

## Soil Matric Potential Sensor Measurements in Real-Time Irrigation Scheduling

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### ABSTRACT

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Soil matric potential, a measure of the holding strength of the soil matrix for water, is a critical variable in crop yield, runoff, evapotranspiration and irrigation scheduling. A method for real-time in-situ measurement of soil matric potential ( $\psi_m$ ) has been developed and tested. The accuracy of the measurement is dependent upon the calibration of the soil matric potential sensor (SMPS) against known standard pressures and independent of salinity, temperature and soil texture. The SMPS has a linear voltage response between  $-10$  and  $-300$  J/kg; and depending upon the data acquisition system used, the resolution of the soil matric potential measurement ranges from 2.5 to 5.5 J/kg. The response time of the SMPS to change in pressure plate pressures is less than 24 h between  $-10$  and  $-100$  J/kg but increases rapidly to several days for soil matric potential lower than  $-120$  J/kg. SMPS were used to monitor soil matric potential in field soil in real time and to control drip irrigation systems automatically by initiating irrigation when a preset threshold was exceeded and terminating irrigation cycles when the time needed to apply 1.2 mm of water had elapsed. The timing of the irrigation cycle is a function of the irrigation method used, the hydraulics of the irrigation system, the soil physical properties and the crop water requirements.

### INTRODUCTION

The availability of adequate food and fiber for future generations will depend greatly on our ability to manage and conserve our soil, water and air resources. To meet these responsibilities, it is necessary to improve our ability to precisely and accurately measure variables which affect the status of these resources. Knowledge of the soil water is of primary importance in hydrology, soil and irrigation science, civil engineering, recreation, and many other areas where people, soil and water interact. The ever-increasing competition for water and overdrafting of groundwater resources dictate that irrigated agriculture which diverts the greatest amount of water must increase its irrigation efficiency.

Many newly developed pressurized irrigation systems, such as drip, center pivot and lateral-move irrigation systems can potentially operate at high irrigation efficiency; however, these systems should be operated at high application frequency which tends to minimize the effects of soil spatial variability and soil as a storage reservoir so that the infiltration phase is dominant and the redistribution and uptake phases are less important. Under high-frequency irrigation scheduling, the soil matric potential should be maintained nearly constant and irrigation water must be applied at least daily, at a rate nearly equivalent to the evapotranspiration rate so that conventional irrigation scheduling techniques are not adequate; hence there is a strong need for "real-time" instantaneous irrigation scheduling.

The soil matric potential, a measure of the holding strength of the soil matrix for water, is a critical variable in crop yield, runoff, erosion, evapotranspiration and irrigation scheduling. Most farmers schedule field operations based on soil water conditions, which in non-saline areas can be fully characterized by the soil matric potential. The advent of pressurized, uniform, and potentially efficient irrigation systems, such as drip and lateral-move irrigation systems, points out that precise management of these units is critical if a high irrigation efficiency is to be achieved.

Several important criteria for measurement of soil water variables are: timeliness, accuracy, and adequacy of range of coverage. Real-time monitoring of soil water for optimizing production and irrigation efficiency requires additional operational criteria such as (1) adaptability to full automation with minimum maintenance; (2) ability to interact with computerized systems providing data storage, calculations, statistics, and decision-making capability; and (3) output through printer and/or telecommunication systems. Although many measurement methods and instruments are available, very few can meet all of the above criteria simultaneously.

The rate of heat dissipation in a porous medium of low heat diffusivity has been shown to be sensitive to water content. Basically, it depends on the fact that air is a good thermal insulator as compared with water, and when water is replaced by air, the remaining water films become thinner and the area available for heat conduction decreases. The water content of a porous material can, therefore, be measured by using a heat source in the porous material and measuring the temperature rise at that point.

Phene et al. (1971a) mathematically modeled such a system and outlined details for constructing a sensor (SMPS) that measures the matric potential ( $\psi_m$ ) component of soil water potential in situ. The performance of the instrument and its usefulness in the laboratory and in the field were tested and evaluated. Results from these tests were reported by Phene et al. (1971b) for the original prototype SMPS, by Phene et al. (1981) for a commercial SMPS using the prototype design (MCS, Inc.) and by Phene (1986b) for another commer-

cial SMPS (Agwatronics, Model AGWA-II)\*. These tests were designed to also demonstrate the use of the SMPS in the concept of real-time high-frequency irrigation control.

