

WATER CONSERVATION POTENTIAL OF LANDSCAPE IRRIGATION SMART CONTROLLERS

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ABSTRACT. *In the past ten years, smart irrigation controllers have been developed by a number of manufacturers and have been promoted by water purveyors in an attempt to reduce excessive irrigation. Legislation has been introduced in California and Texas and passed in Florida mandating or incentivizing the use of these controllers. As a result of the interest in smart controllers, their use is increasing in new installations and retrofits of residential and light commercial irrigation systems. A number of controlled research studies using formal experimental design and statistical analyses indicate substantial water savings of anywhere from 40% to more than 70% when using these devices; however, real-world savings in larger pilot-scale projects indicate savings of typically less than 10%. Reasons for the divergence between the apparent potential savings and the realized savings in pilot projects are related to the lack of: targeting of high irrigation users (on either a relative or absolute scale), education for contractors and end users, and timely follow-up to assess water savings. In addition, much of the scientific research on smart controllers has been conducted in humid regions where higher potential savings are likely due to irrigation needed only to supplement rainfall. Future pilot projects should include comprehensive educational components aimed at irrigation sites with potential irrigation savings based on estimated landscape irrigation demand from climatic variables (i.e., high irrigation users).*

Keywords. *ET, Evapotranspiration, Irrigation Association, Irrigation controller, Smart Water Application Technologies, SMS, Soil moisture sensor.*

Smart irrigation controllers are defined by the Irrigation Association as controllers that “estimate or measure depletion of available plant soil moisture in order to operate an irrigation system, replenishing water as needed while minimizing excess water use. A properly programmed smart controller requires initial setup and will make irrigation schedule adjustments, including run times and required cycles, throughout the irrigation season without human intervention” (Irrigation Association, 2007). Thus, smart controllers measure variables in the irrigated system and adjust irrigation control to maintain well-watered conditions. There are generally two types of smart controllers: climatologically based controllers, also called evapotranspiration (ET) based controllers, and soil moisture sensor (SMS) based controllers. Rain sensors (RS) or rain switches are another type of control mechanism that is discussed in the context of control technologies that respond to weather conditions in the irrigated landscape but are not technically controllers.

The concept of soil moisture based irrigation control is not new and has been used in agriculture (e.g., Muñoz-Carpena et al., 2005; Smajstrla and Locascio, 1996) as well

as in turfgrass irrigation (Snyder et al., 1984) at least since the 1980s. These early efforts typically used switching tensiometers, which are relatively simple but require routine maintenance for proper performance (Muñoz-Carpena et al., 2005). There have been some attempts in landscape irrigation at commercial soil moisture based control using electrical resistance (such as gypsum blocks), but these products were not successful and never became widespread. Thus, automation based on tensiometers remained primarily a research topic and was not widely used commercially. Similarly, automation based on ET estimation has been available for more than two decades, with central control systems for commercial and golf irrigation that are often integrated with on-site weather stations. However, these systems continue to be relatively expensive and are not appropriate for light commercial or residential landscape irrigation.

In 1996, a study was funded by the American Water Works Association Research Foundation (AWWARF, now the Water Research Foundation, WRF), called the Residential End Uses of Water (REUWS) study (Mayer et al., 1999). In this study, more than 1,000 homes in 12 cities across the U.S. were closely monitored (i.e., sub-minute logging) for potable water use patterns during two select two-week periods to represent summer and winter water use (i.e., to capture high and low demand, where high demand includes outdoor use). The goal of the study was to assess indoor potable water use within various categories to understand where water conservation efforts might be best applied. As a byproduct of the study, outdoor use was also determined. The largest component of total use was outdoor

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use, at 58% of the total, most of which was landscape irrigation. Inside the home, toilets and clothes washers were the largest uses, 11% and 9% of the total, respectively. In addition, per capita water use was relatively constant (~ 261 L person⁻¹ d⁻¹) in the home despite regional and climatic variability. Peak potable water demand is driven by irrigation use. An in-ground irrigation system increased water consumption by 35%, and an automatic irrigation timer increased consumption by 47%. Not surprisingly, irrigation use was heavily influenced by climate and water price. This study quantified the magnitude of the peak demand and total volume associated with landscape irrigation.

