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A Pump Monitoring Approach to Irrigation Pumping Plant Performance Testing

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Biological Engineering

by

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Abstract

Traditionally, irrigation pumping plants have been tested using an instantaneous approach, which tests performance parameters over a very short time interval. Using this method, the evaluator measures the necessary work and energy use parameters to calculate the desired pumping plant performance values. The primary limitation of this approach is its inability to determine the season long efficiency of an irrigation pumping plant.

A new approach to evaluating irrigation pumping plant performance is the use of pump monitoring systems which use high frequency, real-time data collection and telemetry to relay information directly from the pump to the user. This method of testing essentially conducts a continuous pumping plant performance evaluation.

Throughout a typical irrigation season, a single pumping plant typically operates at a wide range of total dynamic heads as a result of changes in operational conditions due to factors such as aquifer drawdown and irrigation demand changes. When coupled with telemetry, this approach to irrigation pumping plant testing can provide real-time feedback to the irrigator on pumping plant performance, even as the operating conditions of the system changes throughout the season.

Nearly 100 pumping years of diesel and electric pumping plants were evaluated over four irrigation seasons using a network of these pump monitoring systems. Annual averages and trends in water pumping flow rate, COW per unit volume pumped, and efficiency as a percentage of the Nebraska Pumping Plant Performance Criteria, among other performance values were reported. These pumping performance values can be used to develop recommendations to producers in order to improve pumping plant performance and reduce operating costs as well as identifying the causes of pumping plant inefficiencies.

Acknowledgements

Special thanks are extended to the faculty of the Biological Engineering program at the University of Arkansas for their part in making my time here so special. Thanks in particular to Dr. Chris Henry for serving as my major professor. In addition, thanks to Dennis Carman with the White River Irrigation District and Kim Woodson with the Diesel Engine Motor Company for helping provide the resources to conduct my research. Finally, thanks to Mike Sullivan (Burdette, AR), Terry Dabbs (Stuttgart, AR), Heath and John Stevens (Stuttgart, AR), and the other farmers who so willingly allowed me to use their farms as a laboratory

Dedication

This thesis and all of the work that went toward its completion are dedicated to my family, whose constant support and emphasis on education allowed me to get to this point. For many generations, my family practiced agriculture on the Arkansas Grand Prairie. Their efforts laid the framework for the passion and appreciation that I have for it today. It is my hope that through this work, I can make an impact that will help many more generations be given that same gift.

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Introduction

What is a Pump Monitor?

A pump monitor is an automated, field level control system which uses a variety of automated instrumentation to provide operational pumping plant information. Rather than a traditional instantaneous pumping plant test, a pump monitoring system allows a continuous pumping plant evaluation to occur. The pump monitor developed by Diesel Engine Motors Company in Dardanelle, Arkansas uses a system of sensors including a propeller flow meter, pressure sensor, and a diesel fuel flow sensor or combination of current transformers and voltage measurement equipment to measure all of the parameters necessary for a pumping plant evaluation. As described above, a pumping plant evaluation is a method of testing which allows components of a pumping plant to be evaluated in terms of efficiency. This helps in determining when component(s) should be resized, replaced, and gives an idea of the general economics associated with a pumping plant.

In a pumping plant evaluation, an estimation or direct measure of discharge pressure (P_d) and pumping water level (PWL) to determine total dynamic head (TDH) is required. In addition pumping flow rate (Q_w), and energy consumption rate must be measured. The measurements of these parameters by the DEM pump monitoring systems allows performance values such as cost of water (COW), overall pumping plant efficiency (OPPE), and efficiency as a percentage of the Nebraska Pumping Performance criteria (%-NPPPC) to be calculated. The DEM pump monitoring systems relay this pumping plant performance data to a control box near the pumping plant, which use cell phone signal telemetry to relay the data to a web based user interface.

The DEM user interface also provides on/off control to the user, allowing the systems to be powered on or off remotely as long as cell signal is available. In addition, anyone with username and password access to the website can evaluate irrigation system performance values in real time. Pumping plant data is typically collected in one to five minute time intervals and presented digitally on the user interface of the DEM website. All of the performance data collected for each monitored pumping plant can be exported from the database to Microsoft Excel for evaluation. In addition, historic pumping plant performance data can be viewed graphically on the website. The data can be exported to Excel as instantaneous values (each one or five minute value), hourly averages, or 24-hour averages. As opposed to traditional instantaneous pump testing, irrigation system performance data collected using this pump monitoring approach can be used to evaluate pumping plant performance values for the entirety of an irrigation season. This also allows changes in performance to be evaluated from season to season, which may help develop maintenance scheduling for the monitored pumping plants.

Statement of Purpose

The purpose of this study was to conduct a general survey of irrigation pumping plant performance in Arkansas. This survey will be conducted using both traditional instantaneous testing methods and using the telemetry based pump monitoring approach. The study also compared pumping costs for different energy sources (diesel and electricity) and evaluated annual trends in individual performance parameters using the pump monitoring approach. It has been many years since pumping plant performance has been evaluated on a wide scale in the state of Arkansas. Therefore, this study will help spread knowledge of the pumping plant efficiencies that are present in Arkansas, which system characteristics are most commonly associated with poor efficiency, and the economic impact associated with using pump system maintenance or redesign to improve efficiency.

Objectives

The following were the major objectives of this study:

1) Conduct a survey of approximately 50 electric and 20 diesel irrigation pumping plants using pump monitoring performance data and instantaneous testing on electric and diesel pumping plants in Arkansas. Use these two methods of testing to identify irrigation pumping plant efficiencies are in the state of Arkansas.
2) Efficiency and pumping costs associated with pumping plant characteristics including system type (alluvial well, deep well, or surface relift), energy source (diesel or electric), geographic location, and system size will be evaluated. This will help farmers identify which pumping plant systems have the greatest potential for energy savings associated with maintenance or redesign.
3) Evaluate annual trends in pumping plant performance parameters (Q_w, energy consumption rates, COW, efficiency, etc.) using the continuous pump monitoring approach.
4) Gather and evaluate additional pumping plant information such as irrigation capacity (flow rate per crop area serviced) and electric motor loading (% of power rating) using both instantaneous and pump monitoring approaches. Use these and the rest of the performance results to highlight the pros and cons of the pump monitoring approach to pumping plant testing.

Review of Literature

What is Irrigation?

Irrigation is defined by Merriam-Webster Dictionary as the act of artificially supplying land and/or crops with water to meet evapotranspiration needs. According to Postel (1999), irrigation has been practiced on Earth for an estimated 6000 years, but more innovation in irrigation has occurred in the last one-hundred or so years than in the previous 5900 years combined. Despite this spike in innovation spearheaded by the Green Revolution in the mid-20th century, Postel goes on to state that a worldwide irrigation efficiency of only about forty percent is attained. This statistic suggests vast potential for improvements in irrigation practices moving forward in the 21st century.

Irrigation Worldwide. The importance of water usage worldwide is outlined by Howell (2000), focusing on the importance of improving upon the current global average irrigation efficiency. Irrigated lands worldwide account for only about 20% of cultivated farmland, but produce approximately forty percent of all food and fiber. According to this publication, approximately 36% to 47% of the world's food is produced from land where irrigation is utilized. In addition, irrigation is directly responsible for approximately 80% of the freshwater consumed and about 66% of the freshwater diverted worldwide. This increase in production where irrigation is utilized has led to dramatic increases worldwide of irrigated land since the start of the 19th century. According to the FAO (2012), the total area of irrigated farmland has increased exponentially from about 8 million hectares in 1800 to forty million hectares in 1900. This increase in irrigation then leveled out at approximately 270 million hectares at the beginning of the 21st century. Despite exponential growth in irrigated land over the last 200 plus years, this growth is expected to slow dramatically in the near future. Global irrigation is expected to grow at a rate of approximately 1% per year from the year 2000 to 2025, down from about 3% per year from 1950 to 2000. This slowing in the irrigation growth trend is due to limitations in areas with irrigation potential and the expense required to develop land so that it can be irrigated. According to Jones (1995), irrigation development has an estimated cost of approximately $4800 per hectare worldwide. Since limited land resources and economics are now beginning to limit irrigation expansion in terms of area, focus must shift to implementation of technological advances and further research findings to enhance irrigation practices to improve overall irrigation efficiency. Doing so will help humans produce more food energy resources at less input cost, which is essential to the human race providing for a population that is expected to increase in number by nearly 50% by the year 2050 (Jones, 1995).

Irrigation in the United States. According to Maugh (2009), irrigation in what is now the United States has developed and evolved over time, beginning with the Native Americans diverting water from streams to provide water to squash, corn, and bean plots dating back to at least 1200 B.C.. Today, irrigation is present in every state in the union and occupies roughly twenty-one million hectares of land. In the United States, commodities produced from irrigated farmland are much more valuable as a whole relative to those produced from non-irrigated farmland. Gollehon (2002) states that commodity sales of crops produced from irrigated land as opposed to non-irrigated land are approximately 4.5 times more profitable in terms of overall production for growers. Furthermore, Clemmens and Allen (2008) show that the market value on irrigated crops in the U.S. totals thirty-eight billion dollars per year, representing approximately 40% of the harvested crop market on only about 9% of the amount of land area. The nation’s total irrigated land area is approximately thirty-seven million hectares when including turf grass and about twenty-one million hectares excluding turf grass. Milesi et al.

(2005) identifies corn as the largest irrigated agricultural crop worldwide in terms of total land area occupied and volumetric production.

Irrigated farm ground in the United States declined in the 1980’s due to depressed farm commodities, but rebounded in the 1990’s. Milesi et al. (2005) states that recent growth in irrigated land area has been concentrated to the southeast region of the United States, particularly in the Mississippi River Delta area. A large percentage of these increases occurred in the eastern half of Arkansas in the 1960’s and 1970’s due to increases in row crop irrigation practices that are consistent with flood irrigation demand for rice. The land area irrigated within the United States is primarily concentrated west of the Mississippi River, with all states west of the Mississippi with the exceptions of North Dakota and Iowa having at least 100,000 hectares of irrigated farm ground. In contrast, only seven states east of the Mississippi River have irrigated land in excess of 100,000 hectares according to NASS-USDA (2005). The “Irrigation Water Use” article on the USGS Online Water Science School website states that about 35% of water withdrawals within the United States are for irrigated agriculture. This makes it second only to thermoelectric generation in terms of water use. Of these irrigation withdrawals, over 50% are a result of groundwater pumping from irrigation wells, with the rest accounted for by on-farm and off-farm surface water irrigation systems. As irrigation water supply becomes increasingly expensive due to continuously increasing energy costs (electricity, diesel fuel, etc.), some irrigated agriculture operations are approaching $0.20 in total input costs per hectare-meter of water applied. However, the USGS also states that the average market value of farm commodities resulting from irrigated agriculture nationally is about $0.31 per hectare-meter of water applied. Therefore, outputs typically tend to account for inflated irrigation costs, allowing the practice of irrigation in agriculture to remain economically viable.

What is an Irrigation Pumping Plant?

Irrigation pumping plants, according to Savva and Frenken (2002), are systems that use centrifugal force to transfer energy from an energy source (electricity, diesel fuel, natural gas, etc.) to water resulting in its displacement to a desired location. For agricultural irrigation, this water is usually directed to its desired location for storage purposes or to meet crop water needs. Commonly used methods of irrigation water application include but are not limited to furrow irrigation, flood irrigation, and sprinkler irrigation (Barta, Broner, Schneekloth, and Waskom, 2004). The main sources of over-spending in agricultural irrigation are pump/engine system inefficiencies and over-irrigation, with the main cause of over-irrigation being lack of application uniformity (Solomon, 1988). Overall pumping plant efficiency (OPPE) is a measure of total pumping plant efficiency calculated as a product of the combined efficiencies of the individual components of the pumping plant system. Individual system components commonly found in agricultural irrigation include the gear drive, power unit (diesel engine, electric motor, etc.), pump/bowl assembly, and the well intake screen.

Factors Affecting Pumping Plant Efficiency. Diminished pumping plant efficiencies are often a product of out of adjustment pump impellers, incorrect pump bowl design, impeller damage, incorrect power unit selection, inconsistency in operating conditions, and poor plumbing in horizontal axis/centrifugal pumps (Chávez, Reich, Loftis, and Miles, 2010). According to this publication, out of adjustment impellers are typically the most cost effective and easiest of these causes to correct. Often times, poor pump/bowl selection is a result of poor initial pumping yield testing, an attempt to minimize the number of stages installed to reduce capital cost to maintain market competiveness, or fluctuation in TDH resulting in a change in Q_w.

Cavitation, sand or gravel pumping, and improper impeller adjustment can all lead to impeller damage which can quickly decrease pump efficiency.

Poor motor selection for electric irrigation pumping plants can also cause accelerated deterioration of pumping plant performance due to power unit over-loading which occurs when shaft power of the motor exceeds the nameplate power rating (Arnold, 2007). Conversely, oversizing of electric motors can cause losses in efficiency, particularly when shaft power is below 50% of the nameplate power rating. Typically, electric motors have a service factor of 1.15, indicating that the motor is capable of drawing 15% more power than its nameplate power rating. Despite this capability, servicing loads causing electric motors to operate into their service factor can lead to accelerated degradation and eventual failure of these motors. A motor driving a load exceeding its nameplate power rating will draw additional amperage in an attempt to provide the power needed to drive the load, causing the motor to run at high temperature. The additional heat created can lead to deterioration of motor winding insulation over time, shortening the motor's operational life span according to Beard and Hill (2000).

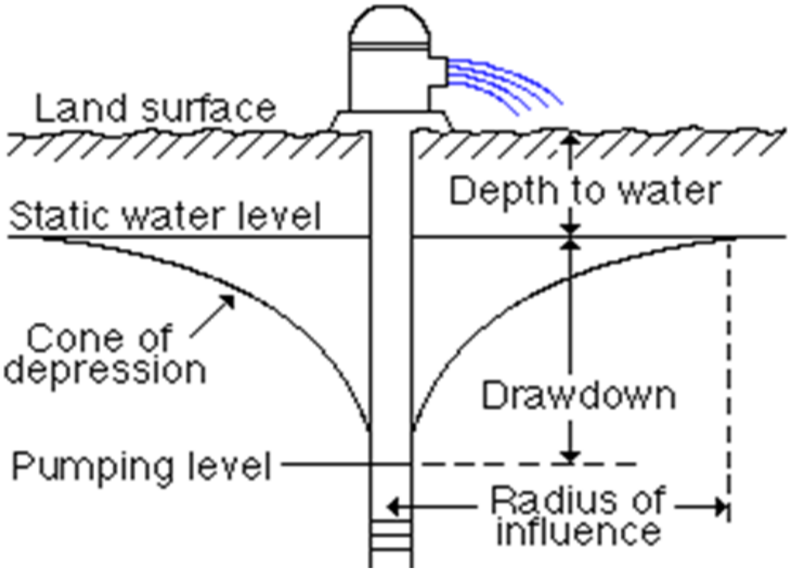
According to the U.S. Department of Energy's "Improving Pumping System Performance: A Sourcebook for Industry" (2006), total dynamic head (TDH) of a pumping system is equal to the sum of the static head and friction head. This publication defines static head as the difference in height between the source and destination of the pumped liquid. Friction head is defined as the loss that must be overcome caused by resistance to flow in pipes and fittings. Fluctuations in operating conditions changing TDH are often caused by changes in the level of the source water being pumped (groundwater, reservoir, ditch, etc.) changing static head, conversion from open discharge to pipeline irrigation increasing friction head, and/or changes between surface and sprinkler irrigation. These changes in TDH can immediately impact whether or not a particular irrigation pumping plant system is operating at acceptable efficiency, regardless of the input energy source being utilized. To help universally quantify pumping plant performance, a series of pumping plant performance benchmarks was developed in the 1950's at the University of Nebraska to allow for direct comparison between pumping plants of different energy sources. Known as the Nebraska Pumping Plant Performance Criteria (NPPPC), this system provides numerical values for expected work done on the water by the pump per unit of energy consumption over the same duration. The NPPPC provides these benchmarks for diesel, gasoline, propane, natural gas, and electric powered irrigation pumping plants. The ratio of total water power delivered (work) per unit of energy consumption by the pumping plant is used to compare pumping plant performance to the NPPPC. The NPPPC is cited by irrigation design engineers worldwide as according to Schleusener and Sulek (1959).

Pumping Plant Performance Testing. Fischbach and Schroeder (1982) states that irrigation pumping plant performance testing requires an accurate instantaneous measurement of P_d, PWL, Q_w, and input energy consumption rate. If these parameters can all be measured, work done by pumping plant system on the water can be determined to compare performance to the NPPPC. It is also recommended that the tester record system information including the number and type of impellers, pump speed of rotation, PTO torque (for diesel pumping plants), and the motor/engine manufacturer and model number according to Kranz and Yontz (2010). Kranz and Yontz also recommend that an electric meter can be used to monitor each leg of three-phase or single-phase electrical pumping plant systems to measure electricity consumption when necessary.

Static Water Level and Pumping Water Level. The first step in a pumping plant performance test is the measurement of static water level (SWL). SWL refers to the vertical distance from the center line of the pumping discharge pipe to the surface of the pumping water source (groundwater, reservoir, river, etc.) before the systems is powered on and pumping begins. SWL is dependent upon environmental factors including aquifer type, water withdrawal, and rate of aquifer recharge in the area, among other preexisting geologic conditions.

Air-line depth gauges can be used for SWL measurement in wells, which measure the pressure required to permit air escaping from the end of an air-line tube to determine the head of water above the air line. On some occasions, air-line gauges are installed by the well driller and can be used to measure the SWL of a well being tested. When this instrumentation is not present, chalked metal tapes or weighted electric water level indicator tapes are often used in the event that the well casing is readily accessible using these instruments. If the well casing is accessible, the same method used to measure SWL can be used to measure PWL. The difference between PWL of and SWL is equal to the vertical distance that the hydraulic surface of the pumping source drops when the pump is powered on and reaches steady state. This difference is known as drawdown. All of the above information regarding testing of SWL and PWL is available in “Care and Maintenance of Irrigation Wells” by Scherer (2013) from NDSU Extension Services.

Figure 1. Sketch of Aquifer Behavior during Pumping. *Source:* Kansas Geological Survey Website (1998).



Discharge Pressure. While PWL accounts for the TDH on the source side of the pumping discharge against which a pump system much work, the pressure within the pipe at the pumping discharge is used to calculate the equivalent height against which the pump must work on the discharge, or downstream side of the pumping system. In irrigation pumping plant testing, a manual read needle pressure gauge is typically tapped into the horizontal discharge pipe or standpipe to measure P_d. The contribution to TDH by P_d is 2.31 feet per psi, or 0.10 meters/kPa. In the event that P_d can't be measured using a pressure gauge, a surveyors rod and hand level can be used to measure vertical lift on the discharge side of the pump. This method for measuring P_d is only valid when the discharge pipe can be considered direct discharge so that friction losses can be assumed negligible. P_d accounts for these losses (Fischbach and Schroeder, 1982).

Pumping Water Flow Rate. After assessing P_d, SWL, and drawdown to determine TDH, Q_w can be measured using a variety of techniques. Portable ultrasonic flow meters, propeller flow meters, or the plumb bob method are often used for measuring Q_w. Portable ultrasonic flowmeters are useful when permanent propeller flow meters are not installed and/or water is being pumped through multiple discharges simultaneously to prevent the need for multiple measurements. Ultrasonic flowmeters typically specify the need for a straight, unobstructed length of discharge pipe with length equaling 10 pipe diameters upstream of the measurement site and 5 pipe diameters downstream. This is a major limitation in measuring Q_w using ultrasonic flowmeters, since a large percentage of systems do not satisfy these conditions. These meters also require the cross section of the pipe to be completely full of water so that the Q_w can be calculated as a function of cross sectional area and average fluid velocity. The pumping flow measurement techniques mentioned above were taken from a factsheet produced by Henry, Bankston, Sheffield, and Hadden (2013). Ultrasonic flow meters use a downstream and upstream ultrasonic pulse transmitted by transducers placed on the pipe at specified locations to measure Q_w as a function of the frequency shift in both waves and the manually programmed cross sectional area of the pipe. Other parameters such as the pipe material, coating, and temperature of the water are programmable within the ultrasonic flow meter to increase accuracy.

A propeller flow meter can be installed at the water discharge location (riser, reservoir pipe, etc.) such as a riser or reservoir filling pipe to measure Q_w. Propeller flow meters consist of a factory mounted propeller within a length of pipe, usually steel, which is attached to the end of the irrigation pipe with an O-ring connector. Some irrigation systems have propeller meters permanently installed inline at the pumping discharge so that the grower can monitor instantaneous Q_w and total water pumped through a growing season, which can be converted to application depth by knowing area irrigated. Further information on the installation and operation of propeller flowmeters can also be found in the “Irrigating Smart” factsheet series by Henry, Bankston, Sheffield, and Hadden (2013).

When using propeller flowmeters, the tester should first measure Q_w using the numeric totalizer, not the needle indicator, to calculate an accurate instantaneous Q_w value. Experience through the course of this study proved the totalizer to be much more reliable than the needle indicator. Totalizers on propeller flowmeters typically look similar to an odometer on a vehicle, measuring total flow through the meter over time. These totalizers are helpful in assessing total annual water pumped from a particular pumping plant.

Another Q_w measurement technique is the plumb bob method. The plumb bob method calculates Q_w as a function of the square of the pipe diameter and the vertical drop of the free discharge stream at the outlet of a pipe. According to Hadden (1985), the following equation can be used on horizontal or slightly angled discharge pipes with full pipe flow to calculate Q_w as a function of horizontal distance (L) per 8 inches of vertical water drop:

$$Q = D^2 \times L$$

Where: Q = flow (gpm); D = inside pipe diameter (in); L = 8" drop discharge distance (in).

If an 8 inch drop cannot be used to evaluate L, Q_w can still be estimated using a plumb bob. An equation relating Q_w to L at variable vertical drops and the cross-sectional area of the pipe is shown below (Rogers and Black, 1993).

$$Q = \frac{3.61 \times A \times L}{\sqrt{Y}}$$

Where: Q = flow (gpm); A = pipe cross-sectional area $\left(\mathrm{in}^2\right)$; L = horizontal discharge distance (in); Y = vertical drop (in).

Comparing Performance to the NPPPC. Upon obtaining values of P_d and Q_w, the rate of energy consumption is measured. The methodology and instrumentation used to obtain energy consumption rate varies by fuel type, and are described in detail in the methods section for diesel and electric systems. Electric energy consumption rates are measured in units of kilowatt-hours consumed per hour (kWh/hr). Diesel energy consumption rates are measured in units of gallons per hour (gph) or liters per hour. By obtaining a value of Q_w and TDH as described above, power transferred from the pump to the water can be determined.

Once water power and energy consumption rate are calculated, pumping plant efficiency can be calculated since there is a known ratio between work done by the pump system and total energy consumption. This ratio is what is used to determine pumping plant performance relative to the NPPPC (%-NPPPC). NPPPC benchmark values are given as a ratio of work (whp-hr) per unit of input energy, shown in Table 1. A table similar to Table 1 with NPPPC benchmark values in metric units is located in the appendix section (Table A - 1). This table allows %-NPPPC to be calculated knowing the ratio of water kilowatt-hours (w-kWh) per unit of energy consumed.

Table 1
NPPPC Values and Assumptions. *Source:* From "Updating the Nebraska pumping plant performance criteria" by W. Kranz and D. Yontz, 2010.

Energy Source	**Energy Unit**	**BHP-hr/unit (1)**	**whp-hr (2)/unit (3)**
Electric	kWh	1.18	0.885
Diesel	gal	16.6	12.5 (4)
Natural Gas	1000 ft^3	88.9 (7)	66.7
Propane	gal	9.2	6.89
Gasoline (6)	gal	11.5	8.66

Assumptions:

1) Horsepower hours (bhp-hr) is the work produced by the power unit including drive losses.
2) Water horsepower hours (whp-hr) is the work produced by the pumping plant per unit of energy at the NPPPC.
3) The NPPPC is based on 75% pump efficiency.
4) Criteria for diesel revised in 1981 to 12.5 whp-hr/gal
5) Assumes 88% electric motor efficiency.
6) Taken from Test D of Nebraska Tractor Test Reports. Drive losses are accounted for in the data. Assumes no cooling fan.
7) Manufacturers' data corrected for 5% gear-head drive loss and no cooling fan. Assumes natural gas energy content of 1000 Btu per cubic foot.

Irrigation Pumping Plant Performance Studies

According to a pumping plant efficiency study by Lundstrom, Burbank, and Bartholomay (1980), more than 50% of newly installed irrigation pumping plants tested from 1977 to 1980 in the state of North Dakota failed to operate at or above 90% of the NPPPC. In other words, less than half of these tested, newly installed pumping plants are operating at a performance level acceptably close to the NPPPC. This statistic suggests that among the systems tested, most were using significantly more energy than if the units had been properly adjusted and sized upon installation. Although it is unreasonable to suggest that all pumping plants should be tested and adjusted to operate at 100% of the NPPPC, the aforementioned statistic shows that many irrigators are unknowingly overspending on irrigation pumping as a result of poor initial design and/or maintenance of the system. Despite this study being limited to one particular state, the high number of units tested over a fairly extended period of time suggests that this lack of efficiency is most likely a widespread issue. NDSU Extension Services advises testing on each pumping plant at least once a year. By doing so, irrigators can be made aware of which systems are operating at adequate efficiency and have an idea of which systems may need maintenance, adjustment, or even re-design.

Scherer and Weigel (1993) outlines the North Dakota Pumping Plant Efficiency Testing program, which has been ongoing since the mid 1970's with the objective of identifying low efficiency pumping plants to outline potential cost and energy savings. At the time of this publication, pump tests had been performed on 621 systems across the state of North Dakota at the request of the irrigator or land owner. Of the systems tested, 591 were electric, 26 were diesel, and four were natural gas powered. During this study, a pumping plant efficiency worksheet was used to record the necessary parameters used to calculate %-NPPPC. In this publication by Scherer and Weigel, %-NPPPC was termed ‘relative pumping plant efficiency’ (RPPE). After completing this worksheet to obtain RPPE for a particular irrigation unit, the grower was then provided a recommendation on how to manage the pumping plant moving forward. If the measured RPPE was over 90%, the pumping plant was considered to be operating at a satisfactory level, and no maintenance or other corrective action was needed. When RPPE fell between 80% and 90%, the grower was advised to consider reviewing the pumps performance and design, with corrective action possibly being economically beneficial. In most cases when RPPE fell in this bracket, it was suggested that corrective action would only be economically viable if accompanied by some other necessary maintenance or repair job. All pumping plants with RPPE less than 80% were said to be operating at “low efficiency”, and the irrigator was encouraged to take corrective action as soon as possible. At this point, the extension service tried to isolate the cause of inefficiency as related to the well screen, a worn or out of adjustment pump bowl or impeller, or a dropping water table increasing TDH causing decreased pump inefficiency. This process was aided by but not completely dependent on obtaining the pump curve for that particular pump system, which was used to determine whether the pump was operating within its peak efficiency range.

The results of this pump efficiency testing program as outlined by Scherer and Weigel showed that, of the 621 systems tested, 460 of tested below 90% of the NPPPC. Assuming each of these units was adjusted to operate at 100% of the NPPPC, it was estimated that about 2.5 million kilowatt-hours of power could be saved during one growing season on these units alone. Based on the total number of pumping plants within the state, this study suggested that approximately 10.8 million kilowatt-hours and about $760,000 could be saved per irrigation year in the state of North Dakota alone at the time of publication. Despite the fact that the sample size was relatively small for diesel pumping plants, the data collected suggested that a higher percentage of electric motors were operating below the 80% low efficiency benchmark. It was concluded that this was likely due to diesel engines requiring more frequent supplemental maintenance since load changes on diesel engines due to poor pump performance are far more detectable. Over the fifteen year duration of this data set, the percentage of systems operating below 80% of the NPPPC stayed nearly constant at about 28%. At the beginning of the study (1978-1980), most tests were performed on newly installed systems. At the latter part of the study (1988-1992), most tests were performed on recently converted low pressure sprinkler packages. Most systems were either new or refurbished at the beginning and end of the testing while still consistently having about 28% of systems operate below 80% of the NPPPC. This is quite significant, suggesting that poor design upon installation could be the driving factor of low efficiency in irrigation pumping plants.

A similar study was performed by Henggeler (2013) through the University of Missouri Commercial Agricultural Program. This study consisted of pumping plant evaluations in the Southeast Missouri (SEMO) region on approximately 150 pumping plants. Diesel and electric driven pumping units were tested at varying PWL's. Since PWL could not be controlled by adjusting groundwater characteristics within the aquifer, increases in P_d caused by adjusting risers or pipe discharges were used to simulate increases in PWL. In addition, the diesel systems were tested at variable pumping speeds, using engine speeds of 1250, 1350, 1450, and 1550 RPM.

