Agricultural Water Management 97 (2010) 182–184

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Letter to the Editor

Comments on "J. Vera et al., Soil water balance trial involving capacitance and neutron probe measurements" [Agric. Water Manage. 96 (2009) 905–911]

Vera et al. (2009) compared estimates of soil profile water content (mm) to a depth of 0.8 m made with the neutron moisture meter (NMM) and a multi-depth capacitance probe (MDCP), using measurements replicated in four drainage lysimeters (5 m × 5 m × 1.5 m deep). Comparisons of water contents at discrete depth ranges and of the soil water variation over time as determined by each method (NMM, MDCP and lysimeter) were also made. Each lysimeter contained repacked clay loam soil and one tree in its center irrigated by 8 drip emitters evenly spaced along a lateral line bisecting the lysimeter. Access tubes were placed at distances of 0.2, 0.6, and 1 m from the lateral on a line perpendicular to the lateral, with NMM access tubes on one side and MDCP access tubes on the other side. Seasonal irrigation of the lysimeters began in 2002 when the trees were planted; and the soil water balance experiment took place in the fifth irrigation season (2006). During the experiment, irrigation was applied continuously for 28 days; and observations were made during that period and during a 21-day drying period after irrigation ceased. The electrical conductivity (EC) of a 1:5 soil extract was given as 0.35 dS m^{-1} (presumably determined in 2002); and the irrigation water EC was given as 1.50 dS m^{-1}. The soil bulk density was reported to be 1.56 g cm^{-3}, which translates into an air filled porosity of 0.41 m^3 m^{-3} in a completely dry soil, assuming a particle density of 2.65 g cm^{-3}. No explanation was given as to why soil water content readings were made to only 0.8-m depth in the 1.5-m deep lysimeters.

The purpose of this communication is to point out some misconceptions in this article and some oversights in the interpretation of the data that caused the authors to wrongly infer that there was negligible difference in performance between the MDCP and NMM.

First, the authors state that the capacitance probe oscillates at >100 MHz, "making it virtually independent of soil salinity and temperature variations…", and they cite Paltineanu and Starr (1997) for the quoted information. However, Paltineanu and Starr (1997) studied the Sentek EnviroSCAN[1] capacitance sensor, not the Agrilink C-Probe used by Vera et al. (2009); they did not study the EnviroSCAN's sensitivity to salinity; and their studies of temperature effects were with non-saline water and air, not with soil, which could have been conductive. Also, 100 MHz is not a sufficiently high frequency to render a capacitance sensor independent of soil salinity, or (more correctly) of the temperature- and water content-dependent bulk electrical conductivity (BEC) that results from salinity (Robinson et al., 1998; Kelleners et al., 2004a). We believe that this misconception led Vera et al. (2009) to misinterpret their data and to ignore the obvious effects of BEC on the water content estimates from the MDCP shown in their Fig. 4.

Second, after prolonged irrigation, the maximum profile mean water content reported by the NMM at 0.2 m from the drip lateral was 0.38 m^3 m^{-3}, based on the profile water content in mm reported in Vera et al. (2009, Fig. 4) and the 800-mm soil depth reported in their Section 3.3 as pertaining to their Fig. 4. This value is slightly smaller than the maximum possible value of 0.41 m^3 m^{-3} (assuming no great amount of soil swelling) and is entirely reasonable since entrapped air usually prevents irrigated soils from reaching complete saturation. At this same distance, the capacitance sensor reported a profile mean water content that initially rose to 0.48 m^3 m^{-3}, 0.07 m^3 m^{-3} larger than physically possible, and then, after 300–400 h of irrigation, the reported water content descended to agree with the NMM. The authors argue that the overestimation "could be explained by … a pronounced three-dimensional hydraulic gradient within the wetted volume and the reduced volume explored by the capacitance sensors", which does not make physical sense.

If the small sensing volume of the capacitance sensors prevented them from sensing the drier soil further from the lateral line (the argument for larger reported water contents), then the maximum water content that they could have sensed would have been the value at complete saturation, 0.41 m^3 m^{-3}. A natural soil might have had large variations in bulk density that could have given rise to localized lower-than-average bulk densities and correspondingly larger porosities. But in the repacked soils of the lysimeters, such natural variations would be expected to be removed and bulk density variation to be minimized. Furthermore, the mean of four replications would not be expected to much exceed porosity in any case.

