxide (NOx) emissions from cropped soils were also performed at national level (Del Grosso et al., 2006). Duval et al (2018) investigated the effects of water and nitrogen management on semi-arid sorghum production and soil trace gas flux under future climate using the DayCent model. Hartman et al. (2011) used the model to report the impact of land use change over 120 years on the greenhouse gas exchange rate in the U.S. Great Plains soils. Apart from the trace gases flux, the model has been successfully adapted to simulate crop yield, soil water dynamics, soil organic carbon (SOC), net primary production (the gross carbon influx discounted for plant respiratory costs of growth and maintenance), litter decomposition (Parton et al., 1998; Cleveland et al., 2013; Bonan et al., 2013). However, little information is available on the impact of non-uniform irrigation on water fluxes, nutrient losses, nitrous oxide emissions etc. for cover crops in Oklahoma.

In this study, the field evaluations of irrigation uniformities were combined with their impacts on soil water dynamics using the DayCent model. Thus, the aim of the present study was (i) to evaluate the uniformities and water efficiencies of center pivot systems in Oklahoma, (ii) to analyze the impact of irrigation non-uniformities on the water flux, nutrient losses, leaching and on-site Nitrous dioxide (N2O) emissions using the DayCent model.

2. Materials and Methods

2.1 Study area

A total of 21 center pivot irrigation systems in western Oklahoma were evaluated for uniformities and water efficiencies from 2015-2017 (figure 4). The systems analyzed varied in size, with the shortest center pivot having a length of 124 m (3 spans) and the longest one being 412 m (10 spans). The long term average annual rainfall varies from 438 mm in the panhandle climatic division to 619 mm in west central climatic division.

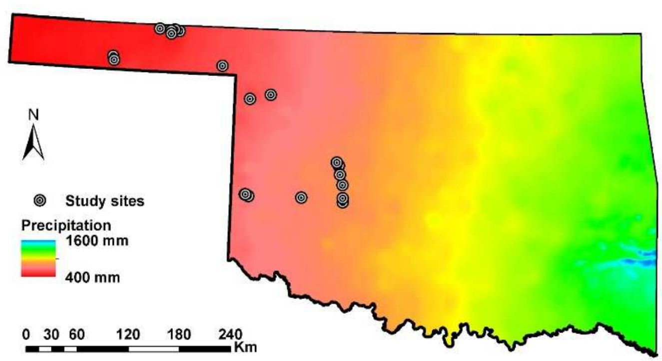

Figure 4. Location of tested systems across Oklahoma

2.2 Water Audits

The global standardized catch-can method (Zhang et al., 2013) was used to estimate center pivot irrigation water application uniformity. For each evaluation, numerous catch-cans were placed on a radius of the irrigated circle at equal distances (3m to 6m). The catch-cans were graduated both in inches and millimeters for direct measurement. The center pivot was allowed to pass completely over the catch-cans while applying water. The amount of water collected in each can was used to estimate the Coefficient of Uniformity (CU) and Distribution Uniformity (DU).

2.2.1. Coefficient of Uniformity (CU)

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

$$CU = 100\% \times [1- \frac{\frac{1}{n}\sum_{i=1}^{n} S_i|V_i - \bar{V}_p|}{\sum_{i=1}^{n} V_i S_i}] \quad (8)$$

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.

2.2.2. Distribution Uniformity (DU)

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

$$DU = \frac{average\ low\ quarter\ depth\ of\ water\ recieved}{average\ depth\ of\ water\ recieved} \times 100 \quad (9)$$

The average low-quartile 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.

2.2.3. Conveyance Efficiency

The conveyance efficiency (CE) is 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:

$$E_c = \frac{V_f}{V_t} \times 100 \tag{10}$$

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 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.

2.3 DayCent Model

The major inputs required for the model are; weather data, soil data and management practices. The weather data like maximum temperature, minimum temperature, and precipitation was obtained from Parameter elevation Regressions on the Independent Slopes Model (PRISM, Oregon State University). The spatial resolution of gridded PRISM data is 4 km (PRISM, 2015). PRISM does not provide information on solar radiation. Information about the soil texture (% of sand, silt, and clay), bulk density and soil pH was obtained from the UC Davis web soil survey. Table (2) describes the soil physical properties (top 20 cm) of the experiment site.

Table 2: Soil physical properties of the experiment site

Depth (cm)	Bulk density (g cm^{-3})	% Sand	% Clay	Field capacity (FC) (volumetric)	Wilting point (WP) (volumetric)	pH
210	1.23	0.35	0.31	0.33	0.14	7.2

The simulation was performed in three stages. First stage was the equilibrium stage. DayCent divides the soil organic matter into three pools based on turnover time i.e. active pool (2-4 years), slow pool (20 to 50) and passive pool (800-1200) (Parton et al., 1987). As it is difficult to establish the carbon content in these pools (the exact values are not available), the equilibrium run is performed to establish initial soil carbon values. A spin up period of 4,000 years considering grassland was used. The equilibrium stage was reached once the soil carbon in all three pools stabilized.

Second stage was the base stage. It was simulated from the years 1980-2000. Data on the management practices adopted in Oklahoma during base years was collected from the Oklahoma Panhandle research and extension center. Two different field crops: sorghum (Sorghum bicolor) (1980-1990) and corn (Zea mays) (1991-2000) were input in the model. Conventional tillage practices were considered. Disks point chisel tandem disks and cultivator were used before planting. Nitrogen fertilizer (100% ammonia) was applied in a single application before planting the crop. The amount of fertilizer used was 27.7 g/m2 in the initial years and then increased to 29.9 g/m2 in the years 1996 to 2000. Automatic irrigation was set to irrigate the field whenever the available water holding capacity dropped below 75%, beginning a day after planting until the end of the growing season. The amount of water to be applied was specified as 3.2 cm. The crop yields values were compared with National Agricultural Statistics Service (NASS) county level yield data. For the years selected for comparison, NASS does not distinguish between irrigated and non-irrigated yield in the county of experiment.