Standard pump testing methods and instruments were used to collect the data needed for Henggeler's study. Q_d was calculated by recording the totalizer value at two different times from a McCrometer propeller located at pumping discharge, using change in total volume of water pumped over a given time interval (dt). PWL and SWL were measured using an e-line depth sounder lowered between the column pipe and well casing. When the tester was unable to drop the depth tape sensor between the casing and column pipe, secondary access was obtained and only SWL could be obtained. P_d was determined using a pressure gauge tapped into the horizontal pumping discharge pipe or vertical standpipe. A graduated cylinder and stopwatch were used to measure fuel flow for diesel powered systems. To test fuel flow, the engine was adjusted to the desired test speed and the intake and return lines placed within a 3000 ml graduated cylinder. Had the return line not been placed back into the graduated cylinder, the mass balance of the measurement would have been compromised, and an inaccurate fuel consumption rate observed. Electric energy consumption was recorded by obtaining data from the meter face and timing a set number of revolutions on the electric meter.

Pumping plants within the SEMO testing area draw from the Southeast Lowlands alluvial aquifer, with most wells having SWL values of approximately 30 m and Q_w values as high as 681 m^3/hr. Automated monitoring wells in the region showed an average annual decrease in SWL of approximately 1.5 m across the study location, with these values ranging from 0.6 m to 4.6 m depending on the amount of water withdrawal in the general vicinity and the geological aquifer characteristics specific to the immediate area of the well. Based on a simulation modeling study by Henggeler (2006), a 1.5 m decrease in TDH for a high-flow/low-head pumping system typically used within the SEMO region would result in a decrease in pumping capacity of approximately 25%. In addition, the 1.5 m decrease in SWL has an even greater impact on PWL. Henggeler identifies head difference as the driving force as water transport through the ground media and into the well casing, so the loss in aquifer head is referred to as the falling head problem validated by Darcy’s Equation.

Not only is a measurement of drawdown needed to calculate TDH, but it was also used by Henggeler to calculate specific capacity (SC). SC is the ratio of Q_w drawdown at the well intake. Despite also being influenced by groundwater head differences, resistance to flow through a well's gravel pack media and/or intake screen can also decrease SC. Therefore, unusually low SC values can identify design/maintenance issues such as improper design of gravel pack particle size, improper well screen design or blockage, and insufficient design of screen size. Also, SC is used to illustrate the "falling head problem" when plotted against PWL. This comparison shows that SC exhibits linear decline as PWL increases. In other words, water pumped from deeper depths results in decreased relative yield from the aquifer.

In terms of diesel powered irrigation systems, the SEMO study is quite useful based on its analysis of individual systems at variable engine speeds. The 1350 RPM tests had, on average, the lowest COW and highest OPPE and %-NPPPC. The highest engine speed, 1550 RPM, yielded the highest COW. Despite yielding the lowest COW on 75% of tests, the 1250 RPM tests resulted in the lowest efficiencies of all speeds. Despite these statistics, it must be taken into account that the trends in COW and pumping plant efficiency at variable engine speeds are a direct result of the amount of PWL and friction losses occurring within the system. For example, a relatively large PWL would require a furrow irrigator to run a diesel motor at high speed (in this case 1550 RPM) to provide adequate flow to meet crop water demand.

Often times, capital cost of diesel engines is the primary factor growers consider when choosing a unit. This often results in diesel power units being purchased that are undersized for a particular load, making it necessary to run the engine at its maximum speed setting to service a particular load. This shortens the operational life of the system and often makes it less efficient in terms of the volume of water that is pumped per volume of fuel consumed. Harrison and

Tyson (2012) of University of Georgia Cooperative Extension show that the diesel engine manufacturer's engine performance data often includes a curve showing "amount of fuel per horsepower hour". They suggest that it is a fiscally responsible practice for irrigators to select a unit based on this curve rather than simply considering capital cost. At higher engine speeds, friction loss and draw down will act to increase TDH, which also increases the COW.

In addition to variable engine speed, the SEMO study also included simulated changes in PWL using both electric and diesel systems. By adjusting a gate valve, P_d values of zero, five, eight, and thirteen psi were introduced to the system, where each additional psi of added P_d simulates a 2.31 foot drop in water level. Regionally accepted values for diesel fuel and electricity ($3.50/gal and $0.11/kWh) were used in calculating COW. The linear relationship between COW and PWL demonstrated a COW increase of about 4.5 cents per acre-inch for diesel systems and three cents per acre-inch on electric systems for each additional foot of PWL introduced to the system. Henggeler also concluded that furrow irrigation systems are much more sensitive to dropping water tables than electric pivot systems, with Q_w reductions of 75% and 11% respectively at 30 feet of additional PWL.

The SEMO pumping plant study also showed that the system characteristic with the greatest impact on water delivery cost was PWL. According to Henggeler, a common misconception is that achieving satisfactory pumping plant efficiency is the key to minimizing delivery costs. However, it was concluded that even if all pumps within the study area were brought to maximum efficiency (100% of the NPPPC), the net benefit would only be about $6.00 annually per acre irrigated. The magnitude of importance for these two parameters in terms of their effect on COW was determined by quantifying the linearity of their respective relationships with COW. PWL (R^2=0.58) far exceeded OPPE when quantifying their linearity using linear regression (R^2=0.17). Henngeler identified well efficiency as being vital in minimizing drawdown which keeps PWL in check. Therefore, it was concluded that proper design and maintenance of down hole well components such as gravel pack media and the well screen is important in minimizing COW when irrigating using groundwater pumping plants.

Pumping plant performance in Arkansas was evaluated in twenty counties during the 1987 and 1988 irrigation seasons. Tacker and Langston (1987) evaluated 102 pumping plant systems, which were a variety of diesel, natural gas, and electrical systems. This publication is unique due to its evaluation of both groundwater and surface water relift systems. Just as in the North Dakota and SEMO pumping plant studies, these evaluations within the state of Arkansas measured PWL, SWL, Q_w, and input energy consumption rate to evaluate pumping plant performance using traditional testing methods. By measuring these parameters, the energy consumption per unit of water pumped and per operational time as well as the amount of energy wasted due to poor pumping plant efficiency was determined.

At the time of Tacker and Langston's publication, it was estimated by the Soil Conservation Service that the average pumping plant efficiency of wells similar to those tested within this study was only about 68% of the NPPPC. In addition, University of Arkansas Cooperative Extension estimated annual spending for pumping irrigation water to be approximately forty million dollars. Therefore, it was concluded that identifying sources of lost efficiency could be a lucrative for farmers as well as environmentally positive due to diminished energy use in the form of fuel, electricity, natural gas, etc.

At the time of the publication by Tacker, approximately 90% of pumping plant systems in the state of Arkansas were either diesel or electric powered systems. Similarly, 78% of the pumping plant systems included in the study were diesel or electric powered, with nearly half of systems tested being categorized as electric submersible wells. Only 76 of the 102 total systems tested were reported in the final publication due to incompletions in data collection on some systems.

Results of Tacker and Langston's study showed minimal variability in terms of average %-NPPPC by energy type. Natural gas, conventional electric, diesel, and submersible electric had %-NPPPC values of 60%, 77%, 71%, and 65% relatively. Submersible electric pumps were separated due to their unique configuration. This publication estimates that, under normal conditions, submersible pumps can be expected to have an optimal pumping efficiency approximately 10% lower than a vertical hollowshaft turbine well installation. Therefore, the realistic standard for submersible pumps is probably somewhere around 85% of the listed NPPPC value for electrical units.

Average COW ($/acre-ft) separated by energy source were $15.04 for electric submersible, $12.13 for conventional electric, $8.25 for natural gas, and $5.51 for diesel. However, energy costs have changed drastically since the time of press, particularly concerning a major price increase in diesel fuel. Since energy cost values used for calculations were included in this paper, reasonable values for energy cost in 2013 can be used to show a present day economic comparison by energy type using this study. This method showed present day equivalent COW values of $16.71 (electric submersible), $13.48 (electric), $11.25 (natural gas), and $31.79 (diesel). Therefore, the cost of diesel increasing nearly five-hundred percent since 1988 has vastly changed the landscape in terms of delivery cost. This publication presents diesel as being the most cost efficient for irrigation in terms of cost per acre-foot of delivery per foot of operating head ($1.04/acre-ft/ft) and electric submersible being the most cost inefficient ($2.26/acre-ft/ft).

Urrestarazu and Burt (2012) with California Polytechnic University evaluated historical pumping plant data in the Salinas, Sacramento, and San Joaquin Valleys of California. This data was collected from the 2005-2009 irrigation seasons, and included over 15,000 electric irrigation pumping tests. Approximately 85% of the systems tested were well pumping plants. Annual energy consumption figures were provided for approximately one third of the entire pump test data set. This study used Minitab 16.1.0 statistical software to perform a multivariate cluster variable analysis on the available pumping plant data. This technique was used to identify trends and correlations between performance variables such as TDH, Q_w, drawdown, P_d, energy consumption per volume of water pumped, annual energy consumption, and OPPE.

To evaluate potential energy savings associated with different system characteristics, pumping plant data sets were grouped by their annual energy consumption, TDH, and Q_w. Within each group, an average OPPE was measured, and all systems below this benchmark within a particular group were said to have potential for improvement. The actual OPPE was then divided by the average OPPE for a particular group, to get a percent-difference in performance level. This value could then be multiplied by the present annual energy consumption for that particular pumping plant and an assumed cost of electricity. This calculation yields a potential savings figure for each particular pumping plant. These values were then summed and averaged across each individual group.

Results of the variable correlations for well pumps proved to be much clearer than for non-well pumps, or relifts. For well pumps, OPPE values proved to be better on average for pumping plants exhibiting high TDH, Q_w, and input power values. This correlation was strongest for TDH, where only 16% of pumping plants tested at TDH greater than 120 meters having an OPPE of less than 50%. Conversely, 85% of pumping plants having OPPE less than 50% were operating at a TDH less than 75 m. Similarly, high pumping Q_w values (even at low TDH values) and high input power values showed correlation with increased OPPE values, only with slightly more exceptions as compared to TDH. Contour plotting also showed a direct correlation between increasing OPPE with increasing annual energy consumption (MWh/year).

As stated above, non-well pumps had overall weaker trends and correlations between variables as compared to well pumps. However, higher values of TDH, Q_w, and input power were still connected to higher OPPE values for non-well pumps. Unlike with well pumps, annual energy consumption and OPPE showed little or no correlation with one another.

Results of the potential savings by category showed that 35% of well pumping plants and 51% of non-well pumps (relifts) within this study had poor OPPEs, meaning their overall efficiency was under 50%. Only 6% and 9% of systems respectively had OPPE values greater than 70%. Potential savings per pumping plant are higher when a higher annual consumption of electricity is realized. For this reason, a small fraction of the well systems evaluated (2.5% of all wells > 400 MWh/year) accounted for about 12% of the total savings that could be achieved. Similar results were found for non-well pumping plants, where systems placed in the high annual power consumption group accounted for 4% of total pumping plants but could be used to achieve 25% of the savings. The savings calculation method mentioned above estimated that for well and non-well pumps, approximately \$7,400/year and \$5,000/year could be saved respectively by OPPE improvement. Contour plots were then created which showed which input power/OPPE combinations exhibited the highest potential savings for both well and non-well pumps. For well pumps, systems with approximately 100 kW input power and 30-40% OPPE showed the greatest potential savings. Non-well pumps showed high potential savings for similar OPPE values, but with more savings to be had in the 150-250 kW input power range.

Materials and Methods

Measuring Input Energy Consumption

An irrigation pumping plant uses an input energy source (electricity, diesel, natural gas) to produce rotational power driving pump impellers for water delivery (Nebraska/MSU Irrigation Audit Manual, 2012). Some of this input energy, depending on system efficiency, is conveyed for to water via pumping. Rate of energy into a system, or power, is a key parameter in pumping plant performance testing. The power supplied must be measured to obtain an accurate assessment of pumping parameters including OPPE, %-NPPPC, and COW.

A variety of input power sources can be used for irrigation purposes. According to Rogers and Alam (1999), input energy forms used in irrigation include but are not limited to natural gas, gasoline, diesel, propane, ethanol, and electricity. For this study, pump monitors were only installed on diesel engines and conventional electric motors (as opposed to variable frequency drives), since these power sources make up the vast majority of pumping plant installments in the state of Arkansas. Therefore, energy consumed by irrigation systems was shown in terms of gallons of diesel burned for diesel systems and kilowatt-hours of electricity consumed for electric systems.

Measuring Diesel Fuel Consumption. Diesel consumption was measured using Futurlec 2.0 to 30.0 L/hr diesel fuel flow sensors. These sensors provide a digital output using a 2.4 V to 26 V supply. The Futurlec sensors were plumbed in line with the primary fuel line connecting the diesel engine fuel intake with the fuel source, which was typically a cylindrical diesel tank. In order to accurately measure total diesel fuel consumption, the diesel return line had to be plumbed into the primary fuel line downstream of the fuel flow sensor. Typically, the return line returns recycled fuel directly to the fuel tank. By plumbing the return line downstream of the fuel sensor, conservation of mass is upheld and fuel flow reported by the sensor represents total fuel consumed by the system. These sensors produce a digital voltage output, so the fuel flow was reported digitally on the pump monitor control box in the field as well as on the Diesel Engine Motor website.

Fuel Flow Sensor Calibration. The digital output by the Futurlec fuel flow sensor was converted to a real time fuel flow value using a “pulses/gallon” calibration factor. This calibration factor was a manual input to the pump monitor, which was adjusted using the menu options on the pump monitoring control box produced by DEM. The control box had the ability to use this calibration input and a pre-determined time step in a programmed algorithm to output a value for fuel consumption rate. The algorithm in place reports diesel fuel flow in units of gallons per hour (gph). The appropriate calibration input values are a non-linear function of the approximate flow rate which they are measuring. Therefore, testing was performed in the lab to determine the approximate pulses per gallon calibration value that should be input when the sensors were installed in the field.

Fuel flow sensor calibration testing was performed using a pressurized diesel tank to create a control flow into a five gallon bucket through 3/8 inch rubber fuel line. Individual sensors were then plumbed into this fuel line to replicate field installations for testing. The control flow generated was measured by recording the mass of diesel fuel in the five gallon bucket in 15 second increments over a time interval of five minutes using a digital precision mass balance.

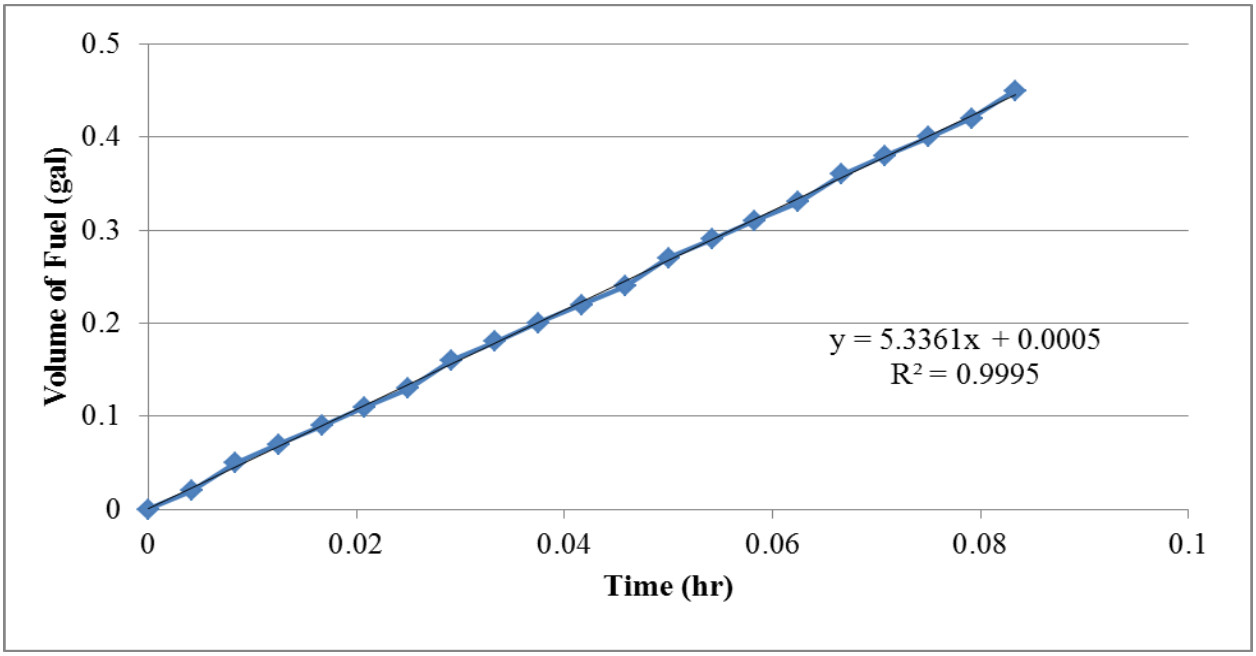
Before diesel fuel flow was initiated through the fuel flow sensor, the digital precision balance was zeroed so that the digital display value would indicate the mass of the fuel which had flowed into the bucket, subtracting the mass of the five gallon bucket. Using a stop watch and laptop computer, the mass of fuel in the bucket at each 15 second time interval was recorded into a spreadsheet, where a graph of mass flow over time was generated. The slope of this graph represented the control flow in terms of weight per unit of time elapsed in units of pounds of diesel fuel per minute (lb/min). Dividing this value by the density of diesel and other simple unit conversions were used to express this flow in the desired units of gph. The density of the fuel tested was measured using a Durac 0.65-1.00 Specific Gravity (SG) Hydrometer. (www.coleparmer.com). The SG Hydrometer showed a diesel density of approximately 7.09 gal/lb. The equations used to determine control diesel fuel flow rate are shown below, followed by an example of the measured control diesel fuel flow data and subsequent graph generated shown in Figure 2:

$$V_{fuel} = W_{fuel} \times \frac{1}{\rho_{fuel}}$$

$$Q_{fuel} = \text{slope} = \frac{\Delta W_{fuel}}{\Delta t}$$

Where: V = volume of diesel (gal); W = weight of diesel (lb); ρ = fuel density $\left(\frac{lb}{gal}\right)$.

Figure 2. Graph of Actual Lab Collected Control Diesel Flow Data used for Fuel Flow Sensor Calibration.



As the equations shown above were being used to determine the exact control diesel fuel flow rate, the same flow was also being measured using a Futurlec fuel flow sensor. A DEM pump monitoring control box was available in the testing lab so that the digital fuel flow reading could be observed and compared to the corresponding control diesel fuel flow value. The pulses/gallon calibration value was then adjusted accordingly through the control box until the diesel fuel flow value reported by the digital display on the DEM control box matched the measured control flow value.

Fuel Flow Sensor Complications. Lab testing was effective in developing a relationship between the actual flow being measured and the appropriate input value of pulses per gallon. The results of this testing were used to manually input calibration values for all previously installed and new fuel flow sensor installations prior to the 2013 irrigation season. The calibration value applied for each diesel fuel flow sensor was made based on the expected range of fuel flow at which a particular system was expected to operate in accordance with the relationship between flow and appropriate calibration value input. Some error in the data collected from these sensors was created by inconsistency between individual sensors in terms of the pulses per gallon value input to make the reported flow value match the actual flow being measured. Variation was approximately 10% within individual sensors, indicating that each individual field installment needed to be calibrated in the lab.

In some cases, diesel pump monitors began reporting consistent and accurate fuel flow data when these lab calibrated sensors were installed in the field. However, inconsistency or complete failure in diesel fuel flow data collection was observed on around 80% of diesel pump monitoring systems. A combination of harsh environmental conditions in the field, improper installment, and/or fuel debris clogging was likely responsible for this lack of consistency in diesel fuel flow data collection. It was suspected that high ambient temperatures were a major source of sensor degradation and/or lack of measurement accuracy. The Futurlec fuel flow sensor used was rated to operate at a maximum fluid temperature of 140 degrees Fahrenheit. A Fluke infrared temperature camera (www.fluke.com) was used to evaluate surface temperatures around the fuel sensors installed on some diesel pumping plant sites. These measurements showed temperatures often exceeding 150 degrees Fahrenheit at the ground surface near the diesel engine where the sensor was located at most monitoring sites. Although a maximum ambient air temperature rating was not listed for the fuel flow measurement instrumentation, it is likely that being subjected to such extreme temperatures for extended periods has an adverse effect on the integrity of the sensor over time.

Spatial orientation of the fuel flow sensors was also a suspected cause of inconsistencies in performance when dealing with fuel flow sensors. Each sensor indicates which side of the device should be pointing upward when installed. In this particular study, the fuel flow sensors were plumbed in line with the main fuel line and often were suspended in air by the connections, often disregarding the need for proper spatial orientation of the sensor. Diesel fuel flow data collection in the future could prove to be more accurate, less noisy, and be more consistent with lab results if the fuel flow sensors are installed with this specification considered.

Despite their installation always being downstream of the fuel filters located at the outlet of the diesel holding tank, debris in the fuel line was another issue causing inconsistencies in data collection and failure of fuel flow sensors. Therefore, it was necessary for fuel filters to be replaced when needed and the fuel flow sensors periodically checked and/or replaced to ensure a consistent and complete data set over the course of an irrigation season. Whether or not this field maintenance could be performed in a timely manner to ensure a complete annual data set was dependent on the geographical location of the particular monitoring site and other labor constraints. A combination of the installation and operational issues mentioned above are likely the main sources of error and inconsistency in fuel flow data collection, and greatly diminished the amount of diesel pumping plant data that could be reported at the time of this publication.

Field Testing and Verification. Due to inconsistency in sensor reliability between monitoring sites and degradation as a result of environmental exposure, field testing for data verification was performed to ensure that the data that was being reported by the online database was accurate. If a particular data set was found to include diesel flow data from a flawed sensor, an attempt was made to retroactively correct the flawed data. If data being reported by the pump monitor was fairly smooth and consistent (minimal noise) at constant engine speed, a percent-difference method of correction was applied. For example, if the recorded flow value proved to consistently be 20% lower than the control value at variable flow rates, the historical data was corrected in Excel by applying a multiplicative correction factor to raise all measured flow values by 20%. In situations where a fuel flow sensor completely failed and either no data or flawed data was recorded, fuel flow estimates could sometimes be salvaged. This was only possible in situations where P_d and Q_w data was available and had been field proofed previous to the fuel flow sensor failure. In addition, a previous PWL measurement was necessary and had to be confidently assumed as constant over time. This assumption was considered reasonable when dealing with certain surface water relift systems where PWL was thought to be relatively static. In these situations, reliable fuel flow data collected previous to the sensor failure could be used to retroactively replace flawed or missing data following the sensor failure. The assumptions/conditions mentioned above allowed previous fuel flow values to be applied to flawed or omitted data only if the TDH (from P_d and PWL) and engine speed at any given time were a reasonable match. Although this method operated using some relatively weak assumptions, it managed to salvage a reasonable estimate to the grower of annual fuel consumption, COW, and %-NPPPC which would not have otherwise been possible. When calibration and/or verification of diesel fuel flow measurements was necessary, one of the methods detailed below was used to measure actual fuel flow in the field.

Graduated Cylinder Method. The most precise method of diesel consumption data verification used was the graduated cylinder method. This method of flow measurement was performed using a 3000 ml graduated cylinder with a flow restricting quarter-turn ball valve and connected hose barb. This valve apparatus allowed the primary fuel line to be removed from the diesel holding tank and plumbed directly into the graduated cylinder using the same fuel line and a hose clamp. A diesel fuel filling jug was always brought to field testing locations since not all diesel holding tanks made it possible to fill the graduated cylinder. Similar to the fuel flow sensors, it was important to ensure that the return line connection was located downstream of the graduated cylinder or placed to return fuel into the graduated cylinder so that fuel flow from the graduated cylinder was a representation of the total amount of fuel consumed by the diesel engine. Where the return line was not plumbed into the primary fuel line downstream of the graduated cylinder, the return line was directed into the top of the graduated cylinder as mentioned above. Running the return line into the graduated cylinder caused turbulence within the cylinder, making it difficult to read the exact volume remaining in the cylinder at a given time. This introduced error into the fuel flow calculation. Therefore, it was ideal to have the return line plumbed into the primary fuel line. The cylinder was also carefully mounted as level as possible to increase accuracy when visually reading volume from the graduated cylinder markings. When the primary fuel line was switched from the diesel holding tank to the graduated cylinder, air bubbles caused by fuel leakage out of the fuel line often formed within the line. Therefore, the fuel pump lever located at the engine’s fuel intake was always used to remove these air bubbles by priming before the engine was powered on. Failure to do so almost always led to issues with getting the engine to start and run properly.

To measure fuel flow using the graduated cylinder method, the graduated cylinder was filled to approximately 2500 ml and the engine was powered on. After allowing the system to run for approximately one minute to reach steady state in terms of fuel consumption, an initial diesel fuel volume within the cylinder was measured. A stopwatch was simultaneously started to measure the elapsed time until a second volume could be measured. Initial and final diesel fuel volumes were always taken at times where the diesel remaining in the cylinder stood exactly at the level of a measurement tic marking on the graduated cylinder to maximize precision. Longer testing times leading to larger volumetric consumptions result in more accurate fuel flow measurement, but care had to be taken to ensure that the graduated cylinder did not run out of fuel. The following equation was used to calculate diesel fuel consumption rate using the graduated cylinder method:

$$Q_{fuel}=\left(\frac{V_0\text{-}V_f}{t}\right)\times\left(3600\ \frac{sec}{hr}\right)\times\left(0.000264\ \frac{gal}{ml}\right)$$

Where: V=cylinder fuel volume (ml); Q=fuel flow $\left(\frac{gal}{hr}\right)$; t=elapsed time (sec).

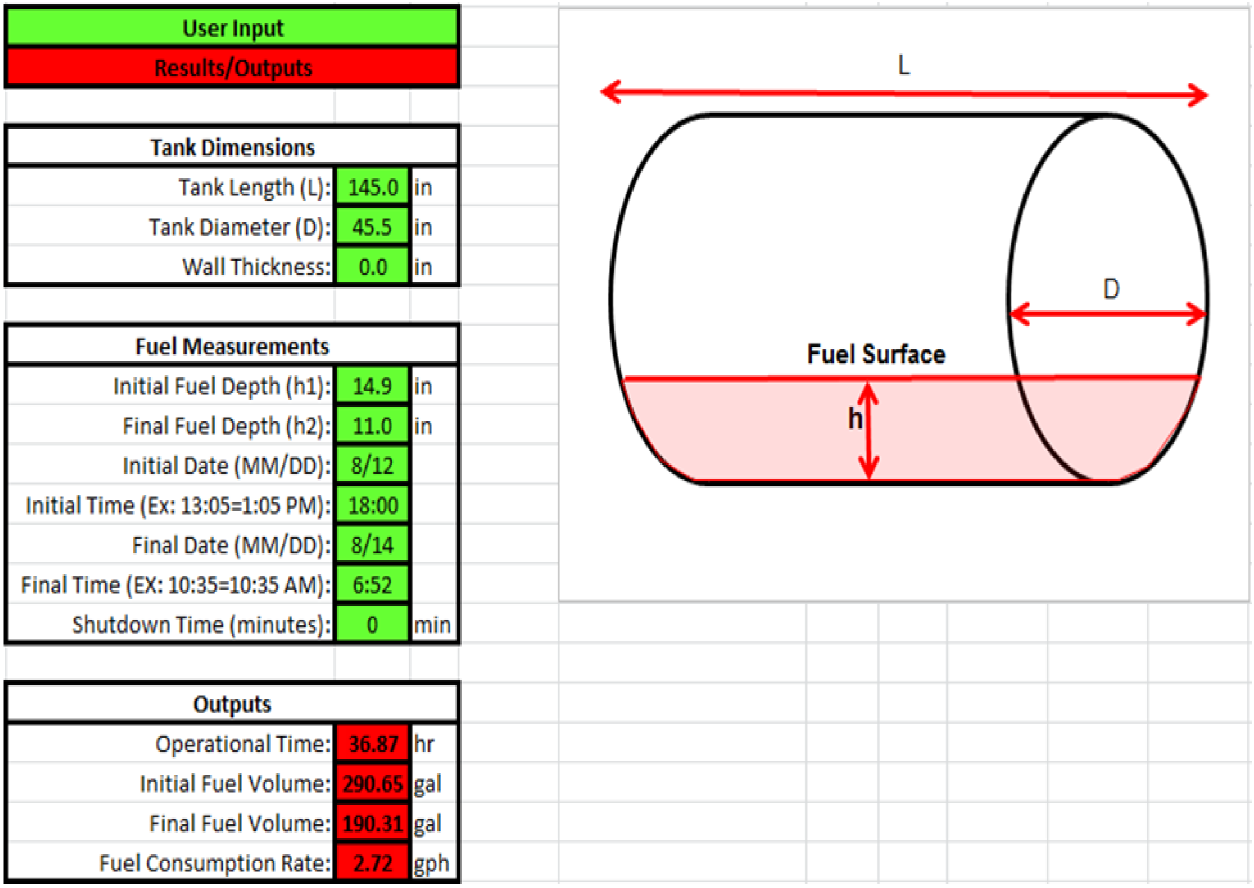
Figure 3. Graduated Cylinder Method of Diesel Fuel Flow Measurement.

