A laboratory evaluation of Watermark electrical resistance and Campbell Scientific 229 heat dissipation matric potential sensors

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Abstract

There is much interest in continuous recording of soil matric potential with porous matrix sensors for irrigation scheduling purposes. Watermark electrical resistance and Campbell Scientific 229 heat dissipation matric potential sensors were simultaneously tested in a modified pressure chamber. Both sensors are suitable for automatic recording of changes in soil water content or matric potential. Initial indications are that individual sensor calibration will be unnecessary for irrigation scheduling purposes. The electrical resistance measurement was shown to be affected by soil salinity and temperature and to be dependent on wetting history. Moderate hysteresis of heat dissipation sensors was recorded. Both the electrical resistance and the heat dissipation measurement provided reliable estimates of soil matric potential in the range from -100 to 0 J·kg^{-1} at various salinity levels. A minimum reading interval of 3 min is recommended for the heat dissipation sensor to allow the block temperature to re-equilibrate.

Introduction

The measurement of soil matric potential Ψ_m, is of cardinal importance for irrigation monitoring and research on soil-plant-water relationships. Irrigation amounts can also be determined from matric potential measurements if a soil water retention curve is available.

Several techniques for measuring water potential components of a medium in equilibrium with soil water are described in the literature: tensiometry (Cassel and Klute, 1986); thermocouple psychrometry (Rawlins and Campbell, 1986); and electrical resistance and heat dissipation (Campbell and Gee, 1986). Tensiometers require frequent maintenance and have a limited range of measurement (approximately -70 to 0 J·kg^{-1}). Thermocouple psychrometry is a highly specialised measurement and requires instruments of extreme accuracy. Electrical resistance sensors estimate matric potential through the measurement of the electrical resistance of the solution in a porous block in matric potential equilibrium with the surrounding soil. Heat dissipation sensors rely on the effect of the water content on thermal conductivity and heat capacity. As the electrical resistance and heat dissipation sensors do not directly measure soil matric potential, empirical calibration is required. The interest in monitoring soil water potential with such soil water sensors is rapidly increasing due to the simplicity of management and particularly since data acquisition and control systems have become accessible to crop producers.

A variety of porous materials have been used to construct electrical resistance sensors: gypsum (Perrier and Marsh, 1958); fibreglass (Colman and Hendrix, 1949); and nylon (Bouyoucos, 1949). Gypsum blocks slowly dissolve providing a saturated solution of Ca^{2+} and SO_4^{2-} ions in the porous block. They are therefore less sensitive to salts than fibreglass and nylon blocks as the saturated solution buffers the effects of changes in soil salinity on measured electrical resistance (Taylor, 1955). The blocks, however, gradually deteriorate due to dissolution of gypsum, changing the pore geometry and thereby alter the calibration and make the measurement of matric potential unreliable. Fibreglass and nylon sensors are longer lasting, but the electrical resistance output includes both matric and osmotic effects. Individual field calibration of fibreglass units was recommended by Seyfried (1993) due to the high variability among calibration statistics of individual sensors. Scholl (1978) built a two-element ceramic sensor for measuring both matric and osmotic potential. The matric potential element is used to determine electrical resistance response during pore drainage, while the salinity block is made of a high-porosity ceramic with a fine pore distribution. The salinity sensor therefore remains saturated over the measured matric potential range, measuring electrical resistance changes due only to salt movement. The Watermark soil water sensor (Irrometer Co., Riverside, CA) is made of a fine sand material held in place by a synthetic porous membrane. [Mention of manufacturers is for the convenience of the reader only and implies no endorsement on the part of the authors, their sponsors or the University of Pretoria]. The membrane prevents penetration of fine soil material which could change the physical properties of the block (England, 1965). An internal gypsum tablet buffers against the salinity levels found in irrigated soils. The sensor consists of two concentric electrodes embedded in the reference matrix material. Thomson and Armstrong (1987) found the variability between the sensors not to differ significantly in the -100 to -10 J·kg^{-1} potential range. According to Eldredge et al. (1993), the resistance response of the sensor to drying in air in an oven and in the field is similar.