The third stage was the experiment simulation from 2000 to 2017. For this period, the tillage practice was changed from conventional tillage to no tillage. To account for the change in the type of tillage the amount of fertilizer was increased by 10% in the first three years. After this time period, the amount of fertilizer was kept the same as the base simulation. The irrigation amount was also maintained the same as the base simulation. Beginning at 2015, variations in the irrigation rates were incorporated in the model. Three different types of irrigations i.e. full irrigation, under irrigation and over irrigation were implemented, keeping all other management practices like the amount of fertilizer, tillage practices etc. constant. The variations in the irrigation amounts were based on averages from the water audits results conducted in the Ogallala aquifer region. Under full irrigation, automatic irrigation was applied whenever the available water holding capacity dropped below 50%. The irrigation event lasted till the field was irrigated to field capacity. This process started a day after planting and was continued till the end of growing season. The highest, lowest and average rates of water application were determined for each site. Following this, the ratio of highest and lowest application to average application was calculated for each site. The average value of the ratio of highest application to average application and of lowest application to the average application for all the sites was chosen as high irrigation treatment and low irrigation treatment respectively. Table (3) below provides additional information on the irrigation treatments.

Table 3: Description of irrigation treatments

Treatment	Irrigation

Full irrigation (FI)	Irrigate to field capacity when soil moisture drops below 50% of total available water
Over irrigation (OI)	2.01×FI
Under irrigation (UI)	0.43×FI

Water fluxes such as evaporation, transpiration, percolation etc. under different irrigation treatments were analyzed using the DayCent model. The model uses the "tipping bucket" approach and Richard's equations for movement and re-distribution of water within the soil respectively (Parton et al., 1998). The model predicts the daily water balance using the following equation:

$$\Delta Si = P + Inet - ETc - RO - DP + GW \quad (11)$$

where, $\Delta S\boldsymbol{i}$ is the net change in soil water at the end of day i and i-1, *P, RO*, and *DP* are precipitation, runoff, and deep percolation on day i, respectively. Inet is the net irrigation on day i. *GW* is the ground water contribution if a shallow water table is present. *ETc* is the actual evapotranspiration on day i (DayCent user's manual, 2017). Transpiration is the function of the relative water content fraction of the wettest soil layer (Parton et al., 1998). Nutrient losses and nitrogen oxide emissions due to non-uniform water application were also assessed.

3. Results and Discussion

3.1 Water Audit

The water audits were performed by calculating the two uniformity indicators: CU and DU. The calculated values of CU and DU were then compared against the recommended standards. High variations in the performance of the systems were observed. The variations could be due to widely different pump operating conditions, clogged nozzles, differences in system pressures etc. While the system with highest uniformity had CU of 94% and DU of 31%. The system with lowest uniformity had CU of 31% and DU of 14% only. Graphs (5a & 5b) below demonstrate the variations in can collections of the systems with highest and lowest uniformities.

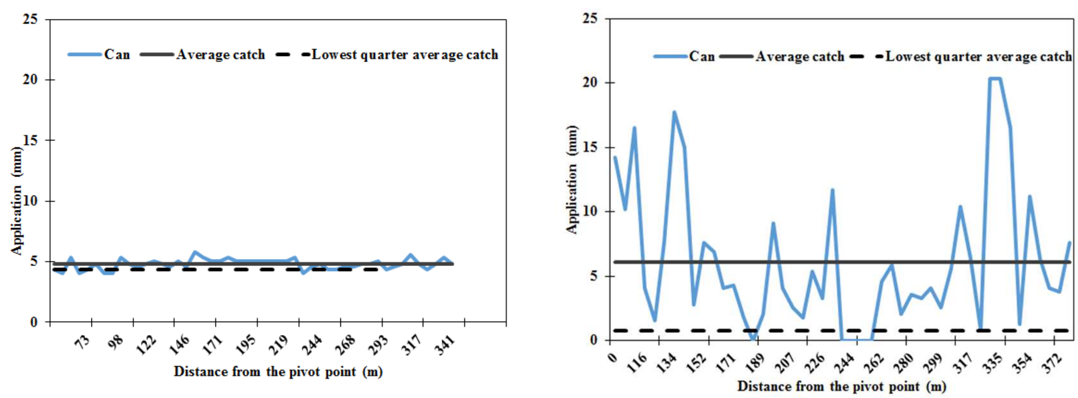

Figure 5: Systems with highest (a) and lowest (b) uniformity, respectively

The CU of all the plants evaluated in Oklahoma ranged from 31% to 94%. Overall, the average CU was estimated to be 79.8%. Although the average CU falls under the poor category according to the classification, it compares well with 78% reported by Henggeler et al (2009) for the irrigation systems tested in Missouri. Of the twenty one plants evaluated only 24% had excellent performance, i.e. had a CU rating in the 90%-95% range. Nearly 33% of the systems had poor application uniformity (figure 6).

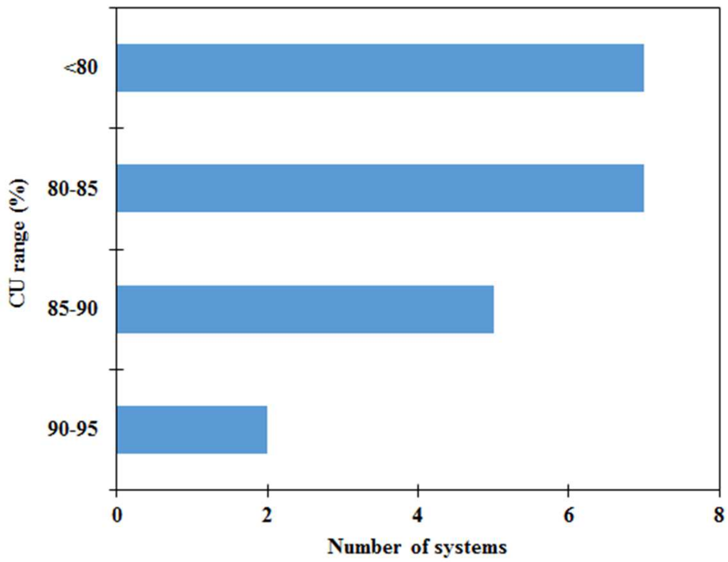

Figure 6: Efficiency Distribution of CU

The distribution uniformity performance fared worse than the coefficient of uniformity performance with an overall average of 71.1%. The average DU is much below the recommended standards. In South Africa, Ascough et al. (2002) reported average DU of 81.4%. Higher variation in the DU performance was observed with lowest being 14% and highest being 88%. Only 14% of the total plants evaluated had excellent performance, i.e. had a DU rating greater than 85%. A significant number, nearly 19% had DU rating less than 65% and fell under the poor and unacceptable performance category (figure 7).