Manual Tank Volume Method. In some cases, general system setup (buried or rigid fuel line) or lack of communication with the producer made it impossible to implement the graduated cylinder method for testing diesel fuel consumption rate. In this case, the volume of diesel within the holding tank, measured at two different times, was used to estimate rate of diesel fuel consumption to verify the fuel flow data being reported. To perform this measurement, a piece of 1 inch PVC pipe was cut and marked in quarter inch intervals to create a device for measuring depth of fuel remaining within the diesel holding tank. Upon arrival at a diesel pump monitoring site, this device was inserted into the opening at the top of the cylindrical holding tank. When the PVC measurement device was removed, the residual diesel remaining on the surface of the pipe was observed using a tape measure, and a depth measurement of diesel within the tank was recorded. The time of day and date at which this measurement was taken was also recorded. In order to minimize error, the measurement pipe was carefully inserted into the opening in the tank, making sure to insert the measurement pipe perpendicular to the surface of the fuel within the tank. Swift or careless insertion of the measurement device would result in a false measurement if not placed perpendicular to the fuel surface. Also, care was taken to ensure that the surface of the fuel was not disturbed. Agitation of the liquid surface would result in a false fuel depth measurement greater than the actual level within the tank due to rippling. Next, the dimensions of the tank were measured. A tank diameter measurement at the circular ends of the cylindrical tanks as well as the length from end to end was measured using a measuring tape. These measurements were then adjusted using an estimated tank thickness, usually 0.25 inches, so that the tanks volume measurements would represent the interior holding capacity of the tank. Upon returning to the monitoring site, the same fuel depth measurement was taken within the diesel holding tank and recorded with the coinciding date and time of day.

To obtain a reasonable value of fuel consumption rate using this method, it was mandatory that the diesel tank not be refilled between depth measurements, and that the engine speed (RPM) of the diesel engine remained constant through the duration of the test. In addition, if the system was powered off at any time between fuel depth measurements, the input value representing elapsed time used in calculating fuel consumption rate had to be properly adjusted.

The DEM website was used to see if constant engine speed was upheld and to monitor whether any shut-downs occurred through the duration of the test. A spreadsheet calculator, shown in Figure 4, was built that takes into account all variables mentioned above including shutoff and startup times. Constant engine speed still had to be maintained for the entire duration of the test to calculate diesel consumption using this workbook.

Figure 4. Screen Capture of Fuel Volume Calculator Created in Microsoft Excel.



User Input

Results/Outputs

Tank Dimensions		
Tank Length (L):	145.0	in
Tank Diameter (D):	45.5	in
Wall Thickness:	0.0	in

Fuel Measurements		
Initial Fuel Depth (h1):	14.9	in
Final Fuel Depth (h2):	11.0	in
Initial Date (MM/DD):	8/12	
Initial Time (Ex: 13:05=1:05 PM):	18:00	
Final Date (MM/DD):	8/14	
Final Time (EX: 10:35=10:35 AM):	6:52	
Shutdown Time (minutes):	0	min

Outputs		
Operational Time:	36.87	hr
Initial Fuel Volume:	290.65	gal
Final Fuel Volume:	190.31	gal
Fuel Consumption Rate:	2.72	gph

When using the tank volume method, calculus was used to calculate volumetric change across each time interval due to the non-linearity of the relationship between fuel volume and fuel depth within a cylindrical holding tank. Assuming the tank is lying parallel to the ground surface, the following equation is used to represent the volume of fuel within a partially filled horizontal cylindrical holding tank according to Weisstein (2014):

$$V_{fuel}=L\left[R^2\cos^{-1}\left(\frac{R-h}{R}\right)-(R-h))\sqrt{2Rh-h^2}\right]$$

Where: V=fuel volume; L=cylinder length; R=end radius; h=fuel depth.

Sonic Level Tank Volume Method. Some diesel pumping plant monitoring systems included fuel depth sensors, which acoustically measured the distance from a point at the top of the tank to the surface of the fuel within the holding tank. A programmed algorithm was then used to convert this distance from the top of the tank to the fuel surface to an actual depth of fuel remaining within the tank. In the case that the grower ran a diesel system for an extended period (3-4 consecutive days) at constant RPM, these measured fuel depth values could be used to calculate fuel flow using the same calculations as the aforementioned manual tank volume method. Rippling on the fuel surface causing noise as well as limited data resolution (0.1 inches) limited the effectiveness of this method, but it was useful as a supplementary verification method to one of the fuel flow measurement methods above. In addition, this pump monitoring feature allowed the grower to accurately determine when diesel holding tanks would need to be refilled, which minimizes the number of times filling has to be performed over the course of an irrigation season.

Measuring Electricity Consumption. Early in the pump monitoring study (2011-2012), electricity consumption (kW) was measured using power measurement instrumentation which was installed into the electrical box on site. These devices measured voltage (V), power factor (PF), and current (A) using current transformers (CTs). PF, according to Emanuel (1993) is a percentage value showing how effectively electricity is being utilized, indicated by a ratio of actual power to apparent power. PF is a measure of how “in phase” the current and voltage are in an AC electrical distribution systems. Most inductive loads (Ex: electric motors) produce a power factor in the 75-90% range according to the article from Lauren's Electric. These measurement instruments, which relayed electrical data to the control box on site, were compatible with Wye and Delta 3-phase configurations. If PF at a particular site could not be measured directly, a multiplicative value of 0.8 (80% PF) was used to calculate electricity consumption applying Watt's Law for 3-phase power shown below as taken from "Principles of Process Engineering" by Henderson, Perry, and Young (1997):

$$\mathrm{kW_{applied}} = \left[\frac{(\mathrm{V_{avg}}) \times (\mathrm{A_{avg}}) \times (\sqrt{3}) \times (\mathrm{PF})}{1000}\right]$$

Since all pumping plant data was analyzed in hourly averages, using this equation with the average voltage and amperage measured across each one hour time interval yielded electricity consumption in kWh. Despite success using this method, a change was made in the method of electricity consumption measurement for two primary reasons. First, frequent damage to pump monitoring systems occurred due to lightning strikes, which primarily affected their ability to measure power consumption. Also, little to no variability in consumption within or between irrigation seasons was observed, which minimized the need for a continuous measure of electricity consumption. For these reasons, only spot field measurements of electricity consumption were used starting approximately half way through this 4-year study. When only spot measurements were taken, a concerted effort was made to take electricity consumption measurements using the electric meter at several points in time throughout the irrigation season and at every irrigation setup if TDH was varied substantially through the season. This method is described below in the section titled "Utility Electric Meter Method".

Field Testing/Verification. The method for verifying the accuracy of electrical consumption data being collected was determined by site-specific characteristics of the electric motor in questions. Where applicable, a Fluke 434-II power analyzer (www.fluke.com) was used to measure electricity consumption on site. Due to arc flash concerns associated with hooking up the Fluke power analyzer to the electrical power source, only certain personnel associated with this study were permitted to access the electrical control box to hook up the analyzer. Therefore, not all electrical pumping plant electrical consumption data could be verified using the Fluke analyzer. Typically, reading of the utility electric meters was used to obtain a control value control value of electricity consumption in units of kilowatt-hours/hour (kWh/hr). In order to implement this method, it was necessary to confirm that the electric motor associated with the irrigation pumping plant in question was the only power draw connected to the meter. In some cases, an analog electrical meter was in place. More often, a digital electric meter was present.

Utility Electric Meter Method. Analog electric meters refer to the traditional meters with a counterclockwise spinning disk in the meter face. To read this type of meter, the number of revolutions of the spinning disk is counted over a measured time interval. For computational simplicity, a number of rotations in increments of 10 (typically 20 or 30 rotations) was counted, depending on the speed of rotation. In addition to this measurement, the Kh multiplier was also required to calculate electrical consumption in kilowatt-hours per unit of time, and could typically be directly observed off of the face of the meter. Since data analysis was performed in Microsoft Excel using hourly averages of each pumping plant performance parameter measured, the electric consumption was calculated in units of kilowatt-hours consumed per operational hour. The following equation was then applied to obtain the electricity consumption value in units of kilowatt-hours per hour, with the methodology described in detail by Henry and Stringam (2013):

$$\frac{\text{kWh}}{\text{hr}} = \frac{(3.6)\times(\text{Kh})\times(\text{Number of Revolutions}) \times (\text{Company Multiplier})}{\text{Time in Seconds}}$$

Digital meters, which are now typically used on new installations, are very similar in principle to the traditional analog meters mentioned above. Rather than a rotating disk which is used to count rotations, digital meters typically feature a flashing bar pulse which acts as a simulated disk. Each full pulse of the simulated disk is equivalent to one rotation of the analog spinning disk as mentioned in the method above. It should be noted that when reading electrical meters, the utility company should be periodically contacted to ensure accuracy in measurement. In some instances, a multiplier is used by the utility when reading these meters, particularly on the older analog meter installations.

Once kilowatt-hours consumed over time was calculated, this value was compared to the value being reported by the DEM website for the corresponding pumping plant. In most instances, the field measurement and value reported by the website were very similar if not identical. If the discrepancy in values was less than 5%, no further data correction or field maintenance was performed. If the field measured value and website values were significantly different, a note was made to correct the corresponding electricity consumption data using a column operation multiplier when the complete annual data set was exported to Excel. All methods for reading and calculating power usage using various types of meters were taken from the factsheet cited above to Henry and Stringam (2013).

Power Analyzer Method. In the event of a discrepancy between these measured values of electricity consumption, a Fluke power analyzer was used to take a more detailed look at the harmonics and power factor associated with the site. Difference in the two values was typically linked to a significant difference between the actual measured power factor of the electricity consumed by the system and the assumed power factor of 0.85 applied by the DEM website. When power consumption per hour was verified using one of the methods described above, the cost of pumping was calculated by multiplying this value by a cost of electricity per kilowatt-hour. Cost of electricity per kilowatt-hour can be obtained from the local power utility, but \$0.10/kWh was applied as a regional average based on information from the U.S. Energy Information Administration website. This value represents a composite average of electricity costs across the pump monitoring study area at the time of publication, and does not take into account rebates from utility programs such as load management shutoffs.

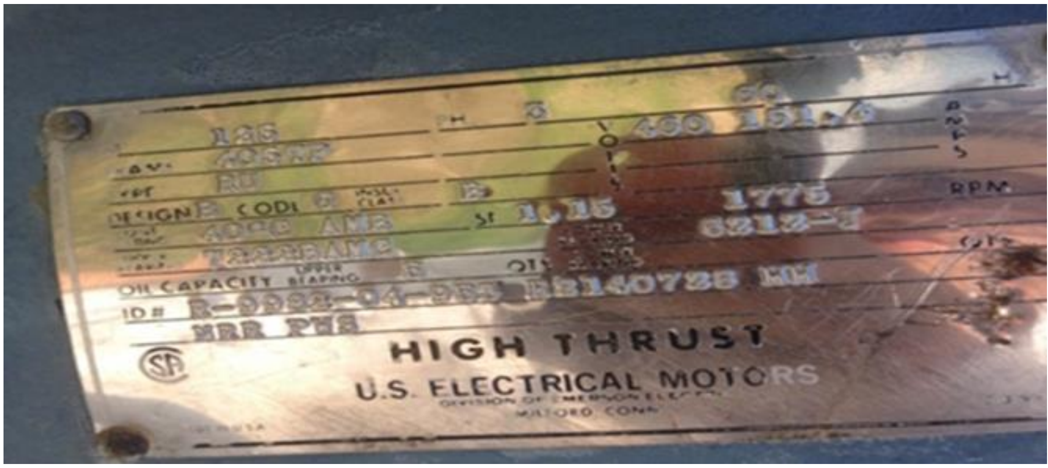
Calculating Loading as Percentage of Nameplate Horsepower. Electricity consumption data collected using pump monitoring was used to compare measured power draw to the nameplate power rating for individual irrigation pumping plants. According to Arnold (2007), electric motors typically operate most efficiently when shaft power is approximately 75-100% of the nameplate power rating. Significant efficiency losses take place when shaft horsepower falls below 50% of the motor's nameplate rating. Despite irrigation motors' typical capability of operating at loads 15% higher than the nameplate power rating (SF=1.15), long term operation into the service factor can result in degradation due to overheating. In addition to significant losses in efficiency, oversizing of electric motors inflates capital costs, as motors with larger nameplate power ratings tend to be more expensive. To evaluate improper electric motor sizing as a potential cause of decreased pumping plant efficiency and increased capital cost, the following equations were applied to the collected electricity usage data:

$$\text{Measured HP} = (\text{Measured kW}) \times 1.341$$

$$\text{Shaft HP} = (\text{Measured HP})\times(\text{NEMA Efficiency})$$

$$\%\ \text{of Nameplate}=\frac{\text{Shaft HP}}{\text{Nameplate HP}}$$

Figure 5. Nameplate from 60 HP (45 kW) Electric Irrigation Motor.



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Water Horsepower and its Components

The section above details the measurement of energy input into irrigation systems using a pump monitoring approach. In order to parameterize irrigation pumping plant performance, the rate at which this energy is used by the pump system to perform work for pumping must be measured. According to Stringam (2013), water-power (whp or w-kWh) is defined as the minimum power required to pump water, or the power requirement of a pump assuming 100% efficiency. Within this study, the calculation of water-power was important because it was used directly to quantify pumping plant performance relative to the NPPPC. This criterion quantifies a “well maintained and well designed” pumping plant performance in terms of the expected ratio of water-power conveyed to the water pumped by the system per unit of input energy consumed. To calculate water-power, P_d, PWL, and Q_w must be measured. These performance values can be applied to the equation shown below to calculate water power in whp:

$$\text{whp}=\frac{\left((P_d \times 2.31)+(\text{PWL})\right)(Q_w)}{3960}$$

Where: P_d=discharge pressure (psi); Q_w=flow rate (gpm); PWL=pumping water level (ft).

During this study, Q_w and P_d were typically measured using a continuous pump monitoring approach. Conversely, a PWL measurement component was not included in the pump monitoring systems, so these values had to be measured manually on an instantaneous basis and retroactively applied to pumping plant performance data to complete the data needed for a complete pumping plant evaluation. The instrumentation, measurement techniques, and calibration methods associated with measuring these components of whp are detailed below.

Pumping Flow Measurement and Calibration. Obtaining an accurate measurement of Q_w and total annual water pumped was a primary focus through the course of this study when performing quality control in the field on pump monitoring installations. In cases where other parameter measurements (P_d, input energy, etc.) failed or were found to be inaccurate, important information could still be provided to both the grower and for research purposes provided an accurate measure of Q_w was still being taken. For example, by knowing total water pumped and the total area being irrigated, the grower could always be aware of the depth of water that had been applied on a particular field or fields serviced by a particular monitored pumping plant. In addition, annual decrease in Q_w due to aquifer drawdown and total water pumped during an irrigation season could still be calculated when analyzing the data for research purposes.

A variety of environmental factors in the field contributed to the data being provided by water flow meters becoming inaccurate and/or out of calibration over time. First, it was found that algal growth within the flow meter rotational mechanisms, particularly during prolonged shutoff periods between irrigation seasons, typically created friction. This compromised the ability of the propeller to spin freely. Any interference or friction within the propeller rotational mechanism caused the number of pulses sent from the flow meter to the control box to decrease for a particular volume of water passing through the outlet pipe, causing the system to become out of calibration. In some cases, this same phenomenon would cause a complete binding of the propeller, making Q_w appear to be zero despite the pumping system being powered on. In this case, the flow meter would have to be removed from the outlet pipe and thoroughly cleaned to return it to an operational state.

Figure 6. Mineralization and Debris Causing Flowmeter Binding.

Another environmental factor leading to inaccuracy or failure of pump monitoring water flow meters was debris being pumped through the discharge pipe, causing the propeller mechanisms to become bound as mentioned above. This problem was particularly common with surface water relift monitoring systems, where water was being pumped from surface canals or ditches by a mixed flow pump. These pumps tend to pump a large amount of debris such as algae and sticks. In the case that the flowmeters in place became bound by debris, the same maintenance procedure mentioned above was performed to free the rotational mechanism.

Figure 7. Servicing a Jammed Pump Monitor Flow Meter to Remove Surface Water Debris. Note. Used With Permission from Photographer Colt Oade.

Flowmeter Quality Control. The primary instrument used in the field for measuring a control value of Q_w was an ultrasonic flow meter. The particular flow meter used was a Sierra InnovaSonic Model 210i. This flowmeter, assuming optimal conditions as given by the user manual, produces a Q_w reading at +/- 1% accuracy on pipes from 1 inch to 48 inches in diameter and water velocities up to 40 feet per second. This system uses clamp on magnetic transducers to measure water velocity within the pipe. The flowmeter uses this measurement of water velocity within the pipe multiplied by the pre-programmed cross sectional area of the pipe being measured to display a Q_w value. The methods used for setting up and obtaining reliable flow measurements using the Sierra ultrasonic flow meter are detailed below.

Flowmeter Setup. Within the user interface on the Sierra ultrasonic flowmeter, there are a wide variety of user inputs, which define the system being measured to ensure accuracy and consistency of flow measurement. Some of these inputs remained constant between sites while others had to be changed at each location. The parameters listed below are the primary user inputs, which had to be changed from site to site when performing irrigation pumping plant flow measurements for calibration purposes:

- Pipe Material (Menu 14): User enters wall material of the pipe, with pre-programmed inputs including PVC, carbon steel, and aluminum.
- Pipe Liner (Menu 16): User enters wall liner material, with pre-programmed inputs including paint, tar, and polyurethane.
- Pipe Outer Perimeter (Menu 10): User enters outer perimeter (circumference) of the pipe, which is measured using a tape measure around the pipe.
- Pipe Wall Thickness (Menu 12): User enters the wall thickness of the pipe, which can be accurately assessed using a thickness probe accessory on the Sierra flowmeter or using a pipe size chart. This value along with the outer perimeter is used to calculate interior cross-sectional area
- Transducer Mounting Method (Menu 24): User enters the mounting method (Z or V Method) depending on the size of the pipe and other characteristics of the measurement location.

The following outputs provided by the Sierra flowmeter were always checked within the menu after the user inputs above had been set to reflect the properties of the system being measured:

- Transducer Spacing (Menu 25): Based on the parameters entered above, the Sierra flowmeter provides a spacing value which is measured then used to space the transducers to ensure a quality flow measurement
- Cross-Sectional Area (Menu 27): Based on the sizing parameters, the Sierra flowmeter calculates the interior cross-sectional area, which should always be checked and compared to the nominal pipe size to check that pipe sizing parameters have been correctly entered.

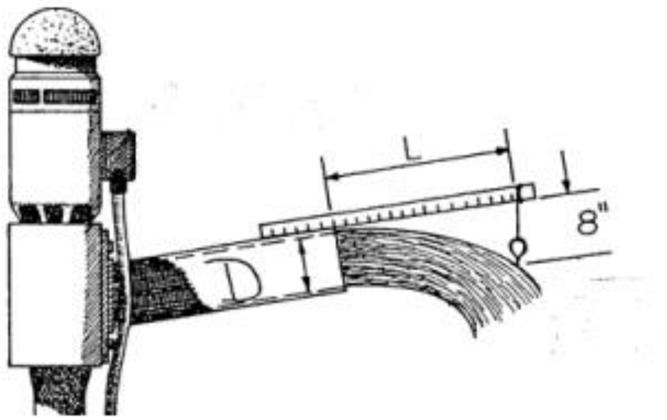
Figure 8. Cross-Checking Flow Values of a McCrometer Saddle Propeller Flowmeter and a Sierra 210i Ultrasonic Flowmeter.

Insertion Flowmeter. Another method of obtaining a control Q_w value for calibrating the pumping Q_w values being measured by the pump monitoring systems was the use of an insertion flowmeter. The insertion flowmeter used was a Badger SDI series digital read propeller flowmeter (www.badgermeter.com). This method involved plumbing a 10 foot length of 8 inch, 10 inch, or 12 inch diameter PVC pipe into a vacant riser bonnet. It was important to ensure that all water that was being pumped at the time of the Q_w measurement was being diverted only through the riser bonnet to which the PVC pipe section was plumbed. The insertion flowmeter value measured, where possible, was cross-checked using the Sierra ultrasonic flowmeter. Comparing the readings from the Badger and Sierra flowmeters consistently produced Q_w values within 5% of one another.

A limitation of the use of insertion flowmeters was the measurement of surface water relift Q_w values. While measuring Q_w of surface water relift systems, debris such as algae, moss, or sticks being pumped by the surface water pumping plants often caused the Badger propeller meter to drag, causing a false zero Q_w reading. In this situation, only the Sierra ultrasonic could be used.

Plumb Bob Method. The plumb bob method was simply used to increase confidence and verify Q_w values measured using any of the techniques listed above. This method proved especially useful where there was a steady, fully laminar flow characteristic exiting the pipe exactly horizontally, or parallel to the ground. This method proved very consistent to control values measured using other techniques where the above water discharge characteristics were observed. An 8 inch drop plumb bob yardstick provided by Delta Plastics was typically used when implementing this method. The method of measuring Q_w using a plumb bob can be seen in *Figure* 9.

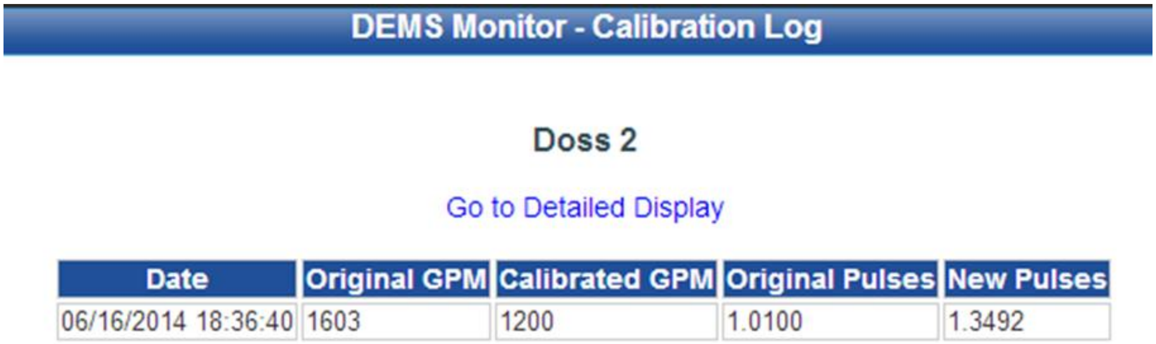
Figure 9. Plumb Bob Method of Water Flow Measurement/Verification. *Source:* University of Arkansas.



DEM Website Calibration Tool. Upon measuring a control Q_w value using one of the methods listed above, the flow value was then entered into the DEM website by the tester for the corresponding pumping plant. When this value was entered, the calibration factor was automatically adjusted to make the Q_w value displayed by the website match the control value measured in the field.

Initially, there was no historical information stored by the website regarding the date, time, and value of the control Q_w values entered for flowmeter calibration. A key adjustment made approximately half way through this study was the addition of a historical flow calibration log. By recording calibration entries, historical Q_w data can be back corrected based on the percent change between the new calibrated Q_w value measured in the field and the previous value being reported by the website. Before this feature was added, prior calibrations had to be detected during data analysis by inspecting a graph of flow over time. The appropriate correction multiplier was then applied to the historical data to gain an accurate assessment of annual water application and other flow information.

Figure 10. Screen Capture of DEM Website Calibration Log. *Note.* From www.dieselenginemotor.com. Reprinted with Permission.



DEMS Monitor - Calibration Log

Doss 2

Go to Detailed Display

Date	Original GPM	Calibrated GPM	Original Pulses	New Pulses
06/16/2014 18:36:40	1603	1200	1.0100	1.3492

Calculating Annual Flow Decrease. The pump monitoring approach to pumping plant testing made it possible to evaluate trends in Q_w throughout entire irrigation seasons for individual pumping plants. Since irrigation pumping withdrawals exceeding recharge rate is typically the driving force in loss Q_w over time, the evaluation of annual Q_w decrease was limited to well systems. Conversely, Q_w values of relift pumping plants in the short term are typically dependent on the level of water within a ditch or reservoir as dictated by rainfall or irrigation runoff.

To quantify annual Q_w decrease of individual monitored well pumping plants, Q_w per volume of water pumped (gpm/acre-in pumped) and a percent-difference from the start of the season to the end was calculated. The percent-difference calculation used the following equation:

$$\%\ \text{Flow Decline} = \left(\frac{Q_0 - Q_f}{Q_0}\right) \times 100$$

Where: Q_0=initial flow rate at beginning of irrigation season (gpm); Q_f=flow rate at beginning of final irrigation set of the season.

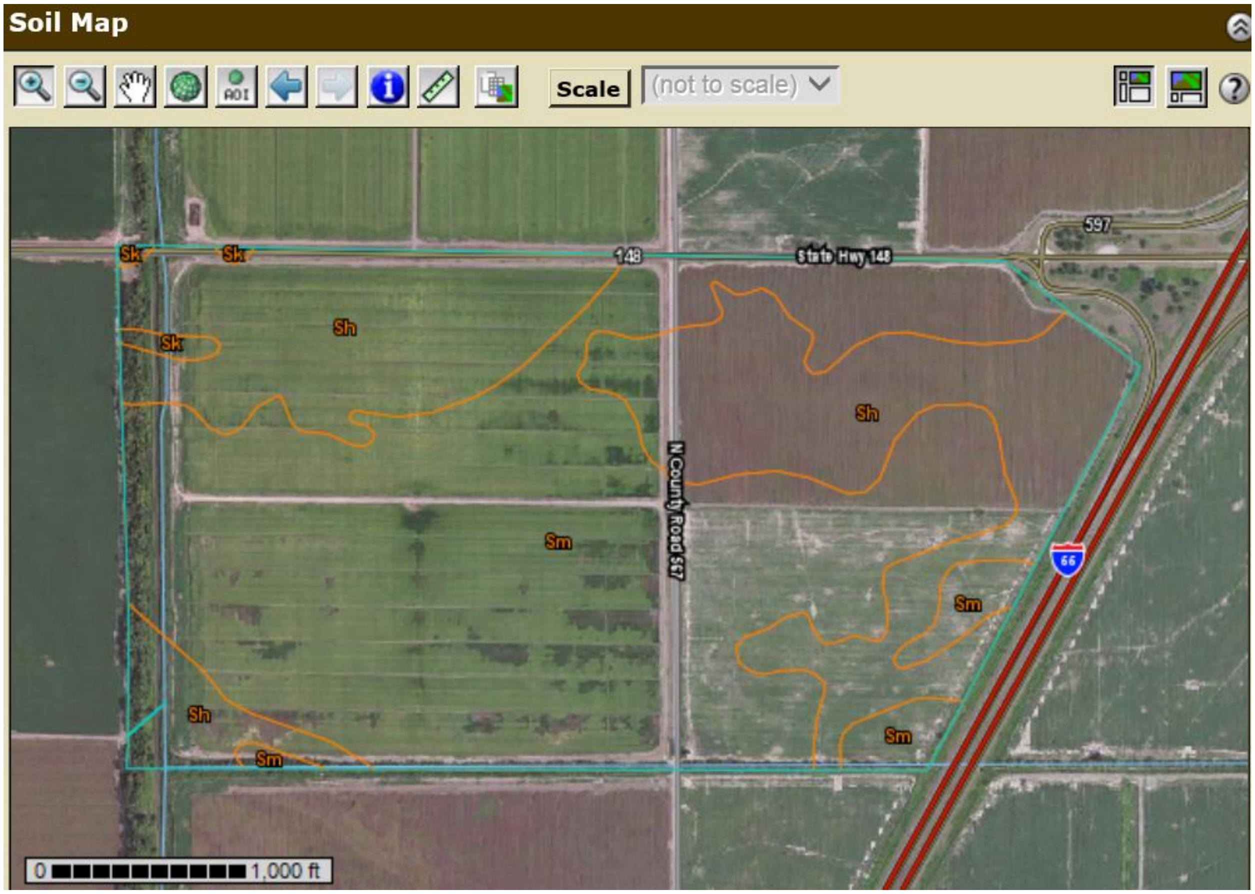
Q_w at the beginning of the first and last irrigation set of the season were used as the final and initial values for calculating Q_w decrease using percent-difference. It should also be noted that when the pumping plant data indicated that multiple irrigation sets were being serviced which changed TDH, the final and initial Q_w values were taken from data measured at the same operational condition. These specifications were used so that the analysis of annual Q_w decrease was consistent and only indicative of changes in pumping performance caused by change in aquifer level over time.