Transient heat-pulse theory is discussed by Jackson and Taylor (1986) and Campbell et al. (1991). In practice, heat dissipation is determined by applying a heat pulse to a heater within the soil sensor and monitoring the temperature at the centre of the block before and during heating. The temperature rise is a function of the thermal diffusivity, and therefore of the water content of the block. The choice of the block material is critical as its pore size distribution determines the useful range of measurement. Construction procedures and the choice of porous material for a heat dissipation block were discussed by Phene et al. (1971). The reference matrix must be large enough, and the amount of heating small enough, to avoid emission of the heat

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pulse into the surrounding soil having different thermal properties from those of the block.

In this study, Watermark electrical resistance and Campbell Scientific Incorporated (CSI, Logan, UT) heat dissipation soil sensors were tested in the laboratory. Objectives were to investigate the need for individual calibration of the sensors and to determine their useful measurement range, salinity response and hysteresis behaviour. The hand-held 30 KTCD meter (marketed by Irrometer Co.) was evaluated and the minimum time required between heat dissipation sensor readings determined.

Materials and methods

Three Watermark Model 200 and three CSI Model 229 soil water sensors were chosen at random and placed in a modified pressure chamber, on a 500 $J{\cdot}kg^{-1}$ ceramic pressure plate. The lid of the pressure chamber was drilled and brass bolts embedded into nylon were fitted into the 10 mm diameter holes. The shape of the nylon provided a press fit. A seal between the nylon and hole walls was provided by silicon rubber. The wires of the sensors and those of the thermocouple used to monitor internal chamber temperature were connected to nuts inside the pressure chamber. External nuts were connected to a 21X CSI data logger supplying excitation voltage (500 mV Watermark, 2000 mV heat dissipation sensors).

Diatomaceous earth, a chemically inert material, was used to provide contact between the sensors and the pressure plate. This material reduces the problem of limited water flow which could occur at the interface between porous block and coarse soil material (Gardner, 1986). The sample of diatomaceous earth to be used in the pressure chamber was previously saturated with deionised water according to the procedure described by Klute (1986). The Watermark sensors were subjected to several wetting and drying cycles prior to installation, as recommended by the manufacturer. A blocking capacitor was installed in the circuits of the Watermark sensors by CSI in order to avoid polarisation of the electrodes and deterioration of the blocks. A fixed 1 kΩ bridge resistor between the excitation and input channel enabled measuring electrical resistance in kΩ and avoided overranging. Electrical resistance of the Watermark blocks, temperature difference of the heat dissipation sensors and chamber temperature were recorded every 10 min and averaged hourly by the data logger. Separate leads were used for each unit in order to avoid electrical current conduction through the diatomaceous earth. Data-logging programs and wiring diagrams for Watermark electrical resistance and CSI heat dissipation sensor measurements are available from CSI.

Simultaneous calibration of the sensors was carried out applying the following pressure levels in the pressure chamber: 20, 40, 60, 80, 100, 150, 200 and 400 kPa. Readings of electrical resistance and heat dissipation were taken at equilibrium, a few hours after water flow from the pressure chamber, monitored with a pipette connected to the outflow pipe, had completely ceased. Pressure was released before taking measurements (Reece, 1996).

Matric potential values predicted by the Watermark sensors were calculated as a function of electrical resistance and temperature using the calibration equation recommended by Thomson and Armstrong (1987):

$$\Psi_m = -\frac{R}{0.01306\,[1.062\,(34.21 - T + 0.01060\,T^2) - R]} \qquad (1)$$

where:

Ψ_m = matric potential ($J{\cdot}kg^{-1}$)
R = electrical resistance (kΩ)
T = temperature (°C)

A similar equation for normalising measured resistance to include a temperature correction factor was recommended by Spaans and Baker (1992) and used by Mitchell and Shock (1996).

The drying procedure was repeated two additional times to ascertain sensor sensitivity to salinity by saturating the diatomaceous earth and sensors with solutions of differing $CaSO_4$ concentrations. Measured electrical conductivities (EC) of the solutions were 156 and 253 $mS{\cdot}m^{-1}$. These are in the range of soil solution EC levels commonly found in irrigated soils.

