Final Report

A Study of Irrigation Scheduling Practices in the Northwest

Phase II: Measurement of Water and Electricity Impacts

Prepared for:
Bonneville Power Administration
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quantec

Principal Investigators:
Hossein Haeri, Ph.D.
Kerstin Rock
Matei Perussi
Quantec, LLC

In Collaboration with:
Dr. Marshall English
OSU Department of Bioengineering

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Quantec Offices

720 SW Washington, Suite 400
Portland, OR 97205
(503) 228-2992
(503) 228-3696 fax
www.quantecllc.com

1722 14th St., Suite 210
Boulder, CO 80302
(303) 998-0102
(303) 998-1007 fax

3445 Grant St.
Eugene, OR 97405
(541) 484-2992
(541) 683-3683 fax

28 E. Main St., Suite A
Reedsburg, WI 53959
(608) 524-4844
(608) 524-6361 fax

6 Ridgeland Rd
Barrington, RI 02806
(401) 289-0059
(401) 289-0287 fax

20022 Cove Circle
Huntington Beach, CA 92646
(714) 287-6521

Printed on recycled paper

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Executive Summary

Irrigated agriculture plays a significant role in the economy of the Pacific Northwest. There are more than 8 million acres of irrigated farmland in the region, using approximately two feet of water per acre annually. About 4.4 million of these acres are irrigated using pressurized water delivery systems, primarily center pivots. The irrigation sector accounted for 652 MWa (average megawatts) of the Northwest's regional electricity consumption in 2002.

For over two decades, Bonneville Power Administration (Bonneville) has undertaken a number of initiatives to promote conservation in the irrigation sector through incentives for pump system efficiency improvements and irrigation water management. Scientific irrigation scheduling is one of the component activities that qualify for Bonneville's Conservation & Renewables Discount (C&RD).

"Scientific" irrigation scheduling (SIS) refers to the practice of meeting crop moisture requirements by supplying the right amount of water at the right time based on measurement of actual soil moisture and crop evapotranspiration (ETc). An optimal irrigation scheduling practice also requires knowledge of the actual amounts of water that are applied.

Effective irrigation scheduling can maximize crop yield[1] and profits to growers and minimize water and energy use. It can also have a direct effect on crop quality. An additional, but no less important, benefit of SIS is that it helps prevent the leaching of agricultural chemicals (e.g., nitrogen) into the ground water, thereby protecting water quality. In addition to protecting the water quality, reducing nitrogen leakage can also reduce the cost of fertilizer. For instance, data from the Willamette Valley indicated that nitrogen losses due to leaching could be up to $100 per acre[2].

In 2002, Bonneville, in a collaborative effort with the Pacific Northwest Generating Cooperative, and the Northwest Energy Efficiency Alliance retained Quantec, LLC, to conduct a comprehensive study of irrigation water management and irrigation scheduling practices in the Northwest. The primary goal of the study was two-fold:

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[1] Yield losses in the order of 3% can routinely expect for various crops from typical levels of excess water use. Marshall English, OSU Department of Bioengineering.

[2] Based on information provided by Marshall English, OSU Department of Bioengineering.

1. Developing a better understanding of and establishing an accurate baseline for current levels and methods of irrigation scheduling in different sub-regions of the Northwest
2. Estimating the relative effects of scientific irrigation scheduling on water and energy use so that a simplified methodology for calculation of deemed savings might be developed

Research was conducted in two phases. Phase I focused on developing a baseline of regional irrigation scheduling practices through a survey of a large sample of farms in the Northwest. The results from Phase I were documented in the December 2003 report titled *A Study of Irrigation Scheduling Practices in the Northwest*. This document summarizes some of the key findings of Phase I and presents the results of Phase II of the study.

The primary objective in Phase II was to provide reasonable and accurate estimates of irrigation water and electricity use. This information, combined with data on crop, farm, irrigation system, and pumping system characteristics is intended to provide the basis for determining potential water and electricity savings resulting from the application of scientific irrigation scheduling.

The study was carried out with assistance from a technical advisory team of irrigation experts from Bonneville, Oregon State University Department of Bioengineering, Columbia Basin Ground Water Management area, IRZ Consulting, an irrigation water management consultancy in Oregon, and the Franklin County Conservation district.

Research on Phase II began in February 2004 and in-field measurement and data collection continued through the growing season until October. The study was carried out in four stages:

- A Review of literature and data available from previous studies of irrigation scheduling in the Northwest
- In-field measurement of actual water use for a small sample of farms in the region
- Development of a model for estimating crop water use, and applying it to field data to calculate water savings from the application of scientific irrigation scheduling techniques
- Design and development of an energy calculator for estimating energy use and savings

The overall approach in this study was based on a quasi-experimental research design involving a comparison of water use between a sample of 19 fields managed with SIS techniques (the treatment group) and a comparable group of 19 fields in which SIS was not employed (the control group). Paired samples were selected from farms in the same geographic area, with the same crops and comparable soils. Below is a synopsis of this study.

1. Effects of scientific irrigation scheduling on water and energy use has been the subject of much interest in the Pacific Northwest for at least the past two decades. A number of studies have been sponsored by various regional stakeholders, particularly Bonneville, to determine water and energy savings that may be expected to result from SIS. The review of this literature shows marked differences with respect to scope of analysis, timing, sample size, methodology, and results. The results with respect to estimated water savings vary greatly across the nine studies, ranging from 7% to nearly 30%. Given the differences in timing, methodology, and sample sizes associated with these studies, it is difficult to obtain a mean value for an estimate of savings. Moreover, given the significant variation in sample sizes, even the weighted average figure produces misleading results.

2. In order to establish a consistent basis for defining water management practices among the treatment group and to facilitate the recruitment and data collection processes, the treatment group was selected from among growers who received water management services through GWMA or IRZ Consulting. To ensure comparability with the treatment group, each treatment field was matched with a local control field with the same crop grown by a farmer known not to practice water management.

The study samples were distributed across the service areas of five utilities, namely Umatilla Electric Co-Op, UEC (16 fields), Franklin County PUD, (10 fields), Grant County PUD (6 fields), Pacific Power (5 fields) and Benton County PUD #1 (1 field) in Washington and Oregon. Corn (13 fields), various species of potatoes (11 fields), wheat (7 fields), and alfalfa (3 fields) were the main crops, with four fields growing peas and mint.

Field acreage ranged from very small half-circles of 27 acres and relatively large 200-acre fields. All fields were irrigated with central pivot systems, three-quarters of which operated at full circles. Farms from which the sample fields were selected also varied significantly, ranging from very small farms with only one circle to large corporate establishments with over 150 fields. Columbia river, irrigation districts, canals and wells were the primary sources of irrigation water.

3. For each field in the two samples, detailed data were collected on general farm characteristics, irrigation system, and water management practices. Water use was recorded for the duration of the irrigation season in 15-minute intervals using pressure gages linked to data loggers and calibrated with ultrasonic flow meter measurements. Soil water content was measured at the beginning of the measurement period using the neutron probe technique in all fields. Additional supporting data on reference evapotranspiration, crop coefficients, and precipitation were compiled throughout the season from Agrimet, the National Weather Service or NRCS for official recording sites located close to the fields.

4- The effects of scientific irrigation scheduling on water use was assessed by comparing the difference between *Actual Water Use* (AW), based on field measurements, and irrigation requirements and *Ideal Water Use* (IW) across the two groups. Ideal water use for each field was calculated using a Water Balance Model, developed for this study.

5. Analysis of cumulative actual and ideal water use showed that actual water use levels depart from the ideal in both the treatment and control groups. The differences are particularly pronounced in the control fields, ranging from nearly a positive 79% (over-irrigation) to a negative 24% (under-irrigation). The variance tends to be markedly smaller for the treatment group, where cumulative actual water use falls within ±22%.

6. Actual water use exceeded the ideal levels in both groups, but the amount of over-irrigation was much smaller in the treatment group than in the control group. This analysis also showed that in the treatment group, actual water use tends to track the ideal levels closely throughout the season; and even in cases where the actual water diverges from the ideal, it is generally compensated by the end of the season, so that the cumulative amounts remain close.

7. Actual water use exceeded the ideal water requirements by 1.9% and 11.4% on average for the treatment and control groups respectively. Adjusting the average amount of overuse for the treatment group by that of the control group yields a comparative difference of 9.5%. Given the assumptions underlying these estimates, the findings suggest that on average, implementation of SIS methods can save up to approximately ten percent (10%) water. This estimate is comparable to the findings from Phase I of this study; which, based on survey information collected from growers, found the average amount of water savings related to different levels of SIS methods ranged between 10% and 12%.

8. Electric energy savings resulting from the application of SIS depend on pump characteristics and are not necessarily proportionate to water savings. Electricity savings were analyzed for the study samples by computing power requirements to deliver the necessary volumes of actual and ideal water use.

The results show that reductions in water use resulting from the application of SIS in the study samples resulted in net electricity savings of 13.1 percent.

9. The methodology for calculation of energy savings was incorporated into a simple-to-use tool, which allows the derivation of water and energy savings over a range of crops, locations, and irrigation systems in the Northwest. It is expected that this tool will provide the means for a generalized approach for calculating location- and crop-specific deemed energy savings throughout the Northwest.

Phase II of this study was designed to provide reasonable and reliable estimates of water and energy savings that are likely to result from the application of scientific irrigation scheduling. It is important to keep in mind that the results of this study apply only to irrigation scheduling practices that at least satisfy the three criteria that define scientific irrigation scheduling, namely the use of accurate information on crop evapotranspiration, regular measurement of soil water content, and continuous monitoring of water use.

Indeed, in addition to scheduling, the experimental fields in this study were all managed by experienced irrigators and received technical assistance from expert irrigation consultants through IRZ Consulting and GWMA. These services encompassed additional measures beyond the three criteria we established for scientific irrigation scheduling. IRZ, Consulting, for instance routinely subjects its client fields to rigorous irrigation system testing and optimization including the use of infrared scanning to ensure uniform water application. Likewise, participants in GWMA water management programs are required to satisfy strict performance requirements by adhering to a rigorous ten-point water management plan. The sophistication, rigor and comprehensive nature of these scheduling services suggest that the 9.5% observed savings might be the best that can be achieved in the study area. A less rigorous irrigation-scheduling regime is unlikely to produce the same results as in this study.

At the same time, given the extensive impact of these irrigation scheduling services in the study area over the past 20 years it is probable that the irrigation practices of all farmers, even those not subscribing to such services, have been influenced by SIS. Consequently, the potential improvements engendered by scientific irrigation scheduling are likely to be greater in other regions where SIS has not been so widely adopted (most of the Columbia Basin).

I. Introduction

This report summarizes the results of a comprehensive study of irrigation water management and irrigation scheduling practices in the Pacific Northwest. The study was commissioned by the Bonneville Power Administration (Bonneville), in a collaborative effort with the Pacific Northwest Generating Cooperative (PNGC), and the Northwest Energy Efficiency Alliance (the Alliance) to characterize irrigation scheduling practices in the Northwest region and to assess the effectiveness of scientific irrigation scheduling on reducing water use and conserving electric power.

The study was managed by Quantec, LLC, in collaboration with a core technical team of regional experts from Oregon State University Department of Bioengineering, IRZ Consulting, the Columbia Basin Groundwater Management Area (GWMA), and Franklin County Conservation District with support from Benton, Umatilla, Franklin, and Grant public utility districts.

Scope and Objectives

Scientific irrigation scheduling (SIS) is one of the component activities that qualify for Bonneville's Conservation & Renewables Discount (C&RD). The results of this study are intended help establish a well-informed basis for future planning and program development efforts within the context of C&RD. The main goal of the study was two-fold:

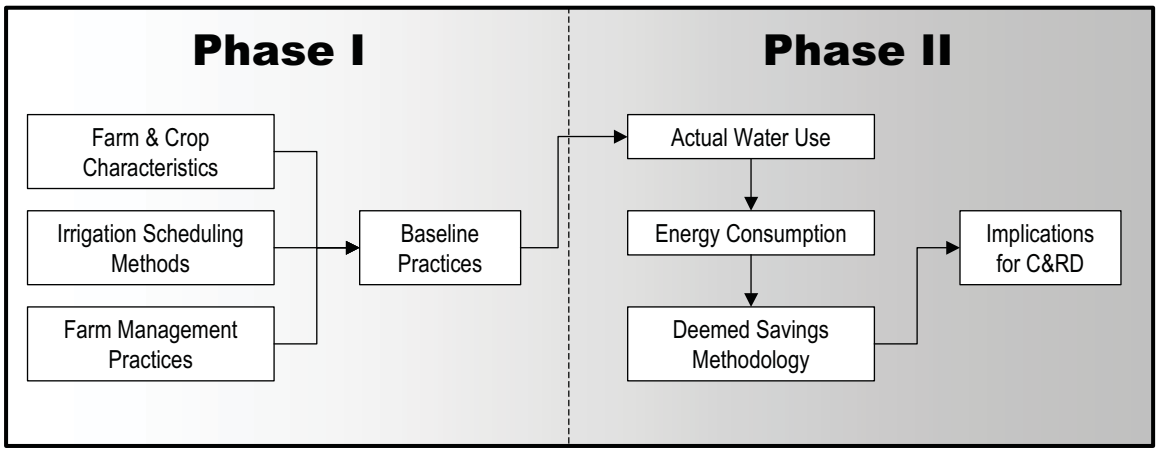
1. Develop a better understanding of, and establish an accurate baseline for current levels and methods of irrigation scheduling in different sub-regions of the Northwest.
2. Estimate the effects of scientific irrigation scheduling and water management practices on water and energy use for the purpose of developing estimates of parameters for a simplified methodology for calculation of deemed savings associated with irrigation scheduling.

The research was conducted in two phases. Phase I focused on characterizing and developing a baseline of regional irrigation scheduling practices through a survey of farms in the Northwest. Phase II consisted of detailed field measurement and monitoring of actual water and energy use on a sample of farms studied in Phase I. The broad context and the elements of the study are shown in Figure I.1.

This document is organized in six parts. The study's background and objectives are discussed in this section. Section II, following this introduction, provides an overview of irrigation water management and irrigation scheduling. The findings and conclusions of Phase I are reported in Section III. Section IV describes the scope of and methodology for Phase II. A

complete description of the methodology for calculation of water use and savings is presented in Section V. Section VI describes a simple model for calculating energy effects of scientific irrigation scheduling and applying it to the results of this study. Synopses of several previous studies of irrigation scheduling in the Northwest are presented in Appendix A. Detailed description, structure, and algorithms used in the water balance model and the energy savings calculator are found in Appendixes A through C. Finally, a copy of the farm data collection protocols developed for this study in shown in Appendix D.