***Measuring Irrigation Pumping Capacity*.** Q_w data measured using both instantaneous testing and pump monitoring were used to calculate irrigation capacity (IC) for individual pumping plants within the study. Different recommendations for minimum and desired Q_w per area of land irrigated are typically provided as a function of geographical area, soil type, and the crop being irrigated. Since most if not all pumps within this study were used to provide irrigation water for rice, this crop was used as a "worst case scenario" since it requires the most pumping capacity of any crop serviced within this study. A recommended minimum IC provided by the 2013 Arkansas Rice Production Handbook (Table 2) was used as the benchmark value to classify the adequacy of IC for pumping plants within this study. Soil types for each pumping plant were determined using Web Soil Survey (Figure 11.)

Table 2
Minimum and Desired Irrigation Capacity Values by Soil Type for Rice Taken
From the 2013 Arkansas Rice Production Handbook.

Soil Textural Group	IC Recommendations (gpm/acre) ; *((m^3/hr/ha))*	
	Minimum	Desired
Silt loam – with pan	10.0 ; *5.7*	10.0 ; *5.7*
Sandy Loam	15.0 ; *8.5*	25.0 ; *14.2*
Silt Loam-no pan	10.0 ; *5.7*	15.0 ; *8.5*
Clay and silty clay	15.0 ; *8.5*	20.0 ; *11.4*

Figure 11.
Using Web Soil Survey (www.websoilsurvey.nrcs.usda.gov) to Determine Soil Type of Fields Serviced by Well Pumping Plants in Mississippi County, AR near Osceola, AR.



The pump monitoring IC data was classified as “Below Adequate”, “Sometimes Adequate”, or “Always Adequate” based on how actual pumping plant performance compared to the Arkansas Rice Production Handbook recommendation for IC by soil type. The instantaneous test data was classified as “Below Adequate” or “Adequate”, since these tests only provide one-time assessments of IC, where it can’t be determined if IC is “Sometimes Adequate”. To determine how often an instantaneous, pre-irrigation flow test may be inaccurate in determining annual IC, the percentage of operational time that a monitored system was adequate or inadequate was also reported.

Measuring Total Dynamic Head. In the equation for whp shown above, Q_w is multiplied by TDH, which is then divided by a unit conversion constant. Therefore, it can be seen that the mathematical term for TDH within this equation is as follows:

$$TDH = (P_d \times 2.31) + (PWL)$$

Where: P_d=discharge pressure (psi); PWL=pumping water level (ft).

This TDH equation assumes that friction loss in the well column and minor losses such as velocity head loss and losses through pipe elbows are negligible. The methods of PWL and P_d measurement used for determining TDH is detailed below.

Pumping Water Level. PWL is the depth at which an irrigation pumping plant must lift water from the hydraulic surface of the water source to the pumping discharge while the system is pumping. SWL is the depth to the hydraulic surface before an irrigation pumping plant becomes operational. The difference between these two parameters is known as drawdown. When possible, SWL and PWL were measured so that drawdown could be assessed. As detailed in the SEMO study by Henggeler (2013), dividing pumping Q_w by drawdown to calculate SC can help identify when there is a downhole issue with the pump, well screen, and/or gravel pack. In many situations, PWL could not be measured because only the well column, and not the casing, could be accessed. Ideally, a plug was in place to that allowed us to use a Global Water WL500 well level sounder tape to access the well casing so that PWL and SWL could both be measured. Unfortunately, no instrumentation was in place to allow depth to water (SWL or PWL) to be measured continuously using the pump monitoring testing approach, so these measurements were limited to instantaneous field measurements. Many of the monitored pumping plant systems within this study did not have plugs to access the well casing, so only the column could be accessed. In these scenarios, SWL could be measured, but not PWL. In other scenarios, neither SWL nor PWL could be measured. An example of the well sounding tape being used to take a PWL measurement on a surface water relift is shown in Figure 12.

Figure 12. Measuring PWL of a Well Pumping Plant Using a Sounding Tape.

Discharge Pressure. P_d, as shown in the equation for TDH above, accounts for the downstream pumping head against which a pump system must operate. P_d was measured continuously using a variety of 4-20 mA pressure transducers, which were selected based on the expected range of pressures that would be measured at the pumping discharge. P_d measurement was often problematic due to surges in pressure causing sensors to fail, resulting in a “zero” reading until the pressure sensor could be replaced. These issues were due to incorrect selection of sensor pressure ranges based on expected ranges of P_d. This problem was fixed later in the study by selecting sensors with higher pressure ratings, meaning that they were able to withstand a higher range of pressures without failing.

Pressure Sensor Verification. Early in the study, a 1/4 inch NPT glycerin filled needle pressure gauge would simply be placed in the tap hole previously occupied by the pump monitoring pressure sensor to verify the P_d value being reported by the DEM website. Later, a Fluke 700G06 0-100 psi precision pressure sensor (Figure 13) was used to perform field verification of P_d measurements, which was used similarly to the manual read pressure gauges. The Fluke precision pressure gauge had a digital readout screen and reported P_d to the nearest one-hundredth of a psi. On most occasions, the pump monitoring pressure sensor measurements being reported by the DEM website were accurate (+- 5%) relative to the control values measured during field verification testing.

Figure 13. Measurement of Discharge Pressure of a Relift Pumping Plant using a Digital Fluke Pressure Gauge.

Calculating Cost of Water. Since the DEM pump monitoring systems were capable of measuring Q_w and energy consumption rate (kWh/hr of electricity or gph of diesel fuel), pumping data was used to calculate COW for each monitored pumping plant throughout an irrigation season. COW refers to the approximate amount of energy cost by per unit volume of water pumped. COW was reported in units of dollars per acre-inch ($/acre-inch) and dollars per hectare-meter ($/ha-cm). One acre-inch represents the volume of water that would stand one inch deep on one acre of land area. Similarly, one hectare-centimeter represents the volume of water that would stand one centimeter deep on one hectare of land area.

In order to calculate COW, regional averages of unit cost of tax-free farm diesel and electricity were collected and these values applied to the Q_w and energy consumption data. Energy cost estimates were made using present day (2011-2014) information from the U.S. Energy Information Administration website (www.USEIA.com). The cost value used for tax free farm diesel was \$3.30/gal. The cost value used for electricity was \$0.10/kWh. The following equation was used to calculate COW for electrical pumping plants using Q_w and electricity consumption data:

$$\frac{\$}{\text{acre-inch}} = \frac{(E_{total}) \times \left(\frac{\$0.10}{\text{kWh of electricity}}\right)}{Q_{total}}$$

Where: Q_{total} = total water pumped (acre-in); E_{total}= total electricity consumed (kWh).

Similarly, the following equation was used to calculate COW for diesel pumping plants using Q_w and diesel consumption data:

$$\frac{\$}{\text{acre-inch}} = \frac{(D_{total}) \times \left(\frac{\$3.30}{\text{gallon of diesel}}\right)}{Q_{total}}$$

Where: Q_{total} = total water pumped (acre-in); D_{total} =total diesel fuel consumed (gal).

When evaluating electric pumping plant data, COW was primarily reported in terms of annual average and how annual values reacted to seasonal Q_w decrease of well pumping plants. Diesel pumping plant COW calculation, while similar to electric, was also evaluated in terms of how it was affected by engine speed (RPM). This analysis was performed in an effort to determine what engine speed(s) resulted in the lowest COW at different operational conditions. COW comparisons between pumping plants of different energy sources (diesel and electric) at similar operating conditions were also made to evaluate potential savings associated with diesel to electric conversion.

Comparing Cost of Water of Diesel and Electric Pumping Plants. Determining the COW for diesel and electric pumping plants operating at similar conditions can help determine whether it is advantageous economically to convert from diesel to electric powered pumping plants. Both pump monitoring annual average data and instantaneous testing data were used to analyze the difference in COW between these two input energy sources. This data was grouped by input energy source and system type. Since TDH directly affects COW, each individual value was also normalized by TDH, allowing COW to be directly compared for systems operating at variable heads. COW data was normalized by TDH by dividing COW values by one tenth of the corresponding TDH value. This resulted in a parameter representing COW per 10 feet of TDH. As seen in Figure 15, the systems were grouped into electric surface relifts, electric alluvial wells, electric deep wells, diesel surface relifts, and diesel alluvial wells. No data for diesel powered deep wells was available.

Calculating Annual Cost of Water Increase. Annual Q_w decrease of well pumping plants also affected COW. As Q_w declines, COW tends to increase, since less water is being pumped and a similar amount of energy is being consumed. This phenomenon can be seen where continuously measured Q_w and COW values were plotted together for each monitored pumping plant in the appendix. Since the DEM pump monitoring systems continuously measured both electricity consumption and Q_w, annual COW was also calculated using the following equation.

$$\text{Annual COW Increase (\% = } \left(\frac{\text{COW}_f\text{-COW}_0}{\text{COW}_f}\right)\times 100$$

Where: COW_0=cost of water at beginning of irrigation season; COW_f=cost of water at end of irrigation season.

Calculating Percent of Nebraska Pumping Plant Performance Criteria. By having a measurement of Q_w and TDH to determine whp, pumping plant efficiency can be determined as a percentage of the Nebraska Pumping Plant Performance Criteria. The following equation is used to calculate %-NPPPC.

$$\text{\%-NPPPC}=\frac{\left(\frac{\text{whp-hr}}{\text{Unit of Fuel Consumed}}\right)}{\text{NPPPC Constant}}$$

The NPPPC constants for each fuel type can be found in Table 1 (Table A - 1 in metric units). Further description of the NPPPC can also be found in the same section. Since no instrumentation was available to continuously monitor PWL, some TDH values used in calculating %-NPPPC were estimates of annual average PWL based on measurements taken at or near the site in question depending on well casing accessibility. If possible, PWL of each pumping plant within the study was measured using a well sounding tape multiple times throughout the irrigation season to allow for a precise assessment of average %-NPPPC.

Calculating Potential Savings from Improving %-NPPPC. Potential savings using annual average operational time and %-NPPPC values was evaluated using a method shown in Table 8 of the NRCS (2009) WQT03 Water Quantity Enhancement Activity, which is available on the NRCS website. This worksheet shows potential energy and cost savings estimated from annual hours of operation using the equations shown below:

$$\text{EEC}=\left(\frac{100\text{-(\%-NPPPC)}}{100}\right)\times\text{EU}$$

Where: EEC = rate of excess energy consumption (unit/hr); %-NPPPC = percent of the Nebraska Pumping Plant Performance Criteria (%); EU = rate of total energy used (unit/hr).

$$\text{PAS}=\text{EEC}\times\text{AHO}\times\text{UCE}$$

Where: PAS = potential annual savings ($/season); AHO = annual hours of operation (hr); UCE = unit cost of energy ($/unit).

For this analysis, the composite averages of pumping plant operational times and energy consumption rates measured using both pump monitoring and traditional instantaneous testing were applied to the equations above. Since some system types had limited data for calculating average operational time, the composite average operational time of every monitored pumping plant was applied to estimate potential savings for each system type. Operational times for each system type can be seen in Table 2. Average %-NPPPC values by system type can be seen in Table 14.

The potential savings values shown in Table 15 are estimates of average savings that could be achieved assuming pumping plant performance is increased to 100% of the NPPPC via system maintenance or redesign. It should be noted that the potential savings values suggested in Table 15 are directly correlated to the composite average operational time value used. Therefore, potential savings estimates could be adjusted for pumping plants where various factors (rainfall, crop demand, etc.) result in different expected or observed values of operational time.

Summary of Statistical Methods

- Linear Regression: Linear regressions were performed in Microsoft Excel to characterize the linearity of data which, when plotted, appeared to be linear in nature. When applying linear regressions to plotted data, Excel can be used to generate a line of best fit and corresponding equation, as well as a measure of "goodness of fit (R^2). An example of applied linear regression can be seen in *Figure **14***, where linear regression is applied to analyze the relationship between annual COW increase and annual Q_w decrease.
- One Way Analysis of Variance (ANOVA): One-Way ANOVA tests were used to compare group mean data between 3 or more groups, and were performed using SigmaPlot statistical software. The one-way ANOVA operates under the assumptions of normally distributed residuals, independent sampling, and equal variance of populations. If these assumptions were met, the software generated a P value based on sum of square

variations about the group means. $P<0.05$ suggested that the null hypothesis, that samples are drawn from identical population means, be rejected. Rejection of the null hypothesis suggests a statistical significant among group means. An example of a one-way ANOVA can be seen in the appendix (Analysis A – 8), where %-NPPPC values are grouped by geographic location and tested for significant differences.

- Tukey Post Hoc Test: A Tukey test was performed in SigmaPlot if the results of a one-way ANOVA suggested significant difference among group means. Tukey tests are used to evaluate significant difference between pairs of individual groupings, which can also be seen in Analysis A – 8. Here, $P<0.05$ suggested significant difference between individual group means.
- Mann-Whitney Rank Sum Test: SigmaPlot suggested the Mann-Whitney Rank Sum test when t-tests were being performed but the data failed to meet either the normal distribution or equal variance assumptions. This test is the non-parametric counterpart to the t-test, which tests for significant difference between two group means. This test analyzes the equality of medians rather than means using a calculated U statistic and critical T value as shown in Analysis A – 1, where COW by energy source was tested for significant difference between group medians.
- Kruskal-Wallis One-Way ANOVA on Ranks: The Kruskal-Wallis one-way ANOVA on ranks is a non-parametric statistical test, which is used automatically by SigmaPlot when one-way ANOVA assumptions are not met. As seen in Analysis A – 3, a test statistic H and P value is calculated, which checks for stochastic dominance between samples suggesting significant difference in mean ranks.

- Dunn's Method: Also seen in Analysis A – 3, Dunn's method was run by SigmaPlot to perform a multiple comparison after a Kruskal-Wallis ANOVA on Ranks. Dunn's method is a non-parametric counterpart to a post hoc Tukey test. The Dunn's method shown in Analysis A-3 is using a test statistic Q and P value for each group pair to check for significant difference of mean ranks of COW by system type.
- Pearson Product-Moment Correlation: The Pearson Correlation is used to check for the degree of linearity between any number of paired variables, as well as positive or negative correlation between these variables. Pearson's correlation coefficient (r, 0-1) is calculated to show these relationships, with r values closer to one being the most linear in nature. Positive r values indicate a positive correlation between variables (as seen in *Figure **14***), while negative values indicate a negative correlation. Pearson correlation results are shown in Table A – 2, analyzing relationships between annual COW increase, annual Q_w decrease, and other pumping plant performance parameters.

Note: All details of the statistical methods listed above are taken courtesy of Devore (1982).

Results and Discussion

General Pumping Plant Performance Results

Table 3
Composite Annual Average Pumping Plant Performance Data from Instantaneous Testing and Pump Monitoring.

System Category	**Operational Time (hr)**	**Q_w (gpm)** ***(m^3/hr)***	**Electricity Consumption Rate (kWh/hr)**	**Diesel Consumption Rate (gph)** ***(l/h)***	**Avg TDH (ft)** ***(m)***	**n**
Electric Alluvial Wells	773	1841 *423*	39.6	-	60.1 *18.3*	38
Electric Surface Relifts	1187	2931 *674*	47.5	-	39.4 *12.0*	10
Electric Deep Wells	1480	1142 *263*	101.4	-	272.0 *82.7*	5
Diesel Alluvial Wells	-	1580 *363*	-	2.4 *9.0*	46.6 *14.2*	9
Diesel Surface Relifts	-	4631 *1065*	-	3.4 *12.8*	33.0 *10.0*	5
Electric Systems	890	1986 *457*	47.4	-	76.7 *23.3*	53
Diesel Systems	-	2670 *614*	-	2.7 *10.4*	41.1 *12.5*	14
All Systems	-	2133 *491*	-	-	70.3 *21.4*	67

General Pumping Plant Performance Discussion

Both pump monitoring and traditional instantaneous testing were used to collect irrigation pumping plant performance data during this study. Table 3 shows collective average performance values measured using both methods grouped by both irrigation system type and input energy source. It should be noted that an assessment of average operational time was only attainable by analyzing data collected using the pump monitoring testing approach. Due to the aforementioned issues limiting the amount of diesel system pump monitoring data collected, no values of operational time for diesel systems were reported. PWL measurements used to calculate TDH could only be measured instantaneously in the field using a well sounding tape. Therefore, the reported values of TDH were calculated using a combination of actual measurements and estimates based on measurements taken at nearby locations with accessible well columns. Q_w values collected using the instantaneous testing and pump monitoring annual averages were both included in the calculation of average Q_w for each category of pumping plant. In the case that diesel pumping plants were instantaneously tested at variable speeds or any pumping plant was tested servicing multiple irrigation sets, data was only included which corresponded to the most common operational condition (engine speed and/or TDH). Information regarding the most common operational condition was first sought by speaking with the grower. Where no information could be obtained from the grower regarding pumping plant operation, the data was averaged from the speeds where reasonable efficiencies and COW were measured. The general performance values in *Table **3*** were used repeatedly for a variety of calculations used to develop results and conclusions for this study.

Annual Pumping Flow Decrease and COW Increase Results

Table 4

Pump Monitoring Annual Pumping Flow Decrease Data of Well Systems.

System ID	**Year**	**Annual Q_w Decrease (gpm) ; *(m^3/hr)***	**Annual Q_w Decrease (% of Initial)**
FL Harr Farm North	2011	101 ; *23*	27.2
MS 11S 12S	2011	780 ; *179*	30.0
MS 11S 12S	2012	370 ; *85*	16.1
MS 11S 12S	2013	190 ; *44*	9.5
MS 14-18	2011	770 ; *177*	30.7
MS 14-18	2012	630 ; *145*	28.6
MS 14-18	2013	280 ; *64*	13.2
MS 17E 17W 18W	2013	130 ; *30*	7.5
MS 19	2013	110 ; *25*	7.8
MS 22-23	2011	385 ; *89*	15.0
MS 22-23	2013	310 ; *71*	10.8
MS 24-25	2011	810 ; *186*	31.3
MS 26-27	2013	290 ; *67*	13.4
MS 26-27	2014	250 ; *58*	11.6
MS 29N 29S	2013	205 ; *47*	9.4
MS 30	2011	218 ; *50*	14.2
MS 30	2013	145 ; *33*	9.3
MS 9N 10N	2011	280 ; *64*	13.0
MS 9S 10S	2011	1175 ; *270*	42.0
MS Rob High School	2013	260 *; 60*	12.6
MS Rob High School	2014	82 ; *19*	4.2
MS Stracener	2012	680 ; *156*	25.4
MS Stracener	2013	870 ; *200*	29.0
Drotar Well	2011	530 ; *122*	36.6
FL Frankie's House	2012	460 ; *106*	31.9
Losak	2011	220 ; *51*	21.6
Losak	2012	231 ; *53*	21.8
MS Stracener	2014	390 ; *90*	13.9

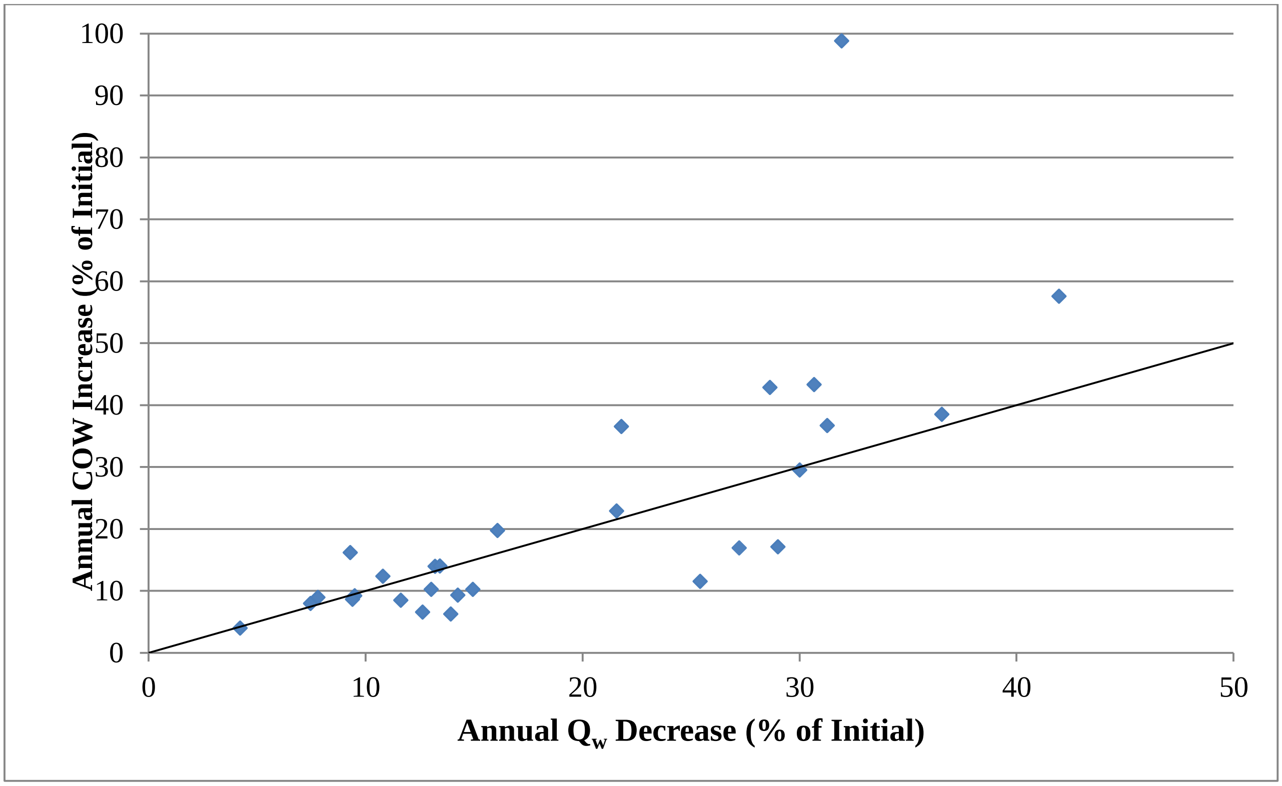
Table 5
Pump Monitoring Annual Cost of Water Increase Data of Well Systems.

System ID	**Year**	**Annual COW Increase ($/acre-in) ; *($/ha-cm)***	**Annual COW Increase (% of Initial)**
FL Harr Farm North	2011	0.36 ; *0.35*	16.9
MS 11S 12S	2011	0.18 ; *0.17*	29.5
MS 11S 12S	2012	0.15 ; *0.15*	19.7
MS 11S 12S	2013	0.08 ; *0.08*	9.2
MS 14-18	2011	0.29 ; *0.28*	43.3
MS 14-18	2012	0.33 ; *0.32*	42.9
MS 14-18	2013	0.11 ; *0.11*	13.9
MS 17E 17W 18W	2013	0.07 ; *0.07*	8.0
MS 19	2013	0.06 ; *0.06*	9.0
MS 22-23	2011	0.09 ; *0.09*	10.2
MS 22-23	2013	0.11 ; *0.11*	12.4
MS 24-25	2011	0.29 ; *0.28*	36.7
MS 26-27	2013	0.14 ; *0.14*	14.0
MS 26-27	2014	0.09 ; *0.09*	8.5
MS 29N 29S	2013	0.08 ; *0.08*	8.6
MS 30	2011	0.13 ; *0.13*	9.3
MS 30	2013	0.21 ; *0.20*	16.2
MS 9N 10N	2011	0.09 ; *0.09*	10.2
MS 9S 10S	2011	0.38 ; *0.37*	57.6
MS Rob High School	2013	0.05 ; *0.05*	6.6
MS Rob High School	2014	0.03 ; *0.03*	4.0
MS Stracener	2012	0.09 ; *0.09*	11.5
MS Stracener	2013	0.13 ; *0.13*	17.1
Drotar Well	2011	1.47 ; *1.43*	38.5
FL Frankie's House	2012	2.51 ; *2.44*	98.8
Losak	2011	0.68 ; *0.66*	22.9
Losak	2012	1.03 ; *1.00*	36.5
MS Stracener	2014	0.05 ; *0.05*	6.2

Table 6
Annual Pumping Flow Decrease and Cost of Water Increase Statistics of Well Systems.

Calculated Value	**Minimum**	**Maximum**	**Average**	**Standard Deviation**
Annual Q_w Decrease (gpm) *(m^3/hr)*	82.0 *18.9*	1175.0 *270.3*	398.0 *91.5*	279.1 *64.2*
Annual Q_w Decrease (% of Initial)	4.2	42.0	19.2	10.2
Annual COW Increase ($/acre-in) *($/ha-cm)*	0.03 *0.03*	2.51 *2.44*	0.33 *0.32*	0.53 *0.51*
Annual COW Increase (% of Initial)	4.0	98.8	22.1	20.5

Figure 14. Plot of Annual Q_w Decrease vs. Annual COW Increase



*Trend line shows expected y=x relationship between annual COW increase and annual Q_w decrease. The equation of the actual linear regression when forcing through zero is: ($y = 1.224x$, $R^2 = 0.53$).

Annual Flow Loss and COW Increase Discussion

As shown in Table 6, the average annual Q_w decrease for well pumping plants within this study was 398.0 gpm (91.5 m^3/hr), with values ranging from 82.0 gpm (18.9 m^3/hr) to 1175.0 gpm (273.0 m^3/hr). These Q_w decrease as a percentage of initial Q_w was 19.2%, with values ranging from 4.2% to 42.0%.

Table 6 also shows average annual COW increase values of well pumping plants within this study. The average annual COW increase was $0.33/acre-in ($0.32/ha-cm), with values ranging from $0.03/acre-in ($0.03/ha-cm) to $2.51/acre-in ($2.44/ha-cm). The average COW increase as a percentage of initial COW was 22.1%, with values ranging from 4.0% to 98.8%.

The study by Henggeler (2013) conducted in the SEMO region, suggests that COW of electric well systems increases approximately $0.30/acre-in per 10 foot drop in water table. Therefore, the average annual COW increase of $0.33/acre-in observed using pump monitoring suggests an average annual water table drop of approximately 11.0 ft (3.4 m). The same comparison suggests annual water table drops ranging from 1.0 ft (0.3 m) to 83.7 ft (25.5 m).

Table A – 2, located in the appendix, shows a Pearson Product Moment Correlation analysis between annual Q_w decrease, annual COW increase, operational time, and annual average Q_w. Annual Q_w decrease and annual COW increase were included as both actual change and percent change. Sigma Plot, which was used to run this test, indicates that the Pearson correlation coefficient (r) is a measure of the linear relationship between the variables in question, with values closer to 1 or negative 1 indicating a stronger association. All significant results ($p<0.05$) are bolded in Table A – 2. Pearson r-values closer to zero indicate more variation around the line of best fit. A positive Pearson r-value indicates a positive correlation between variables, and vice versa. All significant p values ($p<0.05$) are bolded in Table A – 2.

The strongest correlation between all variables tested was between annual Q_w percent decrease and annual COW percent increase ($r(26) = 0.744$, $p<0.0001$). This positive linear correlation is shown in

Figure ***14***.

If constant pump efficiency is assumed at variable TDH, COW would be expected to change perfectly proportionally to changes in Q_w. Therefore, the relationship plotted in Figure 14 between seasonal percent changes in Q_w and COW would be expected to be perfectly linear. Since it is known that pump efficiency does not remain constant as TDH changes, change in pump efficiency can be isolated as the driving force behind variability among the linear line of best fit shown. Using this logic, data points in Figure 14 located above the linear line of best fit where percent increase of COW is greater than percent decrease of Q_w would be associated with systems where pump efficiency decreased as TDH increased through the irrigation season. Conversely, data points located below the line of best fit would be associated with systems where pump efficiency increased as TDH increased with dropping water table levels. One data point in *Figure **14*** shows an annual COW increase of 98.8%, while annual Q_w decrease is only 31.9%. This particular data point is representative of a deep well system in Prairie County, AR in one of the most critical ground water depletion zones in the state. This system was likely designed to operate at much lower TDH, but is continuously moving its operational point further off the optimum efficiency point of its pump curve. This phenomenon seems to be reflected by the high COW increase relative to Q_w decrease. Further research using pump curves associated with the systems from which data was plotted is needed to confirm this theory.

