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SOIL MOISTURE SENSORS FOR URBAN LANDSCAPE IRRIGATION: EFFECTIVENESS AND RELIABILITY[1]

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ABSTRACT: Granular matrix soil moisture sensors were used to control urban landscape irrigation in Boulder, Colorado, during 1997. The purpose of the study was to evaluate the effectiveness and reliability of the technology for water conservation. The 23 test sites included a traffic median, a small city park, and 21 residential sites. The results were very good. The system limited actual applications to an average of 73 percent of the theoretical requirement. This resulted in an average saving of $331 per installed sensor. The sensors were highly reliable. All 23 sensors were placed in service at least three years prior to the 1997 study during earlier studies. Of these, only two had failed by the beginning of the 1997 study, both due to external factors. Including replacement of these failed sensors, the total repair cost for the 1997 irrigation season was less than $270. The effort required to maintain each system was small, only about 6-7 minutes per visit. Each site was visited weekly for this study, but less frequent visits could be made in practice. The sensors observed in this study performed well, significantly reduced water consumption, and were easy to monitor and maintain. Soil moisture sensors appear to be a useful and economical tool for urban water conservation.
(KEY TERMS: evapotranspiration; soil moisture; instrumentation; irrigation; meteorology/climatology; urban hydrology; water conservation; water resources education.)

INTRODUCTION

Urban water use and the factors that modulate it have been studied extensively in order to understand how to promote water conservation (Anderson *et al.*, 1980; Webb, 1997). Many have been economic studies that sought relationships between the price of water and the quantity consumed by means of regression analysis (Howe and Linaweaver, 1967; Danielson, 1979; Foster and Beattie, 1979; Hanke and de Mare, 1982; Nieswiadomy and Molina, 1989; Nieswiadomy, 1992;). However, price is unable to explain all of the variability in water use, particularly within the annual cycle. Hence, other variables have been included to explain additional variation, including air temperature, precipitation, lot size, property value, and number of residents per household (Danielson, 1979; Foster and Beattie, 1979; Maidment and Miaou, 1986; Miaou, 1990; Lyman, 1992; Bamezai, 1994, 1997). A few studies have included some measure of potential evapotranspiration (ET) (Morgan and Smolen, 1976; Anderson *et al.*, 1980; Nieswiadomy and Molina, 1989; Webb, 1997). In contrast to variables related to indoor consumption, such as number of residents per household, weather variables (including air temperature, precipitation, and ET) relate to outdoor landscape irrigation. Although agreement is not unanimous, the findings with respect to weather generally show that irrigation usage is most strongly correlated to air temperature (Danielson, 1979; Maidment and Miaou, 1986). Precipitation is usually a much weaker determinant. When irrigation usage is related to precipitation, usage tends to be more strongly correlated with the number of days of precipitation within a given billing cycle than with the depth of precipitation during that period (Maidment and Miaou, 1986; Miaou, 1990). Some studies that have included ET have found usage to be more weakly correlated with ET than with temperature (Morgan and Smolen, 1976). Net ET, defined as ET less effective precipitation, is even more weakly correlated to usage than is total ET (Morgan and Smolen, 1976).

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Despite the fact that air temperature and number of days of precipitation show up as stronger determinants in actual water consumption, ET and precipitation should be the factors to govern irrigation. These latter two factors directly control the water balance of the soil and vegetation, and therefore determine the quantity and timing of required supplemental irrigation. Given that air temperature and number of days of precipitation are not necessarily the best indicators of plant water requirements, it is advantageous to promote technology that can control water use in a way that is directly related to plant water needs.

Soil moisture sensors represent one such technology. They can be hard-wired into a clock-driven irrigation system so as to inhibit or allow a scheduled irrigation in response to the variations in the moisture state of the soil (Norrie *et al.*, 1994).

There are several categories of soil moisture sensors, which include:

- Capacitance/Time Domain Reflectometry (TDR)
- Neutron Probe
- Resistance
- Tensiometer

Campbell and Mulla (1990) discuss these in detail. We used resistance type sensors in this study. Resistance type sensors include Gypsum block and granular matrix sensors (GMS). These are relatively inexpensive sensors, which rely on variation of the resistance to electrical current within the sensor as a function of soil moisture content.

Soil moisture sensors have been applied mostly for irrigated agriculture (Tripathi, 1992; Norrie *et al.*, 1994; Singh *et al.*, 1995). The large spatial scales, the monetary value of crops, the large quantities of water used, and the corresponding high costs, to buy both the water and the electricity to pump it to a field, compensate for the investment in the sensors. However, soil moisture sensors are valuable for use in urban lawn irrigation as well. Not only can they reduce the direct cost to the consumer associated with the purchasing of water, but they can also reduce peak demand that may postpone or eliminate significant indirect costs associated with increasing the capacity of an existing water distribution system. In the arid to semi-arid west, outdoor water consumption for irrigation in urban areas accounts for approximately 40 to 50 percent of annual water use (Linaweaver *et al.*, 1967; Winje and Flack, 1986). From a study performed in a subdivision of Boulder, Colorado, the average outdoor use was 54 percent of the total annual use (Mayer, 1995). During the summer months, the percentage is much higher. Thus, reduction in urban water use for irrigation has the potential to have a significant impact on water consumption and required system capacity.

There is a hesitance on the part of homeowners and landscape contractors to employ soil moisture technology. Since the areas irrigated are relatively small, there is concern that the cost to purchase, install, and operate soil moisture sensors will outweigh the savings through reduced consumption. Other concerns relate to unknowns such as the longevity of the sensors, difficulty of use, and capability of sensors to modulate irrigation appropriately. Part of this hesitance is justified based on negative past experiences with gypsum block resistance sensors. These dissolve over time, which alters their response to soil moisture, and renders them inoperative within a couple of years.

Granular Matrix Sensors (GMS) may alleviate some of these problems. The granular matrix is made of an inert material so dissolution is not a problem. Some GMSs contain a thin gypsum wafer in their core, but this wafer seems to be less susceptible to the problems of gypsum block sensors (Shock, 1998).