Figure I.1: Study of Irrigation Scheduling Practices Research Context and Elements



Irrigation Water Management

Irrigated agriculture plays a significant role in the economy of the Pacific Northwest. According to the 1998 census of agriculture, there are more than 8 million acres of irrigated farmland in the region, using approximately two feet of water per acre annually. About 4.4 million acres are irrigated using a mix of pressurized water delivery systems, primarily center pivots. The irrigation sector accounted for 652 aMW (average megawatts) of electric power consumed in the Northwest in 2002.

Irrigation is defined as "the artificial watering of land (as by canals, ditches, pipes or flooding) to supply moisture for plant growth" (Webster's Dictionary 1996). This definition, although correct in a literal sense, does not convey the full range of purposes that irrigation serves. Irrigation also helps cool the soil and atmosphere to create a more favorable environment for plant growth, prevents damage to a crop from hard freezing, prevents accumulation of salts in the soil, protects soil from wind erosion, and conditions the soil against cracking and channeling.

Irrigation decisions depend on irrigation goals, specific criteria, and strategy. The level and timing of irrigation depend on irrigation criteria (i.e., the indicators used to determine the need for irrigation) and an irrigation strategy that determines how much water to apply. Irrigation scheduling methods differ based on these criteria and the method by which they are measured. Common and widely used irrigation criteria are soil moisture status, soil moisture tension and cumulative estimated ET.

The importance of applying scientific water management and irrigation scheduling methods is that they enable the irrigator to apply the right amount of water at the right time to achieve specific goals. This increases irrigation efficiency and helps avoid either over-irrigation or under-irrigation. Over-irrigation wastes water, energy, and labor; leaches expensive nutrients below the root zone; reduces soil aeration; and can diminish crop yields. Under-irrigation, on the other hand, stresses the plant and causes yield reduction.

A grower cannot manage water to maximum efficiency without knowing how much water to apply. The timing of irrigation and the amount of water to be applied are determined by a number of factors, including soil properties, crop type, stage of crop development, availability of water, climate and irrigation system characteristics (represented as the application efficiency of the system).[3]

Scientific Irrigation Scheduling

All growers use an irrigation-scheduling regime of some kind. What distinguishes these regimes is the basis on which irrigation decisions are made. The method and intensity with which irrigation scheduling is applied, however, vary greatly and may range from no systematic scheduling to the use of automated computerized systems. "Scientific" irrigation scheduling (SIS) generally refers to the practice of deciding on the timing and amount of water use based on measurement of actual soil moisture and sophisticated modeling of crop evapotranspiration (ETc). An optimal irrigation scheduling practice also requires knowledge of the actual amounts of water that are applied. In the context of this study, SIS is strictly defined as a practice that involves:

1. Knowledge of crop consumptive use (evapotranspiration)
2. Appropriate measurement of soil moisture
3. Measurement of the actual amounts of water applied

Effective irrigation scheduling can maximize crop yield and profits to growers and minimizing water and energy use. It can also have a direct effect on crop quality. An additional, but no less important, benefit of SIS is that it helps

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[3] Irrigation requirement is defined as: net water requirement/irrigation system efficiency; where, net water requirement = ETc – (rainfall + useable antecedent soil moisture).

prevent the leaching of agricultural chemicals (e.g., nitrogen) into the ground water, thereby protecting water quality. In fact, in some areas the Environmental Protection Agency (EPA) has mandated SIS as a precondition for issuing a National Pollutant Discharge Elimination System (NPDES) permit, which is required in most jurisdictions.

II. Phase I Results

Phase I of the this study focused on developing a baseline for regional irrigation scheduling practices through a survey of a sample of geographically representative farms in the Pacific Northwest.[4]

The sample frame for Phase I was a list of 20,657 farms and ranches in the four states of the Pacific Northwest, Idaho, Montana, Oregon, and Washington, purchased from Dun & Bradstreet. Since this study focused primarily on utilities in Bonneville's service area, only farms served by public utilities that agreed to participate in the study were retained in the sample.

A phone survey of 776 farms in the region provided the main source of data. Surveys were administered from January through March 2003, before the start of the planting season. Geographic and size distributions of the survey sample were largely consistent with the results of the 1988 Northwest Farm and Ranch Survey, except that Washington, and to a lesser extent Oregon, were somewhat over-represented in the sample – largely due to the location of utilities willing to participate in the study. With respect to farm sizes, the two surveys showed a close correspondence.

The results of Phase I showed that irrigation scheduling is practiced in the Northwest with different levels of intensity, regularity, and sophistication. In differentiating among these, three distinct practice levels were identified, based on the combinations of techniques used to determine irrigation requirements (Table II.1). Practice level I was the only method qualified as "scientific" based on the study's criteria.

Table II.1: Definition of Irrigation Scheduling Practices

Practice Level	Use of Scheduling Services	Measurement of Soil Moisture or Plant Water Status	Use of ET	Measurement of Applied Water
I	Yes			
		Yes	Yes	Yes
II		Yes	Yes	
			Yes	Yes
III		Yes		
			Yes	

[4] See A Study of Irrigation Scheduling Practices in the Pacific Northwest, Bonneville Power Administration, prepared by Quantec, LLC, December 2003.

Summary of Results

Farm Characteristics

The grower survey was designed to elicit information on four general areas: farm and crop characteristics, irrigation system type and configuration, irrigation management and scheduling methods, and general demographics. The principal findings follow.

- Alfalfa was the dominant crop in the region. Fifty-six percent of all surveyed farms reported planting alfalfa; in 38% of cases, it was the primary crop. Alfalfa accounted for nearly one-third of the planted acreage, followed by corn (15%), potatoes (7%), and grass seed.
- Sources for irrigation water varied widely across the region. Groundwater – mainly from irrigation districts, wells, and local surface water from rivers and ponds – are the primary sources of irrigation water in the region. Water from irrigation districts accounted for 44.3% of total irrigated acreage surveyed.
- In general, 94% of farms used pressurized pump systems for irrigation; in 87% of cases, the local utility was the source of power for pumping. Sprinklers were identified as the predominant irrigation system, used as the primary irrigation system in 82% of the surveyed farms. Gravity irrigation was the primary system in 15% of farms. Only 4% reported using on-site generation or non-electric energy sources for pumping.

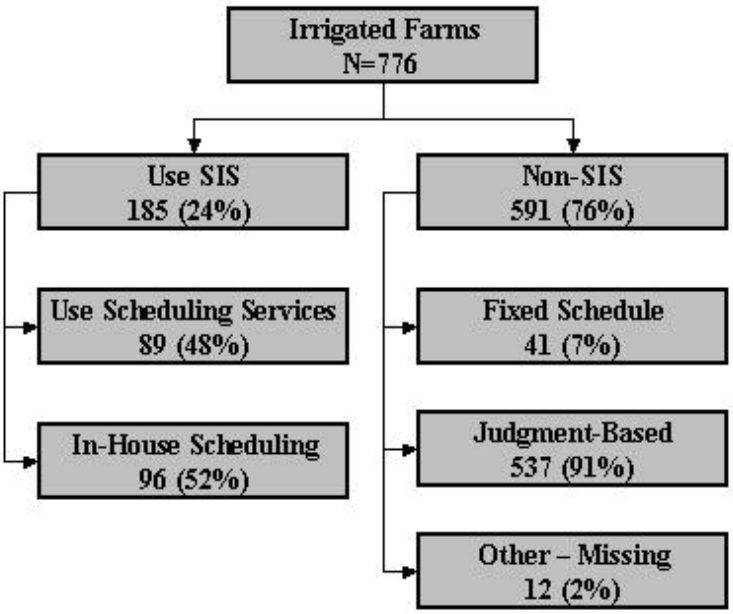
Irrigation Scheduling Methods

As shown in Figure II.1, SIS was practiced in 185 (24%) of the surveyed farms. Of these, 89 (48%) reported using commercial irrigation scheduling services on a contract basis, while 96 (52%) used on-farm equipment and methods. A large majority of farmers (76%) reported using non-scientific irrigation scheduling methods. Of these, 91% reported to rely on "judgment" and 7% used a fixed, or routine, schedule.

Of the farms surveyed, 89 (12%) reported using a commercial irrigation scheduling service at the time of the survey, and 165 (21%) had used such services in the past. Of the 254 farms that use or have used a service, 75 (29.5%) received financial assistance from a utility or local agency for the services they received.

Sources for information on ET included on-line services such as Agrimet, farm-related publications, personal weather stations, and commercial irrigation services. Survey results suggested that only 89 farms (12%) used ET data on a regular basis. On-line services, primarily Agrimet, were the most common source for obtaining this information and accounted for 45% of cases.

Figure II.1: Irrigation Scheduling Methods



The results showed that approximately 15% of growers, particularly in larger farms, perform soil moisture measurement using various techniques and equipment. Neutron probes and tensiometers were identified as the most commonly used devices, accounting for 45% and 23% of cases, respectively. Dielectric instruments are being adopted at an increasing rate as well (24%). Measurement of plant water status was far less common than soil moisture measurement for determining plant water requirements and was nearly always used in conjunction with soil moisture measurement. Less than 2% of respondents reported using plant water status measurement techniques. Of the surveyed farms, 171 (22%) reported using techniques for applied water measurement that are deemed acceptable with respect to accuracy.

Irrigation Scheduling Practices

As shown in Table II.2, a large majority (78%) of the surveyed farms in the Northwest did not use scientific irrigation scheduling practices. However, these cases account for about 57% of total irrigated acreage, indicating that non-scientific irrigation scheduling practices tend to be more common among smaller farms. Practice level I, although reportedly used in only 12% of surveyed farms, accounts for 32% of irrigated acreage and is most common in larger farms, generally more than 500 irrigated acres.

Table II.2: Frequency of Irrigation Scheduling Practices by Number of Farms and Irrigated Acreage

Practice	Farms	Percent	Irrigated Acres	Percent
I	90	12%	155,175	32%
II	75	10%	52,339	11%
III	611	78%	274,270	57%

Sophisticated irrigation scheduling practices were more prevalent in the Horse Heaven Hills (Washington), Moses Lake (Washington), Twin Falls (Idaho), and Hermiston (Oregon) sub-regions. The proportions of irrigated acres within practice level I in the Horse Heaven and Moses Lake sub-regions were significantly higher than in other regions. In utility service areas where SIS methods have been promoted aggressively in the past (Benton County PUD No. 1 and Umatilla Electric Co-Op), scientific irrigation scheduling methods were applied to 65% of the irrigated acreage, compared to 23% region wide.

Application of irrigation scheduling practices also varied across crops. Practice levels I and III were the most prevalent for most crops. The survey results also suggested that the more sophisticated irrigation scheduling practices were more likely to be utilized for higher value crops.

Water Use

Survey respondents were asked to report the actual amount of water in inches or feet per acre applied to each to each crop they grow. The main objective in collecting this information was to determine whether crop-specific water use varies depending on irrigation scheduling practice.

Examination of reported water use and their deviations from known irrigation requirements indicated that, by and large, farms in practice level I tend to use less water than farms that use less sophisticated practices. Comparison of mean water use derived from a regression model of water use showed that application of the combination of methods used in practice levels I and II are likely to result in water savings of approximately 12% and 10%, respectively.

Phase I Conclusions

Phase I of this study was an attempt to develop an understanding of and to establish an empirical baseline for irrigation scheduling methods and practices in the Northwest. A comparison of the geographic distributions of farms between this sample and the 1998 Farm and Ranch Survey sample shows that, in spite of differences in geographic distributions, the two are similar with respect to farm-size distributions.

This comparison also revealed several marked differences. Prevalence of soil moisture sensing devices, for example, was considerably greater than the 6% reported in the 1998 Census; similarly, the proportion of surveyed farms reporting use of commercial services also stood significantly above the 4% reported in the Census. These differences may be due in part to the size characteristics of farms in the survey sample. There may also have been an increase in the adoption of these technologies since 1998 due to the influence of recent market transformation initiatives and programmatic efforts sponsored by several utilities aimed at improving irrigation-scheduling practices in the region.

Based on reported levels of water use, it appeared that more advanced irrigation scheduling practices do indeed result in reduced water use. Comparison of reported water use with estimated net water requirements, however, revealed a pervasive pattern of deficit irrigation. The consistency in this pattern raised concerns regarding the accuracy of self-reports. These findings, therefore, were interpreted as *indicative* rather than *conclusive*.

III. Phase II Study

The effects of scientific irrigation scheduling on water and energy use has been the subject of much interest in the Pacific Northwest for at least the past two decades. A number of studies have been sponsored by various regional stakeholders, particularly Bonneville, to assess the potentials of SIS as an effective measure for conserving water and electricity.

Phase II of this study was intended to build on this body of research by applying a robust research design and method for calculating water savings within the given time and budget constraints. The study focused primarily on deriving accurate and reasonable estimates of water and electricity savings through monitoring of actual water use in a sample of fields. To the extent that these results may be generalized to other areas in the region, this information also could provide the basis for developing a simplified approach for determining the effects of scientific irrigation and establishing a methodology for calculation of deemed savings.

The study was completed in three stages.

1. Reviewing published research reports and previous studies on the water-use and energy impacts of scientific irrigation scheduling, which can help provide a context for the study
2. Determining water savings resulting from SIS by monitoring water use on a sample farms
3. Developing a simplified algorithm and the necessary tools for estimating energy savings due to SIS

Review of Prior Research

To gain a historical perspective on the subject and to provide an informed basis for the design and implementation of Phase II of this study, a thorough review of the methodologies and results of these studies was conducted. A synopsis of each study is presented in Appendix A.

The review of this literature shows marked differences with respect to scope of analysis, timing, sample size, methodology, and results (Table III.1). The results with respect to estimated water savings vary greatly across the nine studies, ranging from 7% to nearly 30%. Other studies have shown expected savings of nearly 13% to slightly over 18%. Given the differences in timing, methodology, and sample sizes associated with these studies, it is difficult to obtain a mean value for savings estimate. Moreover, given the very large differences in sample sizes and in the rigor of the different analyses, even a weighted average would likely produce misleading results.

