Soil Physics Note

Salinity Effects on the Fieldscout TDR 300 Soil Moisture Meter Readings

Michael Benor
Institute of Soil, Water, and Environmental Sciences
Agricultural Research Organization
Volcani Center
Bet Dagan, Israel
and
Dep. of Soil and Water Sciences
The Robert H. Smith Faculty of Agriculture, Food, and Environment
The Hebrew Univ. of Jerusalem
Rehovot, Israel

Guy J. Levy*
Institute of Soil, Water, and Environmental Sciences
Agricultural Research Organization
Volcani Center
Bet Dagan, Israel

Yael Mishael
Dep. of Soil and Water Sciences
The Robert H. Smith Faculty of Agriculture, Food, and Environment
The Hebrew Univ. of Jerusalem
Rehovot, Israel

Arie Nadler
Institute of Soil, Water, and Environmental Sciences
Agricultural Research Organization
Volcani Center
Bet Dagan, Israel

While studying changes in volumetric water content (VWC) of soilless culture (sand and tuff), the need for a quick and easy-to-operate moisture measurement device with accuracy better than ±0.01 has risen. Before full scale application, we performed some basic tests with the Fieldscout TDR 300 soil moisture meter to evaluate the dependency of the VWC measurements on the salinity of the medium. The TDR300 was used to measure VWC in (i) sand and tuff wetted by deionized water or a 0.02 M NaCl solution to different VWC levels, (ii) sand or tuff wetted by solutions of different salinities to a given VWC level, and (iii) aqueous solutions of different salinities. Medium salinity had a significant effect (up to 60%) on the VWC readings of the TDR 300. Our observations suggest that the technology used by the TDR 300 is similar to that of low frequency water content reflectometers.

Abbreviations: DW, deionized water; EC, electrical conductivity; EM, electromagnetic; HF-TDR, high frequency time domain reflectometry; MPR, meter's period reading; T, temperature; VWC, volumetric water content; WCR, water content reflectometer.

Within the framework of a study investigating the effect of water absorbing polymers on changes in VWC of soilless culture (sand and tuff), the need for a quick, easy-to-operate moisture measurement device, with an accuracy better than ±0.01 (m^3 m^{-3}) had risen. In addition, the electrical conductivity (EC) of local irrigation waters, National Carrier or treated wastewater, is 1.05 and 1.55 dS m^{-1}, respectively, resulting in root zone salinity of 2 dS m^{-1}. This fact led us to look for a VWC sensor that will be negligibly dependent on EC up to a level of 2 dS m^{-1}. Our specific experimental conditions demanded repeated measurements of a wide range of VWC and EC conditions in small pots. We also had to limit ourselves to measuring devices that use narrow rods for minimal soil structure disruption. Last but not least was the ergonomic consideration that would enable the operator a quick and easy sensor insertion while remaining standing upright.

A selection of seven potential sensors, using five modes of operation, were presented and discussed by Blonquist et al. (2005). All seven belong to the transmission line electromagnetic (EM) methods but differ by their prices and the frequency of the propagating signal (Blonquist et al., 2005, Tables 1 and 3, respectively). Principle of operation of these EM sensors were divided in several sub-categories: (i) high frequency time domain reflectometry (HF-TDR),e.g., 1502 Cable Tester (Tektronix Inc., Beaverton, OR), and TDR 100 (Campbell Scientific, Logan, UT); (ii) digital time domain transmission (Acclima Inc., Meridian, ID); (iii) transmission line oscillator such as the CS616 water content reflectometer (WCR); (iv) impedance meter, for example, Hydra (Stevens Water Monitoring Systems Inc.,

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*Corresponding author (vwguy@volcani.agri.gov.il).

Beaverton, OR), or the Theta probe mL2X type (Dynamax Inc., Houston, TX); and (v) a capacitance sensor such as the ECH_2O (Decagon Devices Inc., Pullman, WA).

Two additional EM sensors available in the market, beyond those listed by Blonquist et al. (2005), are the Trime-TDR (IMKO Micromodultechniq, Ettlinger, Germany) and the Fieldscout TDR 300 soil moisture meter (model 6430FS, Spectrum Technologies Inc., Plainfield, IL).

