

**Residential Weather-Based Irrigation Scheduling:
Evidence from the Irvine “ET Controller” Study**

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Agency Representatives and Study consultants

**Theodore Hunt and Dale Lessick
Irvine Ranch Water District**

**Joe Berg
Municipal Water District of Orange County**

**John Wiedmann
Metropolitan Water District of Southern California**

Tom Ash (horticultural consultant)

**David Pagano (irrigation consultant)
d. d. Pagano, Inc.**

**Michael Marian (technology consultant)
Network Services, Inc.**

**Anil Bamezai, Ph.D. (evaluation consultant)
Western Policy Research**

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EXECUTIVE SUMMARY

Residential water demand in California accounts for 54% of total urban water demand and is forecasted to reach 58% by the year 2020 as a result of population growth, especially in the hotter, inland regions of the state. The 1999 AWWA *Residential End Uses of Water* study indicates that over half of residential water is used for irrigation. Because of the complexity and constant variability of factors required to irrigate efficiently (e.g., weather conditions, the growth cycles of plants, length of day), it has long been acknowledged that irrigation on residential landscapes is wasteful to some degree. Therefore, the potential for water savings by reducing residential irrigation could be significant.

The water agency solution to date has been to conduct residential audits, leaving the homeowner with a suggested watering schedule, hoping it would then be followed. These programs have had limited effect and a short-term impact. A preferred solution would be to install irrigation controllers that *automatically* adjust watering times based on local weather conditions. Unfortunately, until now these large landscape control systems have been far too complex and expensive for residential applications. This study tested a prototype controller that could provide weather-based irrigation adjustments via a broadcast signal at a reasonable cost, attractive to homeowners and water agencies.

The agencies participating in the study believed an “ET”¹ controller offered the potential to achieve sustained outdoor water savings in residential homes, on the order of or greater than that achieved by plumbing retrofits. As the study progressed, these agencies also recognized that this technology may offer the potential for reducing non-point source pollution caused by excessive run-off from residential sites and may provide a means to better manage peak system demands. A new study is now underway to measure that impact.

Study design

The field trials in this study were undertaken in Irvine, California in selected single-family homes served by the Irvine Ranch Water District (IRWD). The test controllers were off-the-shelf standard “Sterling” irrigation controllers modified specifically for this study to test the effectiveness of the broadcast technology. The test controllers were installed in 40 test homes. Each home’s existing automatic irrigation controller was removed and replaced with the new test controller. The irrigation schedule for these homes was then controlled via a remote satellite signal. Changes in the irrigation schedule (if any were required), were made weekly, as determined by an irrigation professional based on local weather conditions and plant growth characteristics. In addition to the test homes, two other sets of households were included in the evaluation: a reference group to account for extraneous events (other than weather) which might effect customer water usage, and a “postcard” group. The postcard group consisted of homes that were periodically sent a postcard as the weather changed, suggesting what their irrigation schedule should be in number of days per week and minutes per day. The objective of the postcard group was to evaluate an alternative method of increasing household sensitivity to weather.

¹ ET refers to evapotranspiration, the rate at which plants lose water through evaporation and transpiration.

All three household study groups were selected from among high water users (top 23%) located in one of IRWD's development tracts, Westpark Village. Although the developer equipped all homes in this tract with an automatic controller, the study team did not know if all controllers were operational at the time of the study. Savings were estimated by comparing two years of pre- and one year of post-installation water consumption data. At the end of one year the test homes were also surveyed to obtain information about their satisfaction with their weather-based controller.

Program concept

In addition to evaluating water use, the study was designed to test an implementation method or program that could be easily and inexpensively implemented by water agencies. A pre-set base line irrigation schedule was programmed into each test controller using IRWD irrigation scheduling software rather than performing detailed reviews of each residence's landscape and irrigation systems (such as conducting catch-can tests). The base line schedules for station run time, cycle time and frequency were created using the same general scheduling parameters for each of the 40 test homes. These included sprinkler head type, plant palette, slope factor and root depth. For example, all homes using spray heads in a turf area received identical schedules. Irrigation schedules were then modified remotely by the weekly signal based on the previous week's actual ET value. This "hang it on the wall and walk away" approach greatly reduced time for controller installation.

Results

Potential vs. Actual Water Savings

Water savings were estimated through a statistical comparison of weather-normalized consumption before and after the controller retrofit. On an absolute basis, ET controllers were able to reduce total household water consumption by roughly 37 gallons per household per day, representing a 7% reduction in total household use, or 16% reduction in estimated outdoor use. But these results must be extrapolated with care because the retrofit group appears to have attracted households with lower levels of wasteful irrigation prior to the retrofit. In other words, we believe our retrofit households were already well disposed toward conservation, hardly surprising since participation in the study was voluntary.

Conservation potential is the difference between actual outdoor use and what *should have been* used taking weather into account. By way of example, if a home with one person replaces a 3.5-gallon toilet with a 1.6-gallon toilet and saves 1.9 gallons per flush, or 3,500 gallons per year, that home will have maximized the entire *potential* savings from toilet usage. By contrast, if a home with 5 people has a toilet dam in the tank, saving only 1 gallon per flush, that home may save over 9,125 gallons, but *could have* saved almost double by replacing the toilet. The second home had greater *absolute* savings, but the first home captured all of the *potential* savings.

Figure 1 displays the level of over-irrigation that was taking place in each of the three groups before and after the point in time that marks the beginning of our study. This chart shows that the postcard group had the most wasteful irrigation practices and the treatment

group the least. Although both the controller retrofits and postcard reminders generated statistically significant savings, the ET controllers were able to convert roughly 85% of the pre-retrofit conservation potential into achieved savings, while postcard reminders were able to convert only about 30%. Nonetheless, it is worth noting that given the proper circumstances, such as an aggressive tiered rate structure and an effective customer outreach program, simple postcard reminders can produce meaningful reductions in water use. No statistically significant change was observed in the reference group.

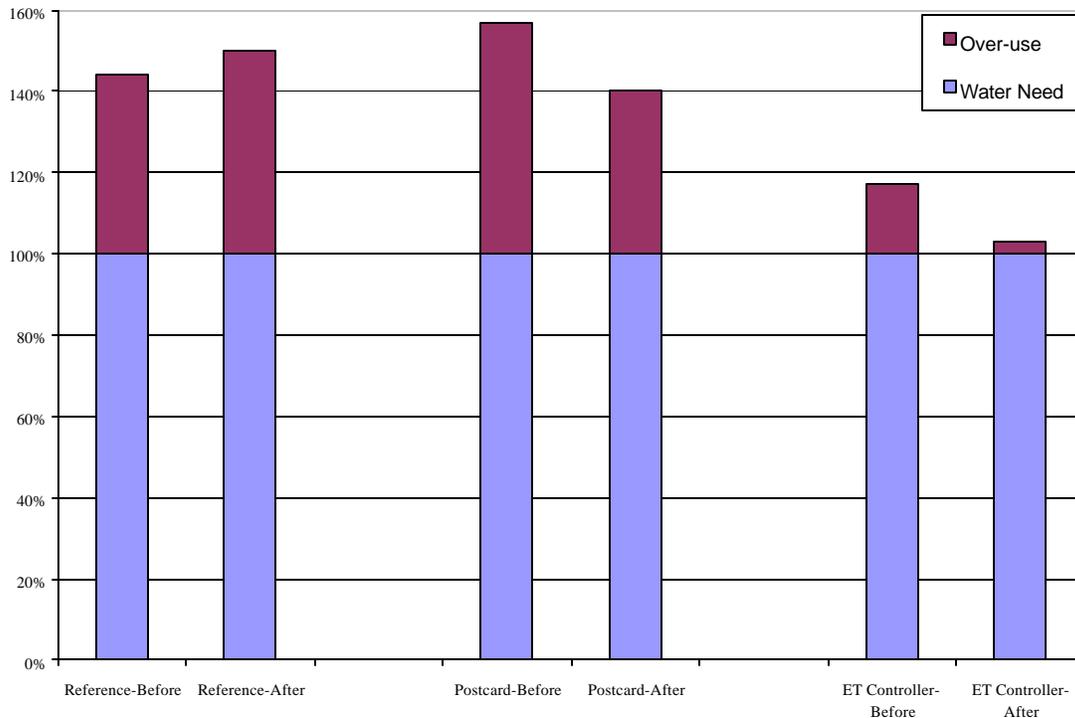


Figure 1 Estimated Outdoor Usage Relative to ETo-Based Water Budget

Extending the analysis to IRWD’s service area

An additional analysis was undertaken to estimate the possible level of savings from a larger and more representative sample of high water-using single-family homes within IRWD. This analysis suggests that by targeting roughly the top third of homes in terms of water use (approximately 10,000 homes) ET controllers might be expected to save roughly 57 gallons per household per day, a reduction of 10% in total water use, or 24% in outdoor use. Combined, these 10,000 single-family homes would be projected to save over 200,000,000 gallons (614 acre feet) per year.

Study results were extrapolated to a larger set of single-family households for illustration purposes only. Without further study of water savings in different communities with different rate structures, different levels of customer education, and different ET requirements, it would be inappropriate to consider 57 gallons per day as a regional savings value.

Customer satisfaction

Results of the post-treatment survey showed almost 97% of the ET controller participants reported either improvement or no change in the appearance of their landscapes and **all** found the ET controller convenient. However, in the course of the study customers often mistakenly attributed problems with their landscapes to the ET controller, suggesting that future programs must devote some attention and resources to customer post-installation education and assistance.

Cost-effectiveness

ET controllers, when available, are expected to cost approximately \$100 per unit, installation an additional \$75, with an ET signal fee of \$4 per month. The signal fee is expected to include the cost of customer service. The useful life is expected to be between 10 and 15 years.

Using 57 gallons savings per home per month as an assumption, the value of saved water to the customer and agency *combined* exceeded the all associated costs of the controller. However, since the customer *alone* did not have enough water savings to counterbalance the costs, one solution might be for the water agency to subsidize the customer's costs in some manner, such as by offering a rebate.

However, if the convenience and other benefits (besides water savings) associated with ET controllers are valued sufficiently, customers may be willing to opt for this technology, *with no additional incentive from the water agency*, especially since the signal fee is not a large up-front cost but spread out over the entire life of the controller. During the pre-test survey, over 66% of the test households appeared willing to pay up to \$125 for the controller and up to \$4 per month for the signal fee.

I. INTRODUCTION

The Problem: Reducing Water Wastage in Residential Landscapes

Residential water demand in California accounts for 54% of total urban water demand, and this proportion is forecasted to reach 58% by the year 2020 due to population growth, especially in the hotter, inland regions of the state (Department of Water Resources, Bulletin 160-98). Landscape experts have long contended that residential landscapes are irrigated beyond actual plant needs. The 1999 AWWA *Residential End Uses of Water* (Mayer, DeOreo, Nelson, Opitz, 1999) study quantifies what local water agencies have always known, that a significant portion of residential consumption is devoted to irrigation (58% among the studied households). The study also found that homes with automatic sprinklers use 47% more water than those without automated systems

From a horticultural standpoint, over-irrigation occurs much too often. However, it is most prevalent in the fall months of September, October and November when ET rates are falling and summer irrigation schedules have not been revised to meet the current weather conditions. Over-irrigation causes three basic problems.

- Over-irrigation pushes water beyond the root zone and is wasted. This occurs most notably in the case of turf grass. .
- Over-irrigation causes excessive run-off which contributes to non-point source environmental pollution.
- Over-irrigation, in general, degrades plant health.

The public, unaware of these complexities, however, views irrigation as a panacea for their landscape's shortcomings and continues to over-water. Excessive irrigation also exacerbates summer "peaking" problems, and makes drought management more difficult. Public resources are wasted when utilities expand capacity at great cost to meet these needlessly inflated peak demands.

Traditionally, residential outdoor water management has been poor because scheduling irrigation according to local weather conditions, soil type and species-specific requirements is a sophisticated and time-consuming process. Residential water users commonly ask, "How long should I water and how many days should I water?" There is no standardized answer to this simple question because every landscape is different in terms of the plant material used, quality of the soil, and sophistication of the irrigation system. For water application to be efficient, it must be specifically tailored for the above factors, and must also track weather accurately.

Plants need a certain amount of water to conduct physiological processes (photosynthesis). Most common plants, however, cannot store water more than they can "take-up" to meet these evapotranspiration needs. Therefore, water applied beyond the plant's evapotranspiration needs (product of the reference evapotranspiration rate [ET_o] and the plant-specific crop coefficient [K_c]), or beyond the soil's moisture holding capacity in the

root zone, is essentially wasted water. Because plant water requirements may change significantly from week to week as weather (ETo) changes, irrigation times must be recalculated and controllers re-programmed at least on a weekly basis. It is the rare resident who changes his/her controller on a weekly basis.

$$\text{Plant water requirement} = \text{Weather (ETo)} \times \text{Plant factor (Kc)}$$

The Opportunity: Remote Weather-Based Irrigation Scheduling

Previous Findings

A previous MWD study found that predominantly turf landscapes could meet a standardized 100% ETo water budget and show improved plant health (*Irvine Spectrum Water Conservation Study*²). In this study, weekly evapotranspiration rates were used to calculate efficient irrigation schedules at commercial landscape sites. With state of the art “central irrigation control”, ETo data was used for irrigation scheduling to produce significant water savings—between 21% and 50% on test sites. This water efficiency was gained at relatively high expense (sophisticated equipment) and human manipulation of weather station information. On a large commercial landscape, the level of water savings justified the cost. Landscapes also showed an improved appearance even though water use declined. This study provided landscape professionals confidence that weather-based irrigation scheduling could provide practical benefits of water savings and improved landscape health.

