Pacific Gas and Electric Company

Emerging Technologies Program

Application Assessment Report #0901

Water-Energy Pumping Optimization

San Jose Water Company
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1. Executive Summary

This report presents a feasibility study for implementing an energy-pumping optimization algorithm through a Supervisory Control and Data Acquisition (SCADA) System using real-time energy consumption data. The study was performed as a collaboration between the San Jose Water Company (SJWC), Pacific Gas and Electric Co. (PG&E), and BASE Energy, Inc. (BASE) over the period of one and a half years.

Four well pump stations at SJWC were selected for the study: two single well pump stations, one two-well pump station, and one multiple well pump (four well pumps and three booster pumps) station. The main results of this study were:

- The utility revenue meter energy data can be used to optimize the water pumping energy
- The utility revenue meter can be easily interconnected to a SCADA system to supply real-time energy data
- A water pumping energy optimization methodology that utilizes real-time energy consumption data can result in electrical energy savings

Table 1.1 shows the water demand profile for 2008, the pumping energy intensity for 2008, and the potential pumping energy intensity after implementation of the proposed optimization for three of the four pump stations (one station was not included in the analysis due to insufficient data).

TABLE 1.1 ESTIMATED ENERGY SAVINGS

Month	**Total Volume** (MG)	**Current Intensity** (kWh/MG)	**Proposed Intensity** (kWh/MG)	**Energy Savings** (kWh)	**Saving Percentage** (%)
January	247.6	1,686	1,514	42,677	10%
February	173.6	1,684	1,496	32,723	11%
March	163.3	1,711	1,513	32,324	12%
April	190.9	1,711	1,499	40,477	12%
May	233.2	1,679	1,505	40,499	10%
June	296.6	1,635	1,542	27,507	6%
July	335.0	1,600	1,552	16,238	3%
August	362.9	1,617	1,602	5,570	1%
September	406.6	1,637	1,607	12,065	2%
October	432.6	1,631	1,610	9,146	1%
November	181.6	1,648	1,498	27,293	9%
December	137.3	1,633	1,438	26,717	12%
Totals/Overall		**1,648**	**1,549**	**313,237**	**6%**

From Table 1.1, implementing an energy-pumping optimization algorithm could reduce the pumping energy intensity by approximately 6% to 1,549 kWh/MG. Based on the water demand profile for 2008, it is estimated that the three well pump stations could have saved approximately

313,237 kWh resulting in an estimated $37,588 (assuming an energy unit cost of $0.12/kWh) cost savings.

Implementing a water-energy pumping optimization algorithm with real-time energy consumption data requires the following steps:

1. Upgrading the SCADA system hardware and software to be able to communicate the energy consumption data from the well pumps stations to the central SCADA system.
2. Identify the variables and develop the formulation (metrics) that will be used to assess water-energy pumping optimization.
3. Develop a company wide model of the water system so that optimization solutions can be checked against system constraints.
4. Develop an advanced optimization algorithm (e.g. neural networks) capable of finding an optimal solution within a satisfactory window of time

2. Introduction

2.1 Project Background

In recent years, water utilities have benefited greatly from the adoption of Supervisory Control and Data Acquisition (SCADA) systems to improve process quality and reliability. Although SCADA systems also can improve energy efficiency in a facility, most water utilities currently do not use these systems to achieve energy efficiency gains. Energy efficiency is often a by-product of process improvement. Furthermore, the operation of many SCADA systems is done manually by operations staff rather than automatically by the systems, which limits the energy efficiency gains. Emerging automated SCADA systems offer the potential for significant energy efficiency gains in the water utility industry.

2.2 Project Objectives

The overall objective of this project is to study the feasibility of implementing an energy consumption optimization algorithm in well water pump stations through a SCADA system by exploiting real-time electrical energy consumption data.

Specific objectives include:

- Explore available energy metering and sub-metering technologies that could be used to efficiently transmit energy consumption data to the SCADA system
- Enabling the utility revenue meter energy output information and connecting it to the SCADA system
- Evaluating the use of real-time energy data for an energy optimization algorithm
- Developing a preliminary water pumping energy optimization algorithm

2.3 Project Scope

The planned tasks to complete the project include:

- Select the pump stations for the study
- Identify a cost-effective method for measurement of electrical energy consumption of pumps at each station
- Devise an optimization algorithm that can utilize real-time electrical energy consumption measurements
- Implement the necessary hardware upgrades to provide electrical energy consumption data to the existing SCADA system
- Measure and evaluate pumping electrical energy consumption under the existing pump control scheme
- Evaluate the potential for energy savings due to optimization
- Implement the optimization algorithm for the selected test pump stations
- Measure and evaluate the pumps electrical energy consumption with the implemented optimization algorithm
- Evaluate the potential electrical energy savings

3. Pump Stations

3.1 San Jose Water Company Pumping System Overview

The San Jose Water Company serves 220,000 customers (population of 1,000,000 people) in the Greater San Jose metropolitan area. Their 102 water pumping stations pump approximately 50,000 million gallons per year into 64 different pressure zones. The total pumping capacity of the water company is approximately 232 MGD. The total electrical energy consumed in one year is approximately 56,400,000 kWh.

3.2 Well Pump Station Selection Criteria

Four well pump stations were selected for the Water-Energy Pilot Project at San Jose Water Company (SJWC). They include:

- Senter, a single well pump station
- Needles, a single well pump station
- Will Wool, a two well pump station
- Tully, a four well pump station with three booster pumps

The commonality between the selected well pump stations is that they all pump into the same water pressure zone, DOW ZONE. The discharge pressure varies because the pump stations are geographically located in different areas and they pump into the DOW ZONE at different points. Figure 3.1 graphs the pressure variation vs. time for three pump stations (please note that Needles station does not have pressure data).

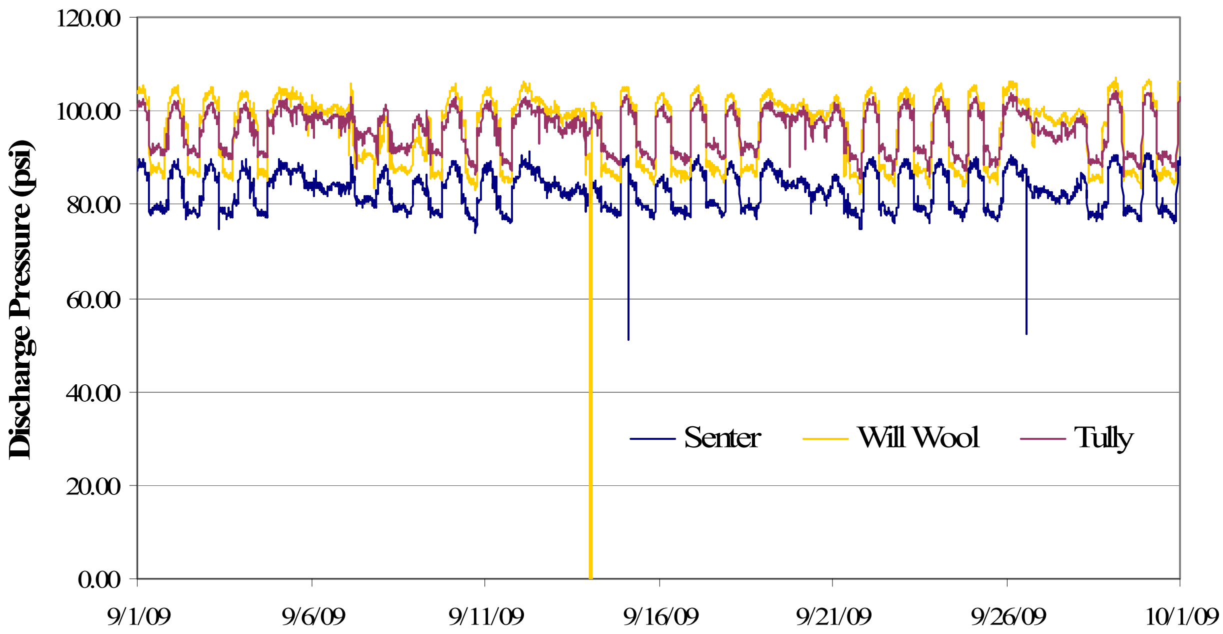

Figure 3.1 – Test Station Discharge Pressure

The DOW ZONE includes a large water tank located above a hill in the San Jose Area. The DOW ZONE pressure at different locations is mostly affected by the water tank level, and to a lesser degree, on the pump operation at each station. Figure 3.1 shows that the station pressure follows a general pattern more related to the water consumption and not dependent on pump operation within stations.

3.3 Well Pump Station Description

The well pump operation of each station is based on station discharge pressure. Different pressure setpoints are used to turn on/off individual pumps at each station. The pressure setpoints change by time-of-day as well as season, which is done by SJWC to control time-of-use energy costs. The various pressure setpoints used to control the pumps can be directly related to the DOW ZONE tank level as well as water flow rate (gpm) required at different tank levels.

The following sections describe the existing equipment and operation of each well pump station.

Tully Road Well Station

The station is comprised of four wells (one pump per well), one suction tank, and three booster pumps. Figure 3.2 shows a schematic of the existing pump configuration.

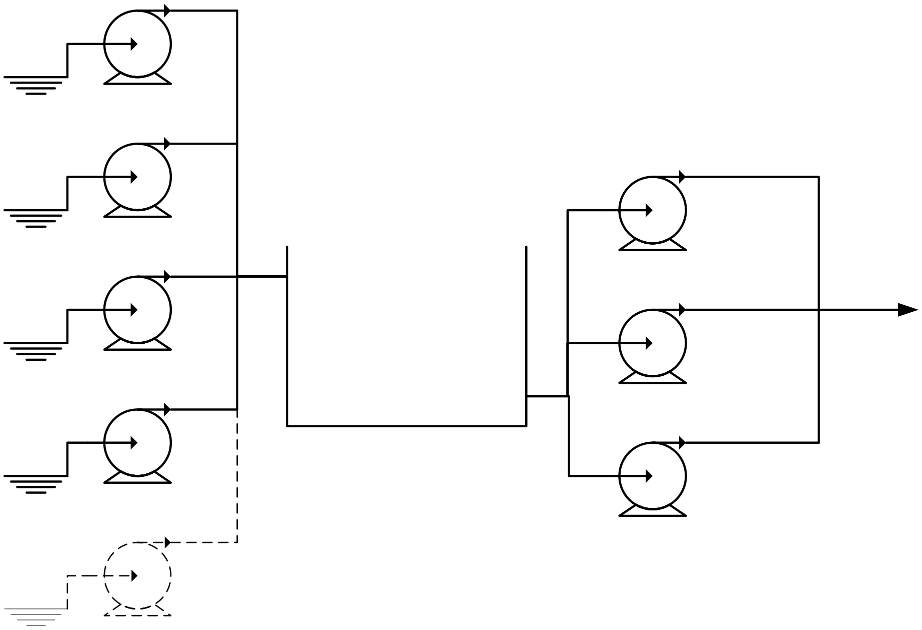

Figure 3.2 – Tully Road Well Station Pump Configuration

Although Tully Station has five wells, water is being extracted from only four wells. The fifth well will be brought online within the next few months. The existing control strategy for this well station is as follows.

Booster Pump Operation

The three booster pumps (B-1, B-2, and B-3) are directly controlled by the SCADA system, and turned on and off based on station discharge pressure. Currently a flow and a pressure sensor at the booster pump discharge feed information to the SCADA system.

In addition to the SCADA system direct control of the booster pumps (through pressure setpoints), there is a (Suction) tank level sensor feeding a local controller which prevents the water level inside the tank to fall below five feet by forcing the booster pumps to turn off.

Well Pump Operation

The four existing well pumps (W-1, W-2, W-3, and W-4) are not being controlled by the SCADA system directly; instead there is a local controller that turns the well pumps on/off in a sequential manner based on the Suction Tank water level. The well pumps are sequenced as follows:

Well Pump	Turn On (ft)	Turn Off (ft)
W-1	8.5	17.4
W-2	8.0	17.3
W-3	7.5	17.2
W-4	7.0	17.1

Suction Tank

Based on sequence of operation of the well pumps, under normal conditions the tank level is allowed to swing between 7 ft and 17.4 ft. The absolute minimum water level the tank is allowed to drop is 5 ft, at which point all booster pumps are forced to turn off.

Based on the sequence of operation of the well pumps, once all booster pumps are turned off, the Suction Tank level is expected to be restored to 17.4 ft.

Figure 3.3 shows the whole station water flow rate (gpm) and electrical demand (kW) for the month of September 2009.

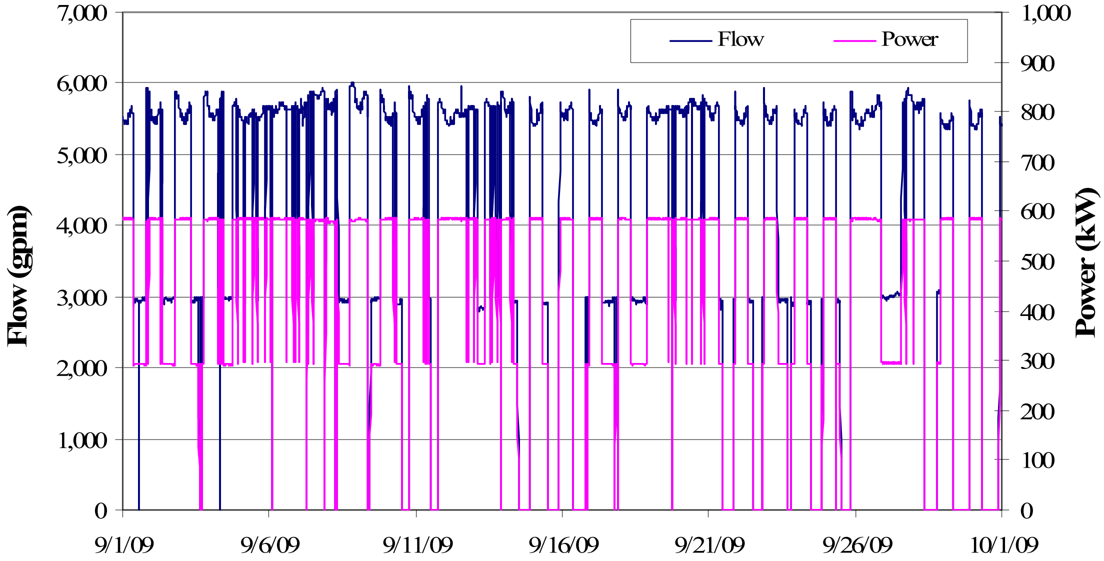

Figure 3.3 – Tully Station Flow Rate and Electrical Demand

Will Wool Station

The station is comprised of two well pumps that feed directly into the DOW ZONE. Figure 3.4 shows a basic schematic of the existing pump configuration.