A Watermark meter model 30 KTCD was used to manually record the output of three other electrical resistance sensors without built-in blocking capacitors. The meter is a hand-held alternating current bridge circuit powered by a standard 9V battery. It gives a digital readout converting electrical resistance into matric potential Ψ_m units ($J{\cdot}kg^{-1}$). The meter incorporates an adjustment setting which compensates for temperature effects on electrical resistance. Manual adjustment of the setting provides temperature compensation of 1.8% per °C deviating from a reference temperature of 21°C. The knob was manually adjusted to the temperature measured with the thermocouple before readings were taken.

A final drying cycle was carried out in the pressure chamber with deionised water in order to determine the hysteresis response of the sensors. The following pressure levels were applied in the pressure chamber: 50, 100, 150 and 200 $J{\cdot}kg^{-1}$. At equilibrium, pressure was released, sensors were read and samples of diatomaceous earth removed and sealed in plastic bags to avoid water loss by evaporation. Once the drying cycle had been completed, the sensors were sequentially embedded in the diatomaceous earth in each of the bags by increasing water content. The bags were re-sealed and firm contact between sensors and diatomaceous earth was assured. The wetting cycle was carried out taking readings once equilibrium conditions had been attained.

Results and discussion

Calibration and application

Figure 1 represents the values of pressure applied in the pressure chamber as a function of electrical resistance measured with three Watermark sensors under non-saline conditions. The range of variation in chamber temperature was between 20 and 24°C during the drying cycle. Water potential values were calculated as a function of measured electrical resistance and chamber temperature using Eq. (1). Good agreement between actual and calculated Ψ_m values was observed indicating that the Eq. (1) is adequate for the range between -200 and 0 $J{\cdot}kg^{-1}$.

Equation (1) was tested for sensitivity to temperature. Calculated soil water potential values were plotted as a function of electrical resistance at different temperature levels (Fig. 2). Differences in temperature of only 5°C cause large variations in estimated soil matric potential values. While using the Watermark sensors in the field, it could be very difficult to determine the actual soil temperature and large errors in soil water potential estimation could be made. The simultaneous measurement of electrical resistance and temperature of the block is therefore recommended.

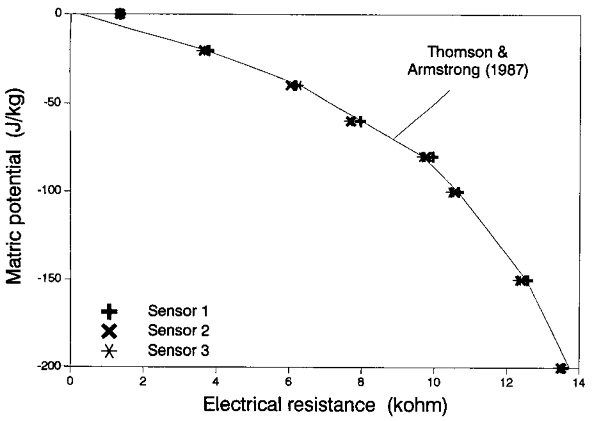

Figure 1
Matric potential as a function of electrical resistance measured with three Watermark sensors under non-saline conditions

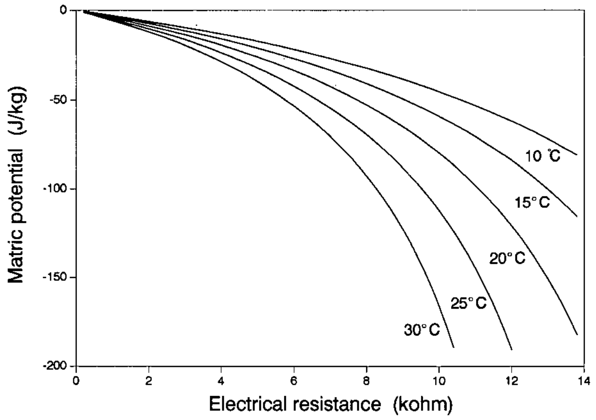

Figure 2
Matric potential calculated using the Thomson and Armstrong (1987) electrical resistance and temperature dependent calibration equation