Since 1991, landscape experts and public agencies have agreed that the accepted method to estimate efficient landscape water application is via the water budget method, i.e., weather-corrected (ETo) for a specific plant’s crop coefficient (Kc). This resulted in the adoption of a statewide landscape water conservation ordinance, *The Water Conservation in Landscaping Act* (Assembly Bill 325, 1990) for cities and counties in California. The science of water budgeting is also the method adopted by the California Urban Water Conservation Council (CUWCC) to set water use targets for all commercial landscape sites, called *Best Management Practice #5*. This state-wide guideline specifies that the goal for landscape water applications is water budgets that do not exceed 100% of ETo. This standard of water budgeting is supported by extensive research by the University of California Cooperative Extension into plant water needs. More than 1,000 plants have been categorized according to their water needs in a university publication titled *Water Use Characteristics of Landscape Species*.³

The Technology

Can weather-based irrigation scheduling be cost-effective in residential settings? By 1997 a variety of technologies were either coming to market or were being produced that looked particularly promising. These included:

- A method of utilizing historical ETo and on-site data (atmometer) to adjust irrigation schedules (Patent # 5,479,339, Miller, 1994)

² *Efficient Turfgrass Management: Findings From the Irvine Spectrum Water Conservation Study*, d.d. Pagano, Inc, James Barry M.S., Western Policy Research, May 1997

³ *Water Use Classification of Landscape Species*, Costello, L. R. and Jones, K. S., University of California Cooperative Extension, April 1994

- A method of utilizing ET and precipitation to re-calculate irrigation schedules and transmitting the information via cable lines (Patent #5,696,671, Oliver, 1997)
- A method to utilize actual ETo (from CIMIS and other accredited data sources) and broadcast weather changes to receiver controllers (Patent # 4,962,522 & 5,208,855, Marion, 1990 & 1994)

After considering the options, the study team anticipated that the Marion technology would probably be the most cost-effective method of yielding the greatest water savings. Aside from water savings, this technology promised to minimize the resident's intervention and maximize convenience, two elements thought to be critical for long-term success.

The Test Controllers

The test controllers were standard Sterling controllers with modified internal software and hardware, including a signal-receiving device. These test controllers had limited customization capabilities, distinguishing only irrigation cycle time, cycle start time and days of irrigation. Noting plant type and irrigation type, base irrigation schedules consisting of irrigation cycle time, cycle start time and days of irrigation were pre-programmed into the test controllers by the test study team when the controllers were installed. Scheduling changes were sent to the test controllers via satellite signal. Satellite signal changes were limited to start time changes, ET changes and water day changes.

Due to the limited programming abilities of the test controllers installed at each test site, the test controllers were set up with a matrix of four programs: Turf vs. Shrubs and Spray Heads vs. Rotors. All turf was calculated as cool season with an annual crop coefficient (Kc) of 0.80 and root depth of 4 inches. The Kc for turfgrass irrigation systems was adjusted monthly based on the monthly "Crop Coefficient Values for California Turf" as listed in Appendix A of DWR's Landscape Irrigation Auditor's Handbook. All other plants were calculated as shrubs with medium water use with a Kc of 0.50 and a root depth of 6-12 inches.

Weather data (ET) was translated into a "percentage change" factor,⁴ which was then transmitted weekly to the test controllers. Each controller had an established baseline schedule based upon valve-specific parameters and the highest local ETo factor. The remote signal altered this baseline schedule, including irrigation minutes, cycles and days to reflect actual weather conditions.

Study Team

The study team included consultants and representatives of the sponsoring water agencies. The team members included:

⁴ Percent change factor: For the purposes of the study, using current ET data from CIMIS weather station #75, a new irrigation schedule was created by the study team. Based on base irrigation schedule resident in the test controllers, the percentage difference between the new and base schedule was transmitted to the test controllers via satellite signal thereby adjusting the base schedule to equal the new schedule.

Metropolitan Water District of Southern California: John Wiedmann

Municipal Water District of Orange County: Joe Berg

Irvine Ranch Water District: Tom Ash (now with ConserVision), Dale Lessick, Theodore Hunt

Irrigation Consultant : Dave Pagano of d.d. Pagano, Inc.

Technology Consultant: Michael Marion of Network Services, Inc.

Statistical Evaluation: Anil Bamezai of Western Policy Research

II. STUDY OBJECTIVES AND DESIGN

Study Objectives & Design

This study design had two objectives: 1) to test a new technology, expected to cost-effectively deliver ETo-based irrigation schedules to residential landscapes; and 2) to implement a *simple* program that would be easy for public agencies to replicate.

The original design concept was to compare homes with the new technology to neighboring homes without an ET-based controller—creating a treatment group and a reference group. The study team added a third group to test the effectiveness of periodically sending postcards advising homeowners what their watering schedule should be. The purpose of the postcard was to determine the level of response, if any, homeowners would give to such an inexpensive device. Conventionally, high water users have been given home water audits and left with an irrigation schedule. These postcards were meant to simulate the public education facet of an audit.

1. Testing the technology

As for the technology, the key objectives were to estimate and assess:

- Water savings
- Cost/benefits of the technology related to water savings
- Landscape appearance
- Participant satisfaction levels with the technology
- The effect of changing the controller only—not altering the rest of the irrigation system
- Independence from resident-initiated actions

2. Simplifying Implementation

The “hang it and walk away” approach was deliberately adopted to simulate our expectation of what would likely happen in the real world. We considered it highly unlikely that water agencies would want to fund detailed reviews of each residence’s landscape and irrigation systems, such as conducting catch-can tests, as part of a controller retrofit program. Consequently, implementation consisted of:

1. Removing the existing controller from the garage wall and returning it to the owner.
2. Replacing the old controller with the new test controller and setting the baseline irrigation schedules based on site-specific parameters.
3. Sending weekly satellite signals as a percentage of the baseline irrigation schedule resident in the test controller based on previous week’s actual ET value.
4. Not doing anything else. (Not altering the non-controller portion of the resident’s irrigation system and instructing the customer not to alter the test controller.)

Participants were free to maintain the non-controller portion of their irrigation system as they normally would. Because this was a study, not an actual program, they were instructed to call IRWD if they felt the controller was not operating properly so problems with the controller or program design could be identified.

Selection of Study Participants

The goal was to study as homogenous a group as possible to improve the validity of the findings. To that end, test sites were selected from “Westpark Village,” a development located in the city of Irvine and serviced by the Irvine Ranch Water District. The development includes 2,200 single-family homes built from 1986 onward. The targeted single-family households had the following characteristics:

- Most homes were the same age (1986-1988)
- All were located in the same microclimate zone
- Landscape area was relatively consistent
- Plant material type was consistent
- Irrigation systems were similar in age and type
- Soil conditions were consistent (clay)
- Historical water use data was available for the same family for one year⁵

Test homes were targeted as per traditional water conservation program guidelines, i.e., top 20% water users. For Westpark, residents with average annual consumption exceeding 200 HCF (hundred cubic feet), derived from three years of billing data defined the top 23%. These 509 homes were sent letters requesting study volunteers in spring 1998. Over 130 households from the targeted group volunteered by phone or letter to participate in the study. From these volunteers, 40 homes were selected for the treatment group based upon the following criteria:

- The automatic irrigation controller was operational
- Residents had lived in the house for at least one year
- The residents said they did not plan on moving for a year or making significant alterations to their landscape

Additional screening was also performed via phone interviews, through database analysis (for length of residency) and through on-site inspections to verify that the treatment homes met the following conditions:

- Working controller and irrigation system
- No broken main or lateral lines
- Acceptable coverage
- Acceptable pressure
- Functioning valves

⁵ Later, it was decided to use two years of historical data for the billing analysis.

Homes that did not meet the criteria were eliminated from the study. The remaining homes from the original target group were randomly selected for the reference group and postcard groups. Detailed screening of the postcard and reference groups was not possible owing to the larger sample size. However, postcard and reference households were screened for residency requirements, which yielded 56 and 155 sites respectively, suitable for the statistical evaluation. Although the original goal was to try to get all homes in all three groups to be as homogenous as possible, the final analysis revealed some significant differences between the three groups.

Pre-test Survey

All treatment group households were surveyed prior to the retrofits to gauge their irrigation knowledge and practices, and to gauge their receptivity and willingness to pay for this technology. Responses to these questions had no effect on determining whether the home was qualified to be in the study.

The tabulated results (included in Appendix B—Pre-test Survey) indicate a fairly strong desire to use water as efficiently as possible, but also insufficient knowledge about how to actually achieve this goal. For example, 65% reported setting their own controllers. As to how often irrigation schedules are updated during the year, 68% reported doing so on a seasonal basis (4 times per year or less) and 11% on a monthly basis. However, during the controller retrofits nearly half of the treatment homes were found to have irrigation schedules for every day or for every-other-day programmed into their existing controllers.

The lack of plant/water knowledge is also apparent in over one-half (58%) of the treatment homes. Roughly 38% reported that trees, shrubs and groundcover require the same amount of water as turf grass. Nearly 12% of respondents thought trees need twice as much water as turf grass, while 20% reported not knowing the correct answer to questions about relative plant water needs.

The pre-test survey also showed a high degree of receptivity to controllers that can automatically track weather, 82%. Over 66% appeared willing to pay up to \$125 for the controller and up to \$4 per month for the ET broadcast service.⁶ The water savings ability of an automatic controller is of high interest to respondents, with 94% claiming that feature somewhat or very important. Respondents also described that saving money with water efficiency is somewhat important or very important, 91%. Finally, the convenience of automatic weather-based irrigation was important to all respondents.

Overall, these results indicate both a genuine customer need as well as willingness to pay for convenient, reasonably priced, weather-based irrigation scheduling technologies and services.

⁶ “Willingness to pay” is a common means of estimating a value for something without direct market experience. Generally, people over-estimate their willingness substantially. Therefore the number presented should be interpreted as an upper bound.

III. INSTALLATION OF TEST CONTROLLERS & PARTICIPANT SUPPORT

Procedure

Screened potential study participants were contacted by phone to schedule an appointment. During the site visit, a final screening was conducted to insure the presence of a “working” irrigation system. The actual retrofit sequence adhered to the following pattern:

1. Have the resident complete a pre-intervention survey and endorse a “Hold Harmless” agreement.
2. Remove the existing automatic irrigation controller (disconnect valve wires, unscrew from wall/mounting, save controller).
3. Install the ET controller (mount, re-attach valve wires)
4. Initiate station-by-station set-up (enter plant type and sprinkler type).
5. Activate each irrigation valve (station) and observe the plants being irrigated, and any sprinkler system deficiencies.

Controller retrofits were done by a two-person team and took anywhere from 30 to 60 minutes per site, including mounting, valve activation, schedule set-up, and pre-test survey.

In keeping with our deliberate programmatic approach aimed at minimizing agency effort and cost, residents were given the following instructions:

1. There is no need to touch (i.e., to program or change) the controller (scheduling changes will occur automatically via the weekly signaling/adjustments).
2. In event of rain, do not change or modify the controller (scheduling changes will occur automatically in accordance with soil moisture depletion factors related to effective rainfall).
3. The controller manual was provided for manual operation. if needed.
4. If any problems arise, contact the IRWD conservation staff.

Secondary Findings

Existing Home Irrigation Systems

The test sites were located in a 12-year old development of single-family homes. The initial home inspection revealed that a variety of problems existed in the irrigation systems of the homes. In other words, there were no perfect irrigation systems among the test homes. This was perhaps an advantage and a disadvantage in terms of the study. It was an advantage because it supported the assumption that most home irrigation systems have some equipment problems that affect water efficiency. It was a disadvantage in that testing for the impact of the controller technology could be biased one way or another by the inherent irrigation system problems.

With some exceptions, most irrigation systems in the test homes had poor coverage and too many heads per valve. Pressure, as observed, was typically excessive. Some down-line heads showed too little pressure. Leaks, blocked heads, clogged heads, mismatched heads—all were noted. As observed, most systems had irrigation system problems that would likely increase overall water use. Each resident was given a description of the problems in the irrigation system. No mandate was issued to repair or upgrade the systems before the test began. Some residents did repair problems; some did not. No official record of these actions was kept. Precipitation rates of systems were also randomly measured. Most sites showed high system precipitation rates.

Residential Irrigation Scheduling

As controllers were retrofitted at the test sites, the current irrigation schedule programmed into the existing controller was observed. It was common to find every-day watering or every-other-day watering set into the controllers. Some controllers were found to be in the manufacturer's default mode (10 minutes per day, every day). Turf and shrubs were found to have the same watering schedule on most test home clocks. Residents were also unaware of the need for a battery backup to prevent scheduling information from defaulting to manufacturer specifications in case of a power outage. All test homes used only one program mode for scheduling. Typical comments by participants about how often they set irrigation schedules included:

Q. When do you change your irrigation controllers?

A. “I change my controller like everyone else, when I change my clocks...”

A. “I change my controller when my buddy comes over and helps...”

A. “ I re-program the controller after a power outage...”

In the pre-test survey, 68% of the treatment group reported changing their schedules seasonally and 11% reported changing them monthly. The field observations of their existing schedules indicated that high levels of water wastage was occurring at most homes. However, the analysis of the residents' water bills, suggested that the residents were changing the watering schedule more frequently than “seasonally” as claimed in the survey.

Rain and Irrigation Scheduling

The effect of rain was factored into the calculation of ET and incorporated into the signal sent to the controllers. Although homeowners were instructed not to touch the test controller, a few homes did change the setting to “Rain – Off” during rain events. It appears as though this change occurred after the unit had received the “shut-off” signal. With this timing, the change had the effect of turning the test controller off completely, such that it was no longer capable of receiving any signal.

It appears that when these homeowners turned the controller back on, the signal to start operating again had already been sent, so their units never received the re-start signal. IRWD staff responded to the customer's call by running the unit through the test cycle, and manually entering the signal, which re-started the controller.

Customer Service Requests

IRWD received phone calls from participants about real and perceived landscape problems. By design, IRWD had encouraged these calls to ensure that the study team received as much feedback as possible about the new untested controller technology, as well as to have an opportunity to soothe customer fears about what the new controllers might be doing to their landscapes and property values.