A new ceramic material developed by Agwatronics has a pore size distribution capable of providing a linear soil matric potential response between  $-10$  and  $-300$  J/kg ( $1$  J/kg =  $10$  mbar) and some measurable response between  $-300$  and air dry soil ( $-3100$  J/kg). This ceramic provides a stable matrix for the SMPS as originally suggested by Phene et al. (1971b).

Laboratory and field evaluations have shown that the AGWA-II SMPS: (a) has a linear measurement sensitivity in the soil matric potential range of interest ( $-10$  to  $-300$  J/kg); (b) is independent of temperature changes encountered in soils; (c) is independent of soil texture; (d) has a rapid response to small changes in soil matric potential; (e) is not affected by salinity; and (f) can measure soil matric potential with an accuracy of  $\pm 2.5$  J/kg in a range from  $-10$  to  $-300$  J/kg (Phene, 1986b).

The objectives of this paper are to present a method for real-time in-situ measurement of soil matric potential, to describe how this system meets the above criteria and to show how the soil matric potential sensors (SMPS) used for this method can be interfaced to a small portable micrologger for real-time monitoring of soil matric potential and for scheduling of high-frequency irrigation systems. There is a potential to use this method, which has been satisfactory for scheduling high-frequency irrigations for other systems where the need for irrigation is less demanding.

#### REAL-TIME MEASUREMENT OF SOIL MATRIC POTENTIAL

Any programmable computerized data acquisition system capable of measuring in  $0.5$ – $5$  V DC ranges with  $\mu$ V resolution, making decisions, communicating via telephone modem, performing basic calculation and storage of data can be used with the SMPS to monitor soil matric potential in real time. A micrologger (Campbell Scientific, Inc., Model 21X) was used to measure several SMPS (Agwatronics, Inc., Model AGWA-II). The standard micrologger includes eight different analog inputs, four pulse counters, four switched excitation outputs, two continuous analog outputs, and six digital control outputs. The input range of the analog input is selectable from  $\pm 5$  V DC down to  $\pm 5$  mV DC with resolutions ranging from  $333$  to  $0.33$   $\mu$ V DC, respectively. The  $5$  V DC range was used to accommodate the output voltage of the SMPS because the  $10$  k $\Omega$  resistor used to convert the current output of the sensor to voltage resulted in a large voltage. This selection limits the SMPS resolution to  $333$   $\mu$ V. The voltage regulation of the  $12$  V DC continuous power supply

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from the 21X was improved to provide constant heater excitation with +10 V DC and to excite the SMPS. A 32 channel relay multiplexer can also be obtained from Campbell Scientific, Inc. (Model AM32) to increase the number of sensors being measured.

The soil matric potential measurement consists of two voltage readings taken 1 minute apart.

(1) At time  $t_i$ , the initial voltage measurements ( $V_i$ ) is obtained across resistor R (Fig. 1A) and is shown graphically in Fig. 1B. This measurement represents the temperature of the sensor and surrounding soil prior to the heat pulse.

(2) The switch  $S_w$  (Fig. 1A) is then closed for 1 min imposing a 10 V DC voltage across the heating resistor  $R_H$  and generating a current of 10 mA and power of 1 W. After 1 min (time =  $t_f$ ), the final voltage reading ( $V_f$ ) is taken across R and the switch  $S_w$  is opened. The change in temperature represented by ( $V_f - V_i$ ) of the sensor subjected to a 1 W heating is proportional to the amount of water in the ceramic and surrounding soil. The greater ( $V_f - V_i$ ),

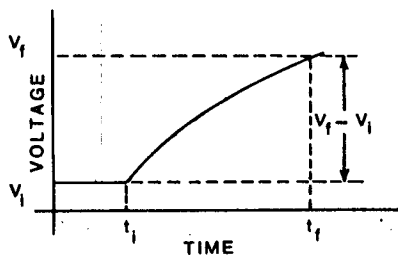
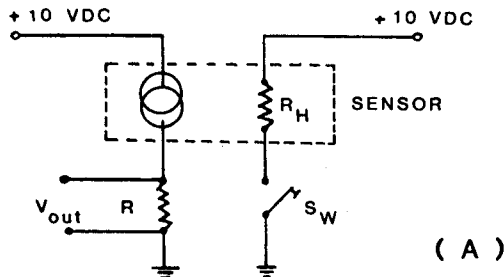


Fig. 1. Soil matric potential measurement using the thermal dissipation method: (A) basic electrical circuit; (B) voltage-time relationship.

the drier the soil is. The voltage difference ( $V_i - V_j$ ) when calibrated at different soil matric potential provides the calibration curve for the measurement of the soil matric potential.

