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SUMMARY:
The development of the Watermark Soil Moisture Sensor has provided a tool for irrigation scheduling of high value horticulture crops. Calibrations of the Watermark Model 200, 200SS, and 200SSX are provided. Mathematical models were developed for each of the Watermark Soil Moisture Sensors that allow for direct conversion of sensor resistance in ohms and soil temperature into soil water potential values. Data used were for sensor resistance measured at soil water potentials in the range of -10 to -75 kPa at either 15 °C or at 25 °C. For Model 200, multivariate polynomial ratio equations predicted linear relationships between soil water potential and the two variables within the range tested; the relationship was curvilinear for Models 200SS and 200SSX. For all GMS models, the temperature effect on estimated soil water potential was greater as the soil became dryer. Different calibration equations proposed by various authors for Watermarks are compared. Changes in commercial and experimental Watermark sensor models are also compared.

INTRODUCTION

Importance of Precision Irrigation Scheduling
Irrigated agriculture provides much of the world's food supply. Nearly 50% of the total annual water used within urban boundaries is used for lawn and landscape irrigation. Because of economic, political, and environmental reasons, there has been increasing pressure to reduce or eliminate waste of irrigation water and energy resources in both agriculture and landscaping. Over-irrigation results in soil erosion, increases the potential for contamination of surface and ground water through water runoff and leaching, and requires additional chemicals and fertilizers. Under-irrigation damages the yield and quality of some crops. Irrigation of crops highly sensitive to water stress, like potatoes (*Solanum tuberosum* L.), onions (*Allium cepa* L.), and many other horticultural crops requires precision scheduling.

Comparisons Between Sensor Types
Careful irrigation management is dependent on instrumentation, including soil moisture sensors. There is no perfect instrument that will provide the lowest cost and most accurate estimates of soil moisture conditions for all crops in all soils. An effective soil moisture sensor for a particular application must accurately respond in the range of soil moisture critical to the economic response of the crop in a given soil.

In the past decades, tensiometers, neutron probes, and gypsum blocks have been commonly used for measuring soil moisture levels. Neutron probes are accurate, but involve a radiation hazard and are difficult to calibrate and interpret. Data from neutron probes cannot conveniently be used to automate irrigation decisions. Tensiometers, although accurate, are limited to estimating soil water potential in the 0 to -70 kPa range with a reduced range in coarse-textured soils (Cassel and Klute, 1986). In certain soils, and with some crops at certain growth stages, measurements lower than -70 kPa are desirable. Tensiometers can be used to automate irrigation decisions if equipped with pressure transducers, but they are subject to freezing temperatures. Gypsum blocks are inexpensive, but tend to break down too quickly in the soil and have large block to block variation in responsiveness. The water content of gypsum blocks depends on the soil water potential rather than the soil water content (Gardner, 1986), and the water content response to wetting and drying of the soil can be slow. Gypsum blocks will slowly lose firm contact with the soil, and may respond inconsistently to soil water changes. Because of these limitations, neutron probes, tensiometers, and gypsum blocks have served only part of the needs for irrigation management.

A granular matrix sensor (GMS) for electronically measuring soil water has been patented (Larson, 1985) and is marketed as the Watermark Soil Moisture Sensor (Irrometer Co. Inc., Riverside, CA). Granular matrix sensor technology reduces the problems inherent in gypsum blocks by use of a mostly insoluble granular fill material held in a fabric tube supported in a metal or plastic screen (Larson, 1985; Hawkins, 1993). Granular matrix sensors operate on the same electrical resistance principle as gypsum blocks and contain a wafer of gypsum imbedded in the granular matrix below a pair of coiled wire electrodes. The electrodes inside the GMS are imbedded in the granular fill material above the gypsum wafer. The gypsum wafer slowly dissolves to buffer the effect of salinity of the soil solution on electrical resistance between the electrodes. According to Larson (1985), particle size of the granular fill material and its compression determines the pore size distribution in the GMS and its response characteristics.

Recent sensor models developed by Irrometer Company have incorporated improvements in production and technology. The GMS models 200SS and 200SSX have stainless steel exterior and uniform internal compaction (Hawkins, 1993). The steel models may be more uniformly manufactured because of automated packing of the granular matrix to a prescribed pressure. The steel also allows more openings for greater sensor contact with the soil. The GMS models 200SS and 200SSX have shown promise for precise irrigation scheduling of potato fields on silt loam soils in eastern Oregon (Feibert et al., 1998; Shock et al., 1998).