IRWD staff found that 99% of customer concerns turned out to be typical landscape and/or irrigation system problems. Few incidents were directly linked to malfunctioning controllers or signal failures. A case in point is the following phone message from a test participant:

Study participant phone message: **“My plants with yellow leaves are turning green.”**

IRWD staff and horticulture advisor visited the site to confirm that leaves of a particular shrub (*Photinia*) were gradually turning from yellow color to green. The resident did not know if this was a problem being “caused” by the “test controller.”

Photinia, a mediterranean shrub, typically has bronze colored new-growth leaves, turning to a dark green over time. In over-watered situations it is common for *Photinia* to show signs of *chlorosis*, or a yellowing of the leaves caused by lack of oxygen in the soil. In over-watered landscapes, oxygen is replaced by water, preventing roots from having adequate oxygen exchange which degrades normal plant physiological processes and produces yellow leaves. As irrigation was reduced at this test site, more oxygen could move back into the soil. This enabled the *Photinia* to regain a more normal physiological balance, and the leaves “greened up”.

This example shows why landscapes at the test sites generally improved in appearance over time. However, it also demonstrates the high potential for questions, concerns and contacts regarding landscape changes likely to occur with proper irrigation scheduling.

Test/Technology Instructions

While the controllers were deliberately installed with minimum instruction, interactions with the test participants show that providing clear and simple instructions in any future use of this type of technology may be important for overall success. Residents of test homes were instructed (1) not to change, re-set or turn off controllers during rain events, and (2) to contact IRWD if they felt irrigation schedules needed adjustment. It was found that a return trip to the test homes was valuable insofar as it invariably led to a downward adjustment in the baseline schedule. These follow-on adjustments were made to roughly 30 of the 40 treatment sites.

If a homeowner complained that the controller was not watering the landscape enough, IRWD visited the test site. The staff performed a “soil probe” test to determine the moisture content of the soil. In each case, IRWD was able to show the homeowner, to his or her satisfaction, that the problem was not due to under-watering. In cases where a portion of the landscape was, in fact, dry, the under-watering occurred as a result of some system

malfunction, (i.e. broken sprinkler head) not related to the controller. In most cases, the IRWD staff was able to fix the problem and did so as a courtesy.

Summary of Secondary Findings

- Irrigation schedules were typically set by the homeowner to apply more water than plants require.
- Many controllers showed default run times (10 minutes every day).
- Irrigation systems displayed a variety of malfunctions that lead to wastage (high or low pressure, blocked, clogged, mismatched or broken heads, faulty valves, etc.).
- There was little knowledge about how much water plants should receive.
- A few residents wanted to adjust water (off) when it rained.
- Often general irrigation problems were mistakenly attributed to the ET controller.
- Soil probe tests at the test site eliminated many customer concerns and assisted with adjusting baseline schedules to better fit each site.

IV. BILLING HISTORY ANALYSIS

This section provides an overview of the billing history analyses and discusses the key findings. Precise details about measures used to control for weather, model specification, and statistical estimation can be found in Appendix A—Model Specification and Estimation.

Water consumption in the treatment homes could have changed over time for several reasons unrelated to ET controller retrofits, such as:

- changes in weather,
- changes in response to the water budget-based inclining rate structure,⁷ or
- modifications in indoor or outdoor end uses.

It is important to remove as many of these confounding factors as possible, by design when feasible, or through analysis. Owing to the small size of the treatment group, several screening criteria were applied to try to control extraneous factors. These criteria include: (1) a one-year⁸ residency requirement to ensure availability of a reliable consumption baseline; (2) absence of changes in major indoor or outdoor end uses during the base period; (3) absence of any plans to make significant alterations to indoor or outdoor equipment, or to move, for at least a year following the ET controller retrofit. In spite of these precautions, data from three treatment households were tainted for one reason or another and were excluded from the water savings estimation.

Detailed screening was not possible in the case of the postcard and reference groups owing to the larger sample sizes. Instead, by using the tenant indicator⁹ in IRWD’s billing system, we identified those postcard and reference group households that had lived in their respective dwellings for at least two years prior to when ET controller retrofits were undertaken and at least one year following the retrofits. The analysis therefore captures reasonable baseline use vs. study period use for these households. The impact of weather on consumption is removed through statistical models that “weather normalize” the data. In a non-experimental setting, weather’s influence cannot be eliminated by design.

Finally, the impact of the water-budget based rate structure was ascertained through the reference group’s behavior over the same period of time.

⁷ IRWD’s rate structure is set up to provide individualized water budgets so that customers can identify when a leak or over-watering occurs on their site. For single-family homes, IRWD uses a default/minimum of 4 residents with 1300 square feet of landscape to calculate the allocation, though homeowners can increase these parameters by submitting a form to IRWD. The allocation is determined by an indoor factor plus an outdoor factor. The outdoor factor is calculated based on the daily ET as recorded by local weather stations.

Consequently, each resident’s allocation changes each month as the weather changes. When customers use water in excess of their allocation, they are assessed progressively expensive penalties—**up to eight times the basic rate, sending a very strong price signal that a leak or over-watering is occurring.**

⁸ At the time of selection, residents needed to live in their homes only one year prior to the installation. Later it was decided that two years of historical data would be better for analysis purposes, even though it meant some treatment homes would drop out of the analysis.

⁹ The “tenant indicator” is a field in the billing system (and part of the account number) that changes when the resident changes.

Our final water savings estimates are based upon two years of pre- and one year of post-intervention consumption. Sensitivity analyses indicate that the statistical models capture weather impacts with greater accuracy when based upon two instead of one year of baseline data. Imposing the two-year baseline requirement resulted in a final analysis sample consisting of 33 treatment, 56 postcard and 155 reference group households. Several homes dropped out of the treatment group either because they did not have complete data, or the customer moved, or some extraordinary anomaly was present in the data. The ET controller retrofits took place during August and September of 1998. Accordingly, meter reads taken between August, 1996 and July 1998 are used to establish the pre-intervention baseline, while meter reads taken between November, 1998 and October, 1999 are used to measure the post-intervention consumption.

Figure 2 displays the reference evapotranspiration rate (ET_o) as well as the crop-coefficient and rainfall-corrected evapotranspiration rate of cool season turf (ET_c) by month for the pre- and post-intervention periods to show that weather is an important confounding factor—the pre- and post-intervention curves don't exactly overlap. During the post-intervention period, the spring season was notably cooler with the opposite being true during the summer season.

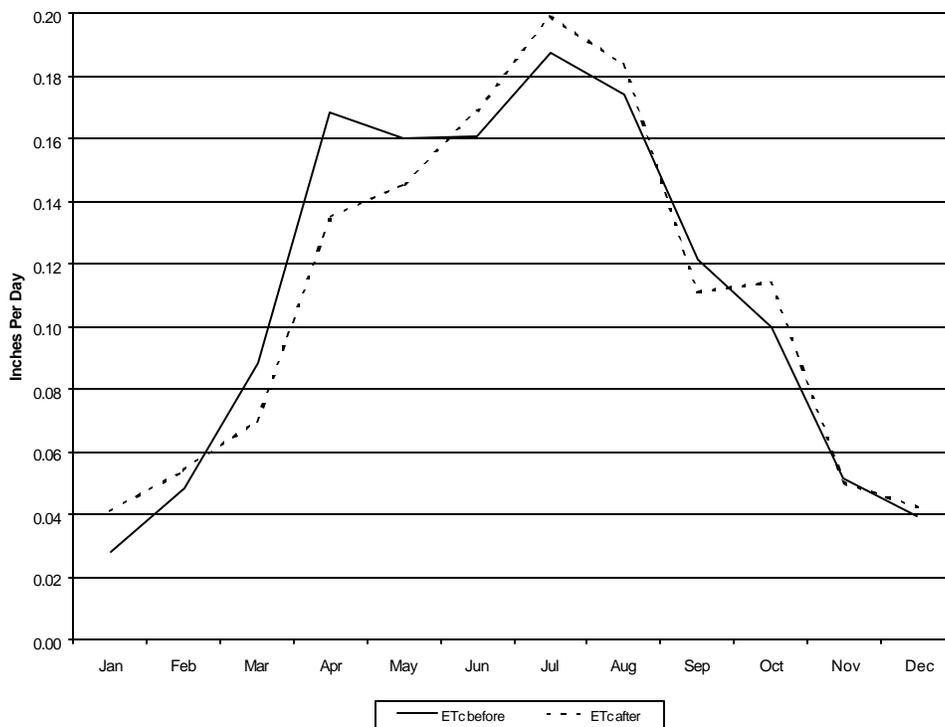


Figure 2 Cool season turf's rainfall and crop-coefficient corrected evapotranspiration (ET_c) 2-year average before and 1-year after the intervention

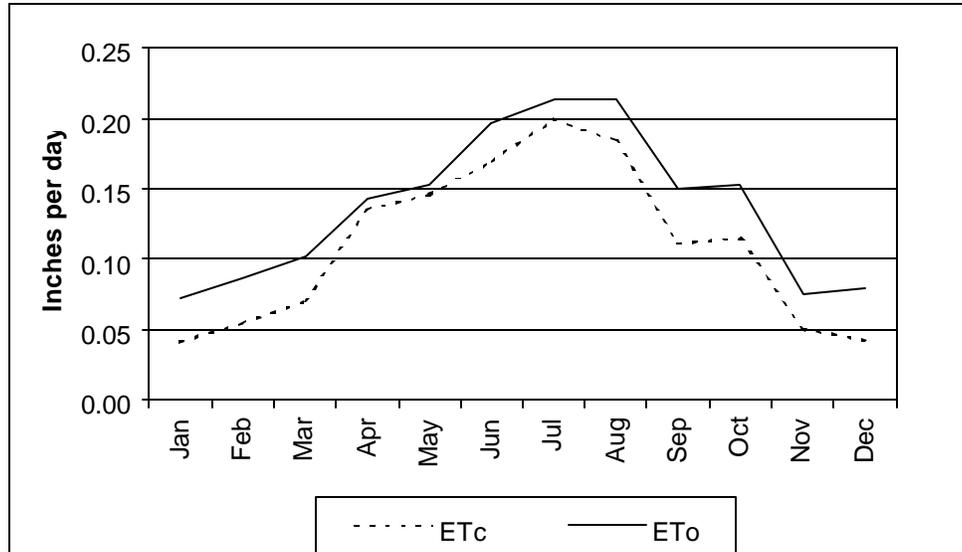


Figure 3 Reference evapotranspiration (ETo) and cool season turf's rainfall and crop-coefficient corrected evapotranspiration (ETc) during the intervention

Figure 3 also shows that turf's actual evapotranspiration rate (ETc) is often less than the reference evapotranspiration rate (ETo). Using the latter to schedule irrigation, as many do, is a wasteful practice. Daily reference evapotranspiration (ETo) and precipitation rates were obtained from the California Irrigation Management Information System's (CIMIS) Irvine station.

Consumption Relative to Weather

To provide a visual feel for the data, we first display how consumption has changed relative to weather for the reference, postcard and ET controller (treatment) groups before and after the controller was installed (Figure 4, Figure 5 and Figure 6). The curves present "applied" and "predicted" outdoor use in inches-per-day across all households included in a given group plotted by the month in which meter reads were taken. Estimates of applied and predicted irrigation are only approximations, and as such do not form the basis for the derivation of water savings. Their function mainly is to provide a visual context for non-technical audiences to help interpret the model-derived savings estimates.

Applied outdoor use is estimated as the positive difference between total use and IRWD's indoor allocation, which is then converted into inches per day using information about landscape areas available from IRWD's billing system. Predicted use is derived as follows. First, for each day covered by a meter read, daily ETc for turf grass is aggregated to yield the read-level ETc. Predicted inches per day are then derived as the product of read-level ETc and the inverse of the irrigation efficiency (assumed to be 80 percent). The above methodology for predicting irrigation demand closely resembles how IRWD estimates outdoor allocations for its customers. Finally, predicted water use is averaged across customers in each group by month to yield the group level average estimate.

