Evaluation of the Decagon® 5TE Sensor as a Tool for Irrigation and Salinity Management in a Sandy Soil

I.R. McCann, M.B. Fraj and A. Dakheel
International Centre for Biosaline Agriculture
PO Box 14660, Dubai
United Arab Emirates

Keywords: sensor, near-continuous, soil water, conductivity, temperature

Abstract

Near-continuous and near-real-time measurement of soil water content is a valuable tool in irrigation management. The Decagon® 5TE is a recently available sensor that simultaneously measures soil water content, bulk soil electrical conductivity, and temperature, and so could be useful under saline conditions. Initial laboratory and field studies were conducted at the International Center for Biosaline Agriculture (ICBA) in Dubai, United Arab Emirates. A sample of four sensors was evaluated in the laboratory under different soil water contents and salinities. In the field, sensors were installed at depths of 10, 30 and 50 cm in the soil in various plots as part of ongoing water productivity experiments that used relatively low (2 dS m^{-1}) and high (8+ dS m^{-1}) salinity irrigation water. The bulk soil electrical conductivity was used to estimate soil pore water conductivity. Results show that the sensors responded well, in a relative sense, to changes in soil water content, electrical conductivity and temperature, and so could be used to assess irrigation events, infiltration, and drainage. Water with conductivity in excess of 10 dS m^{-1} resulted in increased soil water content measurements due to the effect of electrical conductivity on measured dielectric permittivity. Estimates of soil water salinity followed expected patterns, with lower values directly following irrigation and higher values as soil water content decreased due to plant water uptake.

INTRODUCTION

Irrigation is the largest consumer of water resources in many arid and semi-arid regions, including GCC countries such as the United Arab Emirates. There is increased interest in the use of non-conventional marginal quality water (saline water and wastewater) for agriculture in order to conserve freshwater resources for higher value uses such as domestic, commercial and industrial. Good irrigation practice and management is essential to make the most effective and environmentally-sound use of irrigation water, particularly non-conventional water.

Measurement of soil water content (SWC) on a volumetric basis (m^3 m^{-3}) is an important tool for good irrigation management. Ideally, SWC should be maintained within a target range that is constant or that may vary in a systematic way during the cropping cycle depending on various parameters such as crop growth, rooting depth, and leaching requirements. The target range has an upper limit determined by the capacity of the soil to retain water against gravity (such as field capacity), and a lower limit below which the crop suffers yield/quality limiting water stress.

Various instruments to measure SWC and soil water potential (SWP) have been available for many years. Examples include neutron probes, tensiometers, and electrical resistance devices. More recently, sensors that measure SWC using the dielectric permittivity of the soil have become commercially available. These sensors are based on the principle that the dielectric permittivity of water is significantly higher than either air or soil particles. Because soil is essentially a matrix of solid particles with air and water occupying the void spaces, the dielectric permittivity of bulk soil is thus largely dependent on the water content. Topp et al. (1980) quantified the relationship between the dielectric permittivity of soil and SWC.

The two major technologies used by commercially available sensors based on the dielectric properties of soil are Time Domain Reflectrometry (TDR) and Frequency Domain (FD) measurements. The former measures the travel-time through an electrode embedded in the soil, while the latter, (often called capacitance), measures the frequency of an oscillating circuit containing electrodes in which the electromagnetic field extends into the surrounding soil (Fares and Alva, 2000; Paltineanu and Starr, 1997; Noborio, 2001; Payero et al., 2006; Paul, 2002; Starr and Timlin, 2004). The 5TE (Decagon Devices, Inc., USA) is a capacitance sensor. Other examples of capacitance sensors include EnviroScan (Sentek Technologies, Australia), Aquaspy (AquaSpy, USA), 10HS (Decagon Devices, Inc., USA), and Hydra Probe (Stevens Water Monitoring Systems, USA).

Capacitance sensors are typically available in two formats:

- Single stand-alone, in which the sensor is directly installed in the soil at the desired depth.
- As part of a multi-sensor probe in which the sensors are mounted on a "backbone" which is installed in an access tube in the soil. The sensors do not come into direct contact with the soil but measure the soil through an access tube. These probes are typically used to measure SWC in a vertical profile.