The HF-TDR differs from the aforementioned technologies by its high frequency of the transmitted EM signal (1.4 GHz for HF-TDR vs. not more than 0.1 GHz for all the others), resulting in the signal's high velocity of propagation (period is of an order of 0.1 ns, as compared to not less than 1 μs of all the others). A significant outcome of this difference is the reduced sensitivity of the HF-TDR measured VWC to the EC and temperature (T) of the wetted medium. The pioneer of applying the HF-TDR technology for soil VWC measurements, Topp et al. (1980), showed that a single empirical calibration curve could relate VWC to the soil dielectric constant for a wide range of soil types. In their review, Jones et al. (2002) concluded that in most mineral soils Topp's global equation yields VWC estimates with an error of about 0.013 $m^3 m^{-3}$, and Chandler et al. (2004) confirmed that the HF-TDR was the best electronic means for VWC measurement, having a relatively robust calibration, and that it was a reliable method for making continuous, nondestructive VWC measurements.

Considering our experimental conditions and requirements, the two most suitable TDR options were the Tektronix 1502 Cable Tester and the Fieldscout TDR 300 soil moisture meter. The TDR 300 is designed to measure VWC with a resolution of 0.1% VWC and accuracy of ±3.0% in a VWC range from zero to saturation, when the EC of the wetting solution is less than 2 dS m^{-1} (Fieldscout TDR 300 product manual; Spectrum Technologies, 2009). This manual clarifies that "the underlying principle of the TDR involves measuring the travel time of an EM wave along a wave guide and the electronics in the TDR 300 generates and senses the return of a high energy signal that travels down and back, through the soil, along the wave guide, and the high frequency signal information is then converted to VWC" (Spectrum Technologies, 2009, p. 22–23). An attenuation of the high frequency signal is expected in the case of a very high organic matter content or bulk EC > 2 dS m^{-1} (Spectrum Technologies, 2009). Hence, in media containing low organic matter content and bulk EC < 2 dS m^{-1}, the TDR 300 is expected to produce VWC readings whose sensitivity to the EC of the wetted medium is similar to that of an HF-TDR.

Successful use of the TDR 300 was reported, mainly as a reference technology, for correlating with other tools for precision turfgrass management (Stonewell and Gelernter, 2008), uniformity of water distribution by sprinklers (Brent, 2001; Serena et al., 2011), or establishment of bermudagrass [*Cynodon dactylon* (L.)] and seashore paspalum (*Paspalum vaginatum* Sw.) from seeds (Schiavon et al., 2012).

Faced with limited funding and time, concerned by the complication of the HF-TDR 1502 operation, and impressed by the unique structure of the long handle of the TDR 300 that can be operated when standing upright, coupled with the relatively lower price and in-campus availability of the TDR 300, we opted to use this device, yet decided to run some basic tests before moving into a full scale application (300 pots, daily measurements for 9 wk). Hence, the objective of the present study was to test the dependency of the measured VWC of wet soilless culture (sand and tuff) on the bulk EC.

Table 1. Volume of deionized water (DW) or saline solution added to 3.5 L of dry sand or tuff and the resulting volumetric water content.

Substrate	Volume of solution	Volumetric water content
	L	$m^3 m^{-3}$
Sand, Tuff	0	0
	0.175	0.05
	0.350	0.1
	0.525	0.15
	0.700	0.2
	0.875	0.25
	1.050	0.3
Tuff	1.150	0.33

MATERIALS AND METHODS

A Fieldscout TDR 300 soil moisture meter (Spectrum Technologies, Inc., Painfield, IL) was used to measure the VWC of two media, sand (passed through a 2-mm sieve) and a tuff (passed through an 8-mm sieve), and of solutions of different salinity levels. Three different experimental conditions were tested.

Experiment 1

A volume of 3.5 L of sand or tuff (oven dry) was mixed gradually with predetermined volumes of deionized water (DW) or a saline solution (0.02 M of analytical grade NaCl) to form a range of VWCs (Table 1). Sealed with an aluminum foil, we left the wetted solids over-night for moisture equilibration.

