DESIGN AND FIELD EVALUATION OF A NEW CONTROLLER FOR SOIL-WATER BASED IRRIGATION

R. Muñoz-Carpena, M. D. Dukes, Y. Li, W. Klassen

Abstract. *A new irrigation controller was developed using readily available components and coupled with an inexpensive dielectric soil water probe. The electronic controller was designed to be easily adapted to existing commercial irrigation systems that currently use time clocks with a pressurized water supply. The total cost of components used in this controller (not including shipping or labor costs) was US$124 including the US$60 sensor. The new device was field tested against other common automatic scheduling methods (fixed timer and variable timer based on historical evapotranspiration) on a drip-irrigated plastic-mulched tomato field in South Florida. The soil water feedback irrigation control with this new device saved up to 74% water while maintaining yields with respect to the typical fixed irrigation schedule rates applied by commercial tomato growers during the winter season in the area. Comparisons with evapotranspiration-based application rates for the area also showed water savings of up to 61%. Although similar savings (up to 79%) were obtained with switching tensiometers, in the gravelly soils of the area these devices are difficult to maintain requiring refilling at least twice a week whereas the soil-water controller required no maintenance throughout the season. The new controller proved reliable and simple to use. It is recommended that the irrigation set-point be validated in the field at the beginning of the season. The study shows that the combined variability of the soil and the water probes resulted in relatively high variability of water application, although the resulting variability in the yield response was less.*

Keywords. *Soil water, Irrigation, Dielectric probes, Capacitance, Irrigation scheduling, Water conservation, Drip irrigation, Tomato.*

The primary use of agricultural water in the humid region is to supplement rainfall during the typically dry crop production periods. In this region Florida accounted for 12.3% of the total vegetable production value in the United States in 2006, which was equivalent to US$1.2 billion, under approximately 73,500 ha planted (NASS, 2007). Of this production, tomato (*Lycopersicon esculentum L.*) covers 16,700 ha and has a gross value of US$551 million (NASS, 2007). Agriculture is the largest freshwater user in Florida accounting for 45% of the total withdrawals (Marella, 1999), mostly from groundwater sources. Through proper irrigation, average vegetable yields can be maintained (or increased) while conserving water and minimizing environmental impacts caused by excess applied water and subsequent agrochemical leaching.

Submitted for review in August 2005 as manuscript number SW 6008; approved for publication by the Soil & Water Division of ASABE in December 2007.

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The use of automated soil water based feedback to control irrigation has been documented as saving water while maintaining crop yields. For example, Phene and Howell (1984) used a custom-made soil matric potential sensor to control subsurface drip irrigated processing tomatoes. Their results indicated that yields of the automated system were similar to those from tomatoes irrigated with a system based on pan evaporation with the potential to use less irrigation water. Automation in this context generally consists of a sensor (soil water content, soil tension, water level, etc.), a control system, and irrigation system components.

Coarse (sandy, gravelly) soils like those of Florida and many other regions of the world present special challenges when using soil water sensors. Switching tensiometers have been used in sandy soils on commodities such as fresh market tomatoes (Smajstrla and Locascio, 1996) and citrus (Smajstrla and Koo, 1986) to automatically control irrigation events based on preset soil matric potential limits. Smajstrla and Locascio (1996) reported that using switching tensiometers placed at 0.15-m depths and set at 10- and 15-kPa tensions in a North Florida sandy soil reduced irrigation requirements of tomatoes by 40% to 50% without reducing yields compared to common irrigation scheduling practices in the area where water is applied on a fixed schedule (3 to 5 times per/week). Muñoz-Carpena et al. (2005a) found that a switching tensiometer-controlled drip irrigation system set at 15 kPa on tomatoes reduced irrigation 70% compared to typical farmer practices in a South Florida sandy soil while maintaining similar yields. In spite of these results, tensiometers have not been widely adopted for vegetable production in coarse soils due to the very frequent maintenance required (Muñoz-Carpena et al., 2003). This frequent maintenance is due to discharge caused by limited contact with the coarse sandy soil, organic growth on the ceramic cups, and the need for re-calibration (Gee and Campbell, 1990; Smajstrla and Koo, 1986; Muñoz-Carpena et al., 2003, 2005a).

Granular Matrix Sensors (GMS) and dielectric sensors like Time Domain Reflectometry (TDR), capacitance, etc., require less field maintenance than tensiometers (Shock, 2003; Muñoz-Carpena et al., 2005b) and thus have a greater potential for commercial adoption. However, Muñoz-Carpena et al. (2005a) observed that a GMS controlled drip irrigation system in sandy soils of South Florida failed to bypass most irrigation events that were intended to be overridden due to slow response time. Irmak and Haman (2001) found similar results for GMS in sandy soils of North Florida and concluded that these sensors are not sufficiently responsive to changes in soil tension to control irrigation. Low-cost dielectric probes are now available that could be a reliable and low-maintenance alternative to GMS and tensiometers to control irrigation.

The objectives of this study were to: 1) develop a low-cost controller using an inexpensive soil water probe that could function as both an on-demand controller and a bypass controller with a time clock; 2) to perform a preliminary field evaluation of this control system against other irrigation scheduling methods (i.e. switching tensiometers, historical evapotranspiration (ET), and local grower's fixed schedule); and 3) to provide calibration data for soil water based irrigation control in the gravelly soils of South Florida.

Materials and Methods

Soil Water Controller Development

A quantified irrigation control (QIC) system was developed around a custom-built integrated circuit (IC) board and a commercially available capacitance-based soil water probe (0.20 m ECH$_2$O probe, Decagon Devices, Inc., Pullman, Wash.). Table 1 gives a complete list of materials used in the construction of the QIC and their approximate cost. Most materials are readily available electronic components except for the custom-built IC board (fig. 1). The soil water probe used in this research could be replaced with any type of sensor that has a predictable voltage response to variation in soil water or tension. The total cost of the controller components without the sensor, not including shipping of components or labor for assembly was US$64 (US$124 with the sensor) (table 1). This compares favorably with existing commercial alternatives including switching tensiometers and other dielectric probe-based controllers.