## PROCEDURES

Six SMPS were calibrated between  $-20$  and  $-150$  J/kg. The calibration of the SMPS voltage output versus matric potential was accomplished in a pressure plate apparatus (Soil Moisture Equipment Corporation, Santa Barbara, CA). The SMPS were placed in a plastic ring on a 300 kPa bubbling pressure ceramic plate (Soil Moisture Equipment Corp., Santa Barbara, CA) and surrounded with a mixture of 75% diatomaceous earth and 25% soil which passed through a 74  $\mu\text{m}$  screen. Final 24 measurements were taken when nearly constant values were obtained with the micrologger and there was no water flowing from the pressure plate outflow tube. These measurements were used to determine the mean, the standard deviation (SD), and the coefficient of variation (CV) of the measurements. The pressure on the plate was then increased and the procedure was repeated. A regression equation for voltage output versus soil matric potential was obtained statistically for each SMPS.

The SMPS were installed in a weighing lysimeter at the University of California West Side Field Station that was planted to cantaloupes (Phene et al., 1986). They were placed at three depths: 15, 30, and 45 cm from the soil surface and at two locations: a lateral distance of 5 cm from one of the emitters of the subsurface drip system, and at a lateral distance of 5 cm from the drip line halfway between two emitters. The output from each sensor was measured hourly, converted to matric potential, averaged daily and the data were recorded in the memory of the 21X micrologger. The lysimeter was irrigated automatically every time 1 mm of water was evapotranspired. Weekly, the data were transferred into a cassette recorder and processed in the main computer. Approximately 100 days of continuous data were collected for each of the six SMPS.

## RESULTS AND DISCUSSION

### *Calibration*

A typical calibration curve obtained with the above system is shown in Fig. 2. The soil matric potential is a linear function of the voltage output of the sensor  $\psi_m = 652.8 - 15.2$  (mV reading) with an  $R^2 = 0.999$  and a standard deviation of  $\pm 5.5$  J/kg. In this case, the  $\pm 5.5$  J/kg is limited by the resolution of the 5 V scale of the 21X micrologger, which is 0.333 mV. If the initial voltage measurement is offset or the value of the resistor used to convert current to

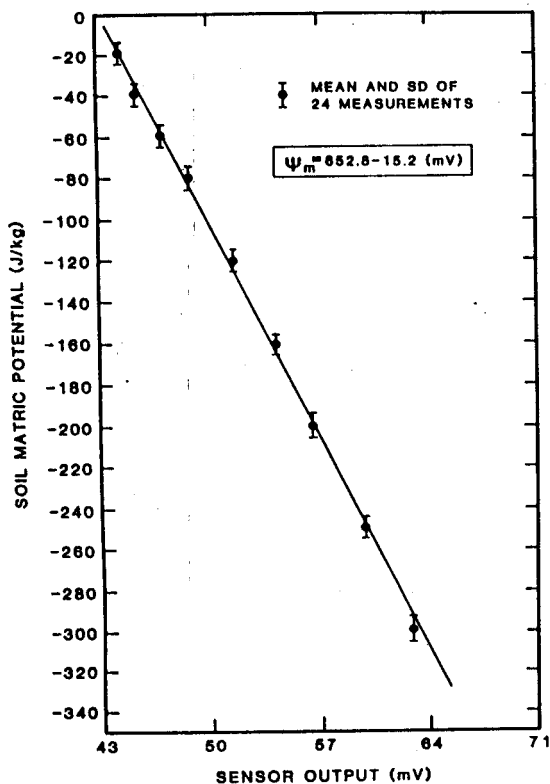


Fig. 2. Calibration curve for a SMPS (Agwatronics, model AGWA-II) obtained with a pressure plate apparatus and the micrologger (CSI, model #21X).

voltage is decreased then measurements can be made on the 0.5 V scale which has a resolution of 33.3  $\mu$ V or the 0.05 V scale which has a resolution of 3.3  $\mu$ V.