GMS sensors have been used in agricultural settings with good results (e.g., Stieber and Shock, 1995; Shock *et al.*, 1996, 1998a, 1998b). In order to demonstrate their potential for urban irrigation, DeOreo and Lander (1995) conducted a two-year urban study of GMSs in Boulder, Colorado. In that study, two GMSs were hardwired into automatic lawn irrigation systems of a traffic median and a small city park, and 33 sensors were installed at single family residences and common areas of homeowner associations. The results are encouraging. For example, during the summer of 1994, which was a drought year, the increase in applied irrigation among the GMS outfitted homes was limited to an increase of 0.68 percent above the average annual irrigation for the previous five years, compared to an average increase of approximately 15 percent for a control group of nine homes from the same neighborhood with automatic sprinkler systems but without GMSs.

Despite the success of the sensors, some homeowners and landscape contractors continue to express reluctance over their use. This is related to the aforementioned concerns over longevity, difficulty of use, etc. In addition, even though it was verified at the end of the season on the basis of meter readings that the sensors had limited irrigation relative to the actual sprinkler system setting, and relative to a control group of homes without soil moisture sensors, some homeowners and landscape contractors felt an uneasiness because they were unable to verify the success of the GMS sensors mid-season.

METHODS

We initiated the present study to address the concerns expressed above. This was done in two ways:. First, we documented the GMSs continued capability to modulate irrigation effectively after several years in the ground, and developed a simple method by which homeowners and landscape contractors could track the performance of the sensor within a season relative to ET based on historical climate records or on readily available current weather conditions. Second, we documented the time and cost required to adjust, maintain, and repair the GMSs. In the following four subsections, we discuss: (1) irrigation system operation with and without soil moisture sensors, (2) how we calculated evapotranspiration, (3) how we determined the theoretical irrigation requirement by means of a water balance for comparison with actual use, and (4) the details of the field work.

Irrigation System Operation

A schematic diagram of the irrigation installations used in this study appears in Figure 1. It consists of four components: (1) a standard clock which may be set to schedule irrigation at regular intervals for a specified duration; (2) field valves that are controlled by the clock to start and stop irrigation; (3) Granular Matrix Sensors (GMS) to measure soil moisture; and (4) an electronic module (WEM) which takes a reading from the soil moisture sensors and either allows or prevents a scheduled irrigation cycle, depending on the soil moisture condition.

Typically, landscape irrigation systems include only the first two components. The user sets the clock to initiate irrigation at regular repeat intervals (e.g., once per day, every other day, etc.). At the scheduled time, the clock sends a signal to the field valves which causes them to open so that water may flow to the

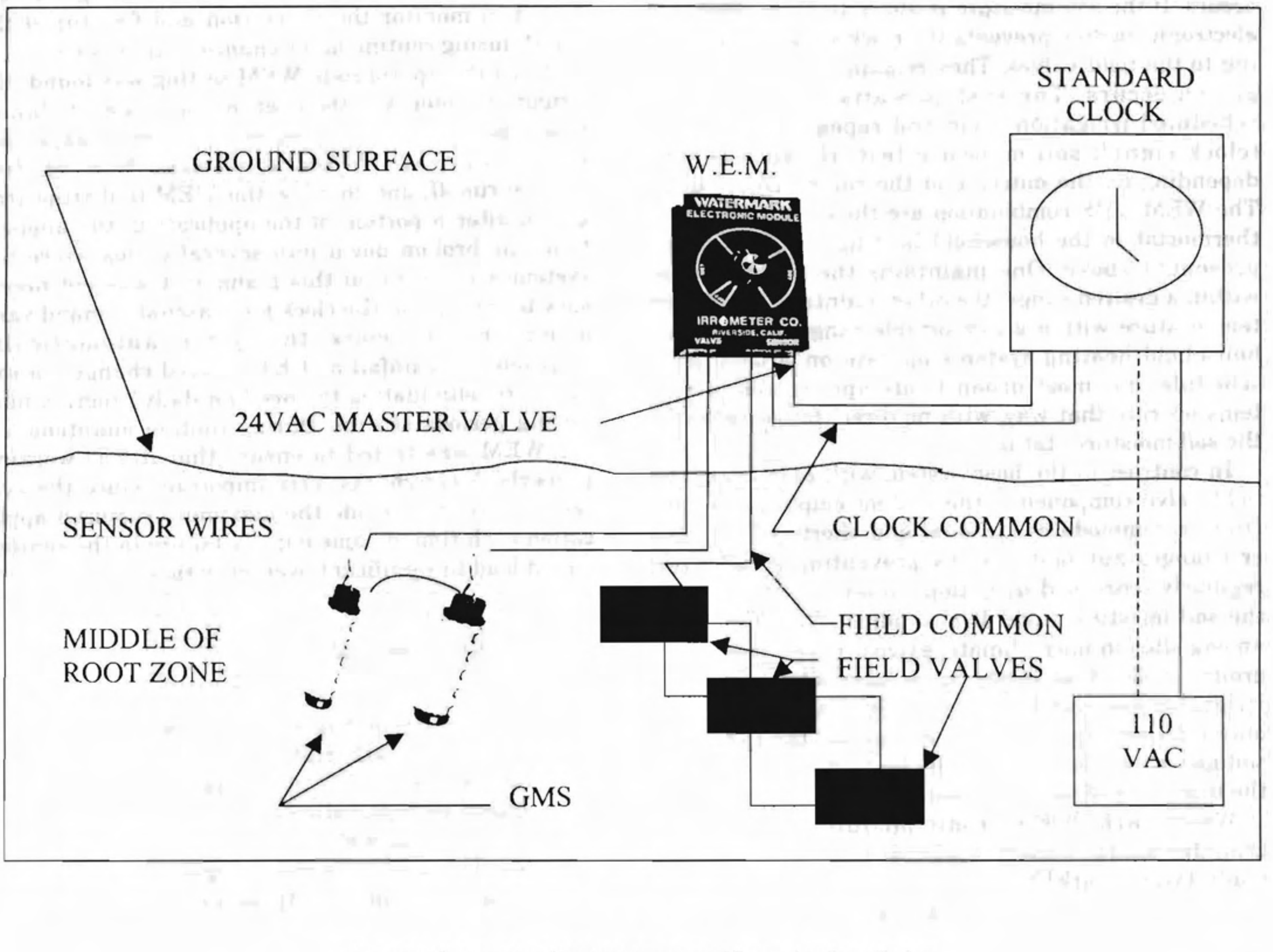

Figure 1. Schematic of Typical Automated Irrigation Installation.

sprinkler heads. The clock holds the valves open for a user-selected duration, then shuts them until the next scheduled irrigation cycle. This process recurs at the user-established interval regardless of whether the landscape needs water. Operating an irrigation system on a regular schedule like this is similar to running one's household heating system on a fixed time schedule. It would be impossible to select a schedule that would maintain the indoor temperature within the desired range from day to day, much less from one season to another. In the context of irrigation, the user must change the clock repeat interval and/or duration settings manually throughout the irrigation season as water demands change due to seasonal and short-term variations in weather.