The programmable microcontroller used in this system (MSP430-FET149, Texas Instruments Inc., Dallas, Tex.) contained a 16-bit timer with a 12-bit analog to digital (A/D) converter and was developed for ultra low power applications (0.1-250 μA). The 12-bit A/D converter allows the 250 (dry) - 1000 (wet) mV signal sent from the probe to be resolved to 0.18 mV, which translates into <0.01% volumetric soil water in South Florida soils.

Figure 2 shows a flow chart describing the operational logic of the controller. The QIC microcontroller queries the probe at user set intervals by sending a 25 millisecond 2.5-VDC excitation signal to the capacitance probe. Normally, this comparison occurs every minute (adjustable via a software interface with the microcontroller). If the voltage returned from the probe is below a user set threshold (potentiometer), then the controller allows the time clock 24-VAC signal to power the irrigation solenoid valve via the on-board latching relay. When the signal is higher than the set point the relay opens to stop irrigation. Since several 1-min sampling cycles are possible within an irrigation event, it is possible for the system to irrigate for periods shorter than the duration of the scheduled event, i.e. there is no minimum irrigation time per se, other than the querying and sensor response lag time.

Figure 3 depicts how a commercially available time clock-based irrigation control system can be retrofitted with the QIC as was done in this research project. As seen in figures 1 and 2, the QIC can be powered by either a 9-VDC battery or by the power from the controller (24 VAC when the

Table 1. Materials and costs for construction of the Quantified Irrigation Controller.

No.	Item	Quantity	Unit Price (US$)	Total (US$)
1	printed circuit board	1	25.00	25.00
2	enclosure AN-1303	1	8.00	8.00
3	6-position terminal block	1	1.20	1.20
4	battery holder	1	1.00	1.00
5	10-turn potentiometer	1	1.85	1.85
6	resistor 2.2k	1	0.05	0.05
7	resistor 180K	1	0.05	0.05
8	resistor 1M	1	0.05	0.05
9	resistor 560	1	0.05	0.05
10	resistor 100K	2	0.05	0.10
11	resistor 240	1	0.42	0.42
12	resistor 1.5K	1	0.42	0.42
13	capacitor 10uF 16V	2	0.61	1.22
14	capacitor .047uF 50V	2	0.14	0.28
15	capacitor .1uF 50V	1	0.13	0.13
16	capacitor 1uF 25V	1	0.42	0.42
17	capacitor 100uF 40V	1	0.40	0.40
18	LED 2mA	1	0.29	0.29
19	2.5-LDO regulator TPS77025	2	0.90	1.80
20	9V latching relay	1	5.86	5.86
21	NPN transistor array	1	0.35	0.35
22	diode 1n4148	2	0.05	0.10
23	diode 1n4006	2	0.24	0.48
24	polyswitch fuse	1	0.43	0.43
25	adjustable regulator	1	0.60	0.60
26	bridge rectifier	1	0.56	0.56
27	2-pin header	1	0.02	0.02
28	14-pin shrouded header	1	1.37	1.37
29	16-bit MCU MSP430FET149	1	9.55	9.55
30	32.768K crystal	1	0.27	0.27
31	shunt with handle	1	0.24	0.24
32	#4 spacer	2	0.10	0.20
33	#6 spacer	2	0.10	0.20
34	0.20-m ECH$_2$0 probe	1	60.00	60.00[a]
35	1/4-in. grommet	2	0.20	0.40
36	4-40 nut	2	0.11	0.22
37	4-40 × 3/8 screw	2	0.04	0.08
			Total	123.66

[a] Reflects bulk pricing.

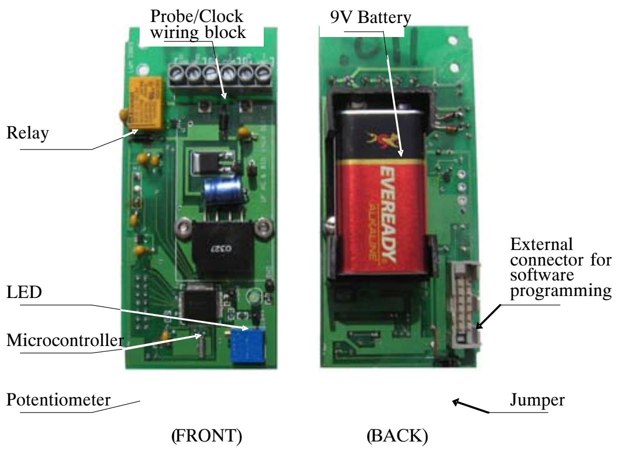

Figure 1. Details of the Quantified Irrigation Controller printed circuit board prototype (front and back).