McCann and Starr (2007) evaluated the EnviroScan multi-sensor capacitance probe for field irrigation management. Evett (2007) provided an overview of soil water sensing, and Chavez and Evett (2102) compared a number of sensors for use in irrigation management (including the 5TE).

In addition to the SWC, it is very useful to be able to measure the concentration of soluble ions in the soil water (the soil solution). These ions may represent nutrients such as nitrates, or salinity such as sodium. The concentration of soluble ions can be measured, at least in a relative sense, by the electrical conductivity (EC) of the soil solution. This in turn can be estimated by directly measuring the bulk electrical conductivity of the soil between electrodes.

There are sensors that measure both the SWC and EC of the bulk soil, such as the Hydra Probe, TriSCAN (Sentek Technologies, Australia) and, the subject of this paper, the 5TE.

The 5TE is a digital sensor inserted directly into the soil at the desired depth. It measures (1) the dielectric permittivity of the soil surrounding the probe (using a frequency of 70 MHz), (2) the bulk soil electrical conductivity, and (3) the soil temperature. It uses the SDI-12 communication protocol to provide digital values associated with these three measurements. The major medium by which soils conduct electricity is the soil solution. Sensors, such as the 5TE, that measure the bulk EC of the soil, have to be used with an equation such as Hilhorst (2000) in order to estimate the EC of the soil solution from the bulk soil EC (which is affected by both the SWC and the EC of the soil solution). The actual EC paths in a soil are complex and depend on the size and configuration of the pores interconnected by the soil water, and by the EC of the soil water in those pores. Rhodes et al. (1992) provide a theoretical and practical discussion of soil EC and the limitations in inferring the EC of the pore water from the bulk soil EC. For any given soil solution EC, the higher the SWC the higher the EC. A lower SWC but with a higher soil solution conductivity can give the same bulk EC as a higher SWC but with a lower soil solution conductivity.

In spite of the complexity and difficulty in obtaining measurements of both the SWC and soil solution EC, there is value in sensors, such as the 5TE, that can provide at least relative values, and that can provide these remotely and in near-real-time directly to the user for use in irrigation management and applied field research.

The objective of this study was to conduct an initial evaluation of the 5TE sensor for irrigation management, particularly when the irrigation water is saline.

METHODS

Laboratory

A sample of four 5TE sensors was used in the laboratory with field soil from the International Centre for Biosaline Agriculture (ICBA), located 25 km south of Dubai, UAE (25°06'31"N; 55°22'59"E). The soil at this site is a desert sand (Carbonatic, Hyperthermic Typic Torripsament) having a negligible level of inherent soil salinity (0.2 dS m^{-1}). The water holding capacity of this soil is low (5-10% vol), and drainage is rapid (saturated hydraulic conductivity >30 mm/h).

The calibration method suggested by Decagon was used as a guideline (Cobos, 2009). Three soil solutions were used. Two of them were prepared by adding specified measured weights of sodium chloride (NaCl) to known volumes of distilled water to produce solutions with target electrical conductivities of 10, and 15 dS m^{-1} at a standard temperature of 25°C. The third "solution" was distilled water alone, which has an EC of 0 dS m^{-1}. The actual conductivities of the three solutions were checked with an EC meter and corresponded well to the target conductivities.

Four 1-L containers of soil were prepared for each EC solution. In each container, a measured weight (and volume) of solution was mixed with a measured weight of soil occupying a volume of 1 L. This volume of soil was large enough to contain the measurement field of the sensor. The resulting soil water contents of the containers ranged from 14 to 26%. One sensor was inserted directly into the middle of each container such that it was completely contained within the soil. A miniature shovel was used to facilitate this complete insertion because it was difficult to continue pushing the sensors into the soil once the prongs were fully inserted. Each combination of SWC and EC solution was measured three times by remixing the soil and reinserting the same sensor. At the end, each container was brought to saturation by adding a measured volume of the same solution sufficient to saturate the soil. The measured SWC at saturation ranged from 30 to 33%.