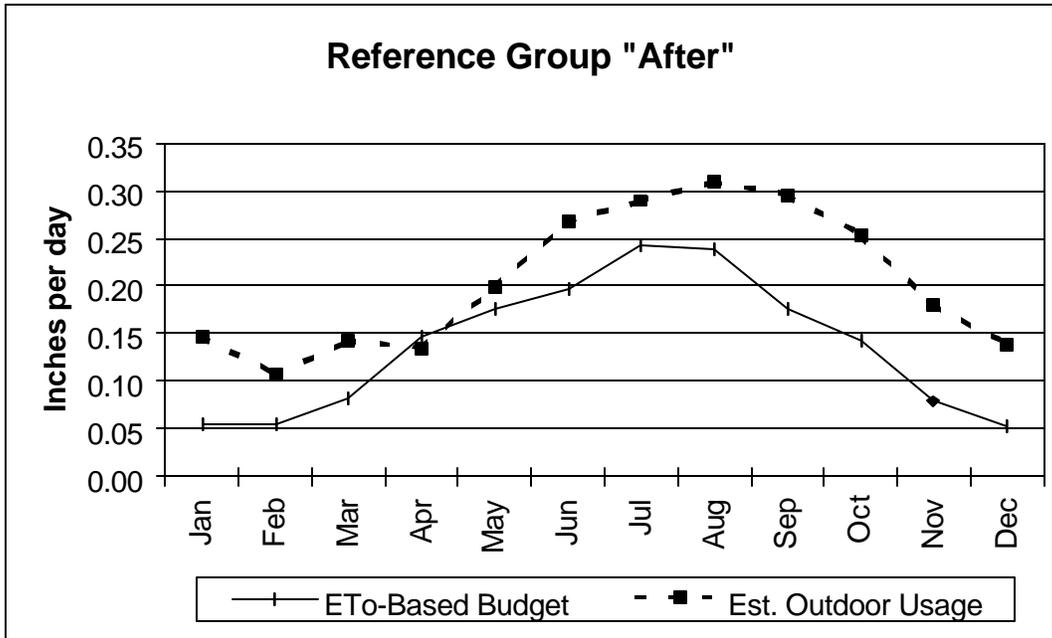
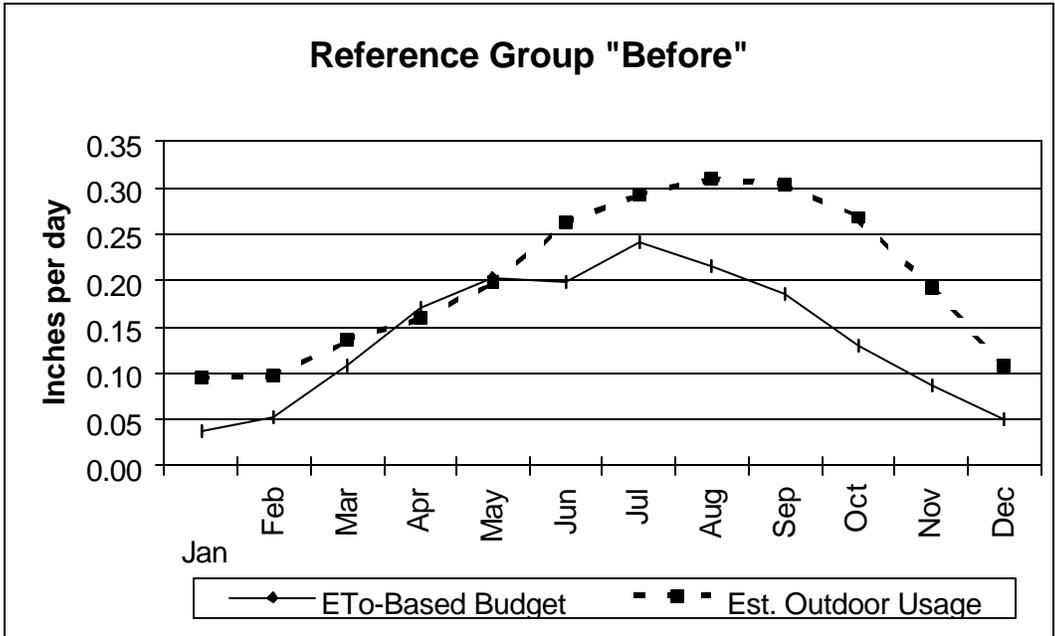


Figure 4 Reference group's estimated irrigation relative to ETo-based budget 2-year average before and 1-year after the intervention

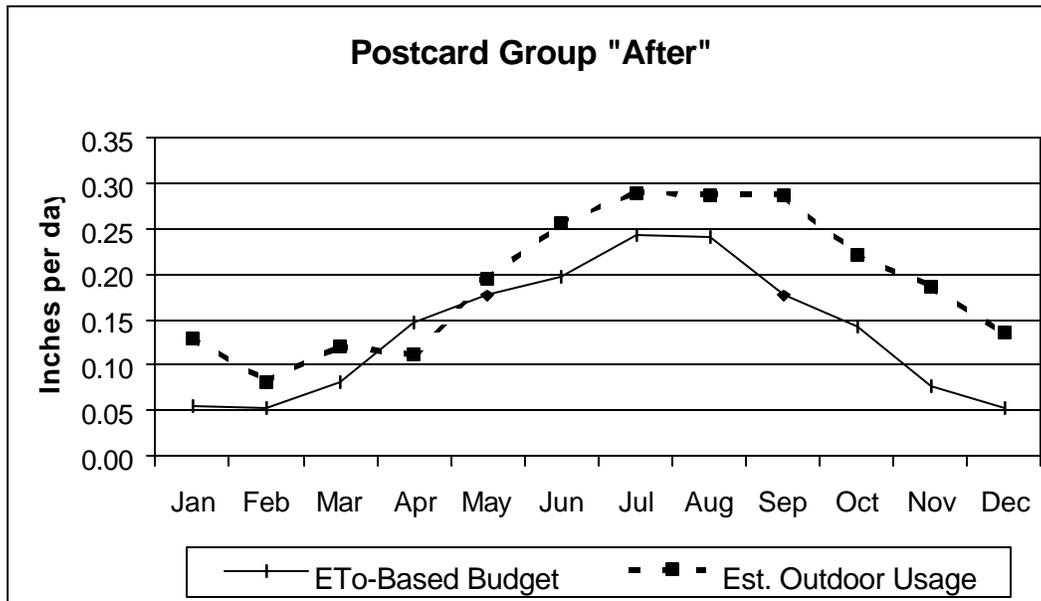
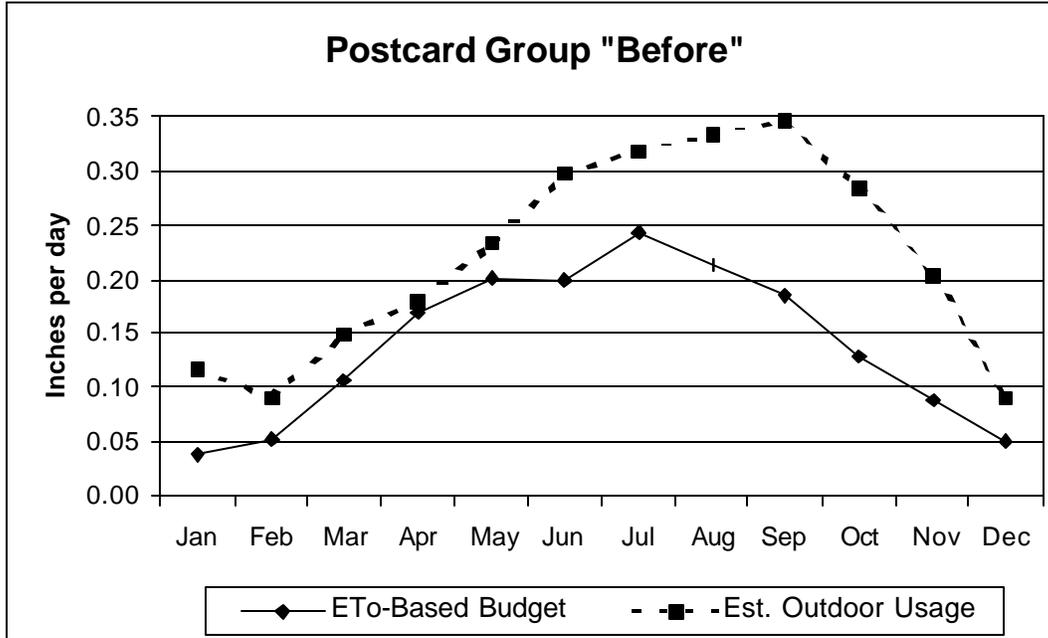


Figure 5 Postcard group's estimated irrigation relative to ETo-based budget 2-year average before and 1-year after the intervention

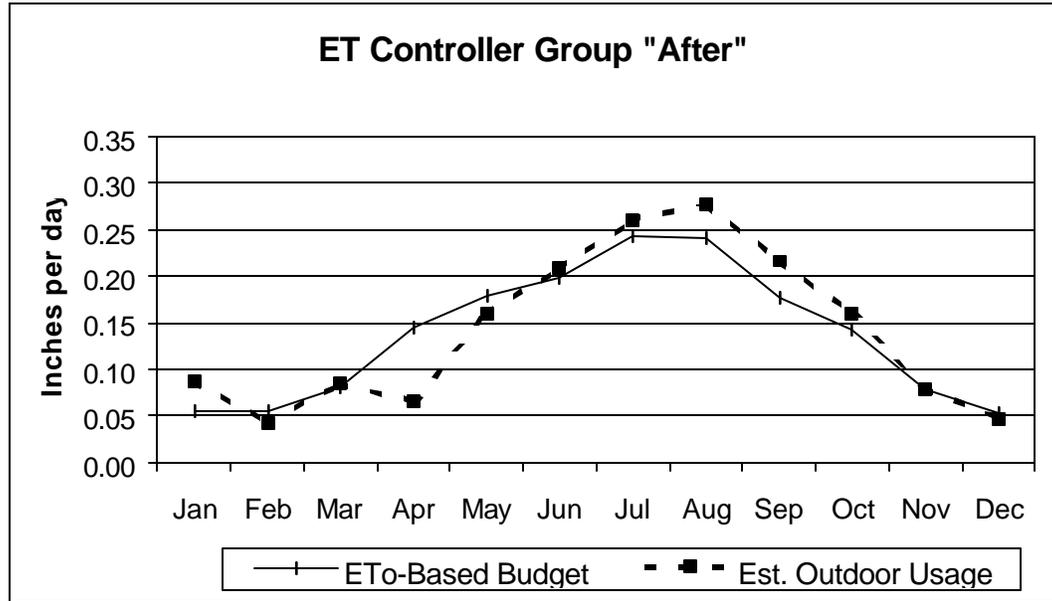
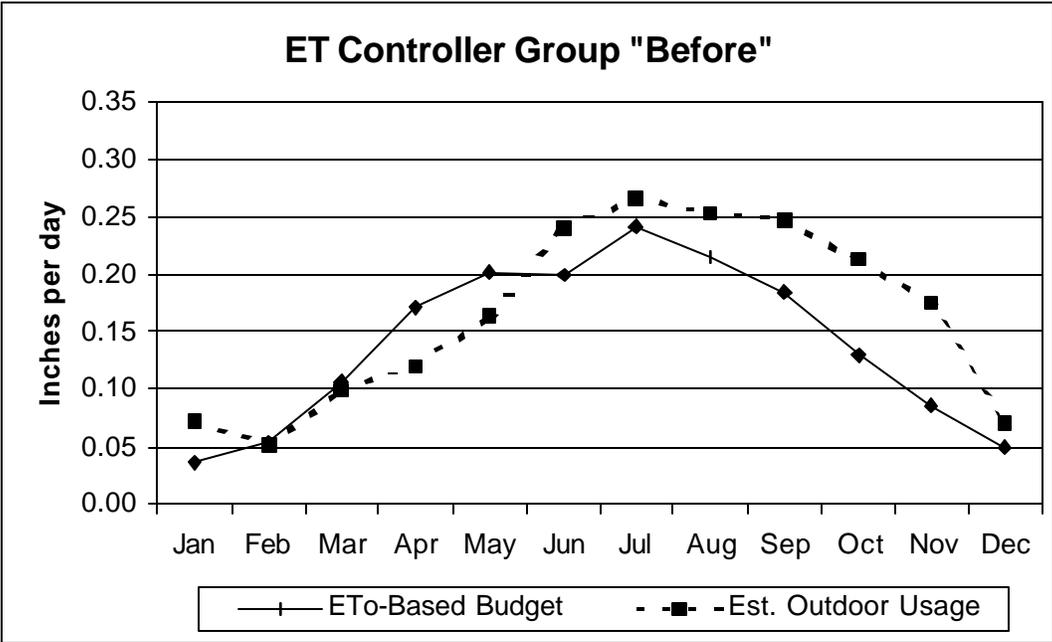


Figure 6 Controller group's estimated irrigation relative to ETo-based budget 2-year average before and 1-year after the intervention

Figure 4 shows that the reference group consistently applied more water to their landscapes than was necessary, both before and after the intervention. The reference group's behavioral stability is an indication that on-going conservation is not a significant confounding factor in

these households in general, which strengthens the overall validity of our study design. The postcard group (Figure 5) appears to have reacted favorably to the postcard reminders. Prior to the intervention, these households were applying far more irrigation than might be reasonably predicted, especially during the fall season. After the intervention the two curves appear closer, but clearly *a large portion* of the savings potential still remains untapped.

Finally, Figure 6 presents the treatment group's applied and predicted water use before and after the ET controller retrofit, which leads to two notable observations.

- First, the treatment group had lower savings potential than either the postcard or the reference group—the applied and predicted curves differ far less before the intervention. As noted earlier, according to the pre-intervention survey roughly 80 percent of the treatment households reported altering irrigation schedules either on a seasonal or monthly basis, which we believe is atypical for residential customers.
- But more importantly, the ET controller successfully *converted most of the outdoor savings potential into achieved savings*—after the intervention the applied and predicted curves almost completely overlap.¹⁰ In other words, were our treatment households to exhibit greater savings potential than they actually do, the estimated savings would correspondingly have been greater, and *vice versa*. This broader context should be kept in mind while utilizing and extrapolating the specific savings estimates presented next.

Model Estimated Savings

Water savings are estimated using a multiple regression model that weather normalizes the billing histories and removes the effects of time-invariant unobserved household heterogeneity (Appendix A). Table 1 presents the key results of these statistical analyses, which are consistent with, and should be interpreted in concert with Figure 4, Figure 5 and Figure 6.

First, the relative stability in the reference group's weather-normalized consumption before and after the intervention indicates that other possible influences, such as the impact of IRWD's budget-based rate structure, were not important confounding factors in the present setting. Second, households that received postcard reminders are quite different from those that received an ET controller retrofit (treatment). The postcard group's average consumption significantly exceeds that of the treatment group, the former has smaller landscapes on average, while the indoor-outdoor split is not appreciably different. In other words, prior to the intervention over-irrigation was a more serious problem among the postcard group relative to the treatment group, a conclusion consistent with Figure 5 and Figure 6. The results show that both the postcard reminders and ET controller retrofits have been effective at saving water, the former reducing consumption by roughly 5% (or 28.95 gallons per household per day), and the latter reducing consumption by 7% (or 37.40 gallons per household per day). Treatment group savings compare favorably to what might be

¹⁰ Appendix D compares ETo and level of irrigation implied by the signal transmitted every week. The curves show that it is possible to track weather very closely even without resorting to daily signals.

expected from a ULFT retrofit program targeted at single-family dwellings, suggesting that ET controller retrofits are an attractive water conservation option.¹¹

Table 1 Estimated Savings

Group	Normalized base use per household (gallons/day)	Average landscape per household (acres)	Reduction in total water use¹ (percent)	Total savings per household (gallons/day)	Outdoor water use as proportion of total² (percent)	Reduction in outdoor water use (percent)
Reference	535.25	0.041	≈0.00	≈0.00	42.75	≈0.00
Postcard	561.12	0.042	5.16	28.95	45.32	11.38
Treatment	533.51	0.051	7.01	37.40	42.76	16.39

NOTES: ¹Model derived estimates, of which only the postcard and treatment group savings are statistically significant (Appendix A). ²Outdoor water use is derived as the positive difference between normalized use and IRWD’s indoor allocation (the proportion is based only on pre-intervention reads).