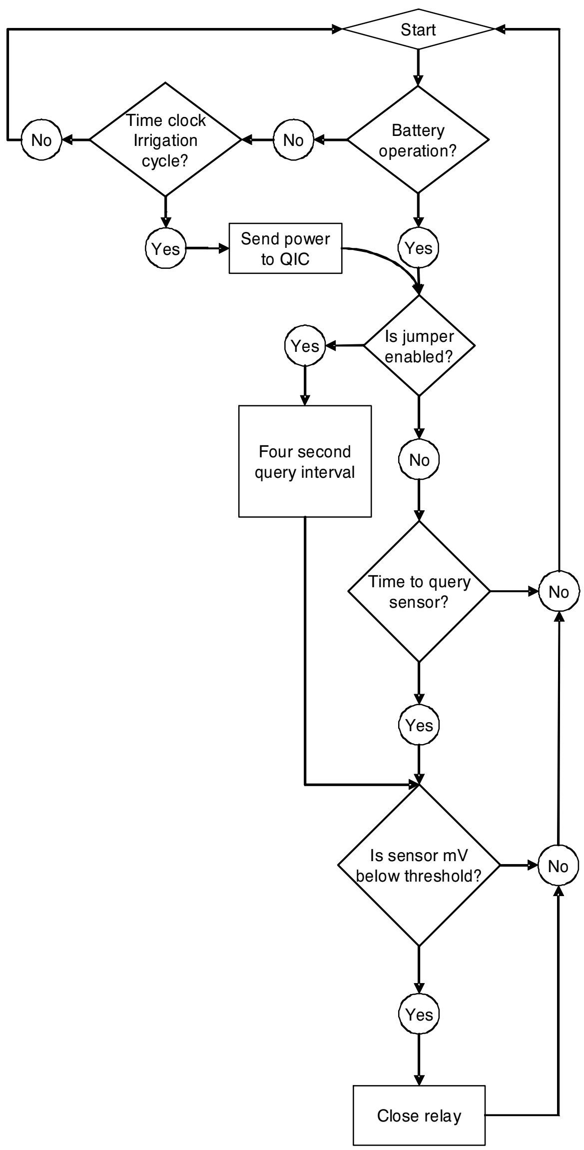

Figure 2. Quantified Irrigation Controller decision logic flowchart. The relay is normally open (closed valve position).

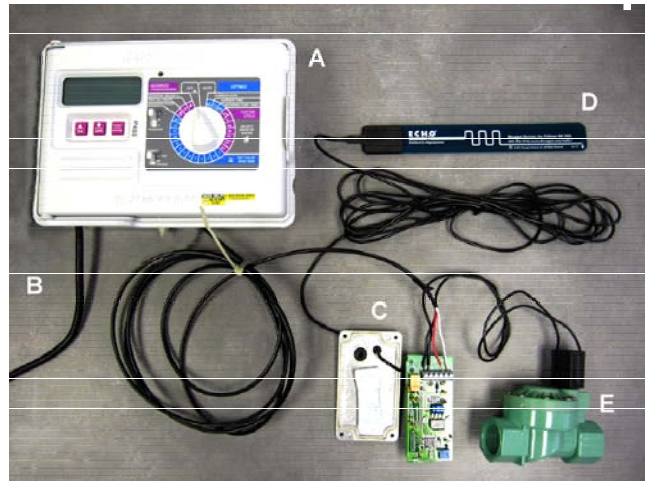

Figure 3. Details of a time clock irrigation control system retrofitted with the soil water sensor and showing: (A) time-based controller, (B) external power supply, (C) Quantified Irrigation Controller circuitry, (D) capacitance soil water probe (ECH$_2$O, Decagon Devices, Inc., Pullman, Wash.), and (E) solenoid valve.

time clock sends a signal), both of which are transformed to 5 VDC. The advantage of using a battery is that the voltage of the soil water probe can be checked while in the field without need for the controller to power the irrigation zone containing the QIC in question. The QIC can also be used in the place of a time based irrigation controller for a single irrigation valve and a 24-VAC power supply. Although this configuration was not used in the experiment, it would allow for complete irrigation control based on soil water conditions. By connecting the on-board jumper (fig. 1), the QIC will query the probe every four seconds to determine the probe output directly from the IC board (see flow chart in fig. 2). The potentiometer can be adjusted until the LED activates, which establishes the QIC set point. This provides the alternative to select the set point in the field when the soil water level is at optimal conditions such as field capacity without the need for a specific soil calibration (figs. 1 and 2).

Site Selection and Probe Calibration

This experiment was conducted at the University of Florida's Tropical Research and Education Center in Homestead, Florida on a Krome gravelly-loam "rock-plowed" soil (loamy-skeletal, carbonatic, hyperthermic Lithic Udorthents) of 0.30-m average depth (with a range of 0.10-0.40 m) overlaying porous limestone bed rock, (USDA, 1996). Table 2 summarizes the physical properties of the soil at the site (Muñoz-Carpena et al., 2002).

Although the manufacturer of the soil water probe used here provides a general linear calibration equation (Decagon Devices, 2002), a specific calibration was developed for soil from our testing field. The soil was sampled at three different field locations from a depth of 0 to 0.21 m with care to obtain the gravel and fine fractions as present in the field. After collection, each sample was homogenized independently by tumbling in a bucket with a lid for 15 s, and then hand-packed in three PVC cylinders (∅0.10 × L0.21 m)bounded at the bottom with a stainless steel fine wire mesh held by a metal bracket around the tube. To achieve the original field bulk density (table 2) the packing was done in four layers of equal

Table 2. Soil physical properties at the experimental site.

Property	Value
Porosity	45%
Bulk density, ρ_b	1420 kg/m^3
Coarse material (>2mm_dia.)	51%
Sand	36%
Silt	40%
Clay	24%
USDA texture classification	Gravelly-loam
Saturated hydraulic conductivity, K_s	8.81×10^{-4} m/s (317 cm/h)
Soil water characteristic curve van Genuchten's parameters θ_r, α, n, m	0.093, 0.092, 1.461, 0.316

thickness. A capacitance probe was inserted vertically in the center of each core and the samples saturated from the bottom up during 24 h using a solution of 0.005 *M* $CaSO_4$ saturated with thymol (Klute and Dirksen, 1986). Once saturated the probe outputs (mV) were read with a handheld reader (ECH_2O Check, Decagon Devices, Inc., Pullman, Wash.) and the cores weighed on a laboratory scale of 0.0001 kg of resolution over the 0- to 8.0-kg range. The saturated cores (volumetric soil moisture close to 45%) were then placed on a wire screen to allow free drainage and air-drying while frequent probe readings (mV) and weights (kg) were recorded. When the volumetric soil water reached 17%, value below those typical of irrigated field conditions, the probe was removed and the soil dried in a laboratory oven to obtain the dry weight needed to calculate the volumetric water content for each reading. A total of 25 paired probe readings and volumetric water content data collected from the three cores were fitted to a straight line. Figure 4 depicts only the points that fell within the normal field soil water range (Al-Yahyai et al., 2006); nine additional points used in the calibration are not shown since they are near soil saturation. Thus, an average calibration over the entire field was applied to all probes used for irrigation control rather than a specific calibration of each probe location.