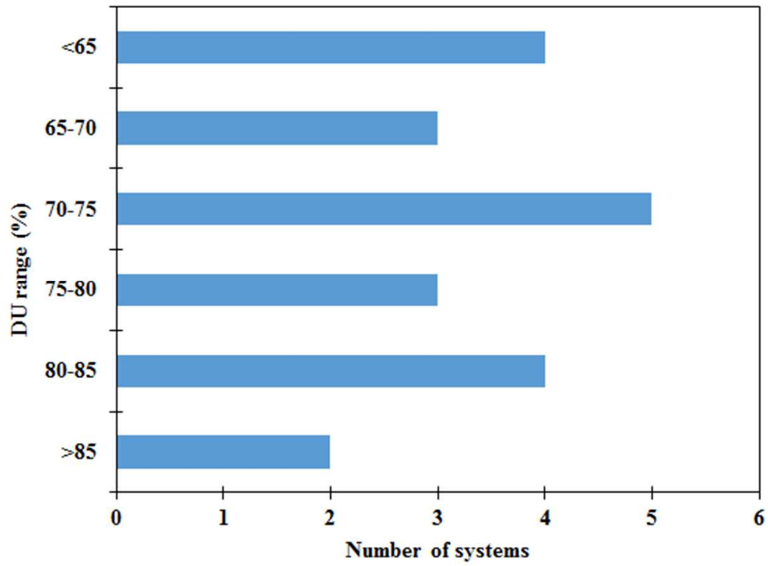

Figure 7: Efficiency Distribution of DU

3.1.1 Water conveyance efficiency

The water conveyance efficiency of most pumps ranged from 85%- 100% (figure 8). Even though the percentage loss might appear insignificant, reducing or eliminating this amount of water loss will result in supplying more water at proper pressures to the field. The average WCE of all the systems was reported to be 94%.

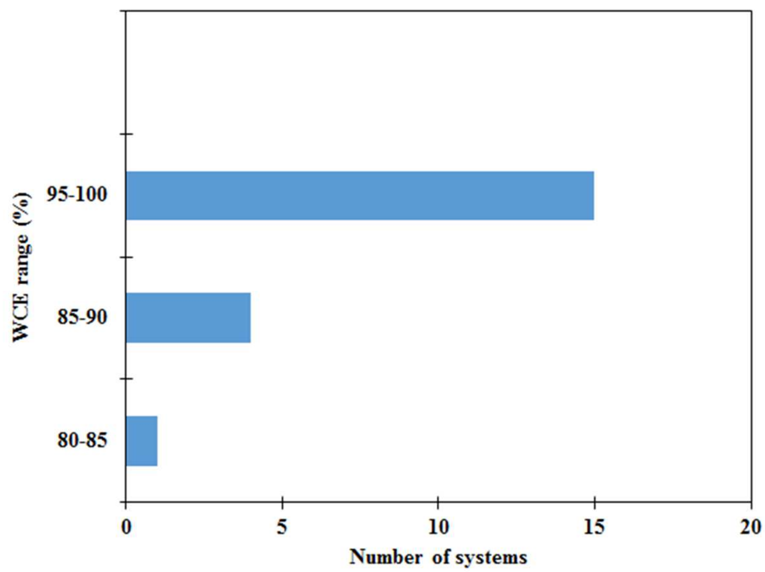

Figure 8: Efficiency Distribution of WCE

3.2 DayCent simulation results

3.2.1 Water fluxes results

Variations in the rates of evaporation, transpiration and percolation were observed under different irrigation treatments. The evaporation rates ranged from minimum 0.002 cm/day to maximum 0.124 cm/day under UI and OI respectively. The average cumulative evaporation for all three years was reported to be 23.93 cm, 23.05 cm, and 21.9 cm for OI, FI, and UI respectively. Compared to 2015 and 2017, the simulated rates of evaporation under all treatments were higher in the year 2016. Although the irrigation scheduling and amounts were similar under different treatments for all three years, the higher average temperature (PRISM) for 2016 could be the cause of higher evaporation rates. In a similar study conducted in Saudi Arabia, air temperature had highest effect on the water losses due to evaporation. The level of irrigation uniformity did not affect the outputs as much as temperature (Kassem, 2009). The transpiration rates ranged from 0.003 cm/day to 0.583 cm/day. The average cumulative transpiration over three years was estimated to be 73.18 cm, 73.11 cm, and 68.54 cm for OI, FI, and UI treatments respectively. Transpiration is affected by water stress. Increased water stress leads to stomatal closure, thereby reducing the transpiration (Hsiao, 1973). Under UI treatment, water stress was induced and the transpiration rate was observed to be significantly lower in comparison to FI and OI. The transpiration rates under FI and OI treatments were similar and not affected much because of no water deficiency. Similar findings were reported in a study conducted in San Joaquin Valley, California (Asher et al., 1990). The researchers performed field experiments using different levels of irrigation uniformities (different CU) to determine the impact of non-uniformities on transpiration and deep percolation. Transpiration rates were found to reach maximum when the water application reached maximum (and vice versa). In our study, percolation to deep storage was also analyzed. The cumulative water flux to deep storage under OI was nearly 3.5 times and 1.66 times higher than UI and FI respectively. Asher et al (1990 a) and Kassem (2009) also highlighted that higher irrigation uniformity lead to smaller deep percolation. Li et al (2005) reported that sprinkler uniformity had minor effects on deep percolation. The increased clay content below 40 cm depth of soil was reported to be the reason for this observation. Figure (9) illustrates the cumulative evaporation, transpiration and percolation under FI, UI and OI over three years.