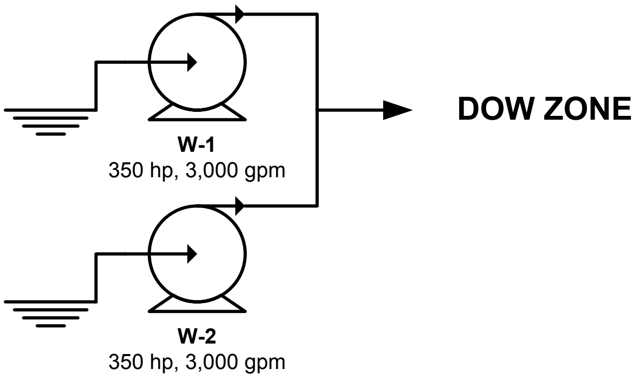

Figure 3.4 – Will Wool Well Station Pump Configuration

The SCADA system directly controls these pumps, which are turned on based on demand. Currently there is a flow sensor and a pressure sensor installed at the pump station discharge that feed data directly to the SCADA system.

Figure 3.5 shows the whole station water flow rate (gpm) and electrical demand (kW) for the month of September 2009.

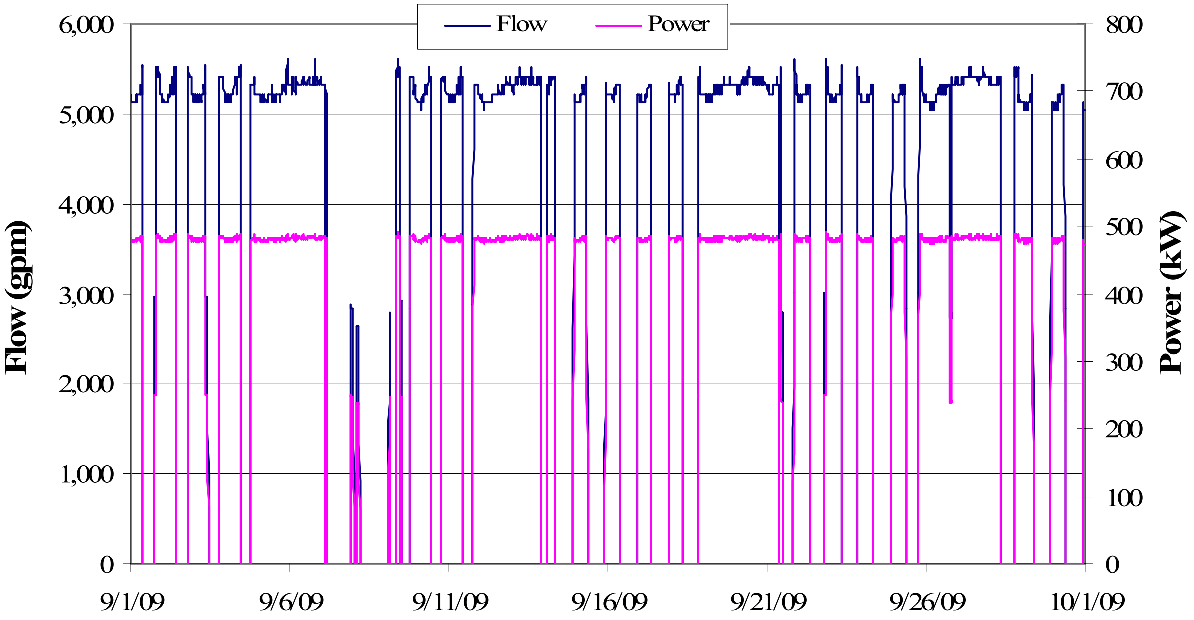

Figure 3.5 – Will Wool Station Flow Rate and Electrical Demand

Needles Station

The station is comprised of a single well that feeds directly into the DOW ZONE. Figure 3.6 shows a basic schematic of the existing pump configuration.

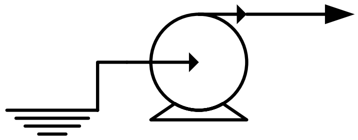

Figure 3.6 – Needles Well Station Pump Configuration

The SCADA system directly controls this pump, which is turned on based on demand. Currently there is a flow sensor and a pressure sensor installed at the pump discharge that feed information directly to the SCADA system.

Senter Station

The station is comprised of a single well that feeds directly into the DOW ZONE. Figure 3.7 shows a basic schematic of the existing pump configuration.

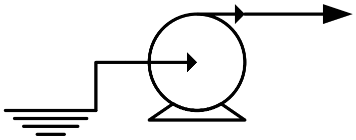

Figure 3.7 – Senter Well Station Pump Configuration

The SCADA system directly controls this pump, which is turned on based on demand. Currently there is a flow sensor and a pressure sensor installed at the pump discharge that feed information directly to the SCADA system.

Figure 3.8 shows the whole station water flow rate (gpm) and electrical demand (kW) for the month of September.

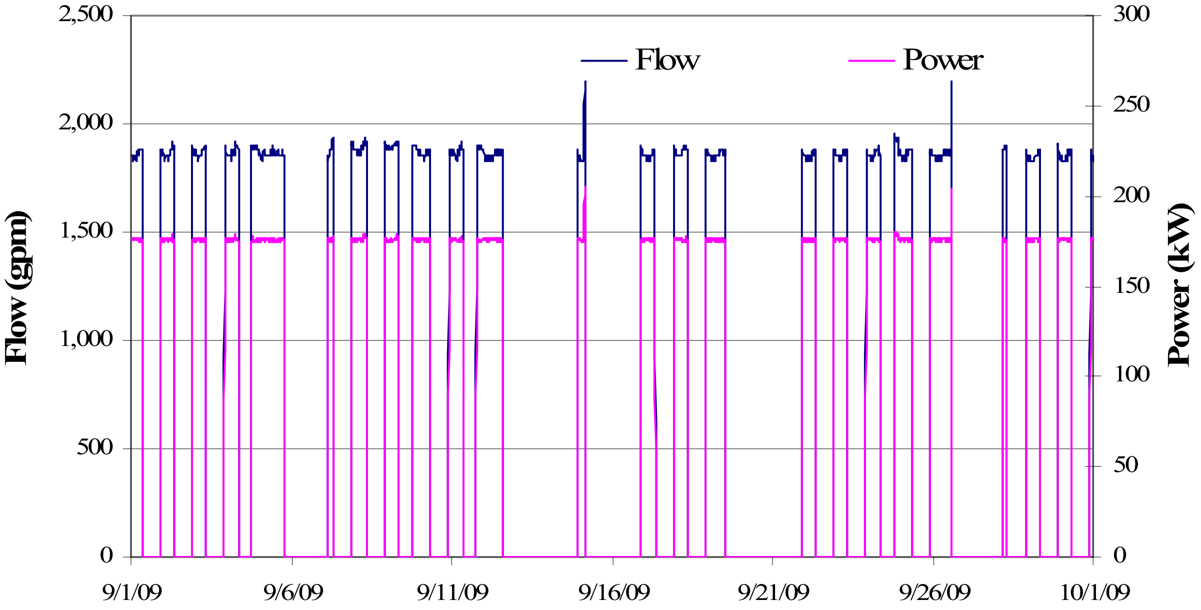

Figure 3.8 – Senter Station Flow Rate and Electrical Demand

4. Energy Metering

4.1 Metering Technology

The energy metering technology used for the project is PG&E's revenue meter. PG&E offers customers the option for enabling energy consumption (kWh) output from revenue meters so that customers can connect and receive energy consumption information from the meter.

The kWh information output from the revenue meter is a KYZ (dry contact) signal. KYZ refers to the contact designations at the signal output: common terminal (K), normally open terminal (Y), and normally closed terminal (Z). As energy is consumed, the revenue meter kWh dial spins triggering a change of state on the Y and Z terminals every time the dial turns a full (or half, depending on the revenue meter used) revolution. Therefore every dial revolution (and corresponding change of state on the Y and Z terminals) signifies a discrete number of kWh consumed.

For the test sites considered in this project, the kWh per change of state (pulse) constants are as follows:

- Tully Station: 0.40 kWh/pulse
- Will Wool Station: 0.54 kWh/pulse
- Needles Station: 0.32 kWh/pulse
- Senter Station: 0.24 kWh/pulse

Since the kWh/pulse constants are relatively small, the KYZ output can be considered a continuous signal. As an example, at Will Wool Station, the lowest electrical load (when only one pump operates) is approximately 250 kW, resulting in approximately 463 pulses per hour. This is equivalent to kWh pulses with a period of 7.8 seconds.

4.2 SCADA Interface Hardware

The SCADA – Revenue Meter interface hardware used for this project is a Digital In/Analog Out (DI/AO) counter module (Durant Eclipse Series). This module has the following capabilities:

- Energize the dry contacts from the KYZ revenue meter output
- Store in memory up to 999,999 pulses
- Seamlessly communicate with the SCADA system used by the host facility

The counter module used to interface the KYZ revenue meter output with the SCADA system had two objectives:

1. Convert the KYZ signal to an analog signal that can be received by the SCADA system
2. Provide an onsite buffer so that pulses generated by the revenue meter can be stored and later retrieved by the SCADA system at a slower rate (e.g. every 5, 10, or 15 min.) than would be required if the pulse train was fed directly to the SCADA system.

4.3 Interfacing Hardware Implementation

One counter module was installed on each of the four test pump stations. The counter modules are connected to PG&E revenue meters to monitor the total pump station electrical energy consumption. A simplified schematic of hardware connections is shown in Figure 4.1 below.

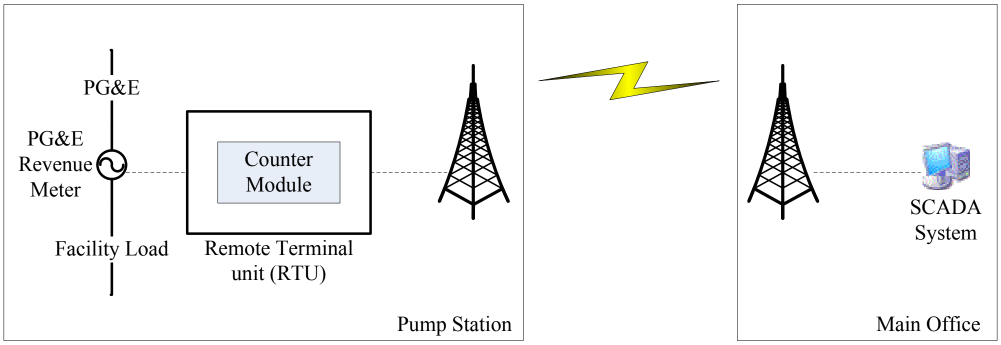

Figure 4.1 – Revenue Meter – SCADA Interface Hardware Implementation

The facility has remote terminal units (RTUs) at each of the pump stations. RTUs house various modules used to monitor and control pump operation. Communication between the RTUs and SCADA system (located at the Main Office) is through radio towers.

The SCADA system has been configured to poll the test pump stations every 15 minutes to download the electrical energy consumption from the counter module.

4.4 Interfacing Hardware Calibration

To ensure that the counter module has been correctly calibrated, energy data loggers were installed at the electrical mains for two of the four test pump stations (Senter and Needles). The bus bars at the electrical mains for the Will Wool and Tully stations were too large to install regular clamp on current probes. To ensure proper counter module calibration (correct meter constant, kWh/pulse) for these stations, the energy consumption recorded by the SCADA system was compared to PG&E interval data. The results are presented below.

Comparison of SCADA Energy Consumption with Data Logger Energy Consumption

Two energy data loggers (DENT Elite Pro data loggers) were borrowed from PG&E's Pacific Energy Center in San Francisco. One data logger was installed at the electrical mains for Senter Station and the other was installed at the electrical mains for Needles Station. The data loggers were installed in a two watt-hour meter configuration set up to record energy consumption every 15 minutes, for the period of two weeks. The SCADA system was setup to record the electrical energy consumption every 5 minutes for the same two week period. Figures 4.2 and 4.3 show the data recorded by the data loggers and the SCADA system for the Needles Station. Figures 4.4 and 4.5 show the data recorded by the data loggers and the SCADA system for the Senter Station.