Field Testing of the Controller

A field at the University of Florida's Tropical Research and Education Center in Homestead, Florida in which sorghum sudangrass had been grown as a summer cover crop was utilized for this experiment. Tomatoes were cultured according to local horticultural practices. On 30 September 2003, fumigant (66:33 volumetric mix of methyl-bromide:chloropicrin, MC-33) was injected into the soil at 392 kg/ha during the formation of the raised beds, and immediately thereafter the drip lines and plastic mulch were installed. Pre-plant dry fertilizer (6-6-12) at 1867 kg/ha was roto-tilled into the bed. The tomato seedlings (cultivar 'FL 47') were transplanted on 20 November 2003 into plastic mulched raised beds spaced 1.8 m apart in one row per bed with plants spaced 0.46 m apart. Each plot was 16.7 m long (fig. 5). Irrigation was supplied with dual drip irrigation lines (T-TAPE TSX 508-12-450, T-Systems International, Inc., San Diego, Calif. with 0.015-m internal diameter, 0.30-m emitter spacing, 1.0-L/h emitter discharge at 69 kPa, and 0.002-m thickness) under the plastic mulch and approximately 0.30 m apart on either side of the tomato row. Dissolved fertilizer (4-0-8) at 19.6 kg N/ha was applied manually to each individual plant only during each of the final five weeks prior to harvest. Tomatoes were harvested four times during the period 1-18 March 2004 from a 6.1-m section within each plot. Harvested fruits were graded following Florida Tomato Committee standards (Brown, 2000).

Irrigation treatments were implemented at 20 days after planting to allow the transplants time to become established. Prior to that date, all experimental treatments were irrigated at least once each day on the same schedule. Thereafter irrigation treatments were established according to table 3 in a completely randomized design with four replications (fig. 5). Irrigation scheduling mechanisms consisted of switching-tensiometer (C1-C2), QIC (C3-C4), historical weather (C5-C8), and practices used by local growers (C10). Two treatments (C7 and C9) were not a part of this study and

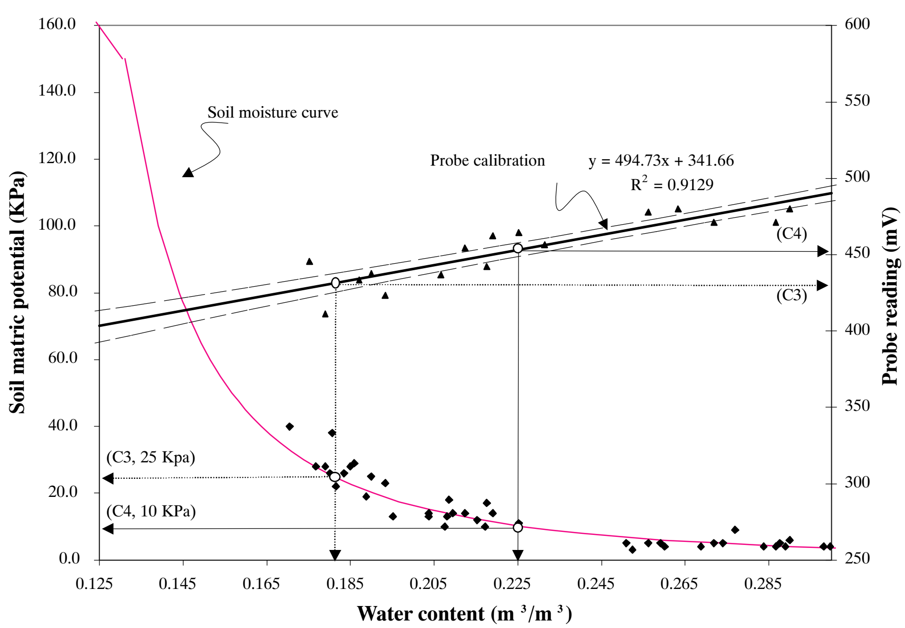

Figure 4. Soil-water characteristic curve for Krome soil showing irrigation set points for treatments C3 and C4. 95% confidence interval lines for the capacitance probe linear calibration are shown with dashed lines.