The installation used in this study and shown in Figure 1 incorporates soil moisture instrumentation. An electronic module is wired into the system so that it intercepts the clock signal intended to open the field valves. The signal causes the electronic module to take a measurement from the soil moisture sensors. If the soil moisture is below a user-adjusted threshold, the electronic module passes the clock signal on to the field valves, they open and irrigation occurs. If the soil moisture is above the threshold, the electronic module prevents the clock signal from passing to the field valves. They remain shut and no irrigation occurs. The system waits until the next scheduled irrigation cycle and repeats the process (clock signal; soil moisture test; irrigate or not, depending on the outcome of the soil moisture test). The WEM/GMS combination are the counterpart to a thermostat in the household heating system analogy presented above. One maintains the soil moisture within a desired range, the other maintains indoor air temperature within a comfortable range. Few, if any, household heating systems operate on a fixed time schedule, but most urban landscape irrigation systems operate that way, with no direct feedback about the soil moisture status.

In contrast to the base system with only clock and field valve components, the system employed in this study accommodates seasonal and short-term weather changes automatically by preventing or allowing regularly scheduled irrigations to occur depending on the soil moisture state. It also adjusts for differences among sites in microclimate, exposure, soil types, and ground slopes that would cause some sites to require irrigation more or less frequently than others. The only requirement is for the user to set the threshold soil moisture level individually on each site's WEM at the beginning of the irrigation season.

Watermark™ Electronic Modules (WEM) and granular matrix sensors (GMS) were employed in this study. (Watermark™ is a registered trademark of the Irrometer Company of Riverside, California. The trade name is provided for information only. This article does not constitute endorsement of Watermark™ sensors on the part of the authors or AWRA.) The soil moisture sensors are electrical resistance sensors in which stainless steel electrodes are protected with both gypsum and granular silica media. The soil moisture sensors were buried at mid-root depth at each study site. A WEM receives the clock signal at the start of each irrigation cycle. It measures the resistance across the soil moisture sensors, which varies with moisture conditions, and overrides the clock signal when soil moisture is above the user selected threshold. The user selects soil moisture levels with an adjustment knob on the WEM.

At the beginning of the irrigation season, we adjusted the dial on the WEM as described below. Initially, we set the WEM dial to the "dry" position. When the turf was just beginning to show signs of stress, typically three to four days after irrigation, the WEM threshold was adjusted to the point where it was on the verge of initiating irrigation. At this setting, the WEM initiated irrigation at the beginning of the next scheduled sprinkler cycle following the onset of mild plant stress. After this initial setting, we continued to monitor the vegetation and fine-tuned the WEM during routine maintenance as necessary.

When the appropriate WEM setting was found, the irrigation timer was then set to come on everyday, or every other day. The duration was set to apply the maximum one or two day requirement. To avoid large surface runoff, and to allow the WEM to disrupt irrigation after a portion of the application, the application was broken down into several cycles. Once the system was set up in this manner, it was not necessary to reprogram the clock for seasonal demand variations. Furthermore, the system automatically responded to rainfall and ET induced changes in soil moisture, eliminating the need for daily programming during periods of rain. During routine maintenance, the WEM was tested to ensure that it was working properly. Field checks were important since the system was set to provide the maximum required application each time it came on; any failure in the sensors would lead to significant over irrigation.

Potential Evapotranspiration

ET can be calculated by several means. Methods that include radiation as the driver of ET have a physical basis since ET is simply one component of the surface energy balance. Two examples are the Penman (1948) and the Priestley and Taylor (1972) methods. However, radiation is not commonly measured. Various "index" methods to estimate ET exist for use where limited climate data are available. These methods relate one phenomenon to another empirically without explicitly considering the physics of the processes relating the two. Blaney and Criddle (1952, 1960) have proposed one such "index" method, which relates ET to mean monthly temperature and daylight hours.

The Soil Conservation Service (1970) modified the original Blaney-Criddle equation (hereafter B-C) to improve its accuracy. The modification introduced an additional monthly climatic coefficient, k_{Tm}, and new tables for the original monthly crop coefficient, k_{Cm} (Soil Conservation Service, 1970; Cuenca, 1989). The climatic coefficient k_{Tm} is a linear function of monthly mean temperature, T_m, in which T_m serves as a surrogate or "index" for changes in monthly mean radiation. The crop coefficient, k_{Cm}, accounts for growth stages throughout the growing season tailored to a particular crop. Monthly ET is given by the B-C method as:

$$E_{Tm} = k_{Cm} * k_{Tm} * f_m$$

$$k_{Tm} = 0.0173 * T_m - 0.314 \tag{1}$$

$$f_m = p_m * T_m/100$$

where the subscript m is a month index, T_m is monthly mean temperature in °F, f_m is the consumptive use factor, and p_m is the percentage of daylight hours in month m to total annual daylight hours. Seasonal gross evapotranspiration requirements may be determined by summing the monthly values throughout the growing season.

Values of p_m, and k_{Cm} for turf grass for April through September in Boulder, Colorado, are given in Table 1 (Blaney and Criddle, 1962; Soil Conservation Service, 1970; Doorenbos and Pruitt, 1977; Chow *et al.*, 1988; Cuenca, 1989; Aquacraft, 1995).

TABLE 1. Monthly Crop Coefficients, k_{Cm} and Percentages of Total Annual Daylight Hours for Boulder, Colorado.