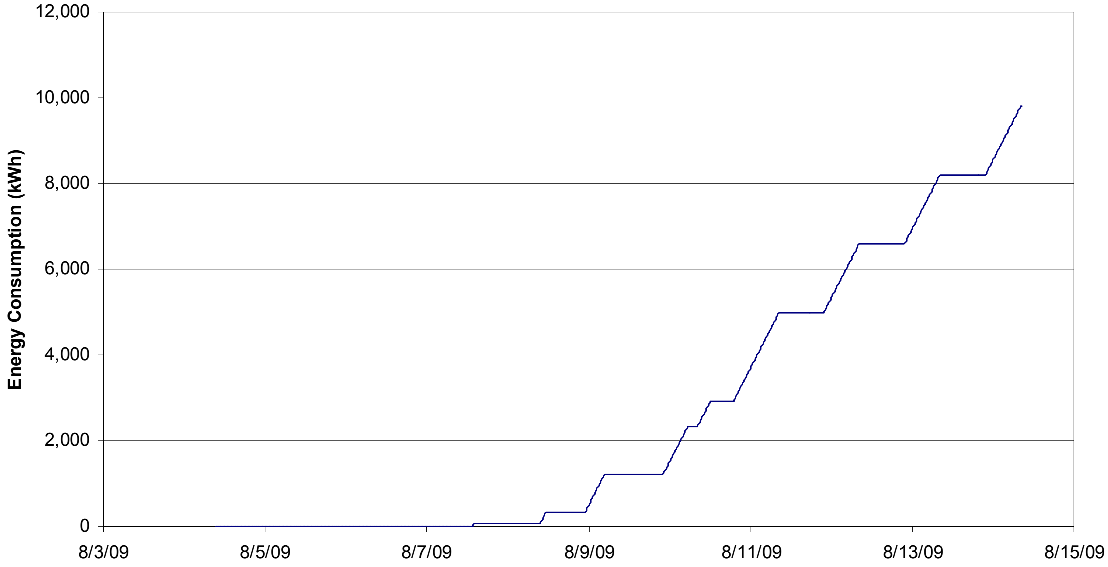

Figure 4.2 – Needles Station Energy Consumption (Data Logger)

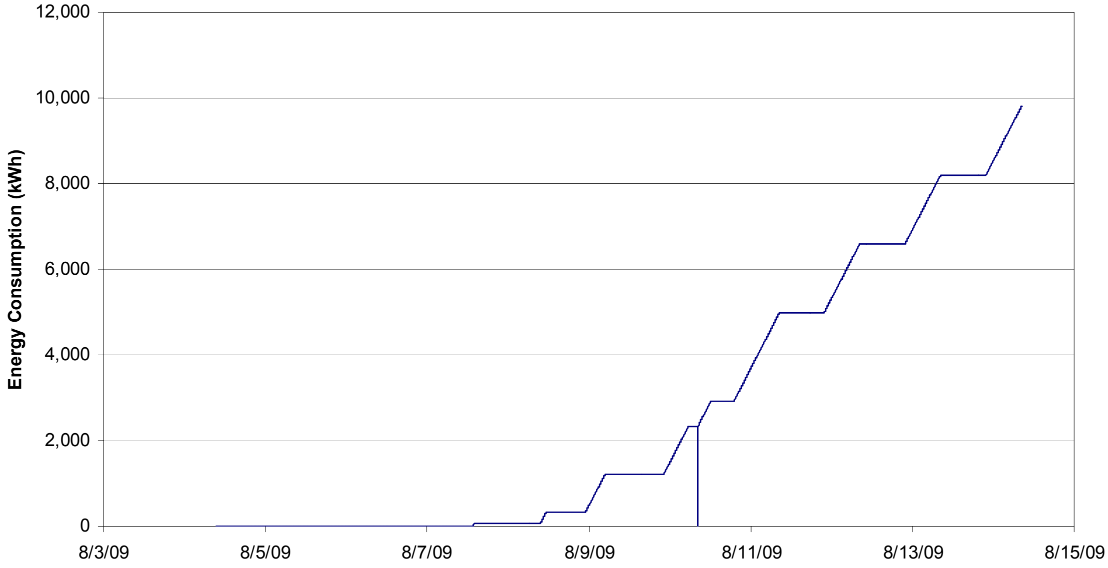

Figure 4.3 – Needles Station Energy Consumption (SCADA)

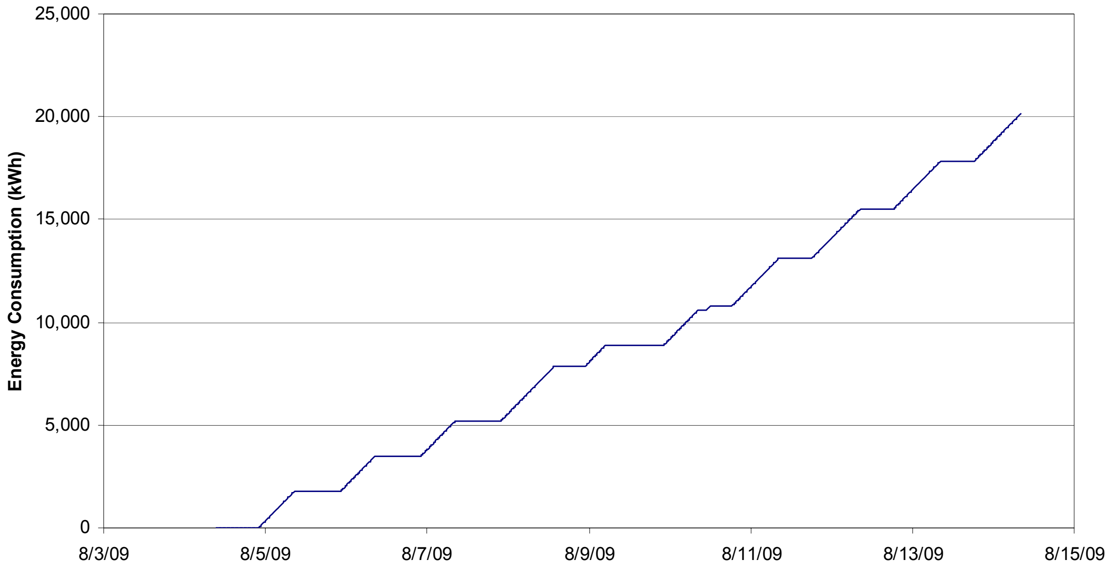

Figure 4.4 – Senter Station Energy Consumption (Data Logger)

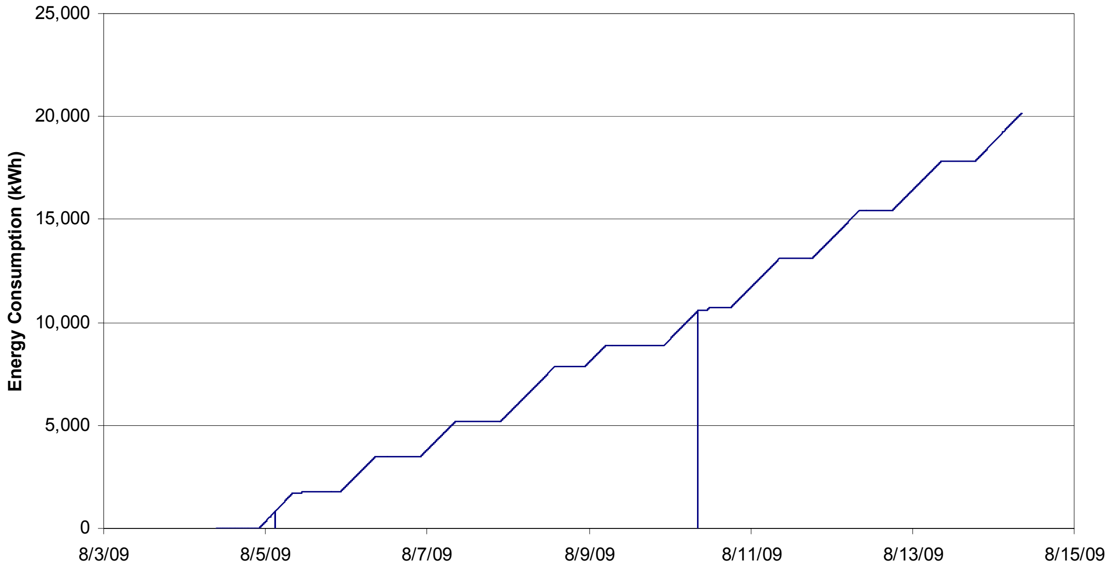

Figure 4.5 – Senter Station Energy Consumption (SCADA)

Table 4.1, on the following page, summarizes the energy consumption for the period of 8/4/2009 9:15 a.m. through 8/17/2009 9:00 a.m. by the data loggers and SCADA system and the percent difference.

TABLE 4.1 – DATA LOGGER AND SCADA SYSTEM ENERGY CONSUMPTION COMPARISON			
Pump Station	**Data Logger Record**	**SCADA System Record**	**Difference**
Needles	9,820 kWh	9,799 kWh	0.2%
Senter	20,160 kWh	20,135 kWh	0.1%

Comparison of SCADA Energy Consumption with PG&E Billing and Interval Demand Data

Tully Station has an electric meter connected to the InterAct[1] system. PG&E provided demand interval data for the month of September 2009. The energy consumption reported by the InterAct system and the SCADA system are compared and shown in Table 4.2.

Will Wool Station does not have the electric meter connected to the InterAct system. However, PG&E has provided the monthly billing statement for the month of September 2009. The energy consumption reported in the billing statement has been compared to the energy consumption reported by the SCADA system. Table 4.2 summarizes the results.

TABLE 4.2 – PG&E AND SCADA SYSTEM ENERGY CONSUMPTION COMPARISON			
Pump Station	**PG&E Record**	**SCADA System Record**	**Difference**
Tully	315,374 kWh*	315,372 kWh	0.001%
Will Wool	235,200 kWh**	235,553 kWh	0.2%

* Interval Demand Data
** Monthly Billing Statement

From Table 4.2 the percent difference between PG&E billing and interval demand records and the SCADA system for Tully and Will Wool stations are 0.001% and 0.2% respectively. For Will Wool station the PG&E data made available was the monthly billing statement (no demand interval data was available). Since it is not clear at what time of day the electrical meter was read, the 0.2% difference may be attributed to the SCADA dataset being off by a few hours when comparing it to the billing dataset.

4.5 Interfacing Hardware Costs

Connecting the PG&E revenue meter to the SCADA system is a three step process:

1. Enabling the KYZ output from the revenue meter
2. Installing the counter module in the RTU and wiring the KYZ revenue meter output to the counter module
3. Programming the SCADA system to receive the kWh data from the counter module

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[1] InterAct is an online energy-usage, analysis, reporting, and curtailment –notification service for PG&E Customers. For details, please visit : http://www.pge.com/mybusiness/energysavingsrebates/demandresponse/tools/ (site accessed on 01/04/2010)

Enabling the KYZ Output

Only PG&E personnel has access to modify/alter the revenue meter, therefore enabling outputs from the meter requires contacting PG&E. The existing revenue meter at each pump station may, or may not, have KYZ outputs. PG&E charges a flat rate for enabling the KYZ output, regardless of whether the revenue meter needs to be changed or not. The cost to enable a KYZ output is $834.67 per meter, or $3,338.68 for all four pump stations.

Purchasing and Installing the Counter Module

The counter module used in this project is the Eaton Durant Eclipse Series Counter. This unit can be purchased for approximately $462.95 (including tax and freight), or $1,851.80 for all four modules. The counter modules were installed by SJWC personnel. Based on conversation with SJWC, it is estimated that installing the module took approximately 6 hours per module, at a rate of $45/hr. The purchasing and installation cost for all four modules was $2,931.80.

Programming the SCADA

In addition to installing and connecting the counter module, it is necessary to enable the new inputs into the SCADA system. This entails opening new ports so that the SCADA system can receive the kWh data from the counter module. Enabling the counter module input in the SCADA was performed by SJWC personnel. Based on conversation with SJWC, it is estimated that enabling the new inputs in the SCADA system took approximately 1 hour per input, at a rate of $45/hr. The cost for enabling all four inputs to the SCADA system was $180.

Therefore the total cost for interfacing the four PG&E revenue meters with the SJWC SCADA system is $6,450.48.

Notes:

1. All labor work provided by SJWC was done in-kind and not charged to the project. The labor costs for equipment installation and enabling is presented in this report to give a comprehensive evaluation of all costs associated with installation of the above equipment.
2. For the test sites considered, there were enough open slots in the RTUs to install the additional counter module. Adding extension slots to the RTUs may result in added costs not considered in this study.
3. Overall coordination of the work was done by BASE personnel, and is not considered in the above cost.

5. Baseline Analysis

5.1 Introduction

The modeling approach used to determine the energy performance of the pump stations is based on profiling the aggregate water flow rate and energy intensity occurrences of all pump stations (from now on, the aggregate performance of all pump stations will be referred as the Super Station[2]). This is accomplished by developing a histogram that quantifies the amount of time the Super Station operates at the various energy intensities. For details on the modeling approach please see Appendix 11.3 *Measurement and Evaluation*.

5.2 Baseline Description

The baseline data for characterizing the energy performance of the test sites are represented in the form of a histogram identifying the percentage of time (frequency) the Super Station operates at the various energy intensities (kWh/MG). Pertinent parameters, such as energy consumption, water flow rate, etc. are extracted from SCADA data and used as basis for comparison.

Using the histogram helps track the energy performance improvement of the Super Station by showing a shift to a higher number of low energy intensity occurrences when compared to the baseline.

It should be noted that because pressure data from the Needles Station to the SCADA was not made available until much later during the project, the baseline data presented in this section excludes Needles Station.

Section 5.3 – *Super Station Baseline* summarizes the baseline energy performance of the Super Station (the combined energy performance for all three test stations). Section 5.4 – *Individual Well Pump Station Energy Performance Characterization* presents the energy performance results for each of the four pump stations.

5.3 Super Station Baseline

Figure 5.1 shows the aggregate flow from all pump stations for the month of September. Typically the Super Station supplies water to the DOW ZONE at a rate between 3,000 gpm and 12,500 gpm. There are times when all pump stations are off resulting in no water being supplied to the DOW ZONE.

Figure 5.2 shows the combined energy intensity of all pump stations into one Super Station energy intensity. Operating points for the Super Station show that at some output flow rates the energy intensity has large variations suggesting that optimizing pump schedule could result in an overall pumping energy intensity reduction. As an example, at approximately 6,000 gpm, the pumping energy intensity for the Super Station varies from approximately 1,450 kWh/MG to 1,750 kWh/MG. Additionally, some of the energy intensities shown at higher gpm are lower

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[2] Super Station is defined in Section 6.2 *Optimization Methodology*

than the pumping energy intensity at lower flow rates, corroborating the findings discussed relative to Figure 5.2.