Smart irrigation controllers targeted at smaller irrigation systems (less than 16 zones, but often 4 to 8) have become available for the light commercial and residential market. The first weather-based controllers (ET controllers) were introduced into the western U.S. The earliest documented study of ET controllers was in a pilot study in Irvine Ranch, California, in 1998-1999, in which standard irrigation controllers (time clocks) were modified to accept an ET signal and adjust irrigation accordingly (Hunt et al., 2001). It is interesting to note that all of the smart controllers developed during this time period were from small startup companies. Since that time, the larger manufacturers have developed, purchased, or adopted smart control technologies.

The Irrigation Association has developed a program, Smart Water Application Technologies (SWAT), aimed at marketing and incentivizing the use of water-conserving irrigation technologies such as smart controllers (Irrigation Association, 2011). As part of the SWAT program, testing protocols have been developed to assess the performance of ET controllers by measuring irrigation run times for a virtual landscape over a 30-day test based on measured or estimated climatic variables by individual controllers. At the end of the test, controllers are scored for their irrigation adequacy (measure of under-irrigation) and scheduling efficiency (measure of over-irrigation). A test protocol for rain sensors has also been developed, and one for SMS controllers is in development.

This article summarizes the literature reports of smart controller testing and performance, ranging from research studies to pilot-scale implementations. Differences in reported irrigation savings of various projects will be discussed along with recommendations for future implementation of the technology.

EVAPOTRANSPIRATION-BASED CONTROLLERS

ET-based control systems have been available for many years; however, similar to SMS-based control systems, until recently the technology has not been reliable or inexpensive enough for widespread landscape irrigation applications. The oldest type of these systems consists of a full weather station that interfaces with a controller typically intended for large irrigated areas, such as golf courses. However, a full weather station costs several thousand dollars and requires frequent maintenance for accurate meas-

urements. ET is calculated based on the meteorological parameters measured by a weather station, and either some type of soil water balance (SWB) is calculated continuously by the controller or run times are adjusted in real time relative to historical peak ET (non-SWB controllers).

There are several approaches to residential and commercial ET-based irrigation control. Common to all of these approaches are settings programmed into the controller to specify variables from the landscape being irrigated. For example, most controllers include settings for variables such as plant type, plant density, shade, slope, and sprinkler application rate. These variables are used to adjust reference evapotranspiration (ET_0 ; ASCE-EWRI, 2005) to match a particular landscape irrigation zone and calculate soil water depletion and run time. Specific techniques vary by controller manufacturer, but the basic approach to deriving ET_0 is as follows:

- Signal-based: Meteorological data are collected either from publicly available sources or from agreements with weather station networks, and ET_0 is calculated. ET_0 data are then sent to controllers via wireless communication. Some controllers are sent weather data, and the ET_0 value is then calculated at the controller. In either case, the ET_0 value is based on some type of point weather data or on a regional interpolation of point data. The ET controller adjusts the irrigation run times, watering days, or both according to changing climate throughout the year.
- Historical: This approach for ET controllers uses a pre-programmed ET_0 curve for different regions. To qualify as a smart controller, the curve must be modified by a sensor such as a temperature or solar radiation sensor that measures on-site weather conditions. A variation of this approach is common for non-SWB controllers. These devices typically adjust user-input maximum seasonal run times based on measured climate variables such as solar radiation and temperature. The maximum run times should be input based on a selection in the controller of maximum seasonal daily ET (i.e., the peak of the historical curve).
- On-site weather measurement: Weather data are measured on-site at the controller to calculate ET_0 continuously, and irrigation is adjusted according to weather conditions using either a SWB or replacing ET since the last irrigation event.

Application of ET_0 data varies by manufacturer and product. Some devices aim to maintain calculated soil moisture content between maximum allowable depletion (MAD) and field capacity (FC). The simplest controllers are non-SWB devices. Generally, most controllers with any type of SWB have settings for the following:

- Soil type, to define available water holding capacity.
- Plant type, to adjust ET_0 to estimated plant ET (ET_c).
- Emission device/application rate, to convert depth of ET_c to minutes of runtime.

Some controllers also have settings for percent slope, percent shade, as well as other customizable inputs.

Table 1 shows a summary of plot-based ET controller research results and measured irrigation savings. Davis et

Table 1. Summary of smart irrigation controller studies and irrigation savings in plot-scale scientific studies.