Expressing model-estimated total savings as a percentage of outdoor consumption suggests that postcard reminders and ET controllers reduced outdoor consumption by 11.38% and 16.39% respectively. These estimates are only indicative because reliable separation of indoor and outdoor use is somewhat difficult. We have used the positive difference between total consumption and IRWD’s indoor allocations to estimate outdoor use and thereby the indoor-outdoor split, but potentially other methods can be employed as well. For example, statistical models can be used to predict minimum winter usage at a zero evapotranspiration level to estimate indoor use. Although not foolproof, this method was tried and it tended to lower the proportion of outdoor to total water consumption—for the treatment group the model-based estimate worked out to 35 percent in contrast to the roughly 43 percent generated by the indoor-allocation method. A lower estimate of outdoor base use implies that ET controllers may have caused a greater percentage decline in outdoor use than Table 1’s results imply—up to 20 percent in the case of the treatment group.

Results of ET Controllers vs. Postcards

Some may be tempted to conclude from Table 1 that the marginal effectiveness of ET controller retrofits is quite small relative to postcard reminders. This line of reasoning is faulty for several reasons. Figure 6 clearly indicates that the treatment group had a lower savings potential to begin with, but more importantly, most of this potential was successfully converted into achieved savings by the ET controller. Although postcard reminders also generated significant savings, a large part of the savings potential still remains unexploited (Figure 5).

The data underlying **Figure 5** and **Figure 6** suggest that ET controllers were able to convert roughly 85 percent of the outdoor conservation potential into achieved savings whereas postcard reminders converted only about 30 percent.

¹¹ Just how attractive ET controller retrofits will be for water agencies depends on the cost of the controller and the expected water savings. See the section on cost effectiveness for a more complete discussion.

IRWD's steep inclining rates and extensive customer education in combination with the postcard group's high consumption perhaps explains to a great extent why postcard reminders worked so well. Accordingly, this finding may not apply to other agencies that have not opted for aggressive conservation rates. A more reasonable interpretation of these findings is that in the presence of conservation rates and customer education, postcard reminders can serve as a useful backup option for reducing outdoor consumption in large single-family homes that choose not to opt for an ET controller.

Estimating Potential Savings in IRWD's Service Area

Estimating likely savings from ET controllers involves a different set of uncertainties than, say, a ULFT retrofit program. In the case of ULFTs, an unobserved behavioral parameter such as flushes per day remains an important driver of total savings along with observed parameters such as people and toilets per household. With ET controllers, however, behavioral uncertainty is not as significant an issue because irrigation scheduling passes into expert hands. Instead, ET controller savings are mostly a function of irrigation efficiency (extrapolated from prior consumption history) and landscape size, factors that are potentially observable at low cost. Plant material is also an important factor, but much less significant than landscape area and efficiency and was therefore removed from the remainder of the estimation model. In other words, the key drivers for achieving savings (landscape size and historical consumption) can be formulated into eligibility criteria for an individual home to participate in an agency-sponsored program.

We saw earlier that the treatment group's pre-intervention conservation potential was much less than both the reference and postcard groups. So, the next question we asked was how well does the treatment group's savings potential compare to what might be broadly found in IRWD's service area?

IRWD's Service Area

The study team sought to expand the estimate of water savings potential across differing sized residential landscapes, based on the 33 treatment home results. IRWD's billing database includes the landscape square footage, or its approximation, for all its residential customers. This data was used to construct a model of savings potential throughout IRWD's service area.

IRWD divides its service area into 29 villages, with the bulk of single-family homes located in 21 villages. Billing data for the year 1999 was collected for roughly 27,000 single-family customers located in these 21 villages. From these, 9,927 customers were identified as potentially suitable for an ET controller retrofit.

Two simple criteria were used to screen suitable customers. First, customers were eliminated if their metered consumption in the months of May through November fell below their indoor allocation, which, at a minimum, is 12 hundred cubic feet (HCF) for a thirty day period. This criterion was used to remove both the low water using households as well as the extended summer vacationers. Extended summer vacationers would taint estimates of conservation potential (although many of these homes may be perfectly suited for an ET

controller retrofit). Second, customers were eliminated if their average use in February and March of 1999 fell below 90 percent of the indoor allocation. This second criteria removes those households for whom the indoor allocation is so generous that estimates of outdoor use would be significantly understated. While average consumption was not used to screen households, over 85 percent of the selected households have a normalized base use greater than 400 gallons per day.

Outdoor conservation potential among the screened households was estimated as follows. Each meter read was matched with actual and long run normal weather by aggregating daily actual and normal ETc of turf grass for all days covered by the read. Outdoor water use was estimated as the positive difference between total consumption and the indoor allocation. Outdoor water use was then weather normalized to reflect what it would have been in a normal weather year, aggregated across all reads in the year, and converted into applied inches-per-day using information about landscape areas contained in IRWD’s billing system. “Predicted” inches-per-day corresponding to each read is estimated as the product of normal ETc and the inverse of the irrigation efficiency (assumed to be 80 percent). Both the applied and predicted inches per day reflect annual daily averages. The difference between applied and predicted inches-per-day then provides an estimate of the conservation potential.

For this model, the likely achieved savings were obtained by taking the product of the conservation potential in inches, landscape area, appropriate scaling constants, and the ET controller’s efficiency in converting conservation potential into achieved savings—85% as per the treatment group’s experience. Good arguments can be made for using a figure either higher or lower than 85 percent as the potential savings estimator, so the study team opted for this figure for illustrative purposes as it was the number resulting from the analysis.

Table 2 Conservation Potential Among Targeted Single-Family Homes

Village	No. of customers	Per household		Applied irrigation (inches/day)	Predicted irrigation (inches/day)	Per household normal year savings (gall./day)	Per household reduction in total use (percent)	Per household reduction in outdoor use (percent)
		normal year use (gall./day)	Average landscape area (acres)					
CAL HOMES	161	505.71	0.0351	0.2061	0.1360	56.80	11.23	28.90
COLLEGE PARK	281	499.56	0.0380	0.1915	0.1362	48.49	9.71	24.56
CULVERDALE	174	519.81	0.0438	0.1816	0.1359	46.27	8.90	21.40
DEERFIELD	239	508.81	0.0400	0.1936	0.1363	52.91	10.40	25.16
FOOTHILL RANCH	966	530.64	0.0488	0.1751	0.1362	43.86	8.27	18.89
GREENTREE	191	500.86	0.0378	0.1924	0.1349	50.27	10.04	25.43
IRVINE WEST	110	489.16	0.0335	0.2101	0.1361	57.18	11.69	29.92
NEWPORT BEACH	23	499.11	0.0351	0.2156	0.1371	63.49	12.72	30.95
NEWPORT COAST	388	656.06	0.0655	0.1997	0.1360	96.33	14.68	27.12
NORTHWOOD	2017	511.23	0.0380	0.2028	0.1361	58.49	11.44	27.96
PEPPERTREE	138	522.83	0.0442	0.1863	0.1362	51.16	9.78	22.88

PORTOLA HILLS	462	571.71	0.0594	0.1654	0.1362	40.01	7.00	14.99
RACQUET CLUB	120	511.89	0.0348	0.2243	0.1361	70.82	13.84	33.44
THE COLONY	243	506.56	0.0405	0.1862	0.1364	46.44	9.17	22.70
THE RANCH	283	515.43	0.0416	0.1892	0.1359	51.20	9.93	23.95
TURTLE ROCK	1241	632.86	0.0681	0.1766	0.1359	64.17	10.14	19.63
TUSTIN RANCH	813	571.38	0.0489	0.2052	0.1359	78.24	13.69	28.70
UNIVERSITY PK	168	475.18	0.0389	0.1688	0.1360	29.44	6.19	16.50
WESTPARK	759	512.04	0.0395	0.1994	0.1362	57.70	11.27	26.96
WILLOWS	133	478.81	0.0352	0.1867	0.1361	41.03	8.57	23.02
WOODBIDGE	1017	506.81	0.0372	0.2009	0.1360	55.70	10.99	27.46
OVERALL	9927	539.69	0.0460	0.1903	0.1360	57.67	10.69	24.24

The Results

To repeat, the questions we were attempting to answer were:

- How well does the treatment group’s savings potential compare to what might be broadly found in IRWD’s service area? (In other words, what would the eligibility criteria have to be to achieve savings in excess of 37 gallons per household per day?)
- How many single-family homes in IRWD’s service area meet such a criteria?
- Which is most important, efficiency or landscape size?

We can infer the answers from the above model (Table 2) results.

To the first question: Westpark Village (the setting for our pilot study) does not by any means stand out as a unique sub-region of IRWD with low conservation potential. While Westpark Village homes are not collectively different from other IRWD villages, as noted earlier, the treatment group was significantly different. It is purely due to adverse selection¹² that our treatment group came to include homes with lower than average conservation potential. Of course, early adopters of any new conservation technology tend to be those already predisposed toward conservation, so adverse selection in this instance is hardly surprising. Relative to the 759 Westpark households in this analysis, the treatment group exhibited only half as much pre-intervention conservation potential, while the postcard group exhibited roughly a quarter more, with the reference group being representative of the 759 households.

To the second question, roughly a third of Irvine’s single-family homes had sufficiently high outdoor water use to achieve savings far in excess of the 37 gallons per day achieved by the 33 test homes.

To the third question, savings in gallons-per-day differ across villages because of both differences in average landscape size as well as the conservation potential, or level of

¹² The “adverse selection” being addressed by the analysis is “observable” selection bias, namely participating households had less conservation potential than neighboring non-participating households. Not specifically verified is the “non-observable” characteristics that would cause lower-potential homes to fall into the treatment group. We posit that homes volunteering to test this technology might have some conservation ethic that pre-disposes them towards greater efficiency.

efficiency (difference between applied and predicted inches-per-day). Though there was a great deal of variation, in general, the larger landscapes did appear to be more efficient.

Overall, conservation potential appears to be 0.0543 (0.1903 – 0.1360) inches-per-day. If ET controllers were able to accomplish the 85% rate of increased efficiency observed in the treatment homes, they could yield per-household savings around 57 gallons per day, which translates into a 10.69% reduction in total water use, or a 24.24% reduction in outdoor water use.¹³

Targeting households by landscape area

For the district-wide model, we did not screen households based upon landscape area because IRWD's billing system contains mostly estimates, not actual measurements of these areas, though some homes do have actual landscape area. If a household has a larger landscape relative to what is coded in the billing system, our estimate of conservation potential is likely to be too high since using the correct area would lower applied inches-per-day, leading to a smaller difference between applied and predicted inches-per-day, and *vice versa*. Although we expect positive and negative differences between actual and estimated landscape areas to substantially cancel out over such a large sample, the overall estimate of conservation potential (Table 2) may nonetheless be somewhat overstated.

If for now, however, one takes the estimate of average conservation potential as a given (0.0543 inches-per-day), it is possible to address how setting eligibility standards according to landscape area is likely to affect achieved savings. For example, if IRWD desired to obtain household savings of no less than 50 gallons-per-day, it would target only homes with landscapes exceeding 1,738 square feet ($0.0543/12$ feet of average conservation potential per day \times 1738/43560 acres of landscape \times 325900 gallons per acre-foot \times 0.85 [85 percent] conversion of potential to achieved savings = 50 gallons per household per day). To the extent conservation potential is higher or lower in areas other than IRWD, which it may well be because of prior conservation history and rate structures, appropriate adjustments must be made to the above estimation procedure.

Program cost-effectiveness

The newness of ET controllers makes it difficult to pin down with certainty key drivers of cost-effectiveness, such as the initial purchase price or useful life. Although water savings per household also remains uncertain given the limited scope of this study, water agencies may partially influence this parameter by targeting certain homes or setting appropriate eligibility criteria. The best information available at this time suggests that the controller will cost approximately \$100 per unit, installation an additional \$75, with an ET signal fee

¹³ The reader is reminded that the original sample from which the treatment group was drawn was the top 20% consuming households in Westpark. That factor, along with the other observable and non-observable characteristics of the treatment group make the assumption of an 85% rate of improved efficiency to other households questionable. As noted earlier in the text, this rate was used for illustrative purposes, not as true predictor of expected savings.

of \$4 per month. The signal fee is expected to include the cost of customer service. The useful life is expected to be between 10 and 15 years.

We present two example cost-effectiveness scenarios; one with a six percent discount rate and one without. Per-household daily savings are assumed to be 57 gallons (.064 acre feet per year) as per results presented earlier (Table 2).¹⁴ The discount rate is set at 6 percent as per MWD’s practice and recommendation.

Table 3 Cost-Effectiveness of Weather-Based Controller Retrofits

	10-year useful life, 6% discount			10-year useful life, no discount				
	Cost	Cust. benefit ¹	IRWD benefit ²	MWD benefit ³	Cost	Cust. benefit ¹	IRWD benefit ²	MWD benefit ³
Purchase cost	\$100				\$75			
Installation cost	\$75				\$75			
Lifecycle signal cost (\$4 per month)	\$353				\$480			
Lifecycle water savings (.064 AF per year)		\$338	\$204	\$72		\$460	\$278	\$98
LIFECYCLE TOTAL	\$528	\$338	\$204	\$72	\$655	\$460	\$278	\$98

NOTES:

¹Valued at \$720 per acre-foot, the average retail price of water in Southern California.