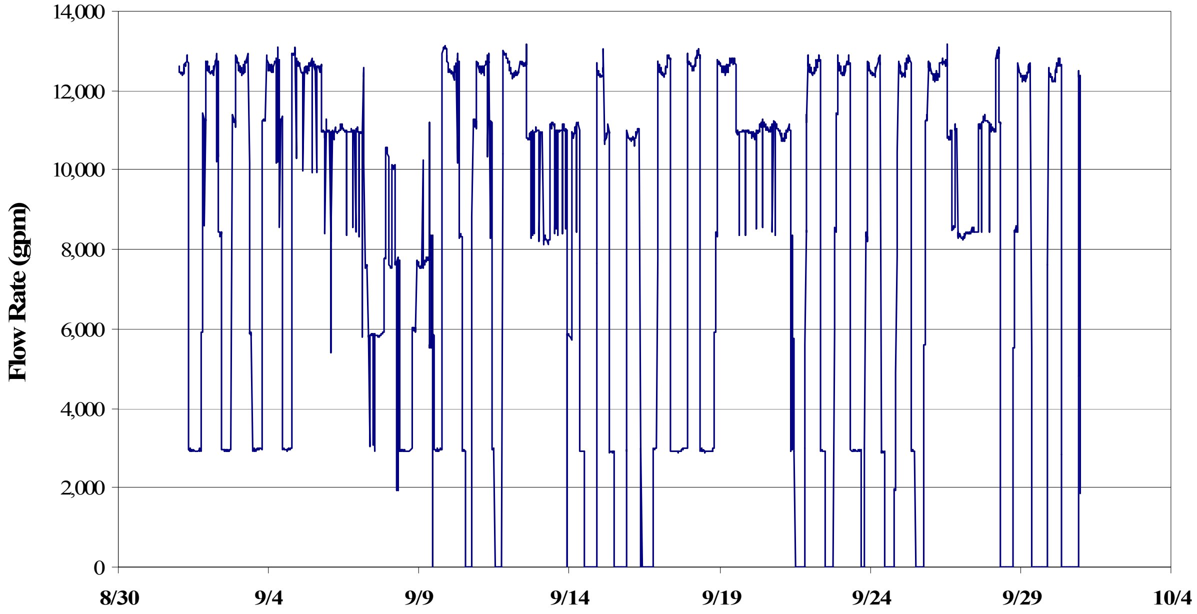

Figure 5.1 – Super Station Water Demand

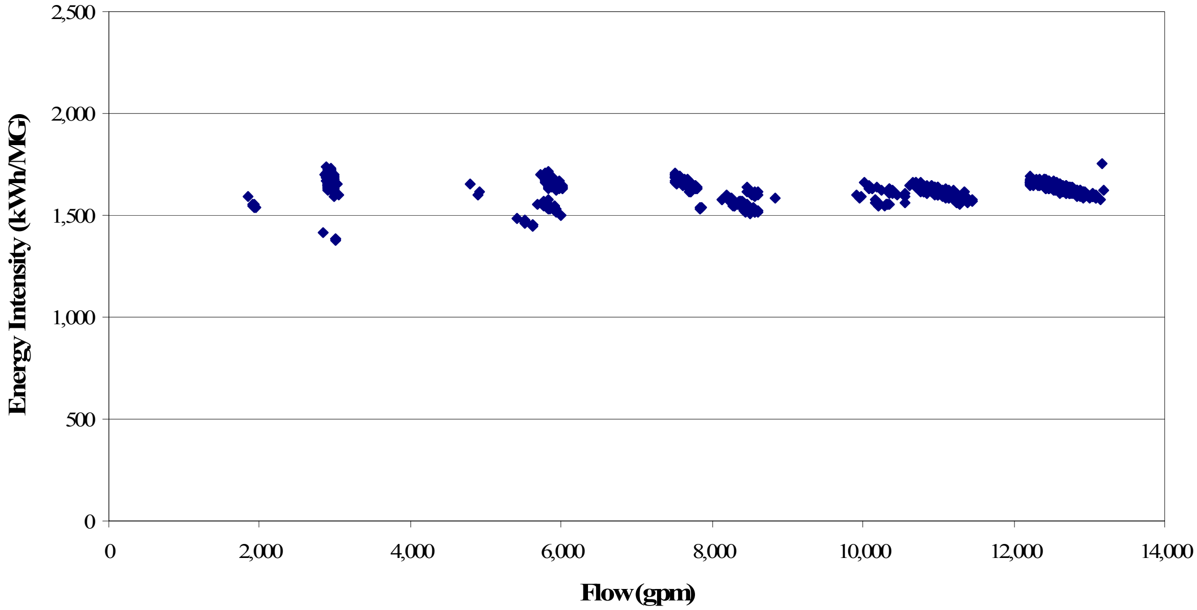

Figure 5.2 – Super Station Energy Intensity vs. Flow Rate

Table 5.1, on the following page, summarizes the average values extracted from Figure 5.2

TABLE 5.1 BASELINE SUPER STATION AVERAGE WATER-ENERGY PERFORMANCE

Flow Range (gpm)	**Average** (gpm)	**Time** (%)	**Average** (kW)	**Intensity** (kWh/MG)
1,500-3,500	2,907	19%	284	1,629
3,500-5,500	5,034	0%	388	1,283*
5,500-7,500	6,010	6%	580	1,608
7,500-9,500	8,163	11%	772	1,576
9,500-11,500	10,723	27%	1,062	1,651
11,500-12,500	12,373	37%	1,241	1,672

*This data point has a very high level of uncertainty due to the low number of measured data points operating under this condition.

Figure 5.3 shows the distribution of operating energy intensities for the Super Station based on the data presented in Figure 5.2 (15 minute interval data).

Table 5.1 shows that the average aggregate energy intensity from all pump stations does not significantly vary. However, comparing these average values with Figure 5.3 suggests that there may be a significant benefit from implementing an optimization algorithm that continuously updates to account for changing system conditions.

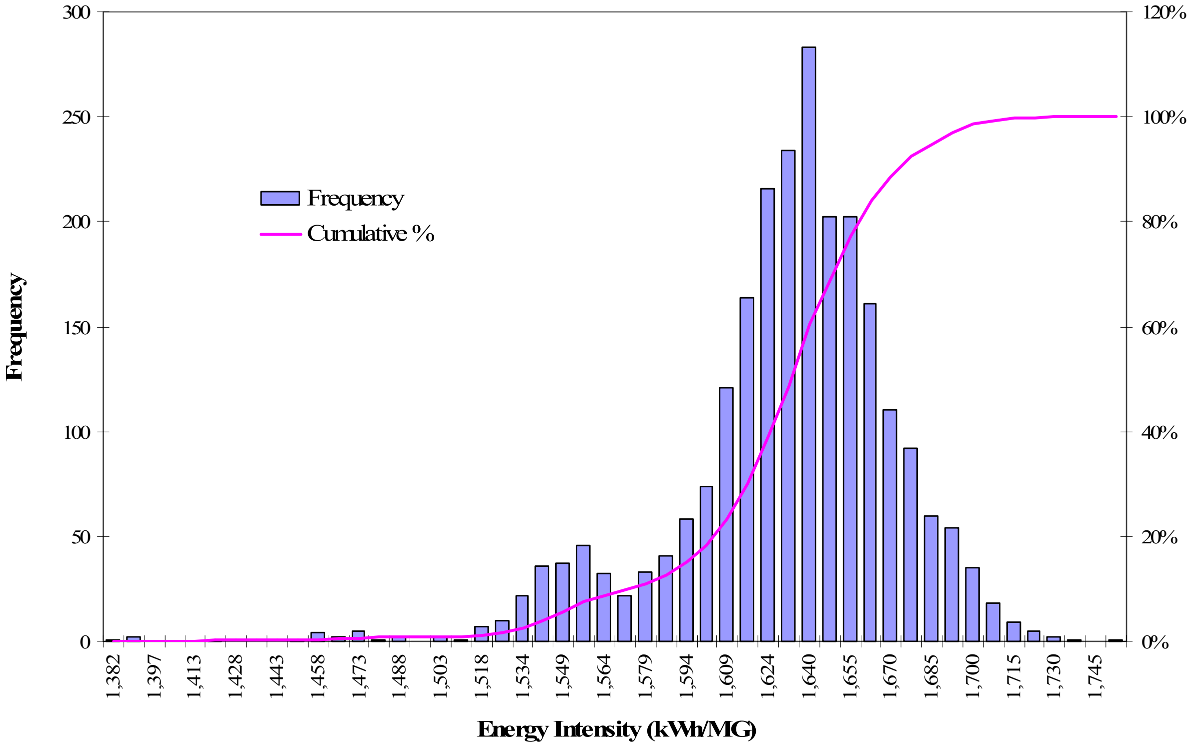

Figure 5.3 – Super Station Energy Intensity Histogram

The most frequent pumping energy intensity for the Super Station was 1,640 kWh/MG, with a standard deviation of 41 kWh/MG (2.5 % of the mode). Ignoring outlying points, the range of energy intensities for the Super Station varied from 1,518 kWh/MG to 1,730 kWh/MG (representing a 13% variation over the mode). Finally, the Cumulative % curve in Figure 5.3 shows that 50% of the data was above 1,632 kWh/MG.

5.4 Individual Well Pump Station Energy Performance Characterization

Two charts are presented for each of the well pump stations considered in this study:

- Pumping Energy Intensity vs. Flow
- Energy Intensity Histogram

Although an energy intensity histogram chart is sufficient to establish baseline energy consumption, pumping energy intensity vs. flow is included to help explain the energy performance of each station as well as identify potential energy consumption optimization opportunities.

All data presented for the Tully, Senter, and Will Wool Stations in the following charts was collected for the month of September 2009.

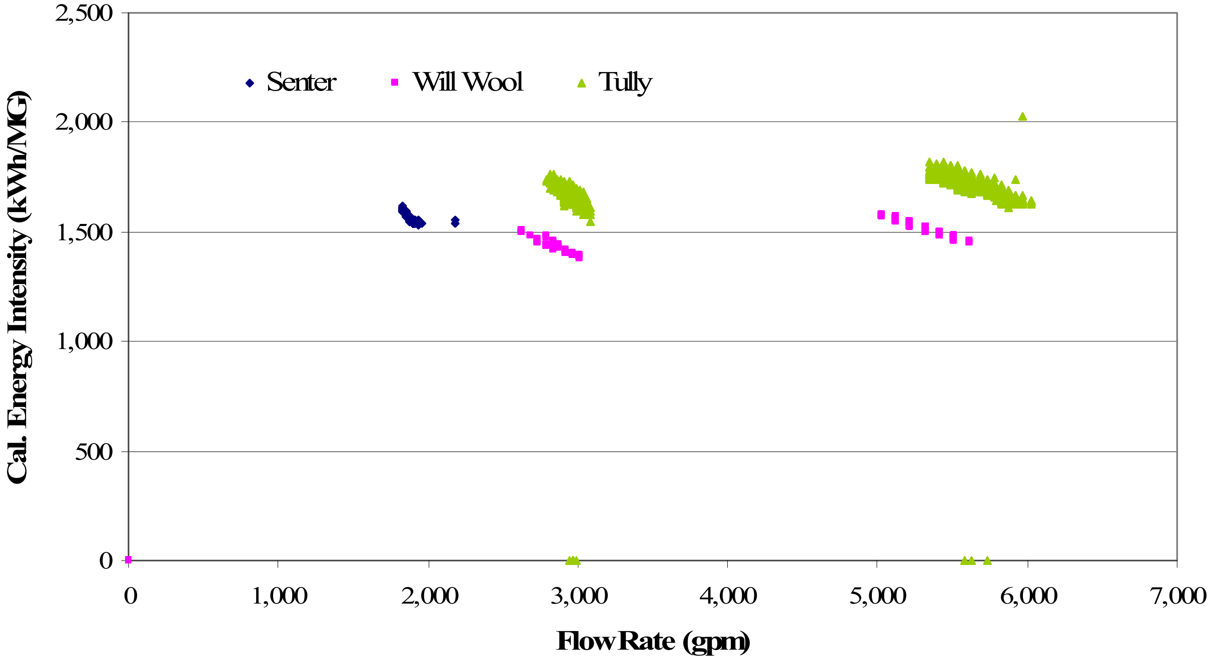

Figure 5.4 –Station Energy Intensity vs. Flow Rate

Figure 5.4 shows the energy intensity at various station flow rates for the three pump stations analyzed for this project. Tully Road and Will Wool stations have multiple "operating ranges" since those stations have more than one pump (Tully Road has three booster pumps and Will

Wool has two well pumps). Although Tully Road has three booster pumps, only two pumps operated at any given time (shown in Figure 5.4 as only two distinct "operating conditions").

Figure 5.4 suggests that although at any "operating range" pumping energy intensity within a station can vary depending on the flow, the greatest pumping optimization opportunity is from correctly sequencing individual pumps in the stations (i.e. depending on the flow some pump stations are more efficient at moving water due to reduced resistance).

In addition to correctly sequencing pump stations, Figure 5.4 shows that another optimization opportunity is to use only one pump per station (for multiple pump stations) and meet water demand flow with pumps in other stations before deciding to use a second pump within a station. Turning on a second pump in a station increases the total dynamic head resulting in wasted energy used to overcome the higher head to pump water.

Finally, Figure 5.4 also shows that there are cases where pumping at a higher flow rate (gpm) for a shorter period of time may be more energy efficient (although electrical demand would be higher) than pumping at lower gpm. For example, Senter station can pump approximately 2,000 gpm with an energy intensity of approximately 1,600 kWh/MG, while Will Wool Station can pump at 3,000 gpm with an energy intensity of approximately 1,400 kWh/MG.

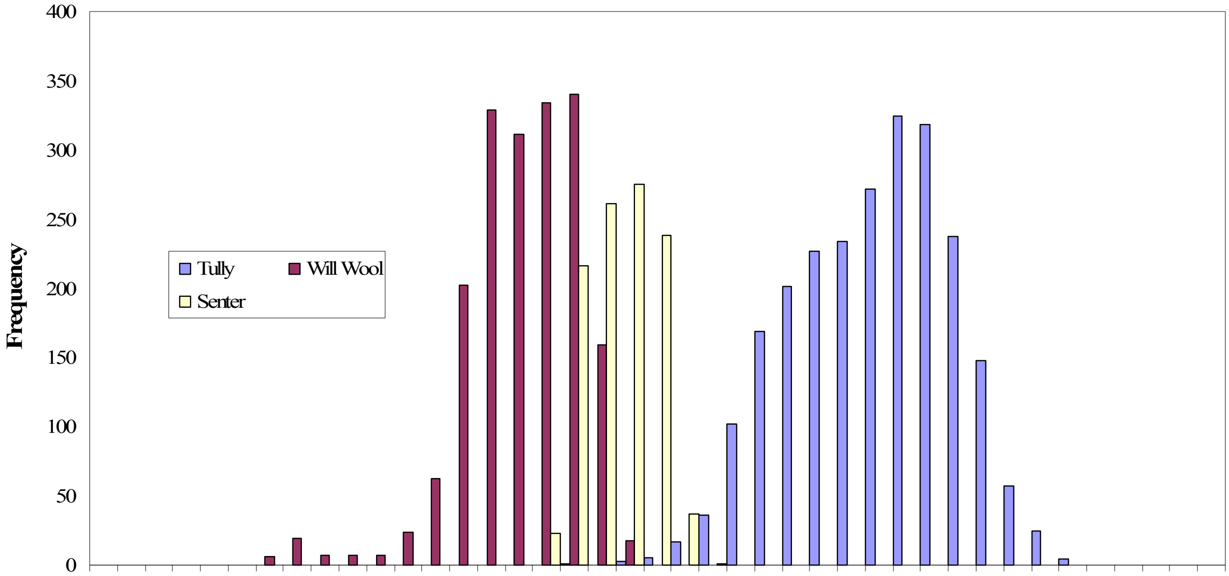

Figure 5.5 – Energy Intensity Histograms for Tully, Will Wool, and Senter Stations

Figure 5.5 plots the histograms which show the spread of energy intensities for the three test stations. The histograms show that within each station there is a range of operating energy intensities, which becomes wider with increasing number of pumps:

  - Senter Station has only one well pump (narrow energy intensity distribution)
  - Will Wool Station has two well pumps
  - Tully Station has three booster and four well pumps (the widest energy intensity distribution)

Table 5.2 summarizes the results from Figure 5.5

TABLE 5.2 STATION ENERGY INTENSITIES

Station	**Mode** (kWh/MG)	**Average** (kWh/MG)	**Standard Deviation** (kWh/MG)	**Standard Deviation** (% variation from Average)
Tully	1,692	1,711	43	2.5%
Will Wool	1,530	1,519	31	2.0%
Senter	1,575	1,571	17	1.1%

6. Optimization Methodology

6.1 Energy Performance Metric Description

Even though all the equipment considered in this project are pumps, understanding their energy performance can be complex. Some of the aspects that affect energy performance analysis include:

- Four well pump stations were considered in this project.
- Although all stations pump into the same water zone, they are in different geographical locations. Thus the "system curve" seen by each of the stations is different.
- Two of the four stations have multiple pumps per station, which gives them the flexibility to operate the stations at different flow rates (gpm).
- Pumps are allowed to work within a band of pressures affecting the individual pump flow rate and corresponding station output flow rate (gpm).