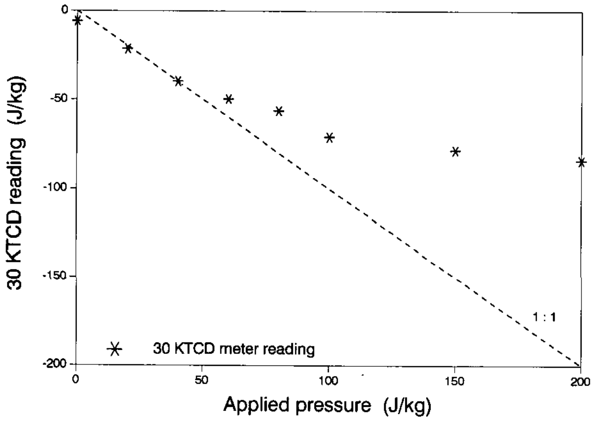

Figure 3
The 30 KTCD meter matric potential reading as a function of pressure applied in the modified pressure chamber

The performance of the 30 KTCD meter was tested under non-saline conditions. Readings were taken when equilibrium conditions were achieved in the pressure chamber and averaged for three sensors. Figure 3 represents the relation between Ψ_m measured with the 30 KTCD and pressure applied in the pressure chamber. The 30 KTCD meter overestimated Ψ_m in the range below -50 $J{\cdot}kg^{-1}$. Improved versions of the meter are being tested by the same manufacturing company. They should be able to provide a linear relation between the reading and matric potential in the range from -200 to 0 $J{\cdot}kg^{-1}$.

A 20 s heat pulse was applied to the heat dissipation sensors under saturated and air-dry conditions. Temperatures at the centre of the block were monitored every second during heating. Figure 4 shows the difference in temperature before and after heating (ΔT) as a function of $\log_{10}$ time. Under both saturated and air-dry conditions, the slope of the regression line (solid) was similar to the slope of the dashed line connecting readings taken 1 s and 20 s after heating commenced. The difference in temperature 20 s and 1 s after heating is therefore recommended as a simple indicator of ΔT.

The interval between subsequent heat dissipation measurements of a block should be long enough to permit the heat pulse to dissipate without affecting the following reading. Scan frequency mainly depends on the characteristics of the medium in which the heat dissipation sensor is set up. Bristow et al. (1993) report that sensor and reference temperatures seldom take longer than 20 min to re-equilibrate in a coarse-loamy soil. Figure 5 represents the average ΔT for three blocks under saturated and air-dry conditions as a function of the reading interval. Actual ΔT values were assumed to be 0.75°C under saturated conditions and 2.79°C under air-dry conditions. Lower ΔT values were observed at shorter reading intervals as the sensor was still approaching thermal equilibrium after the previous heating. Very similar ΔT values were recorded while applying heat pulses every three or more minutes. For safety sake, a scanning interval of 10 min was chosen in this experiment.

Heat dissipation sensors were calibrated in the modified pressure chamber using deionised water to saturate the diatomaceous earth. Figure 6 reports Ψ_m values as a function of average ΔT measured with three heat dissipation blocks in the range between -400 and 0 $J{\cdot}kg^{-1}$. The exponential relation and the squared correlation coefficient are shown in the inset. Standard errors of ΔT measurement were extremely small (maximum 0.0221°C). The heat dissipation sensor could be safely used for measuring soil matric potential values between -100 and 0 $J{\cdot}kg^{-1}$. Beyond this range, the measurement of matric potential could be problematic as small changes in ΔT correspond to large changes in Ψ_m.

Salt sensitivity

Samples of diatomaceous earth were saturated with $CaSO_4$ solutions and drying cycles carried out in the pressure chamber. Figure 7 represents the average values of Ψ_m obtained from three electrical resistance blocks at three salinity levels, as a function of pressure applied. Matric potential values measured with the Watermark sensors were not expected to be affected by salinity because of the internal soluble gypsum tablet. This expectation held in the range from -100 to 0 $J{\cdot}kg^{-1}$, but at higher pressure levels, measured Ψ_m values were overestimated. This error was larger at higher salinity levels. Increased conductivity of soil solution is therefore expected to influence the measurement of electrical resistance at $\Psi_m < -100$ $J{\cdot}kg^{-1}$.