### *Time constant*

Figure 3 shows the time response of the SMPS to changes in pressure during the calibration process. These data are converted to a calculated running average line of five hourly measurements. The vertical dashed lines denote the time at which the pressure in the pressure plate apparatus was raised. The horizontal dashed lines represent the mean output of the SMPS at equilibrium pressures. These data show that the response of the SMPS is nearly immediate for changes in pressure up to 100 kPa. It takes about 24 h to reach equilibrium between -100 and -120 kPa and about 60 h between -120 and -140 kPa.

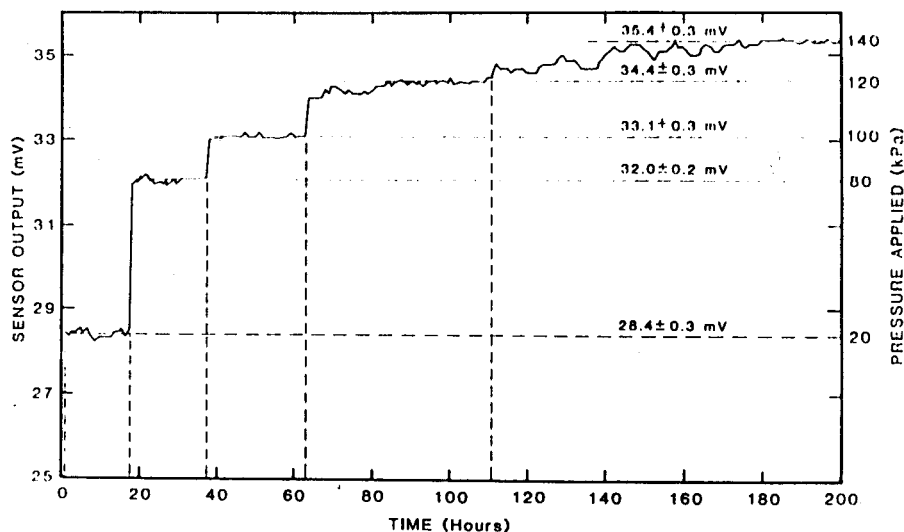


Fig. 3. Time response and voltage output of a SMPS (AGWA-II) to pressure changes in the pressure plate apparatus using a 300 kPa ceramic plate and a mixture of 75% diatomaceous earth and 25% soil which passed through a 74  $\mu$ m screen.

Again the resolution of the measurements is limited to  $\pm 5.5$  kPa by the use of the 5 V scale of the 21 X micrologger.

### Monitoring $\psi_m$

Measurements of soil matric potential for the SMPS next to the emitters in the field lysimeter experiment are given in Fig. 4 and for the SMPS halfway between two emitters in Fig. 5. When the SMPS were installed, the soil had been sprinkler irrigated for germinating the crop and the entire soil profile was wet. Almost immediately after installation, the SMPS installed at the 15 cm soil depth at both locations showed rapid decrease in soil matric potential from  $-25$  J/kg to about  $-175$  J/kg. This rapid decrease can be attributed to combined root extraction by the new crop and to soil evaporation at the soil surface. Between 5 and 10 days after installation (Figs. 4 and 5), the soil matric potential of the two SMPS installed at the 30 cm depth started to decrease at a rate nearly similar to that of the shallow SMPS. The SMPS installed at 45 cm depth next to the emitter and halfway between the two emitters (Figs. 4 and 5) show essentially no change in soil matric potential and indicated water saturated soil conditions. Since the SMPS' response between 0 and 12.5 J/kg is questionable because of hysteresis and non-linear response, it is difficult to estimate exactly what the absolute values are in this range of soil matric po-