Month	k_{Cm}	p_m (percent)
April	1.00	8.93
May	1.25	10.01
June	1.30	10.09
July	1.30	10.22
August	1.20	9.55
September	0.95	8.39

In order to track the effectiveness of the soil moisture sensors in modulating irrigation, we calculated ET at a weekly or smaller time step. The B-C method was modified to correspond to the daily time step of the temperature and precipitation data used in this study. Daily values of mean temperature, T_d, were substituted for monthly mean temperatures, T_m, and p_m was converted to percentage of daily daylight hours to total annual daylight hours, p_d, as a constant for a given month. Values for p_d are determined by dividing the monthly percentage of daylight hours p_m by the number of days in the month, n_m. The equations are summarized below:

$$ET_d = k_{Cm} * k_{Td} * f_d$$

$$k_{Td} = 0.0173 * T_d - 0.314 \tag{2}$$

$$f_d = (p_m/n_m) * T_d/100$$

where ET_d is daily evapotranspiration in inches, k_{Td} is the climatic coefficient calculated with daily mean temperatures, and f_d is the daily consumptive use factor.

ET_d may be aggregated over any time period to produce an estimate of the cumulative ET over that time period. In this case, it will be aggregated over week-long periods to correspond to the frequency of irrigation water meter readings. Due to the nonlinearity in Equation (2), the estimate of cumulative ET based on the summation of daily values over a month, ΣET_d, will exceed ET_m slightly. It can be shown that $\Sigma ET_d - ET_m$ is equal to $0.0173*k_m*p_m*var(T_d)*(n_m-1)/n_m/100$, where $var(T_d)$ is the variance of mean daily temperature during the month m. During 1997, this amounted to an average of 0.077 inches per month, or 0.462 inches over the entire six-month irrigation season from April through September. This was less than 1.4 percent of the cumulative seasonal ET, which is an acceptable error.

Consumptive use by plants is not well correlated with temperature over short time periods (Blaney and Criddle, 1962). Nevertheless, one expects ET to increase on warm days and decrease on cool days so calculation of ET on a daily time step provides a view of the general trend in ET. Furthermore, aggregation of ET over weekly or longer time steps reduces the errors so that they are negligible as indicated above. While the Blaney-Criddle method may be inappropriate where precise estimates of daily ET are required, the methods proposed in this study are intended to provide homeowners and contractors with a simple, rough estimate of ET to provide feedback as to whether a soil moisture sensor is properly modulating irrigation. The Blaney-Criddle method, which uses readily available empirical constants and temperature data, lends itself well to this type of application.

Water Balance

In order to measure the performance of the soil moisture sensors it was necessary to have a standard against which actual irrigation applications could be compared. The most reasonable value to use for this purpose was the weather driven irrigation requirement based on net evapotranspiration (ET_N). ET_N is the amount of water in excess of rainfall that the vegetation requires to satisfy its metabolic requirements for maximum growth, given by

$$ET_N = ET - P_e \qquad (3)$$

where P_e is effective precipitation, defined for irrigation applications as the amount of precipitation that can be applied to meet evapotranspiration requirements (Cuenca, 1989; ASCE, 1990).

Since the soil acts as a small reservoir, a simple water balance may be written to account for changes in storage due to precipitation input and ET demand.

$$\Delta S = P_e + I_e - ET = I_e - ET_N \qquad (4)$$

where ΔS is the change in moisture stored in the soil, and I_e is effective irrigation. In the present study, we ran a simulation of Equation (4) on a daily timestep to determine the cumulative theoretical irrigation requirement and its temporal distribution. In the simulation, we assumed the soil moisture reservoir to be full initially, due to accumulation of water from snowmelt and spring rains. When the soil moisture deficit due to ET_N exceeds a specified threshold, the theoretical irrigation requirement is the depth of water needed to replenish the soil reservoir. The cumulative theoretical irrigation requirement, which will be equal to cumulative ET_N divided by the irrigation efficiency, discussed below, will be used as the standard against which actual GMS-controlled irrigation application is compared.

Neither precipitation nor irrigation is 100 percent effective in replenishing soil moisture. For sprinkler irrigation there may be system leaks, water may be blown from the intended area before it reaches the turf, runoff may occur, and some of the applied water may be intercepted and evaporate from the surface of the leaves without having the chance to infiltrate and increase the soil moisture storage. In this study, the irrigation efficiency, e_I, was taken as 90 percent. This number is typical of sprinkler applications during nondaylight hours (Barrow, 1987; Dash, 1995; Mays, 1996).

The quantity of effective precipitation, P_e, depends upon the amount, duration, and intensity of the precipitation, current soil moisture conditions, and the depth of the root zone of a specific crop (Blaney and Criddle, 1962). The Soil Conservation Service (1970) and Blaney and Criddle (1962) developed empirical methods to determine P_e. In order to simplify the methods for daily use by homeowners and landscape contractors, P_e was taken to be 80 percent of the total rainfall. Also, any rainfall in excess of that needed to replenish the soil moisture deficit at the time of rainfall was excluded from P_e (Criddle, 1958).

Using P_e, ET, and the irrigation system application efficiency, e_I, the theoretical irrigation requirement was determined to be

$$I = I_e/e_I = ET_N/e_I = (ET - P_e)/e_I \,. \qquad (5)$$

Field Study

As noted in the introduction, this study, which was performed in 1997, was aimed at collecting information about the reliability and cost-effectiveness of the use of soil moisture sensors to govern clock driven irrigation systems. During an earlier study (Aquacraft, 1995), a number of sensors had been installed. The fieldwork conducted for the present study was aimed at collecting complete information about the same sensors to address the concerns raised in the soil sensor review meeting by participants in the earlier studies. The participants included homeowners and landscape contractors. The issues to be addressed were: (1) how well this group of sensors operated after being in the field for several years; (2) how frequently problems and errors occurred with the sensors; (3) the types of remedial actions required; and (4) the time and cost required to operate and troubleshoot the system in the field.

Of the original participants, we were able to reenlist the 23 sites identified in Table 2. Two were located in a park and traffic median owned and maintained by the City of Boulder, four were on residential properties, and the remaining 17 sensors were installed in two residential communities maintained by two independent landscape contractors.

We field checked each system initially, made any necessary repairs, and documented the time and money spent on this process. Subsequently, each site was visited weekly to collect and record data. Water use data were collected manually from water meter readings associated with each sprinkler clock. Where the meters provided domestic, as well as irrigation water, the meter's historic record was obtained from the city Utility Billing Office and the average winter

TABLE 2. Water Application Data for Each Site.