Experiment 2

A single VWC value was generated in each medium using solutions of different EC levels; 0.525 L of each solution was added to 3.5 L dry sand resulting in VWC of 0.15 $m^3 m^{-3}$, and 0.700 L of each solution was added to 3.5 L of tuff resulting in a VWC of 0.20 $m^3 m^{-3}$. Five solutions with different EC levels were studied for the sand solutions of 0.002, 0.591, 1.15, 1.69, or 2.28 dS m^{-1} and for the tuff solutions of 0.0024, 0.67, 1.324, 1.92, or 2.5 dS m^{-1}. The EC of the solutions was determined using the auto-ranging EC/temperature meter (model TH2400, El Hamma Instruments, Israel).

Experiment 3

The impact of solution salinity alone was tested by preparing 4 L of solutions having EC of 0.003, 0.54, 1.04, 1.59, or 2.16 dS m^{-1}.

In the aforementioned three experiments, each given combination of salinity and VWC was triplicated, measured with the TDR 300 and the MPR readings were then averaged. The TDR 300 measurements were performed in an air-conditioned laboratory where T was 24 ± 1°C.

RESULTS

The critical and consistent influence of the bulk EC on the relationships between the TDR 300 output and the VWC of the tested media is demonstrated by the following observations: Linear relations were found (Fig. 1a) between the TDR 300 output expressed in meter's period reading (MPR) and the VWC for the sand wetted by either DW (Slope = 2750 and R^2 = 0.987) or by a 0.02 M NaCl solution (Slope = 3926 and R^2 = 0.992). Namely, the same MPR reading will result in a higher VWC if the sand is wetted with DW relative to wetting by a saline solution. A similar pattern was noted for the tuff when wetted by DW or saline solutions but with different slopes: 1501 and 2319 for the DW and saline solutions, respectively (Fig. 1b).

Linear relations existed between the TDR 300 MPR and the EC of the wetting solution for a fixed VWC, exhibiting a slope of 55.31 in the sand and a slope of 39.38 in the tuff (Fig. 2a). Moreover, when immersed in aqueous solutions, the TDR 300 MPR maintained linear relations with the EC of the solution having a slope of 605 (R^2 = 0.98, Fig. 2b).

DISCUSSION

Noticeably, the bulk EC of the tested media affected the resulting VWC (or the MPR; the two are correlated) values obtained with the TDR 300 in both the sand and the tuff (Fig. 1a and 1b). Comparing sand wetted by either DW or a 0.02 M NaCl solution, an MPR of, e.g., 2680 results in a VWC of 0.23 $m^3\ m^{-3}$ in DW and 0.16 $m^3\ m^{-3}$ in saline solution. Similarly, comparing tuff wetted by DW or a 0.02 M NaCl solution, an MPR of, e.g., 2500 results in a VWC of 0.3 $m^3\ m^{-3}$ in DW and 0.21 $m^3\ m^{-3}$ in saline solution. Moreover, the results in Fig. 1 clearly indicate that the sensitivity of the TDR 300 output to salinity intensifies with the increase in VWC. In the case of a fixed VWC (0.15 $m^3\ m^{-3}$ for the sand and 0.2 $m^3\ m^{-3}$ for the tuff) and different salinity levels (Fig. 2a) the change in MPR over the wide EC range (from 0 to 2 dS m^{-1}) tested was relatively small (4–5%). However, in aqueous solutions, for the same EC range (0 to 2 dS m^{-1}), the salinity induced a >20% increase in MPR, from 4200 for DW to 5300 for the 2 dS m^{-1} solution (Fig. 2b).

Instruments like the TDR 1502 Cable Tester, which use the HF-TDR technology (characterized by a multifrequency signal where the highest frequency reaches 1.4 GHz), show a significantly lower salinity/texture dependency compared with that noted in our study for the TDR 300. We suspect, therefore, that the principle of operation used by the TDR 300 is not fully identical to that used by the HF-TDR. Our doubts are based on the following reasons.