Analyzing the test stations energy performance requires determining a metric that considers these various aspects. Pumping energy intensity (kWh/MG) is a parameter that addresses all these issues and is defined as follows:

$$f(gpm) = \frac{kWh}{MG}$$

A Note on Pump Efficiency vs. Energy Intensity

In a distributed water system where water sources (wells) are spread over a large area, it is advantageous to consider energy intensity (kWh/MG) rather than pumping efficiency. Energy intensity is a global metric that can compare the net amount of energy required to move a fixed volume of water from the water source to the main distribution point (storage tank). On the other hand, pumping efficiency is a localized metric that assesses the energy efficiency of the equipment (pumps). To further illustrate the above, consider the following example:

- Station A which has as pumping efficiency of 80% is 10 miles away from the main distribution point
- Station B which has a pumping efficiency of 75% is 1 mile away from the main distribution point

Although Station A has more efficient pumps, it may be less energy intensive to pump from Station B since less work needs to be done to move water 1 mile instead of 10 miles.

6.2 Optimization Methodology

The optimization methodology has been developed based on the data that was collected from the pilot pump stations. The methodology was presented to SJWC and although they were very interested in it, SJWC did not implement the optimization methodology due to the significant upgrades that the SCADA system would need. Instead of fully implementing the proposed optimization algorithm, BASE developed test procedures that could help assess the impact on energy efficiency of the optimization algorithm. The proposed methodology is explained below.

The proposed water-energy pumping optimization method is based on determining the pump combination with the lowest pumping energy intensity (kWh/MG) capable of delivering the required flow rate (gpm).

To this end, all four pump stations have been grouped into a single Super Station capable of controlling individual pumps from any of the four test stations. The water demand from all stations is aggregated to determine the amount of water that must be supplied by the Super Station. The Super Station then selects the pump combination capable of supplying the required flow rate (gpm) with the lowest energy intensity (kWh/MG).

6.3 Implementation of the Proposed Optimization Methodology

The water-energy optimization methodology can be broken down into four main parts:

- Determining the aggregate flow rate required from all four pump stations
- Updating station Water-Energy Performance Tables (tables relating gpm, MG, and kWh) based on measured flow rate, calculated MG pumped the previous 15 minute interval, and measured electrical energy consumption for the previous interval. Finally, display the overall pumping efficiency (kWh/MG) and flow rate (gpm) for the last 15 minute interval.
- Selecting the pump configuration with the least kWh capable of providing the required aggregate flow rate (gpm)
- Output the pump schedule (combination of pumps) to be used in the next 15 minutes.

The following sections describe in more detail the different steps required to accomplish the above procedures. For a more detailed optimization implementation methodology please refer to Figure 6.1.

Determine Aggregate Flow from All Four Pump Stations

The pump stations in this test project are controlled based on the DOW ZONE tank level, which can be related to individual station discharge pressure. When the discharge pressure drops below the station's setpoint, local PLCs will turn on the station pump (the SCADA system is used to adjust the pressure setpoint of local PLCs based on time-of-day and season). The pump stations considered in this project do not have a "water demand profile" by which they operate; instead station discharge pressure is the main control variable that determines how much water the station needs to supply.

Therefore, to successfully implement the water-energy optimization algorithm (which has water flow as a control variable) it is necessary to relate station discharge pressure to station flow rate. All pumps considered in this study are constant speed. Therefore using pump curves based on pump test data), measured station pressure, and the existing pressure setpoints used to turn pumps on/off at each station, it is possible to relate the station pressure to what the output flow from each station would be at any given time. The procedure required to do this is as follows:

1. Measure the Pump Station Pressure (with the SCADA system)
2. Based on the existing pressure setpoints, determine which pumps would be on or off
3. Using pump curves and station pressure, calculate the station output flow at each station
4. Sum up the output flow of all four stations to determine the Aggregate Flow required by the system

The Aggregate Flow calculated in the above procedure would feed into the optimization algorithm which will determine the best pump combination (lowest kWh) capable of supplying an aggregate flow rate that is greater than or equal to the calculated aggregate flow rate.

Update Station Water-Energy Performance Table and Display Pumping Efficiency

Choosing the most energy efficient pump combination capable of delivering the water demand will require updating the Water-Energy Performance Table for each pump station. The steps for updating the Water-Energy Performance Tables should be as follows:

1. Measure the station output flow
2. Calculate the total volume of water pumped (from gpm measurement)
3. Measure the electrical energy consumption
4. Update the energy intensity entry in the Water-Energy Performance Table.

Once all the pertinent Performance Tables have been updated with the new entries, it is possible to display the existing aggregate pumping efficiency onto the SCADA display. The following procedure will be required to perform this:

1. Calculate the total water flow rate from all pump stations
2. Calculate the total volume of water pumped by all pump stations by multiplying the total water flow rate from Step 1 by the polling interval (15 minutes)
3. Calculate the total electrical energy consumption from all pump stations
4. Calculate the pumping energy intensity (kWh/MG)
5. Display the pumping energy intensity vs. water flow rate [(gpm), (kWh/MG)]

In addition to displaying the existing Aggregate Efficiency Value, it is possible to calculate the pumping efficiency under the old control strategy to visually compare the improvement of the optimization algorithm.

Select Optimal Pump Configuration

Once the Aggregate Flow is known, and the correct Water-Energy Performance Table entry is known (based on station discharge pressure) for each station, the optimization software will be able to choose the pump combination that will supply the required aggregate flow rate with minimal energy intensity. This process will require the following steps:

1. Determine all the possible pump combinations that can supply the required flow (from pump curves and measured station discharge pressure)

2. Eliminate pump combinations that conflict with water system constraints (e.g. aquifer limitations, maximum number of on/off pump cycles exceeded, etc.)
3. For the pump combinations that can provide the same (or greater) flow than the measured aggregate flow required, calculate the total energy intensity (kWh/MG) for that pump combination
4. Find the pump combination that yields the lowest energy intensity

The selected pump combination will represent the recommended pump schedule for the next 15 minutes. Figure 6.1 on the following page shows the overall block diagram for the proposed Water-Energy Optimization software.

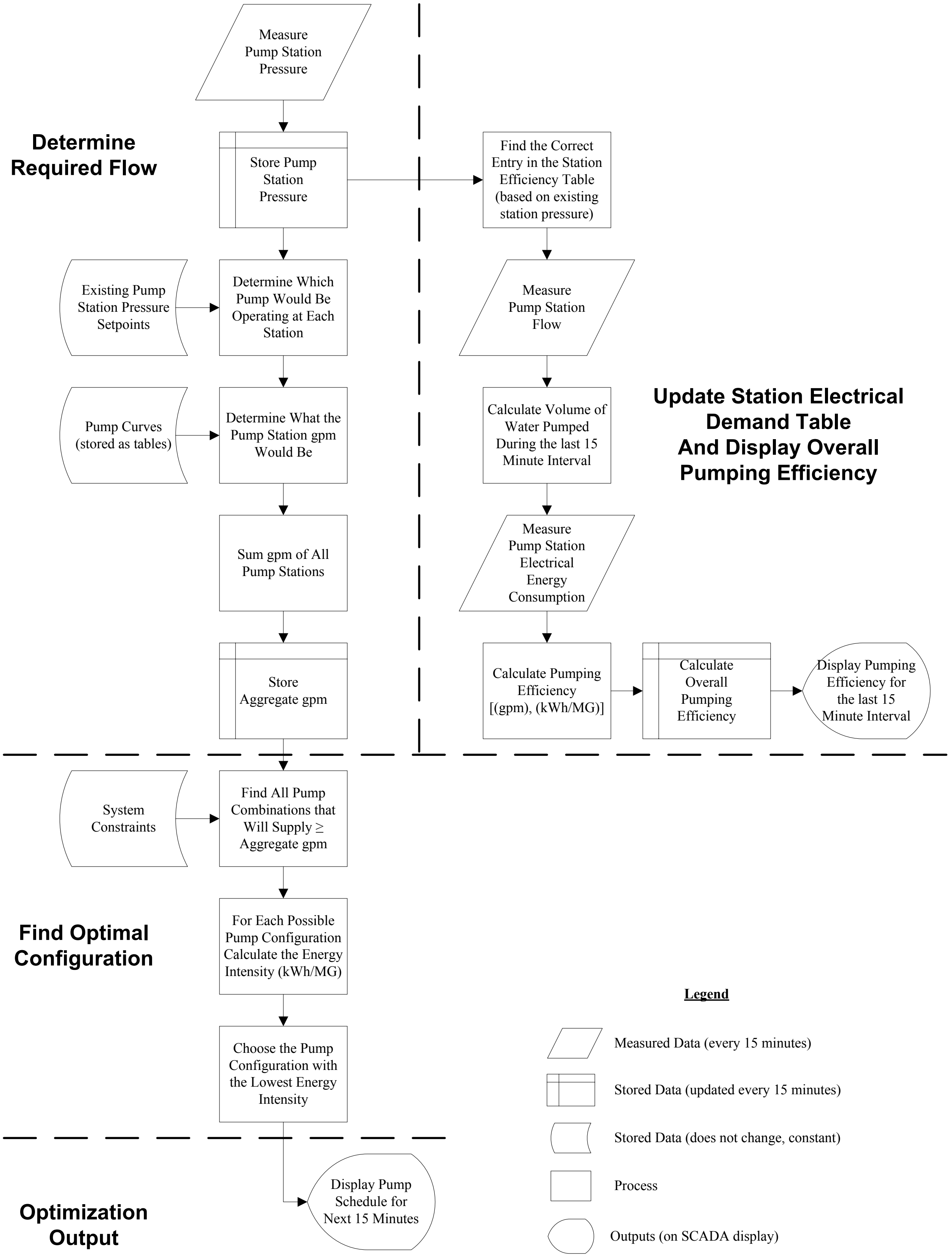

Figure 6.1 – Water-Energy Optimization Software Block Diagram

6.4 Optimization Methodology Limitations

Although the proposed optimization algorithm can work when scaled to a large system (e.g. an optimization algorithm that optimizes pump schedules for a whole water agency), there may be some implementation challenges:

- **Finding the most efficient pump configuration:** Finding the best pump configuration in a small scale project can be easily done by brute force (i.e. try out all possible pump configurations and choose the one with the lowest energy consumption), however the computation time required to find the best pump configuration in large scale system grows exponentially (2^n, where n is the number of pumps in the system). To overcome this, there are various advanced mathematical methods that can help cut down computation time (e.g. neural networks, etc.).
- **Polling station pressure frequency:** Based on conversation with facility personnel, it takes approximately 10 seconds to poll a station to gather information (the SCADA central system communicates with the station through radio frequency). If this system is implemented in a larger scale (where the number of pumps is in the hundreds), it would become very taxing on the SCADA system to poll all stations every 15 minutes. For example, if the water agency has 100 pump stations, it will take approximately 17 minutes to poll all pump stations. Implementing an optimization algorithm in a large scale system may require incorporating a forecasting model capable of predicting water demand for up to 1 day in advance to avoid frequently polling stations.
- **Optimizing pump operation with respect to operation cost rather than energy:** Water agencies, as a business, are interested in reducing operational costs rather than saving energy. Although energy costs are a large percentage of the operational costs, there are other factors that may override reducing electrical energy consumption, for example:
    - Time-of-use energy and demand charges (over-pumping with less efficient pumps during the Off Peak Period to avoid Peak Period charges)
    - Buying water from a third party instead of pumping water from facility owned wells

There may be other factors that can complicate implementing a water-energy pumping optimization algorithm. The issues identified above became apparent as the project developed.

7. Energy Savings

7.1 Introduction

Although it was not possible to implement the proposed optimization algorithm due to the significant SCADA system upgrades, we were able to collect sufficient data to help us estimate the potential energy savings impact. The detailed procedure used to estimate the potential energy savings are described in the following section.

7.2 Potential Yearly Energy Savings

The yearly savings estimation methodology considers three of the four pump stations: Will Wool, Senter, and Tully. The pressure sensor at Needles did not come online until after the analysis was performed.

The potential energy savings analysis is based on SJWC 2008 water demand profile and electrical energy consumption for the above stations. Table 7.1 shows the 2008 monthly aggregate water demand and pumping energy intensity for the three well pump stations considered. Table 7.1 also summarizes the calculated electrical energy savings for the same water profile if SJWC would have implemented an energy-pumping optimization algorithm.

From Table 7.1, the total electrical energy savings after implementing an energy-pump optimization algorithm would have been approximately 313,237 kWh/yr. The efficiency improvement that the optimization algorithm can provide depends on the aggregate flow rate required by all well pump stations. During periods of high water demand, more pumps need to operate therefore giving the optimization algorithm a reduced number of pumps to select from. Since the highest water demand happens during the Peak Period, the optimization algorithm is not expected to result in significant electrical demand savings. Figure 7.1 shows the effect on the expected energy savings by month (shown in the high/low water season effect).