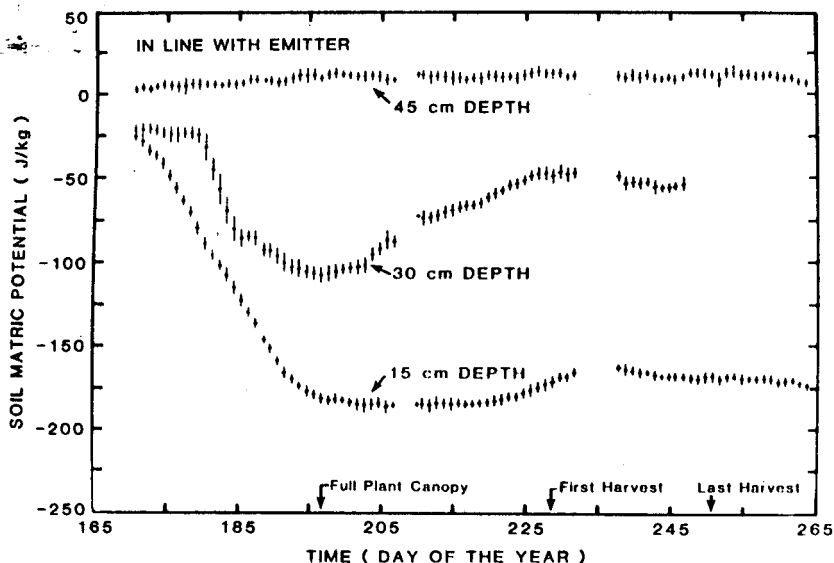


Fig. 4. Soil matric potential at three depths, measured hourly and averaged daily in a weighing lysimeter planted to cantaloupes. The soil was irrigated with a high-frequency subsurface drip system, installed 45 cm below the soil surface, every time one mm of evapotranspiration occurred. Measurements were taken vertically above the subsurface drip line with the sensor at 45 cm depth being installed next to one of the emitters.

tential. It is interesting to note that SMPS at depths of 15 and 30 cm reached minimum values of  $-150$  and  $-100$  J/kg, respectively, after full plant canopy was achieved; after that time, the soil matric potentials of these SMPS seemed to stabilize slowly for about 30 days (until harvest). The SMPS near the emitter (45 cm depth) remained nearly constant during the season since the lysimeter is irrigated automatically every time 1 mm of evapotranspiration occurs, so that all water losses are replenished immediately. Breaks in data which occurred on days 207–210 and 233–237 resulted from losses in data transfer between the lysimeter and the laboratory. After day 245, the SMPS at 30 cm depth (Fig. 4) failed and the SMPS at 15 cm depth (Fig. 5) became noisy from time to time due to a loose wire connection. It will be demonstrated in the following section that for the purpose of irrigation scheduling, a SMPS located at a radial distance of 15 cm from the emitter and slightly above it could have scheduled the irrigation automatically in a feedback mode and could have performed nearly as well as the lysimeter-based irrigation controller system.

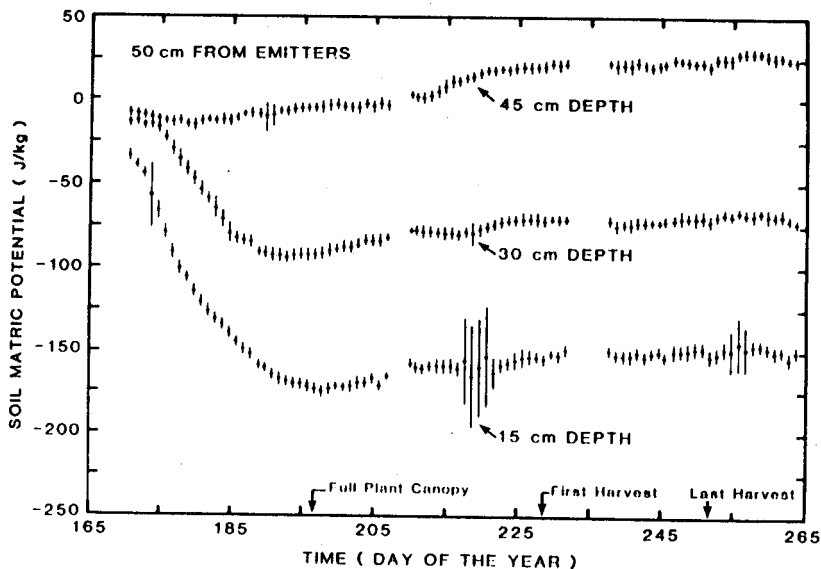


Fig. 5. Soil matric potential at three depths, measured hourly and averaged daily in a weighing lysimeter planted to cantaloupes. The soil was irrigated with a high-frequency subsurface drip system installed 45 cm below the soil surface every time one mm of evapotranspiration occurred. Measurements were taken vertically above the subsurface drip line and halfway between two emitters.