The GMS are convenient for sensing soil water potential to automatically start an irrigation because they do not require periodic maintenance during the growing season. Granular matrix sensors have advantages of low unit cost and simple installation procedures, similar to those used for tensiometers. Data acquisition with GMS can be remote from the measurement site by use of electrical wires, so the plants and soil at the measurement site remain undisturbed. Granular matrix sensors can be easily logged, and the output can be readily used to control automated irrigation decisions. Automation of subsurface drip irrigation or sprinklers can be accomplished using a combination of soil moisture sensors, data logger, controller, solenoid switch, valve, and pressurized water source.

GMS CALIBRATION NEED

To obtain soil moisture potential estimates from GMS, their resistance and soil temperature must be measured along with independent and accurate measurements of soil water potential measurements. The manufacturer of Watermark Model 200 provided the following equation expressing the relationship between sensor resistance and water potential for the temperature calibration built into the 30KTC meter, based on 21.1 $^{\circ}$C:

$$R = 0.5 - [0.1275\, S\, (1.38 - 0.018\, T)] \qquad (1)$$

where R = resistance in k ohms; S = soil water potential in kPa (the Model 30KTC meter scale x 10); and T = temperature in °C. When equation (1) is solved for S, the empirical relationship designed for the 30KTC meter by the manufacturer becomes:

$$S = \frac{-(R-0.5)}{0.1759\, (1-0.013\, T)} \qquad (2)$$

Using three Model 200 sensors and a pressure plate, Thomson and Armstrong (1987) reported that the relationship between sensor readings and temperature within 4 to 38 °C varies with soil water potential. They developed the following equation to describe soil water potential as a function of Model 200 resistance for temperatures between 4 and 38 °C:

$$S = \frac{-R}{0.01306\, [1.062\, (34.21 - T + 0.01060\, T2) - R]} \qquad (3)$$

Wang and McCann (1988) concluded that the effect of temperature on the relationship between Model 200 sensor reading and water potential is linear within the range of 14 to 26 °C. Comparing GMS 200 readings to tensiometers in the root zone of a potato crop in the field, Eldredge et al. (1993) reported that tensiometers and GMS 200 readings were linearly related over the range 0 to -80 kPa with the following equation:

$$S = -6.44 - 0.738\, X \qquad (4)$$

where S = soil water potential (kPa) measured by a tensiometer and X = the 30KTC meter reading of GMS, with $r^2 = 0.89$. Eldredge et al. (1993) further indicated that differences between this calibration and that of Thomson and Armstrong (1987) were within 7.6 kPa over the range of meter readings from 0 to -50 kPa, and are fairly close for the range of water potential for water-stress-sensitive crops that is 0 to -60 kPa. Combining equation (4) with the 30KTC meter performance expressed as equation (2) through substitution and simplification of terms results in:

$$S = -6.44 - \frac{(4.196R-2.098)}{(1-0.013\, T)} \qquad (5)$$

Little information is available on calibration of new commercial model 200SS and experimental model 200SSX, and comparison of these new models with the model 200. The new models may have different responses to soil water potential than the Model 200, and may have different temperature compensations. Our objectives were to measure the comparative responses of GMS models 200, 200SS, and 200SSX in the laboratory at -10 to -75 kPa soil water potential, and at 15 and 25 °C temperatures. Resistance of GMS sensors buried in soil were calibrated against tensiometer soil water potential readings in controlled temperature drying experiments.

PROCEDURES

A 1 m^2 by 68.6 cm deep 14 gal galvanized steel hopper-bottom tank weighing 108.4 kg (398 lb.) was suspended from a Measurement Systems International MSI-4260 portable overhead scale mounted within a moveable support structure. A 0.30 m^3 of Owyhee silt loam soil (coarse-silty, mixed, mesic Xerollic Camborthid) weighing 374.67 kg (826 lb.) at 7.13 percent moisture was evenly spread over a double layer of a porous synthetic cloth, which was laid over the 1.5 cm #20 flattened expanded metal floor at 38 cm depth from the lip of the tank. Perennial ryegrass seed was sown at 11.2 kg/ha (10 lbs/ac).

The soil surface within the tank was divided into 24 micro plots (replications), each 16 cm long by 12 cm wide. One of each Watermark Soil Moisture Sensors Models 200, 200SS, and 200SSX and one Irrometer Model RSR 32 cm Tensiometers (Irrometer Co.) were randomly placed at a depth of 25 cm within each replication. An Omega Model 44004 thermistor was placed in the soil profile at the mid-point, on the dividing lines between each pair of replicates (between replicates 2 and 3, 6 and 7, etc.). All sensors were connected to one of three Campbell Scientific, Inc. Model AM416 Relay Multiplexers, which were in turn connected to a Campbell Model 21X Micrologger. The micrologger was set to collect data from all sensors on an hourly basis throughout each run of the experiment. Data stored in the micrologger were periodically downloaded to an IBM PC computer and stored on disk.