Study	Technology ^[a]	Conditions	Savings (%)	Statistical Comparison	Irrigation Savings Comparison ^[b] (mm)	Comments
Qualls et al., 2001	SMS	Landscapes	26	Yes	726	Based on estimated net irrigation requirement.
Cardenas-Lailhacar and Dukes, 2008	RS	Virtual	3 to 44	Yes	818	Based on recommended 2 d week ⁻¹ schedule.
Cardenas-Lailhacar et al., 2008	SMS	Bermudagrass turf plots	72	Yes	1,514	Normal rainfall conditions every 2 to 3 days.
	RS		34			
Davis et al., 2009	ET	St. Augustine grass turf plots	47	Yes	840	95% to 100% irrigation efficiency settings.
	RS		24			
	ET		37			
	RS		21			
McCready et al., 2009	SMS	St. Augustine grass turf plots	38	Yes	1,185	Drought conditions with extended dry periods.
	ET		32			
	RS		19			
Vasanth et al., 2007	SMS	Fescue turfgrass plots	33	Yes	448	Compared to an on-demand SMS system. Attributed to drier than normal conditions and overestimated ET _o .
	ET		-26			
Cardenas-Lailhacar et al., 2010	SMS	Bermudagrass turf plots	34	Yes	602	Drought conditions with extended dry periods.
	RS		13			

^[a] ET, SMS, and RS indicate evapotranspiration-based controllers, SMS-based controllers, and rain sensors, respectively.

^[b] Irrigation savings is typically in comparison to a time clock schedule that is either typical or recommended for the region.

al. (2009) showed that ET controllers in a research plot study resulted in average irrigation savings of 43% compared to typical homeowner schedules, with no reduction in turf quality. Furthermore, savings were 60% in the winter months. Devitt et al. (2008) reported that signal-based ET controllers reduced irrigation by an average of 20% for homes in Las Vegas, Nevada, compared to homes with homeowner-scheduled irrigation. However, while 13 of 16 ET controller homes reduced water use, three of the homes actually had increased irrigation. McCready et al. (2009) reported ET controller irrigation savings ranging from 25% to 63% when compared to a typical homeowner irrigation schedule on research plots.

Davis and Dukes (2012) summarize and review outcomes of ET controller research in Florida. They found that ET controllers can match irrigation application with seasonal demand and in particular reduce irrigation in the winter when plant demands are dramatically reduced. In addition, they point out that when ET controllers are applied to sites irrigating at levels less than plant demand, those controllers will likely increase irrigation. Properly accounting for rainfall was a challenge for most of the ET controllers tested.

A number of pilot studies on ET controllers have been performed (table 2), with many study details summarized by USBR (2008). Hunt et al. (2001) reported 16% savings from a pre/post one-year installation study of a prototype that was to become the WeatherTRAK controller on 33 homes in the Irvine Ranch Water District, Irvine, California. Bamezai (2001, according to USBR, 2008) later reported that savings were consistent for two years after the initial study. Additional pilot projects have been conducted in the western states of the U.S., including Colorado (Aqua-craft, 2003), Washington (The Saving Water Partnership, 2003), Oregon (Griffiths and Olson, 2007, according to USBR, 2008), and Arizona (Quanrud and France, 2007, according to USBR, 2008). The common link between all of

these studies is that they were conducted with small numbers of homes (<35) and typically compared pre-installation water use to post-installation use. Often, a statistical analysis considering random error was not used for the comparisons, and in no case were the studies verified by an independent third-party review as to the methodology used and the soundness of the conclusions. Pittenger et al. (2004) conducted a study evaluating several ET controllers based on virtual testing of the controllers when they were connected to a datalogger to record irrigation cycle times based on real weather variability. They found that several different brands of ET controllers could roughly adjust irrigation schedules over varying climate periods for different types of landscapes, but the performance varied substantially based on specific controller programming.

Two studies evaluated ET controller performance over larger numbers of homes and commercial installations (table 2). Kennedy/Jenks Consultants (2008) reported results for 1,222 residential and commercial sites in Orange County, California, that had ET controllers installed. Eight brands of devices were installed without any apparent rationale except to include multiple brands. The controllers were distributed through rebate programs without assessing water use patterns on individual sites. Pre- and post-installation water use was analyzed while accounting for weather differences between the two time periods. Of the residential sites, 33% had a significant decrease in water consumption, 18% had an increase in water consumption, and 50% had no change. Overall savings was 3.9% and increased to 7.6% when considering only sites with a significant change. In a similar review of ET controller performance in northern and southern California pilot-scale implementations, Mayer et al. (2009) evaluated the pre- and post-installation water use of 2,294 smart controllers. Overall, ET controllers reduced irrigation by 6.1%; however, it was found that 56.7% of the sites were responsible for a significant decrease in irrigation application, while 41.8%

Table 2. Summary of smart irrigation controller pilot tests and irrigation savings in home/commercial landscapes.