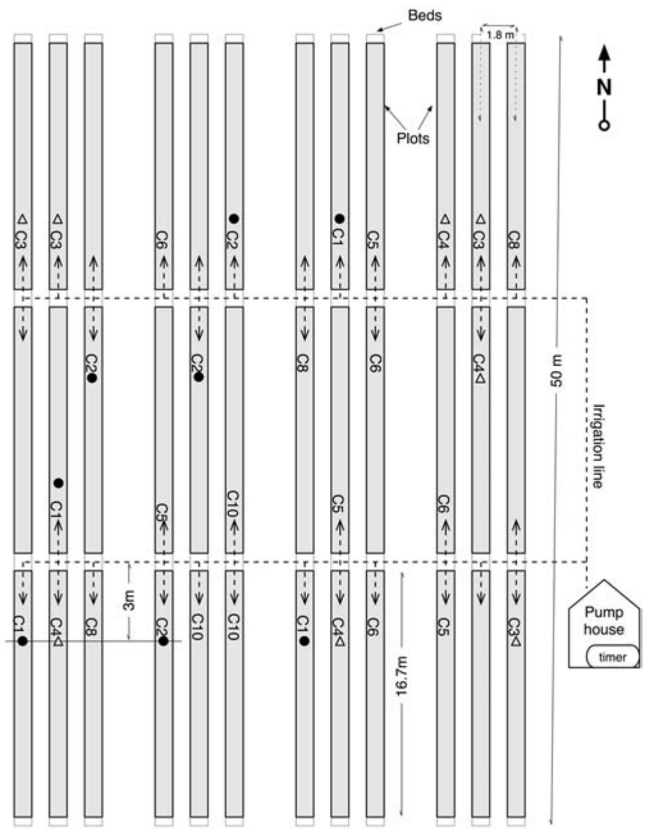

Figure 5. Tomato field layout used to test the QIC controller (not drawn to scale). Beds are divided into three irrigation plots, each controlled by independent solenoid valves (arrows). Each unit is a replication for the corresponding irrigation treatment (C1-C10). Replications for treatments C1-C4 have soil water sensors buried 3 m from the solenoid valve with controllers wired in closed-loop with the timer at the pump house (● switching tensiometers; ∇ QIC/capacitance probes).

will not be discussed here. The tensiometer, QIC, and weather-based methods were set to irrigate a maximum of five times each day for one hour total. To closely mimic local grower practices, treatments C5-C10 were irrigated on a fixed calendar (based on historical ET or daily grower schedule), regardless of precipitations conditions. The grower-based treatment (C10) was irrigated once each day for one hour similar to practices in the region. The local practices are likely a result of convenience (fixed daily schedule), efforts by the University of Florida Cooperative Extension Service (calendar based on historical ET), and belief (plastic does not let water into the root system).

Table 3. Irrigation treatments, scheduling thresholds, and mechanisms used to test the Quantified Irrigation Controller.

Treatment	Scheduling Threshold	Scheduling Mechanism
C1	10 kPa	Switching tensiometer
C2	25 kPa	Switching tensiometer
C3	425mV - 25 kPa[a]	QIC/ECH$_2$0
C4	450 mV - 10 kPa	QIC/ECH$_2$0
C5	ET_c*1.00 (100% needs)[b]	Historical weather data
C6	ET_o	Historical weather data
C8	ET_c*0.75 (Deficit irrigation)	Historical weather data
C10	Typical grower schedule	1 h/day (3.7 mm/day)

[a] ECH$_2$O probe mV corresponding to a given soil tension.
[b] ET_c estimated as $K_c.ET_o$ based on historical weather parameters and published crop coefficient values (Simonne et al., 2004).

Tensiometer and QIC methods allowed irrigation only if soil tension exceeded set points for tensiometer treatments, or if soil water was below set points for QIC treatments, respectively. The tensiometer treatments consisted of switching tensiometers (low tension model TGA-LT, Irrometer Co., Riverside, Calif.) set at 10 and 25 kPa for C1 and C2 treatments, respectively. The QIC treatments were set at two thresholds of 425 mV (95% confidence interval of 420-430 mV) and 450 mV (95% confidence interval of 445-455 mV), corresponding to the soil water status at 25 and 10 kPa (C3 and C4 treatments, respectively) obtained using the soil water release curve given by Al-Yahyai et al. (2006) for the gravelly-loam soil of this site (fig. 4). This voltage threshold was used previously for the gravelly-loam soil (Muñoz-Carpena et al., 2005a) and verified at the beginning of the experiment. Weather-based treatments were irrigated according to calculated crop evapotranspiration (ET_c) that was calculated by the local historical daily average reference ET (ET_o) multiplied by the published crop coefficient (K_c). For our crop and area the K_c values used were: 0.3 (from 11/20-12/3), 0.6 (12/4-12/23), 1.15 (12/24-2/12) and 1.00 (2/13-3/18) (Simonne et al., 2004). Historical average seasonal ET_c for tomatoes in this area is 291 mm (Simonne et al., 2004), and ET_o is 418 mm (USDC, 2007). In addition, these amounts were adjusted to 100% and 75% (C5 and C8) of the estimated crop ET according to table 3. Treatment C6 was irrigated according to the average long-term maximum daily ET_o throughout the season. The grower practice irrigation schedule (C10) consisted of one hour of irrigation per day throughout the season (3.7 mm/d).

Water use in each plot was continuously and independently recorded by a positive displacement water meter equipped with a magnetically actuated reed switch [PSM-T 0.016 × 0.013 m (5/8 × 1/2 in.), ABB Water Meters, Inc., Ocala, Fla.] connected to an event data logger (H7-002-04, Onset Computer Corporation, Bourne, Mass.). Weekly readings were also manually taken from the counters in each water meter. The water meters were installed at the inlet of each plot upstream of the pressure regulator and a solenoid valve. Average seasonal irrigation depths were calculated by dividing volumes applied for each treatment over the total field area. For each treatment, irrigation water use efficiency (IWUE, kg/m^3) was calculated as:

$$IWUE = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{MY_i}{I_i}\right) \quad (1)$$

where MY_i is marketable yield (kg/ha) for each plot i within the treatment, n is the total number of plots for that treatment (n = 4 for treatments C1 through C4, and n = 3 for the rest), and I_i is total seasonal irrigation applied for that same plot (m^3/ha). Implicit in this equation is that non-irrigated yield is zero.

One-way analysis of variance and comparison of means using Tukey-Kramer HSD were performed on irrigation water, yield and IWUE (JMP 6, SAS Institute, Cary, N.C., 2005). This test controls the type I errors of all comparisons simultaneously, rather than a pair of means at a time.