During each run of this experiment the hopper tank, instruments, and support structure (apparatus) were placed in a temperature controlled room (chamber). Artificial light was provided for 14 hours of each 24 hours starting at 6 AM using two Holophane, 460 watt, 120 volt AC, grow lights which were mounted on the support structure and connected to an Intermatic, Inc. Model T101, 120/240/460 volt AC, 24 Hour Dial Time Switch.

At the beginning of each experimental run, the gross weight, weight of the hopper tank, soil weight, gravimetric water, crop fresh weight, sensors and hardware weight were recorded. The weight of the ryegrass was estimated on the basis of one clipped sample taken from each replication. Gravimetric water was determined by subtracting the established base tare weight (hopper tank weight, estimated oven dry soil weight, and estimated weight of the sensors and hardware) plus the estimated crop weight from the beginning tare weight. All tensiometers were serviced, refilled and vacuumed as prescribed by the manufacturer. The crop was then sprinkle irrigated until all tensiometer readings approached zero. The apparatus was then placed in the temperature controlled chamber and sensor readings and daily gross weight were recorded until the majority of the tensiometers broke tension to zero after which the run was terminated.

The second calibration run was at 25 ^{o}C and the third calibration run was at 15 ^{o}C. Instrument readings at 6 AM for each day of both runs were used to develop relationships between differential instrument response to soil water and temperature. One Delmhorst GS-1 gypsum block was also placed in the soil profile within each replication during the second run. For the duration of the second run data was collected once daily from the gypsum blocks with a Delmhorst Model KS-D1 hand held digital meter. During the third run, data from the Delmhorst gypsum blocks was again collected once daily with the hand held meter. Hand held meter readings were converted to resistance using an empirical equation, r^2=0.99.

RESULTS

Sensor changes in resistance were highly non-linear with changes in soil water potential in the range of 0 to -10 kPa and nearly linear with changes in soil water potential in the range of -10 to -75 kPa. For illustration purposes, soil water potential measured with a tensiometer was plotted against sensor resistance for a single GMS model 200SS at 15 and 25 ^{o}C (Figure 1). Similar curvilinear responses were found for 200SSX sensor model within soil water potential range between -10 and -75 kPa. The temperature effect on sensor resistance gets larger as soil becomes dryer. For this particular set of measurements, when sensor resistance was 10 kohms, the soil water potential was -53 kPa at 15 ^{o}C soil temperature and -71 kPa at 25 ^{o}C soil temperature.

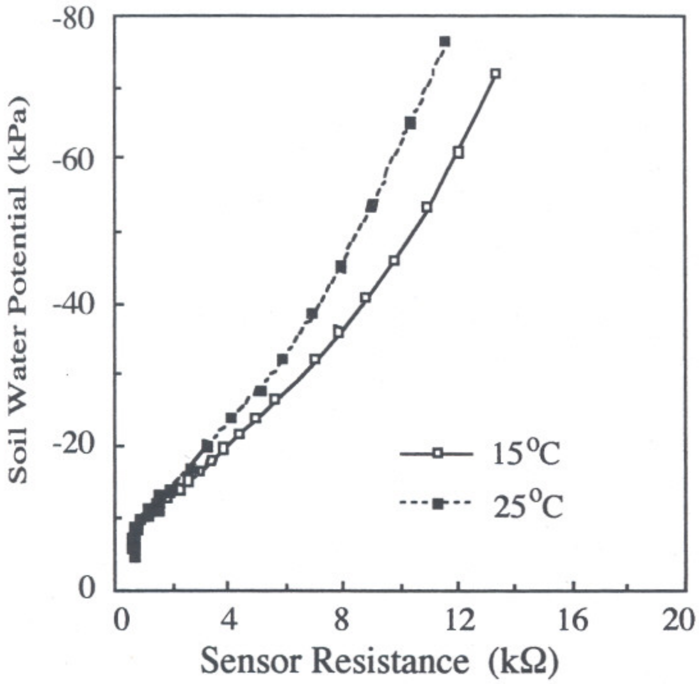

Figure 1. Soil water potential measured with a tensiometer as a function of sensor resistance using a Watermark soil moisture sensor model 200SS at either 15 or 25 °C. The data at each temperature are from a single sensor for illustration purposes. All the readings were made at 6 AM daily through two soil drying cycles.