Study	Technology ^[a]	Conditions	Savings (%)	Statistical Comparison ^[b]	Irrigation Savings Comparison ^[c]	Comments
Hunt et al., 2001	ET	33 residential landscapes	16	Yes	Adj. pre-install usage	Top 23% of water users selected.
Bamezai, 2001 ^[d]	ET	34 residential landscapes	18	Yes	Adj. pre-install usage	Additional year on Hunt et al. (2001) study as reported by USBR (2008).
Aquacraft, 2003	ET	10 residential landscapes	19-21	No	Adj. pre-install usage	Applied 1% to 5% less than ET _o .
The Saving Water Partnership, 2003	ET	35 residential landscapes	Not reported	No	Adj. pre-install usage	10 to 21 kgal year ⁻¹ .
Pittenger et al., 2004	ET	Virtual landscapes	Variable	No		Compared to estimated plant water requirements.
MWDOD and IRWD, 2004	ET	97 residential landscapes	10	Yes	Adj. pre-install usage	High users not targeted.
		15 commercial landscapes	21			
Griffiths and Olson, 2007 ^[d]	ET	29 public and commercial sites	41	Unknown	Pre-install usage	As reported by USBR (2008).
Allen, 1997	SMS	26 residential landscapes	10	No	Nearby non-SMS landscapes	
Quanrud and France, 2007 ^[d]	ET and SMS	27 residential landscapes	3 to 25	Unknown	Adj. pre-install usage	As reported by USBR (2008).
Kennedy/Jenks Consultants, 2008	ET	1,222 residential/commercial sites	3.9	Yes	Adj. pre-install usage	High users not targeted. Sites with only a significant water savings.
			7.6			
Mayer et al., 2009	ET ^[e]	Residential landscapes	6.1	Yes	ET _o -effective rain estimate	High users not targeted.

^[a] ET and SMS indicate evapotranspiration-based and SMS-based controllers, respectively.

^[b] "Statistical comparison" denotes studies using analysis of variance or other measures to account for inherent variability. Note that none of the studies with statistical comparisons included a third-party review process that controlled publication.

^[c] "Adj. pre-install usage" indicates a weather-adjusted comparison to pre-installation water use.

^[d] According to USBR (2008).

^[e] One SMS controller in the entire study.

were responsible for a significant increase. The sites with increased water use after the installation of a controller were sites that historically irrigated less than the theoretical landscape irrigation requirement.

SOIL MOISTURE SENSOR BASED CONTROLLERS

Two types of control methodologies use soil moisture sensor (SMS) controllers. The simplest is known as bypass control, in which an SMS controller is connected in series with a timer to control solenoid valves. In bypass control, the SMS controller has a user-adjustable threshold setting such that the scheduled time-based irrigation event is bypassed if the soil moisture content exceeds the user-adjustable threshold. It should be noted that the simplest SMS-based controllers operate in interrupt mode, whereby the sensor interrupts the control circuit as soon as soil moisture exceeds the adjustable threshold.

In recent years, research has accelerated on bypass SMS control systems for landscapes (table 1). Cardenas-Lailhacar et al. (2008) showed average irrigation savings of 72% with four brands of SMS controllers relative to homeowner irrigation schedules with a timer. These same four SMS controllers had savings of 34% under dry conditions (Cardenas-Lailhacar et al., 2010). Irrigation savings in the same region under relatively dry conditions ranged from 11% to 53% under optimum threshold settings but still showed that wasted irrigation due to excessive homeowner schedules can be reduced while maintaining good turfgrass quality (McCready et al., 2009). Ideally, soil moisture sen-

sors should be installed in the root zone for each irrigation zone. If the sensor system contains only one soil moisture probe, then that probe should be installed in the irrigation zone that will need irrigation most frequently, and the run times of all other irrigation zones should be reduced to minimize overwatering. In such a system, the irrigation zone with the sensor acts as an indicator of whether the entire landscape will receive irrigation. In practice, bypass-configured SMS systems in which only one sensor controls the entire irrigation system (e.g., on homes in southwest Florida) have been shown to reduce irrigation by 65% compared to homes with only timers (Haley and Dukes, 2012). Cardenas-Lailhacar and Dukes (2012) present a detailed summary and review of SMS research. As can be seen in table 2, there have been no substantially sized pilot-scale SMS irrigation controller projects to date, and few demonstration projects compared to ET controllers.