Table III.1: Summary of the Results of Previous Research

Study Title	Author	Study Year(s)	Average Water Savings	No. Fields
1993 Grant Co. Irrigation Scheduling Project	Pacific Northwest Laboratory	1994	29.7%	1
1986 Irrigation Scheduling Study	Agrimanagement	1987	7.0%	1
Pasco Aquifer Technical Documentation	Unknown	Unknown	12.9%	1
Franklin 2002 GWMA IWM—Case Example	GWMA	2002	15.7%	1
Scientific Irrigation Scheduling, Grower Training	Royal Consulting Services	2001 - 2003	12.4%	255
Case Study: Grant PUD	Royal Consulting Services	1997 - 1999	18.1%	165
Consumptive Use Data by Crop and Year 1994 -2003	Professional AG Services	1994 - 2003	17.7%	4,643
Scientific Irrigation Scheduling	Washington State University	Unknown	15.8%	15
Summary of GWAMA/NRCS IWM Program	GWMA	2000 - 2004	16.7%	1,088
Nine Canyon Ranch Irrigation Scheduling	IRZ Consulting	2002	12.9%	12

IV. Study Approach and Methodology

Sample Selection

The overall approach in this study was based on a quasi-experimental research design comparing water use between a sample of fields managed with SIS techniques (the treatment group) and a comparable group of fields in which SIS was not employed (the control group). Paired samples were selected from farms in the same geographic area, with the same crops and comparable soils. Each group initially contained 22 matched fields. However, due to logger failures, three pairs were dropped from the final analysis samples.

Identification of growers and proper assignation to the treatment and control groups was a particularly challenging aspect in this study. Initially, it was planned to identify and to recruit growers based on responses to the Phase I survey. However, several difficulties arose which precluded the use of Phase I surveys as the basis for sample selection, mainly:

1. Time constraints dictated by the growing season and the importance of starting the measurements on or near planting date
2. Geographic dispersion of the survey respondents, hence the difficulties of pair-wise matching of the two samples
3. Lack of specific and complete knowledge of growers' water management practices
4. The difficulty of recruiting control fields without completely explaining the purpose of the study, hence potentially modifying their behavior and introducing bias in the study

It was therefore decided to select the treatment group from among growers who received water management services through GWMA or IRZ Consulting, and to select the control group from farms in close proximity to the treatment farms. The main advantage of this approach was that it offered a more consistent basis for defining water management practices among the treatment group and significantly helped the recruitment and data collection processes.

To ensure comparability with the treatment group, each treatment field was matched with a local control field with the same crop grown by a farmer known not to practice water management.

A copy of the survey forms used in the Phase II data collection effort is included in Appendix D. The treatment group was comprised of farms that

subscribed to professional services offered through GWMA, or IRZ Consulting under partial funding from the local utilities.

Of the 22 initial matched pairs, three treatment and three control fields were dropped from the study samples due to malfunction or failures of the data logging equipment early in the measurement period. Summary characteristics of the 38 fields in the final samples are shown in Tables IV.1 and IV.2.

The study samples were distributed across the service areas of five utilities, namely Umatilla Electric Co-Op, UEC (16 fields), Franklin County PUD, FPUD (10 fields), Grant County PUD, GPUD (6 fields), Pacific Power, PP&L (5 fields) and Benton County PUD #1, BPUD (1 field) in Washington and Oregon. Corn (13 fields), various species of potatoes (11 fields), wheat (seven fields), and alfalfa (three fields) were the main crops, with four fields growing peas and mint.

Field acreage ranged from a small half-circles of 27 acres and to a large 200-acre field. All fields were irrigated with central pivot systems, three-quarters of which operated at full circles. Farms from which the sample fields were selected also varied significantly, ranging from very small farms with only one circle to large corporate establishments with over 150 fields. Columbia river, irrigation districts, canals and wells were the primary sources of irrigation water.

Table IV.1: Basic Characteristics of Study Samples – Treatment Group

Site ID	County	Utility	Crop	Field Acres	No. Fields	Irrigation System	Water Source
4	Morrow	PP&L	Mint	123	53	Full Circle	Columbia River
5	Morrow	PP&L	Wheat	123	53	Full Circle	Columbia River
8	Morrow	PP&L	Potatoes	125	53	Full Circle	Columbia River
12	Umatilla	UEC	Alfalfa	40	23	1/2 Circle	Well
16	Morrow	UEC	Peas	128	23	Full Circle	Columbia River
16b	Morrow	UEC	Corn	128	25	Full Circle	Columbia River
17	Benton	BPUD	Potatoes	99	154	Full Circle	Columbia River
18	Morrow	PP&L	Peas	124	53	Full Circle	Columbia River
18b	Morrow	PP&L	Corn	124	53	Full Circle	Columbia River
19	Morrow	UEC	Corn	128	25	Full Circle	Columbia River
20	Morrow	UEC	Corn	120	16	Full Circle	Columbia River
24	Franklin	FCPUD	Potatoes	63	2	1/2 Circle	Well
28	Franklin	FCPUD	Potatoes	112	1	Full Circle	Irrigation District
30	Franklin	FCPUD	Corn	84	1	1/2 Circle	Irrigation District
32	Franklin	FCPUD	Potatoes	57	4	1/2 Circle	Well
34	Franklin	FCPUD	Potatoes	124	1	Full Circle	Well
35	Grant	GCPUD	Corn	127	1	Full Circle	Irrigation District
38	Grant	GCPUD	Corn	130	1	Full Circle	Irrigation District
39	Grant	GCPUD	Wheat	132	1	Full Circle	Irrigation District

Table IV.2: Basic Characteristics of Study Samples – Control Group

Site ID	County	Utility	Crop	Field Acres	No. Fields	Irrigation System	Water Source
1	Umatilla	UEC	Alfalfa	32	1	1/2 Circle	Canal
2	Umatilla	UEC	Wheat	27	20	1/2 Circle	Canal
3	Umatilla	UEC	Potatoes	47	20	1/2 Circle	Canal
6	Morrow	UEC	Wheat	126	2	Full Circle	Well
7	Morrow	UEC	Wheat	154	2	Full Circle	Well
9	Umatilla	UEC	Peas	159	21	Full Circle	Columbia River
9b	Umatilla	UEC	Corn	159	21	Full Circle	Columbia River
10	Umatilla	UEC	Potatoes	126	21	Full Circle	Columbia River
11	Morrow	UEC	Alfalfa	122	6	Full Circle	Well
13	Morrow	UEC	Corn	202	5	Full Circle	Canal
14	Morrow	UEC	Corn	142	5	Full Circle	Canal
23	Franklin	FCPUD	Potatoes	134	1	Full Circle	Well
25	Franklin	FCPUD	Wheat	36	1	1/2 Circle	Irrigation District
27	Franklin	FCPUD	Potatoes	110	2	Full Circle	Well
29	Franklin	FCPUD	Corn	155	1	Full Circle	Well
31	Franklin	FCPUD	Potatoes	55	1	1/2 Circle	Irrigation District
36	Grant	GCPUD	Corn	143	1	Full Circle	Irrigation District
37	Grant	GCPUD	Corn	131	1	Full Circle	Irrigation District
40	Grant	GCPUD	Wheat	129	1	Full Circle	Well

Data Development

To support the analytic tasks in the study, it was necessary to compile a large amount of data regarding basic farm characteristics, irrigation practices, and in-field measurements. These data fall into three general categories:

- Primary farm and field data
- In-field measurements
- Precipitation and evapotranspiration.

Preliminary Site Data

The first step in the data collection and analysis process was the preparation of primary site data. Project representatives met with all participating farmers and gathered information within the following three categories:

1. ***General farm data*** – including location by county and GPS coordinates, soil type, crops grown with acreage and growth stages defined per crop, current methods of irrigation scheduling, sources of information and indicator data used for irrigation scheduling.
2. ***Irrigation system data*** – including number and type of pump/motor systems with particular details
   - Pump flow rating
   - Nominal pumping lift
   - Horsepower of the drive motor
   - Irrigation system specification (make, model and configuration)
   - Number and type of nozzles or nozzle package
   - Presence of pressure regulators
3. ***Initial setup of site for analysis*** – including assigning a Farm and Field ID and taking an initial soil water content reading (balanced by a final water content reading).

In-Field Measurements

Measurement of Water Use: For each field in the sample, water use was measured for the duration of the irrigation season using pressure gages linked to data loggers and calibrated with periodic ultrasonic flow measurements. The instrumentation packages used in each field included digital pressure gages installed at the input point of each pivot system and a digital memory device that receives and accumulates the pressure data continuously at 15-minute intervals. This data provided a continuous record of times when the system was under pressure, i.e. when each pivot was actually applying water, and the operating pressure of the system.

An important advantage of the 15-minute interval (as compared to a less frequent interval such as weekly or monthly readings) is that it gives a more accurate indication of irrigation timing and amounts relative to crop water needs and soil storage capacity. In other words, it will facilitate detection of errors in timing and amount of applied water.

Sprinkler discharge was calculated by relating the sprinkler pressure to the volume flow rate. The functional form of that relationship was determined based on theoretical models of nozzle discharges along a line of sprinklers based on intake pressures and nozzle characteristics (accounting for pressure regulation as appropriate). The theoretical functional forms derived in this fashion were then calibrated using paired values of input pressure and ultrasonic flow meter readings (see section on Ultrasonic flow meters, below).

The installed systems were expected to determine water use within a few percentage points (e.g., within 3% of true water use). This is comparable to the accuracy of an in-line flow meter that is permanently installed in an irrigation system.

In a few cases, delays in the installation of the monitoring equipment resulted in the project team not being able to commence data collection at the beginning of the irrigation season. However, even in these cases, the ideal and actual water use levels were determined for the most of the season, including the periods of greatest water use, and thus are expected to have little or no negative impact on the overall study results.

Ultrasonic Flow Meter Readings: Ultrasonic flow meter readings were used to calibrate the theoretical pressure-flow relationships discussed above. Two portable, high precision, ultrasonic flow meters were used to make these periodic measurements of the rates of flow into each irrigation system. These non-intrusive flow meters will measure the flow in the pipe externally, and therefore will require no drilling or cutting of the irrigation pipe. Although ultrasonic flow measurement is more accurate, the high cost of the meters made it impractical for continuous monitoring, hence the decision was made to use pressure sensors with data loggers to monitor operating pressures and run-times and to measure water use indirectly.

Flow rates in each irrigation system were measured at least twice during the season: once during equipment testing and setup and once a few months later to test the assumed pressure to flow relationship at a second and presumably different pressure. Combining the flow data with corresponding sprinkler pressure data enabled the analytical team to derive the relationship between pressure and sprinkler discharge for each system monitored. At the time of equipment installation and testing, electric consumption at the pump station was measured for corresponding flow measurements from the ultrasonic flow meter to give a power-to-flow relationship for each system.

Soil Water Content: The amount of moisture in the soil available for the crop is an important indicator for water application scheduling. The preferable soil-water content varies by crop and soil type. Each type of soil has a unique field capacity; knowing the difference between the current moisture content and the preferred level or field capacity aids in determining the timing and amount of water application. Soil water content was measured at the start and end of the study period as well as at least two additional times in most cases during the season. Soil water content was then estimated on a daily basis using a mass-balance equation; the soil water content on day *n* was increased by irrigation and rainfall, and decreased by ET or deep percolation.

Application Efficiencies

Estimation of the change in soil water content following an irrigation required first estimating the percentage of applied water that was effective, *i.e.* the net applied water for each irrigation event, then adding that net application to the total soil moisture. Net applied water is determined by multiplying the total water delivery by the application efficiency of the irrigation system. The attainable application efficiency of center pivots that are well designed and maintained is generally taken to be about 90%. However, achieving the attainable efficiency depends upon accurate irrigation scheduling; irrigating too soon will over-fill the soil profile and the resulting deep percolation losses will reduce the overall application efficiency. Conversely, irrigating too late may actually increase application efficiency, but may also cause unintended crop stress that reduces yields. The procedures for calculating losses are discussed in Section V.

Neutron probe sampling was used to measure the hydrogen atoms present in the soil, which is related to the water content by a calibration reference curve specific to the equipment and soil sample. Samples from three locations within each monitored field were taken from multiple depths to get a profile of water distribution in the soil. The result of sampling was a measurement of soil water content in terms of inches of water per foot of soil in the active root zone throughout the field. These measurements were used to establish antecedent soil moisture at the beginning of the season, and to verify the accuracy of estimates of consumptive use of water as the season progresses.

Evapotranspiration and Precipitation Data

Evapotranspiration: There are two main sources for daily reference ET data in the Northwest: Agrimet and PAWS. The data on ET used in this study were gathered primarily from the Agrimet stations at Hermiston, OR and George, WA. Daily crop evapotranspiration values were derived by multiplying reference ET information by crop coefficients obtained from Agrimet. Crop coefficients account for differences in resistance to transpiration from the reference crop due to crop height, roughness, groundcover, and rooting characteristics. The product of reference ET and the crop coefficient is the

potential ET for the crop when the soil is adequately supplied with water but the soil and crop canopy surfaces are dry. This potential ET is then multiplied by an adjustment factor to account for wet surface conditions after irrigation or rainfall events. Analysis of the coefficients provided by Agrimet indicated that they have been adjusted in advance to account for surface wetting from moderate irrigation frequencies.

Precipitation: A critical variable needed to complete the ongoing water balance calculations is local precipitation on a daily basis. This information was collected from the National Weather Service or NRCS for official recording sites located close to the fields.

All data collected for the study were organized and maintained in a working database, electronically linked to field-specific water balance models. Fifteen-minute interval pressure readings, collected in regular downloads throughout the study period, were converted to water usage on a 15-minute basis and aggregated to daily values for analysis.

V. Calculation of Water Savings

Actual water use over the season for both treatment and control fields were compared to the calculated "ideal" water use for each field. The analysis determined whether actual water use matched the ideal water use for the SIS fields more closely than for the control fields. Water savings due to SIS were then estimated from the difference between these calculations.

Calculation of Actual Irrigation Water Use

Determination of actual irrigation water use for each field was derived from measured "run times," the intervals when the systems were actually applying water. Determinations of run times were based on time-tagged measurements of line pressures at the point of delivery to the pivot. When the system was applying water, line pressures would necessarily be high; when no water was being pumped through the line, the pressure would be low.

The depths of applied water were calculated based on pressures measured at 15-minute intervals and recorded on a data logger. These recorded 'on-times' were multiplied by the sprinklers' design flow rates to determine corresponding field average depths of application. Although pressure variations were observed during irrigation events that could, in principle, affect discharge rates, the prevalence of pressure regulators minimized variations in discharge rates. All calculations are in inches of applied water.

The use of pressure measurements as an indicator of irrigation time had two advantages:

- Only accounted for times when water was actually being applied, not those times when the pivot might be moving but not applying water (for example, when the system was being repositioned in the field)
- Provided definitive information about system pressures, a necessary element for determining energy use

Calculation of Ideal Water Use

Ideal water use can be defined as the minimum amount of water required to produce maximum potential yields. The ideal water use for a given irrigated field depends upon weather conditions, the variety and stage of growth of the crop, soil factors, and the characteristics of the irrigation system. To achieve the level of accuracy desired for this analysis, each of these factors had to be explicitly accounted for.