Calibration Equations

The data for all 24 sets of sensors for each model were used to develop the following equations describing the relationships between resistance of sensors and soil water potential. Only the data between the range of -10 to -75 kPa were used to develop the equations that were intended to compensate for temperature differences between 15 and 25 °C. Although there were sensor to sensor variations, the probability values for all equations and parameters reported were smaller than 0.0001. The relationship of soil water potential to sensor resistance and soil temperature was evaluated with stepwise regression on the ratio of polynomials:

$$S = (c1 + c_2 R + c_3 R^2 + c_4 T + c_5 T^2)/(1 + c_6 R + c_7 R^2 + c_8 T + c_9 T^2) \qquad (6)$$

For Model 200 $$S = -\frac{(4.691 + 3.559\, R)}{1 - 0.008456\, T} \qquad r^2 = 0.872, \quad n=710 \qquad (7)$$

For Model 200SS $$S = -\frac{(4.093 + 3.213\, R)}{1 - 0.009733\, R - 0.01205\, T} \qquad r^2 = 0.945, \quad n=729 \qquad (8)$$

For Model 200SSX $$S = -\frac{(4.734 + 2.859\, R)}{1 - 0.01856\, R - 0.01316\, T} \qquad r^2 = 0.949, \quad n=731 \qquad (9)$$

Using equations 7, 8 and 9, Figure 2 shows estimated soil water potential as a function of sensor resistance for each sensor model 200, 200SS, and 200SSX at either 15 or 25 °C. The equation for the relationship between soil water potential and sensor model 200 resistance was linear, but the relationships for both sensor models 200SS and 200SSX were curvilinear. For all GMS models, the temperature effect on estimated soil water potential was greater as the soil became dryer.

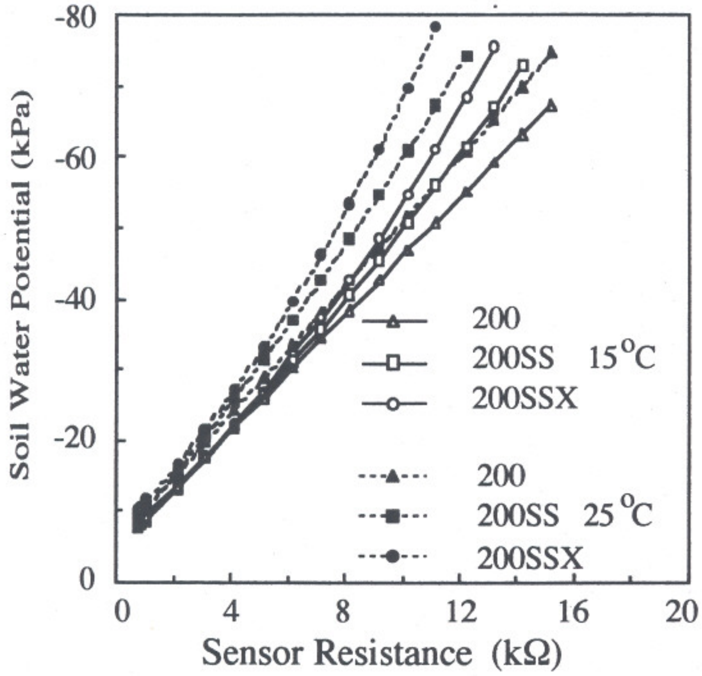

Figure 2. Soil water potential as a function of sensor resistance at either 15 or 25°C based on equations 7, 8, and 9 developed in the present study for Watermark soil moisture sensors model 200, 200SS, and 200SSX .

Comparison of Model 200 Response With Previously Published Equations

The calibration equations provided by manufacturer (equation 2) and by Eldredge et al. (equation 5) predict a linear relationship between soil water potential and sensor resistance between -10 and -75 kPa (Figure 3). Results of the present study also were linear; however, for sensor resistance greater than 3 kΩ, both equations 2 and 5 estimated a considerably lower water potential than equation 7, and the differences become greater at lower soil water potentials. Equation reported by Thomson and Armstrong (1987; equation 3) predicts a curvilinear relationship between soil water potential and sensor resistance similar to our equations for sensor models 200SS and 200SSX (equations 8 and 9), which we did not observe in -10 to -75 kPa range used in our equation.