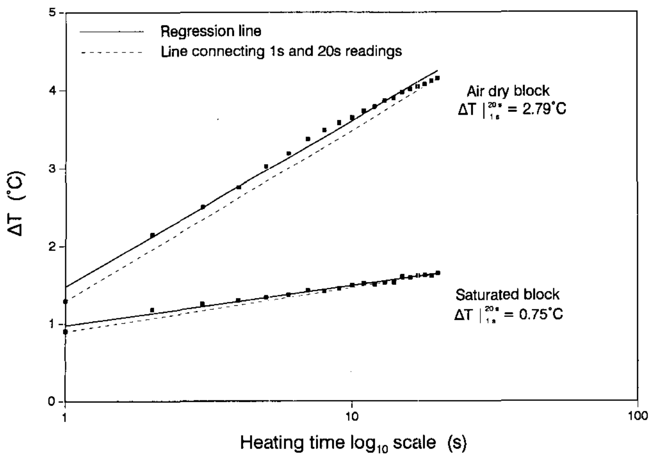

Figure 4

Average temperature difference (ΔT) of three heat dissipation sensors as a function of time during heating under saturated and air dry conditions. Solid line represents the regression; dashed line joins 1 s and 20 s readings. The time axis is plotted on a $\log_{10}$ scale.

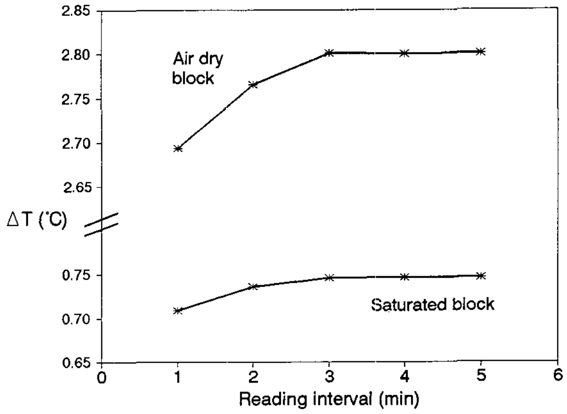

Figure 5

Average temperature difference (ΔT) of three saturated and air dry heat dissipation blocks as a function of reading interval

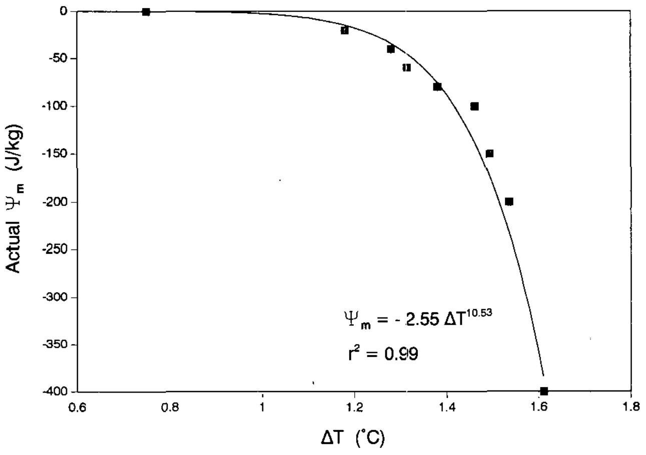

Figure 6

Actual matric potential (Ψ_m) as a function of average temperature difference (ΔT) measured with three heat dissipation sensors