Ideal water use was calculated using a "water-balance" model to estimate soil water content in the crop root zone on a daily basis for each of the fields in the

study. The water balance for each field was initialized with the soil water content measured at the start of the irrigation season. Then daily estimates of soil water content in the active part of the root zone were calculated using the following estimates or measured values:

- Daily crop water uptake
- Precipitation
- Applications of irrigation water
- Increases in available soil moisture as root zone extension brings additional soil water within reach of the crop root system

The resulting daily estimates of root zone water content were then used to determine when and how much water must be applied to meet full crop water requirements. When irrigation was called for, the application efficiency for that irrigation event was estimated and used to compute the net application (the portion of applied water that would be successfully stored in the root zone, available to the crop).

The sequence of calculations used to determine the ideal *gross* water use (i.e. the amount the irrigator must deliver to the field during the irrigation season) is outlined below. The irrigation season here refers to the interval between the date the antecedent moisture was measured and the harvest date. The seasonal water balance must satisfy the following equation:

$$\sum_S ET_C - R_{Eff} - \Delta SM_S - \sum_S Gross\ IR \times E_{appl} = 0$$

Where,

- Gross IR_S is the gross seasonal water requirement
- $\sum_S ET_C$ is the cumulative seasonal crop consumptive use of water
- R_{Eff} is the effective rainfall during that period
- ΔSM_S is the change in soil water storage during the season (the storage at end of season less the antecedent moisture)
- E_{appl} is the application efficiency, the proportion of water delivered to the field that is effectively stored in the root zone for use by the crop

If the water balance equation is used to estimate *ideal* water use, each of the above terms is predicated on best irrigation management practices. The gross irrigation requirement is then defined as the minimum amount of water that can be applied to a specific field with a given irrigation system without incurring crop stress that would reduce yield or quality. The cumulative ET must be the seasonal ET required to achieve maximum potential crop yields. The application efficiency would be the highest efficiency that could

reasonably be attained with a given irrigation system while still achieving maximum yields. The soil water storage at the end of the season would presumably be depleted as much as possible without unduly stressing the crop.

In principle, spray losses and distribution losses are accounted for in the above water balance equation by the application efficiency term. However, application efficiency was not explicitly estimated in the analysis. Rather, the losses themselves were estimated in a two-step process. The losses normally expected for well-managed center pivots were based on an attainable application efficiency of 90% (i.e. normal losses would amount to 10% of applied water). Additionally, where mismanagement of irrigation schedules would result in excess soil water (from early or excessive irrigations) the resulting additional deep percolation losses were calculated from the amount by which soil water content exceeded field capacity (see page V-12).

Computational Procedure

In order to achieve the highest accuracy in this analysis, irrigation requirements for an entire season must be derived from cumulative daily calculations that explicitly account for variations in weather and crop development (canopy development and root zone extension). These factors determine the ideal timing and amount of required irrigation. When an irrigation event occurs, it is necessary to model the disposition of applied water. Since the disposition of water is strongly influenced by weather and crop condition at the time of irrigation, as well as soil characteristics, irrigation system characteristics and operating procedures, it is necessary that field-specific factors and ambient conditions at the time of irrigation be fully considered in the analysis.

Irrigation should be initiated when soil moisture has declined to a predefined critical level chosen by the irrigation manager. The level of soil water at which depletion should trigger irrigation can be computed from the equation:

$$Allowable\ depletion = AC \times RZ_{Eff} \times MAD$$

Where:

- Allowable depletion is the amount of water (expressed as depth, in inches) that the crop can draw from the soil profile before an irrigation event.
- AC is the available capacity of the soil, the depth of available water per unit depth of soil (the difference between field capacity and wilting point); units are inches of water per inch of soil, or inches per inch
- RZEff is the effective root zone, the soil depth from which the crop can effectively extract all available water. The total water available to the crop before wilting is then the product of the terms; AC and RZEff.

- *MAD* is the management allowed depletion, the proportion of total available water that the irrigation manager will allow the crop to extract before irrigating

If the root zone soil moisture was filled to capacity at the last previous irrigation, the next irrigation event should be initiated when the following equation is satisfied:

$$\sum_{t=0}^{T_I} ET_C(t) = allowable\ depletion$$

That is, the ideal irrigation interval would be the number of days it takes for cumulative crop water use to reach the allowable depletion level. As a first approximation, this can be expected to occur *Ti* days after the last irrigation event. Once the soil water content has reached the critical level and irrigation is called for, the required depth of irrigation can be determined by another mass balance equation for the period of time between irrigations. That equation, after rearranging the terms, would be:

$$Gross\ IR_{T_i} = \frac{\sum_{T_i} ET_C - R_{Eff}}{E_{appl}}$$

Note that the subscript *S* used in the earlier equation to represent full season totals has been replaced by the subscript T_i, which represents the interval since the last irrigation. The term for seasonal change in soil moisture that appeared in the earlier equation is not considered here because it would only be relevant for a partial irrigation at the end of the season. (The refill level is also not shown as it is assumed that the amount to be applied will replace the cumulative depletion since the last irrigation.)

When an irrigation event takes place, the water balance calculation is updated to account for that portion of the gross applied water that is stored in the root zone (the net applied water). When estimating ideal water use, the net applied water would correspond to the allowable depletion. Where actual water use is being analyzed, the net applied water would be the measured gross application multiplied by an estimate of application efficiency (see below).

Determination of Parameter Values

Measurements and algorithms used to estimate the various terms in the above equations are discussed in greater detail below.

Allowable Depletion: The allowable depletion was calculated from the available capacity (AC) of the primary soil type in the given field, the effective root zone depth (RZ_{Eff}) of the crop, and the management allowed depletion (MAD). AC was determined from the NRCS Soil Surveys for the

fields in question. The maximum effective root zone and MAD values for the various crops were based on standard NRCS recommendations (National Engineering Handbook).

The analysis also accounted for root development during the first weeks of the season, starting at germination (6 inches) and increasing linearly at about the same rate as the canopy development, reaching the maximum effective root zone at the same time as the canopy reaches effective full cover. The analysis, therefore, calculated the root zone on a daily basis by linear interpolation between the minimum and maximum over the same period of time as required for full canopy development.

Note that recommended values of MAD for some crops vary with stage of crop development. The analysis, therefore, used variable values of MAD.

Application Efficiency (E_{appl}): Application efficiency accounts for losses, including spray losses, deep percolation from uneven application of water, and runoff (much of which will redistribute to become percolation losses). Since these losses may amount to 10% to 40% of applied water, an accurate estimate of application efficiency is a key element of this analysis. But application efficiencies cannot be known *a priori*. Though commonly assumed to be constant for a given irrigation system type, the reality is that application efficiencies vary from one field to another and from day to day depending on weather, soil type, crop development, and management practices. Published, standard estimates of application efficiencies presume ideal management. In the case of center pivots (the only system type involved in this analysis) a reasonable estimate of attainable irrigation efficiency would be 90%, and that figure was used to calculate net applied water for purposes of estimating ideal water use. Since modern pivot design and management generally minimizes distribution losses, the 10% losses would be primarily spray losses (wind drift and evaporation from droplets) and increased evaporation from the frequently wet surface.

For other-than-ideal management, which this analysis is particularly concerned with, actual application efficiencies must be estimated for each of the individual irrigation events actually observed. In those cases where significant excess water is applied, there may be significant deep percolation losses as well. The procedures for estimating the soil water balance following an irrigation event were then:

- Assume that net applied water would be 90% of the gross application, and that amount would be added to the soil water balance. That is:

  $$Net\ Irrigation\ Application = (Gross\ Applied\ Water) \times 0.90$$

- In cases where the net applied water would over-fill the soil profile (after allowing for ET during drainage, as noted earlier), any excess water was presumed lost to deep percolation.

Effective Rainfall (R_{Eff}): Effective rainfall was based on measured rainfall at the Agrimet station closest to the field. All rainfall measured during the irrigation season was assumed to be effective for the following reasons:

- In the arid regions east of the Cascades, most rainfall events during the irrigation season are about the same order of magnitude as typical daily ET (up to about 0.30 inches). Most of that water will evaporate (and offset crop transpiration), infiltrate the soil and/or be captured in place by surface retention storage.
- For the few irrigation events that exceed 0.30 inches the disposition of rainfall becomes quite complex; some will infiltrate the soil, some will be captured as surface storage, and most of the balance will be redistributed and form ponds around the field. Much of the ponded water will eventually be recaptured as infiltration or evaporation from the surface. There is no practical algorithm for estimating the effective fraction of rain from such complex processes on a daily time basis.
- Errors due to the assumption that all rainfall was effective will be cancelled out to some extent because we are comparing pairs of fields, for both of which the same assumption was applied.

Crop Evapotranspiration (ETc): Daily crop water use was derived from the Agrimet system using data from the station nearest each farm (either George, Washington, or Hermiston, Oregon). Note that posted Agrimet estimates of water use for individual crops was ***not*** used for this purpose; those estimates are based on assumed planting dates and anticipated crop development rates. Instead the ETc estimates used in this study were derived from Agrimet estimates of reference ET, multiplied by a crop coefficient curve that was adjusted to account for observed planting dates of individual fields.

The most scientifically rigorous way to derive crop coefficients would begin with published 'basal' coefficients, defined as the coefficients for vigorously growing crops with dry surface and ample available water in the root zone. These coefficients would then be adjusted to account for wet surface conditions or dry soil profile conditions. However, published Agrimet crop coefficients already incorporate an adjustment for high frequency irrigation such as would occur under center pivot irrigation. Consequently, the Agrimet coefficients were used in this analysis.

The Water Balance Model

The analyses were done using an MS Excel spreadsheet model. The computational sequence for determining ideal water use was as follows:

1. Initialize daily spreadsheet starting with measured soil moisture from neutron probe readings at the beginning of the season. (Where the antecedent moisture measurements indicated a full soil profile, which was true in most cases, we started the water balances with full

available water and then started calculation of soil water depletion from that level).

2. Locate crop planting date and calculate root depth going forward from planting date with linear growth until maturity date (the date of effective full canopy cover); then continue with maximum root depth through the balance of the season.
3. Set up MAD as related to crop growth throughout the season, and determine the allowable depletion (the product of MAD and available capacity, adjusted daily for the current effective root zone).
4. Determine the minimum allowable soil moisture (the total available capacity minus the allowable depletion) for each day in the season.
5. List daily inputs and outputs (precipitation, ET, and irrigation) for the season.
6. Calculate actual available soil moisture as the initial value less depletion [where depletion is cumulative ETc less precipitation] for each day in the season.
7. For each day, compare soil moisture in the current root zone to the minimum allowable soil moisture for that date. If the current soil moisture falls below the minimum allowable level, estimate the required net irrigation depth to bring the soil moisture back to the refill level, and calculate the corresponding gross water applied requirement.
8. Determine the system delivery capacity of the given center pivot system (the daily maximum application depth). If the gross water requirement exceeds the daily system capacity, set the gross water requirement equal to system capacity.
9. Multiply the gross water requirement by application efficiency to determine the daily net irrigation depth. Add the net irrigation to the soil water balance and continue with the ongoing daily calculation of actual available soil moisture (return to step 6).

Actual water use data were entered on the same spreadsheets used for analysis of the ideal cases, and the procedure outlined above was followed, with the following exceptions:

- In Step 9, the actual gross irrigation depth was entered; in some cases this may have been less than the system capacity.
- After Step 10, the soil water balance was checked to see if it exceeded field capacity; and if so, then the soil water content was reduced to available capacity and the difference added to cumulative deep percolation

The actual and ideal irrigation regimes were then compared for each field in the study to see how well the actual and ideal water use schedules matched over the season.

Summary of Results

The methodology for calculating water savings due to scientific irrigation scheduling is based on a comparison of difference between *Actual Water Use* (AW), based on field measurements and irrigation requirements, and *Ideal Water Use* (IW) across the two groups, that is:

$$Water\ Savings = -(AW_{Treatment} - IW_{Treatment}) - (AW_{Control} - IW_{Control})$$

The above formulation thus would yield "net" water savings that are likely to result from scientific irrigation scheduling. The results of the in-field measurements of actual and ideal water use levels derived from water balance models in inches the treatment and control groups are summarized in Table V.1. The start and end dates of the measurement period for each field is also shown in Table V.1. As can be seen, measurement periods are not always the same for same crops in different fields. This is mainly due to the fact that measurement did not always begin at planting for same crops in different fields. However, in all cases periods for actual and ideal water use determinations correspond exactly.

Table V.1: Summary of Ideal and Actual Irrigation Water Use – Treatment and Control Group

Site	Crop	Start	End	Ideal	Actual	Variance
Treatment Group						
4	Mint	4/10/2004	10/17/2004	37.79	39.19	4%
5	Wheat	4/9/2004	7/27/2004	28.92	24.45	-15%
8	Potatoes	4/9/2004	10/18/2004	35.84	40.54	13%
12	Alfalfa	6/4/2004	9/24/2004	31.41	30.72	-2%
16	Peas	5/7/2004	6/16/2004	6.53	6.32	-3%
16b	Corn	6/16/2004	10/11/2004	22.05	26.99	22%
17	Potatoes	5/13/2004	10/12/2004	33.36	28.82	-14%
18	Peas	5/7/2004	6/15/2004	6.41	5.16	-19%
18b	Corn	6/18/2004	9/3/2004	15.19	18.07	19%
19	Corn	6/16/2004	10/8/2004	30.80	34.03	10%
20	Corn	5/13/2004	9/10/2004	28.29	34.20	21%
24	Potatoes	4/8/2004	6/10/2004	6.32	5.08	-20%
28	Potatoes	4/30/2004	7/16/2004	13.20	14.41	9%
30	Corn	5/11/2004	9/19/2004	24.03	22.65	-6%
32	Potatoes	5/10/2004	9/11/2004	27.84	31.28	12%
34	Potatoes	5/10/2004	9/22/2004	28.96	26.64	-8%
35	Corn	4/12/2004	7/19/2004	15.37	16.07	5%
38	Corn	4/21/2004	9/1/2004	24.87	23.64	-5%
39	Wheat	4/9/2004	6/23/2004	12.78	10.02	-22%
Total				*430.0*	*438.3*	*1.9%*
Control Group						
1	Alfalfa	5/4/2004	9/12/2004	35.35	59.77	69%
2	Wheat	4/9/2004	6/30/2004	12.81	16.26	27%
3	Potatoes	4/9/2004	7/26/2004	22.72	19.98	-12%
6	Wheat	4/9/2004	6/30/2004	15.11	12.46	-18%
7	Wheat	4/9/2004	6/30/2004	16.19	16.80	4%
9	Peas	4/14/2004	6/1/2004	6.54	6.72	3%
9b	Corn	6/1/2004	8/19/2004	13.45	20.58	53%
10	Potatoes	5/18/2004	9/24/2004	31.51	34.68	10%
11	Alfalfa	4/14/2004	8/30/2004	28.22	36.81	30%
13	Corn	5/16/2004	8/20/2004	22.85	19.20	-16%
14	Corn	7/17/2004	9/6/2004	15.42	12.64	-18%
23	Potatoes	4/6/2004	7/27/2004	21.52	20.88	-3%
25	Wheat	4/14/2004	7/1/2004	12.55	11.04	-12%
27	Potatoes	4/30/2004	7/7/2004	10.60	17.55	66%
29	Corn	5/13/2004	9/10/2004	23.90	22.63	-5%
31	Potatoes	5/10/2004	9/2/2004	26.08	25.48	-2%
36	Corn	4/12/2004	7/18/2004	15.79	18.20	15%
37	Corn	4/14/2004	9/1/2004	25.35	30.60	21%
40	Wheat	4/17/2004	7/9/2004	16.00	12.16	-24%
Total				*372.00*	*414.44*	*11.4%*

It is expected that, in the treatment group, actual water use would correspond with the ideal water requirements more closely than it does in the control group. A comparison of variances between the ideal and actual water use between the two groups show that in both groups actual water use levels depart from the ideal to some extent. Variances are particularly large in the control fields, where the difference in cumulative water application ranges from nearly a positive 79% (over-irrigation) to a negative 24% (under-irrigation). However, this variance tends to be smaller for the treatment group, where cumulative actual water use tends to fall within ±22%. In aggregate, the variance between actual and ideal water is significantly smaller in the treatment group than in the control group.