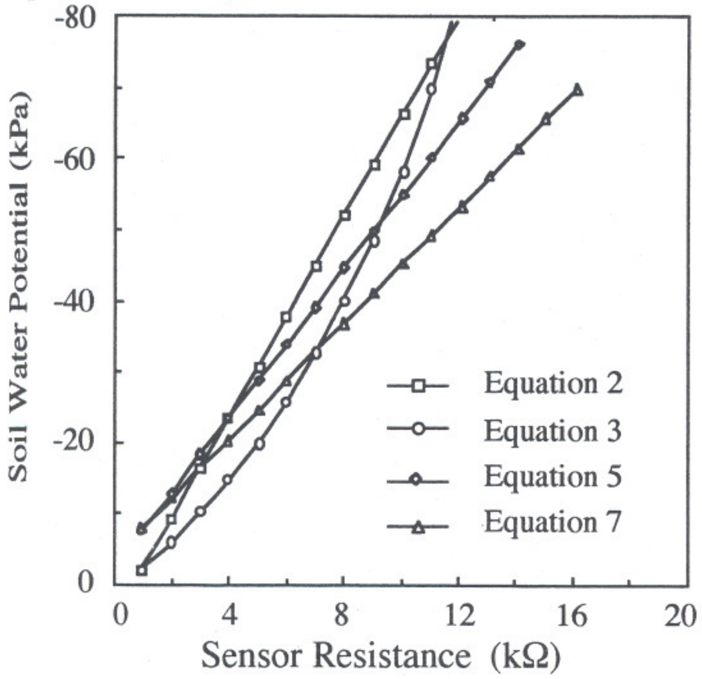

Figure 3. Soil water potential as a function of sensor resistance at 15°C based on equations developed for Watermark soil moisture sensor model 200 by the manufacturer (equations 2), Thomson and Armstrong (equation 3), Eldredge et al. (equation 5), and the one developed in the present study (equation 7).

DISCUSSION AND CONCLUSION

Calibration equations indicated that the relationship between soil water potential in range of -10 and -75 kPa and sensor resistance was linear for Model 200, whereas it was curvilinear for Models 200SS and 200SSX . The growth chamber runs at 15 °C and 25 °C confirmed that the relationship between GMS resistance and soil water potential is also a function of temperature. Calibration equations further indicated that temperature compensation was related to water potential, with greater temperature effect on sensor reading at higher soil water tension. This means that if temperature effects are ignored, the error in the estimated soil water potential will be greatest when the growers need to make an irrigation decision.

Calibration equations presented here are useful in the soil water potential and temperature range experienced with much of irrigated agricultural crops. In some cases, however, it may be desirable to achieve higher soil suction than the range of tensiometer. Also, in landscape and turfgrass production, soil water is generally maintained in the wetter end than -10 kPa. Water potential responsiveness of tensiometers at the wet end (0 to -10 kPa) and the dry end (<-80 kPa) of soil water potential were limiting factors in GMS calibration outside the range of -10 to -80 kPa. We do not recommend that presented equations be used for water potential measurements beyond the range of tensiometer data that the sensors were calibrated against.

Another factor that was not examined in the present study was the speed of responsiveness of sensors to wetting and drying. Beside sensor resistance response to steady-state soil water potential, the dynamic response to typical soil wetting and drying cycle is very important. The speed that a sensor responds to these cycles determine if the measurement lags behind actual soil water content. The dynamic response of Watermark Model 200 sensors is apparently good during typical soil drying cycles following complete rewetting, but the response to rapid drying or partial soil rewetting is slow or non-existent (McCann et al., 1992). Other issues that are beyond the scope of present experiment are GMS response to salinity, temperature compensation outside of the limited range tested, and response in different soil types. Also, the following questions are usually raised by researchers and growers and need to be addressed:

1. Is field calibration of sensors accurate? Do they need to be calibrated for different fields?
3. Is there a better sensor design?
4. What soil textures are appropriate? Do GMS fail in sand?
5. Does salinity affect the sensor?
6. Where should sensors be placed in the field?
7. How many sensors are needed?
8. Do sensors respond fast enough to changes in soil water or do they lag too much?

Both stainless steel models used in this experiment had greater accuracy with less sensor to sensor variation than the Model 200 (data not shown). It is difficult to explain the differences between equations developed for Model 200 in this experiment (equation 7) and the ones previously reported (Figure 3). Thomson et al.(1996) recently evaluated all the calibration equations that have been developed for Watermark Model 200, and concluded that many factors could have been contributing to differences among models including changes in sensor design over time, the meter used to read sensor resistance, and the method of sensor excitation. Nevertheless, the good fit of the models presented here and the strong correlation found in comparison of tensiometers with GMS indicates that GMS sensors can be calibrated and used to estimate soil water potential for irrigation decisions.

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