Weather parameters such as temperature, relative humidity, incoming solar radiation, wind speed, and precipitation were measured on-site by the Florida

Automated Weather Network (FAWN, http://fawn.ifas.ufl.edu) system. Daily ET_o was calculated by the modified Penman method as described in Jones et al. (1984).

Field Installation and Operation of the Controller

The soil water probes in treatments C1-C4 were installed vertically 3 m away from the solenoid valves (fig. 5) in the center of the bed, between the paired irrigation lines and two consecutive tomato plants of each experimental plot. For C3 and C4, the dielectric probes were inserted in the top 0.20 m, roughly equivalent to the total bed depth, whereas C1 and C2 the porous cup of the switching tensiometers was placed at the midpoint of the bed depth, i.e. 0.10 m. Thus an average soil water status was obtained for entire bedded soil profile of the tomato plants with both types of probes.

The QIC in treatments C3 and C4 was placed nearby on top of the vegetable bed. Although the QIC was designed within a waterproof metal housing (fig. 3), the entire apparatus was placed within a plastic food storage container. Both the QIC and plastic container contained a desiccant to prevent condensation on the inside of the containers. For the first week of QIC operation readings were collected from manual tensiometers buried 0.10 m deep near the QICs. Using these readings the set point of the QIC potentiometer was verified to match the target set points of 10 and 25 kPa (table 3). It is important to note that QICs were checked weekly for proper operation but the set-points were not adjusted for the remainder of the season.

An independent set of dielectric probes (0.20 m ECH_2O probe, Decagon Devices, Inc., Pullman, Wash.) connected to individual dataloggers (HOBO H08-006-04, Onset Computer Corporation, Pocasset, Mass.) was installed vertically in the top 0.20 m next to the switching tensiometers and QIC probes from all treatments C1-C4. Soil water content was recorded hourly from these 16 probes and average seasonal values for each treatment were calculated.

Results and Discussion: Field Evaluation

Water Use

Although a total of 152 mm of rainfall occurred over the tomato-growing season, 88% of it occurred in only four storm events (fig. 6). This rainfall likely contributed only minimally to the crop water requirements since any water entering the plastic mulch openings during these isolated large events would quickly percolate through the gravelly soil. As a result rainfall was not considered in the calculations. Seasonal ET_o and ET_c were similar in magnitude at 232 and 222 mm, respectively. However, ET_c was lower than ET_o at the beginning of the season due to the relatively low K_c values (0.3-0.6) for the first four weeks (fig. 6). The switching tensiometer and QIC treatments (C1-C4) resulted in seasonal irrigation ranging from 117 to 202 mm all below ET_c (table 4). This was because the K_c values recommended to calculate ET_c were developed for sprinkler irrigation (Simonne et al., 2004) where the entire field area is wetted during irrigation and not for the plastic mulched drip irrigated crop where ET is significantly reduced. Recent studies using eddy-covariance ET_c estimation for plastic mulched drip irrigated tomatoes

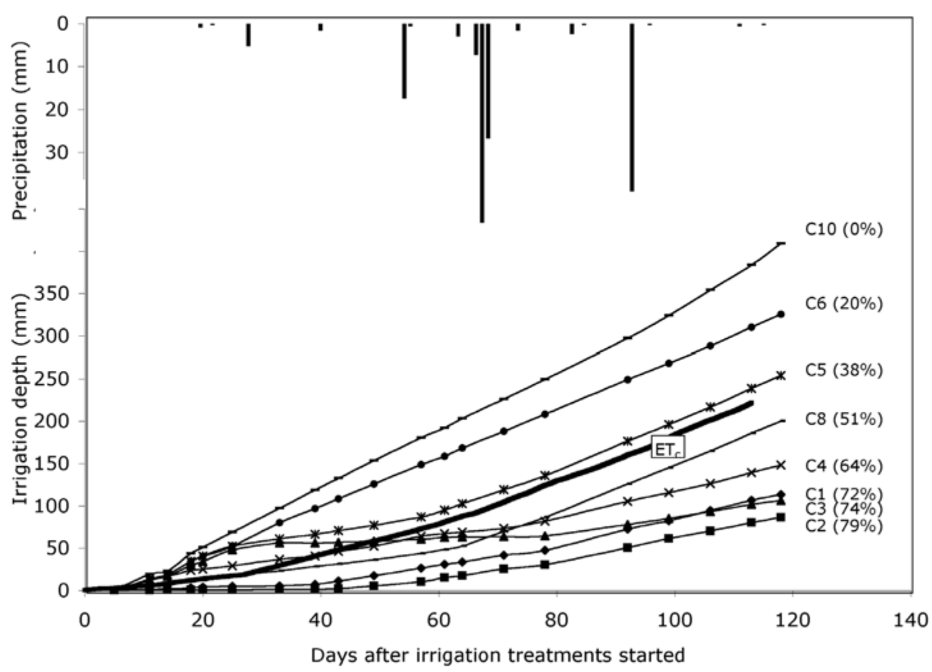

Figure 6. Average cumulative irrigation curves for each treatment, daily precipitation (vertical bars) and cumulative estimated crop ET (K_c.ET_o, labeled thick black line). Values do not include water applied during seedling establishment before the treatments were started. Labels at the end of the curves represent the irrigation treatments (C1-C2 are tensiometer based, C3-C4 QIC based, C5 crop ET based, C6 ET_o based, C8 based on 75% of crop ET and C10 is typical grower daily irrigation), Percent reductions in water use with respect to the typical grower schedule are included in parenthesis.