1. In the high frequency range used by devices such as the TDR 1502 a unique, expensive detection technology (called "sampling-scope"), or a not less expensive alternative, is required to fully detect the transmission and reflection of the fast signal. The price tag of HF-TDR instruments is in the range of $6000–13,000 US (Blonquist et al., 2005, Table 1) namely, a factor of 10 to 20 times relative to the price of the TDR 300 (~$400 US).
2. The effect of all the galvanic contributions (σ_{dc}, dS m^{-1})

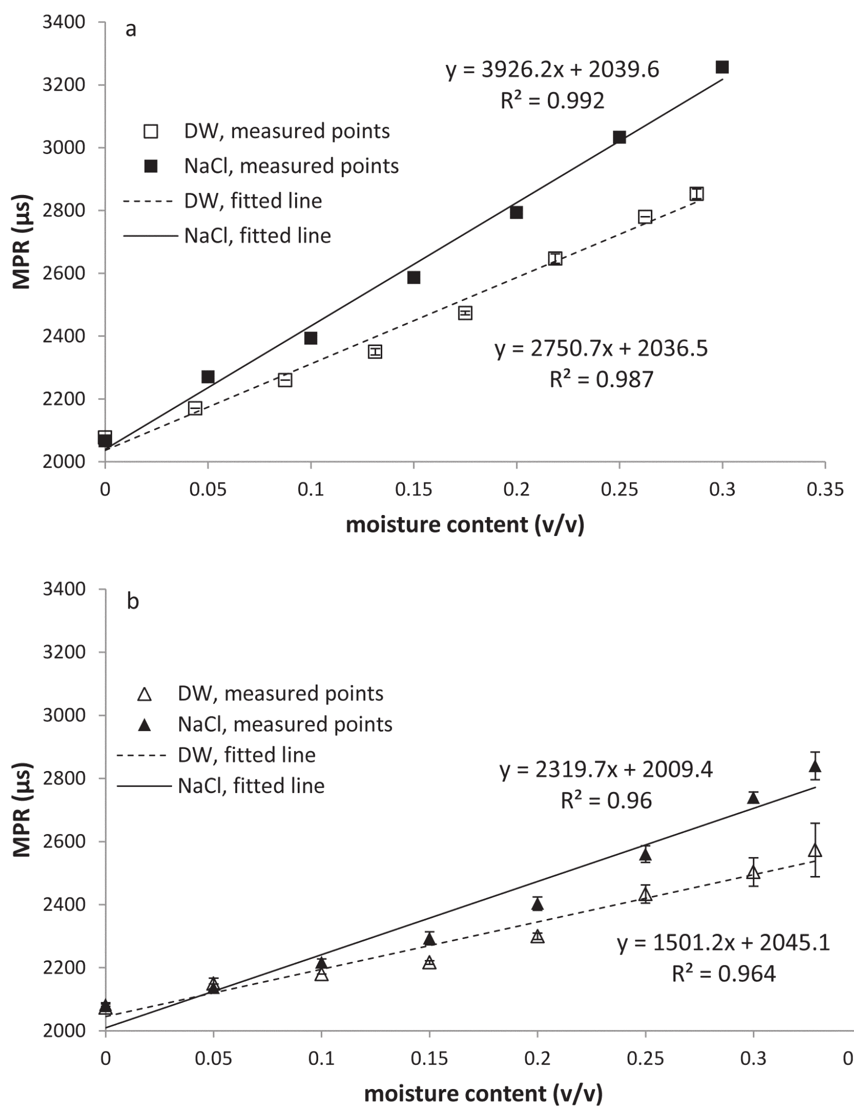

Fig. 1. TDR 300 output (meter's period reading, MPR) vs. moisture content for: (a) sand and (b) tuff, each wetted with deionized water and a 0.02 M NaCl solution. Bars indicate one standard deviation.