An explanation that does make physical sense can be based on the known (Evett et al., 2006; Kelleners et al., 2004a,b; Robinson et al., 1998) sensitivity of similar capacitance sensors to BEC, and on the likely movement of salts (accumulated during previous irrigation seasons) outward normal to the drip lateral with the wetting front after irrigation began. This explanation is consistent with the fact that the peak overestimate of water content by the MDCP occurred just as the NMM showed that the wetting front had fully engulfed the position at 0.2 m from the lateral line (Fig. 4A, Vera et al., 2009). It is also consistent with the fact that a similar peak (0.49 m^3 m^{-3}) of overestimation by the MDCP occurred later at the distance of 0.4 m from the lateral line and occurred just before the NMM data at that position reached a plateau in water content of ~0.33 m^3 m^{-3}. In fact, we are struck by the similarity of Fig. 4A and B to breakthrough curves observed in solute transport studies.

Since we have published a calibration method that models the effect of EC on apparent permittivity (Schwartz et al., 2009), we

[1] The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

0378-3774/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.agwat.2009.07.015

offer a simulation exercise to support this physical explanation. As the impedance across the electrodes is reduced due to increased bulk electrical conductivity, the oscillator is damped and the oscillation frequency falls. The apparent (measured) capacitance thus appears greater than the true capacitance. For this simulation exercise, we assume that the apparent permittivity as surmised from the measured capacitance for an oscillator circuit can be approximated from the apparent permittivity calculated based on the wave propagation velocity relative to the speed of light (von Hippel, 1954). Robinson et al. (1999) has demonstrated that this assumption approximately holds, based on a high degree of correspondence between apparent permittivity measured using time domain reflectometry and using an oscillator circuit. At a frequency of 100 MHz, an elevated BEC increases the apparent permittivity of a medium, and this increase is preserved in the water contents inferred using calibrations (like that used by Vera et al., 2009) that do not consider fluctuations in EC.

This increase in apparent (but not actual) water content due to increase in BEC can be demonstrated by considering one-dimensional water flow and advective–dispersive transport of a conservative solute. Using the time-dependent transport solution for resident solution concentration given by Parker and van Genuchten (1984) permits an estimate of BEC using the relationship of Mualem and Friedman (1991). Combining this result with the complex permittivity model of Schwartz et al. (2009), and using the volumetric water contents reported by the NMM in Fig. 4A of Vera et al. (2009), gives a BEC-dependent estimate of apparent permittivity, which can be used to estimate water content (Fig. 1) based on the equation of Topp and Reynolds (1998). Although the Topp and Reynolds (1998) equation was based on high frequency TDR soil water content calibrations, it permits a reasonable approximation of inferred changes in water content based on apparent permittivity measurements that have not been corrected for changes in bulk electrical conductivity. This simulation produces a breakthrough curve, essentially preserved in the inferred soil water contents (Fig. 1), that is strikingly similar to the MDCP data in Fig. 4A of Vera et al. (2009). This illustrates one of the limitations of calibration equations that do not consider BEC effects.