Reference ID	Irrigation Area (sq. ft.)	Actual Application (inches)	Percent Used	Dollars Saved
RH1	7,121	15.35	53.6	189.10
RH2	11,241	16.09	56.1	281.92
RH3	5,929	18.60	64.9	119.01
RH4	10,466	23.64	82.5	104.85
Park	10,000	16.23	56.6	248.01
Median	1,000	19.52	68.1	18.24
RCA1	17,487	14.73	51.4	486.02
RCA2	15,325	15.63	54.5	398.41
RCA3	27,718	27.83	97.1	46.00
RCA4	9,487	15.83	55.2	242.85
RCA5	73,000	14.68	51.2	2,036.18
RCA6	84,919	20.50	71.5	1,382.68
RCA7	9,226	19.80	69.1	163.10
RCA8	29,095	21.54	75.2	413.37
RCA9	83,035	21.16	73.8	1,242.67
RCA10	16,796	31.40	109.6	-91.75
RCB1	3,341	21.00	73.3	51.07
RCB2&3	16,913	20.27	70.7	283.14
RCB4	9,005	35.03	122.2	-114.40
RCB5	5,691	28.00	97.7	7.51
RCB6	19,690	22.53	78.6	240.86
RCB7	34,618	30.42	106.1	-121.42
Average	22,777	21.03	73.4	331.63
Total	50,1102			7,627.42

consumption (AWC) was subtracted from the current meter reading to obtain the outdoor use as proposed by Howe and Linaweaver (1967). The times required to test each WEM and to perform any remedial actions were recorded. The condition of the vegetation was rated on a greenness scale of 1 to 10, where a 1 corresponds to a totally brown lawn and a 10 corresponds to a completely green lawn. Intermediate values were determined in accordance with the estimated percentage of green vegetation. Daily temperature extrema and precipitation was obtained from a weather station located on the grounds of the National Institute of Standards and Technology in Boulder, Colorado. Results were tabulated concerning both the hydrologic performance and time and money required to operate and to maintain the system. Simple tables were designed to assist homeowners and landscape contractors in monitoring the performance of their irrigation systems either on a daily or monthly basis.

RESULTS AND DISCUSSION

1997 Study Results: Reduction in Water Usage

The results of this study indicate that the GMSs were successful at saving water and cost effective to operate. On a seasonal basis, the systems limited applications to a combined average of 73.4 percent of the theoretical requirement, I, of 28.7 inches. Table 2 shows how the individual results varied. It can be seen that the percentage of the theoretical requirement actually applied ranged from a low of 51 percent to a high of 122 percent. Figure 2 is a bar graph of application percentages. Most of the data fell between 50 and 80 percent of I. In fact, 16 of the 23 sensors used less than 80 percent of I. Only three of the sites had applications equal to or greater than the theoretical requirements.

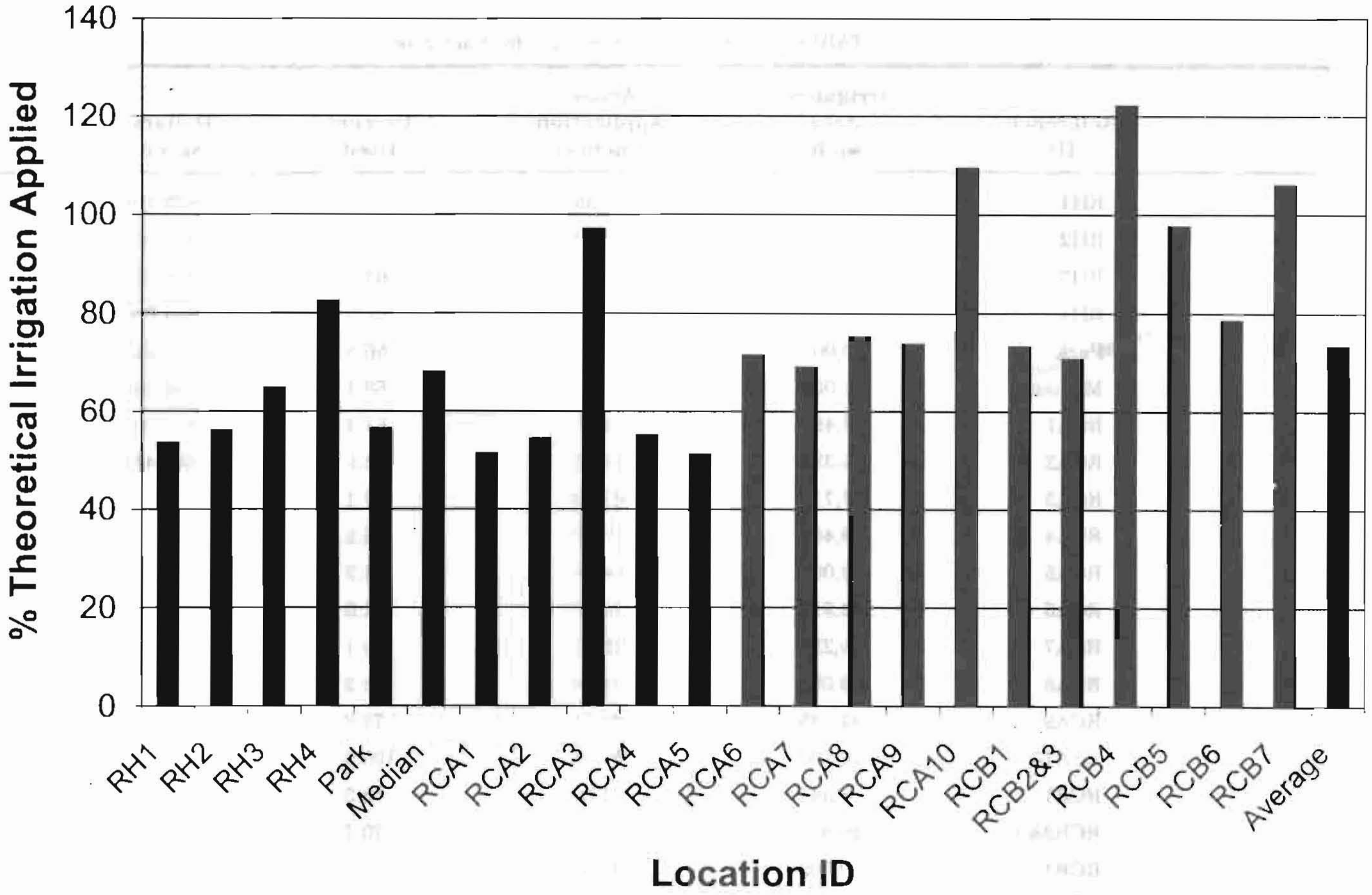

Figure 2. Ratio of Actual Application to Theoretical Requirement Expressed as a Percentage for Each Sprinkler Clock With a Watermark Electronic Module and Granular Matrix Sensors.