### Irrigation scheduling

A properly calibrated SMPS can be used to monitor soil matric potential and control irrigation automatically. Figure 6 shows an example of the optimal range of  $\psi_m$  for good plant growth in a Hanford fine sandy loam. In addition to water availability, soil physical properties such as critical oxygen diffusion rate (ODR) (aeration) shown by the shaded portion of the curve between 0 and  $-10$  J/kg, and soil mechanical strength (impedance to root growth) shown by the shaded portion of the curve between  $-60$  and  $-100$  J/kg are used to define the range of soil  $\psi_m$  optimal for root growth and activity (Phene and Beale, 1976). Within this range, a soil matric potential is defined at which irrigations are to be started (threshold). Depending on the soil depth, the optimal  $\psi_m$  was found to be about  $-25$  to  $-35$  J/kg and has a range extending between about  $-10$  and  $-60$  J/kg. Generally, the optimal  $\psi_m$  has a range which increases as soil texture becomes finer but is extremely narrow in compacted coarse-textured soils (Phene et al., 1976; Campbell and Phene, 1977). Therefore, physical characterization of sandy soils is usually necessary, whereas the optimal  $\psi_m$  for fine-textured soils can be approximated.

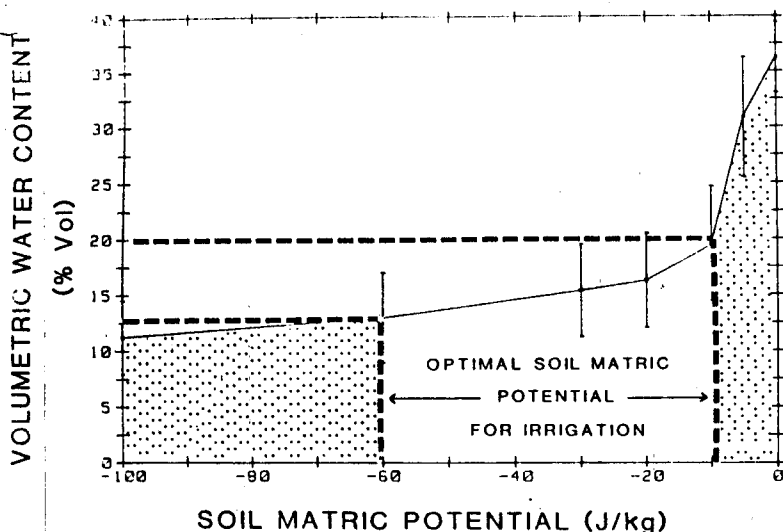


Fig. 6. Water adsorption curve and optimal  $\psi_m$  for irrigation of a Hanford fine sandy loam soil (Typic Xerorthents). (After Phene and Howell, 1984.)

For closed-loop feedback automated irrigation, the soil sensor should be placed near the expected center of the root zone of the mature crop. In this location the soil is never allowed to dry below the  $\psi_m$  threshold before the sensor detects the drying trend and triggers another irrigation. Early in the season, when the roots are shallow and the soil near the surface dries out, the threshold  $\psi_m$  can be increased to a higher  $\psi_m$  value so that water will be available where the roots are located. Figure 7 depicts the closed-loop automatic system used to control high-frequency irrigation systems (Phene, 1986a). In this system, the variable evapotranspiration ( $E_t$ ) causes water extraction from the soil which disturbs the  $\psi_m$  measured by the SMPS. Electrical signals are transmitted to the computer which analyzes the soil matrix potential information with respect to the threshold level and either calls for irrigation or if not needed, prints out the status and repeats the operation in the next field. Irrigation is shut off based on time. The amount of time allowed for the irrigation cycle depends on the type of irrigation system, the hydraulics of the system, the soil water holding capacity, the soil capillarity and depth, and the crop water requirements. Typically, the system should allow enough time to apply 1 mm of water, although in fine-textured soil 2–3 mm is not excessive. In coarse-textured soil, such as sand, 0.5 mm is preferable.