This result shows that actual water use throughout the season better tracks the ideal water requirements in the treatment group than it does in the control group. It also suggests another benefit of scientific irrigation scheduling that should be noted. Crop yields are reduce by over-irrigation as well as under-irrigation. The greatly reduced variance of the treatment group implies that SIS reduced the degree of both excess and deficit irrigation. Apart from the water and energy savings, it is also probable that crop yields and net farm incomes would have been correspondingly improved.

Examination of cumulative water use in the treatment and control group shows the actual water use exceeded the ideal levels in both groups, but the over-irrigation was much smaller in the treatment group than it was in the control group. The analysis also revealed markedly different patterns in how the actual water use diverges from the ideal over the season. Two general patterns are readily observed among the treatment group:

1. Actual water use tracks the ideal levels closely throughout the season; but tends to fall bellow it for long periods (see Figure V.1).
2. Actual water use periodically diverges from the ideal, but is compensated by the end of the season so that cumulative water use approaches or meets the ideal requirements (see Figure V.2).

The results also show two distinct patterns in the relationship between the actual and ideal irrigation levels in the control group:

1. Actual water use patterns seem to exceed the ideal levels consistently throughout the season (Figure V.3).
2. Cumulative actual and ideal water use are relatively close, actual water use tracks the ideal closely, but tends to exceed it throughout the season (Figure V.4).

Figure V.1: Cumulative Actual and Ideal Irrigation Patterns – Treatment Group

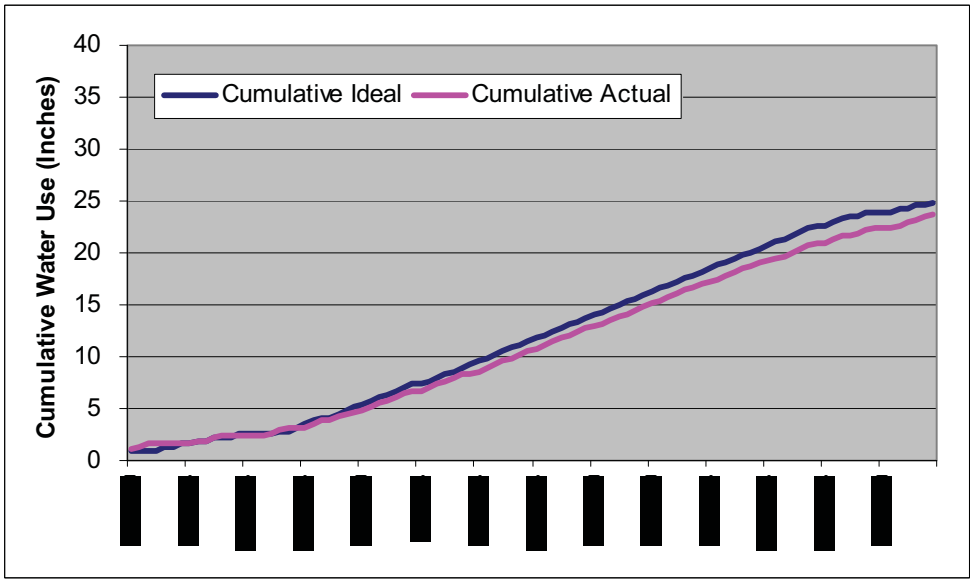


Figure V.2: Cumulative Actual and Ideal Irrigation Pattern – Treatment Group

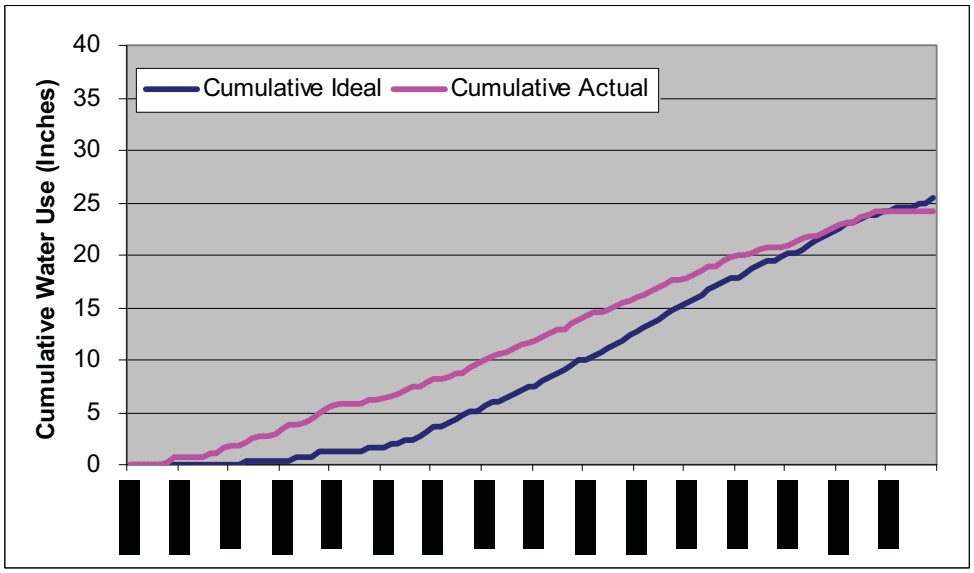


Figure V.3: Cumulative Actual and Ideal Irrigation Pattern – Control Group

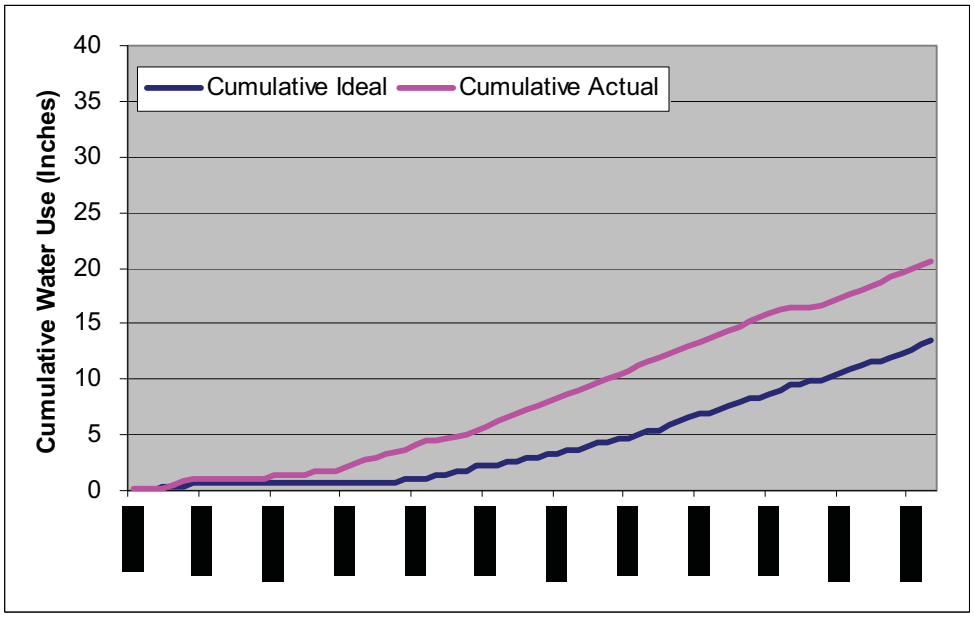
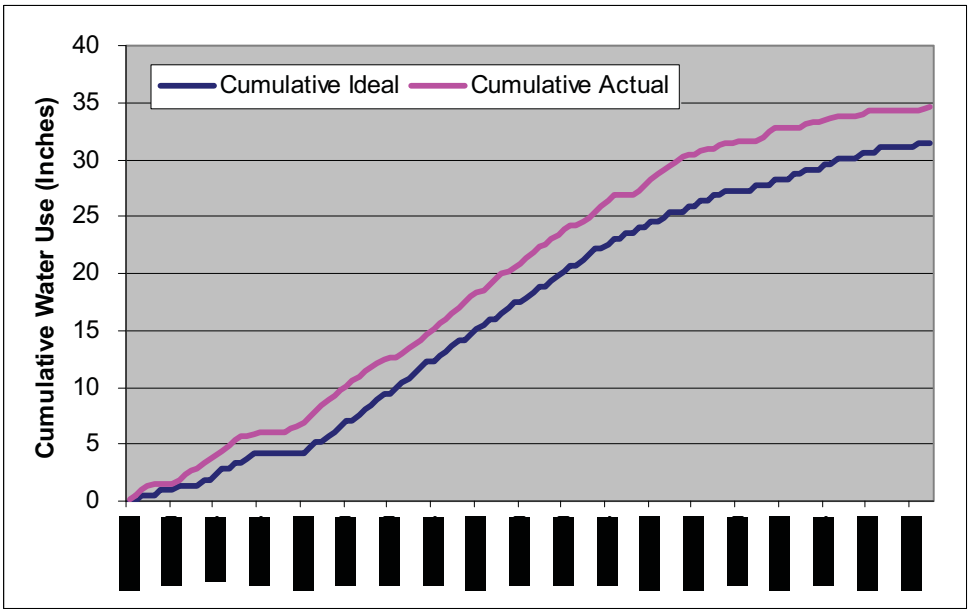


Figure V.4: Cumulative Actual and Ideal Irrigation Pattern – Control Group



Based on the information presented in the Tables V.1, the treatment and control group, on average, exceeded the ideal water requirements by 1.9% and 11.4%, respectively. Adjusting the average amount of overuse for the control group by that of the treatment group yields a comparative difference of approximately 9.5%. Therefore, given all the assumptions underlying these estimates, the findings suggest that on average, implementation of SIS methods can save up to 9.5% water. This estimate is comparable to the findings from Phase I of this study, which based on survey information collected from growers, the average amount of water savings related to different types of SIS methods ranged between 10% and 12%. For the purpose of estimating potential energy savings related to SIS, an average value of 10% water savings was used.

VI. Calculation of Electricity Savings

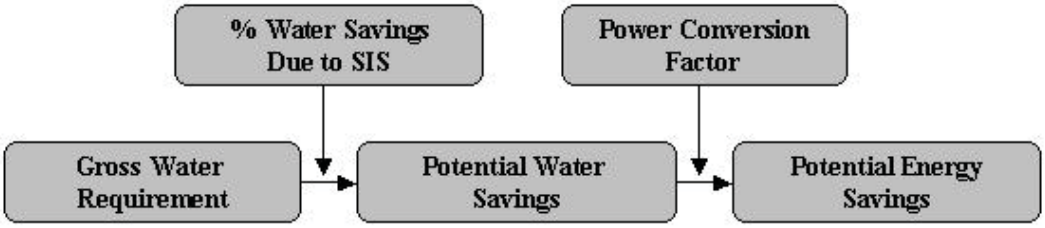
Reductions in water use resulting from the application of SIS method translates into a difference in pumping energy use and therefore a basis for calculation of energy savings. Although every pump/motor system will have varying efficiencies and losses, the water-to-energy use relation is sufficiently generic that it can readily be applied over a range of irrigation system configurations.

The methodology underlying the estimation of the gross water requirements and the corresponding water savings follow the approached described in Section V. Based on the findings from both Phase I and the analysis of data from the sample fields analyzed as part of this study, the average water savings due to implementing SIS methods is approximately 10 percent.

Using this assumption, information pertaining to the location of a farm, type of crop, soil type, type of irrigation system, lift requirements, power and flow ratings, and other system information, Quantec developed a spreadsheet-based calculator to estimate energy savings. The calculator, a description of its layout, assumption, methodology, and outputs are presented in Appendix C.

Figure VI.1 illustrates our general approach. Applying the assumed percentage reduction in water use to the estimate gross water requirements generates an estimate of potential water savings due to SIS. Using a power conversion factor, the potential water savings are then converted into energy savings.

Figure VI.1: Process of Estimating Energy Savings



Specifically, the energy savings were calculated based on the following formula:

$$ElectricitySavings = water\ savings \times \frac{TDH}{PPE} \times PCF$$

where:

- *TDH* = total dynamic head (pumping lift, pressure and head losses)
- *PPE* = pumping plant efficiency
- *PCF* = a factor to convert energy use from units of (force x distance) to kWh

TDH accounts for the change in elevation from the water level at the source to the point of discharge. The change in elevation is typically separated into two parts: the suction lift and the discharge lift. The suction lift refers to the difference in elevation (feet) from the pumping level of the water source (river, well, etc.) to the pump suction. The discharge lift refers to the difference in elevation (feet) from the pump discharge to the highest point in the irrigation system.

$$TDH = suction\ lift + discharge\ lift + friction\ loss$$

Where:

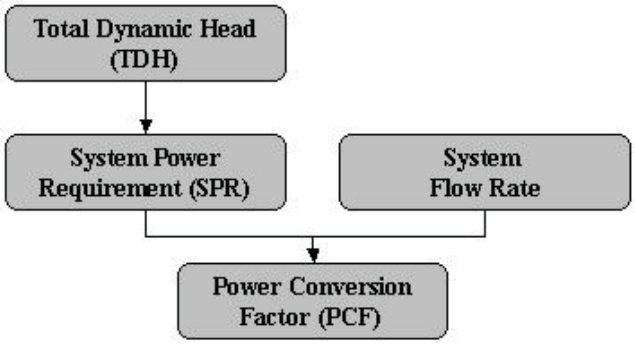
- *Suction lift* = The height in feet from the water source to the ground level
- *Discharge lift* = The height in feet from the ground level to the highest point in the irrigation system
- *Friction loss* = Resistance to water flow expressed as height in feet per foot of pipe

For simplicity, this program does not include piping system friction loss in the TDH calculation. Instead the calculator uses a default value of 10 percent to account for piping system friction loss. If a grower indicates that the estimated friction loss in a particular system exceeds 10 percent, the incremental value in feet could be added to the discharge lift.