A Decagon EM50 logger was used to record the raw digital values of permittivity, temperature and bulk soil EC. This logger provides both the raw data for dielectric permittivity, temperature and bulk EC, and for the processed values that yield the SWC based on the Topp equation (m^3 m^{-3}), temperature (°C), and bulk soil EC (dS m^{-1}). The equation of Hilhorst (2000) was used to estimate pore water conductivity from these three measurements:

$$\sigma_p = (\varepsilon_p \, \sigma_b) \, / \, (\varepsilon_b - \varepsilon_{\sigma b=0}) \qquad (1)$$

where σ_p= eElectrical conductivity of the pore water (dS m^{-1}); σ_b= electrical conductivity of the bulk soil (dS m^{-1}); ε_p = dielectric permittivity (real portion) of the pore water (unitless); ε_b = dielectric permittivity (real portion) of the bulk soil (unitless); $\varepsilon_{\sigma b=0}$ = dielectric permittivity (real portion) of the soil when bulk; soil electrical conductivity = 0 (unitless).

The dielectric permittivity of the pore water (ε_p) is affected by its temperature (T_{soil}):

$$\varepsilon_p = 80.3 - 0.37(T_{soil} - 20) \qquad (2)$$

Field

Sensors were installed in the field at depths of 10, 30 and 50 cm in drip-irrigated plots of pearl millet at the ICBA experiment station. One plot was irrigated with relatively low salinity water (approximately 2 dS m^{-1}) while the other was irrigated with relatively high salinity water (approximately 8 dS m^{-1}). The irrigation amounts were targeted to replace crop water uptake using reference evapotranspiration (ET_0) as determined by a nearby weather station. The sensors were read at 10-min intervals using Decagon EM50G loggers equipped with GSM cellular communication.

RESULTS AND DISCUSSION

The laboratory calibrations are summarized in Figure 1, in which measured bulk soil electrical conductivity (a) and measured dielectric permittivity (b) are shown for soil solution conductivities of 0, 10 and 15 dS m^{-1}, as a function of the volumetric water content of the soil as measured gravimetrically.

Figure 1a clearly shows that when distilled water is used (where soil solution conductivity is 0 dS m^{-1}), the bulk soil EC is essentially low and and does not increase with increasing SWC. In contrast, when the soil solution EC was high (10 and 15 dS m^{-1}) the bulk soil EC increased with the SWC. The maximum values of EC, for the highest soil solution EC in saturated soil, were approximately 3 dS m^{-1}, which were much lower, as expected, than the soil solution EC. In all cases, the bulk soil EC is low when the SWC is low, illustrating that it is not practically possible to even qualitatively infer any information about soil solution conductivity from bulk soil EC measurements when these are observed in dryer soils. It is only when the soil is wet that there are sufficient differences in the bulk soil EC to distinguish between different soil solution conductivities. These results illustrate that, in accordance with theory, bulk soil EC measurements made in the field are of little practical value when the soil is either not wet or when the measurements are made when the soil is wet but without incorporating the SWC in the measurement.

Figure 1b shows that the measured dielectric permittivity increases with the SWC, as expected. The Topp equation, which is used as a default by the manufacturer to estimate the SWC, is also shown. The Topp equation appears to reasonably fit the data for soil solution ECs of 0 and 10 dS m^{-1}, but underestimates the dielectric permittivity at the higher solution EC of 15 dS m^{-1}. Again, this is in line with theory and the manufacturer's specifications. The sensor uses an operating frequency of 70 MHz to minimize the effect of electrical conductivity on measured dielctric permittivity, but at high conductivities the effect does becomes significant. Electrically, the problem becomes one of measuring the capacitance of an increasingly "leaky" capacitor.

The results from the sensors installed in the field show that they provide valuable information for irrigation and salinity management, at least in a qualitative and relative sense. Figure 2a shows an example of the measured SWC at 10, 30 and 50 cm for a two-week period under low salinity irrigation. Irrigation water was applied with varying frequencies, ranging from twice per day to once in three days in order to test the response of the sensors to irrigation events and to crop water uptake.

On 1, 2, 3 and 7 July there were two irrigations per day, and these two daily peaks in the SWC can be seen at 10 cm, as can the peaks resulting when one irrigation per day was applied. Infiltration to 30 and 50 cm can also be seen from 1 to 3 July. When there was at least one day without irrigation, the "stair-step" pattern, characteristic of daytime root water uptake, can be seen (McCann and Starr, 2007; McCann et al., 2012). Longer-term trends such as soil water depletion and replenishment can also be seen. Such trends can be used to modify irrigation schedules to correct for over-application or under-application.