Although these results are good, they represent a large degree of variability. Several possible reasons for this relate to microclimate, exposure, soil type, and slope at individual sites. The same theoretical requirement was assumed for all sites, based on data from the weather station at NIST. Individual sites differed in microclimate and exposure to wind and radiation that would affect actual evapotranspiration, and in soil types and ground slope that would affect surface runoff and percolation. At each study site, the GMS was individually calibrated to maintain sufficient moisture in the soil to ensure healthy, green turf. Therefore, due to intersite differences, one would expect the actual depth of water required at each site to vary, and possibly exceed, the theoretical irrigation requirement. Quantification of the effects of these factors at individual sites goes beyond the scope of this study.

The results on a short-term basis were also good. Figure 3 shows cumulative theoretical requirement, I (solid line), and actual applications versus time. The application curve, based on the average of all 23 sites over the entire season, is shown by the coarse dashed line and solid square symbols. The applications by the largest and smallest users are shown by fine dashed, and dash-dot-dotted lines, respectively. This shows that during the early seasons when conditions were wet, the actual application rates were low and as I increased, so did the application rates.

The largest user (RCB4, shown in Figure 3) applied 122 percent of the theoretical requirement, or 36 inches of water. This may have been due to excessive runoff due to low permeabilty or steep slopes as mentioned earlier. Whatever the reason, it is evident that the GMS was functioning because: (1) the cumulative application curve tracked I; and (2) these clocks were programmed to apply more than 60 inches of water over the season, whereas the GMS limited the actual application to 36 inches

The smallest user (RCA5, shown in Figure 3) applied just under 15 inches of water. In contrast to the system that applied 122 percent of the theoretical requirement, this system was more similar to other system observations. That is, seven of the 23 systems,

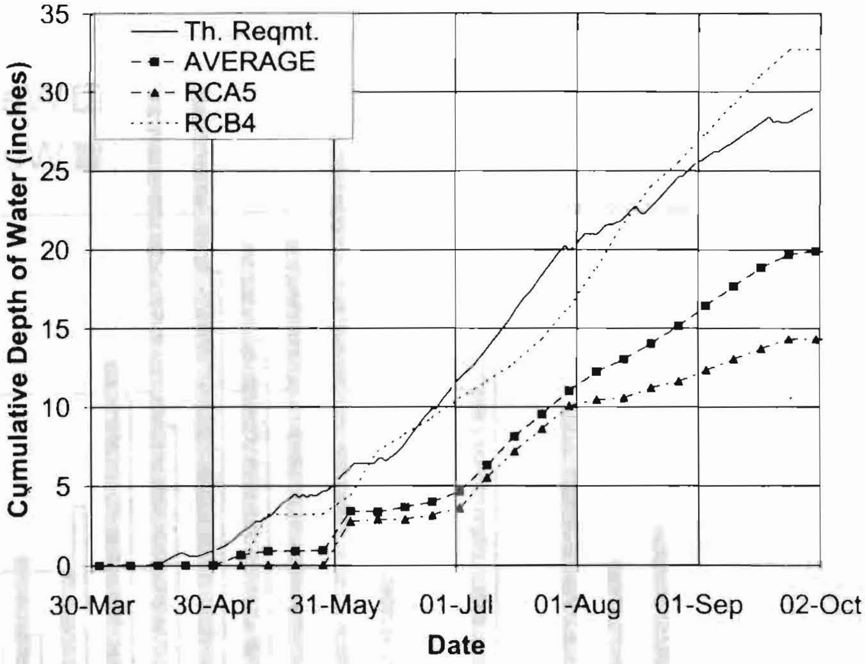

Figure 3. Comparison Among Theoretical Irrigation Requirement and Average, Maximum (RCB4), and Minimum (RCA5) Actual Applications With Respect to Time.

or nearly one-third, applied less than 60 percent of I, and nearly seven-tenths of the systems applied less than 80 percent of I. Despite the low application, the owner of this single-family residence never expressed concern over the performance of the system or the appearance of the lawn. However, if a higher application had been desired, a simple adjustment of the WEM to a wetter setting would have accomplished this.

The degree to which the sensors tracked the theoretical requirement, I, during the season is illustrated in Figure 4. This bar graph shows weekly applications averaged over all sites, and weekly I. It can be seen here that for the first 14 weeks, I often exceeded the average application substantially, but the two tracked much more closely for the last half of the season. This may have been due to the large reserve of water stored in the soil from snowmelt and spring rains. As this reserve was depleted, average applications tracked the theoretical requirement much better. It is interesting to note that in week 10, a large I and correspondingly large application occurred, but that due to precipitation during Weeks 11 and 12, both I and the average applications were small. The large application in Week 10, and the rainfall during Weeks 11 and 12 appear to have replenished the soil moisture, so that during Weeks 13 and 14, when I increased substantially, the average application remained small. As one might expect, this lag effect only occurs during times of rapid increases in I. When I decreases, the soil moisture sensors reduce the actual application immediately, as illustrated in Weeks 17-21. The presence of this lag only during increasing I causes the correlation between I and the average application at weekly time steps to be poor. If one plots I and average applications versus time on a monthly basis, as shown in Figure 5, the lag is still apparent, but the correlation is more significant. The coefficient of determination between I and monthly application is 0.79. In other words, the soil moisture sensors are able to apply irrigation at a rate that tracks 79 percent of the variability in I on a monthly basis. This statistic is significant at the 98 percent confidence level