The power conversion factor (PCF) is calculated based on an estimate of total system power requirements, based on the total dynamic head (TDH) and system efficiency, and the system flow rate. In order to estimate the energy needs of the irrigation system, the total pumping system horsepower (HP) nameplate needs to be known. Ideally, the actual power draw for each pump would be considered. For the purpose of the SIS calculator, however, the sum of the nameplate HP ratings for all pumps associated with the selected irrigation system is used as an approximation. By imposing this simplifying assumption estimated energy savings likely represent a conservative estimate.

Figure VI.2 illustrates the calculation of the PCF. For a detailed description of how the PCF is calculation including an algebraic formulation, see Appendix C.

Figure VI.2: Calculation of Power Conversion Factor



The specific inputs used to calculate the power conversion factor include:

- Type of irrigation system
- Design capacity
- Pumping system efficiency
- Suction lift & discharge lift
- Maximum required nozzle pressure
- Average cost per kWh

Type of Irrigation System

Information regarding the type of irrigation system is used to approximate the application efficiency that accounts for losses, including spray losses, deep percolation from uneven application of water, and runoff. The percent of application efficiency can vary significantly by crop as well as the actual configuration and operation of the system.

Design Capacity

The system's design capacity or where available, actual flow rate estimates, are used to calculate the PCF

Pumping System Efficiency

In general, the determination of pumping plant efficiency depends on the actual configuration and operation of the system. However, given the lack of system-specific estimates, the energy savings estimate produced as part of this study assumed an average pumping system efficiency of 65 percent based on information provided by IRZ.

It must be recognized that actual efficiencies may be lower if the pumping rates or the TDH differ significantly in actual operations from the assumed

values. To the extent that pumping systems are operating below their nominal efficiencies, the energy savings from reduced water use would be greater. Determination of actual pumping system efficiencies, however, requires much more involved data collection and analysis, which was outside the scope of this project.

Suction Lift & Discharge Lift

The calculation of TDH requires the estimation of the total change in elevation, typically separated into suction lift and discharge lift. The suction lifts vary depending on the water source and were based on information provided by the grower.

Maximum Required Discharge Pressure

In addition to the information on elevation, the calculation of TDH requires the maximum required discharge pressure.

Average Cost per kWh

In order to calculate estimated energy savings, the avoided cost per kWh needs to be specified. As a default, the calculator uses $0.028 per kWh based on data provided by the Bonneville in March 2005. This value may need to be updated in the future.

Summary of Results

Applying the methodology described above, Quantec estimated energy savings for all fields using the SIS calculator. As mentioned previously, while most of the data underlying the energy savings estimate are specific to a particular site, the following simplifying assumptions were made:

- The average water savings due to implementing SIS are approximately 10%.
- Friction loss is included by means of a flat 10% adjustment of the TDH.
- Overall pumping plant efficiency is assumed to be 65% based on IRZ estimates.
- Total power requirement only incorporates total estimated pumping system needs and ignores the power needs associated to auxiliary pumps and motors.

Given the above assumptions and the data collected as part of this study, the energy savings were estimated for each site.

Table VI.2: Estimated Energy Savings

Site	Crop	Total Pumping Lift (ft)	Flow Rate (gpm)	Ideal (kWh)	Actual (kWh)	Difference
Treatment Group						
4	Mint	878	875	6,924	7,181	3.71%
5	Wheat	798	985	4,883	4,127	-15.49%
8	Potatoes	824	971	7,654	8,657	13.10%
12	Alfalfa	1,096	421	6,990	6,837	-2.18%
16	Peas	695	1,115	982	949	-3.32%
16b	Corn	695	1,115	3,534	4,326	22.43%
17	Potatoes	1,262	817	10,366	8,956	-13.60%
18	Peas	876	800	1,173	945	-19.46%
18b	Corn	876	800	2,778	3,305	18.98%
19	Corn	714	1,077	5,049	5,578	10.48%
20	Corn	657	832	4,327	5,232	20.91%
24	Potatoes	176	639	382	307	-19.58%
28	Potatoes	14	962	447	487	9.16%
30	Corn	14	694	704	664	-5.72%
32	Potatoes	1,012	915	7,106	7,986	12.39%
34	Potatoes	1,012	868	7,391	6,801	-7.99%
35	Corn	14	781	450	471	4.61%
38	Corn	14	781	729	693	-4.95%
39	Wheat	14	733	374	294	-21.57%
Total / Average				***72,242***	***73,796***	***2.2%***
Control Group						
1	Alfalfa	1,241	352	8,790	14,863	69.09%
2	Wheat	1,254	388	3,430	4,353	26.90%
3	Potatoes	1,242	384	6,205	5,457	-12.06%
6	Wheat	635	745	2,247	1,853	-17.56%
7	Wheat	643	1,118	2,433	2,524	3.72%
9	Peas	824	1,087	1,135	1,165	2.66%
9b	Corn	824	1,087	2,334	3,571	53.04%
10	Potatoes	891	1,121	6,764	7,445	10.07%
11	Alfalfa	561	1,084	3,558	4,641	30.45%
13	Corn	714	1,410	3,512	2,950	-16.01%
14	Corn	679	1,006	2,272	1,862	-18.04%
23	Potatoes	95	839	906	879	-2.98%
25	Wheat	14	311	345	303	-12.02%
27	Potatoes	201	999	798	1,321	65.58%
29	Corn	132	910	1,434	1,358	-5.33%
31	Potatoes	14	550	882	862	-2.32%
36	Corn	14	1,149	463	534	15.29%
37	Corn	14	952	743	897	20.70%
40	Wheat	900	809	3,195	2,429	-23.98%
Total / Average				***51,446***	***59,267***	***15.2%***

The results show that reductions in water use resulting from the application of SIS in the study samples resulted in net electricity savings of 13.1%. The findings furthermore appear to reflect the fact that, all other things held constant, energy savings are positively related to the total lift required to move the water from the water source to the field.

Appendix A.
Summary of Existing Research

Over the past decade, interest in quantifying the potential water and energy savings related to scientific irrigation scheduling has increased. In an effort to document and project such savings, numerous studies have been conducted. Following is a summary of studies that were based on data from growers within the Columbia River Basin.

Evaluation of the Grant County Irrigation Scheduling Project – 1993 Growing Season and Final Report
By Pacific Northwest Laboratories, March 1994
Letter Report Prepared for the Bonneville Power Administration

The purpose of the study was to evaluate the conservation agreement proposed by Grant County PUD (utility) to the Bonneville Power Administration in 1993. Based on 1991 growing season data, the utility contended that implementation of its proposed irrigation plan could generate 206 kWh/acre of energy savings and water savings of 0.3 to 0.5 acre-feet per irrigated acre at the irrigation site. The resulting savings in distribution energy were estimated at 420 kWh/acre-ft of saved water. Lastly, running the saved water through dams was estimated to generate 450 kWh/acre-ft of electricity.

To estimate the on and off-site energy and water savings, the timing of the savings, and the potential demand reductions, Bonneville commissioned the Pacific Northwest Laboratory (PNL) to review the utility's proposal. PNL's results indicated that the utility's proposed scheduling program is likely to generate 11.2 inches in water savings plus or minus 2.3 inches. Compared with the averaged unscheduled water use for the same sample, this represents 29.7%. For winter wheat, the crop with the highest savings potential, the expected savings were estimated to be 39.3%. The lowest savings were identified for grain corn at 13.7%.

1986 Irrigation Scheduling Program
By Agrimanagement, August 1987
Report to the Bonneville Power Administration

The report summarizes the findings from a test study that implemented irrigation scheduling in a selected number of fields in the Yakima Valley between 1985 and 1986. In general, the findings indicate that electricity and water savings greatly depended on the crop and irrigation system used. The study found that crops such as corn and alfalfa typically showed signs of under irrigation while crops such as mint showed great potentials for savings through irrigation scheduling.

More specifically, the findings suggest that the potential electricity savings due to implementing irrigation scheduling are approximately 7%. The report further states that, in the long run, the average electricity savings could increase to 25%. This range translates into potential irrigation savings of 4 inches to 12 inches per acre or 92 kWh to 275 kWh per acre per year. The study further found that growers with greater than average lift would likely see considerably larger energy savings.

While the potential energy cost savings resulting from implementing irrigation scheduling were found to be substantial, the cost savings related to saving water through irrigations scheduling was found to be limited. However, this finding is primarily based on the fact that the irrigators in the sample typically paid a flat fee for a set amount of water. The potential cost savings would presumably be larger if a grower's water bill were tied more closely to actual water consumption.

1987 Irrigation Scheduling Program
By Agrimanagement, February 1988
Report to the Bonneville Power Administration

The report is a follow-up report on Agrimanagement's 1987 report regarding the implementation of irrigation scheduling in the Yakima Valley. The findings of the report mirror some of the findings from the 1987 report including: savings potentials due to irrigation scheduling vary widely and depend on the crop, the electricity savings are higher for growers using pumps with higher lifts, and the amount of irrigation for some crops (e.g., corn and alfalfa) may increase due to irrigation scheduling.

Other findings included that many of the participants of initial Bonneville-sponsored test program had indicated that they would continue using irrigation scheduling even after conclusion of the program. The authors argue that one likely reason contributing to this high response maybe the fact that, after 1986, the availability and quality of site- and crop-specific weather and irrigation greatly improved.

Pasco Aquifer Technical Documentation: Methodology of Crop Use and Ground Surface Application 1986 Growing Season

Using sample data for randomly selected fields located within the Pasco Aquifer in Franklin County, Washington, the study develop crop water use curves by crop and location based on evaporation data. The projected crop water use was then compared to the actual water applications. The potential water savings varied greatly by crop, ranging from an estimated 41.94% for sweet corn, 18.42% for alfalfa, to only 1.04% for spring grass. On average, the findings indicate that implementation of irrigation scheduling is likely to save 4 inches of water or 12.9%.

2002 GWMA IWM – Case Example – Franklin PUD, GWMA, and Franklin CD
By Ground Water Management Associates (GWMA), 2002

Using potatoes as a sample crop, Ground Water Management Area (GWMA) in association with Franklin Public Utility District, and Franklin Conservation District estimated potential water savings due to implementing irrigation scheduling. The results indicate that an average of 15.7% water savings could be generated

Year 2001 Final Report: Scientific Irrigation Scheduling, Grower Training and Electrical Energy Conservation
By Royal Consulting Service, January 2002
Submitted to Franklin Conservation District

Royal Consulting Service conducted a three-year study assessing the potential water savings by crop for a sample of fields in Franklin County, Washington. The study analyzed data for the 2001 through 2003 growing seasons. While the individual savings by crop varied widely by year and presumably weather, the average water savings for all crops due to implementing scientific irrigation scheduling for 2001, 2002, and 2003 were 9.4%, 14.0%, and 13.2%, respectively.

Case Study: Grant PUD
By Royal Consulting Services

Based on data collected for a sample of farms in Grant Public Utility District's service area, Royal Consulting Services developed estimates for water savings and related energy cost savings. The study developed water and energy savings estimates for the years 1997 through 1999. Each year's estimate in turn was based on three years of historical data from the preceding years. Comparison of the crop water use to the actual applied irrigation water suggested, that the weighted average savings from implementing scheduled irrigation were 18.1%. Assuming marginal cost of electricity of 3 cents for 1997 and 1998 and 4 cents for 1999, the average cost savings per field were estimated to be $2,058.

Consumptive Use Data by Crop and Year 1994 –2003
By Professional AG Services

Using historical data of actual applied irrigation inches by crop and estimated crop water use, this study estimates the average potential water savings due to scientific irrigation scheduling. The study is based on historical irrigation data for 1994 through 2003 for nearly 4,500 fields. Comparing the average applied irrigation water in inches to the estimated crop water use yields potential average savings of 17.7% for all crops. Specifically, the highest potential savings are expected from onions (34.6%), wheat (34.5%), and alfalfa

(27.8%). Early and late potatoes (12.3% and 13.6%) were identified as providing the lowest potential for water savings due to implementing irrigation scheduling.

Scientific Irrigation Scheduling – The Right Amount of Water at the Right Time
By Washington State University, 2004 (website[5])

As study of 15 growers in the Pacific Northwest sponsored by the Northwest Energy Efficiency Alliance during the years of 1992 through 2004showed that proper upkeep of irrigation systems and implementation of scientific irrigation scheduling could generate an average energy cost savings of 15.8%.