TABLE 7.1 ESTIMATED ENERGY SAVINGS

Month	Total Volume (MG)	Current Intensity (kWh/MG)	Proposed Intensity (kWh/MG)	Energy Savings (kWh)	Saving Percentage (%)
January	247.6	1,686	1,514	42,677	10%
February	173.6	1,684	1,496	32,723	11%
March	163.3	1,711	1,513	32,324	12%
April	190.9	1,711	1,499	40,477	12%
May	233.2	1,679	1,505	40,499	10%
June	296.6	1,635	1,542	27,507	6%
July	335.0	1,600	1,552	16,238	3%
August	362.9	1,617	1,602	5,570	1%
September	406.6	1,637	1,607	12,065	2%
October	432.6	1,631	1,610	9,146	1%
November	181.6	1,648	1,498	27,293	9%
December	137.3	1,633	1,438	26,717	12%
Totals/Overall		**1,648**	**1,549**	**313,237**	**6%**

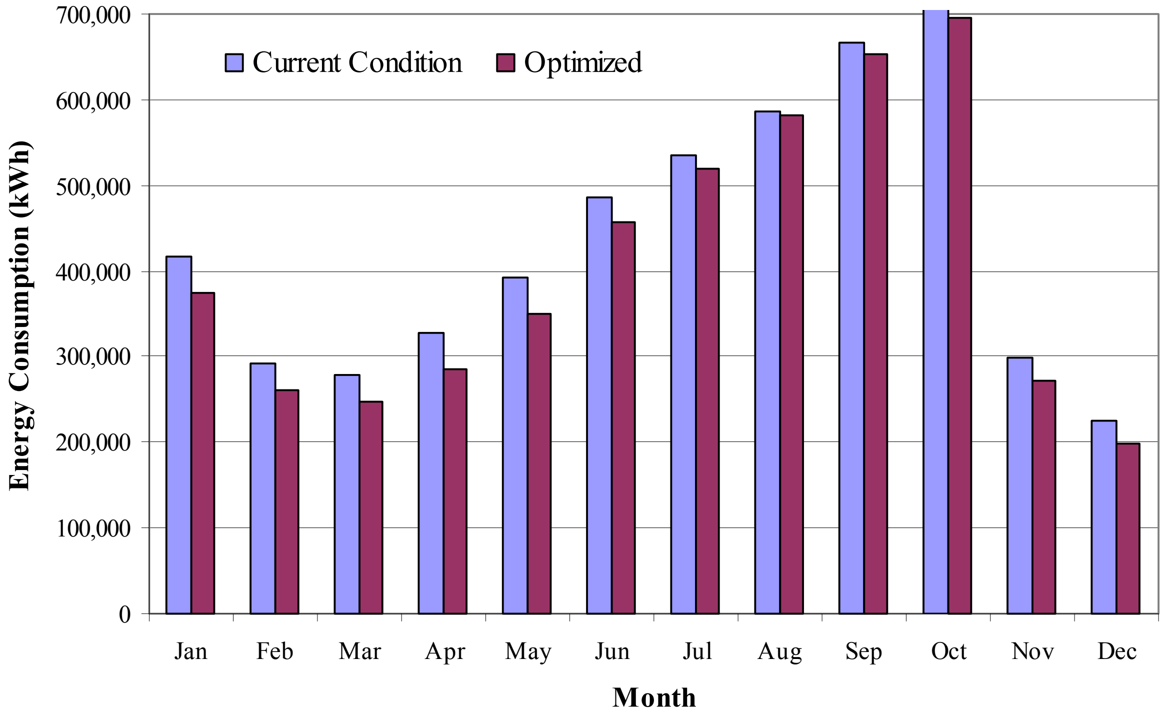

Figure 7.1 – Comparative Energy Consumption with and without Optimization

The methodology used to calculate the potential yearly electrical energy savings from implementing a water-energy pumping optimization algorithm is as follows:

1. Determine the average monthly water flow rate (gpm) for each well pump station
2. Calculate the electrical energy consumption of each station by multiplying the pumping energy intensity (at the average flow rate calculated in Step 1) by the monthly volume of water for each well pump station
3. The electrical energy consumption calculated in Step 2 was verified considering the PG&E electrical billing data
4. Sum the electrical energy consumption of all three well pump stations
5. Calculate the optimized (best pump configuration) overall pumping energy intensity of the Superstation based on the aggregate monthly average flow of all pump stations
6. Calculate the electrical energy consumption of the Superstation by multiplying the pumping energy intensity (at the average flow rate calculated in Step 5) by the monthly aggregate volume of water for all well pump stations
7. Calculate the potential energy savings as the difference between the optimized and non-optimized energy consumption.

7.3 Additional Energy Savings

Besides the proper sequencing of pumps, BASE proposed two additional methods by which pumping energy intensity could be further reduced. With help from SJWC staff BASE developed and implemented protocols to test the following two hypotheses which could result in additional energy savings:

1. It is sometimes better to distribute water pumping across more than one pump station before deciding to turn on a second pump in any given station. For example, it would be better to run one pump in Tully and one pump in Will Wool, before deciding to turn on a second pump in Tully.

2. Often it is better to run pumps that can operate at a higher water flow rate (gpm) modulating them down with on/off control to help meet water demand than operating pumps that would closely match water demand. Operating pump combinations at higher gpm often have lower pumping energy intensities than operating them at lower gpm.

Two separate M&V protocols were developed to test the above hypotheses. The M&V protocols are as follows:

Protocols for Hypothesis 1 (both combinations provide similar flow rate):

1. Run two pumps at Tully Station for 14 hours
2. Run one pump at Senter Station and one pump at Tully Station for 14 hours
3. Record gpm and kWh every 15 minutes
4. Calculate the total gpm and total kWh for the following two combinations:
    a. Two pumps at Tully Station (base case)
    b. One pump at Tully Station and one pump at Senter Station (optimized case)
5. Calculate the overall energy intensity for both combinations

Protocols for Hypothesis 2 (second combination has a larger flow rate)

1. Run one pump at Tully Station (for 14 hours) and one pump at Senter Station (for 21 hours)
2. Record gpm and kWh every 15 minutes for these two stations
3. Run one pump at Tully Station (for 8.5 hours), one pump at Will Wool Station (for 8.5 hours), and one pump at Senter Station (for 21 hours)
4. Record gpm and kWh every 15 minutes for these three stations
5. Calculate the total gpm and total kWh for the following two combinations:
    a. One pump at Tully Station and one pump at Senter Station (base case)
    b. One pump at Tully Station, one pump at Senter Station and one pump at Will Wool Station (optimized case)
6. Calculate the overall energy intensity for both combinations

The test results are summarized in Table 7.2 on the following page:

TABLE 7.2 TEST RESULTS

Test	**Pumping Energy Intensity**		**Savings** (%)
	Base Case (kWh/MG)	**Optimized Case** (kWh/MG)	
Hypothesis 1	1,632	1,622	0.6%
Hypothesis 2	1,611	1,527	5.2%

Test Results Discussion

Hypothesis 1
Test results show that pumping from two different stations instead of pumping from one pump station result in a minimal effect of reducing pumping energy intensity. However, theoretically it is expected that pumping from different stations before turning on a second pump within a same station could have a sizable impact on the pumping energy intensity. The amount of savings will directly depend on the layout of the waterway grid (please note that the layout of the waterway grid was not made available to us). The pumping energy intensity savings would materialize from reducing the dynamic losses between the pump stations and the main water pipe by a factor of V^2 (V is the water velocity within the pipe). If the pipe distance between the pump station and the main water pipe is significant, it is expected that there could be a potential energy intensity reduction. As a general rule, it is recommended that SJWC implement this strategy to the extent possible.

Hypothesis 2
Test results show that over pumping (i.e. providing a higher gpm than what is required by the system) could reduce the overall pumping energy intensity. Energy savings would be realized because:

1. The pumps would operate closer to their optimum efficiency resulting from interaction of the system and performance curves.

2. Station proximity to the pressure zone (Tank) where they are pumping to. As an example, a station that can pump water at a higher rate is significantly closer to the pressure zone where it is pumping to than another station that is further away. The extra work require to move the needed volume of water the extra distance may be significantly larger than the friction losses due to the higher flow rate.

It is important to note that although implementing this strategy would reduce the overall energy consumption for moving water, it may increase the overall electrical demand since a higher flow rate would be supplied.

8. Lessons Learned

The following list itemizes various lessons learned throughout implementing the project:

- Interfacing electrical energy consumption meters (at the station level) is fairly straightforward and can be done with minimal costs.
- Utilizing real-time metered electrical data can reveal beneficial information resulting in energy savings as well as maintenance cost savings (early identification of pump efficiency deterioration).
- Consistently utilizing the energy data provided can be a complex process since it would require significant changes to control and operational schemes, as well as work processes at the utility, which can be slow to implement.
- It is necessary to process the real-time data that is collected from the electrical revenue meter (e.g. removing the time component inherent in energy consumption data).
- System implementers need to have detailed knowledge on pumps, pumping system, electrical system, and SCADA systems to successfully complete projects.
- Although a comprehensive system-wide optimization system is desirable, energy savings can also be realized by optimizing a subset of pumps within the whole pumping system.
- Implementing a water-energy optimization algorithm could greatly benefit the concept of Continuous Improvement in Energy Efficiency since energy performance data could be used to modify the pump control schemes to save energy.
- Successful completion of the project required a close cooperation and coordination between the San Jose Water Company, BASE Energy, Inc., and the Pacific Gas and Electric Company.

9. Next Steps

Moving the project into full implementation of a water-energy optimization algorithm would require the following:

1. Develop a detailed model of the SJWC water pumping system clearly identifying system boundaries and constraints
2. Develop a water demand model capable of forecasting water flow rates to help expedite search of optimal pump configuration
3. Develop other non-technical constraints (e.g. business constraints) that may affect the decision process of the optimization algorithm
4. Develop and prioritize a list of objectives that the optimization algorithm should attempt to achieve
5. Add the required hardware upgrades to incorporate electrical energy consumption data into the SCADA system
6. Implement the optimization algorithm into the SCADA system

10. Bibliography

Emerging Technologies Scoping Study for Process Optimization Tools for the Water Supply Industry, Pacific Gas and Electric Company Emerging Technologies Program Application Assessment Report #0804 (Global Energy Partners, LLC)

Energy Savings Analysis Generated by a Real Time Energy Management System for Water Distribution, Sarah Thorstensen, Derceto Ltd.

Multiobjective Evolutionary Algorithms in Pump Scheduling Optimization, A. Sotelo, C. von Lucken and B. Baran, National Computing Center, National University of Asuncion, San Lorenzo, Paraguay

Integrated Hydraulic Model and Genetic Algorithm Optimization for Informed Analysis of A Real Water System, Chris Clark and Zheng Yi Wu, ASCE 8th Annual International Symposium on Water Distribution System Analysis, Cincinnati, OH, August 27-30, 2006

The following references developed by S. Bunn from Derceto Ltd. were used:

> *Operations optimization of water distribution systems to achieve energy conservation: Case studies fro four major US utilities*
>
> *Reducing Energy Demand in Water Supply through Real-Time Scheduling Operation*
>
> *Pump Scheduling Optimization in Four US Cities: Case Studies*

The following reference was developed as a collaboration between MW Soft, Inc., RBF & Associates, Black & Veatch, Corp., and Earth Tech Inc.

> *Optimal Pump Operation of Water Distribution Systems Using Genetic Algorithms*,

Multiojective Evolutionary Algorithms for Electric Power Dispatch Problem, Abido, M.A., IEEE Transactions of Evolutionary Computation, Vol. 10, No. 3, June 2006

American Water Works Association Standard on Horizontal and Vertical Line-Shaft Pumps

11. Appendix

11.1 Well Level and Tully Well Pump Power Measurement Protocols

When performing well water level measurements, please make sure to allow the well to reach steady state before measuring the water level (to avoid capturing the transient period). The following well water level measurement protocols were performed by San Jose Water Company personnel:

Tully Road Station

Tully Road Station currently has four well pumps (with a fifth well pump coming online soon). Well level measurements should be done by following the sequence in which well pumps are turned on (based on the Suction Tank level controller). The procedure is sequentially outlined as follows (based on the sequence of operation posted inside the electrical panel at Tully Station):

1. Turn Well Pump 1 on and measure Well 1 water level
2. While Well Pump 1 is on, turn on Well 2 Pump and measure Well 1 and Well 2 water levels
3. While Well Pumps 1 and 2 are on, turn on Well Pump 3 and measure Well 1, Well 2, and Well 3 water levels
4. While Well Pumps 1, 2, and 3 are on, turn on Well Pump 4 and measure Well 1, Well 2, Well 3, and Well 4 water levels.

It is suggested that for now, well level measurements be performed based on the existing sequence of pumping (without consideration to the 5th well pump coming online). If significant variation in the water levels is observed additional measurements will be requested.

Will Wool Station

Will Wool is a two-well station. Assessing the well level at this station will require performing the measurements in the following sequence:

1. Turn on Pump 1 while Pump 2 is off and measure Well 1 water level
2. Turn on Pump 2 (while Pump 1 is still running) and measure water level in Well 1 and Well 2
3. Turn off both pumps
4. Turn on Pump 2 and measure water level in Well 2
5. Turn on Pump 1 (while Pump 2 is still running) and measure water level in Well 2 and Well 1

Needles Station

This is a single well station. Therefore one well level measurement should be performed, with the well pump on.

Senter Station

This is a single well station. Therefore one well level measurement should be performed, with the well pump on.

Table 11.1 summarizes the results for the well water level tests. Please note that BASE personnel was present during the well water tests at Tully Road Station. In addition to the well water level test performed by SJWC personnel, BASE performed spot power (kW) and flow rate (gpm) measurements on the four existing well pumps. The results are also presented in Table 11.1.

TABLE 11.1 WELL WATER LEVEL TEST RESULTS

Pumps that Are On	Pump	Flow Rate (gpm)	Power (kW)	Well Water Level (ft)
Tully Road Station				
None	W1	12.8	0	98.4
	W2	1.2	0	88
	W3	1.8	0	87
	W4	12.2	0	82.2
W1	W1	1,955	74.5	128
W1, W2	W1	1,890	73.9	130
	W2	2,200	88.9	112
W1, W2, W3	W1	1,870	73.2	133
	W2	2,130	88.6	115
	W3	2,090	82.6	111
W1, W2, W3, W4	W1	1,820	73.2	137
	W2	2,020	87.8	118
	W3	1,940	80.8	116
	W4	2,470	99.4	125
Will Wool Station				
None	W1	N / A	N / A	100
	W2	N / A	N / A	97
W1	W1	2,910	N / A	113
	W2	N / A	N / A	100
W1, W2	W1	2,760	N / A	116
	W2	2,690	N / A	112
Needles Station				
None	W1	N / A	N / A	106
W1	W1	1,420	N / A	188
Senter Station				
None	W1	N / A	N / A	111
W1	W1	1,854	N / A	151

11.2 Collected Data

The following supporting documentation has been included in electronic form in a CD:

- Pump Curves
- Pump Tests
- Yearly Water Demand
- Billing Information
- Interval Data Information
- Excel spreadsheet with analysis

11.3 Measurement and Evaluation

Overview

The objective of the proposed measurement and evaluation (M&E) plan is to fully characterize the energy performance of pumping stations by determining the pumping energy intensity (kWh/MG) at different flow rates (gpm).