Electric Motor Sizing Results

Table 7
Electric Motor Loading Pump Monitoring Data.

System ID	Year	NEMA Efficiency (%)	Nameplate Power (HP) ; *(kW)*	Min % Nameplate Power	Max % Nameplate Power
Drotar Well	2011	93.0	200 ; *149*	60	80
FL Harr Farm South	2011	88.5	30 ; *22*	44	65
FL Harr Farm North	2011	88.5	30 ; *22*	59	71
MS 11S 12S	2012	89.5	50 ; *37*	88	97
MS 11S 12S	2013	89.5	50 ; *37*	88	97
MS 11S 12S	2011	89.5	50 ; *37*	88	95
MS 26-27	2013	90.2	60 ; *45*	92	99
MS 9N 10N	2011	90.2	60 ; *45*	74	104
MS 9N 10N	2013	90.2	60 ; *45*	78	84
MS 22-23	2013	90.2	60 ; *45*	110	120
MS 28S	2013	91.0	40 ; *30*	77	86
BMCC-4	2012	92.0	100 ; *75*	74	86
BMCC-5	2012	92.0	100 ; *75*	75	86
MS Stracener	2013	95.0	60 ; *45*	89	108
MS 22-23	2011	90.2	60 ; *45*	90	107
MS 29N 29S	2013	90.2	60 ; *45*	89	102
MS 11N 12N	2013	89.5	50 ; *37*	82	97
MS Stracener	2012	95.0	60 ; *45*	76	97
Losak	2011	92.0	125 ; *93*	66	96
MS 24-25	2011	90.2	60 ; *45*	83	95
MS 30	2013	88.5	60 ; *45*	86	94
MS 30	2011	88.5	60 ; *45*	87	93
MS 17E 17W 18W	2011	90.2	60 ; *45*	65	89
MS 14-18	2013	90.2	60 ; *45*	78	86
MS 9S 10S	2011	90.2	60 ; *45*	71	89
MS 14-18	2012	90.2	60 ; *45*	71	78
MS 14-18	2011	90.2	60 ; *45*	72	78
FL Frankie's House	2012	93.0	200 ; *149*	62	77
MS 19	2013	90.2	60 ; *45*	39	44
MS 26-27	2014	90.2	60 ; *45*	95	104
MS Stracener	2014	95.0	60 ; *45*	84	101

Table 8
Electric Motor Loading Instantaneous Testing Data.

System ID	Year	NEMA Efficiency (%)	Nameplate Power (HP) ; *(kW)*	% Nameplate Power
Grubbs Well	2013	94.3	75 ; 56	68
Holaday Well 1	2014	90.2	60 ; 45	91
Holaday Well 2	2014	91.0	60 ; 45	83
Holaday Well 3	2014	91.0	60 ; 45	92
Holaday Well 5	2014	90.0	40 ; 30	111
Hilsdale Well 1	2014	88.5	60 ; 45	102
MS Hardy	2013	90	60 ; 45	80
Hazen West	2013	95.4	50 ; 37	104
Hazen Interstate	2013	89.5	40 ; 30	107
Hazen Jenkins	2013	90.2	60 ; 45	89
Stuttgart Relift	2013	93.0	150 ; 112	105
Station West Electric	2014	93.0	40 ; 30	70
Station East Electric	2014	93.0	40 ; 30	70
Station Old Electric	2014	89.0	20 ; 15	119
Rob Roy East	2014	91.3	75 ; 56	98
Rob Roy West	2014	90.2	60 ; 45	85
CP Shop Well	2013	92.0	150 ; 112	104

Table 9
Percentage of Undersized, Oversized, and Appropriately Sized Electric Motors.

Testing Type	Undersized Motor (%)	Oversized Motor (%)	Appropriate Motor (%)
Pump Monitoring (n=31)	19.4	25.8	54.8
Instantaneous Testing (n=17)	41.2	17.6	41.2
Total (n=48)	27.1	22.9	50.0

Electric Motor Sizing Discussion

As shown in *Table **9***, analysis of electric motor loading was performed using both instantaneous testing and pump monitoring. 24 of the 48 systems analyzed (50%) were considered appropriately sized, operating between 75% and 100% of the nameplate power rating. Roughly the same number (about 1/4) of systems were categorized as either undersized or oversized.

Pump monitoring gives a range of electric motor loading (% of nameplate power) to be observed, while instantaneous testing only gives one such value. The average difference between minimum and maximum loading observed annually was 13.3% (SD=6.8, n=31). This highlights the advantage of using the pump monitoring approach, since instantaneous testing may suggest an appropriately sized motor, while the motor could in fact be oversized or undersized.

Cost of Water by System Type Results

Figure 15. Actual and TDH Normalized Cost of Water by System Type.

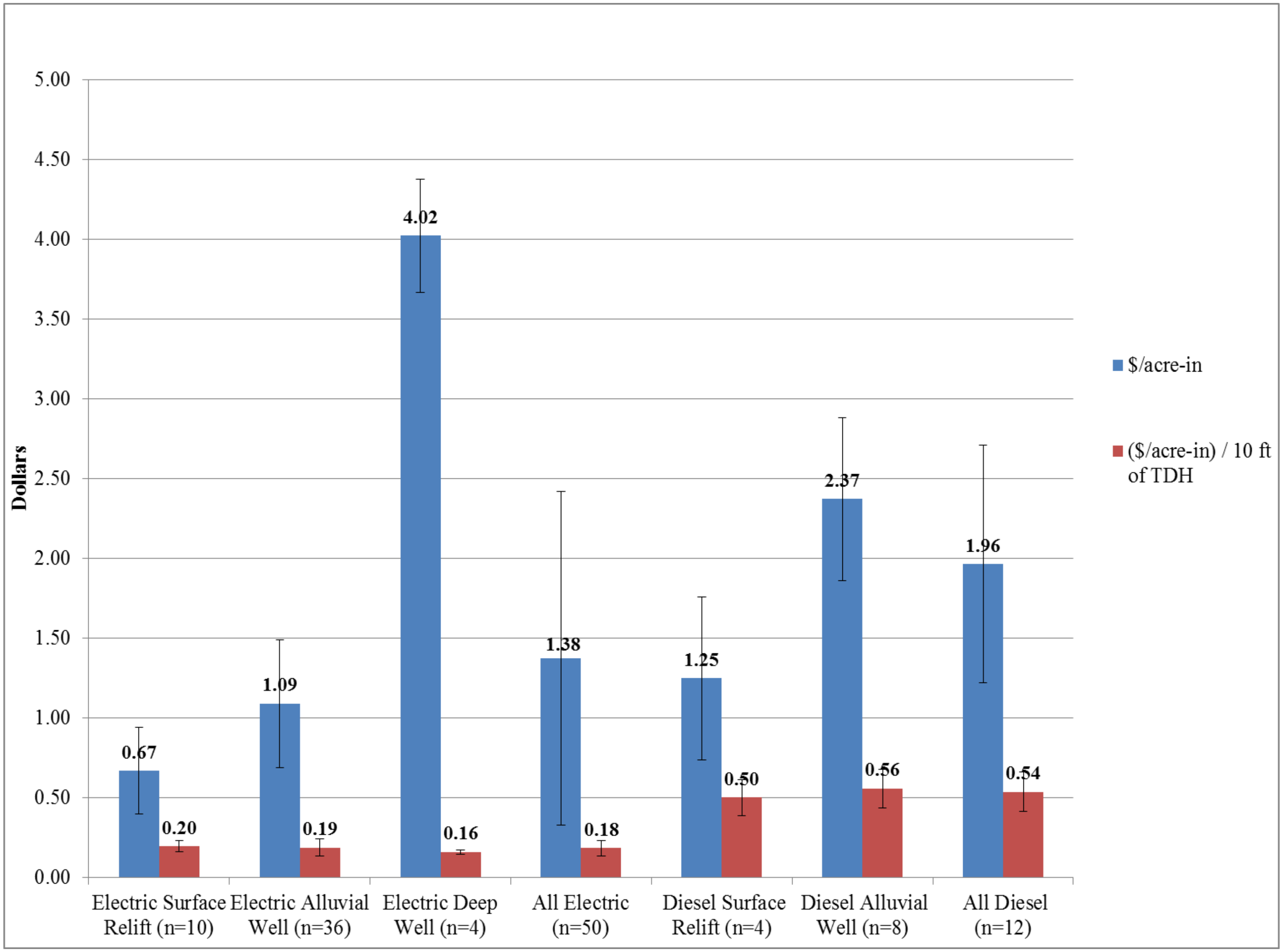


Table 10
Actual and TDH Normalized Cost of Water Data Categorized by System Type.

System Category	**COW ($/acre-in)** ***($/ha-cm)***	**SD**	**TDH Normalized COW ($/acre-in) / (10 ft of TDH)** ***($/ha-cm) / (m of TDH)***	**SD**	**n**
Electric Surface Relifts	0.67	0.272	0.20	0.034	9
	0.65	*0.264*	0.06	*0.011*	
Electric Alluvial Wells	1.09	0.401	0.19	0.054	40
	1.06	*0.389*	0.06	*0.017*	
Electric Deep Wells	4.02	0.355	0.16	0.015	5
	3.90	*0.345*	0.05	*0.005*	
All Electric	1.38	1.045	0.18	0.050	54
	1.34	*1.015*	0.06	*0.016*	
Diesel Surface Relifts	1.25	0.509	0.50	0.114	4
	1.21	*0.494*	0.16	*0.036*	
Diesel Alluvial Wells	2.37	0.511	0.56	0.123	7
	2.3	*0.496*	0.18	*0.039*	
All Diesel	1.96	0.743	0.54	0.123	11
	1.90	*0.721*	0.17	*0.039*	

Cost of Water by System Type Discussion

The results shown in Figure 15 and Table 10 suggest that irrigation using diesel as an input energy source is approximately 3 times more costly than electricity. This suggestion is backed by the TDH normalized COW group medians between diesel and electric systems being significantly different using the Mann-Whitney Rank Sum Test (U=0.00, T=660.00; P<0.001). The results of this test are shown in Analysis A-2 in the appendix section. This difference in average diesel and electric pumping cost does not take maintenance costs or any additional capital costs into consideration. Also, the constant change in costs of diesel and electricity make this number subject to change.

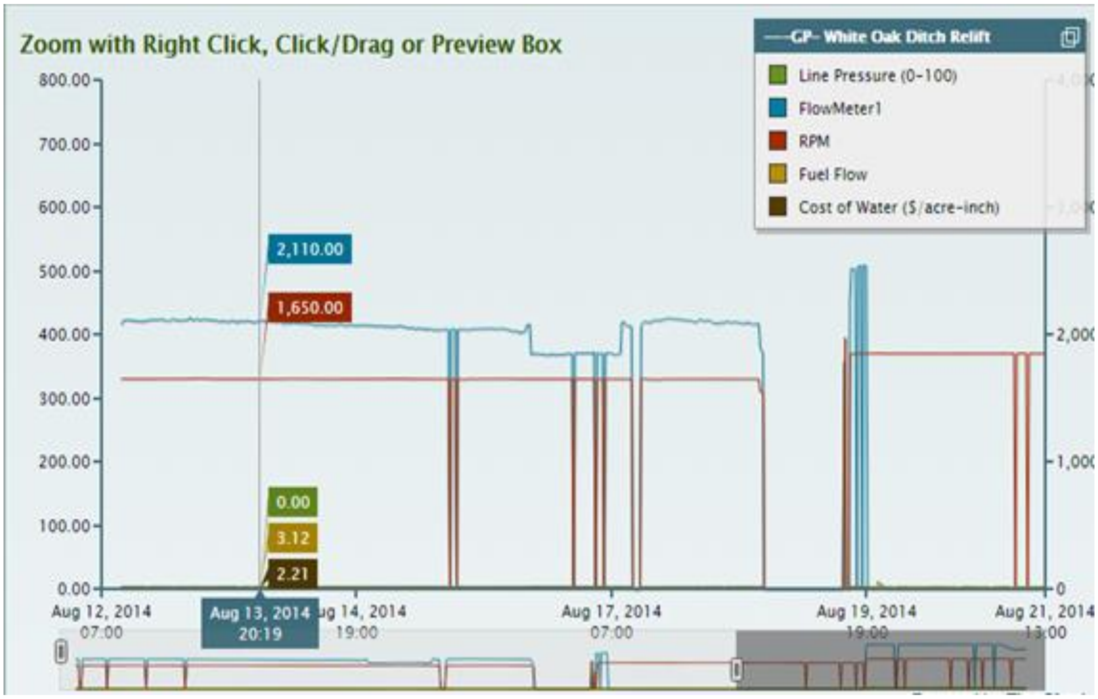
The higher standard deviation of the TDH normalized COW values for diesel powered systems is likely a result of their variable speed capability. This feature of diesel pumping plants makes COW somewhat dependent on management practices by irrigators in terms of what speed a particular system is operated at a given operating condition. Since each diesel pumping plant has any number COW values associated with it at variable pumping speeds, the COW value used in this analysis was the value corresponding to the most commonly used operational speed by the irrigator, which did not necessarily coincide with the lowest COW. If no such information was available, the results were averaged from each pumping speed tested where reasonable COW values were observed.

As would be expected due to TDH variability, the group median values of COW grouped by system type were significantly different between surface relifts, alluvial wells, and deep wells using a Kruskal-Wallis One Way ANOVA on ranks ($H=19.947$, $P<0.001$). Dunn's Method was used to isolate the groups medians that significantly differ from one another, and all proved to be significantly different ($P<0.05$). The Kruskal-Wallis and Dunn's Method tests for COW by system type are shown in Analysis A-3 in the appendix. Conversely, the group medians grouped by system type were not significantly different when evaluating TDH normalized COW ($H=5.491$, $P=0.064$) using the Kruskal-Wallis One Way ANOVA on Ranks. Therefore, there is no statistical evidence to suggest that one particular system type is typically better maintained or designed as reflected by TDH normalized COW.

Optimizing Cost of Water using Pump Monitoring of Variable Rate Systems.

Despite extensive effort to appropriately calibrate and install diesel fuel flow sensors for use in the field on pump monitoring systems, this component proved to be a major limitation throughout this study when attempting to perform continuous performance tests on diesel pumping plants. Although this limitation diminished the total amount of reliable data extracted using pump monitoring on diesel systems, some important information was still extracted from these efforts. For example, a user interface on the DEM website was developed which can be used to show the response of COW to changes in engine speed. This 'evaluation graph' feature added to the website can be seen in Figure 16.

Figure 16. Screen Capture of Diesel Pump Monitoring Interface from DEM Website.



As shown in Figure 16, COW (shown in burgundy) can be analyzed at any point in time while the pumping plant is operational using this evaluation graph feature. Therefore, this feature of the website can be used to optimize COW at variable TDH by adjusting engine speed (RPM, shown in red).

Irrigation Capacity Results

Table 11

Pump Monitoring Irrigation Capacity Data for Electric Alluvial Well Pumping Plants.

System ID	Year	Recommended IC (gpm/acre)	Avg IC (gpm/acre)	Min IC (gpm/acre)	Max IC (gpm/acre)	Adequate Time (%)	Below Adequate Time (%)	Classification
FL Harr Farm North	2011	10	10.5	8.7	12.0	72	28	Sometimes Adequate
MS 11S 12S	2011	15	19.6	17.0	24.2	100	0	Always Adequate
MS 11S 12S	2012	15	19.0	18.0	21.4	100	0	Always Adequate
MS 11S 12S	2013	15	18.3	16.9	18.6	100	0	Always Adequate
MS 14-18	2011	15	21.2	17.2	24.9	100	0	Always Adequate
MS 14-18	2012	15	17.8	15.5	21.8	100	0	Always Adequate
MS 14-18	2013	15	19.6	18.2	21.0	100	0	Always Adequate
MS 17E 17W 18W	2011	15	20.6	20.5	22.1	100	0	Always Adequate
MS 19	2013	15	26.6	25.4	27.6	100	0	Always Adequate
MS 22-23	2011	15	15.9	14.8	17.4	82	18	Sometimes Adequate
MS 22-23	2013	15	18.1	17.3	19.4	100	0	Always Adequate
MS 24-25	2011	15	13.3	11.5	16.7	20	80	Sometimes Adequate

Table 11 (cont.)

System ID	**Year**	**Recommended IC (gpm/acre) *((m^3/hr)/ha)***	**Avg IC (gpm/acre) *((m^3/hr)/ha)***	**Min IC (gpm/acre)** ((m^3/hr)/ha)	**Max IC (gpm/acre) *((m^3/hr)/ha)***	**Adequate Time (%)**	**Below Adequate Time (%)**	**Classification**
MS 26-27	2013	15	14.0	13.2	15.2	1.0	99	Sometimes Adequate
MS 26-27	2014	15	14.0	13.4	15.1	4	96	Sometimes Adequate
MS 29N 29S	2013	15	13.7	13.2	14.5	2	98	Sometimes Adequate
MS 30	2011	15	17.2	16.3	19.0	100	0	Always Adequate
MS 30	2013	15	18.4	17.6	19.4	100	0	Always Adequate
MS 9N 10N	2011	15	15.2	14.4	16.6	59	41	Sometimes Adequate
MS 9S 10S	2011	15	20.1	15.0	25.9	100	0	Always Adequate
MS Rob HS	2013	15	13.6	12.9	14.7	0	100	Below Adequate
MS Rob HS	2014	15	12.7	13.3	13.9	0	100	Below Adequate
MS Stracener	2012	15	14.9	13.9	18.6	38	62	Sometimes Adequate
MS Stracener	2013	15	16.0	14.8	20.8	89	11	Sometimes Adequate
MS Stracener Zero	2014	15	16.7	15.0	19.4	100	0	Always Adequate
FL Harr Farm South	2011	10	11.2	9.7	13.1	89.0	11	Sometimes Adequate

Table 12
Instantaneous Irrigation Capacity Data.

System ID	**Year**	**System Type**	**Energy Source**	**Recommended IC (gpm/acre)** ***((m^3/hr)/ha)***	**IC (gpm/acre)** ***((m^3/hr)/ha)***	**Classification**
Grubbs Well	2013	Alluvial Well	Electric	10	8.4	Below Adequate
MS Hardy	2013	Alluvial Well	Electric	15	17.1	Adequate
Hazen West	2013	Surface Relift	Electric	10	12.5	Adequate
Hazen Interstate	2013	Surface Relift	Electric	10	9.4	Below Adequate
Hazen Jenkins	2013	Surface Relift	Electric	10	8.3	Below Adequate
Stuttgart New Relift	2013	Surface Relift	Electric	10	4.4	Below Adequate
MS Robbins NE	2013	Alluvial Well	Diesel	15	14.1	Below Adequate
MS Lake NW	2013	Alluvial Well	Diesel	15	19.8	Adequate
Stuttgart Old Relift	2013	Surface Relift	Diesel	10	2.3	Below Adequate
MS 9N 10N	2013	Alluvial Well	Electric	15	11.4	Below Adequate
MS 28S	2013	Alluvial Well	Electric	15	21.9	Adequate
Craft Farm Relift 1	2013	Surface Relift	Electric	10	7.0	Below Adequate
Craft Farm Relift 2	2013	Alluvial Well	Electric	10	5.5	Below Adequate
Skeet Well #1	2013	Alluvial Well	Electric	10	8.4	Below Adequate
Skeet Well #2	2013	Alluvial Well	Electric	10	4.3	Below Adequate

Table 12 (cont.)

System ID	**Year**	**System Type**	**Energy Source**	**Recommended IC (gpm/acre) *((m^3/hr)/ha)***	**IC (gpm/acre) *((m^3/hr)/ha)***	**Classification**
Rob Roy East	2014	Alluvial Well	Electric	10	12.6	Adequate
Rob Roy West	2014	Alluvial Well	Electric	10	13.5	Adequate
Yoder Relift	2014	Surface Relift	Diesel	10	10.4	Adequate
Rob Roy Highway	2014	Alluvial Well	Diesel	10	10.0	Adequate

Table 13

Summary of Pump Monitoring and Instantaneous Irrigation Capacity Results

Testing Method	**Below Adequate (% of Systems)**	**Sometimes Adequate (% of Systems)**	**Adequate (% of Systems)**
Pump Monitoring (n=25)	8	40	52
Instantaneous Testing (n=19)	58	-	42

Figure 17. Example of Poor Irrigation Capacity in Prairie County, AR due to Critical Alluvial Aquifer Depletion. The Bright Orange Color of the Water is Due to its High Iron Content.

Irrigation Capacity Discussion

*Table **13*** indicates that just under half of all of the systems tested had IC values constantly exceeding the recommendation by the Arkansas Rice Production handbook for flow capacity needed per area serviced. It should be noted that some systems analyzed using pump monitoring (40%) were above this IC threshold at some points during the irrigation season, and below it at other times. As seen in Figures A – 1 through A – 28, this seems to be driven by annual decrease in Q_w values due to aquifer drawdown, where systems would begin the season above the IC threshold and finish below it. Systems categorized as “sometimes adequate” had IC values above the threshold 46% of operational time, and below it 54% of the time. This statistic suggests that instantaneous testing, particularly at the beginning or end of the irrigation season, may be misleading in terms of the adequacy of the ratio of pumping flow rate to area serviced. The average annual difference for individual pumping plants between maximum and minimum IC was 3.6 gpm/acre (SD=2.4, n=25).

IC was also evaluated based on geographic location of the pumping plant in question. To do so, the difference between average IC and recommended IC was calculated for each pumping plant and categorized based on geographic location. A one-way ANOVA (Analysis A – 8) was used to analyze this data. Pumping plants in the “Northeast Arkansas” grouping had the best IC values relative to the recommended value, with average annual IC exceeding the recommendation by 2.1 gpm/acre. “Grand Prairie Area” and “Other” systems were 0.4 gpm/acre and 3.3 gpm/acre below the recommended IC relatively (F (2, 41) = .022, p=0.002). “Northeast Arkansas” was likely best in terms of IC due to the majority of these systems being alluvial well systems with low PWL resulting rapid aquifer recharge from the nearby Mississippi River.

Nebraska Pumping Plant Performance Criteria Results

The results of calculating %-NPPPC by system type and input energy source are shown below. Since diesel engine speed affects TDH and %-NPPPC, the values coinciding with the operational speed most commonly used by the irrigator at the set tested were used in this analysis for diesel pumping plants. If no such information was available, the average %-NPPPC value across all reasonable test speeds was used.

Table 14
%-NPPPC Results by System Type and Input Energy Source.

System Category	Average %-NPPPC	SD	n
Electric Surface Relifts	70.6	8.6	8
Electric Alluvial Wells	73.6	17.7	39
Electric Deep Wells	82.6	8.2	5
Diesel Surface Relifts	69.8	13.1	4
Diesel Alluvial Wells	59.6	10.4	7
Electric Systems	74.0	16.1	52
Diesel Systems	63.3	12.4	11
All Systems	72.1	16.1	63

Nebraska Pumping Plant Performance Criteria Discussion

The results of a Kruskal-Wallis ANOVA by ranks test of average %-NPPPC values grouped by system type showed no significant difference among mean ranks (H=2.847, 2 d.f., P=0.241). The same test performed by energy source grouping did show significant difference in mean ranks (H=4.487, 2 d.f., P=0.034), with diesel systems showing average %-NPPPC values (63.3%) lower than that of electric systems (74.0%). The lower %-NPPPC values of diesel systems were likely caused by their different operational speeds. The observations of diesel %-NPPPC values were taken at operational speeds most commonly used by the grower. In many cases, these operational speeds were not associated with optimal efficiency. These tests are shown in Analysis A – 6 and A – 7 in the appendix.

%-NPPPC values were also analyzed based on geographic location groupings. Geographic locations were identified as either “Grand Prairie Area”, “Northeast Arkansas”, or “Other”. Analysis A – 7 in the appendix shows these group means analyzed using a one way ANOVA. Results of the ANOVA showed a statistically significant difference between groups (F(2, 60) = 14.592, p<0.001). A Tukey post-hoc test showed that the %-NPPPC values of “Northeast Arkansas” systems had a mean %-NPPPC value 26.7% greater than “Other” (P<0.001) and 13.3% higher than “Grand Prairie” (P=0.002). “Grand Prairie” systems had %-NPPPC values 13.3% higher than “Other” systems (P=0.046).

Systems located in Northeast Arkansas were all very near the Mississippi River, meaning that groundwater recharge was likely more rapid than at the other geographical location groupings. This rapid recharge allows pumping plant systems to more consistently operate at or near the TDH for which the system was designed. Systems in the “Other” grouping were mostly in the north-central area of Arkansas, which does not have many large rivers to provide groundwater recharge. The “Grand Prairie” location grouping, despite including some of the most critical ground water depletion zones in Arkansas, also included some systems which were very major water bodies (White River, Arkansas River, Bayou Meto) which are capable of providing rapid groundwater recharge. Despite other factors such as system design and maintenance scheduling affecting %-NPPPC, groundwater recharge of well systems is suspected to be the driving factor behind the difference in %-NPPPC values according to geographic location.

As stated in the Literature Review, the Soil Conservation Service estimated the average statewide %-NPPPC of irrigation pumping plants in Arkansas to be approximately 68% at the time of the study by Tacker and Langston (1987). This is strikingly similar to the 72.1% average of all systems tested within this study, which suggests that little progress has been made in Arkansas in terms of irrigation pumping plant efficiency over the last 25 years. This is backed by the similarities in average %-NPPPC by energy source observed by Tacker and Langston (1987) and those observed in this study. Average %-NPPPC for electric systems tested was 77.0% and 74.0% relatively in Tacker and Langston's study and this study. Similarly, average diesel %-NPPPC was 71.0% and 63.3%. The lower value for diesel %-NPPPC in this study compared to Tacker and Langston was likely due to the method of collecting diesel efficiency data at the operational speed used by the grower.

Potential Savings of Improved Pumping Plant Efficiency Results

Table 15
Potential Savings using %-NPPPC and Annual Operational Time.

System Category	Energy Consumption Rate (kWh/hr) (gal/hr) , *(l/hr)*	Average %-NPPPC	Potential Energy Savings (kWh/hr) (gal/hr) , *(l/hr)*	Potential Cost Savings ($/hr)
Electric Surface Relifts	39.6	70.6	11.6	1.16
Electric Alluvial Wells	47.5	73.6	12.5	1.25
Electric Deep Wells	101.4	82.6	17.6	1.76
Diesel Surface Relifts	3.4 *12.8*	69.8	1.0 *3.8*	3.39
Diesel Alluvial Wells	2.4 *9.0*	59.6	0.9 *3.4*	3.20
All Electric Systems	47.4	74.0	12.3	1.23
All Diesel Systems	2.7 *10.4*	63.3	1.0 *3.8*	3.27

Potential Savings of Improved Irrigation Efficiency Discussion

*Table **15*** shows estimations of the potential energy and cost savings per operational hour that would result from improved pumping plant efficiency to 100% of the NPPPC. Diesel systems showed higher potential cost savings due to the higher energy cost of diesel relative to electricity. Potential cost savings were not calculated for each individual pumping plant tested since TDH often was not directly measured, but estimated. This method of combining data by system type and energy source was used to help minimize error by homogenizing estimates of TDH (assuming some were too high and some too low).

According to the 2013 Farm and Ranch Irrigation Survey, part of the 2012 Census of Agriculture, there are 53,829 irrigation pumping plants in the state of Arkansas. Of these systems, 49.7% are diesel powered, 47.4% are powered by electricity, and 2.9% are powered by other sources including natural gas, propane, LP gas, and gasoline. These estimates were applied to the hourly energy and cost savings values in *Table **15***. Results suggest that improving all systems to 100% of the NPPPC would save approximately 21.7 million gallons of diesel fuel and 264.4 million kWh of electricity. Assuming energy costs of $0.10 USD/kWh (electricity) and $3.30 USD/gal (diesel), this energy savings would result in a total savings of approximately $94.2 million USD. Using average operational times of electric pumping plants by system type resulted in estimated average annual savings values of $897 USD for electric alluvial wells, $1484 USD for electric surface relifts, and $2605 USD for electric deep wells assuming improvement to 100% of the NPPPC. The greater potential savings of electric deep wells is driven mainly by larger average operational hours due to the relatively lower well capacity of these high TDH systems.