Figure 2b shows that soil temperatures at 10 cm reached peaks close to 37°C at 10 cm. The temperature pattern at all depths was as expected, with the amplitude of the daily cycle decreasing with depth. From 5-7 July, temperatures at 10 cm increased, and this was reflected at 50 cm, where a 2°C increase was observed. Also evident was the effect of the temperature of the irrigation water on soil temperature at 10 cm.

Figure 3 shows the estimated pore water EC from 1 July to 12 August for a plot irrigated with (a) low salinity water and (b) high salinity water. The method of Hilhorst (2000) as referenced in the 5TE sensor manual was used with a value of 4.1 for $\varepsilon_{\sigma b=0}$ (as used in the laboratory). The manufacturer suggests a value of 6 for $\varepsilon_{\sigma b=0}$, but it is not clear from this particular calibration that changing the value from 4.1 to 6 improves the results. Visually, pore water EC under the higher salinity irrigation was generally higher.

However, there was a 5-day gap in the record at 10 cm from 10-15 July under the higher salinity irrigation due to a sensor that became disconnected. There is a lot more "noise" with the estimates of pore water EC compared with the SWC and temperature, and further work will be needed to refine the estimates, both in terms of the values used in the equation and in the laboratory calibration and analysis.

To reduce the short-term fluctuations and noise, a simple analysis was conducted using the daily average of the estimated pore water EC, and deriving an index (salinity-day) similar to the calculation of heat units (degree-days) in which values above a threshold contribute to the index while values below the threshold do not:

$$SDI_i = EC_p - EC_b,\ EC_p > EC_b \tag{3}$$

$$SDI_i = 0,\ EC_p <= EC_b \tag{4}$$

where SDI_i = salinity-day index for day i; EC_p = pore water EC; EC_b = threshold pore water EC.

Figure 4 shows an example of the (a) daily and (b) cumulative daily SDI values for the pore water conductivities shown in Figure 3, using a value of 2 dS m^{-1} for the EC_b. The SDI is clearly higher under the higher salinity irrigation, but further laboratory and field research should be conducted to determine how best to use the bulk soil conductivity measurements provided by the sensor.

CONCLUSION

The number of commercially-available sensors, that can measure both soil water content and pore water electrical conductivity, is limited. The results of this evaluation of the Decagon® 5TE sensor are promising and indicate that it would be worthwhile to conduct additional research on its capabilities, limitations, and use as a practical tool for field research and commercial agricultural production, particularly in saline environments. Additional research on this and other sensors is planned at the ICBA.

Literature Cited

Chavez, J.L. and Evett, S.R. 2012. Using soil water sensors to improve irrigation management. Proc. 24th Annual Central Plains Irrigation Conference, Colby, KS, USA. Feb. 21-22.

Cobos, D.R. 2009. Calibrating ECH2O Soil Moisture Sensors. Decagon Devices, Inc., USA. Available at : http://www.decagon.com/assets/Uploads/CalibratingECH2OSoilMoistureProbes.pdf.

Evett, S. 2007. Soil water and monitoring technology. In: R.J. Lascano and R.E. Sojka (eds.), Irrigation of Agricultural Crops. 2nd edition. Agronomy monograph 30. Am. Soc. Agronomy.

Hilhorst, M.A. 2000. A pore water conductivity sensor. Soil Science Society of America Journal 64:1922-1925.

McCann, I.R. and Starr, J.L. 2007. Use of multisensor capacitance probes as irrigation management tool in humid areas: case studies and experiments from the Mid Atlantic Region. Applied Engineering in Agriculture 23:475-483.

McCann, I., Fraj, M.B. and Al-Dakheel, A. 2012. Real time soil water measurement technology for improved irrigation management in arid environments. 10th Gulf Water Conference, Doha, Qatar.

Noborio, K. 2001. Measurement of soil water content and electrical conductivity by time domain reflectometry: a review. Computers and Electronics in Agriculture 31:213-237.