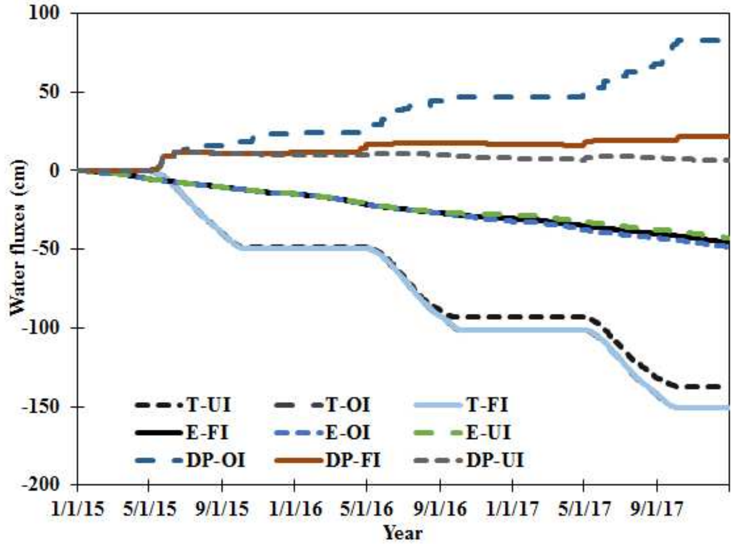

Figure 9: Cumulative transpiration, evaporation and deep percolation under different treatments

3.2.2 Nutrient losses and leaching

Intensive irrigation stimulates rapid movement of nutrients beyond the root zone (Endelman et al., 1974). Sprinkler uniformity also impacts the concentration of nutrients and leaching (Li et al., 2005; Brito et al., 1982). At the end of our study, the NO_3 concentration in the soil profile under UI treatment was found to be the highest. It was nearly 18 and 154 times higher than FI and OI respectively. Treatment OI with highest irrigation and non-uniformity had the highest loss of NO_3 from the soil profile. Spatial distribution of NO_3 in the soil layers was not taken into account. Similar observations were made for the concentration of ammonium (NH_4) in the top 10 cm of the soil profile. The NH_4 concentration under UI was 4.5% higher than FI and 9.4% higher than OI. Figures (10&11) show cumulative NO_3 concentration and NH_4 concentration in the last and top 10 cm of the soil layer.

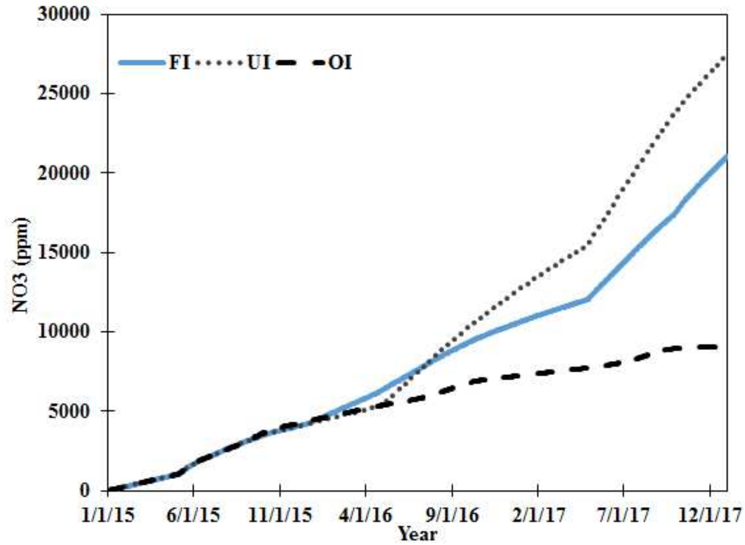

Figure 10: Cumulative NO_3 concentration in last soil layer under different treatments

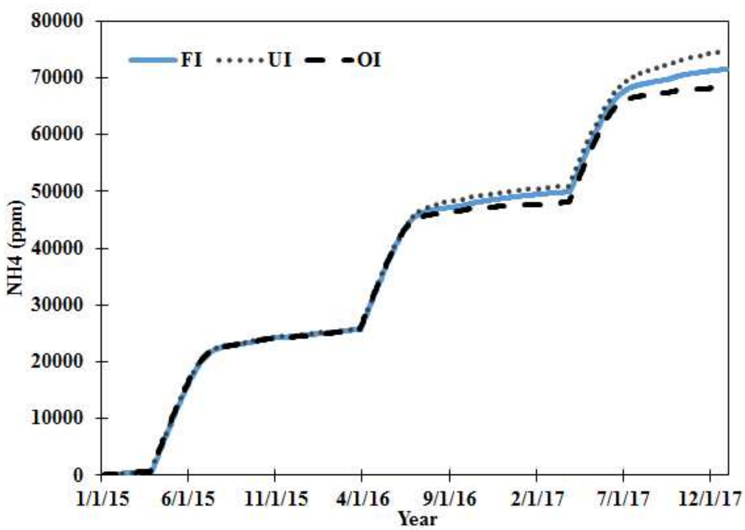

Figure 11: Cumulative NH_4 concentration in top 10cm under different treatments

The daily organic N leached at our experiment site ranged from 0.006 g N/m^2 to 0.09 g N/m^2. A significant difference in the amounts of N leached under different treatments was observed. The average cumulative organic N leached under OI was 90% higher than UI and 69% higher than FI. The results are in agreement with previous findings that better uniformity leads to lower leaching (Brito et al., 1982). In addition to uniformity, leaching was also impacted by precipitation. The lower average rainfall in 2016 (1.126 mm) as compared to 2015 (2.143) and 2017 (1.65 mm) was responsible for smaller leaching in 2016 (PRISM).