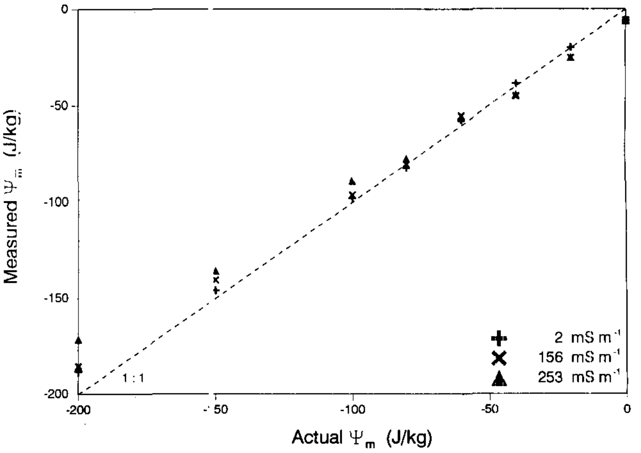

Figure 7

Average values of matric potential (Ψ_m) measured with three Watermark electrical resistance sensors as a function of actual Ψ_m at three salinity levels

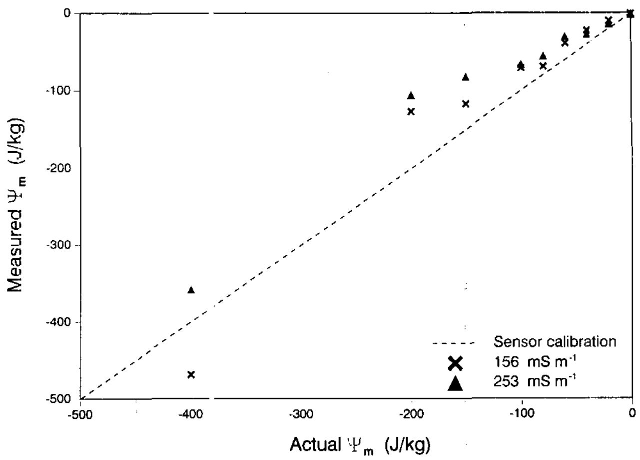

Figure 8

Average values of matric potential (Ψ_m) measured with three heat dissipation sensors as a function of actual Ψ_m at two salinity levels

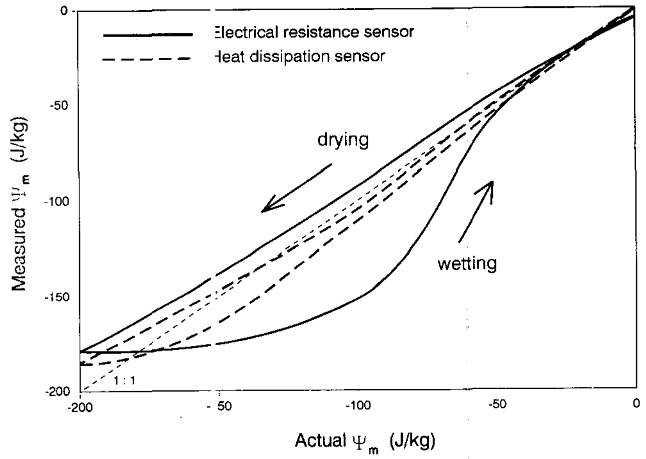

Figure 9

Wetting and drying cycle of matric potential (Ψ_m) measured with Watermark electrical resistance and heat dissipation sensors as a function of actual Ψ_m

TABLE 1
PROPERTIES OF THE WATERMARK ELECTRICAL RESISTANCE AND CSI HEAT DISSIPATION SENSORS

Property	Watermark sensor	CSI sensor
Range of measurement	-200 to 0 J·kg^{-1}	Full Ψ_m range (optimal from -100 to 0 J·kg^{-1})
Calibration relation	Linear	Exponential
Variability between sensors	Maximum ± 0.1373 kΩ	Maximum ± 0.0221 °C
Reading	Manual (30 KTCD) from -50 to 0 J·kg^{-1}; or data logger	Data logger
Time between readings	-	> 3 min
Temperature sensitivity	High (Eq. 1)	None
Salt sensitivity	Little at < -100 J·kg^{-1}	Negligible (Noborio and McInnes, 1993)
Hysteresis	Large < -50 J·kg^{-1}	Moderate < -100 J·kg^{-1}
Application	Simple	Simple
Cost	US$35/sensor; US$78/sensor with blocking capacitor	US$200/unit; power supply required for monitoring several sensors