Based on the existing instrumentation at each of the well pump stations, the SCADA system is capable of monitoring and trending the following (at 15 minute intervals):

- Well pump station output flow (gpm)
- Well pump station discharge pressure (psi)
- Well pump station electrical consumption (kWh), established in this project
- Individual well and booster pump on/off status (except for well pumps at Tully Road Station)

Unfortunately, utilizing the above raw (unprocessed) data, as collected by the SCADA system, to determine well pump station energy performance presents the following challenges:

- Station output flow (gpm), which is sampled every 15 minutes, shows a snapshot of the flow rate at that particular instance in time
- Station electrical energy consumption (kWh) is a cumulative measurement (e.g. it keeps track of all the energy consumption during the 15 minute interval)
- Actual amount of water (MG) is not measured and needs to be estimated based on flow rate (gpm)

These issues present a problem when trying to determine the energy performance of a station where pumps operate less than 15 minutes. If only the snapshot gpm recorded by the SCADA system is used, and it is assumed that the pump operates for the full 15 minutes, the pumping energy intensity (kWh/MG) of the station would be unrealistically low. Please note that the proper kWh is measured in each interval.

To overcome these challenges it was necessary to create a model in order to reconcile the data points so that a potential trend on the variation in energy intensity could be shown. The proposed model works as follows:

1. Determine the station discharge pressure (psi) as recorded by the SCADA system
2. Determine which pumps were operating based on records from the SCADA system
3. Use pump test curves to determine what the total kWh of the pumps would have been if they operated continuously for 15 minutes

Figures 11.1 through 11.3 show the pumping energy intensity at various flow rates for all three pump stations. The data presented is the raw data as collected by the SCADA system, and the data after applying the above model. Figure 11.1 shows the scatter in the raw data for Senter Station. Figure 11.3 can be directly compared with Figure 11.4 to show that the model represents the raw data population.

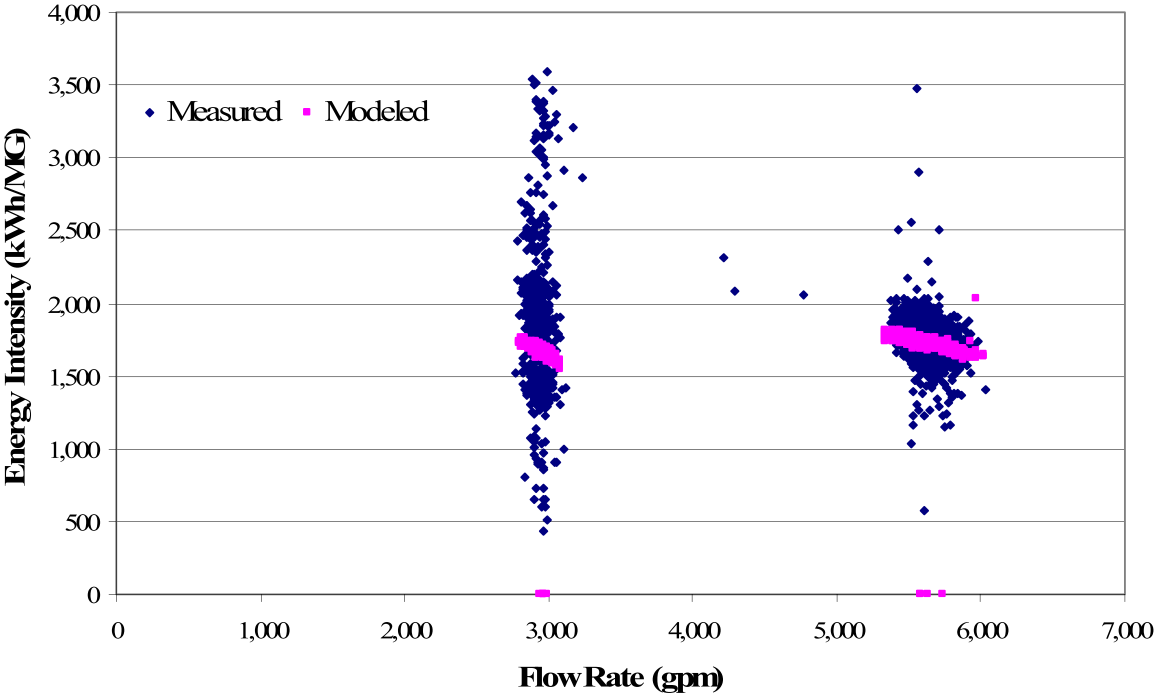

Figure 11.1 – Tully Road Station Energy Intensity (raw and modeled data)

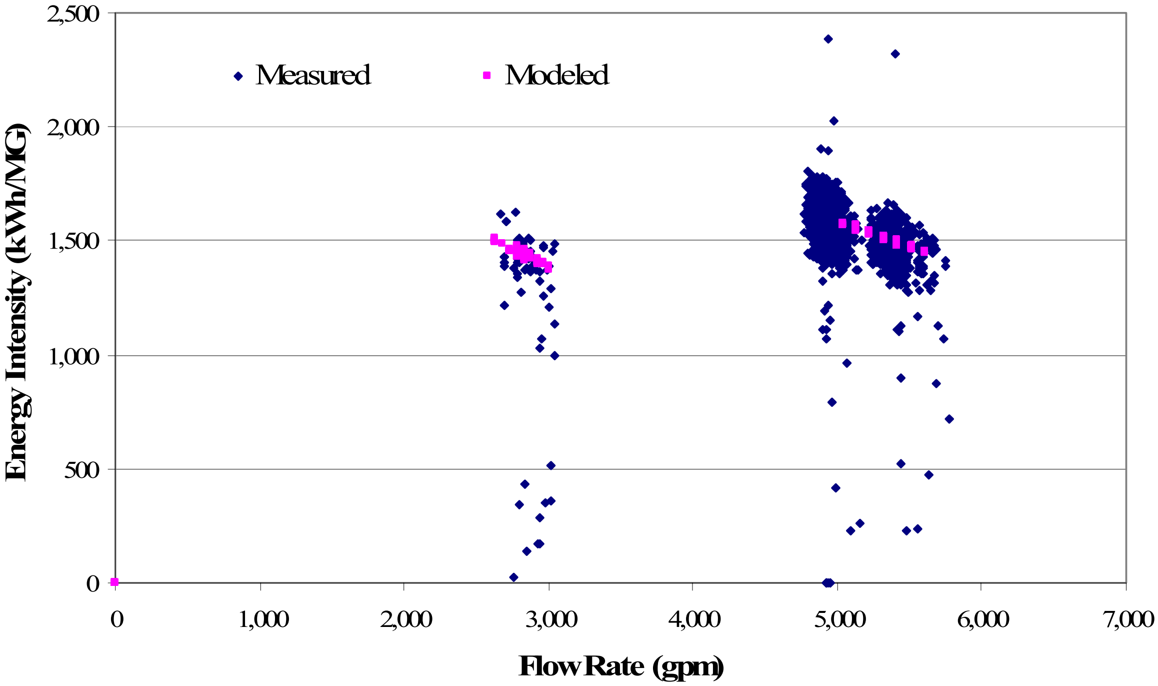

Figure 11.2 – Will Wool Station Energy Intensity (raw and modeled data)

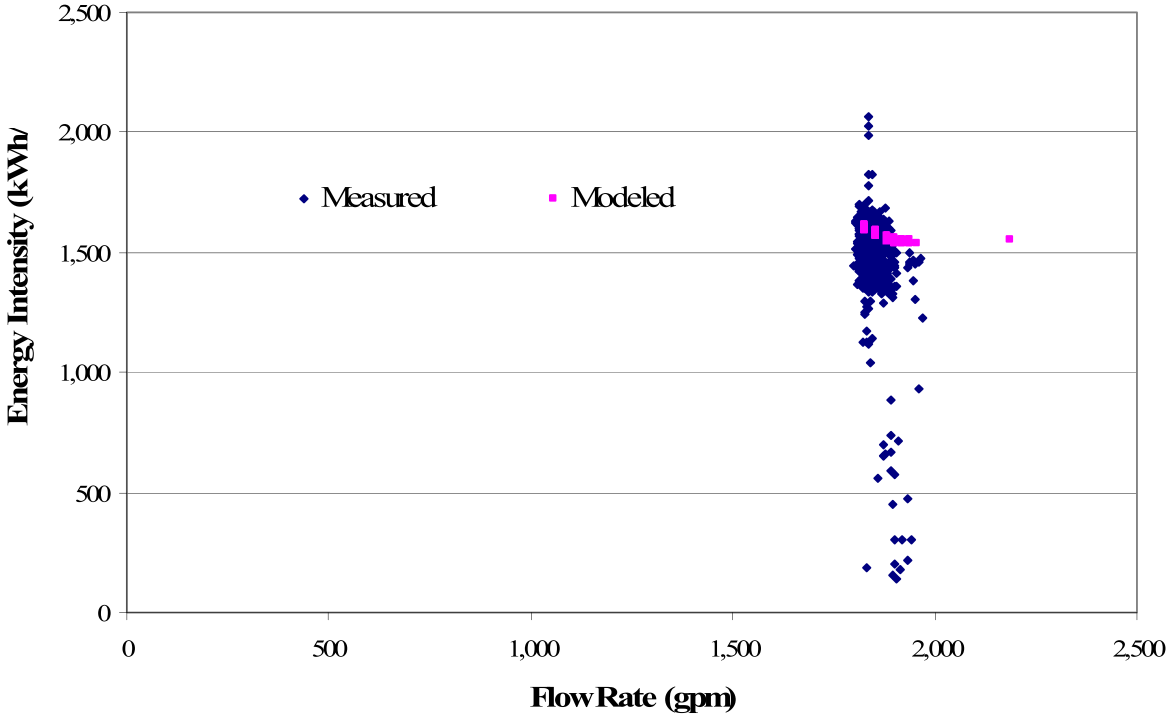

Figure 11.3 – Senter Station Energy Intensity (raw and modeled data)

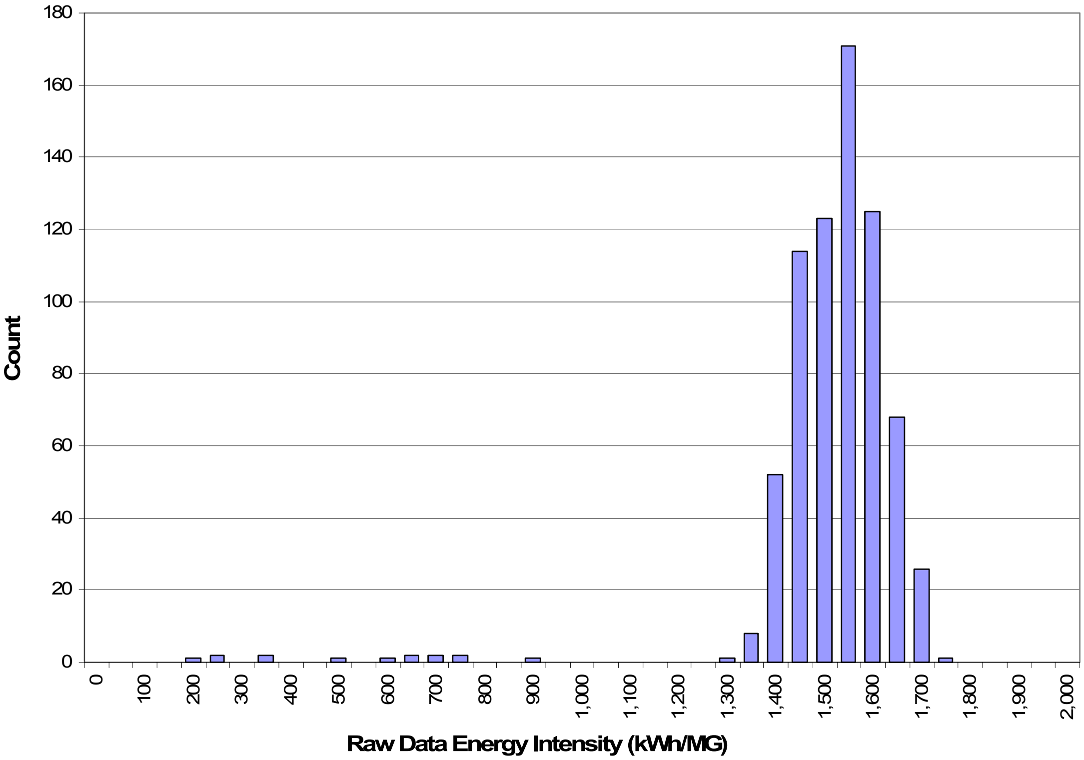

Figure 11.4 – Senter Station Energy Intensity Scatter (raw data)

Implementation of the proposed model requires determining the suction pressure of each pump (to calculate the total dynamic head of the pump) so that it can be used in conjunction with pump test data to calculate kW and kWh of individual pumps. The approach to modeling the individual pumps at each station is presented below in the *Modeling Approach* section.

The following subsection, *Measurements*, describes all spot and data logging measurements performed to develop the pump performance model for each station.

Measurements

To correctly understand station behavior and calibrate the pump models required the following measurements:

- Instantaneous well water level measurements at each pump station
- Instantaneous power measurements for all four well pumps at Tully Station
- Data log the current for each of the four well pumps and three booster pumps at Tully Station
- Data log the energy consumption for Senter and Needles

Well Water Level for all Pump Stations

Modeling the well pump behavior at each station requires understanding the differential pressure across each pump. Currently the SCADA system only records pump discharge pressure, therefore through well water level measurements the pump suction pressure (and differential pressure) was calculated. For detailed well water level protocols please refer to Section 11.2 - *Well Level and Tully Well Pump Power Measurement Protocols*.

Well Pump Power Measurements at Tully Station

The electrical energy consumption for all other stations can be easily deduced from the whole station electrical energy consumption revenue meter (which is trended through the SCADA system). However, due to the number of pumps used at Tully Station, it was necessary to perform instantaneous power measurements of the well pumps. The power measurements of the booster pumps at Tully Station can then be determined from the whole station revenue meter by subtracting the measured power from the well pumps and determining which booster pump is operating (the SCADA system tracks the on/off status of booster pumps). The well pump power measurements at Tully were done in conjunction with the well water level measurements. The protocols used and measurement results can be found in Section 11.2 - *Well Level and Tully Well Pump Power Measurement Protocols*.