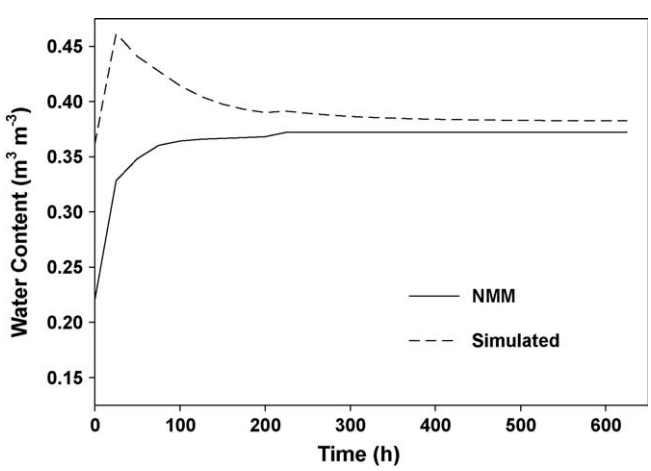

Fig. 1. Comparison of soil water contents determined using the neutron moisture meter (NMM) (from Vera et al., 2009, Fig. 4A) with water contents inferred from simulated values of apparent permittivity using a calibration equation (Topp and Reynolds, 1998) that does not adjust for fluctuations in BEC. Simulation of apparent permittivity was a three-step process. First, assuming an initial soil solution EC of 1 S m^{-1} with influent solution at 0.15 S m^{-1}, one-dimensional, steady state transport (Parker and van Genuchten, 1984) was calculated for a Peclet number of 0.5. Second, bulk EC was calculated using the Mualem and Friedman (1991) expression with a tortuosity coefficient of 1.8. Third, apparent permittivity was calculated following Schwartz et al. (2009) assuming a specific surface area of 200 m^2 g^{-1}, water content measured by the NMM, and a frequency of 100 MHz.

The data at a distance of 0.6 m from the lateral line (Fig. 4B, Vera et al., 2009) are also consistent with increasing BEC as the wetting front swept soluble salts away from the lateral line. The MDCP showed an increase in estimated water content that continued until well after irrigation ceased and that peaked at ~0.51 m^3 m^{-3}. By contrast, the NMM showed that water content became more or less constant several hundred hours before irrigation ceased, and never exceeded ~0.28 m^3 m^{-3} at that distance from the lateral line. The fact that NMM-estimated water contents at 0.6 m from the lateral line did not reach values close to saturation during irrigation is consistent with the considerable and persistent drainage from the lysimeters that began 52 h after irrigation began. The fact that the MDCP estimated water contents reached a peak value greater than the soil porosity more than one hundred hours after irrigation ceased, and at the same time that drainage had decreased to less than a tenth of its rate during irrigation, is not consistent with the physics of soil water flux (considerable drainage would have continued if the soil had been at saturation), but it is consistent with common patterns of solute transport away from drip laterals and with the known effects of increasing BEC on capacitance sensor estimates of water content (Evett, 2007).

Finally, the authors inferred incorrectly that there were no important differences between the performance of the NMM and the MDCP based on the fact that statistical analysis of changes (variations) of stored soil water content (mm of water in the profile) showed no significant differences between data from the lysimeters, the NMM and the MDCP. Because of this error, they concluded that the "final selection criteria for choosing a particular measuring device will depend on economic circumstances, ease of device management, etc." We believe that this conclusion is the result of a poor choice of the property chosen for statistical analysis. The conclusion is inconsistent with the fact that there were large and demonstrable errors in the water content estimates from the MDCP; and it discounts the clear evidence that the MDCP errors were varying due to the labile nature of soil BEC. Water contents from the MDCP were sometimes reasonable and consistent with the field calibrated NMM and sometimes greater than physically possible. Also, the inference of Vera et al. (2009) is incorrect because there can be more than one reason for a lack of statistically significant differences. A lack of significant difference may arise because two methods are indeed equivalent; or, it may arise because the standard deviation of one of the methods is so large that the power of the statistical test is too weak to show a difference when in fact an important difference exists. The standard deviations of data from the MDCP were much larger than those of data from the NMM (see Fig. 4, Vera et al., 2009), making it likely that lack of significance could mask a real difference in the case of the MDCP and less likely that a lack of significance would hide a real difference in the case of the NMM. In addition, the comparison that the authors made, illustrated in their Fig. 5, is not the most useful comparison. More useful would be comparison of the evapotranspiration values derived from the soil water balance by the three methods. Two comparisons should be made: (1) comparing the daily or weekly ET values determined using the NMM and the MDCP versus those found by the soil water balance of the lysimeter and (2) comparing the cumulative ET as determined by the three methods over the season. The latter comparison is key in the case of capacitance sensors since soil salinity (actual salt content) typically changes over time in drip irrigated systems, and because soil temperatures also change over an irrigation season. Since soil BEC increases with water content, temperature and salinity (Rhoades et al., 1976, 1989), the effect of BEC on soil water estimation by capacitance sensors can be cumulative over a season, resulting in cumulative errors in ET estimation by soil water balance. Because important variations of BEC in space and time can occur in irrigated soils, due to both the

movement of salts and to the change of BEC with soil water content, data from MDCP sensors are typically more variable in space and time than are NMM or gravimetric data (Evett et al., 2009; Mazahrih et al., 2008).

We urge Vera et al. to re-analyze their data in light of the arguments and theory presented above, and to re-draw their conclusions accordingly.

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29 May 2009
Available online 13 August 2009