3.2.3 Crop yield

The impact of water management practices on the crop yield was also analyzed. The average yield over three year was estimated to be 12,441 kg/ha, 14,526.23 kg/ha, and 14,458 kg/ha for UI, FI, and OI treatments respectively. Water deficit or waterlogging caused due to poor uniformity affects the crop yield (Doorenbos et al., 1979; Solomon, 1983). The crop experienced water stress in UI treatment. The water available for plant growth in the soil profile under UI was 21% and 15% less than OI and FI respectively. Very negligible difference in the yield was observed under FI and OI treatment. Although, the water available in the soil profile was maximum under OI treatment, the crop yield is also affected by a variety of other factors such as the amount of nutrients available, aeration etc. As such, the decrease in the concentration of nutrients like NH_4 and NO_3 could be responsible for smaller yield under OI treatment. Previous studies have also reported a minor impact of non-uniformity on crop yields (Mateos et al., 1997; Li et al., 2005; Kassem, 2009). Factors like depth of irrigation, total nitrogen content, nitrogen uptake etc. had dominant effect than irrigation uniformity. However, some studies have indicated that better uniformity enhances crop yield (Ayars et al., 1990; Montazar et al., 2008).

3.2.4 N_2O emissions

Reduction of NO_3- or NO_2- to gaseous N oxides by bacteria is known as denitrification. A sufficient amount of organic matter is critical for the process of denitrification. Components like soil nitrate concentration, soil texture, soil bulk density, volumetric field capacity, heterotrophic CO_2 respiration rate, and soil water filled pore space are used to calculate denitrification in the model (DayCent manual). The yearly N_2O emissions were calculated. Corresponding to varying irrigation uniformities, variations in emissions were observed beginning from year 2015. The average NO_3 concentration in the soil layers with maximum bacterial activity (up to 30 cm) was examined. The average NO_3 concentration in the UI treatment was 70 and 274 times higher than the FI and OI treatments respectively. The N_2O emissions were highest for the FI treatment. The UI treatment had the smallest emissions.

4. **Conclusion**

The irrigation uniformities of the systems tested show significant potential for improvement. The average CU and DU were reported to be 79.8% and 71.1 % respectively. The average WCE was 94%. Although the average WCE appears to be high, significant amount of water can be conserved if it is improved. In this study, the major impacts of non-uniform irrigation on the crop production, water fluxes, nutrient losses etc. were observed. The average cumulative transpiration was reported to be highest under OI treatment. The average cumulative evaporation for all three years was reported to be 23.93 cm, 23.05 cm, and 21.9 cm for OI, FI, and UI respectively. The cumulative water flux to deep storage under OI was nearly 3.5 times and 1.66 times higher than UI and FI respectively. Treatment OI with highest irrigation and non-uniformity had the highest loss of NO_3 from the soil profile. The average yield over three year was estimated to be 12441 kg/ha, 14526.23 kg/ha, and 14458 kg/ha for UI, FI, and OI treatments respectively.

This is important because the irrigation auditors observed that producers with low water application uniformities (CU and DU) tended to over-water the field in order to bring the areas of low water application up to some acceptable crop production. This in turn, leads to over-watering other areas of the field. In essence, a low uniformity field often experiences aspects of OI, FI and UI simultaneously. The corresponding low crop production, nutrient loss, soil outgassing and over-use of water can occur in a single irrigated field. The aggregate effect of many irrigated fields in this situation can have significant impacts for agricultural areas.

CHAPTER IV

CONCLUSIONS

A substantial potential for improvement in the OPE and application uniformities was observed for the irrigation systems tested in Oklahoma. Improving the OPE of the tested systems to NPPPC standard could reduce the energy consumption by 34% and 19% and subsequently lower the GHG emissions by 52% and 20% for the electricity and natural gas powered pumping plants respectively. Improving the OPE could also lead to decrease in operating costs of the pumping plants. Growers could on an average save $2,190 and $1,195 for every 1,000 hours of operation for electricity and natural gas powered pumping plants respectively. For application uniformities, the average CU, DU and WCE of all the systems tested were reported to be 79.8%, 71.1% and 94% respectively. Non-uniformities lead to considerable amount of water losses in terms of evaporation, deep percolation, and transpiration. Losses were also incurred in terms of nutrients being lost beyond the crop root zone. Improving the application uniformities would help conserve water and soil nutrients.

REFERENCES

Allaire-Leung, S. E., Wu, L., Mitchell, J. P., & Sanden, B. L. (2001). Nitrate leaching and soil nitrate content as affected by irrigation uniformity in a carrot field. *Agricultural Water Management*, *48*(1), 37-50.

ANSI/ASAE S436.1 Test Procedure for Determining the Uniformity of Water Distribution of Center Pivot and Lateral Move Irrigation Machines Equipped with Spray or Sprinkler Nozzles.

ASABE. (2007). Test procedure for determining the uniformity of water distribution of center pivot and lateral move irrigation machines equipped with spray or sprinkler nozzles (pp. 1033–1039). ASAE Standards 2007, ANSI/ASAE S436.1 JUN1996 (R2007), ASABE, Michigan, Saint Joseph.

Ascough, G. W., & Kiker, G. A. (2002). The effect of irrigation uniformity on irrigation water requirements. *Water Sa*, *28*(2), 235-242.

Ayars, J. E., Hutmacher, R. B., Vail, S. S., & Schoneman, R. A. (1991). Cotton response to nonuniform and varying depths of irrigation. *Agricultural water management*, *19*(2), 151-166.

Barefoot, A. D. (1980). Investigation of Factors Affecting Energy for Irrigation Pumping. *Oklahoma Water Resources Research Institute*.

Ben-Asher, J., & Ayars, J. E. (1990). Deep seepage under nonuniform sprinkler irrigation. II: Field data. *Journal of irrigation and drainage engineering*, *116*(3), 363-373.

Bonan, G. B., Hartman, M. D., Parton, W. J., & Wieder, W. R. (2013). Evaluating litter decomposition in earth system models with long-term litterbag experiments: an example using the Community Land Model version 4 (CLM 4). *Global change biology*, *19*(3), 957-974.