Programming of a bypass soil moisture sensor controller requires input of a run time into a time-based schedule. This run time should not exceed the water-holding capacity of the soil, defined as the difference between the threshold capacity programmed in the SMS controller and the field capacity. Ideally, frequent irrigation events should be programmed into the irrigation timer, and the sensor will allow irrigation as conditions in the root zone dictate in response to rainfall and ET. For example, if peak annual weekly ET_o for a site is 100 mm week⁻¹, and the maximum allowable depletion of the soil/plant system is 38 mm, then the net irrigation for any particular cycle should not exceed 38 mm. For a given week, 2.7 cycles (three cycles in practice) are required to meet ET demands. In regions where unpredict-

able rainfall occurs in the irrigation season or where soils do not have sufficient storage, the 38 mm net irrigation cycle should be divided into multiple events per day to provide a buffer in the soil as storage for rainfall.

The second type of soil moisture control is on-demand control, in which the soil moisture based irrigation control system consists of a stand-alone controller and multiple soil moisture sensors. This SMS controller completely replaces the timer. On-demand soil moisture based control utilizes high and low limits such that irrigation occurs only within those limits. Thus, the water content level at the maximum allowed depletion level or reduction in water extraction point would be the low or irrigation initiation threshold, and field capacity or just below would be the upper threshold signaling irrigation termination. Although the performance of all SMS control systems depends on sensor installation, extra care must be taken with an on-demand system to ensure that excessively low or high irrigation amounts do not occur. The irrigation manager should track this type of system after initial installation and make adjustments as needed. Many of these systems include data logging capability; therefore, soil water status can be tracked for excessive values. This type of system is typically an order of magnitude more expensive than bypass controllers and is warranted only on larger residential and commercial landscapes.

RAIN SENSORS

Another type of device that has been used in landscape irrigation for many years is a rain sensor, sometimes called a rain switch. While not considered a smart controller, such as SMS and ET based controllers, a rain sensor interrupts the signal between the timer and solenoid valves in response to rainfall. These devices may consist of a cup that captures rainfall and either uses weight in the cup or depends on water in the cup to conduct an electrical signal. More common, however, is the expanding-disk rain sensor that uses hygroscopic disks to open a switch in the solenoid valves' electrical circuit when the disks expand in response to wetting. On traditional time clocks, rain sensors are wired to interrupt the valves' common wire when activated. These devices can be connected and in fact are used as standard equipment on some ET controllers to respond to on-site rainfall.

Most expanding-disk sensors have adjustable setpoints to cause an open circuit (i.e., irrigation interruption) at different amounts of rainfall. These devices can be useful in humid regions where irrigation only supplements rainfall to satisfy plant water demands. Cardenas-Lailhacar and Dukes (2008) showed that one type of expanding-disk rain sensor was relatively accurate at interrupting irrigation at three setpoints. They calculated the payback of this technology as less than a year with relatively inexpensive potable water costs. However, they pointed out that on numerous occasions sensors responded erratically to rainfall or even high humidity conditions. In subsequent long-term monitoring of rain sensors, Meeks et al. (2012) found that their accuracy averaged 62%, and some brands needed replacement

each year for optimum performance. Rain sensor savings as high as 34% have been documented under rainy conditions in a humid climate (Cardenas-Lailhacar et al., 2008). During dry conditions, savings lower than 10% were found in one study (McCready et al., 2009) and 15% to 20% in another (Davis et al., 2009). SMS devices generally result in two to three times more savings than expanding-disk rain sensors (Cardenas-Lailhacar et al., 2008; McCready et al., 2009; Davis et al., 2009). Most of the time, drying of the wetted disks allowed irrigation within 24 h of interruption at a recommended setpoint of 6 mm and within 48 h when the disks were completely dry regardless of the setpoint (Cardenas-Lailhacar and Dukes, 2008).