Conclusions

- The average operational time of electric systems tested using pump monitoring was approximately 809 hours. Operational times ranged from 290 hours to 1735 hours.
- Q_w of well pumping plants decreased 19.2% annually on average. Conversely, COW of well pumping plants increased 22.1% annually on average.
- Annual Q_w decrease and annual COW increase of well pumping plants showed a direct positive correlation. It is suspected that this relationship can be used to identify systems that have rapidly decreasing pump efficiencies as PWL increases through the irrigation season. Annual COW increase will be much greater than annual Q_w decrease on a percentage basis in these situations.
- Approximately 50% of electric motors tested were either undersized or oversized based on their loading as a percentage of nameplate power. This is likely a widespread problem, and could be a major contributor to decreased pumping plant efficiencies.
- Irrigation using diesel as an energy source is approximately 3 times more expensive than using electricity. Normalizing COW data by TDH and categorizing data by energy source was used to generate this conclusion.
- Pump monitoring of variable speed irrigation systems can be used to optimize COW at variable TDH.
- Just under half of the systems tested exceeded the IC recommendation by the Arkansas Rice Production Handbook. When grouped by geographical area, only systems in Northeast Arkansas had average IC exceeding this recommendation. This is likely due in large part to their close proximity to the Mississippi River, which provides rapid and consistent recharge of the alluvial aquifer in that region.

- Measurement of IC highlighted a major advantage of pump monitoring to traditional instantaneous testing. 40% of monitored pumping plants began the season with adequate IC and ended the season below the IC recommendation. This shows that instantaneous testing can be misleading when determining IC. In addition, time of year relative to the irrigation season must be considered when collecting Q_w data for computerized hole selection models such as Pipe Planner and PHAUCET.
- Average pumping plant efficiency relative to the NPPPC was 72.1%. This value suggests that little to no improvement has been made in Arkansas over the last 3 decades concerning irrigation pumping plant efficiencies.
- Improving irrigation pumping plant efficiencies to 100% of the NPPPC could save approximately 21.7 million gallons of diesel fuel and 264.4 million kWh of electricity annually. This decrease in energy consumption would result in annual irrigation cost savings of approximately 94.2 million dollars for farmers in Arkansas.

Recommendations

- An alternative method of measuring diesel fuel flow must be considered. The instrumentation currently being used was inconsistent in its ability to accurately and continuously measure fuel flow data. These inconsistencies were likely due to adverse environmental conditions such as heat exposure and debris in fuel lines causing clogging. In addition, some growers were hesitant to plumb fuel flow sensors upstream of the return line ‘T’ due to potential issues with introduction to air in the fuel line and/or hot fuel damaging the fuel pump. An alternative method being considered is the implementation of acoustic depth measurement sensors or liquid level measuring “e-tape” to measure fuel depth within the holding tank. Measurement of fuel depths at two points in time assuming constant engine speed could be used to calculate the rate of diesel fuel consumption at different speeds.
- A reliable and affordable method of measuring depth to water (SWL and PWL) needs to be tested and installed. Continuous measurement of this parameter would allow important performance values such as OPPE and %-NPPPC to be calculated in real time. Potential methods include the installment of bubbler lines or pressure transducers within the well column to measure distance of the hydraulic surface within the well to the center point of the horizontal well discharge.
- In order to consistently obtain accurate measurements of pumping flow rates, an organized scheduling of calibration and maintenance of all pump monitoring flow meters installed needs to be developed. Mineralization and algal growth within flow meter bearings, particularly on systems where surface water is being pumped by mixed flow pumps, appears to be causing friction in flowmeter bearings which has caused some

flowmeters to become inaccurate between irrigation seasons. Limitations in labor availability may result in the need for a maintenance checklist or guide which could be provided to the grower to help reduce the amount of field visits which must be made to each pump monitoring system. Extremely accurate measurements of pumping flow are important, particularly when totalizing flow annually to calculate depth of water applied at individual locations.

- A variable "acreage serviced" input value could be added to the DEM website for each pump monitoring system. This area value and totalized pumping flow along with a simple algorithm could be used to report a "total depth of water applied" to the grower which could aid in managing the amount of time irrigation systems are being run and the total amount of water being applied.
- The appropriate rain gauge design needs to be chosen, which would allow a continuous measurement of total rainfall at each pump monitoring location. Often times, total rainfall during a rainfall event is highly variable between two very close locations. Therefore, total rainfall needs to be measured and reported at in real time at each pump monitoring location in order to further improve management of pumping application. Ideally, call or text alerts to the grower could be programmed which would inform the grower in real time when a rainfall event has occurred at particular location(s), indicating that an operational pump system should be powered off to prevent over-irrigation.

List of Abbreviated Terms/Units

- %-NPPPC: percentage of the Nebraska Pumping Plant Performance Criteria at which an irrigation pumping plant system is performing
- COW: cost of water
- bhp: brake horsepower
- Btu: British thermal units
- CT: current transformer
- ET: evapotranspiration
- gph: gallons per hour
- gpm: gallons per minute
- kWh: kilowatt-hours
- NPPPC: Nebraska Pumping Plant Performance Criteria
- OE: overall efficiency (used the same as ‘OPPE’ in some publications)
- OPPE: overall pumping plant efficiency
- PF: power factor
- IC: irrigation capacity
- psi: pounds per square inch
- PWL: pumping water level
- RE: relative efficiency (used the same as ‘%-NPPPC’ in some publications)
- SC: specific capacity
- SD: standard deviation
- SEMO: Southeast Missouri Region
- SF: service factor
- SG: specific gravity
- TDH: total dynamic head
- whp: water horsepower

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Appendix

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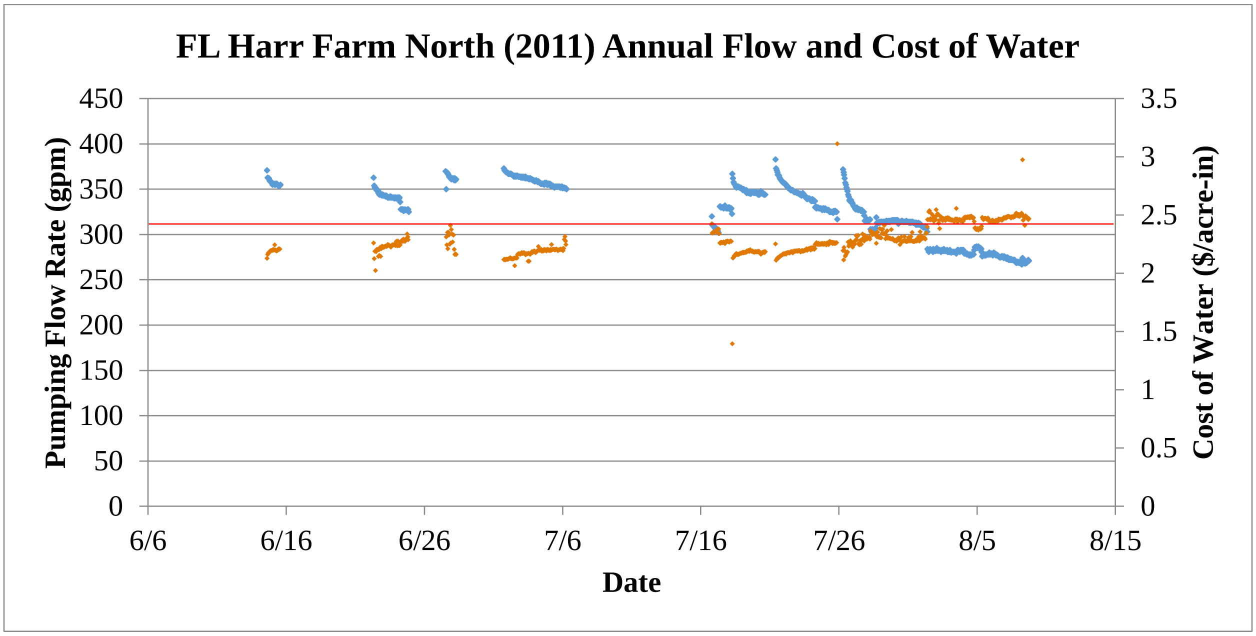

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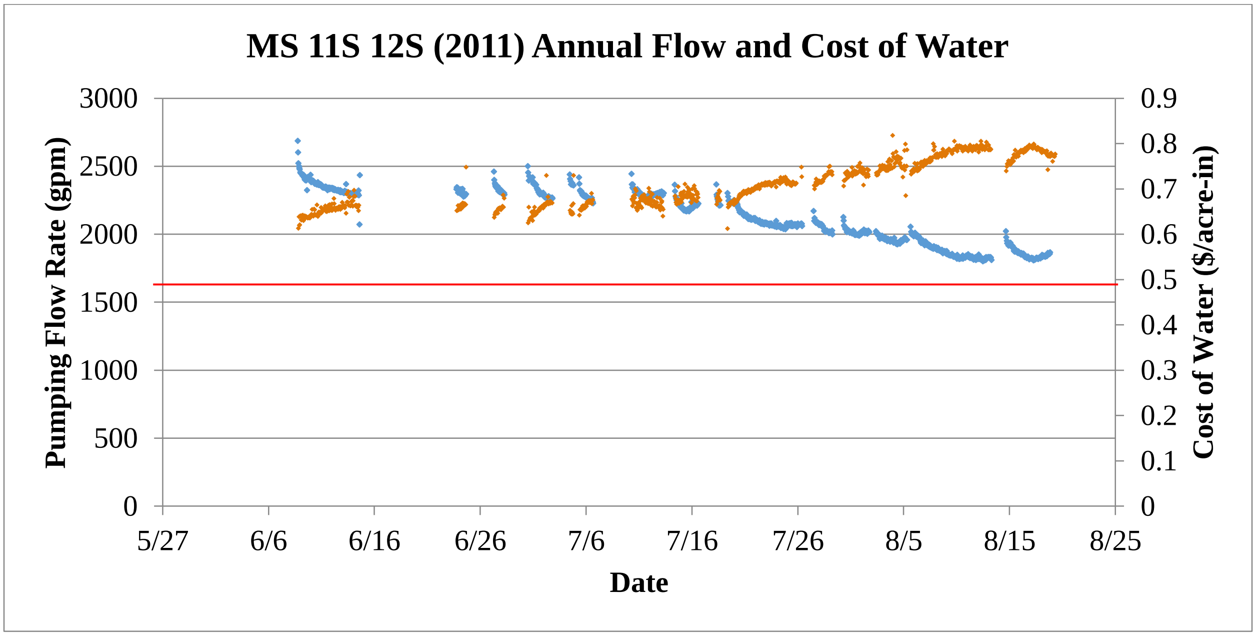

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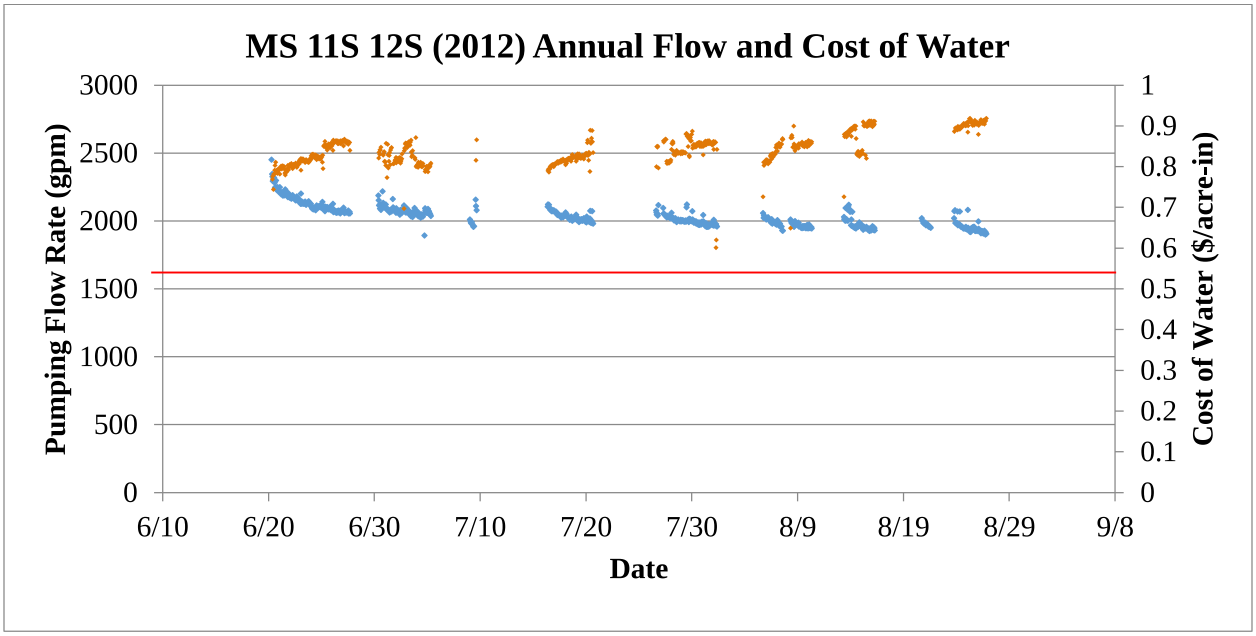

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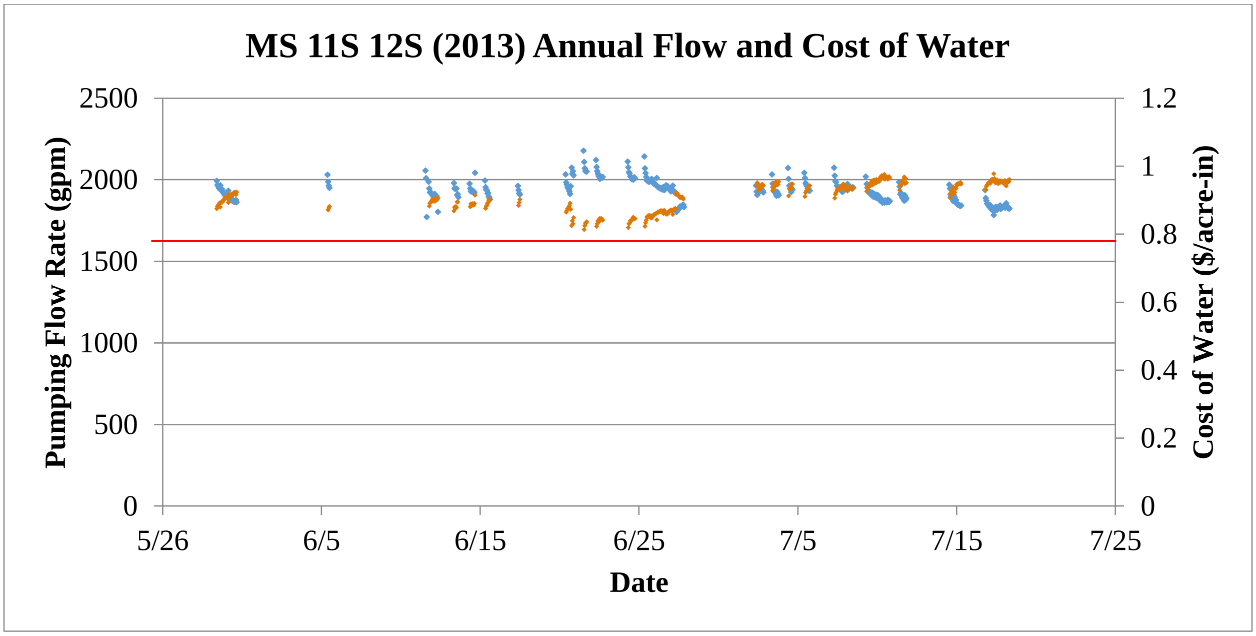

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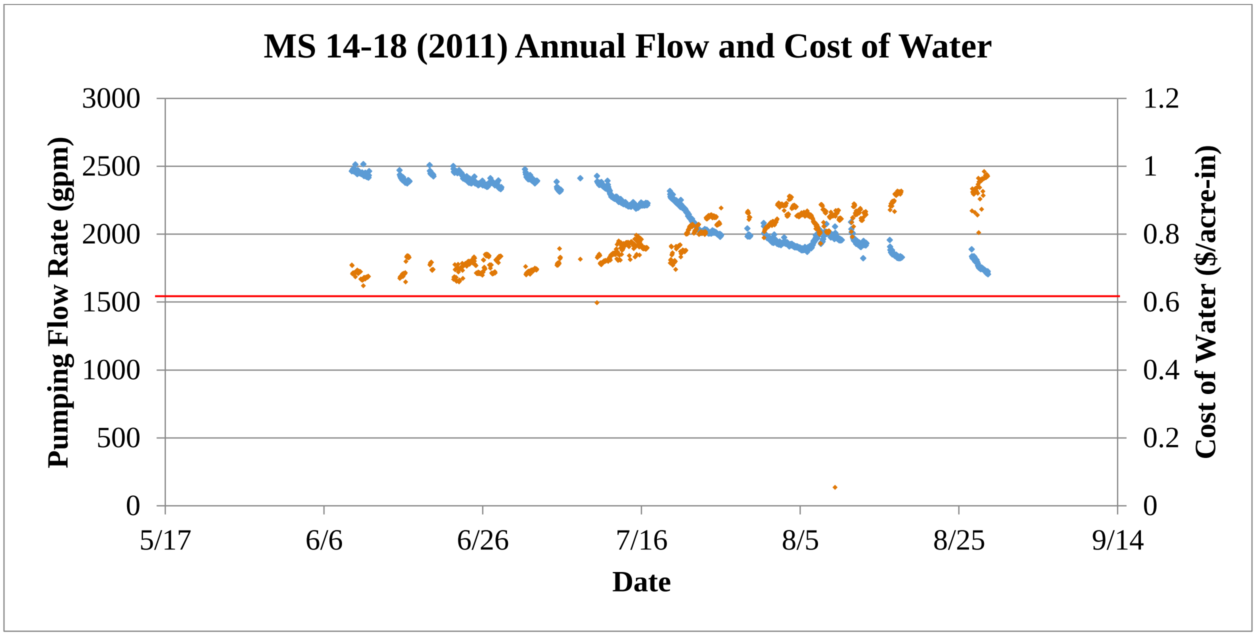

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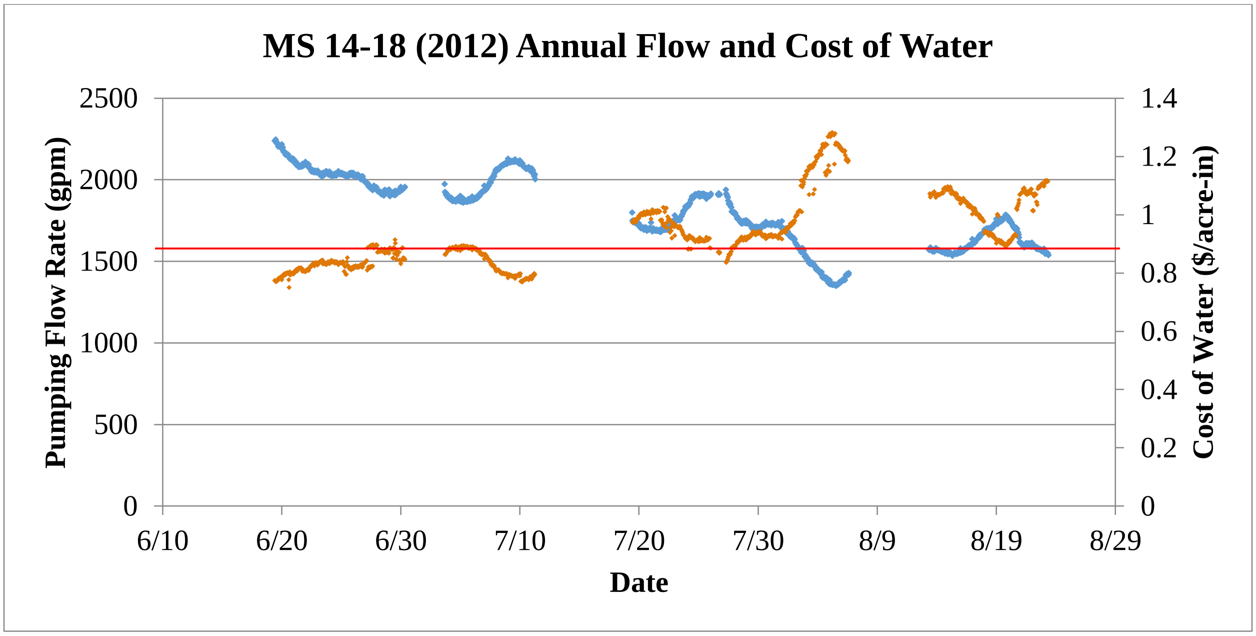

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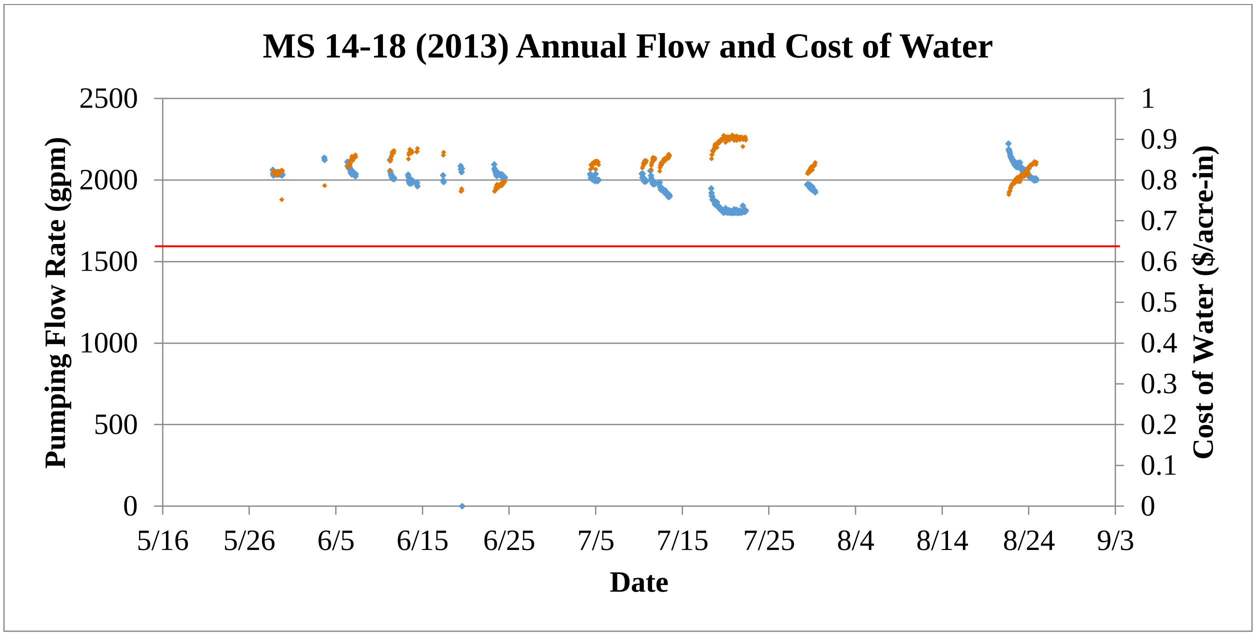

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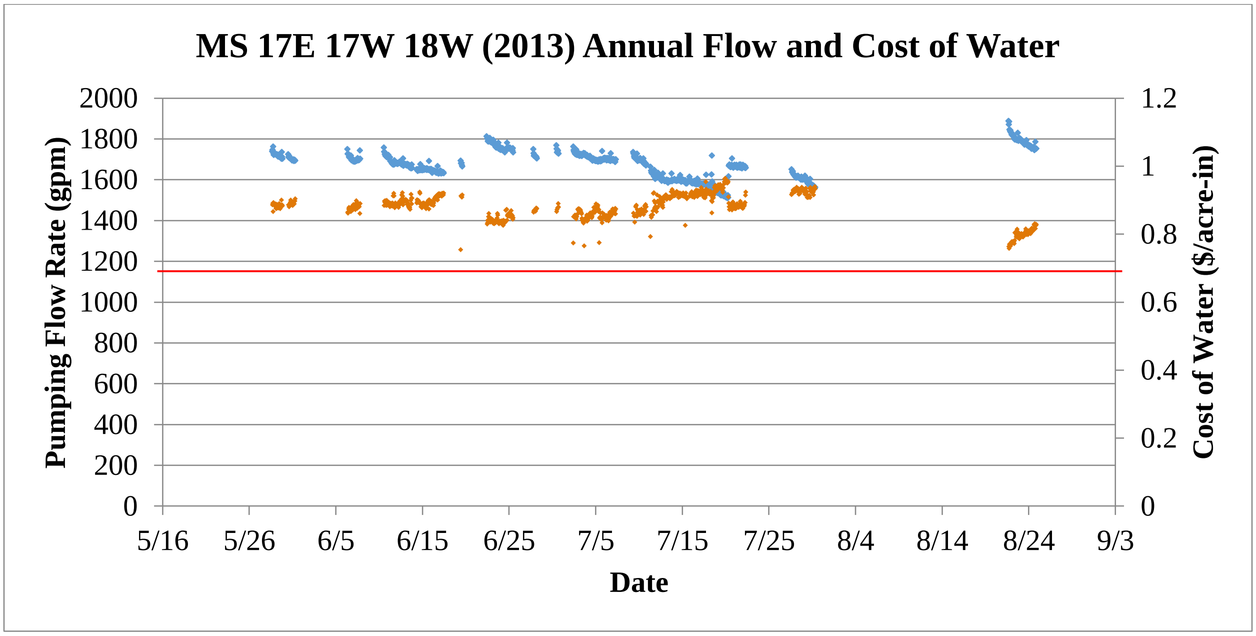

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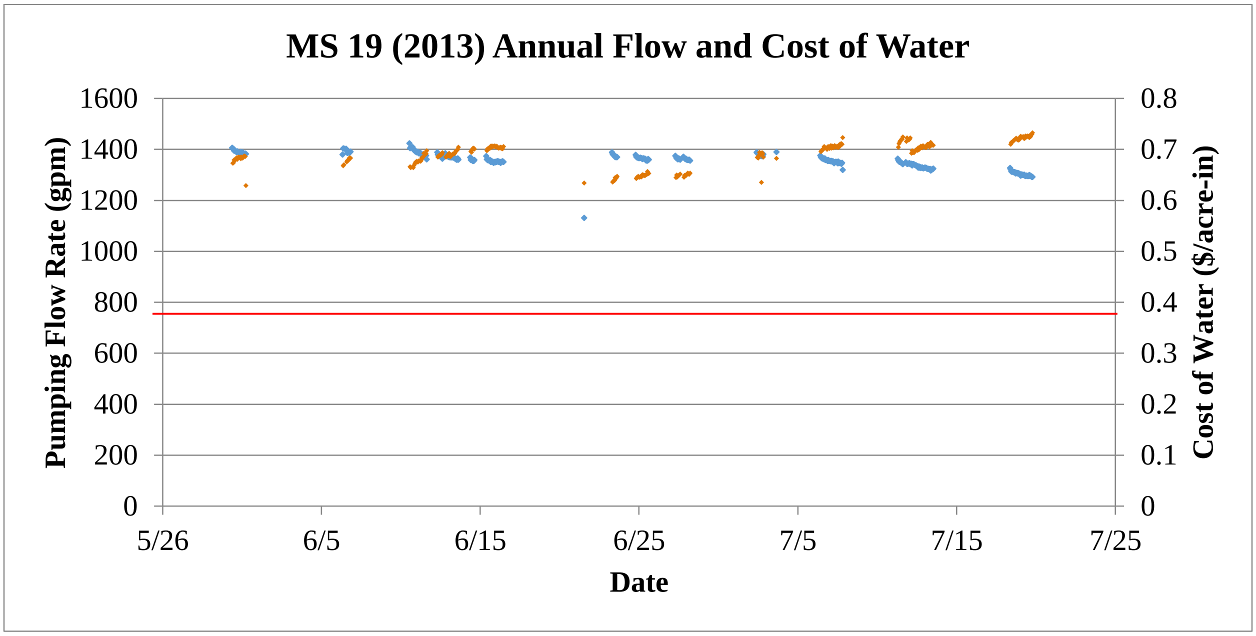