Summary of GWAMA/NRCS IWM Program
By GWMA, 2004

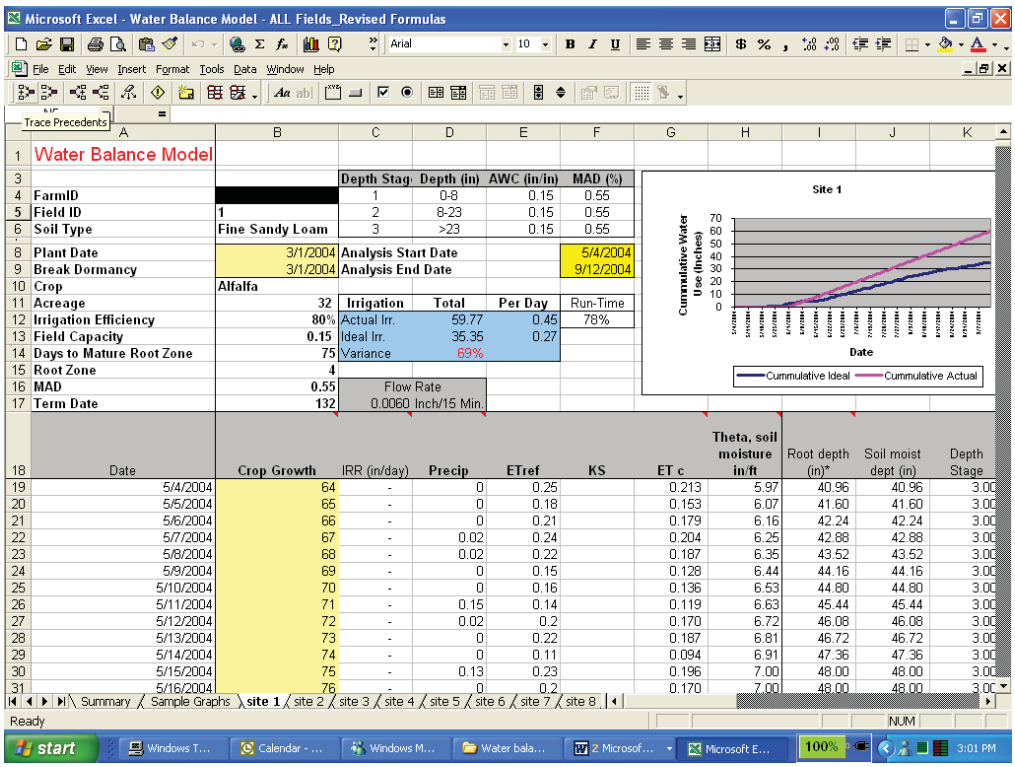
Between 2000 and 2004, GWMA collected data on implementing irrigation watering management (IWM) for Adams, Grant, and Franklin Counties in the state of Washington. Based on data collected from 1,088 fields, the average savings applied to implementing IWM was found to be 16.7%.

[5] http://sis.prosser.wsu.edu/brochure.htm

Appendix B. Water Balance Model

The water balance model was specifically designed to calculate and compare actual and ideal irrigation levels. The model is an MS Excel-based spreadsheet with electronic links to raw daily actual water use and calculates ideal irrigation requirements based on the algorithms defined in Section V of this report. A sample screen shot of a hypothetical field is shown in Figure B.1. A summary of data requirements and analytic procedures are summarized below.

Figure B.1: Sample Water Balance Model



Data Inputs

The model calculates ideal water use for each farm based on the well-documented *checkbook method.* Data needed for the checkbook method include:

1. *Precipitation*. Daily weather data downloaded from Agrimet was the primary source of the precipitation data.
2. *Actual irrigation*. The amount of irrigation is calculated based on the amount of time the system was actually running (the 'on' time) as recorded in 15 minute intervals, multiplied by the system discharge

rates as determined by operating pressures and calibrated with ultrasonic flow meters (see Data Development in Part IV of the main report)

3. *Crop Evapotranspiration* (ETc). Estimates of reference ET[6] were downloaded from Agrimet. The reference ET values were multiplied by Agrimet crop coefficients adjusted for field-specific planting and harvest dates.
4. *Available Water Capacity* (AWC). The AWC refers to the difference between field capacity and wilting point. It represents the amount of water per unit depth of soil that is available for crop water uptake. These data were based on Natural Resource Conservation Service (NRCS) soil surveys.
5. *Plant date*. These refer to the specific planting and harvest dates for each field. Crop water use (Et_c) calculations are based on these dates by adjusting the crop coefficients to conform to these dates. Soil water depletion is assumed to begin on the planting date.
6. *Effective root zone*. Rooting depth varies by crop and throughout the season. The rooting depth is assumed to start at about six inches and increases linearly until full canopy development. However the soil water uptake from the deeper root zone is usually relatively small compared to the upper root zone. The uneven update pattern is accounted for by assuming an *effective root zone*, a fraction of the rooting depth (usually about 60%) from which the crop can be assumed to draw essentially all water it consumes.
7. *Total available water capacity.* The amount of water in the *effective root zone* that is available for crop water uptake; it is the product of the AWC and the depth of the effective root zone.
8. *Maximum Allowable Depletion* (MAD). The percentage of total available capacity that the crop can use before it begins to suffer water stress. MAD varies by crop type and growth state.

Procedure

The essential procedure is to set up a spreadsheet that calculates soil water contents on a daily basis. The soil water content is initialized using neutron probe readings at the start of the season. Almost all of the initial soil water content readings indicated soil moisture levels greater than the nominal values of total available capacity. Since the soil can be assumed to drain to field capacity within a couple of days the model assumed a full soil water profile at the beginning of the season; that is, the spreadsheets for each field were

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[6] Calculated using the Kimberley-Penman method, which has been calibrated for this region.

generally initialized by the maximum total available capacity. Soil moisture was then calculated on a daily basis by subtracting daily values of Etc and adding rainfall and irrigation applications. The daily step-by-step procedure follows:

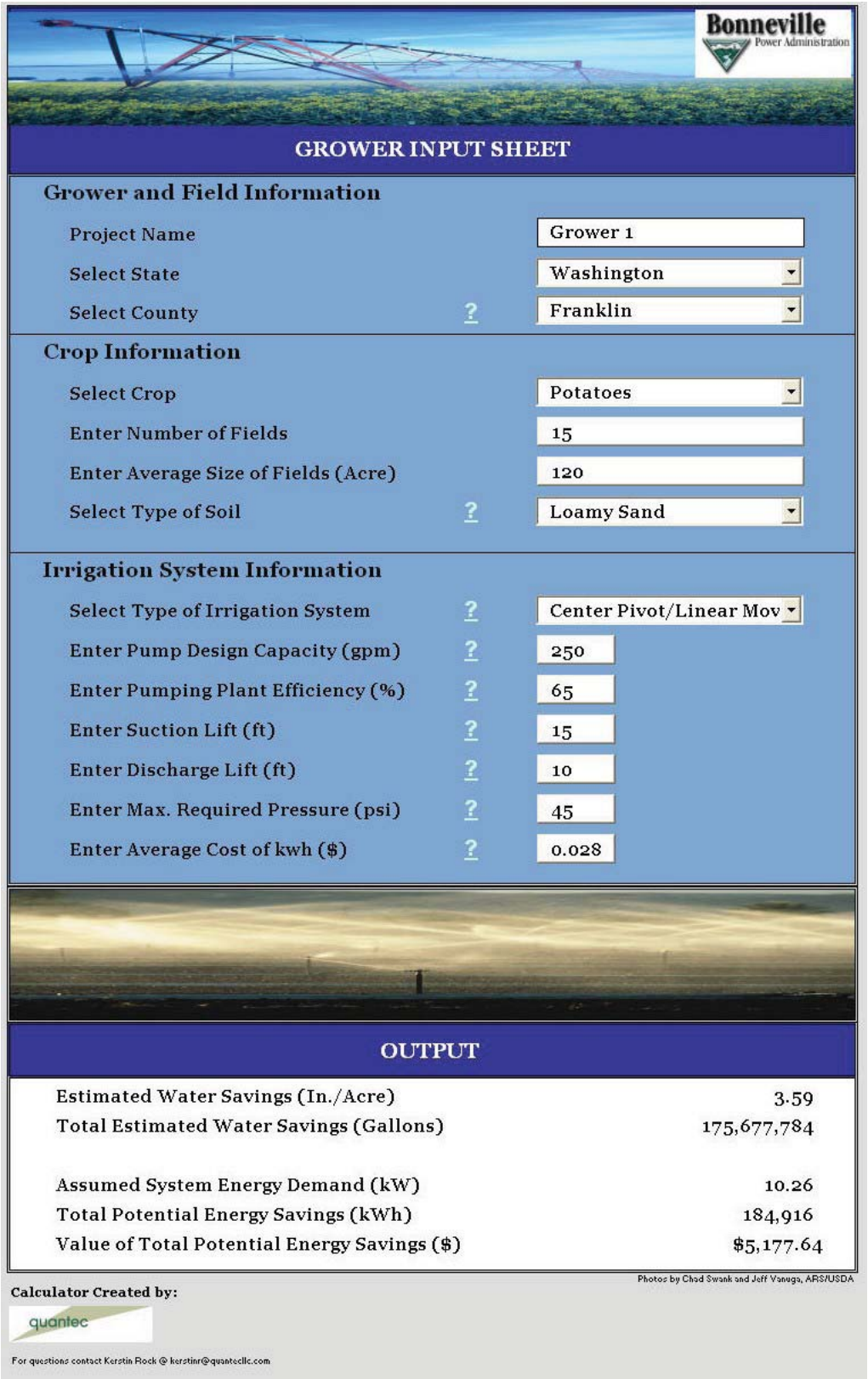
1. Determine field-specific planting date for each case
2. Set up effective root zone going forward from the planting date with linear growth until full canopy development, then remaining constant at that maximum effective root zone
3. Calculate the total available capacity for each date based on the AWC and the effective root zone for that date
4. Choose the MAD for the crop for different stages of growth
5. Calculate the allowable depletion for each date based on the total available capacity on the given date and the MAD for that part of the season
6. Set the minimum allowable soil water content for each data by subtracting the allowable depletion from the total available capacity
7. Initialize the soil water content in the effective root zone (both the current day root zone and the maximum effective root zone) based on the initial neutron probe reading for each case
8. List daily values of the reference ET and crop coefficient, and compute the daily Et_c values
9. Compute daily values of soil water content by subtracting Etc and adding any irrigation applications for that date (as explained below) and daily rainfall values
10. Compare the calculated actual available water in the active root zone and the minimum allowable soil water content (Step 6 above)
11. When actual water content falls below the minimum allowable level calculate the net irrigation requirement for that date by subtracting actual available water from total available capacity
12. Calculate the gross irrigation requirement for that date by dividing the net requirement by an assumed application efficiency (expressed as a decimal fraction)
13. Update the estimated soil water content by adding the net applied water to the preceding day's soil water content
14. If the resulting soil water content exceeds the total available capacity (indicating that soil moisture is above filed capacity) the excess is assumed to be lost as deep percolation. The soil water content is then reset at the total available capacity

Using this step-by-step procedure, the model calculates a daily history of soil water content and season totals of gross applied water and deep percolation.

Appendix C. Description of Savings Calculator

In order to develop a simplistic tool to estimate potential energy savings from implementing scientific irrigation scheduling (SIS) by farmers, Quantec developed a spreadsheet based calculator, which is described in this appendix Figure C.1 presents a screen shot of the SIS calculator.

Figure C.1: SIS Calculator



Bonneville Power Administration

GROWER INPUT SHEET

Grower and Field Information

Project Name		Grower 1
Select State		Washington
Select County	?	Franklin

Crop Information

Select Crop		Potatoes
Enter Number of Fields		15
Enter Average Size of Fields (Acre)		120
Select Type of Soil	?	Loamy Sand

Irrigation System Information

Select Type of Irrigation System	?	Center Pivot/Linear Mov
Enter Pump Design Capacity (gpm)	?	250
Enter Pumping Plant Efficiency (%)	?	65
Enter Suction Lift (ft)	?	15
Enter Discharge Lift (ft)	?	10
Enter Max. Required Pressure (psi)	?	45
Enter Average Cost of kwh ($)	?	0.028

OUTPUT

Estimated Water Savings (In./Acre)	3.59
Total Estimated Water Savings (Gallons)	175,677,784
Assumed System Energy Demand (kW)	10.26
Total Potential Energy Savings (kWh)	184,916
Value of Total Potential Energy Savings ($)	$5,177.64

Photos by Chad Swank and Jeff Vanuga, ARS/USDA

Calculator Created by:

quantec

For questions contact Kerstin Rock @ kerstinr@quantecllc.com

Given the variations in climate, soil characteristics, crops, irrigation, and pumping systems, precise estimates of potential energy savings require a detailed analysis for each particular farm. The SIS calculator is not intended as a replacement for such an analysis but rather as a tool to calculate a rough estimate of potential water and energy savings due to implementing SIS for a particular farmer.

Due to the scope of this project, the SIS calculator is limited to three states (Washington, Oregon, and Idaho), 7 crops, 13 soil types, and 7 irrigation system types.

Layout

At the most basic level, the calculator is divided into two sections, an input section and an output section. The input section is divided into three subsections: grower and field information, crop information, and system information. The output section does not contain any subsections. Following is a brief description of each required data input field by section.

Grower Input Sheet

Grower and Field Information

- *Grower*. This is simply a data entry field for the grower's name or other applicable identification.
- *State*. The user can select one of three states: Idaho, Oregon, and Washington. The state selection is used to populate the *County* drop down menu with the appropriate choices.
- *County*. Depending on the selected State, the user can select the appropriate county. Using climactic and other agricultural data, each state was divided into multiple zones corresponding to agricultural areas rather than specific climate zones[7]. Each zone was then overlaid with county maps to correlate each county to one or more zones. In cases where a county is split between multiple zones, the County drop-down options will present multiple choices for that county (e.g., Grant North, Grant South). The selection of the County drives the identification of the agricultural zone, the associated Agrimet station, and therefore the crop and weather data used in the calculations. The zones by state along with the corresponding Agrimet station selected are presented in Table C.1.

[7] Data developed by Marshall English, OSU Department of Bioengineering.

Table C.1: Agricultural Zones

	Zone Name	Agrimet Station
Idaho	Panhandle	Moscow
	Magic Valley	Nampa
	South Central	Fairfield
	Twin Falls	Twin Falls
	Teton	Fort Hall
	Southeast	Challis
Oregon	Willamette	Corvallis
	Medford	Medford
	Hood River	Hood River
	Central Oregon	Madras
	Kalamath	Kalamath Falls
	Burns	Christmas Valley
	Hermiston	Hermiston/HERO
	La Grande	Imbler
	Baker	Baker
	Malheur	Ontario
	Jordan	Ontario
Washington	Puget Sound	Willamette
	Southwest	Willamette
	Omak	Manson/Omak
	Ellensburg	Harrah
	Moses Lake	George
	Ritzville	Odessa
	Yakima	Harrah
	Horse Hev'n	HERO/Bickleton
	Walla Walla	Lind

Crop Information

This section of the grower input sheet contains three input fields: crop, acres irrigated, and soil type. See Figure C-1 for a picture of this section.

Crop. The crop selection forms the key variable in the calculation of gross water requirement. The crops available for selection include:

- Alfalfa
- Orchard
- Pasture
- Spring Wheat
- Winter Wheat
- Field Corn
- Potatoes

Number of Fields. The grower is asked to input the number of fields that are irrigated and to be considered in calculation.

Average Size of Fields. The grower is asked to enter the average size field in acres.