Brar, D., Kranz, W. L., Lo, T. H., Irmak, S., & Martin, D. L. (2017). Energy conservation using variable-frequency drives for centerpivot irrigation: Standard systems. Trans. ASABE, 60(1), 95-106. https://doi.org/10.13031/trans.11683

Brito, R. A., & Willardson, L. S. (1982). Sprinkler irrigation uniformity requirements for the elimination of leaching. *Transactions of the ASAE*, *25*(5), 1258-1261.

Cheng, K., Ogle, S. M., Parton, W. J., & Pan, G. (2013). Predicting methanogenesis from rice paddies using the DAYCENT ecosystem model. *Ecological modelling*, *261*, 19-31.

Cleveland, C. C., Houlton, B. Z., Smith, W. K., Marklein, A. R., Reed, S. C., Parton, W., ... & Running, S. W. (2013). Patterns of new versus recycled primary production in the terrestrial biosphere. *Proceedings of the National Academy of Sciences*, *110*(31), 12733-12737.

DayCent Ecosystem Model (2017). User manual, scientific basis, and technical documentation, Colorado State University.

DeBoer, D. W., Lundstrom, D. R., & Wright, J. A. (1983). Efficiency analysis of electric irrigation pumping plants in the upper midwest, USA. *Energy in Agriculture*, *2*, 51-59.

Del Grosso, S. J., Parton, W. J., Mosier, A. R., Walsh, M. K., Ojima, D. S., & Thornton, P. E. (2006). DAYCENT national-scale simulations of nitrous oxide emissions from cropped soils in the United States. *Journal of Environmental quality*, *35*(4), 1451-1460.

Del Grosso, S. J., Halvorson, A. D., & Parton, W. J. (2008). Testing DAYCENT model simulations of corn yields and nitrous oxide emissions in irrigated tillage systems in Colorado. *Journal of environmental quality*, *37*(4), 1383-1389.

Doorenbos, J., & Kassam, A. H. (1979). Yield response to water. *Irrigation and drainage paper*, *33*, 257.

Duval, B. D., Ghimire, R., Hartman, M. D., & Marsalis, M. A. (2018). Water and nitrogen management effects on semiarid sorghum production and soil trace gas flux under future climate. *PloS one*, *13*(4), e0195782.

Endelman, F. J., Keeney, D. R., Gilmour, J. T., & Saffigna, P. G. (1974). Nitrate and Chloride Movement in the Plainfield Loamy Sand Under Intensive Irrigation 1. *Journal of Environmental Quality*, *3*(3), 295-298.

Farm and ranch irrigation survey, 2013. Available at https://www.nass.usda.gov/Publications/AgCensus/2012/Online_Resources/Farm_and_Ranch_Irrigation_Survey/fris13_2_029_029.pdf, accessed on November, 2018.

Fipps, G., & Neal, B. (1995). Texas irrigation pumping plant efficiency testing program. *Texas Energy Office Final Report*.

Frazier RS, Taghvaeian S, Handa D (2017) Measuring depth to groundwater in irrigation wells. Oklahoma Cooperative Extension Service publication BAE-1538. Available online at: http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Document-10865/BAE-1538web.pdf

Follett, R. F. (2001). Soil management concepts and carbon sequestration in cropland soils. *Soil and Tillage Research*, *61*(1-2), 77-92.

García-Tejero, I. F., Durán-Zuazo, V. H., Muriel-Fernández, J. L., & Rodríguez-Pleguezuelo, C. R. (2011). Water and sustainable agriculture. In *Water and Sustainable Agriculture*(pp. 1-94). Springer, Dordrecht.

Greenhouse Gas Inventory Guidance, Direct emissions from stationary combustion sources, US EPA (2016). Available at https://www.epa.gov/sites/production/files/2016-03/documents/stationaryemissions_3_2016.pdf. Accessed November, 2018.

Griffiths-Sattenspiel, B., & Wilson, W. (2009). The carbon footprint of water. *River Network, Portland*.

Hanson, B. (2002). Improving pumping plant efficiency does not always save energy. California Agriculture, 56(4), 123-127.

Hardin, D. C., & Lacewell, R. D. (1979). Implication of improved irrigation pumping efficiency for farmer profit and energy use. Journal of Agricultural and Applied Economics, 11(1), 89-94.

Hartman, M. D., Merchant, E. R., Parton, W. J., Gutmann, M. P., Lutz, S. M., & Williams, S. A. (2011). Impact of historical land-use changes on greenhouse gas exchange in the US Great Plains, 1883–2003. *Ecological Applications*, *21*(4), 1105-1119.

Henggeler, J. C., & Vories, E. D. (2009). Evaluating center pivot distribution uniformity from catch can tests. In *2009 Reno, Nevada, June 21-June 24, 2009* (p. 1). American Society of Agricultural and Biological Engineers.

Hodges, A. W., Lynne, G. D., Rahmani, M., & Casey, C. F. (1994). Adoption of energy and water-conserving irrigation technologies in Florida. *EES (USA)*.

Howell, T. A. (2003). Irrigation efficiency. Encyclopedia of water science. Marcel Dekker, New York, 467-472.

Howes, D. J., Ellenson, S., Hoffmann, L., & Gaudi, F. (2014). Center Pivot Sprinkler Distribution Uniformity Impacts on the Spatial Variability of Evapotranspiration. *Journal of Irrigation and Drainage Engineering*, *141*(8), 04014085.

Hsiao, T. C. (1973). Plant responses to water stress. *Annual review of plant physiology*, *24*(1), 519-570.

Karimi, P., Qureshi, A. S., Bahramloo, R., & Molden, D. (2012). Reducing carbon emissions through improved irrigation and groundwater management: A case study from Iran. *Agricultural water management*, *108*, 52-60.

Kassem, M. A. (2009). Effect of Sprinkler İrrigation Uniformity on Wheat Productivity, Water Losses And Water Use Efficiency. *Misr J. Ag. Eng*, *26*(3), 1201-1222.