²Valued at \$435 per acre-foot, the price at which IRWD purchases water from MWD.

³Valued at \$154 per acre-foot, per MWD’s Conservation Credits Program guidelines.

Under both scenarios, the combined benefits of the customer and water agencies exceed the costs. Since neither the customer nor the agencies alone have benefits that exceed costs, the solution may be for agencies and customers to split costs in some manner. Again, the underlying numbers are assumptions used for illustration.

Cost-effectiveness For The Customer

At the rate of 57 gallons per day, the ET controller is not cost-effective for the customer, based on water savings alone. The customer’s water savings would have to exceed 89 gallons per day to equal the \$528 total lifecycle cost. However, a customer could perceive benefits from an ET controller other than just water savings, such as convenience, savings in time, landscape appearance improvement, and so on.

Although the true amount customers would be willing to pay for these additional lifestyle features remains unknown, post-test survey results support the expectation that customers would be willing to at least pay the monthly signal fee. The fact that total cost is borne partially up-front and mostly in small increments over a long period may influence customer purchases. These payment and “lifestyle features” may prove so valuable to some customers that they would be willing to pay the entire associated costs, regardless of whether any water was saved or not.

¹⁴ The 57 gallons is used for presenting this example only. It is not to suggest that this number would *actually* be achieved in any implemented program.

Cost-effectiveness for The Water Agencies

This sample cost-effectiveness analysis indicates that the value of water savings alone does not exceed the entire associated costs. However, likely savings are significant enough to warrant some type of subsidy program, such as a rebate, installation assistance, co-payment of the signal fee, or some combination.

Ideally, an agency should create a subsidy for customers just high enough to get the customer to respond, but no higher than is cost-effective for the agency. In this example, per-household water savings alone are worth anywhere between \$204 and \$278 to IRWD and \$72 and \$98 to its wholesaler MWD, the maximum level of resources the respective agencies can cost-effectively commit to a program. Because customers' level of willingness to pay is unknown at this point, the optimal level of subsidy is also unknown. As noted in the previous section, it is possible that customers will so highly value the payment and/or lifestyle features of the ET controllers they would buy them outright, needing no subsidy from the agency to encourage the purchase.

V. CUSTOMER SATISFACTION

Post-test Survey

Treatment group households were re-surveyed roughly a year (October 1999) after the ET controller retrofits took place with two purposes in mind: (1) to gauge customer satisfaction with the new controllers and the appearance of their landscapes; and (2) to identify households that had made significant alterations to indoor and outdoor end uses even though all treatment households had in principle agreed not to do so for a year following the retrofits (Appendix C—Post-test Survey Results). Although approximately a quarter of the households reported having made some change to their landscapes or irrigation systems, or reported a change in the number of residents, only in the case of three treatment households were these changes deemed significant enough to warrant exclusion. Field personnel were highly familiar with sites reporting either landscape or irrigation system changes and were able to provide feedback about which of the reported changes were significant.

Key findings from the post-test survey include:

- 97% of the households described landscape appearance as improved (51%) or stayed the same (46%) during the trial period.
- 97% found the controller technology convenient.
- 54% saw a decrease in water bills. (Analysis of water bills showed that 85% of test homes water bills went down when compared to the previous 3 years of bills)
- 22% did not know if bills changed.
- 14% described that bills stayed the same. (Analysis of water bills showed that 9% of test homes bills stayed relatively the same when compared to the previous 3 years of bills.)
- 8% claimed bills increased. (Analysis of water bills showed that 6% of test homes bills increased when compared to the previous 3 years of bills.)

Further analysis of responses revealed that while 77% did not experience any problems with the ET controller, 23% cited experiencing some type of problem, which in their view was associated with the new controller. The problems described included:

- No signal received. IRWD staff site visits suggest that perhaps controllers in a few test sites failed to receive 3 signals during the 12-month study period. This is thought to be a result of localized, intermittent interference with signal reception at a particular site or the result of residents turning the controllers “off” during rains, causing the failure of the signal to be picked up by the controller.
- Residents attempted to change the controller times. The controller and transmitted signal account for rain events and soil moisture depletion rates and as such no resident intervention is necessary.

- Too much water was applied to backyard. Test sites were re-visited as appropriate and total run-times were reduced until an appropriate irrigation level was reached (i.e., no wet spots in yards). Over-watering can happen if plant type, sprinkler precipitation rate, sun or shade, etc. are not correctly identified and input into the initial controller set-up.
- The controller came on during or after a rainstorm. If too small an amount of rain falls, the controller would activate to apply water to satisfy the need for an adequate soil moisture reservoir, but the customer being unaware of the underlying irrigation science may perceive this occurrence as a problem.
- Not enough water was applied, or “my grass is turning brown...” IRWD staff inspected these sites to find a variety of *non-controller* related problems, such as broken sprinkler heads, valves stuck closed, or a break in the irrigation wiring. When customers complained that their landscape “looked dry,” IRWD staff used a soil probe to determine that there was adequate soil moisture in the plant root zone. Residents were observing the soil surface which appeared dry and concluded that too little water was being applied. In other words, these people associated visible moisture with appropriate irrigation, which usually is not the case.

Based on the field inspections, IRWD staff found that malfunctioning controllers were not the cause of any of reported problems. Problems were due to other factors, such as broken sprinkler heads, stuck valves, shorted valve wiring, and so on. But these sorts of complaints underscore the need for after-installation assistance for residents who opt for weather-based controllers. Overall, 83% of the test home respondents felt the controller performed well or very well.

Landscape Quality and Customer Satisfaction

It was apparent from customer responses and visual inspections that the landscape quality remained steady or improved in the majority of test homes during the study. Without adequate or improved plant quality, no amount of water savings will convince households to utilize such a technology. The fact that water use and water bills generally decreased while landscape appearance held steady or improved, contributed to the high level of customer satisfaction with the ET controller.

It is not a surprise to the study team that general landscape quality improved with the proper application of water. Plants were neither drowned nor stressed during the test. Water was applied in a way so as to move it deeper into the soil and plant root zones, potentially increasing root depth. Yet, ample opportunities were also created to allow the soil to dry adequately, allowing oxygen to move into the soil profile, which is known to improve general root health.

VI. CONCLUSIONS AND RECOMMENDATIONS

Through the 1990s water agencies have tried to promote efficient outdoor water use through home audits and education. The impact of audits and education programs, however, declines rapidly over time.¹⁵ The prospect of irrigating residential landscapes on the basis of scientific principles, without intervention by the homeowner, is largely a result of advancements in wireless technology, microprocessor size, memory capacity and lower data transmission costs. These new satellite messaging controllers promise to make a significant dent in residential outdoor consumption—not just over the short-term—but spanning the life of the controller, at present expected to be around 10-15 years. Reducing the behavioral uncertainty associated with the homeowner should, in theory, lead to reliable and long-lived water savings. The much greater certainty of these savings should allow water agencies to (1) design new conservation programs for residential customers, (2) save significant amounts of urban water, (3) potentially reduce the cost, size and timing of infrastructure expansion, (4) provide for improved peak demand management, and lastly, (5) provide a new drought management tool.

Synopsis of Study Intent and Design

This study reports findings from the first field trial undertaken to evaluate the water savings and cost-effectiveness of real-time, ET-based controllers. The controllers reflected the science underlying irrigation scheduling, ensuring that the right amount of water is applied at the right time and at the proper root depth.

The test controllers were installed in 40 homes and remotely scheduled until a full year of post-retrofit consumption data had been obtained. At the end of the year, seven homes had to be excluded from analysis for various reasons, such as a change of the resident. In addition to the test homes (treatment group), two other sets of households were included in the evaluation: a “reference group” to identify extraneous factors (if any) that would account for any changes measured in the treatment group, and a “postcard group.” The postcard group was created to evaluate an alternative method of increasing customer sensitivity to weather by periodically sending a postcard with a suggested watering schedule as the weather changed. All these households were selected from among high water users (top 20%) located in one of IRWD’s single-family development tracts (Westpark Village). Savings were estimated by comparing two years of pre- and one year of post-retrofit consumption data. At the end of one year the test homes were also surveyed to obtain information about their satisfaction with weather-based controllers.

Water Savings

The statistical analyses demonstrate that weather-based (or ET) controllers are very effective at curbing wasteful irrigation practices, or in other words, converting conservation potential into achieved savings. In the test homes, ET controllers were able to convert almost 85% of

¹⁵ Chestnutt, T.W., C.N. McSpadden, and D.M. Pikelney, *What is the Reliability Yield from Residential Home Water Survey Programs?*, presented at the AWWA Conference in Anaheim CA, June 1995.
Whitcomb, J.B., *Residential Water Audit Evaluation*, prepared for Contra Costa Water District, August 1994.

the pre-retrofit conservation potential into achieved savings, while postcard reminders were able to convert only roughly 30%. But the data also suggest that in spite of targeting high water users, the treatment group attracted households that were already predisposed toward water conservation and, as a result, the conservation *potential* was relatively low. Still, ET controllers were able to reduce total household consumption by roughly 37 gallons per household per day, representing a 7% reduction in total household use or roughly 16% reduction in outdoor use.

Given the self-selected nature of our treatment group, additional analyses were undertaken to estimate the likely level of savings from a more representative sample of high water-using single-family homes in Irvine. These analyses suggest that by targeting roughly the top third in terms of water use, ET controllers might save roughly 57 gallons per household per day throughout Irvine Ranch Water District representing a reduction of 10 percent in total use, or 24% in outdoor use. Generalizing these savings to other communities should be done with caution.

IRWD's Unique Billing Structure

It is possible that other agencies may have a greater savings potential than IRWD because of IRWD's unique billing structure. This structure provides an individualized monthly allocation for each account, based on actual weather data fed into the billing system and calculated into each water bill. When IRWD customers use water over their allocation, it triggers progressively expensive "penalties," *up to eight times the base rate*, sending a very strong pricing signal that something is amiss with their water usage. A customer's water bill can go from the average of \$20 a month to well over \$100 in penalties alone. Consequently, it is likely that IRWD customers, collectively, are more water efficient than customers with other billing structures. Therefore, the water savings potential for this technology may be greater at other water agencies that do not have such aggressive conservation rate structures.

Customer Satisfaction

In terms of customer satisfaction, almost 97% of post-test survey group reported either no change or improvement in their landscapes, and 97% found the ET controller convenient. However, customers frequently and mistakenly attributed problems with their landscapes to the ET controller, suggesting that future programs would be greatly enhanced by devoting resources to customer education and assistance.

Problems Discovered and Recommended Solutions

Resident Misperceptions

When the soil surface looked dry, some participants assumed that the controller was not providing enough water for the plants. IRWD corrected this misperception by visiting the site and taking soil samples using a soil probe so that residents could "see" and "feel" that the moisture level was sufficient. In a large program, this problem could be overcome by providing a soil probe and instructions with every home controller so that residents can perform this simple test for themselves or be talked through it over the phone.

Rain Events

Although participants were instructed to not change the settings on the controller, a few participants still turned their controllers off during rain events. If a resident turns the controller off during a short rain, the rain alone may not be enough to wet the soil down into the plant's root zone. The test controller used ET and its relation to the depletion of soil moisture to determine if landscapes need water with or without rain events. Therefore, homeowners need to get a clearer message not to re-program the controllers.

Rain falls unevenly across communities. A single weather station cannot provide site-specific measurement. Due to the high public scrutiny of running irrigation during a rain event, this finding shows the need to provide simple rain shut-off devices as a level of protection against too much water being applied and/or sprinklers coming on during or directly after rain events.

Irrigation Systems

While the study did not attempt to fix irrigation systems in test homes, it was clear that even more water could have been saved if irrigation systems (leaks, breaks, pressure, blocked heads, etc.) were upgraded. It is evident that an irrigation system "fix-it" program could help save additional water.

Customer Assistance

The study team believes that the personal response provided to the participants during the study was intrinsic to the overall success of the controllers. Because the test controller did not have sophisticated customization features of the new satellite messaging controllers, the study team believes the simpler, yet more advanced model may likely reduce customer queries. Nevertheless, the study team believes that ET-based controllers should include assistance from staff (of the agency or a privately contracted firm) with horticultural and irrigation system expertise to address the variety of questions and problems that some (or many) customers will inevitably have. The new model will be easier to apply across-the-board percentage adjustments to baseline schedules as well as to make specific adjustments for new plantings, plant establishment, and rain events, but will not be a panacea for all irrigation problems that will arise.

Cost-Effectiveness and Targeting

Apart from water savings, customers may value and desire the convenience associated with ET controllers so highly that they purchase them without any agency involvement. During the pre-test survey, over 66% of the treatment group appeared willing to pay up to \$125 for the controller and up to \$4 per month for the signal fee.

On the other hand, agencies may find that customers do not install these controllers at a desirable rate and they may have to offer a subsidy of some sort (rebate, assistance, co-payment, etc.) to encourage installations. In this case, agencies will find that targeting select

homes with greater potential will be more cost-effective. Water agencies can employ one or more of the following criteria for targeting single-family homes in their service area:

- Outdoor water use as percentage of total
- Summer/winter differential
- Higher water users
- Square footage lots (assuming larger landscapes and more water usage)
- Existing home survey data indicating potential for landscape savings

In Irvine alone, the expanded analysis projected that roughly 10,000 single-family homes (about one third of the total stock) might benefit with an ET controller and that, combined, these homes could possibly save over 200,000,000 gallons (614 acre feet) per year.

Installation

For a large-scale retrofit program to be cost-effective, however, these controllers must have a short set-up time and perhaps also have customer self-install capability.