Data Logging Current of All Pumps at Tully Station

A current data logger was installed on each pump (four well pumps and three booster pumps) at Tully Station. The data collected by the current data loggers was used to confirm the control scheme used for the well pumps that was described by SJWC personnel.

Modeling Approach

Senter, Needle and Will Wool Pump Stations

Three of the four pump stations (Senter, Needles and Will Wool) have similar configuration in that well water is pumped directly to the Dow Zone while the well pumps at Tully Station pump water to a suction tank and booster pumps pump water from the suction tank to the Dow Zone. The adjusted electrical energy consumption of the pumps is estimated using the following method.

The calculated electrical energy consumption of the pumps, EEC, is estimated as follows.

$$EEC = Q \times TDH \times W \times C_0 \times C_1 \times OH / (Eff_M \times Eff_P \times C_2)$$

Where,

Q = water flow rate (estimated based on total dynamic head and pump test curve), gpm
TDH = total dynamic head (measured), ft
W = weight of volume of water, 62.4 lbf/ft^3
C_0 = conversion constant, 2.228×10^{-3} cfs/gpm
C_1 = conversion constant, 0.746 kW/hp
OH = operating hours considered (sampling intermval), 0.25 hr (15

minutes)
Eff_M = efficiency of motor (nameplate), no units
Eff_P = efficiency of pump at operating condition (pump test curve), no units
C_2 = conversion constant, 550 lbf-ft/hp-sec

The total dynamic head at the operating point is estimated as follows.

$TDH = H_{f\_wp} + H_{z(s)} + H_o$

Where,

H_{f_wp} = pipe friction loss between well level and pump suction, ft
$H_{z(s)}$ = static suction head between well level and pump suction, ft
H_o = pump discharge head (trend data), ft

As an example, the discharge head of the Senter pump station is 87.91 psig (203 ft) at 12:15 AM, 9/1/2009. The pipe friction loss between well water level and pump suction is assumed to be constant and it is estimated to be 4.99 ft (based on the pipe diameter, pipe length, and the average gpm). The static suction head between well water level and pump suction is expected to be constant at 151 ft based on results from the pump test. Thus, the total dynamic head of the 200 hp well pump at the Senter station, TCH_1, is estimated to be:

$TDH = H_{f\_wp} + H_{z(s)} + H_o$
$TDH_1 = (203) + (4.99) + (151)$
$TDH_1 = 359$ ft

Based on the pump curve developed from pump tests performed by SJWC, the flow rate is estimated to be 1,854 gpm and the pump efficiency is estimated to be 0.74 at a total dynamic head of 359 ft. The electrical energy consumption of the 200 hp well pump at Senter station during a 15-minute period, EEC_1, is estimated to be:

$EEC = Q \times TDH \times W \times C_0 \times C_1 \times OH / (Eff_M \times Eff_P \times C_2)$
$EEC_1 = (1{,}854)(359)(62.4)(2.228 \text{ x } 10^{-3})(0.746)(0.25)/$
$[(0.958)(0.7466)(550)]$
$EEC_1 = 43.8$ kWh

The pump energy intensity, EI, is calculated as follows.

$EI = EEC \times C_3 /(Q \times T)$

Where,

EEC = electrical energy consumption (calculated), kWh
Q = water flow rate (trend data), gpm
T = minutes of time considered, 15 minute

C_3 = conversion constant, 10^6 gallon/MG

Therefore, the energy intensity of the 200 hp well pump in the Senter station at 12:15 AM, 9/1/2009, EI_1, is estimated to be:

EI = $EEC/(Q \times T)$
EI_1 = $(43.8)(10^6)/[(1,854)(15)]$
EI_1 = 1,575 kWh/MG

Tully Pump Station

The total electrical energy consumption of the Tully pump station, EEC_T, is the sum of the well pump and booster pump energy consumption and is calculated as:

EEC_T = $EEC_B + EEC_W$

Where,

EEC_B = electrical energy consumption of the booster pumps, kWh
EEC_W = electrical energy consumption of the well pumps, kWh

The electrical energy consumption of the booster pumps, EEC_B, is estimated as:

EEC_B = $Q \times TDH_B \times W \times C_0 \times C_1 \times OH / (Eff_M \times Eff_P \times C_2)$

Where all parameters are the same as in EEC, except:

TDH_B = total dynamic head of the booster pump, ft

The total dynamic head of the booster pumps, TDH_B, is estimated as follows.

TDH_B = $H_o - H_{z(s)}$

Where,

H_o = booster pump discharge head (trend data), ft
$H_{z(s)}$ = static suction head between suction tank water level and pump suction, ft

The suction tank water level fluctuates based on the number of booster and well pumps operating, and is controlled between 7 and 17.4 ft. An average tank level of 12.2 ft is used to estimate the average suction head of the booster pumps. As an example, based on trend data provided from the SCADA system, the discharge head of the Tully pump station is 100.63 psig (232 ft) when Booster Pumps 1 and 3 operated at 12:15 AM, 9/1/2009. The total dynamic head of the booster pumps at Tully station, TCH_{B1}, is estimated to be:

TDH_B = $H_o - H_{z(s)}$

$TDH_{B1} =$ (232) – (12.2)
$TDH_{B1} =$ 219.8 ft

Using equation EEC_B (in the previous page) for Booster Pumps 1 and 3 with a TDH_{B1} of 219.8 ft and the flow rates (2,695 gpm and 2,842 gpm, respectively) and pump efficiencies (0.755 and 0.807, respectively) estimated from the pump test curves, the electrical energy consumption of the booster pumps, EEC_{B1}, is estimated to be 90.6 kWh.

The well pumps are controlled based on suction tank water level. Please refer to Section 11.2 for details about the well pump control scheme. Based on spot power measurements of the well pumps and spot water flow rate measurement, tank level setpoint for well pump on/off control, and Tully station output flow rate, the utilization factors of each well pump can be estimated. For example, when Boosters 1 and 3 operate, Well Pumps 1 and 2 run continuously while Well Pump 3 modulates on/off with an estimated utilization factor of 0.771. The electrical energy consumption of the well pumps, EEC_{W1}, is thus estimated to be 55.8 kWh during a 15-minute period when Boosters 1 and 3 are operating.

The total electrical energy consumption for Tully station at 12:15 AM, 9/1/2009 during a 15-minute period, EEC_{T1}, is calculated as:

$EEC_{T1} =$ $EEC_{B1} + EEC_{W1}$
$EEC_{T1} =$ (90.6 kWh) + (55.8 kWh)
$EEC_{T1} =$ 146.4 kWh

Thus, the energy intensity of the Tully pump station at 12:15 AM, 9/1/2009 for a 15-minute interval, EI_2, is estimated to be:

$EI = EEC_T/(Q \times T)$
$EI_2 = (146.4)(10^6)/\{[(2{,}695)+(2{,}842)](15)]\}$
$EI_2 =$ 1,763 kWh/MG

Baseline Validation

The model used to calculate the electrical energy consumption in a 15 minute interval as well as the model used to estimate the station output flow rate have been validated by comparing the gpm and kW difference between calculated values and measured values. Figures 11.5 and 11.6 show the distribution in error between measured and modeled values for flow rate and kW for all stations.

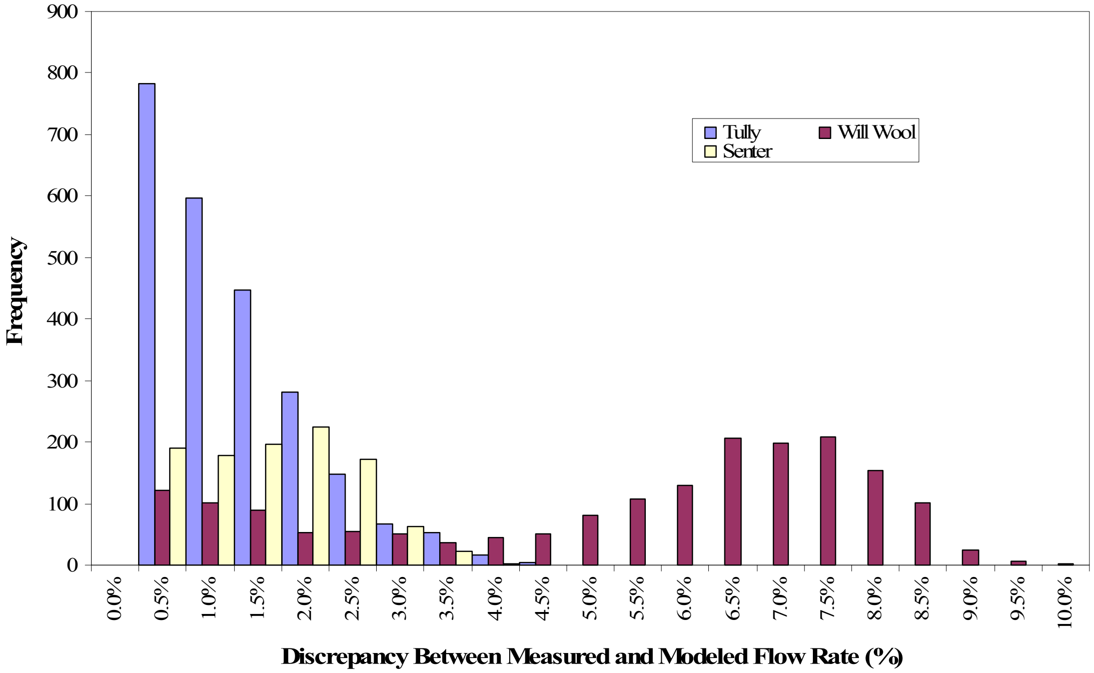

Figure 11.5 – Flow Rate Discrepancy Histogram

Figure 11.5 shows the absolute discrepancy between measured and modeled flow rate (based on station discharge pressure measured by the SCADA system). From Figure 11.5:

- Tully flow rate discrepancy was within 4.5%
- Will Wool flow rate discrepancy was within 9.5%
- Senter flow rate discrepancy was within 3.5%

The relatively high flow rate discrepancy for Will Wool was discussed with SJWC personnel. SJWC acknowledged that their own measurements in the past have shown that Will Wool station operates at two distinct points. This effect is also shown in Figure 6.9. SJWC attributes this behavior to the well water level at Will Wool being significantly affected by nearby wells. The well water level affects the differential pressure across the pump in turn affecting the flow rate that is calculated by our model, which assumes a constant well water level.

Therefore, the two "humps" seen in Figure 11.5 for Will Wool can be attributed to the two distinct well water levels at which the station may be operating. Accounting for these two distinct operating points, the discrepancy between measured and modeled flow rate shown for Will Wool is similar to the other two stations. For example, the distance between the first "hump" and the lowest error point is roughly 3.5% and the distance between the second "hump" and the lowest error point is roughly 3.5%.

Figure 11.6 shows the absolute discrepancy between measured and modeled power (based on station output flow rate measured by the SCADA system). From Figure 11.6:

- Tully average power discrepancy was 10% (standard deviation 11%)
- Will Wool power discrepancy was 5% (standard deviation 6%)
- Senter power discrepancy was 7% (standard deviation 6%)

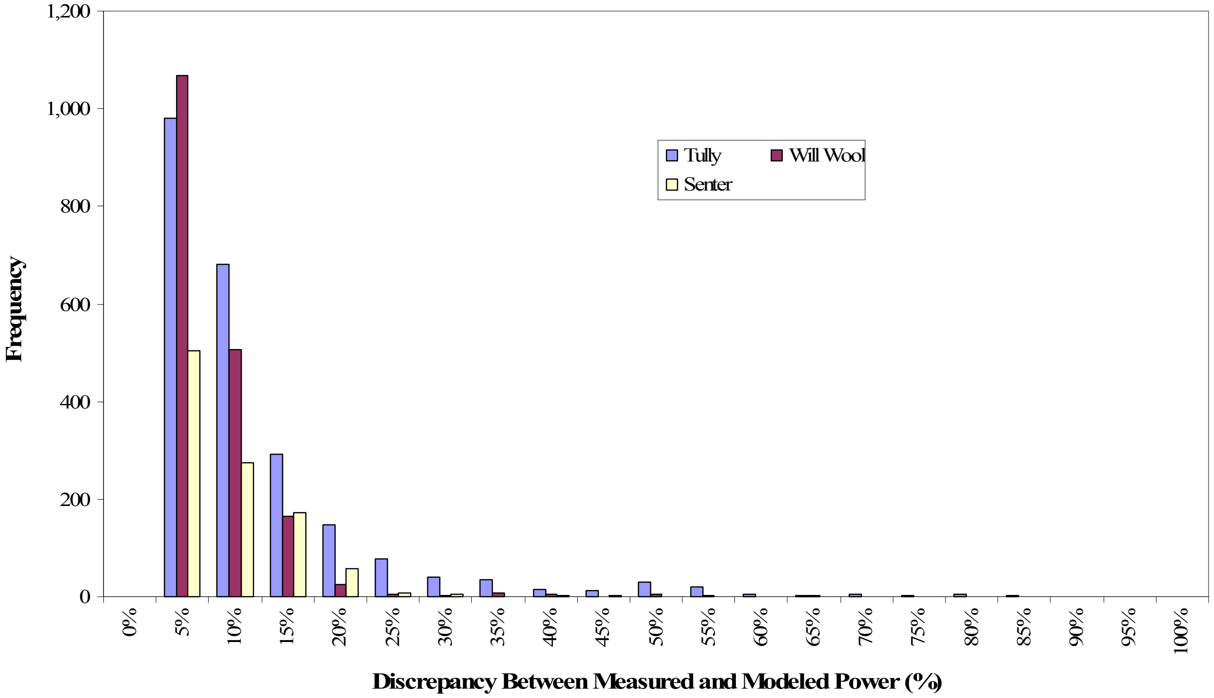

Figure 11.6 – Power Discrepancy Histogram

Compared to the flow rate discrepancy, the power discrepancy histograms shown in Figure 11.6 are high. This is mainly attributed to the type of power measurement used, a demand meter that averages the electric power every fifteen minutes. As an example, if a pump operates only during the last five minutes of the fifteen minute interval, the power model will assume that the pump was operating for the full fifteen minute interval resulting in an overestimate of the power.

The histogram does show a larger concentration of discrepancies between measured and modeled values within 5%.