Khan, M. A., Khan, M. Z., Zaman, K., & Naz, L. (2014). Global estimates of energy consumption and greenhouse gas emissions. Renewable and Sustainable Energy Reviews, 29, 336-344.

Levidow, L., Zaccaria, D., Maia, R., Vivas, E., Todorovic, M., & Scardigno, A. (2014). Improving water-efficient irrigation: Prospects and difficulties of innovative practices. *Agricultural Water Management*, *146*, 84-94.

Lianhao, L., Xinyue, Z., Xiaodong, Q., & Guiming, L. (2016). Analysis of the decrease of center pivot sprinkling system uniformity and its impact on maize yield. *International Journal of Agricultural and Biological Engineering*, *9*(5), 108-119.

Li, J., Li, B., & Rao, M. (2005). Spatial and temporal distributions of nitrogen and crop yield as affected by nonuniformity of sprinkler fertigation. *Agricultural water management*, *76*(3), 160-180.

Luc, J. P., Tarhouni, J., Calvez, R., Messaoud, L., & Sablayrolles, C. (2006). Performance indicators of irrigation pumping stations: application to drill holes of minor irrigated areas in the Kairouan plains (Tunisia) and impact of malfunction on the price of water. Irrigation and drainage, 55(1), 85-98.

Martin, D. (2011). Innovations in center-pivot irrigation. *Resource Magazine*, *18*(5), 7.

Masasi B., Frazier R., Taghvaeian S. (2017). Review and operational guidelines for portable ultrasonic flowmeters. Oklahoma Cooperative Extension Service publication BAE-1535. Available at: http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Document-10723/BAE-1535web.pdf

Mateos, L., Mantovani, E. C., & Villalobos, F. J. (1997). Cotton response to non-uniformity of conventional sprinkler irrigation. *Irrigation Science*, *17*(2), 47-52.

Merriam, J. L., & Keller, J. (1978). Farm irrigation system evaluation: a guide for management. *Farm irrigation system evaluation: a guide for management.*

Montazar, A., & Sadeghi, M. (2008). Effects of applied water and sprinkler irrigation uniformity on alfalfa growth and hay yield. *Agricultural water management*, *95*(11), 1279-1287.

Mora, M., Vera, J., Rocamora, C., & Abadia, R. (2013). Energy Efficiency and Maintenance Costs of Pumping Systems for Groundwater Extraction. *Water resources management*, *27*(12), 4395-4408.

New, L., & Schneider, A. D. (1988). *Irrigation Pumping Plant Efficiencies, High Plains and Trans-Pecos Areas of Texas*. Texas Agricultural Experiment Station, Texas A & M University System.

Parton, W. J., Hartman, M., Ojima, D., & Schimel, D. (1998). DAYCENT and its land surface submodel: description and testing. *Global and planetary Change*, *19*(1-4), 35-48.

Parton, W. J., Stewart, J. W., & Cole, C. V. (1988). Dynamics of C, N, P and S in grassland soils: a model. *Biogeochemistry*, *5*(1), 109-131.

Patle, G. T., Singh, D. K., Sarangi, A., & Khanna, M. (2016). Managing CO 2 emission from groundwater pumping for irrigating major crops in trans indo-gangetic plains of India. *Climatic change*, *136*(2), 265-279.

Plappally, A. K. (2012). Energy requirements for water production, treatment, end use, reclamation, and disposal. *Renewable and Sustainable Energy Reviews*, *16*(7), 4818-4848.

Pradeleix, L., Roux, P., Bouarfa, S., Jaouani, B., Lili-Chabaane, Z., & Bellon-Maurel, V. (2015). Environmental Impacts of Contrasted Groundwater Pumping Systems Assessed by Life Cycle Assessment Methodology: Contribution to the Water–Energy Nexus Study. Irrigation and drainage, 64(1), 124-138.

PRISM Climate Group (2015), Oregon State University. Accessed at http://prism.oregonstate.edu/explorer/ on October, 2018.

Qiu, G. Y., Zhang, X., Yu, X., & Zou, Z. (2018). The increasing effects in energy and GHG emission caused by groundwater level declines in North China's main food production plain. *Agricultural Water Management*, *203*, 138-150.

Ross, E. A., & Hardy, L. A. (1997). National engineering handbook; Irrigation guide. USDA, Beltsville, MD.

Rothausen, S. G., & Conway, D. (2011). Greenhouse-gas emissions from energy use in the water sector. *Nature Climate Change*, *1*(4), 210.

Shah, T. (2009). Climate change and groundwater: India's opportunities for mitigation and adaptation. *Environmental Research Letters*, *4*(3), 035005.

Shahdany, S. M. H., Firoozfar, A., Maestre, J. M., Mallakpour, I., Taghvaeian, S., & Karimi, P. (2018). Operational performance improvements in irrigation canals to overcome groundwater overexploitation. Agricultural Water Management, 204, 234-246.

Siddiqi, A., & Anadon, L. D. (2011). The water–energy nexus in Middle East and North Africa. *Energy policy*, *39*(8), 4529-4540.

Siegel, F. R. (2008). *Demands of expanding populations and development planning: clean air, safe water, fertile soils*. Springer Science & Business Media.

SoilWeb, California soil resource lab, UC Davis. Available at https://casoilresource.lawr.ucdavis.edu/gmap/ , accessed September, 2018.

Solomon, K. H. (1983). "Irrigation unifonnity and yield theory," PhD thesis, Utah State Univ., Logan, Utah.

Taghvaeian S. (2014). Irrigated Agriculture in Oklahoma. Oklahoma Cooperative Extension Publication BAE-1530. Accessed at: http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Document-9561/BAE-1530web.pdf

Taghvaeian S, Frazier RS, Livingston D, Fox G (2016) The Ogallala aquifer. Oklahoma Cooperative Extension Service publication BAE-1531. Available online at: http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Document-10183/BAE-1531web.pdf

U.S. Energy Information Administration. Accessed at: https://www.eia.gov/electricity/state/oklahoma/ September, 2018.

U.S. Energy Information Administration. Accessed at: https://www.eia.gov/dnav/ng/hist/n3035ok3m.htm September, 2018.