SUMMARY

Automation of landscape irrigation scheduling by smart controllers promises to improve convenience and minimize irrigation application while balancing high landscape quality. However, ET controllers have been found to increase irrigation application (Mayer et al., 2009) when the controllers were installed on sites that were already deficit irrigated. Devitt et al. (2008) reported increased water use on several sites as well. This phenomenon may be isolated to ET controllers since they are designed to provide well-watered conditions, unlike bypass SMS controllers that bypass irrigation cycles beyond a given soil water threshold. There have been cases in which SMS controllers were improperly installed in non-representative landscape areas (i.e., extremely dry or wet locations) and either did not result in water savings or did not allow irrigation. Potential smart controller sites should be screened to ensure correct application of the technology where potential irrigation savings exist (e.g., where over-irrigation is occurring). Figure 1 shows an example of customer screening on a current project by the author's research group in Orange County, Florida, where estimated single-family home irrigation is compared to the gross landscape irrigation requirement. The irrigation system must be designed adequately and function properly before any smart technology is used. In particular, obvious problems, such as sprinkler target adjustment and leaks, should all be repaired before installing a smart controller. Significant irrigation savings have been documented from the proper use of smart technologies in arid regions, and especially in humid regions where irrigation supplements rainfall. One commonality between ET and SMS irrigation controllers is that either type of system will likely need fine-tuning after initial installation to achieve maximum potential water conservation benefits. Suggestions for future implementation of the technology include:

- Identify "over-irrigators" based on an index using landscape ET estimation and effective rainfall (see fig. 1).
- Offer retrofits or rebates to "over-irrigators" in preference to other users.
- Implement educational programs, particularly for contractors but also for end users.

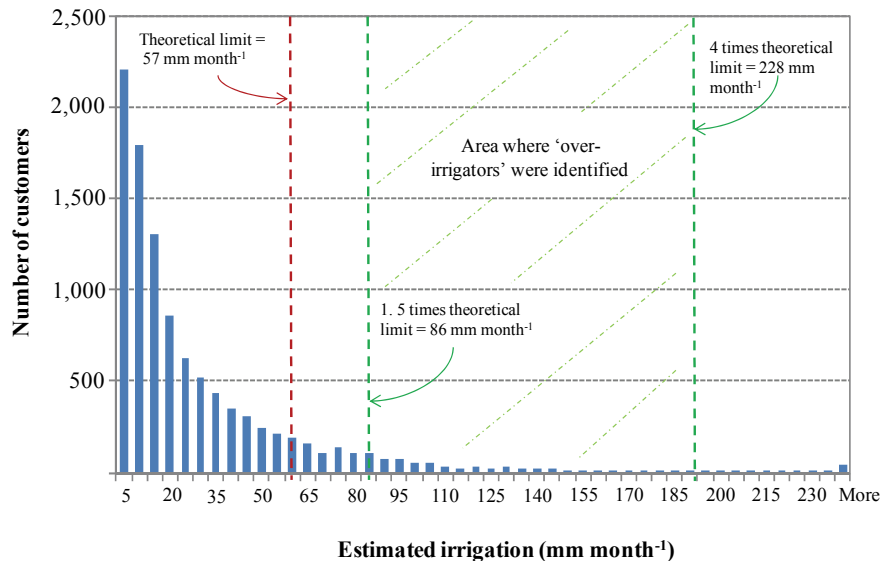


Figure 1. Histogram showing distribution of Orange County Utilities estimated single-family home irrigation in Orange County, Florida. Potential sites for smart controller implementation have between 1.5 and 4 times average gross annual irrigation requirement (GIR). Sites irrigating less than 1.5 times GIR will see little if any water conservation from a smart controller, whereas sites beyond 4 times GIR are more likely leaks or multiple accounts misidentified as single-family homes, although some could be legitimately due to over-irrigation. The theoretical limit was determined by a daily soil water balance to estimate irrigation requirement and summed for each month of the period of record.

- Conduct routine monitoring to verify anticipated water savings occur.

Research studies conducted by universities result in peer-reviewed publications by an unbiased third party. Therefore, the results can be counted on to include statistical analysis and to be vetted by experts in the field. However, these studies are typically not representative of the larger population involved as irrigation customers of a utility. As a result, the reported irrigation savings results will likely not transfer directly. Larger-scale demonstration projects, such as those reported by Kennedy/Jenks Consultants (2008) and Mayer et al. (2009), use large populations to compare water use before and after smart controller installation using accepted statistical practices. However, there is no guarantee that the irrigation practices in the “before” case are representative; furthermore, it is likely that the population with controllers is not representative of the utility’s broader customer population. Finally, smaller-scale demonstration projects with no assessment of irrigator profile nor statistical analysis of results have little value since the irrigation savings are not reported in the context of the variation inherent in utility customer data. Future work should include demonstrations at a broad scale (hundreds of users or more) to determine the actual water conservation potential of smart controllers.

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