The ΔT value of the heat dissipation sensors was also measured at different levels of matric potential and salinity. In Fig. 8, the average values of Ψ_m measured with three sensors are plotted against the pressure applied in the pressure chamber. Differing solution concentrations had little effect on the sensor readings in the Ψ_m range between -100 and 0 J·kg^{-1}. Noborio and McInnes (1993) reported that soil thermal conductivity could decrease by as much as 20% at solution concentrations > 1 mol·kg^{-1} compared with salt free-soil solution. In this work, the most concentrated solution applied to the diatomaceous earth was 0.01 mol·kg^{-1} making the effect of salts on thermal conductivity negligible. Large variations in measured Ψ_m values below -100 J·kg^{-1} are due to the exponential calibration curve which makes estimates unreliable.

Users of these matrix sensors must be aware of the large errors that can be made by assuming Ψ_m as a measure of total soil water potential. The sensors are not recommended for irrigation scheduling on saline soils or while saline water is used for irrigation, unless the osmotic potential of the soil solution is measured and added to the total soil water potential.

Hysteresis

Hysteresis of soil sensors seldom matches the hysteresis found in natural soils. Knowledge of wetting history is therefore indispensable for correct use of the sensors. The effect of wetting and drying cycles on matric potential measured with the two sensors is reported in Fig. 9. Large hysteresis effects of the Watermark electrical resistance block were recorded at Ψ_m values < -50 J·kg^{-1}. Equation (1) is therefore not applicable in almost the whole measurement range during wetting. Tanner and Hanks (1952) found similar results for gypsum blocks.

Hysteresis of heat dissipation blocks was recorded at $\Psi_m <$ -100 J·kg^{-1} (Fig. 9). In this range, errors in Ψ_m estimation could be as large as 20 J·kg^{-1} during wetting. However, the previously suggested calibration equation for the sensor (Fig. 6) could be applied also during wetting in the range of interest from an irrigation scheduling point of view (-100 to 0 J·kg^{-1}).

Conclusions

Table 1 summarises the properties of the Watermark electrical resistance and CSI 229 heat dissipation sensors. Initial indications obtained sampling three electrical resistance and three heat dissipation sensors, are that individual sensor calibration will be unnecessary for irrigation scheduling purposes.

The Watermark electrical resistance sensor provides a desorption estimate of soil water potential in the range between -200 and 0 J·kg^{-1}. It is simple to use and suitable for data logging. Manual measurement of matric potential with a hand-held meter would certainly be a cheaper option than the installation of a datalogging system. If the problems with the 30 KTCD meter can be solved, the Watermark sensors could provide a cheap and convenient alternative to the use of several tensiometer stations for soil water measurements. Block temperature should be measured in order to compensate for the effect that soil temperature has on the electrical resistance reading to obtain reliable estimates of soil water potential. The manufacturer should consider measuring both block temperature and electrical resistance and then applying Eq. (1) which accurately estimates Ψ_m. The choice of the matrix material should also be reconsidered by the manufacturer due to the large hysteresis observed. Electrical resistance readings are affected by the presence of salts in the solution at Ψ_m values < -100 J·kg^{-1}, where decisions regarding irrigation need to be taken. An unbuffered dual block system could be considered where salinity is a problem.

The CSI heat dissipation sensor is expensive, but well suited to irrigation scheduling. Until cost can be lowered, it is likely to be used more for research than for practical irrigation scheduling. It can be easily connected to data acquisition systems limiting the disturbance of plants and soil at measurement sites. A minimum of 3 min is recommended between readings in order to permit block temperature to re-equilibrate. The CSI sensor estimates Ψ_m over a wide soil moisture range, but the optimal range of measurement is from about -100 J·kg^{-1} to saturation. Due to the exponential relation between soil matric potential and heat dissipation, the estimation of matric potential becomes difficult below -100 J·kg^{-1}. Moderate hysteresis was recorded at matric potential values below -100 J·kg^{-1}. The sensor is not sensitive to salts in the salinity range common to irrigated soils.

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