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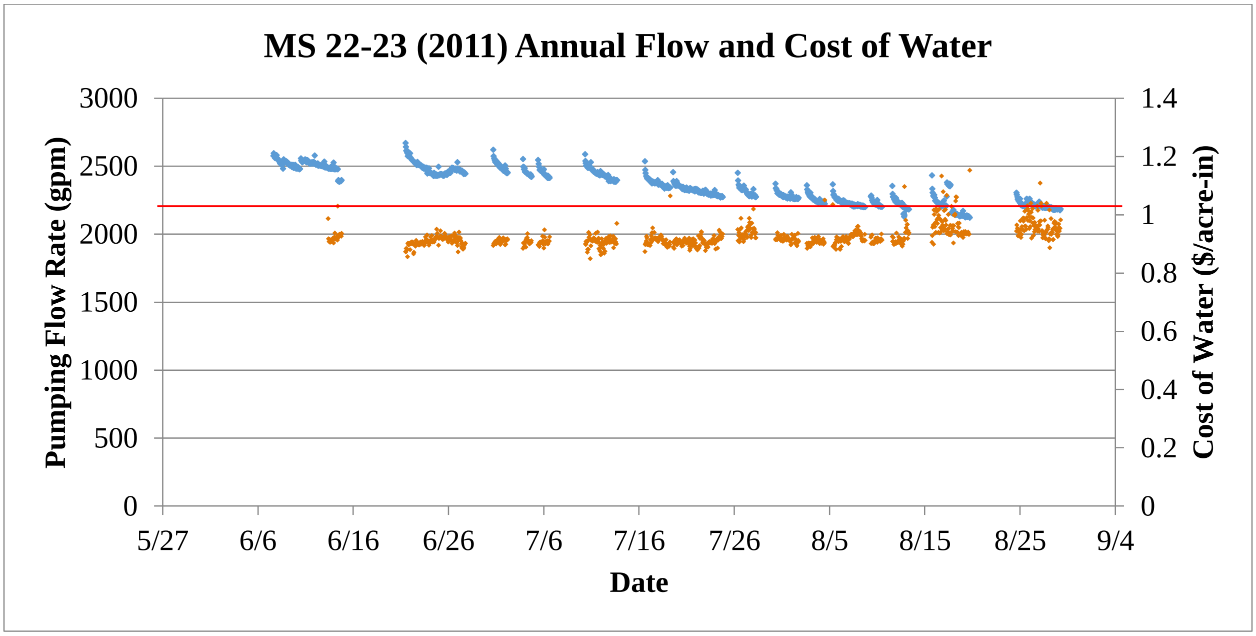

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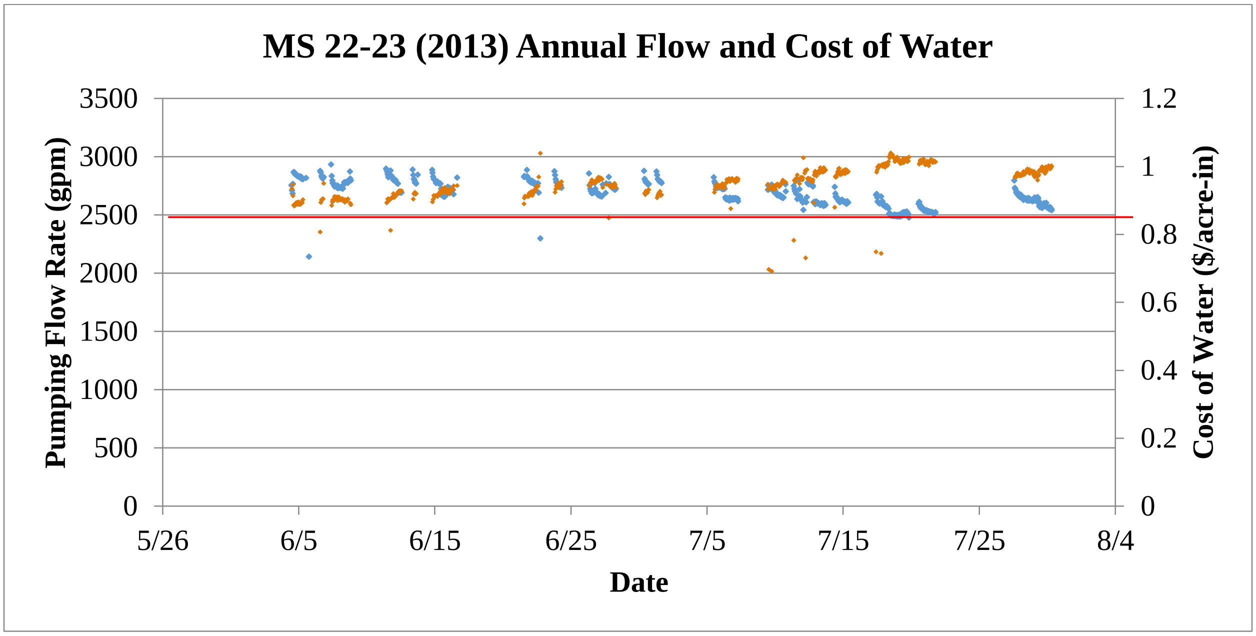

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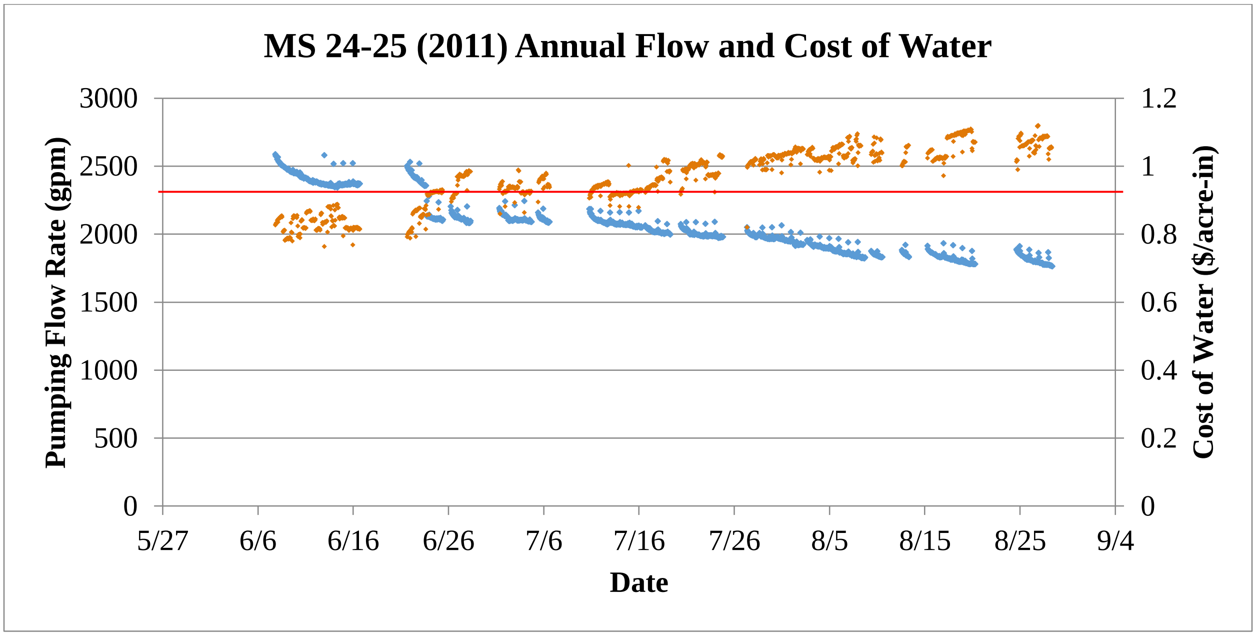

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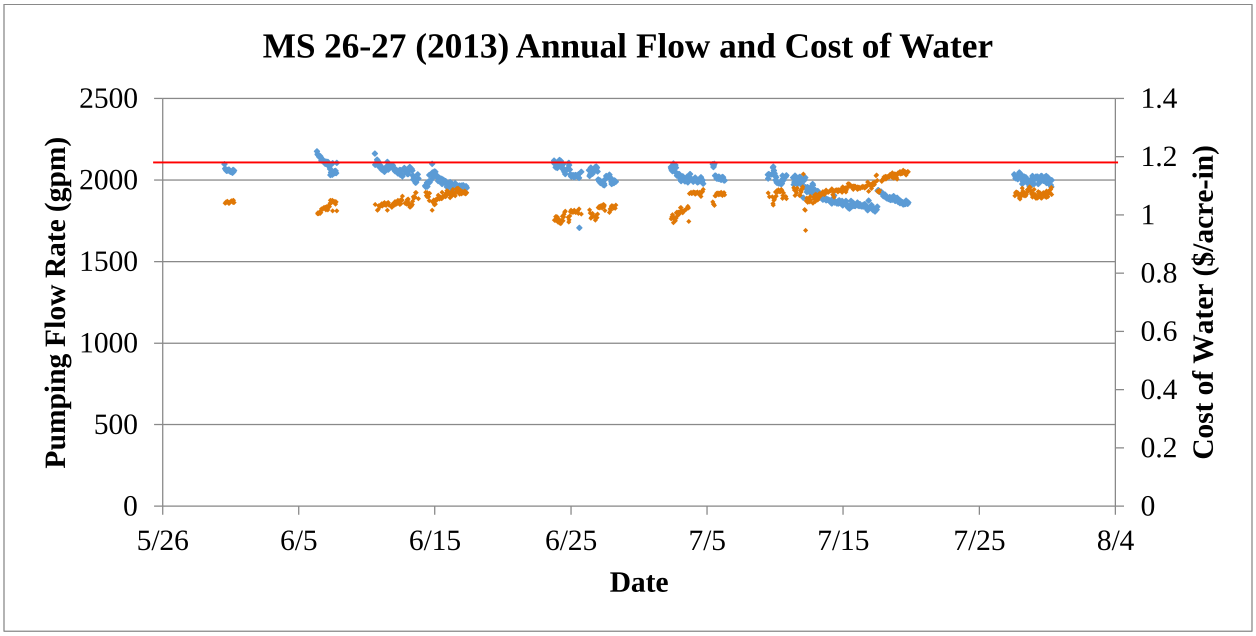

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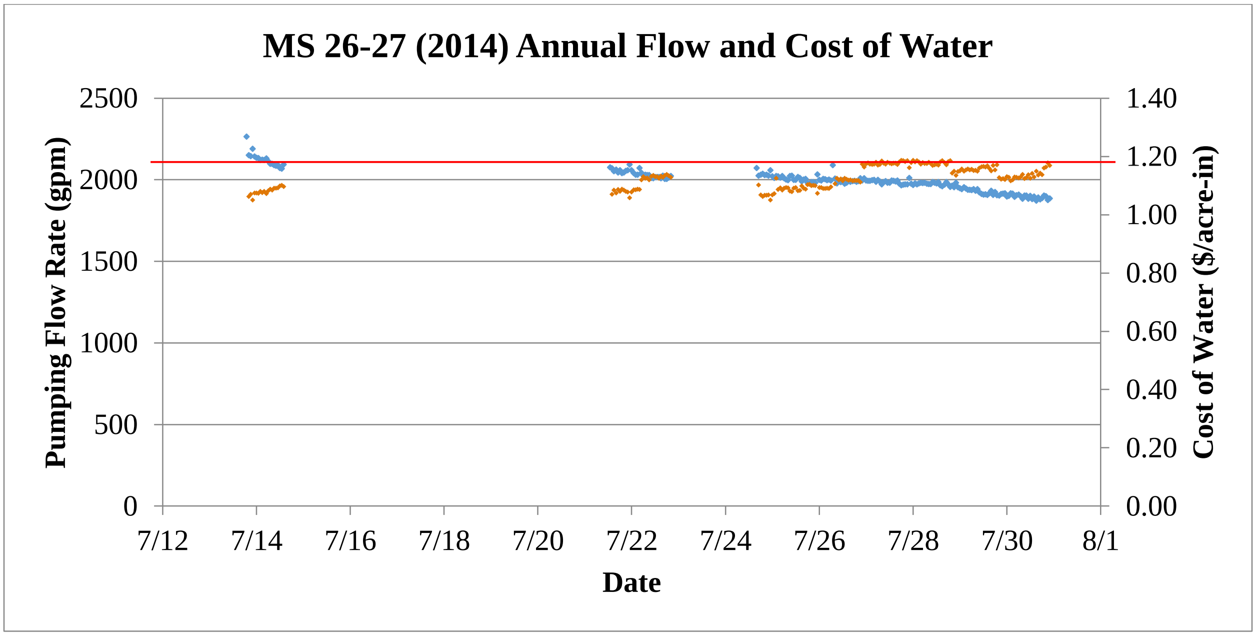

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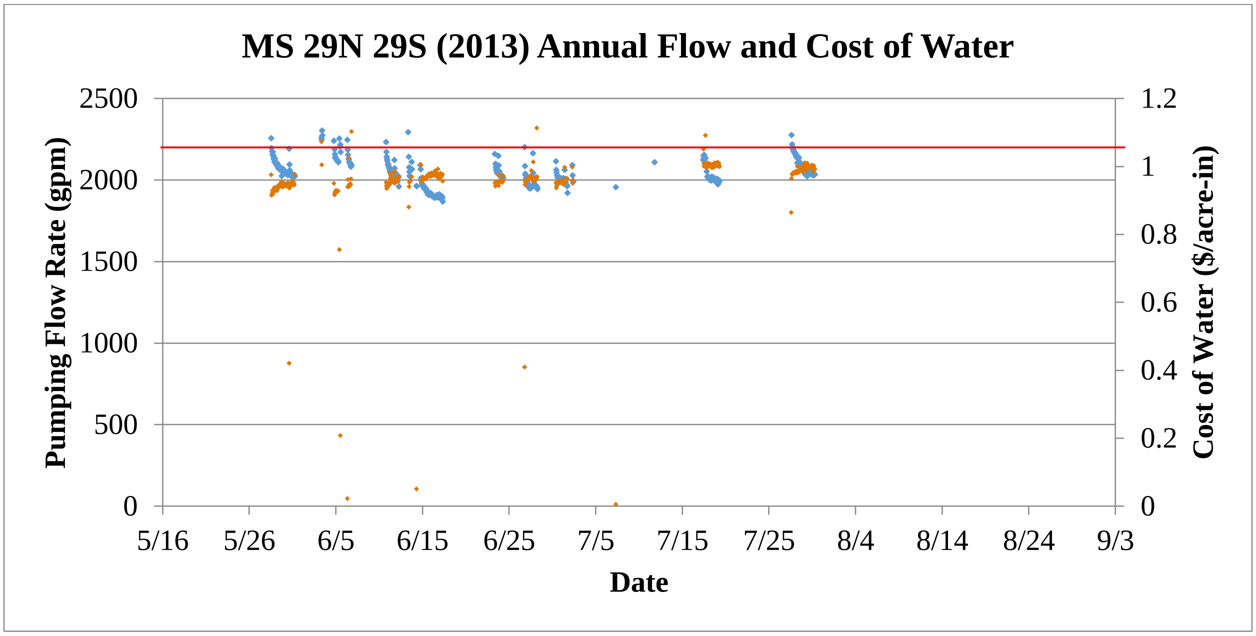

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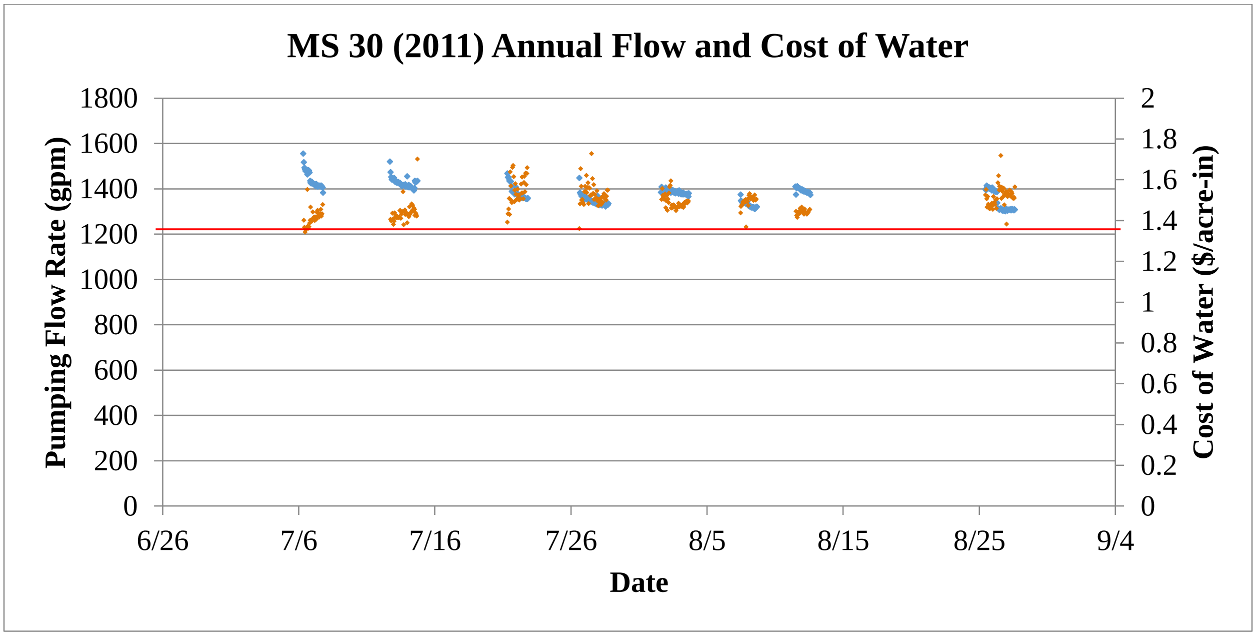

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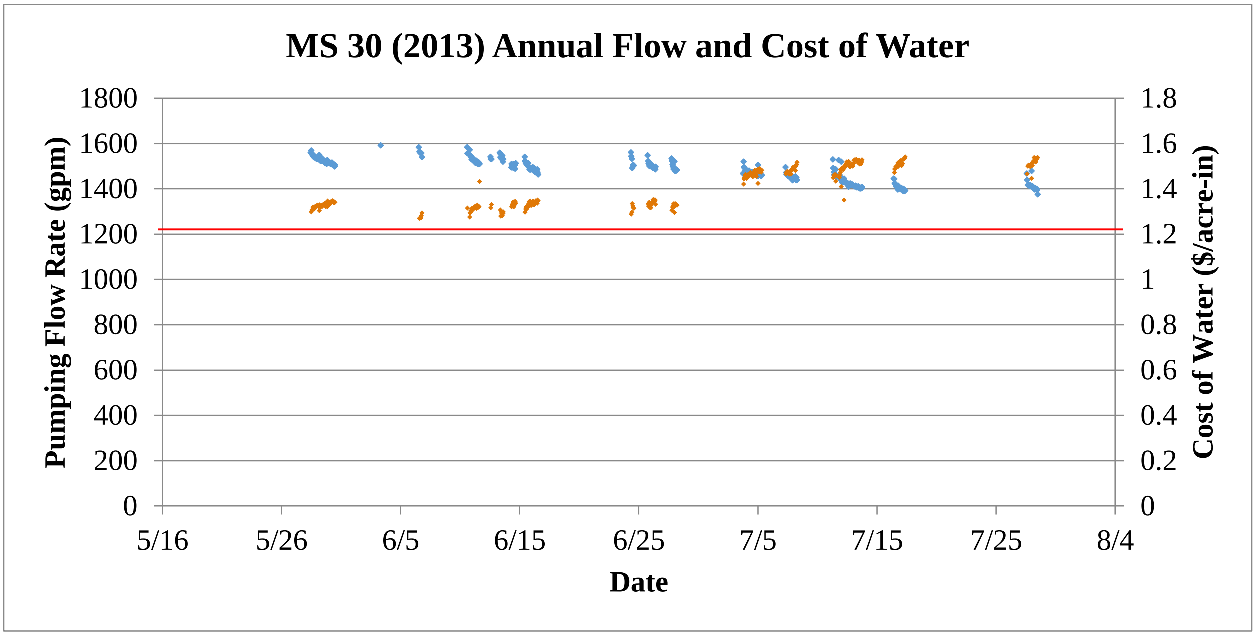

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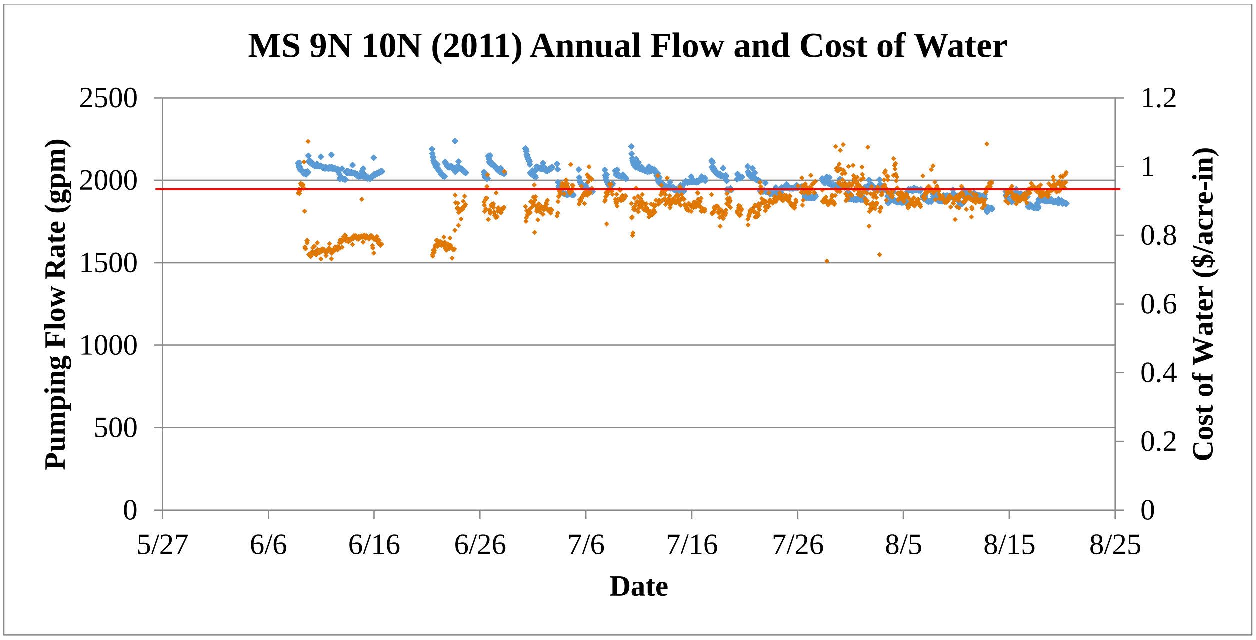

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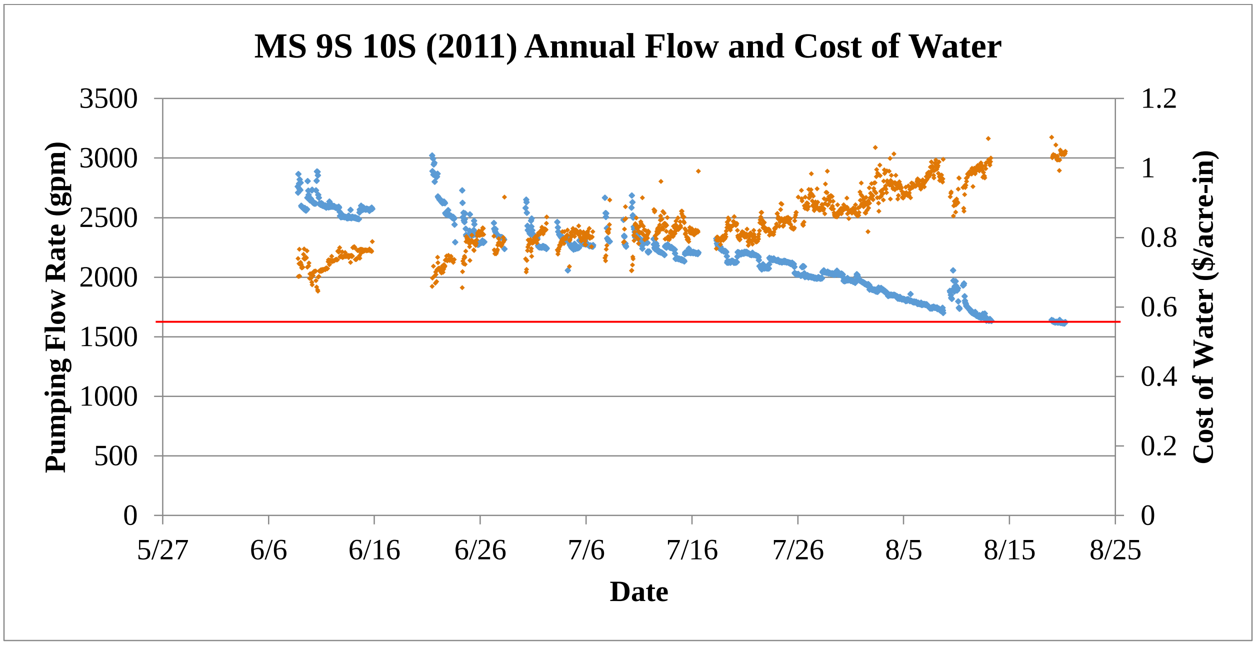

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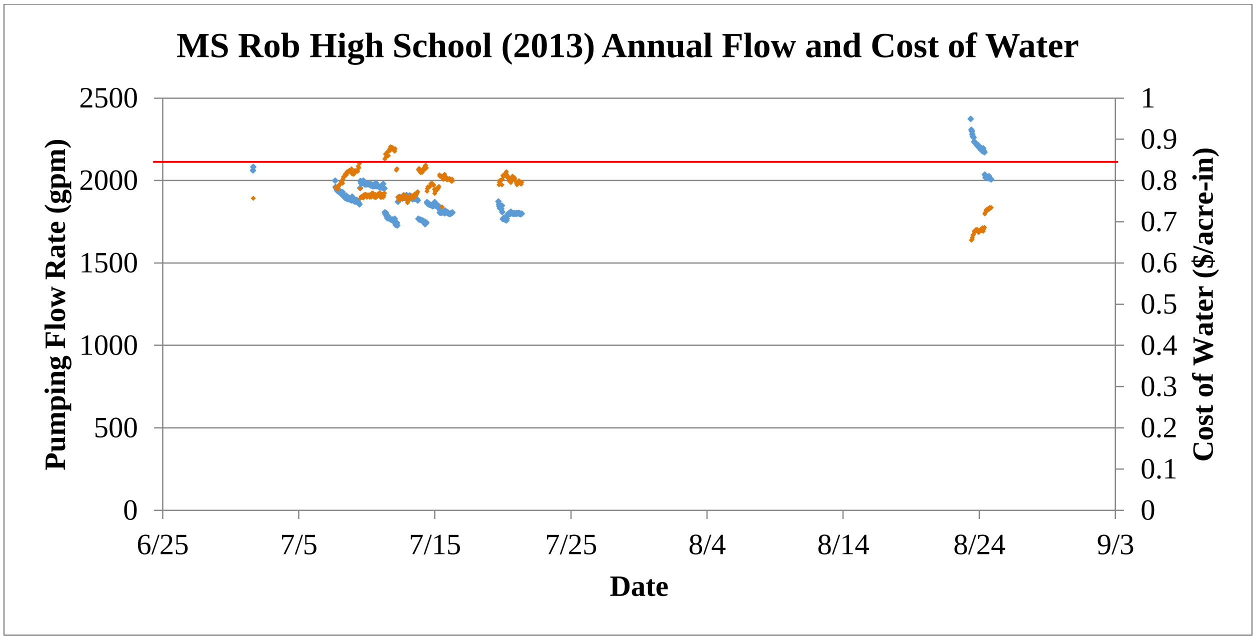

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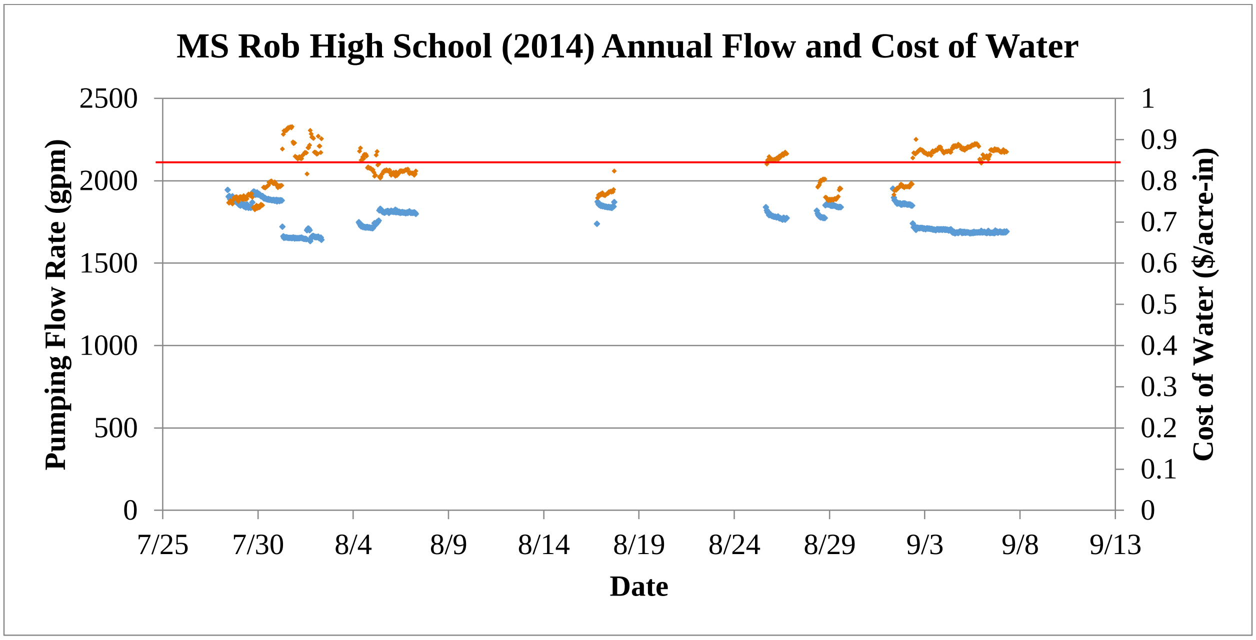