The installation experience indicates that set-up of the individual irrigation scheduling parameters, per valve, are important to achieve maximum water savings. These parameters include:

- Type of soil (for infiltration rate of water)
- Type of sprinkler heads (for precipitation rate of water being applied)
- Type of plants being irrigated on the valve (for appropriate crop coefficient and root depth)
- Slope of area being irrigated (to establish run-time and eliminate water run-off)
- The exposure for the plants (sun, part sun, shade, part shade, etc.)

While self-installation of such technology is attractive from a cost standpoint, water agencies may better meet water saving goals by providing trained installation and set-up. Installation options are suggested with distribution options below.

Potential Distribution Design Options

Below are few program design options for water agencies to consider based upon each option's pros and cons, as well as each agency's unique circumstances. Our options are meant to be illustrative, not exhaustive, nor does the study team endorse any particular one option.

New Development

The water agency can require builders to include ET controllers in all new single-family and multi-family homes as part of the permitting process. Activation and payment of the signal service is done by the eventual resident.

Existing Development

The goal of current conservation efforts statewide is to identify and retrofit high water use with low water use fixtures. The public recognizes and accepts these types of programs, and agencies are well versed in their implementation.

PROS

CONS

Option 1: Rebate on controller and installation; resident pays for ongoing signal service

- Fastest method to distribute technology to end users
- Existing rebate program models
- Resident pays long-term signal fee
- High quality installation
- Residential data can be collected/verified
- Product and program costs for agency
- Resident could jeopardize savings by discontinuing signal service

Option 2: Rebate on controller, agency charges/pays for signal service on water bill, resident installs or pays for installation

- Agency insures signal service is maintained
- High distribution expectation
- Installation quality uncertain
- Set up of signal fee billing
- No potential for collecting site data

Option 3: Agency finances controller, installation and signal fee and recoups costs from customers over time through water bills. Can be provided with or without rebates.

- High quality installation
- Ease for customer
- No or low long-term cost for agency
- Site data collected/verified
- Agency provides total up-front cost
- Legality of controller billing at the time of home resale unclear

Option 4: Water agencies educate customers on the benefits of ET controllers and purchase locations; a rebate voucher may be included; self installation

- Low agency cost
- Installation quality uncertain
- No potential for collecting site data
- Resident could jeopardize savings by discontinuing signal service
- Low likely distribution rate
- Free ridership may be high

APPENDIX A—MODEL SPECIFICATION AND ESTIMATION

Conceptual Model

A logical way of modeling staggered billing data is to conceive the model at a daily level and then scale it up to the meter-read level. Equation (1) expresses logarithmically transformed daily consumption (U_{it}) for customer (i) at time (t) as a function of the daily weather index (W_t), say, the evapotranspiration rate, customer characteristics (X_i), daily intercept terms (\mathbf{a}_i) and random error (\mathbf{e}_{it}). This model is very flexible insofar the intercept terms and weather coefficients are conceptually allowed to vary on a daily basis. Intercept terms are necessary because intervening human factors make consumption's relationship with weather somewhat sticky. Irrigation decisions, to some extent, are based upon experience and "gut feel." A weather index alone is therefore unlikely to fully capture variation in consumption by time of year.

$$\begin{aligned} \ln(U_{it}) &= \mathbf{a}_i + \mathbf{b}_i W_t + \mathbf{h} X_i + \mathbf{e}_{it} & (1) \\ \text{where } \mathbf{e}_{it} &\sim N(0, \mathbf{s}^2) \end{aligned}$$

Daily consumption is logarithmically transformed because water consumption is generally distributed with a long right-hand tail. And usually, even accounting for customer heterogeneity and seasonality is not sufficient for normalizing model error. A couple of explanations can be offered for skewed model error. First, the most seasonal component of consumption—irrigation—is a discrete event, even when scheduled according to scientific principles. A landscape is supposed to be irrigated when daily evapotranspiration has depleted the soil water content below a certain threshold (Snyder and Sheradin, 1992). When daily evapotranspiration is low and uncertain, or rainfall is received periodically, average daily consumption may exhibit a rightward skew. Second, landscape professionals often set irrigation schedules by varying a preset baseline schedule in proportion to changes in the evapotranspiration rate. Errors are therefore proportionally magnified or diminished.

Averaging consumption across the (N) days included in a read taken at time (T) yields the meter read-level model (Equation 2). Throughout, summation operators are subscripted backward in time because meter read-dates signal the end of a consumption period. If consumption days (N) vary markedly across reads, averaging insures error homoscedasticity at the meter-read level when daily error is homoscedastic. Of course, in spite of averaging, meter read-level error will be heteroscedastic if daily error itself is heteroscedastic, in which case (2) should be estimated using generalized least squares. Autocorrelation is a different matter, however. Because of error averaging, autocorrelation at the meter-read level should be low to nonexistent even if daily error is highly autocorrelated. It can be mathematically shown that if daily autocorrelation is as high as 0.9, even then observed autocorrelation will only be 0.092 for 30-day cycle reads, and 0.025 for 61-day cycle reads (Bamezai, 1997).

$$\frac{1}{N} \sum_{i=T}^{T-N} \text{Ln}(U_{it}) = \sum_{i=T}^{T-N} \mathbf{a}_i \frac{1}{N} + \sum_{i=T}^{T-N} \mathbf{b}_i \frac{W_t}{N} + \mathbf{h}\mathbf{X}_i + \frac{1}{N} \sum_{i=T}^{T-N} \mathbf{e}_{it} \quad (2)$$

$$\text{where } \frac{1}{N} \sum_{i=T}^{T-N} \mathbf{e}_{it} \sim N(0, \mathbf{s}^2)$$

Estimation of (2) as it stands requires the creation of at least 365 daily indicator variables (equal to $1/N$ for days included in the read) for capturing the daily intercepts and another 365 interactions of these indicators with the daily weather index to capture the daily weather response. For days not included in a specific meter read the corresponding daily indicators and their interactions take on the value of zero. Such an enormous estimation exercise is unlikely to succeed not only because of the immense computing resources required but also because of multicollinearity among many of the daily indicator variables. Meter reads must be available for every day in the year to provide the variation necessary for estimating these daily parameters, but read-dates are often clustered by design. Thus, for estimation purposes, it is necessary to impose some simplifying restrictions on these daily parameters.

An option is to assume that the daily intercepts (\mathbf{a}_i) and the weather response coefficients (\mathbf{b}_i) are equal for all days in a given month. Doing so reduces the estimation problem down to 12 monthly intercepts, 12 weather coefficients, and other customer characteristics included in the model. It is not necessary to place the same restrictions on (\mathbf{a}_i) and (\mathbf{b}_i). For example, the daily intercept terms (\mathbf{a}_i) may be fit with piece-wise linear or cubic splines (Suits et al., 1978; Robb, 1980), while the weather coefficients (\mathbf{b}_i) may be assumed constant for either all days in a month or all days in a season. The daily intercepts can also be captured using Fourier harmonics (Bamezai, 1996).

Because monthly restrictions are perhaps the most obvious choice with billing data that follow a 30-day cycle, the implication of these restrictions is developed in greater detail. Equation (3) shows what these restrictions imply for meter reads that span a total of (N) days, with (m) days falling in one month and (n) days in the next.

$$\frac{1}{N} \sum_{i=T}^{T-N} \text{Ln}(U_{it}) = \mathbf{a}_m \frac{m}{N} + \mathbf{a}_n \frac{n}{N} + \mathbf{b}_m \sum_{i=T}^{T-m} \frac{W_t}{N} + \mathbf{b}_n \sum_{i=T-m-1}^{T-m-n} \frac{W_t}{N} + \mathbf{h}\mathbf{X}_i + \frac{1}{N} \sum_{i=T}^{T-N} \mathbf{e}_{it} \quad (3)$$

To estimate (3) it is necessary to allocate the total number of days covered by a meter read to each month. In other words, 12 monthly variables must be created of which 2 take on the values (m/N) and (n/N) for any given read, the rest being zero. Similarly, the daily weather index during a read interval must also be split into month-specific aggregates. Once again 12 weather variables are required of which only at most 2 take on a nonzero value for any given read. Meter reads taken bimonthly can be handled just as easily in the above framework, the only difference being that such reads are likely to span 3 instead of 2 months.

Construction of the dependent variable in (3), however, still poses a minor problem. The dependent variable is equal to the sum of logarithmically transformed daily consumption.

But billing histories yield only the sum of daily untransformed consumption which after a logarithmic transformation does not equal the desired dependent variable (Equation 4).

$$\frac{1}{N} \sum_{i=T}^{T-N} \text{Ln}(U_{it}) \neq \text{Ln}\left(\frac{1}{N} \sum_{i=T}^{T-N} U_{it}\right) \quad (4)$$

The above inequality, however, can easily be resolved by leaning on well-known properties of a lognormal distribution.

$$\begin{aligned} \text{If} \quad & \text{Ln}(U_{it}) \sim N(\mathbf{m}, \mathbf{s}^2) \\ \text{then} \quad & E\left(\frac{1}{N} \sum_{i=T}^{T-N} \text{Ln}(U_{it})\right) = \frac{1}{N} \sum_{i=T}^{T-N} \mathbf{m} \end{aligned} \quad (5)$$

Similarly

$$\begin{aligned} \text{Ln}\left(E\left(\frac{1}{N} \sum_{i=T}^{T-N} U_{it}\right)\right) &= \text{Ln}\left(\frac{1}{N} \sum_{i=T}^{T-N} e^{\mathbf{m}_i + \frac{\mathbf{s}^2}{2}}\right) = \frac{1}{N} \sum_{i=T}^{T-N} \mathbf{m}_i + \frac{\mathbf{s}^2}{2} + \text{Ln}\left(\frac{1}{N} \sum_{i=T}^{T-N} e^{\mathbf{e}_i}\right) \quad (6) \\ \text{where} \quad & \mathbf{e}_i = \mathbf{m}_i - \frac{1}{N} \sum_{i=T}^{T-N} \mathbf{m}_i \end{aligned}$$

Under most plausible scenarios of the rate of change in average daily consumption (\mathbf{m}) over the course of 30 or 61 days, the last term in (6) converges to zero. In other words, the two quantities cited in (4) differ approximately by a constant (that is, half of the daily variance), hence are readily substitutable.

Approximating Nonlinearity and Reducing Measurement Error

If data and model diagnostics indicate that the weather index (say, the evapotranspiration rate) should either be logarithmically transformed, or that higher powers should be included as well, the framework developed in (1) through (6) can easily include such possibilities. One such case is discussed below for illustration.

Assume daily consumption is a quadratic function of weather instead of a linear function (Equation 7).

$$\begin{aligned} \text{Ln}(U_{it}) &= \mathbf{q}_i + \mathbf{w}_i W_i + \mathbf{y}_i W_i^2 + \mathbf{h} X_i + \mathbf{e}_{it} \quad (7) \\ \text{where} \quad & \mathbf{e}_{it} \sim N(0, \mathbf{s}^2) \end{aligned}$$

Under the assumption of monthly restrictions, estimation of (7) now requires 12 additional variables to capture the weather index's second power. But by applying a linear

approximation to (7) both the computational burden and the impact of measurement error can be minimized. The daily weather index is first reexpressed in terms of deviations from the daily mean, but then higher powers of the deviations are dropped (Equation 8).

$$\begin{aligned}
 \ln(U_{it}) &= \mathbf{q}_t + \mathbf{w}_t(\bar{W}_t + \Delta W_t) + \mathbf{y}_t(\bar{W}_t + \Delta W_t)^2 + \mathbf{h}\mathbf{X}_t + \mathbf{e}_{it} & (8) \\
 &\Rightarrow \ln(U_{it}) \approx \mathbf{a}_t + \mathbf{b}_t\Delta W_t + \mathbf{h}\mathbf{X}_t + \mathbf{e}_{it} \\
 \text{where } \mathbf{a}_t &= \mathbf{q}_t + \mathbf{w}_t\bar{W}_t + \mathbf{y}_t\bar{W}_t^2 \\
 \mathbf{b}_t &= \mathbf{w}_t + 2\mathbf{y}_t\bar{W}_t
 \end{aligned}$$

After the linear approximation the essential structure of (8) is identical to (1), except that by working with daily deviations in the weather index, an approximate nonlinear weather specification is implicitly assumed without any increase in the computational burden. Bamezai (1997) demonstrates the validity of this approximation. Two additional benefits also accrue from the above approximation. First, the daily intercepts (or monthly if so constrained) provide a direct measure of average consumption on a particular day (or month) in a normal weather year—the differenced weather index is centered at the mean by construction. Second, a systematic time bias in the weather index’s mean caused by lack of information about plant material by customer is likely to influence the deviations significantly less. A differenced weather specification (8) therefore simultaneously minimizes the impact of systematic measurement error while capturing an approximate nonlinear weather response. Even if weather response is linear, a differenced weather index is preferable to an undifferenced index: either index will yield identical results in the absence of measurement error, but the former is likely to be more accurate in the presence of measurement error.

Weather Index Construction

For the analyses that follow, weather variation is captured through a rainfall adjusted evapotranspiration-rate index (Equation 9). The evapotranspiration rate measures a plant’s total water demand. It is necessary to subtract effective rainfall from the evapotranspiration rate to accurately predict net irrigation demand. The daily evapotranspiration and rainfall data are obtained from CIMIS’s Irvine station.

$$W_t = \max[0, (ET_t^R K_t^C - P_t u)] \quad (9)$$

where

W	daily weather index (inches)
ET^R	daily reference evapotranspiration rate (inches)
K^C	monthly crop coefficient
P	daily precipitation (inches)
u	effective proportion of precipitation
SR	surplus effective rainfall carryover

CIMIS's ET^R represents the water demand of 4- to 6-inch-tall, cool-season grass transpiring at its maximum rate. In reality, plant height, plant roughness, plant age, ground shading, and other factors, all influence actual evapotranspiration needs of a plant (Snyder, 1993). To stay consistent with how IRWD calculates outdoor allocations, monthly crop coefficients for cool season turf are used to correct the reference evapotranspiration rate. Meyer and Gibeault (1987) originally estimated these crop coefficients. Half of daily rainfall is assumed to be effective as per CIMIS's recommendation, but when effective rainfall exceeds total evapotranspiration demand, net evapotranspiration demand is floored at zero. As mentioned earlier, the science underlying irrigation is essentially a stock and flow problem (Snyder and Sheradin, 1992). Soil moisture content (stock) must be maintained within a certain threshold. Evapotranspiration (flow) reduces the stock on a daily basis, effective rainfall adds to it intermittently, with irrigation acting as the balancing lever. A weather index constructed using a stock and flow framework is likely to be a better predictor of irrigation demand—the most weather-sensitive portion of total demand.