Table 4. Average tomato seasonal irrigation depths, marketable yields, irrigation water use efficiency (IWUE) and seasonal average soil water content obtained in the 2003 field study.[a][b]

Treatment Number	Seasonal Irrigation (mm)	Seasonal Irrigation CV (%)[d]	Marketable Yield (kg/ha)	Marketable Yield CV (%)[d]	IWUE[c] (kg/m^3)	IWUE[c] CV (%)[d]	Soil Water (%)[e]
C1	154 a (64-246)	51	36,852 a (25,108-43,362)	23	30.7 a (13.8-57.0)	34	18.7±1.1
C2	117 a (37-270)	90	40,835 a (39,756-42,474)	3	57.9 a (14.9-108.0)	71	16.3±1.1
C3	144 a (77-232)	52	37,538 a (26,283-52,449)	29	31.9 a (11.3-47.0)	49	18.2±1.1
C4	202 ab (90-330)	49	35,732 a (28,108-46,026)	21	22.5 a (8.5-39.0)	66	22.8±1.1
C5	345 abc (333-345)	5	36,728 a (32,163-39,029)	8	10.1 a (9.6-11.0)	9	--[f]
C6	442 bc (419-465)	7	27,834 a (23,565-35,536)	19	7.2 a (5.8-8.0)	12	--[f]
C8	272 abc (240-304)	17	37,306 a (32,531-39,994)	11	13.3 a (13.0-14.0)	18	--[f]
C10	556 c (465-648)	23	28,300 a (25,736-30,400)	8	5.1 a (4.0-6.0)	31	--[f]

[a] Numbers followed by the same letter are not significantly different based on Tukey-Kramer HSD test at the 95% confidence level.
[b] Ranges (min - max) are provided in parenthesis.
[c] IWUE for each treatment is the marketable yield divided by the irrigation water use for each plot and then averaged.
[d] Coefficient of variation.
[e] Mean±standard error.
[f] Soil water monitoring probes not installed on these plots.

(Amayreh and Al-Abed, 2005) and the Bowen ratio for drip irrigated processing tomatoes (Hanson and May, 2006) reported K_c values 30% to 40% lower than tabulated K_c values such as those used in the current work. Reducing K_c values by 30% to 40% in our case would result in seasonal total ET_c of 162 to 140 mm. These revised values agree well with those obtained for the soil water based irrigation treatments. Weather based irrigation treatments ranged from 272 to 442 mm, greater than estimated ET_c.

Figure 6 shows the cumulative irrigation water use for each treatment over the tomato season. As expected, time-based scheduling treatments C6 and C10 display a linear increase in irrigation water applied as a result of their fixed irrigation rate. Water application on C5 and C8 varied according to ET_c throughout the season based on changes in K_c (fig. 6). The soil water sensor-based treatments had lower cumulative water use slopes during the first 40 days of the season (0 to 1 mm/day) when compared to ET-based (1 to 3 mm/day) and the farmer treatments (3.7 mm/day). The smaller water application of the sensor-based treatments in the early part of the season matches the reduced water demands of the small plants. The cumulative water use slopes of the sensor based treatments increased between 40 and 80 days after transplanting to a rate of 0.5 to 1.0 mm/day and 1.0 to 1.8 mm/day from 80 days after transplanting until the end of the season. The ET-based treatments increased to 3.0 mm/day by the end of the season.

Crop Yields and Irrigation Water Use Efficiency

There were no significant differences in yields across treatments (table 4). Most treatments resulted in average yields (table 4) at or above state average yields of 36,570 kg/ha and the best treatments were nearly as high or higher than typical yields in Miami-Dade County of 39,177 kg/ha (FLASS, 2005; Li et al., 2002). Treatments C1-C4 resulted in the highest marketable yields (36,852-40,835 kg/ha) and used significantly lower irrigation volumes (at the 95% confidence level) than the typical grower schedule (C10) and ET_o (C6) treatments (table 4). On the other hand, the larger irrigation amounts of C6 and C10 seem to have resulted in lower (although not significantly different) yields. This indicates that these two commonly used scheduling methods for the area could over-irrigate the crop.

The irrigation water use efficiency ranged from 5.1 to 58.7 kg/m^3 across all the treatments (table 4). The lowest efficiency values were observed on the grower irrigation scheduling practice (C10) and the ET_o based treatment (C6); compared to the highest on the switching tensiometer set at the 25 kPa threshold (C2). Although there were no statistical differences in irrigation water use efficiencies, the group of treatments using soil water as a feedback mechanism (C1-C4) had IWUE values greater than 17 kg/m^3 while the rest of the treatments (C5-C6, C8, C10) had an IWUE of 13 kg/m^3 or less (table 4). The lack of statistical differences in IWUE was partly due to the plot variation in irrigation water applied to particular treatments (see ranges in table 4). In particular, the soil water based treatments (C1-C4) resulted in highly variable irrigation volumes across individual plots within a treatment. The coefficient of variation in seasonal irrigation ranged from 49% to 90% on these treatments compared to 5% to 23% on the time-based and grower treatments (table 4). The highest coefficient of variability found in C2 (the "dry" tensiometer treatment) can be partially explained by the tendency found for the tensiometers in this soil to break suction around the 20- to 30-kPa values. For the QIC-based treatments the variability found was likely due in part to intrinsic variability in soil water properties as well as variability in the soil water probe calibration that ultimately affects the response of a specific controller system. Although soil differences may have resulted in substantial irrigation variability due to localized sensor control, harvested yield was not as sensitive to irrigation variation at the thresholds used in this study. Hartz (1993) found that IWUE in California varied between 33 and 42 kg/m^3 for drip irrigated tomato scheduled based on 0.8* ET_c (ET_c calculated based on ET_o and crop canopy cover, and a soil water deficit approach), with average water use from 323 to 243 mm over three years. This range in irrigation is equivalent to 86% to 64% of ET_o for the crop season. In the present study, irrigation was applied to treatments C1-C4 at 50% to 87% ET_o, in the range of data presented by Hartz (1993). This supports that in our study, the ET based time treatments used excessive irrigation due to a combination of inadequate K_c values and the fact that historical average weather data typically does not represent actual condition in any given year. In particular, the seasonal ET_o estimated at the site for the period of the study (November 2003 to March 2004) was 21% lower than the historical (long-term) average total seasonal ET_o (USDC, 2007) for the area. However, these treatments (C5, C6, and C8 at 345, 442, and 272 mm, respectively) still applied less water than the treatment set up on a representative grower schedule (C10) at 556 mm. These results show that the use of soil water controlled irrigation at frequent intervals can result in irrigation application to match crop demands and possibly lead to the development of improved crop ET and K_c values for this production system.