Paltineanu, I.C. and Starr, J.L. 1997. Real-time soil water dynamics using multisensor capacitance probes: laboratory calibration. Soil Sci. Soc. Am. J. 61:1576-1585.

Paul, W. 2002. Prospects for controlled application of water and fertilizer, based on sensing permittivity of soil. Computers and Electronics in Agriculture 36:151-163.

Payero, J.O., Tarkalson, D.D. and Irmak, S. 2006. Use of time domain reflectometry for continuous monitoring of nitrate-nitrogen in soil and water. Applied Engineering in Agriculture 22:689-700.

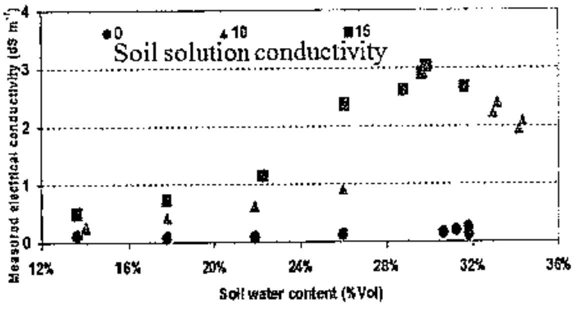
Rhodes, J.D., Kandiah, A. and Mashali, A.M. 1992. The use of saline waters for crop production. Irrigation and Drainage Paper 48. Food and Agriculture Organization of the United Nations, Rome, 133p.

Starr, J.L. and Timlin, D.J. 2004. Using high-resolution soil moisture data to assess soil water dynamics in the vadose zone. Vadose Zone J. 3:926-935.

Topp, G.C., David, J.L. and Annanm, A.P. 1980. Electromagnetic determination of soil water content: measurement in coaxial transmission lines. Water Resources Research 16:574-582.

Figures

(a) Electrical conductivity



(b) Dielectric permittivity

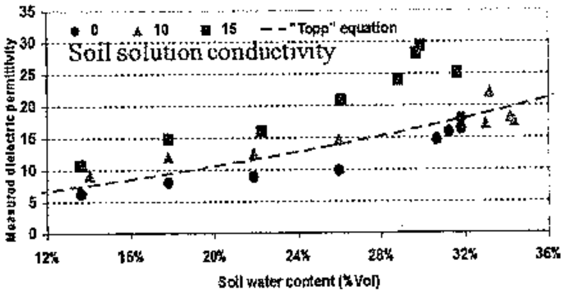


Fig. 1. Laboratory measurements showing measured (a) bulk soil electrical conductivity and (b) measured dielectric permittivity, along with the Topp (1987) equation, for actual pore-water conductivities of 0, 10 and 15 dS m^{-1}.

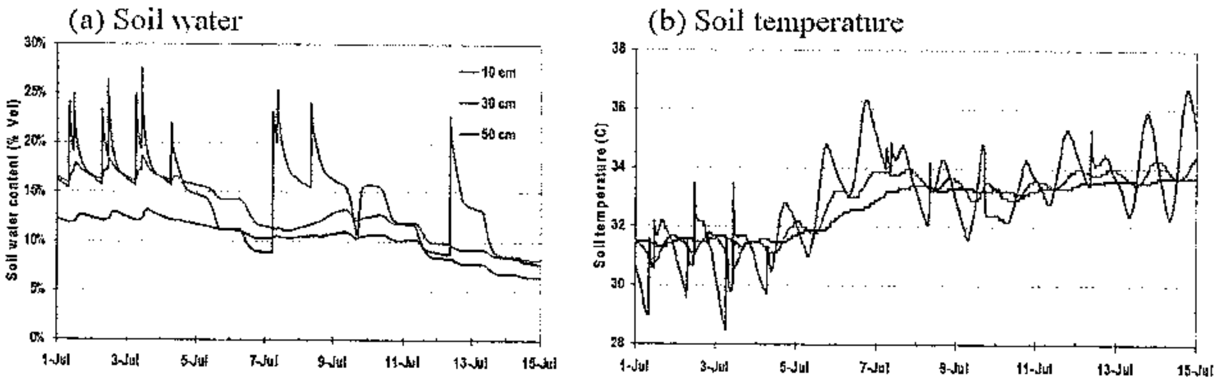


Fig. 2. Example of (a) measured soil water content and (b) soil temperature, at 10, 30 and 50 cm depths.