In a field experiment conducted in Fresno, California, three SMPS were installed at 45 cm depth midway between two emitters and 15 cm from the subsurface drip line. The SMPS were used with a desktop computer and data

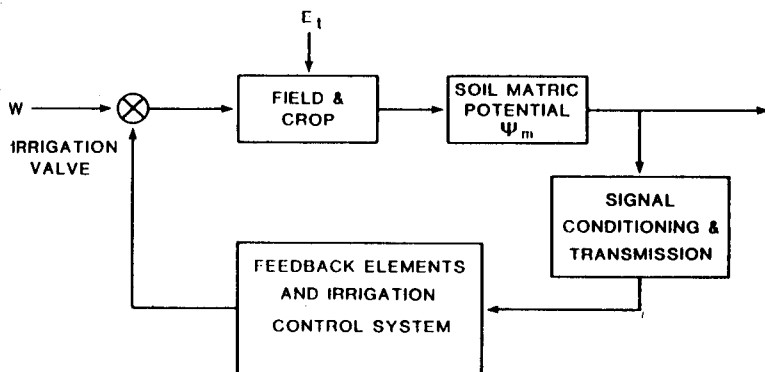


Fig. 7. Closed-loop feedback irrigation control system using soil matric potential ( $\psi_m$ ) as the control variable. The time variable is used to adjust the amount of water being applied. Here  $\psi_m$  is dependent on crop evapotranspiration ( $E_t$ ) and the irrigation depth of applied water ( $d_i$ ).

acquisition system (Hewlett Packard, Model # HHP85 & HHP3497) to initiate a 30 min irrigation (1.2 mm per irrigation) when the mean  $\psi_m$  reached  $-20$  J/kg early in the season. Later the  $\psi_m$  threshold was readjusted to  $-35$  and  $-45$  J/kg and finally to  $-55$  J/kg before harvest in order to impose a water stress on the crop and increase the soluble solids in the tomatoes. Figure 8 shows the responses of the three SMPS to rapid  $\psi_m$  changes in three plots irrigated simultaneously as a treatment by high-frequency subsurface drip irrigation. Hourly, the computer calculated the average of the measurements of the three SMPS, then compared the average  $\psi_m$  to the threshold to determine the need for irrigation to maintain the desired constant  $\psi_m$  level, in this case  $-20$  J/kg. The number of irrigations per day, shown for each day above the x axis, varied between 5 and 15 per day during the seven day period. There were 168 individual SMPS measurements made in each of these plots. The mean of 504 measurements made in the three plots was  $-20.0$  J/kg. Similarly, the means, standard deviations, and ranges of each sensor were  $-23.2 \pm 0.8$  and  $3.7$ ;  $-14.6 \pm 0.1$  and  $2.1$ ; and  $-22.1 \pm 0.4$  and  $2.3$  J/kg, respectively for SMPS in each plot. From day 162 to 165 the mean reference evapotranspiration was 12 mm/day. The two SMPS at the lower  $\psi_m$  (SMPS #2 and 3) responded rapidly and an increasing number of irrigations were scheduled automatically to meet the unusually high  $E_t$  requirement. One of the sensors, SMPS-1 was consistently higher than the other two sensors because of soil spatial variability. When the sensors were retrieved from the soil, SMPS-1 was found to be installed in a compacted clay lense which restricted root growth and remained relatively more saturated than the other two sensors. Hence, under extremely variable soil conditions it may be necessary to use the mean of several sensors to schedule irrigation properly.

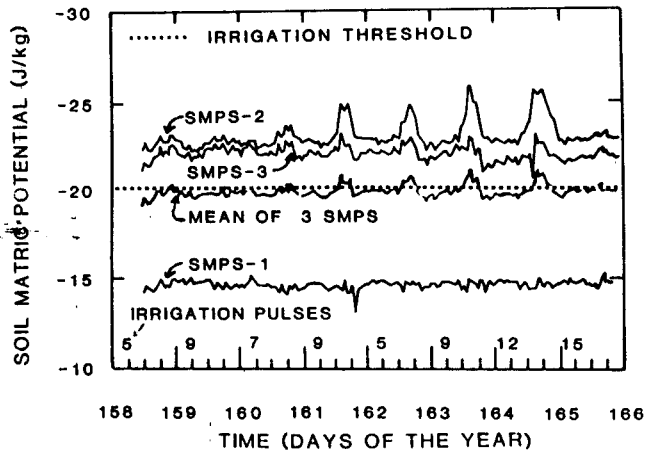


Fig. 8. Soil matrix potential measurements at 45 cm depth, measured by three SMPS in field plots irrigated automatically when the mean  $\psi_m$  dropped below the threshold of  $-20$  J/kg.