The average irrigation volume applied to treatments C1-C4 was 72% lower than the grower scheduled treatment and 65% lower than the next highest treatment, which was the ET_o based treatment (C6) (fig. 6).

In view of these results, where yields do not seem to be affected by the reduction in irrigation even for the lowest irrigation treatments, the argument can be made that in fact the lower threshold or baseline for irrigation might not have been reached in this study. Based on this, lower irrigation amounts could be recommended for the area, without further need for the sensor system developed herein. In fact, any of the scheduling techniques used in this experiment resulted in substantial water savings compared to typical grower practices in the region, without negatively impacting yields. However, the limited data from this study is insufficient to issue general irrigation recommendations, other than the fact that current practices result in over-irrigation. In the absence of such longer-term studies, sensors (switching tensiometer and QIC controllers) proved useful to produce substantial water savings when compared to grower practices and historical ET based methods.

Calibration, Field Maintenance, and Adjustment of the QIC Device

The calibration of the new controllers was strongly dependent on the properties of the probe selected for the study and on the properties of the soil in which the probe was placed. The site-specific probe calibration obtained for this extremely gravelly soil was different to that provided by the manufacturer (Decagon Devices, 2002). As an example, for the two set points selected of 425 and 450 mV the measured volumetric soil water contents were 16.8% and 21.9% compared 0.5% and 2.5%, respectively, predicted with the manufacturer calibration. In spite of the laboratory calibration performed for this soil, it is recommended to verify the set-point during the first week of the season, based on additional manual tensiometer and QIC probe paired readings. Since the calibrated capacitance probes give soil water units (m^3/m^3), the values need to be converted to the units of soil water matric potential (kPa) through the soil water characteristic curve measured for this field (fig. 4). As seen in figure 4, several sources of uncertainty aggregate in this non-linear conversion that make the initial verification of the system necessary (i.e., noise from the capacitance probe calibration, soil water characteristic data, thermal effect, etc.). As a result the average soil water values obtained for each of the soil water treatments differ between the "wet" tensiometer and the QIC treatments (C1 and C4) as well as between the "dry" C2 and C3 treatments (table 4).

The QIC controllers proved to be much more reliable than the switching tensiometers because they needed no maintenance over the season, while the tensiometers had to be frequently refilled with water (up to twice a week during the peak crop water use), as is typical in coarse soils and high evaporative demand environments (Muñoz-Carpena et al., 2005a). The QIC did not require maintenance after the initial set-point verification in the first two weeks of the season after transplant establishment and just before irrigation treatments were initiated. This level of maintenance is in stark contrast to switching tensiometers that required refilling and pumping twice a week during this study. Although tensiometers have been proposed for years in this area (Smajstrla and Koo, 1986; Smajstrla and Locascio, 1996; Olczyk et al., 2002; Muñoz-Carpena et al., 2005a), less than 50% of vegetable growers report having used them and few have continued doing so after the initial testing (Muñoz-Carpena et al., 2005a) due to the frequent maintenance they require to keep them operational. The underlying concept in the QIC device represents a solid-state alternative without the maintenance issues that promises to be useful to vegetable producers faced with similar water management challenges elsewhere.

Conclusions

This research project demonstrated that the soil water based control system developed with a custom circuit board and a commercially available capacitance soil water probe is reliable and as effective as the proven switching tensiometer method for drip irrigation control under vegetable production. Both of these methods resulted in yields similar or greater than those obtained from grower based irrigation scheduling and historical data based irrigation scheduling. Moreover, the treatments with soil water feedback mechanisms saved on average 72% irrigation water compared to grower scheduling and 65% compared to historical (long-term) evapotranspiration based methods). Much of the water savings achieved with the soil water based treatments (C1-C4) can be attributed to the lower irrigation amounts automatically applied by the sensor-based systems early in the season to better match crop needs (fig. 6). This indicates the limitation of historical average weather data for irrigation scheduling during a short season crop. The Quantified Irrigation Controller (QIC) resulted in irrigation application similar to switching tensiometers but required nearly no maintenance while the tensiometers had to be refilled at least twice a week. In spite of these results, it is important to recognize that a robust and low cost soil water-based control system like the one presented is only a part of irrigation management. The intrinsic uncertainty in soil and water relationships, soil water-probes and thermal effects can introduce uncertainty in the controller response that results in water application variability. Although reduced cost of these technologies can open the future to widely spread acceptance among irrigators, the issues of repeatability, accuracy and reliability of the controller system will be key to the success of this irrigation strategy and will need to be verified in future studies.

Acknowledgements

The authors would like to thank Larry Miller at the University of Florida (UF) Agricultural and Biological Engineering Department for his electronics support during the implementation and development of the controller; and Tina Dispenza, Harry Trafford, Luis Barquín and the field crew at the UF Tropical Research and Education Center for their field efforts. This research was supported by USDA -- CSREES -- SARE, Project LS03 -- 148, the Florida Fruit & Vegetable Association, and by the Florida Agricultural Experiment Station, and approved for publication as Journal Series No. R-10887.

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