If the water savings is calculated as an area weighted average, there results an average savings of 7.6 inches relative to I. This exceeds 2.3 million gallons over the 23 study sites, or an average of 108,000 gallons per site over the 1997 irrigation season. The City of Boulder has a three-tiered, increasing block rate structure for water billing. Block 1 charges apply to average winter consumption (AWC). Block 2 rates apply to the amount of water used in excess of AWC, up to 350 percent of AWC. Block 3 rates apply to water used in excess of 350 percent of AWC. The actual water usage during the 1997 irrigation season at each of the sites used in this study extended into the Block 3 tier. Thus, all of the water savings between

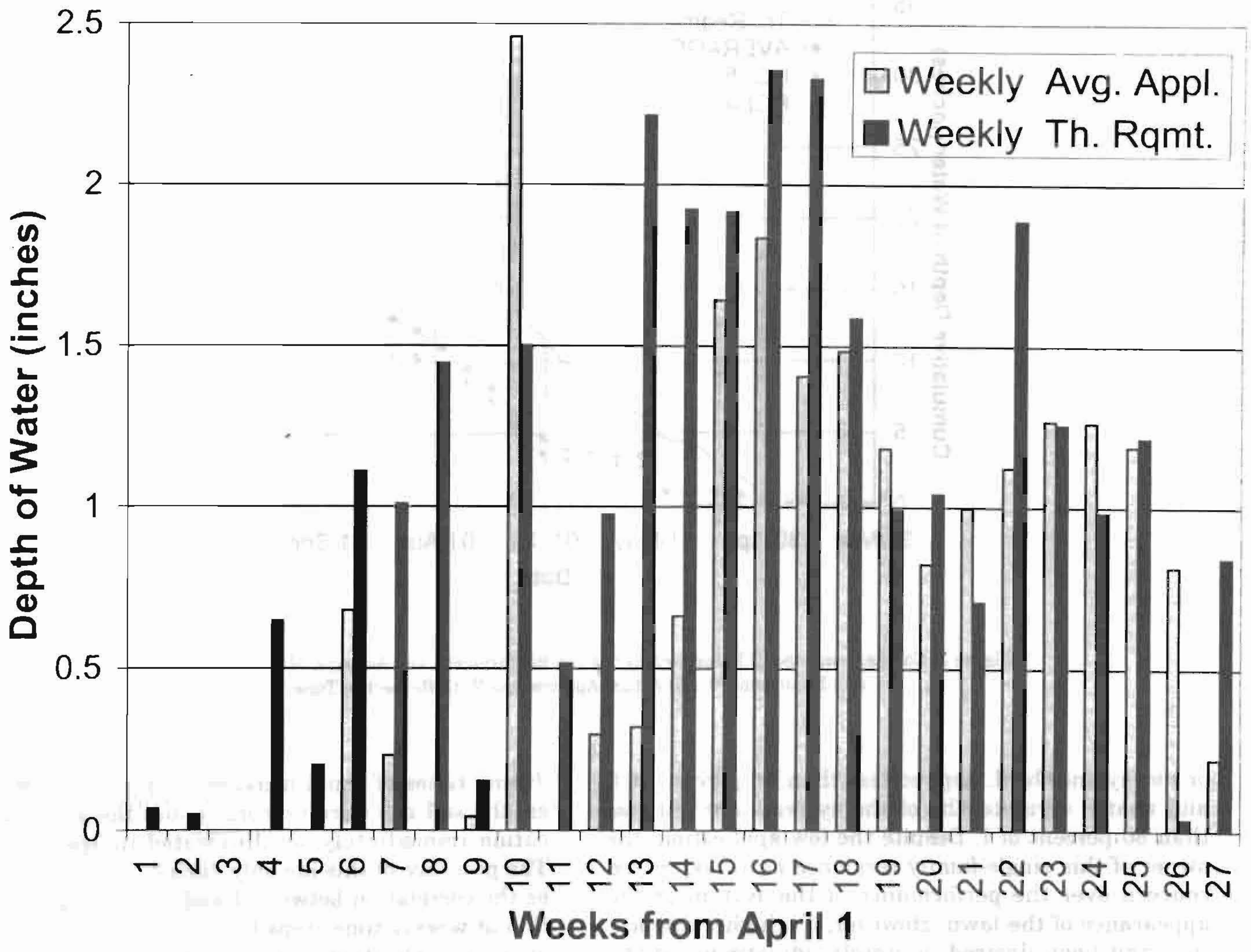

Figure 4. Comparison Between Site-Averaged Applications and Theoretical Irrigation Requirement on a Weekly Time Step.

actual consumption and the theoretical requirement, I, would have been charged at the block three rate of $3.20/thousand gallons. This amounted to a total savings of $7,627, or an average of $331 per site. Among the single-family homes, the average savings per household was $174. This is probably larger than the actual savings realized since owners of automated irrigation systems generally modulate the irrigation application, to some degree, to mimic the vegetation requirements, which reduces the applied irrigation somewhat below I. However, in an earlier study, DeOreo and Lander (1995) found that the soil moisture sensors were more successful at limiting irrigation application than were users who modulated irrigation based on qualitative observations of the weather and of the condition of the turf. Consequently, we consider the numbers listed above to represent an order of magnitude estimate of the savings.

Our experience indicates clearly that the primary obstacle to use of the soil moisture sensors is the lack of a clear-cut feed back mechanism between the irrigation system and the user. Without this the user is never quite certain whether the irrigation system is on target with respect to applications. This is particularly true if the user is accustomed to adjusting the sprinkler application rate throughout the season in response to increases or decreases in daily temperature or disabling the system manually in response to precipitation events.