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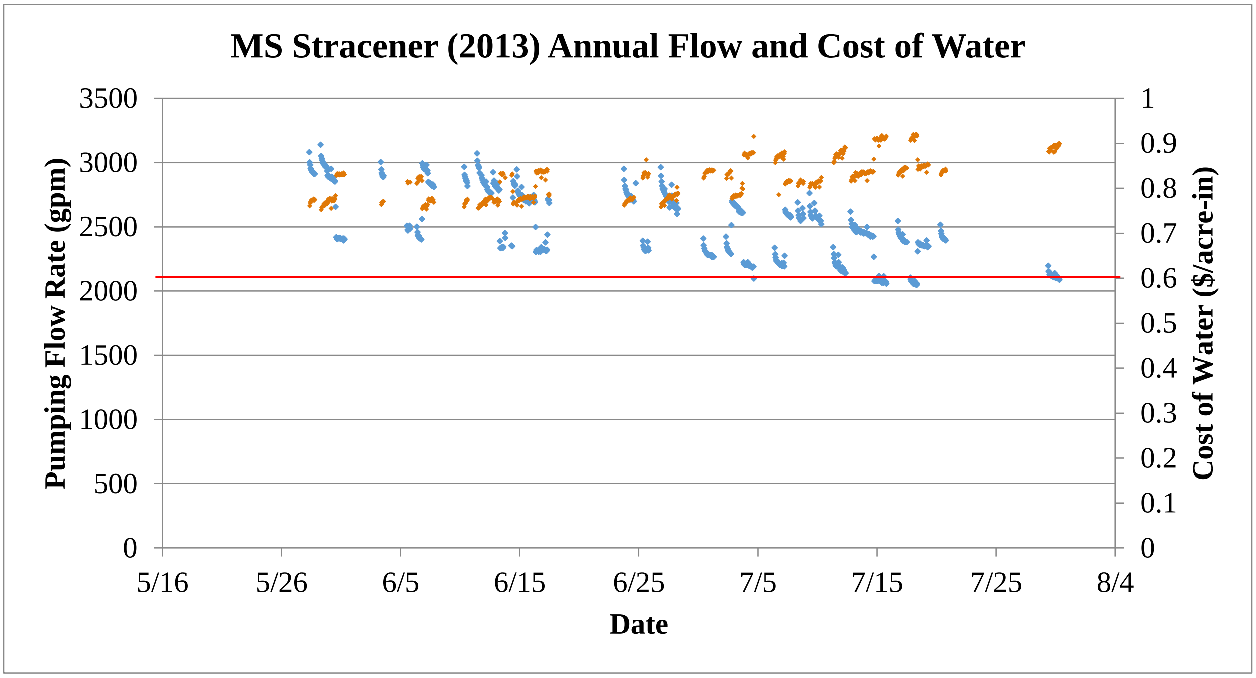

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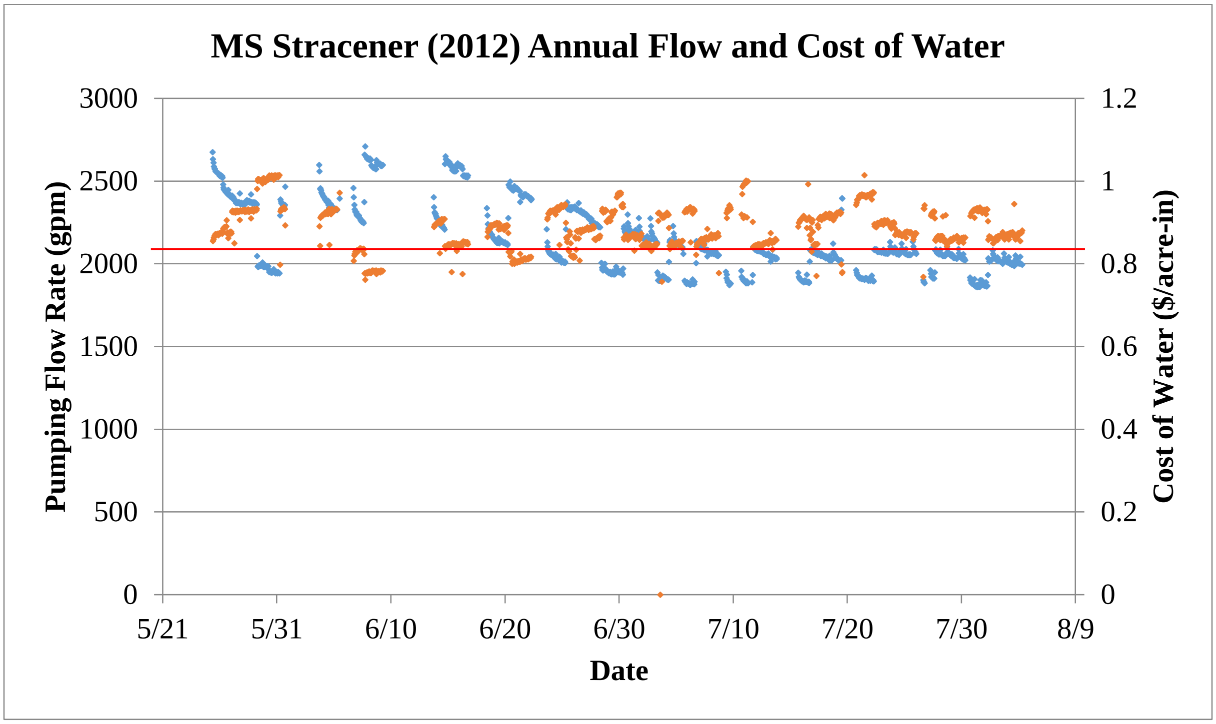

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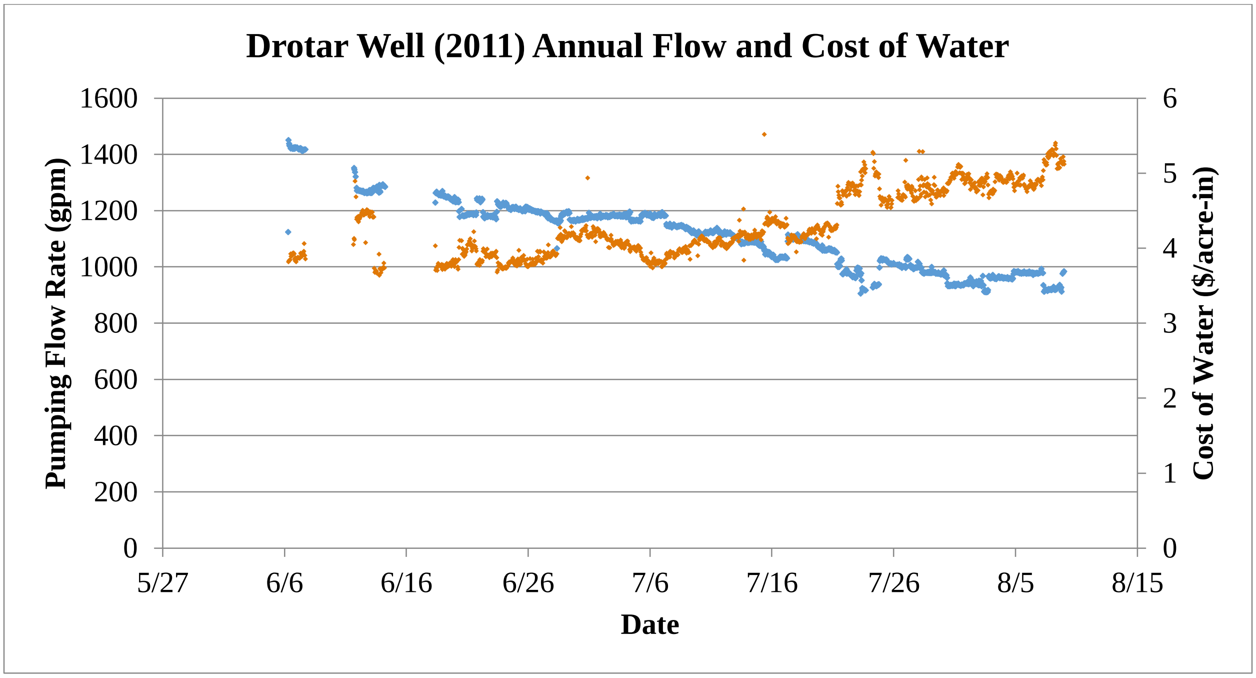

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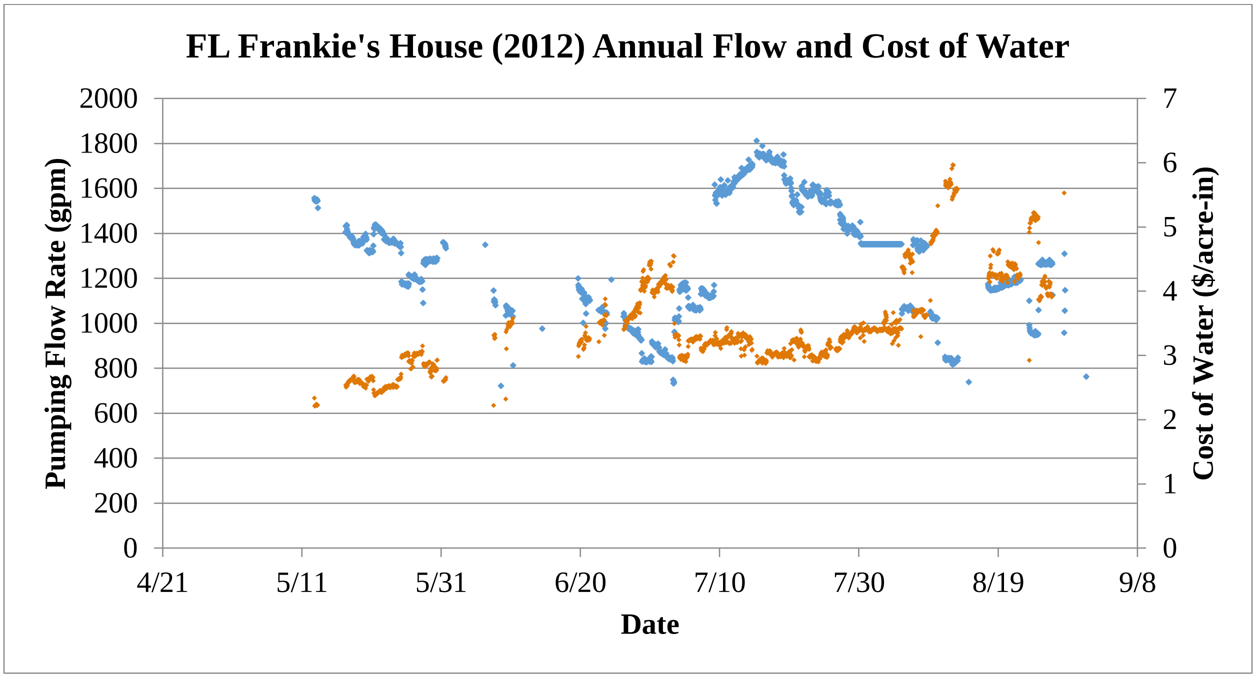

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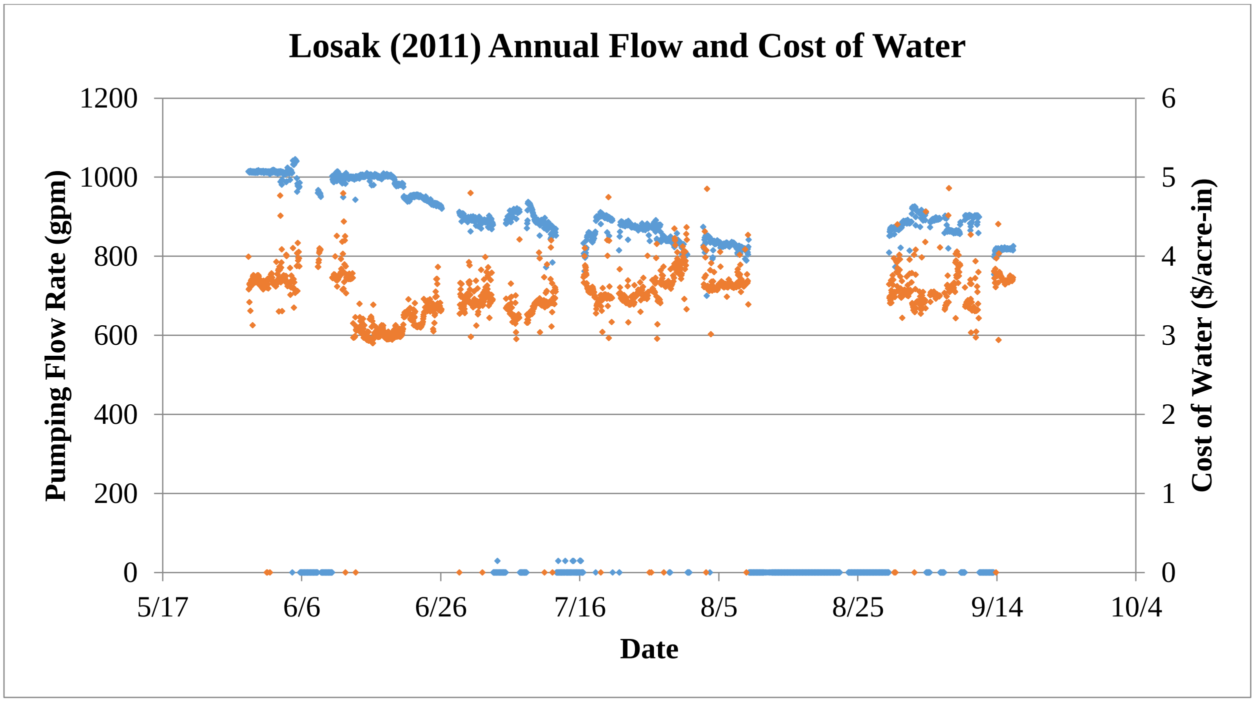

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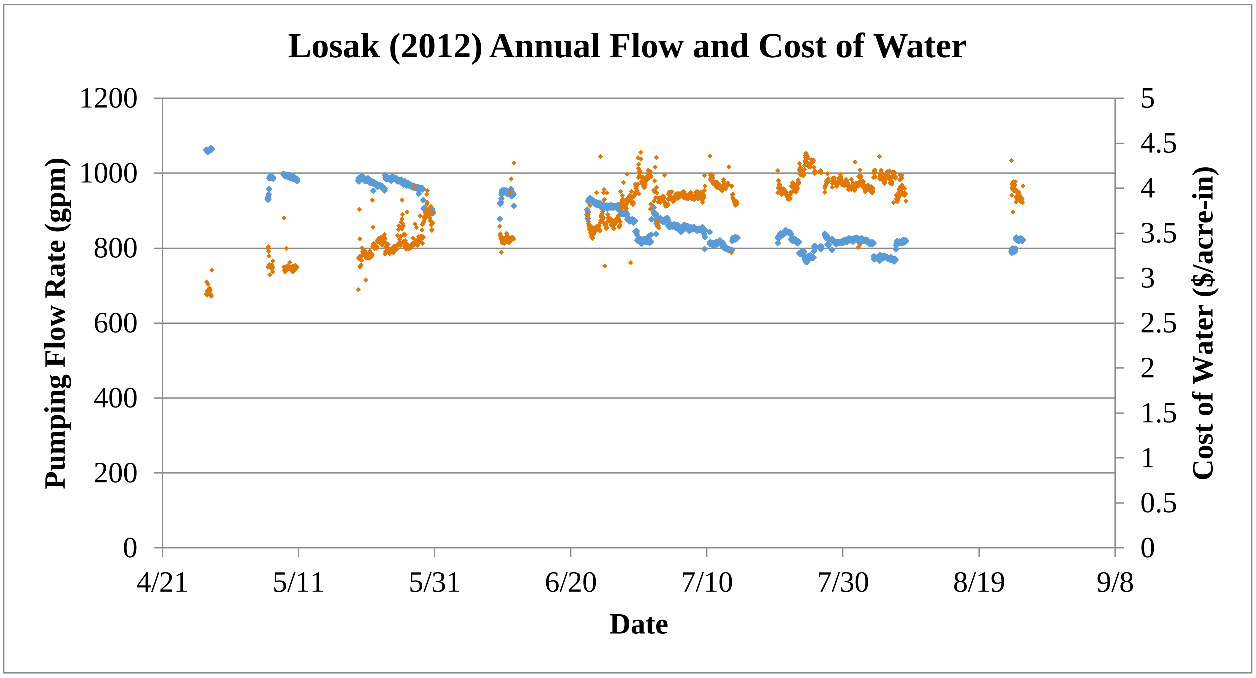
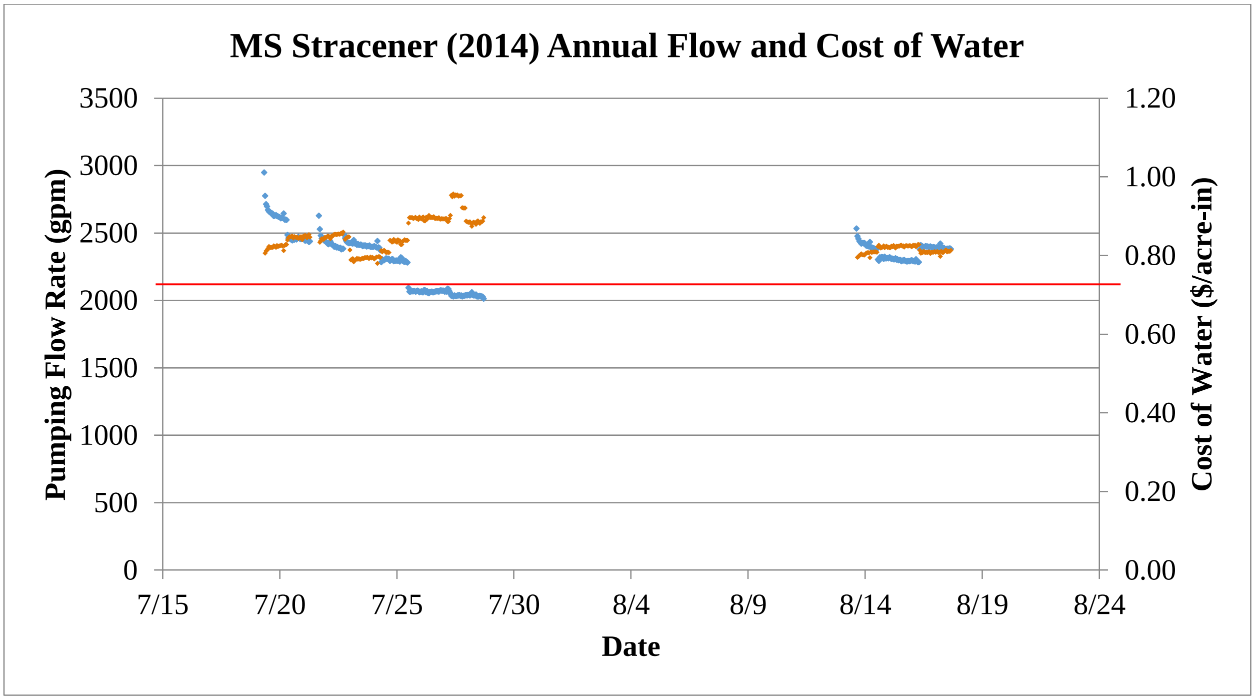


Figure A - 28.



Analysis A - 1.

COW by Energy Source Mann-Whitney Rank Sum Test

Group	**N**	**Missing**	**Median**	**25%**	**75%**
Electric	54	0	0.930	0.830	1.274
Diesel	11	0	1.991	1.270	2.836

Mann-Whitney U Statistic= 131.000

T = 529.000 n(small)= 11 n(big)= 54 (P = 0.004)

The difference in the median values between the two groups is greater than would be expected by chance; there is a statistically significant difference (P = 0.004)

Analysis A - 2.

TDH Normalized COW by Energy Source Mann-Whitney Rank Sum Test

Group	**N**	**Missing**	**Median**	**25%**	**75%**
Electric	54	0	0.173	0.148	0.214
Diesel	11	0	0.500	0.440	0.591

Mann-Whitney U Statistic= 0.000

T = 660.000 n(small)= 11 n(big)= 54 (P = <0.001)

The difference in the median values between the two groups is greater than would be expected by chance; there is a statistically significant difference (P = <0.001)

Analysis A - 3.

COW by System Type Kruskal-Wallis One Way Analysis of Variance on Ranks

Group	**N**	**Missing**	**Median**	**25%**	**75%**
Surface Water Relift	13	0	0.760	0.485	1.195
Alluvial Well	47	0	1.029	0.864	1.500
Deep Well	5	0	3.960	3.680	4.390

H = 19.947 with 2 degrees of freedom. (P = <0.001)

The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = <0.001)

To isolate the group or groups that differ from the others use a multiple comparison procedure.

All Pairwise Multiple Comparison Procedures (Dunn's Method) :

Comparison	**Diff of Ranks**	**Q**	**P<0.05**
Deep Well vs Surface Water	44.154	4.438	Yes
Deep Well vs Alluvial Well	29.277	3.292	Yes
Alluvial Well vs Surface Water	14.877	2.511	Yes

Note: The multiple comparisons on ranks do not include an adjustment for ties.

Analysis A - 4.

TDH Normalized COW by System Type Kruskal-Wallis One Way Analysis of Variance on Ranks

Group	N	Missing	Median	25%	75%
Surface Water Relift	13	0	0.214	0.174	0.410
Alluvial Well	47	0	0.177	0.147	0.273
Deep Well	5	0	0.160	0.145	0.172

H = 5.491 with 2 degrees of freedom. (P = 0.064)

The differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.064)

Analysis A - 5.

%-NPPPC by Energy Source Kruskal-Wallis One Way Analysis of Variance on Ranks

Group	N	Missing	Median	25%	75%
Electric	52	0	75.212	63.265	88.194
Diesel	11	0	62.000	55.000	74.000

H = 4.487 with 1 degrees of freedom. (P = 0.034)

The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.034)

All Pairwise Multiple Comparison Procedures (Dunn's Method) :

Comparison	Diff of Ranks	Q	P<0.05
Electric vs Diesel	12.886	2.118	Yes

Analysis A - 6.

%-NPPPC by System Type Kruskal-Wallis One Way Analysis of Variance on Ranks

Group	**N**	**Missing**	**Median**	**25%**	**75%**
Alluvial Well	46	0	72.957	59.634	88.718
Deep Well	5	0	81.300	76.119	89.831
Surface Relift	12	0	72.308	61.487	75.618

H = 2.847 with 2 degrees of freedom. (P = 0.241)

The differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.241)

Analysis A - 7.

%-NPPPC by Geographic Location One Way Analysis of Variance

Normality Test (Shapiro-Wilk) Passed (P = 0.200)

Equal Variance Test: Passed (P = 0.780)

Group Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
Grand Prairie Area	26	0	67.672	13.719	2.690
Northeast Arkansas	29	0	81.018	13.207	2.452
Other	8	0	54.356	14.041	4.964

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Between Groups	2	5335.180	2667.590	14.592	<0.001
Residual	60	10968.864	182.814		
Total	62	16304.044			

The differences in the mean values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = <0.001).

Power of performed test with alpha = 0.050: 0.999

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **Geographical Area**

Comparison	**Diff of Means**	**p**	**q**	**P**	**P<0.050**
Northeast Arkansas vs. Other	26.663	3	6.983	<0.001	Yes
Northeast Ar vs. Grand Prairi	13.346	3	5.169	0.002	Yes
Grand Prairie Area vs. Other	13.316	3	3.445	0.046	Yes

Analysis A - 8.

IC One Way Analysis of Variance

Dependent Variable: IC Actual minus Recommended

Normality Test (Shapiro-Wilk) Passed (P = 0.699)

Equal Variance Test: Passed (P = 0.680)

Group Name	N	Missing	Mean	Std Dev	SEM
Grand Prairie Area	11	0	-0.447	3.447	1.039
Northeast Arkansas	28	0	2.149	3.382	0.639
Other	5	0	-3.280	1.807	0.808

Source of Variation	DF	SS	MS	F	P
Between Groups	2	150.960	75.480	7.022	0.002
Residual	41	440.727	10.749		
Total	43	591.687			

The differences in the mean values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.002).

Power of performed test with alpha = 0.050: 0.870

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **Geographic Location**

Comparison	Diff of Means	p	q	P	P<0.050
Northeast Arkansas vs. Other	5.429	3	4.823	0.004	Yes
Northeast Ar vs. Grand Prairi	2.596	3	3.146	0.079	No
Grand Prairie Area vs. Other	2.833	3	2.266	0.256	No

Table A - 1

NPPPC Benchmark Values in metric units

Energy Source	**Energy Unit**	**b-kWh/unit (1)**	**w-kWh (2)/unit (3)**
Electric	kWh	0.88	0.66
Diesel	Liter	3.27	2.46 (4)
Natural Gas	10 m^3	23.4	17.6
Propane	Liter	1.81	1.36
Gasoline (6)	Liter	2.27	1.71

Assumptions:

1) Kilowatt-hours (b-kWh) is the work produced by the power unit including drive losses.

2) Water kilowatt-hours (w-kWh) is the work produced by the pumping plant per unit of energy at the NPPPC.
3) The NPPPC is based on 75% pump efficiency.
4) Criteria for diesel revised in 1981 to 2.46 w-kWh/l
5) Assumes 88% electric motor efficiency.
6) Taken from Test D of Nebraska Tractor Test Reports. Drive losses are accounted for in the data. Assumes no cooling fan.
7) Manufacturers' data corrected for 5% gear-head drive loss and no cooling fan. Assumes natural gas energy content of 37,259 kJ/m^3.

Table A - 2

Table of Pearson Product Moment Correlation Results Comparing Annual Flow Loss, Annual Cost of Water Increase, Average Flow Rate, and Operational Time for Well Pumping Plants.

	Annual Q_w Decrease (% of Initial)	**Annual COW Increase** ($/acre-in) , *($/ha-cm)*
Annual Q_w Decrease (% of Initial)	Correlation Coefficient	0.514
	P Value	**0.00511**
	# of Samples	28
Annual Q_w Decrease (gpm) , *(m^3/hr)*		0.118
		0.551
		28
	Annual COW Increase (% of Initial)	**Operational Time** (hr)
Annual Q_w Decrease (gpm) , *(m^3/hr)*	0.522	0.363
	0.00442	0.058
	28	28
Annual Q_w Decrease (% of Initial)	0.744	0.569
	0.00000559	**0.00158**
	28	28
Annual COW Increase ($/acre-in) , *($/ha-cm)*		0.563
		0.0018
		28
Annual COW Increase (% of Initial)		0.598
		0.000779
		28
	Annual Average Q_w (gpm) , *($/ha-cm)*	
Annual Q_w Decrease (gpm) , *($/ha-cm)*	0.426	
	0.0236	
	28	
Annual Q_w Decrease (% of Initial)	-0.113	
	0.567	
	28	
Annual COW Increase ($/acre-in) , *($/ha-cm)*	-0.431	
	0.0221	
	28	
Annual COW Increase (% of Initial)	-0.154	
	0.434	
	28	
Operational Time (hr)	-0.211	
	0.281	
	28	

Table A – 3

Comparison of Results to Tacker and Langston (1987)

	This Study	**Tacker and Langston (1987)**
Average Electric COW ($/acre-in) *($/ha-cm)*	1.38	1.12
Average Diesel COW ($/acre-in) *($/ha-cm)*	1.96	2.65
Average Electric %-NPPPC	74.0	77.0
Average Diesel %-NPPPC	63.3	71.0