## CONCLUSION

A method for real-time in-situ measurement of soil  $\psi_m$  has been developed and tested, and results have shown that several operational criteria required for real-time accurate monitoring of soil  $\psi_m$  and for scheduling irrigation systems were satisfied. The SMPS can be measured automatically with many data acquisition systems and thus can provide real-time information about soil water. The accuracy of the measurement is dependent upon the calibration of the SMPS against known standard pressures; hence, because of the linearity of the response between  $-10$  and  $-300$  J/kg, the calibration is easier to accomplish than for non-linear sensors. Depending upon the data acquisition system used, the resolution of the measurement ranges from  $\pm 2.5$  to  $\pm 5.5$  J/kg. The response time of the SMPS is less than one hour between  $-10$  and  $-100$  J/kg but increases rapidly to several days for soil matrix potential lower than  $-120$  J/kg.

Monitoring soil matrix potential in real-time and controlling irrigation systems automatically requires equipment to (a) sample automatically several sensors sequentially, (b) compare the output of each sensor or the mean of several sensors to the threshold value, and (c) have computer outputs capable of controlling and monitoring the irrigation system. Desktop computers and microprocessors capable of storing data, performing calculations, and making decisions and with printer and/or telecommunication output systems were used successfully. Automated irrigation scheduling based on SMPS was accomplished by initiating irrigation when a preset  $\psi_m$  threshold was exceeded and

irrigation cycles were terminated when a given amount of time has elapsed. The timing of the irrigation cycle is a function of the irrigation method used, the hydraulics of the irrigation system, the soil physical properties, the soil depth and the crop water requirements.

## REFERENCES

- Campbell, R.B. and Phene, C.J., 1977. Tillage, matric potential oxygen and millet yield relationships in a layered soil. *Trans. ASAE*, 20: 271-275.
- Phene, C.J., 1986a. Automation. In: F.S. Nakayama and D.A. Bucks (Editors), *Trickle Irrigation for Crop Production. Developments in Agricultural Engineering*, 9. Elsevier, Amsterdam, pp. 188-215.
- Phene, C.J., 1986b. Measurement of soil water by the thermal diffusion method. In: *Proc. California Plant and Soil Conf.*, 28-30 January 1986, Sacramento, CA., pp. 40-47.
- Phene, C.J. and Beale, O.W., 1976. High-frequency irrigation for water nutrient management in humid regions. *Soil Sci. Soc. Am. J.*, 40: 430-436.
- Phene, C.J. and Howell, T.A., 1984. Soil sensor control of high-frequency irrigation systems. *Trans. ASAE*, 27: 392-396.
- Phene, C.J., Hoffman, G.J. and Rawlins, S.L., 1971a. Measuring soil matric potential in situ by sensing heat dissipation within a porous body: I. Theory and sensor construction. *Soil Sci. Soc. Am. Proc.*, 35: 27-33.
- Phene, C.J., Rawlins, S.L. and Hoffman, G.J., 1971b. Measuring soil matric potential in situ by sensing heat dissipation within a porous body: II. Experimental results. *Soil. Sci. Am. Proc.*, 35: 225-229.
- Phene, C.J., Campbell, R.B. and Doty, C.W., 1976. Characterization of soil aeration in situ with automated oxygen diffusion measurements. *Soil Sci.*, 122: 668-678.
- Phene, C.J., Fouss, J.L., Howell, T.A., Patton, S.H., Fisher, M.W., Bratcher, J.O. and Rose, J.L., 1981. Scheduling and monitoring irrigation with the new soil matric potential sensor. In: *Proc. Irrigation Scheduling for Water and Energy Conservation in the 80's*. ASAE Publ., 23-81: 91-105.
- Phene, C.J., Miyamoto, J.M., Davis, K.R., McCormick, R.L. and Liu, R.C., 1986. Automated feedback irrigation scheduling and control with a weighing lysimeter. In: *Proc. 2nd Int. Conference and Exposition on Automation in Agriculture*, 3-5 March 1986, Chicago, IL. American Society of Agricultural Engineers, St. Joseph, MI, pp. 135-147.