Soil Type. The exact soil types and therefore the soil moisture characteristics are specific to a particular field and often vary even within that field. The ISI calculator uses a simplified range of 13 typical soil types:

- Sand
- Loamy sand
- Fine sandy loam
- Loam
- Silt loam
- Sandy clay
- Clay
- Fine sand
- Sandy loam
- Very fine sandy loam
- Sandy clay loam
- Clay loam
- Silty clay

System Information

Type of Irrigation System. While the types and configuration of irrigation systems are varied and unique to each grower, the SIS calculator provides the user with a list of up to seven irrigation systems, depending on the crop selected previously. Each type of irrigation system has a specific application efficiency associated with each crop. This analysis is designed to only deal with one type of irrigation system at a time. In cases where different types of irrigation systems are involved, a separate analysis needs to be run for each system. The irrigation systems available for selection include:

- Center pivot/linear move
- Solid set
- Furrows/rills/corrugations
- Drip/micro
- Traveling big gun
- Wheel line/hand lines
- Other surface methods

Pump Design Capacity (gpm). The grower is asked to provide information regarding the system's design capacity or flow rate in gallons per minute (gpm) for the selected irrigation system type.

Pumping Plant Efficiency (%). The grower is asked to provide an estimate of the overall efficiency of the pumping system, not just that of a specific pump. This should be a combined value for all of the pumps accounted for in the determination of the Total Pump Rating. Again, an accurate estimate of potential water and energy savings would require a detailed analysis of each

pump and their respective efficiencies. For estimating purposes, this calculator uses an approximation of the overall pumping system efficiency.

Suction Lift (ft). To estimate the system's total energy needs, its Total Dynamic Head (TDH) needs to be calculated. TDH accounts for the change in elevation from the water level at the source to the point of discharge. The change in elevation is typically separated into two parts: the suction lift and the discharge lift. The suction lift refers to the difference in elevation (feet) from the pumping level of the water source (river, well, etc.) to the pump suction.

Discharge Lift (Pump to Nozzle) (ft). The discharge lift refers to the difference in elevation (feet) from the pump discharge to the highest point in the irrigation system. For simplicity, this program does not include piping system friction loss in the TDH calculation. Instead the calculator uses a default value of 10 percent to account for piping system friction loss. If a grower indicates that the estimated friction loss in a particular system exceeds 10 percent, the incremental value in feet could be added to the discharge lift.

Max. Required Discharge Pressure (psi). In addition to the change in elevation, the calculation of TDH requires the maximum discharge pressure required in the system. The grower is asked to provide this information in pounds per square inch (psi), which the calculator converts into feet.

Average cost per kWh ($). To calculate the estimated energy savings, the cost per kWh needs to be specified. As a default, the calculator uses $0.028 per kWh based on data provided by the Bonneville Power Administration in March of 2005. This value may need to be updated in the future. However, the grower can also overwrite this value if more accurate energy costs are available.

Output

Potential Water Savings per Acre (Acre-Inch). The potential water savings per acre is equal to the gross irrigation requirement per acre times a default percentage savings due to SIS. Phases I and II of Quantec's analysis of the potential impact of SIS in the Northwest found that the expected level of savings ranges from 9.5 to 12 percent. The calculator assumes a default value of 10 percent savings due to SIS.

The gross irrigation requirement (IR) accounts for cumulative seasonal evapotranspiration (ET), rainfall (R), attainable application efficiency (EE), and usable antecedent soil moisture (ASM). Specifically, IR is calculated based on the following formula:

$$IR = \frac{ET_{mean} - R - ASM}{EE}$$

where:

- ET_{cum} is the cumulative seasonal ET.
- R is the total precipitation in the months from break of dormancy to the last cutting.
- ASM is the water stored in the profile at the time of planting or end of dormancy. The ASM varies by soil and crop type and is determined by soil moisture measurement at the start of the season.
- EE is the combined application efficiency and conveyance system efficiency, reflecting canal or pipe delivery losses, spray losses and distribution losses; i.e., losses after the point of measurement. The EE depends on the type of irrigation system, the crop type and the soil.

Total Potential Water Savings (Inches). This represents the total estimated potential water savings in inches for the specified irrigation system, which is calculated by multiplying the above potential water savings per acre times the number of acres specified by the grower.

Assumed System Energy Demand (kWh). The estimated irrigation system energy demand in kWh is based on the estimated brake horse power (BHP). The formulae underlying this calculation follow.

Total Potential Energy Savings (kWh). The total potential energy savings are calculated by converting the total potential water savings into energy savings by mean of a power conversion factor (PCF). The formulae underlying this calculation follow.

Value of Total Potential Energy Savings ($). This number is calculated by multiplying the total potential energy savings in kWh by the assumed avoided cost per kWh.

Algebraic Formulation

Following is the algebraic formulation of calculations underlying the SIS calculator. The definitions of the variables follow the formulae.

Calculation of Energy Savings

1. $Sw_c = IR * S$	Calculation of potential water savings by crop per acre (seasonal gross water requirement * assumed reduction in irrigation due to SIS).
2. $Se_c = Sw_c * PCF$	Calculate potential energy savings by crop per acre (potential water savings *

power conversion factor). See below for details on the PCF.

3. $Sw = (Sw_c * A) / 12$ — Calculate total potential water savings and convert to acre-inch.

4. $Se = (Se_c * A)$ — Calculate total potential energy savings in kWh.

5. $\$ = \$e * Se$ — Calculate the total value of energy savings due to SIS in dollars.

Calculation of PCF

a. $TDH = SL + DL + ((DP + FL^{8}) * 2.307)$

Calculate total dynamic head including unit conversion from psi to ft.

b. $BHP = P = (FR * TDH) / (3960 * PE)$

Calculate system brake horse power used as an approximate total system energy requirement (P) in horse power[9].

e. $E_{kW} = P / 1.3413$ — Convert system horsepower requirement into kW.

f. $E_{kWh} = E_{kW} * 24$ — Convert system energy requirement from kW to kWh. (Assumes 24 hour/day operation)

g. $F_{gpm} = FR / A$ — Calculate irrigation flow per acre in gpm (flow rate in gpm / number of acres).

h. $F_{Daily} = (F_{gpm} * 60 * 24) / 27{,}154.25$

Convert irrigation flow from gpm into daily irrigation flows in acre-inch.

i. $PCF = E_{kWh} / (F_{Daily} * A)$ — Calculate power conversion factor.

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8 Given the purpose of this calculator and the significant data requirements related to estimating friction loss for a particular irrigation system (e.g., pipe material, length & diameter of pipe) the calculator assumes a 10% friction loss factor.

9 Technically, total system energy requirement is the sum of the BHP of the pumps and the power requirements of all motors (e.g., pivot motors and booster pumps) throughout the system. For the purpose of this calculator, the motor-related energy demands were ignored.

Definition of Variables

Name	Units	Definition
$……	Dollar ($)	Total value of energy savings
$e……	Dollar per kwh ($/kwh)	Dollar value per kwh (applied to kwh saved from Irrigation Water Management (IWR)
A……..	Number	Number of acres
BHP……..	horse power (HP)	Break horse power needed to stop pump. Used to determine HP estimate of pump
DL……	Feet (ft)	Discharge lift
DP…….	Pounds per square inch (psi)	Design pressure for irrigation system (maximum nozzle pressure)
E_{Kw}……	Kilowatt (Kw)	Total system energy in kilowatts
E_{kWH}…….	Kilowatt-Hour (kWh)	Total system energy in kilowatt-hours
F_{Daily}…….	Acre-Inches (Acin)	Daily Irrigation flow per acre in inches
F_{gpm}……	Gallons per minute (gpm)	Actual irrigation flow per acre in gallons per minute
FL…….	Pounds per square inch (psi)	Friction loss = resistance to water flow in pipes
FR…….	Gallons per minute (gpm)	System flow rate
IR…...……	Acre-Inches (Acin)	Gross seasonal irrigation requirements for a given crop based on ET, antecedent moisture, and system efficiency.
P……	Horse power (HP)	Total system energy requirement
PCF…….	Kilowatt-Hour/Acre-inch (kWh/Ac-in)	Power conversion coefficient
PPE……	Percent (%)	Pumping plant efficiency
S……..	Percent (%)	Percent of water savings due to IWR
Se……..	Kilowatt-Hour (kWh)	Total potential energy savings
Se_c……	Acre (Ac)	Potential energy savings by crop per acre
SL……	Feet (ft)	Suction lift
Sw…….	Acre-feet (Acft) or gallons (gal)	Total potentail water savings in acre-feet or gallons
Sw_c……	Acre-Inches (Acin)	Potential water savings by crop per acre
THD…….	feet (ft)	Total dynamic head of pump

Appendix D. Survey Form

Irrigation Scheduling Practices in the Pacific Northwest Survey

Farm ID (T1-T25 for Treatment, C1-C25 for Control) _____
City _____
County _____
GPS Coordinates _____lat_____long
Total Acreage _____Ac
Irrigated Acreage _____%
Number of Irrigated Fields _____
Soil Type and Texture _____

Crops

Primary Crop _____
Acreage _____Ac
Growth Schedule Stage 1_____Approx. Dates_____
Stage 2_____Approx. Dates_____
Stage 3_____Approx. Dates_____

Secondary Crop _____
Acreage _____Ac
Growth Schedule Stage 1_____Approx. Dates_____
Stage 2_____Approx. Dates_____
Stage 3_____Approx. Dates_____

Tertiary Crop _____
Acreage _____Ac
Growth Schedule Stage 1_____Approx. Dates_____
Stage 2_____Approx. Dates_____
Stage 3_____Approx. Dates_____

Irrigation Methods

1. [CONTROL GROUP] What is the decision to irrigate based upon?

- ❍ Schedule determined in advance (check all that apply)
  - ❍ Based on established routine
  - ❍ Based on published guidelines
  - ❍ Based on scheduled water delivery (not controlled by participant)
  - ❍ Based on system design, as recommended by system supplier
- ❍ Flexible Schedule based on farmer's judgment (check all that apply)
  - ❍ Based on visible check of crop condition (color, turgor, leaf angle)
  - ❍ Based on soil conditions (feel of the soil, visual check of the soil)
- ❍ Estimated ET

❍ Computer models of crop water use based on ET estimates and soil-moisture measurements

❍ Don't know techniques used

2. [TREATMENT GROUP] What is decision to water based upon? (Check all that apply)

❍ Measurements of soil water content or soil water tension

❍ Measurements of plant water status
(For example leaf water potential, canopy temperature, stem diameter)

3. If soil moisture measurements are made, what measurement techniques are used? (Check all that apply)

❍ Neutron Probe ❍ Watermark Sensors

❍ TDR or Capacitance Probes ❍ Gravimetric Sampling

❍ Tensiometers ❍ Gypsum Blocks

❍Don't Know ❍ Other: _____

How often is soil moisture measured? _____

How many locations are sampled in a single field? _____

How many fields are sampled? _____

4. If plant water status is measured, what measurement techniques are used? (Check all that apply)?

❍ Pressure bomb (leaf water potential) ❍ Infrared thermometry

❍ Heat pulse (sap flow) ❍ Stem diameter

❍ Leaf push ❍ Porometer (stomatal conductance)

❍ Other: _____ ❍ Don't Know

5. If estimated reference and crop ET is used, source for data? (Check all that apply)

❍ On-line services (check all that apply)

❍ Agrimet ❍ PAWS ❍ WISE

❍ CIMIS ❍ IRZ Northwest Irrigation Network

❍ Media (newspapers, radio, or TV)

❍ Your own weather stations and software

❍ Other: _____

❍ Don't Know

6. Is aerial photography or aerial infrared monitoring of fields used?

❍ Yes ❍ No ❍ Don't Know

If so, what platform is used? ❍ Aircraft ❍ Ultralight ❍ Satellite ❍ Model Airplane

Do you use these observations for problem detection or deciding when to irrigate?

❍ Problem detection ❍ Irrigation decision ❍ Both

Irrigation Water Source

Ground Water from on-farm wells _____%

Surface water not provided by a water supply organization (ditch, stream, pond, etc.) _____%

Water supplied by an irrigation district or other off-farm provider

Recaptured tail water or return flows _____%

Other: _____ _____%

Pump/Motor Combinations

Pump/Motor Combination #	Manufacturer / Model	# Of Pivots Served	HP Rating	Rated Flow Rate	Total Acres Served	Crop (s)	% Acreage per Crop
1							
2							
3							
4							
5							
6							

Monitored Pumping Systems

System 1:

Pump/Motor Combination # (from above table) _____

Field ID(s) served with this system _____

Crop (s) served with this system _____

Water source _____

Total Acres Irrigated _____Ac

If more than one crop irrigated with this system:

Acres irrigated for Crop 1 _____Ac

Acres irrigated for Crop 2 _____Ac

Acres irrigated for Crop 3 _____Ac

Pumping Lift _____feet

Pressure at the Pump _____ psi

Pump Efficiency Rating _____%

Rated Discharge _____gpm

Nozzle Diameter or Nozzle Package _____(in)

If pressure regulators and/or flow control nozzles are used on the pivots, what are the make and model of the equipment _____

Motor Voltage at Flow _____V
Motor Amperage at Flow _____A
# of Nozzles _____
Nozzle Spacing _____ feet

System 2:

Pump/Motor Combination # (from above table) _____
Field ID(s) served with this system _____
Crop (s) served with this system _____
Water source _____

Total Acres Irrigated _____Ac
If more than one crop irrigated with this system:
Acres irrigated for Crop 1 _____Ac
Acres irrigated for Crop 2 _____Ac
Acres irrigated for Crop 3 _____Ac

Pumping Lift _____feet
Pressure at the Pump _____ psi
Pump Efficiency Rating _____%
Rated Discharge _____gpm
Nozzle Diameter or Nozzle Package _____(in)

If pressure regulators and/or flow control nozzles are used on the pivots, what are the make and model of the equipment _____

Motor Voltage at Flow _____V
Motor Amperage at Flow _____A
# of Nozzles _____
Nozzle Spacing _____ feet

Total Irrigation Systems

Sprinklers, # Acres served by each type:

Center Pivot _____ acres
Linear Move _____ acres
Wheel Line _____ acres
Traveling Big Gun _____ acres
Hand Move _____ acres
Solid Set, Permanent _____ acres

Micro-Irrigation, # Acres served by each type:

Surface Drip _____ acres
Sub-Surface Drip _____ acres
Micro-Spray _____ acres

Gravity Irrigation, #Acres served by each type:

Furrows or Corrugations	_____ acres
Border Strip	_____ acres
Basin	_____ acres
Contour Strip, Wild Flooding	_____ acres
Other	_____ acres

Power Sources

Electric - From Utility	_____%
Electric - From On-Site Generator	_____%
Non-Electric (internal combustion)	_____%

Fuel Type If On-Site Gen ~

a. ❍Diesel ❍ Gasoline ❍ Propane ❍ Other