Wang, J., Rothausen, S. G., Conway, D., Zhang, L., Xiong, W., Holman, I. P., & Li, Y. (2012). China's water–energy nexus: greenhouse-gas emissions from groundwater use for agriculture. *Environmental Research Letters*, *7*(1), 014035.

Weiler, D. A., Tornquist, C. G., Zschornack, T., Ogle, S. M., Carlos, F. S., & Bayer, C. (2018). DayCent Simulation of Methane Emissions, Grain Yield, and Soil Organic Carbon in a Subtropical Paddy Rice System. *Revista Brasileira de Ciência do Solo*, *42*.

Zhang, L., Merkley, G. P., & Pinthong, K. (2013). Assessing whole-field sprinkler irrigation application uniformity. Irrigation science, 31(2), 87-105.

Zou, X., Li, Y. E., Li, K., Cremades, R., Gao, Q., Wan, Y., & Qin, X. (2015). Greenhouse gas emissions from agricultural irrigation in China. *Mitigation and Adaptation Strategies for Global Change*, *20*(2), 295-315.

APPENDICES

APPENDIX A: CATCH CAN TESTS DATA

Table 4: System with highest uniformity

Distance (ft)	Can ID	Application (in)	Average of all cans (in)	Lowest quarter average (in)
	1		0.19	0.17
	2		0.19	0.17
	3		0.19	0.17
	4		0.19	0.17
	5		0.19	0.17
	6		0.19	0.17
	7		0.19	0.17
	8		0.19	0.17
180	9	0.17	0.19	0.17
200	10	0.16	0.19	0.17
220	11	0.21	0.19	0.17
240	12	0.16	0.19	0.17
260	13	0.17	0.19	0.17
280	14	0.19	0.19	0.17
300	15	0.16	0.19	0.17
320	16	0.16	0.19	0.17
340	17	0.21	0.19	0.17
360	18	0.19	0.19	0.17
380	19	0.18	0.19	0.17
400	20	0.19	0.19	0.17
420	21	0.2	0.19	0.17
440	22	0.19	0.19	0.17
460	23	0.18	0.19	0.17
480	24	0.2	0.19	0.17
500	25	0.18	0.19	0.17
520	26	0.23	0.19	0.17
540	27	0.21	0.19	0.17

560	28	0.2	0.19	0.17
580	29	0.2	0.19	0.17
600	30	0.21	0.19	0.17
620	31	0.2	0.19	0.17
640	32	0.2	0.19	0.17
660	33	0.2	0.19	0.17
680	34	0.2	0.19	0.17
700	35	0.2	0.19	0.17
720	36	0.2	0.19	0.17
740	37	0.2	0.19	0.17
760	38	0.21	0.19	0.17
780	39	0.16	0.19	0.17
800	40	0.18	0.19	0.17
820	41	0.19	0.19	0.17
840	42	0.17	0.19	0.17
860	43	0.17	0.19	0.17
880	44	0.18	0.19	0.17
900	45	0.18	0.19	0.17
920	46	0.19	0.19	0.17
940	47	0.19	0.19	0.17
960	48	0.2	0.19	0.17
980	49	0.17	0.19	0.17
1000	50	0.18	0.19	0.17
1020	51	0.19	0.19	0.17
1040	52	0.22	0.19	0.17
1060	53	0.19	0.19	0.17
1080	54	0.17	0.19	0.17
1100	55	0.19	0.19	0.17
1120	56	0.21	0.19	0.17
1140	57	0.19	0.19	0.17

Table 5: System with lowest uniformity

Distance (ft)	Can ID	Application (in)	Average of all cans (in)	Lowest quarter average (in)
0	1		0.24	0.03
0	2		0.24	0.03
0	3		0.24	0.03
0	4		0.24	0.03
0	5		0.24	0.03
0	6		0.24	0.03
0	7		0.24	0.03
0	8		0.24	0.03
0	9		0.24	0.03
0	10		0.24	0.03
0	11		0.24	0.03
0	12		0.24	0.03
0	13		0.24	0.03
0	14		0.24	0.03
0	15		0.24	0.03
0	16		0.24	0.03
340	17	0.56	0.24	0.03
360	18	0.4	0.24	0.03
380	19	0.65	0.24	0.03
400	20	0.16	0.24	0.03
420	21	0.06	0.24	0.03
440	22	0.3	0.24	0.03
460	23	0.7	0.24	0.03
480	24	0.59	0.24	0.03
500	25	0.11	0.24	0.03
520	26	0.3	0.24	0.03
540	27	0.27	0.24	0.03
560	28	0.16	0.24	0.03
580	29	0.17	0.24	0.03
600	30	0.07	0.24	0.03
620	31	0	0.24	0.03
640	32	0.08	0.24	0.03
660	33	0.36	0.24	0.03
680	34	0.16	0.24	0.03
700	35	0.1	0.24	0.03
720	36	0.07	0.24	0.03
740	37	0.21	0.24	0.03
760	38	0.13	0.24	0.03

780	39	0.46	0.24	0.03
800	40	0	0.24	0.03
820	41	0	0.24	0.03
840	42	0	0.24	0.03
860	43	0	0.24	0.03
880	44	0.18	0.24	0.03
900	45	0.23	0.24	0.03
920	46	0.08	0.24	0.03
940	47	0.14	0.24	0.03
960	48	0.13	0.24	0.03
980	49	0.16	0.24	0.03
1000	50	0.1	0.24	0.03
1020	51	0.22	0.24	0.03
1040	52	0.41	0.24	0.03
1060	53	0.25	0.24	0.03
1080	54	0.03	0.24	0.03
1100	55	0.8	0.24	0.03
1120	56	0.8	0.24	0.03
1140	57	0.65	0.24	0.03
1160	58	0.05	0.24	0.03
1180	59	0.44	0.24	0.03
1200	60	0.25	0.24	0.03
1220	61	0.16	0.24	0.03
1240	62	0.15	0.24	0.03
1260	63	0.3	0.24	0.03

VITA

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