To address this problem we designed a very simple, one-page worksheet that an irrigation manager can fill in to track applications. The worksheet guides the user in converting from volume of applied water, obtained from the water meter in thousands of gallons, to depth of applied water in inches. This latter quantity may be compared with the theoretical

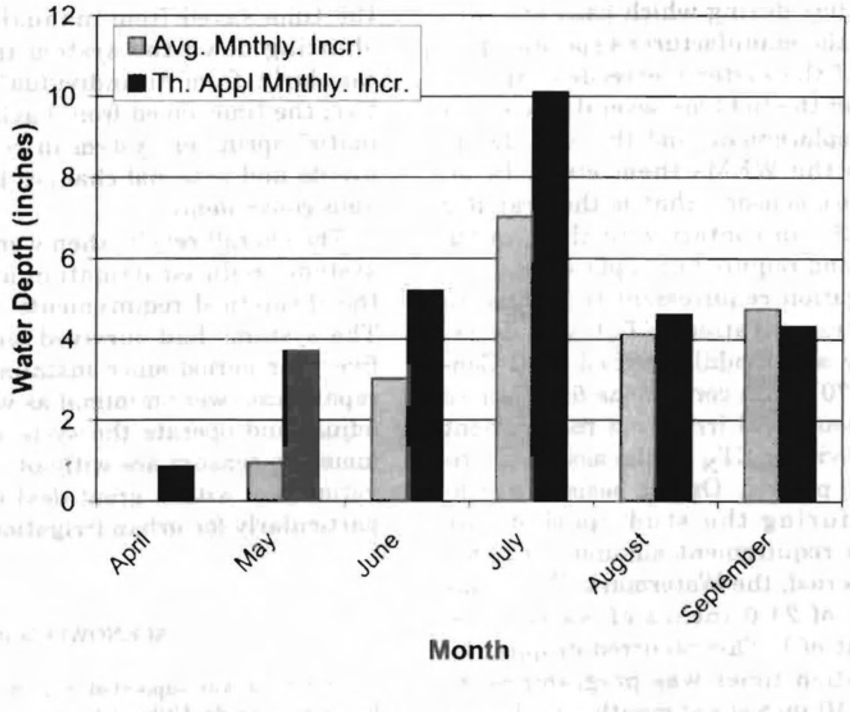

Figure 5. Comparison Between Site-Averaged Actual Applications and Theoretical Irrigation Requirements on a Monthly Time Step.

requirement based either on local historical climatological data (the simplest case), or on climatological data for the current year (for greater accuracy). Using current data, this may be performed at any desired time step from daily to seasonal.

1997 Study Results: Time and Cost Associated With System Operation

It was the experience of the study team that a minimal amount of time was required to become familiar with the sensor systems. Learning the operation of the different timers, locating the sensors, and understanding how the WEMs were wired to individual clocks took an average of 12 minutes per system. A tour of the largest site, the first residential community with 10 WEMs, took about two hours, and included an introduction to the hardware and a preliminary check to see that the WEMs and soil moisture sensors were working properly.

The time required to maintain sprinkler systems controlled with a Watermark^{TM} soil moisture system was tracked for this study. Each site was checked weekly. The system check consisted of recording the water meter reading, the condition of the vegetation, and irrigation days and times, and testing the WEM and moisture sensors. This took an average of six to seven minutes per WEM, excluding problem resolution. An operator who is familiar with the Watermark^{TM} system and the different irrigation clocks could monitor many systems at a rate of about ten staff hours per 100 WEMs per visit, excluding travel time. For this study, a typical week's round of visits took approximately four hours, which included travel time (20 miles of driving) and a system check of 23 sensors and WEMs.

During the course of this study, a few problems arose. Two WEMs required replacement at the beginning of the season due to external factors – one at the City park was vandalized, and one at one of the residential communities was shorted out by a failed irrigation clock. It is worth noting that no soil moisture sensors required replacement.

The total cost for repair and replacement of the sensors in this study was $269. This averaged out to just under $12 per unit. All of the sensors had been in place since 1994 or earlier, so this cost could be distributed over three or more years.

SUMMARY AND CONCLUSIONS

This study reported on the performance and time required to maintain 23 Watermark^{TM} soil moisture sensors and Electronic Switching Modules (WEMs) used to control urban irrigation timers during 1997. All sensors were installed during or prior to 1994. The performance of the systems was verified weekly by field inspections in 1997 during which each unit was checked according to the manufacturer's specified procedures. Durability of the systems exceeded expectations. Despite being in the field for several years only two WEMs needed replacement, and this was due to causes unrelated to the WEMs themselves. In all cases the soil moisture sensors, that is the granular matrix sensors (GMSs) in contact with the ground, remained functional and required no replacement.

The effective irrigation requirement (I_e), equal to net potential evapotranspiration (ET_N), was determined by the Blaney and Criddle method (Soil Conservation Service, 1970), with corrections for effective precipitation. The theoretical irrigation requirement (I) was obtained by dividing ET_N by the assumed irrigation efficiency of 90 percent. On the basis of weather data collected during the study period, the theoretical irrigation requirement amounted to 28.6 inches. During this period, the Watermark^{TM} systems allowed an average of 21.0 inches of water to be applied, or 73 percent of I. This occurred despite the fact that each irrigation timer was programmed to apply approximately 10 inches per month, or 60 inches over the entire season. At current City of Boulder water rates, the monetary savings due to reduction of water consumption relative to I amounted to $7,627 over the entire season, or an average of $331 per installed sensor. The average savings at single-family residential sites was slightly lower, $174 per home, due to smaller irrigated areas. In addition to overall success, comparison of I with actual irrigation water usage on a weekly basis showed that the system was successful in reducing the application during periods of rainfall.

The study showed that the time required to add soil moisture sensors to a group of irrigation timers was minimal. This study included weekly site visits during which a check of each system was performed. Less frequent visits are certainly allowable, however we chose this frequency based on the interest to obtain reasonably fine resolution water meter readings. This system check took an average of six to seven minutes per irrigation timer. The wiring connection of WEMs to irrigation systems and the interaction between WEMs and GMSs is easy to understand. Users unfamiliar with the Watermark system can be initiated in less than 15 minutes. Only three repairs were necessary and were performed in less than 15 minutes each, at a total cost less than $270.

The ability of the WEMs to interrupt irrigation cycles during periods of rain is particularly important on managed properties where contractors may be on the site only once a week or less. From a business perspective, the time spent installing and operating a GMS system will be more than compensated for by the time saved from manually reprogramming and shutting down the system in response to rainfall. Similarly, from an individual homeowner's perspective, the time saved from having to monitor an "automatic" sprinkler system in response to precipitation events and seasonal changes in weather is a tremendous convenience.

The overall results then were that the soil moisture systems reduced irrigation applications well below the theoretical requirements, and tracked ET_N well. The systems had survived well during the three to five year period since installation. Maintenance and repair costs were minimal as was the time required to adjust and operate the system. Granular matrix soil moisture sensors are without a doubt a water conservation tool with a great deal of unrealized potential, particularly for urban irrigation control.

ACKNOWLEDGMENTS

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