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.		
Post Doc		
Total		

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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.

(R. Scott Frazier), Energy and Water Efficiency of Center Pivot Irrigation, 2016 Oklahoma Irrigation Conference, Caddo County.

(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):

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

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).

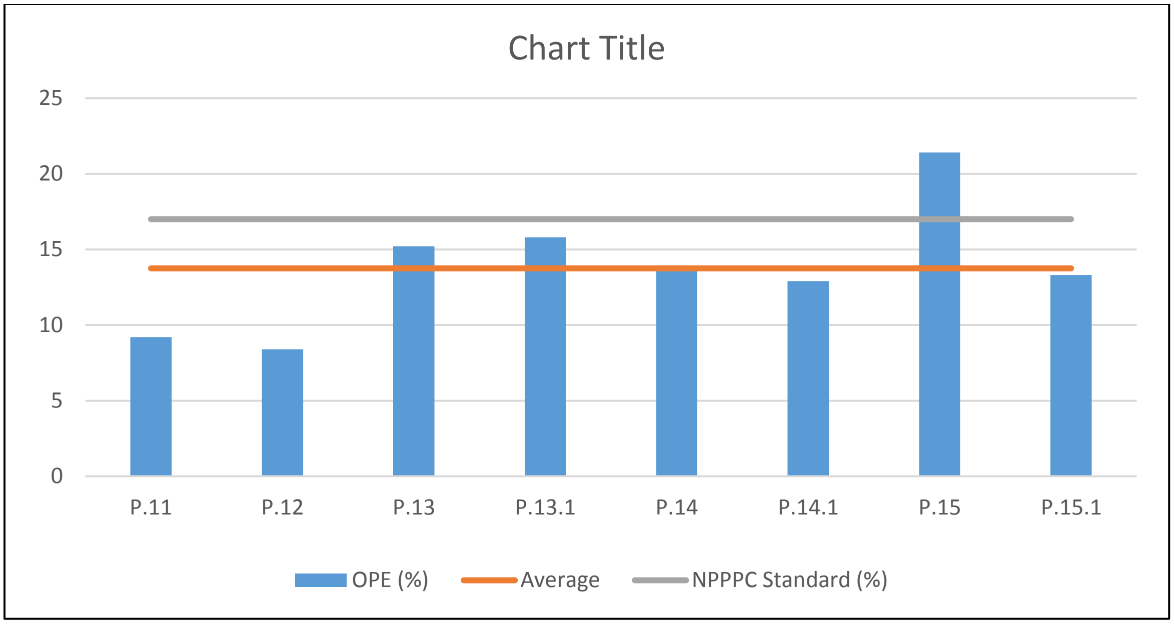

Figure 1. Actual OPE of natural gas (IC Engine) powered pumping plants as compared to NPPPC standards.

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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