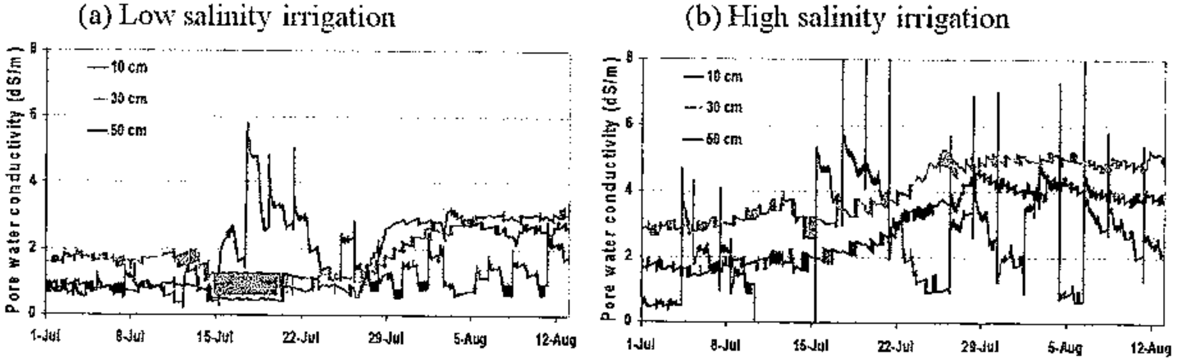
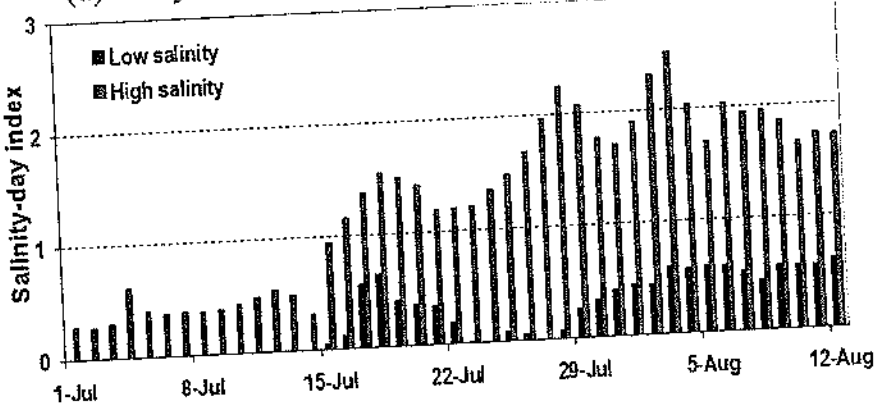


Fig. 3. Estimated pore water EC under (a) low salinity irrigation and (b) high salinity irrigation.


(a) Daily salinity index

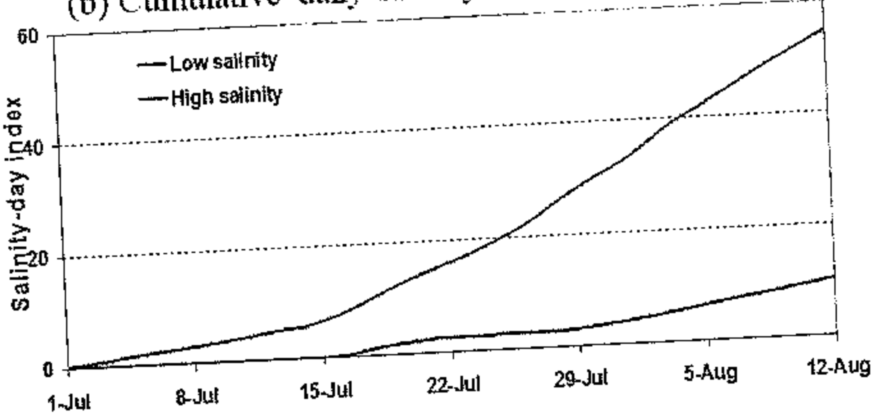

(b) Cumulative daily salinity index

Fig. 4. Field example of (a) daily salinity index and (b) cumulative daily salinity index, for irrigation with low and high water salinities.