Model Results

Water reductions achieved through the ET controllers and postcard reminders were estimated by analyzing billing histories controlling for weather and other unobserved time-invariant differences across households. All households analyzed here follow a 30-day billing cycle. Thus the model relates the logarithm of average daily consumption to a vector of covariates including monthly time indicators and weather deviations constructed as per the conceptual framework described earlier. Weather variables were constructed from daily deviations in the weather index to capture a nonlinear weather response. Weather effects for the months of July through October were pooled since the month-specific weather effects were not significantly different from one another. The weather index is not logarithmically transformed since it does not exhibit a rightward skew. Upon examination, model errors reveal significant heteroscedasticity. The final models therefore incorporate a heteroscedasticity correction based upon methods discussed by Carroll and Ruppert (1988).

Table 4 displays three models among which the last (Fixed-Effects Model B) is our preferred specification. This model accounts for unobserved heterogeneity across households, and exhibits strong predictive power as indicated by the highly significant time dummies and weather coefficients, as well as a relatively high adjusted-R Square. The time dummies behave as per expectation, indicating minimum usage in the month of February and maximum in the months of July and August. A RESET test was unable to reject the null hypothesis of no omitted variables bias. This model shows that after the intervention average daily consumption declined by 7.01 percent ($e^{(-0.073 - ((0.016^2)/2)} - 1)$) in the treatment group and 5.16 percent ($e^{(-0.053 - ((0.012^2)/2)} - 1)$) in the postcard group.

The other two models are included to make the following additional observations. First, the savings estimates are not sensitive to the selected model specification because the treatment and postcard group savings estimates are virtually identical across all three models. Second, the postcard group used more water than both the reference and treatment groups prior to the intervention as indicated by the positive and significant postcard-group indicator coefficient (OLS Model). Finally, the reference group's consumption did not change significantly over

the time period analyzed here, a conclusion that holds whether one ignores household heterogeneity (OLS Model) or takes it into account (Fixed-Effects Model A).

Table 4 Estimated Water Savings Model

Covariate	OLS Model	Fixed Effects Model A	Fixed Effects Model B
	Coefficient (Std. Err.)	Coefficient (Std. Err.)	Coefficient (Std. Err.)
February indicator	-0.166** (0.037)	-0.169** (0.030)	-0.171** (0.030)
March indicator	0.002 (0.029)	0.001 (0.023)	-0.001 (0.023)
April indicator	0.099** (0.030)	0.096** (0.025)	0.094** (0.024)
May indicator	0.282** (0.029)	0.280** (0.023)	0.278** (0.023)
June indicator	0.362** (0.033)	0.361** (0.026)	0.362** (0.026)
July indicator	0.415** (0.030)	0.413** (0.024)	0.410** (0.024)
August indicator	0.415** (0.030)	0.414** (0.024)	0.413** (0.024)
September indicator	0.398** (0.031)	0.394** (0.025)	0.392** (0.025)
October indicator	0.279** (0.030)	0.278** (0.025)	0.276** (0.024)
November indicator	0.145** (0.031)	0.144** (0.025)	0.142** (0.025)
December indicator	-0.092** (0.040)	-0.096** (0.032)	-0.098** (0.032)
January weather deviation	9.248** (2.066)	9.360** (1.663)	9.738** (1.625)
February weather deviation	8.312** (1.237)	8.297** (0.995)	8.320** (0.995)
March weather deviation	6.946** (1.009)	6.894** (0.812)	6.741** (0.799)
April weather deviation	6.141** (0.951)	6.078** (0.766)	5.818** (0.726)
May weather deviation	4.595** (0.635)	4.510** (0.511)	4.455** (0.509)
June weather deviation	4.308** (2.446)	4.432** (1.968)	4.918** (1.915)
July through October weather deviation	0.896 (0.510)	0.918** (0.411)	0.952** (0.409)
November weather deviation	8.635** (2.665)	8.640** (2.145)	8.613** (2.145)
December weather deviation	8.057** (2.560)	7.950** (2.060)	8.154** (2.051)

Covariate	OLS Model	Fixed Effects Model A	Fixed Effects Model B
	Coefficient (Std. Err.)	Coefficient (Std. Err.)	Coefficient (Std. Err.)
Treatment group indicator	0.004 (0.012)		
Postcard group indicator	0.040** (0.010)		
Treatment group indicator × Post-intervention indicator	-0.071** (0.020)	-0.071** (0.016)	-0.073** (0.016)
Postcard group indicator × Post-intervention indicator	-0.051** (0.016)	-0.052** (0.013)	-0.053** (0.012)
Reference group indicator × Post-intervention indicator	0.009 (0.010)	0.009 (0.008)	
Constant	-0.585** (0.024)	-0.014 (0.047)	-0.011 (0.047)
Adjusted R-square	0.271	0.528	0.528

NOTE: **Significant at 5 percent level.

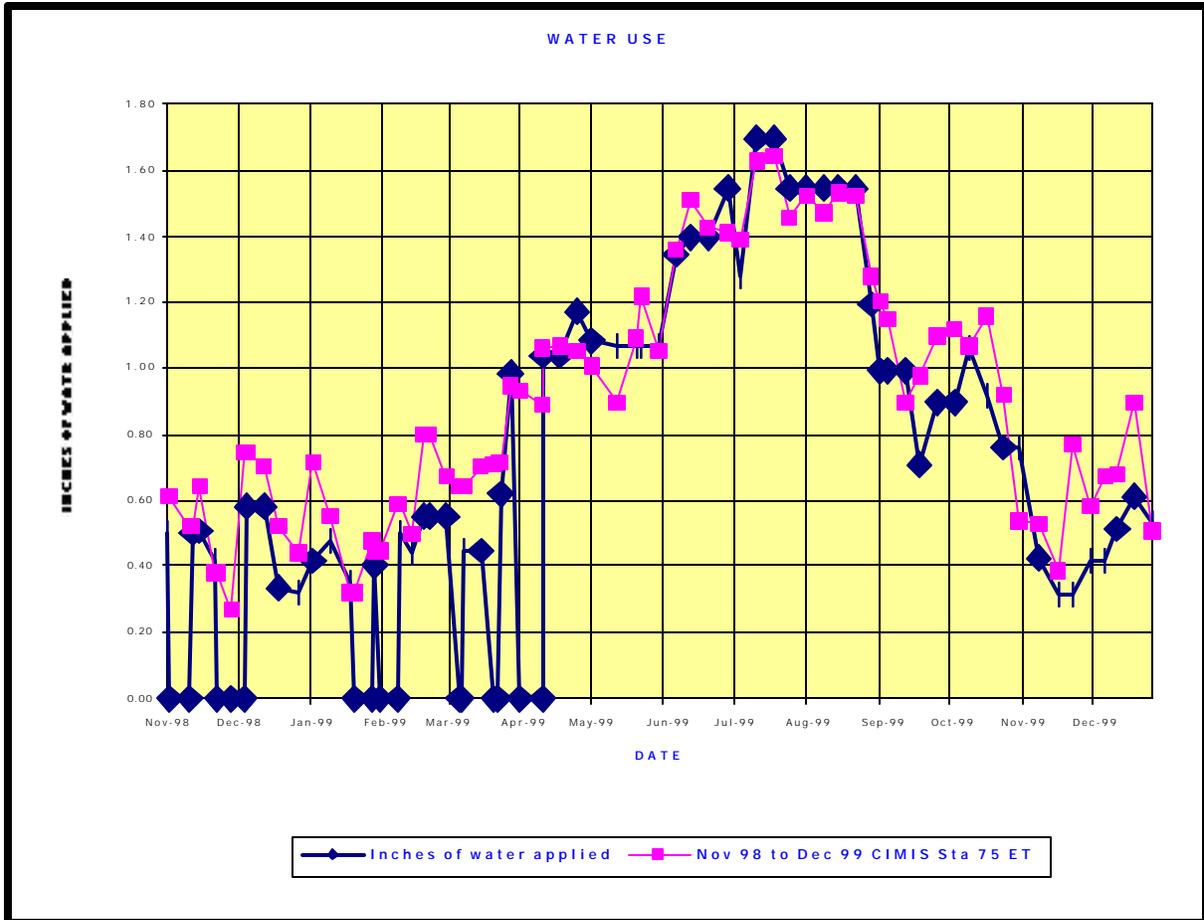
APPENDIX B—PRE-TEST SURVEY RESULTS

Name: _____ IRWD ACCT # _____

1. Who currently sets or programs your controller?
You (64.7%) Gardner (17.6%) Other (17.7%)
 2. How often do you change or reprogram your landscape irrigation controller?
Weekly (0.0%) Monthly (11.8%) Seasonally (67.7%) Never (5.9%) DK (14.7%)
 3. Is your current controller easy to program or schedule?
Easy (38.2%) Somewhat Easy (47.1%) Somewhat Difficult (8.8%) Difficult (5.9%)
 4. Do you know how often and/or how much to water?
Always (2.9%) Most of the time (38.2%) Sometimes (26.5%) DK (32.3%)
- How much water is needed for trees, shrubs and ground cover relative to turf?
- | | | | | | | | |
|----------------|---------|---------|---------|---------|---------|------|---------|
| 5. Trees | 25% | 50% | 75% | Same | 200% | 300% | DK |
| | (14.7%) | (14.7%) | | (38.2%) | (11.8%) | | (20.6%) |
| 6. Shrubs | 25% | 50% | 75% | Same | 200% | 300% | DK |
| | (14.7%) | (17.7%) | (5.9%) | (38.2%) | | | (23.5%) |
| 7. Groundcover | 25% | 50% | 75% | Same | 200% | 300% | DK |
| | (8.8%) | (11.8%) | (11.8%) | (38.2%) | | | (29.4%) |
8. What do you like most about your current irrigation controller?
 9. What do you like least about your current irrigation controller?
 10. Would you be willing to pay for a controller that allows the watering to be automatically adjusted to weather conditions?
Yes (82.3%) No (17.7%)
 11. How much would you pay for a controller that allows the watering to be automatically adjusted to weather conditions?
\$75 (20.6%) \$100 (41.2%) \$125 (8.8%) \$150 (14.7%) \$200 (2.9%) No (11.8%)
 12. How much would you pay every month for a paging service that adjusts your controller to weather conditions for you?
\$1 (26.5%) \$2 (14.7%) \$3 (17.7%) \$4 (5.9%) \$5 (20.6%) No (14.7%)
 13. When selecting a controller, how important is saving water?
Very important (70.6%) Somewhat important (23.5%) Somewhat unimportant (0.0%) Not Very Important (5.9%)
 14. When selecting a controller, how important is saving money?
Very important (64.7%) Somewhat important (26.5%) Somewhat unimportant (8.8%) Not Very Important (0.0%)
 15. When selecting a controller, how important is convenience?
Very important (76.5%) Somewhat important (23.5%) Somewhat unimportant (0.0%) Not Very Important (0.0%)
 16. Rank the overall appearance of your home landscape.
Excellent (5.9%) Good (61.8%) Fair (32.3%) Poor (0.0%) Very Poor (0.0%)

17. Is IRWD's home water allocation process fair?
Always (23.5%) Most of the time (47.1%) Sometimes (17.6%) Rarely/Never (11.7%)
18. Overall, how satisfied are you with the service you receive from IRWD?
*Very Satisfied (67.7%) Somewhat Satisfied (32.3%) Somewhat Dissatisfied (0.0%)
Very Dissatisfied (0.0%)*

APPENDIX D—WEATHER TRACKING SCHEDULE



APPENDIX E—TEST CONTROLLERS VS. SATELLITE MESSAGING CONTROL SYSTEMS

This appendix is meant to clarify the known differences between the controllers tested in this study and other remotely-controlled irrigation controllers. The major thrust of this appendix is to emphasize the simplicity of the study’s controllers. These controllers’ primitive, limited features make them unlike any controller found in the market or ever likely to come on the market.

The purpose of the study was more to test the effectiveness of the signal and residential customer response to this type of device rather than provide the flexibility needed in marketable home controllers.¹⁶

	<u>Test Controller</u>	<u>Retail Controller</u>
<u>Type of sprinkler</u>	Limited to “spray heads” or “rotors.”	Program in the manufacturer’s precipitation default or individualized precipitation rate.
<u>Soil type</u> (for appropriate infiltration rate and soil moisture depletion rate)	Did not have this feature, but all sites had the same clay soil type, which was factored into the signal.	Program in clay, loam, sandy loam, sandy, etc.
<u>Plant type</u> (for individualized water requirement setting and root depth for setting proper run cycles)	Limited to “cool-season turf” or “shrubs.”	Program in type of turf, shrubs, trees, flowers, etc.
<u>Microclimate</u>	Could not distinguish microclimates.	Program in for each valve: sun, part sun, shade, part shade, etc..
<u>Slope</u> (to determine the proper maximum run-time that minimizes water run-off)	Could not distinguish slope.	Program in degree of slope

¹⁶ The manufacturer of the test controllers has developed a marketable product, WeatherTRAK™, in part based upon the feedback and in-field experience with the test devices.

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