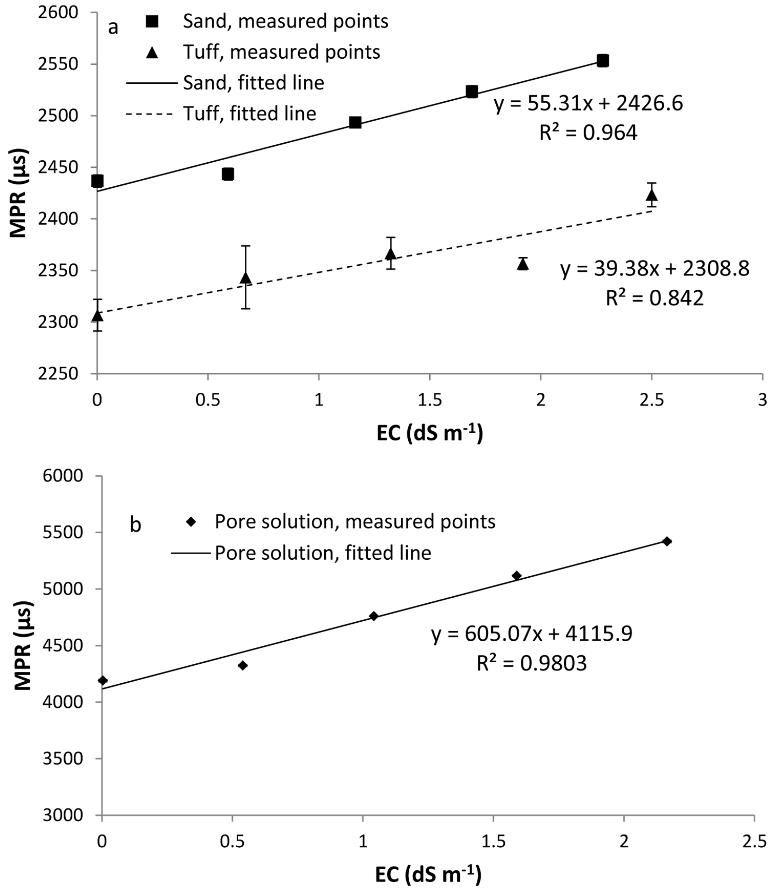

Fig. 2.TDR 300 output (meter's period reading, MPR) vs. solution electrical conductivity (EC) for: (a) sand having a VWC of 0.15 m^3 m^{-3} and tuff having a VWC of 0.20 m^3 m^{-3} and (b) NaCl aqueous solutions.

and the measuring frequency (f, MHz) on the dielectric constant (ε', unitless) through the imaginary component (ε'', unitless) are represented in Eq. [1] (Logsdon and Hornbuckle, 2006, Eq. [7]) .

$$\varepsilon''(f) = \sigma_{dc}/2\pi f \varepsilon_v + \varepsilon_{r''} \qquad [1]$$

where σ_{dc} is the direct current electrical conductivity, ε_v is the permittivity of vacuum (8.854×10^{-12} F m^{-1}), and $\varepsilon_{r''}$ (unitless) is the relaxation component of the imaginary permittivity. The measuring frequency (f) of the TDR 1502 is up to 1.4 GHz. Appearing in the denominator of Eq. [1], it practically zeroes the galvanic contributions altogether. Therefore, when using the TDR 1502, or any HF device, under higher salinities (e.g., >6 dS m^{-1}), the EM signal will be partly, and above a certain value of VWC, fully attenuated. Full attenuation prohibits reflection and disables measurement. Still, the VWC values determined before full pulse attenuation will not decrease or increase due to the presence of high salinity (Nadler et al., 1999).

3. The TDR 300 manual (Spectrum Technologies, 2009, p. 28) describes two calibration procedures while in most common applications the HF-TDR instruments do not need a specific calibration and the majority of users apply the Topp et al. (1980) global equation. Topp et al. (1980) report that the conversion of the dielectric constant into VWC only rarely requires a specific calibration. One way to explain the gap between the HF-TDR category and the TDR 300 is by arguing that the two instruments differ by their principle of operation and that the TDR 300 possibly belongs to the WCR category.

The TDR 300 seems to be probably a transmission line based oscillator soil moisture sensor that belongs to the WCR category (like the CS616 and its preceding version CS615, Campbell Scientific Logan, UT). It generates an interior voltage pulse, which propagates along the sensor rods back and forth. The number of such rounds per time unit is related to the soil dielectric properties because the water molecule dipoles slow down the signal propagation. The reciprocal of the number of rounds per second is called a period, and its value is linearly related to the dielectric properties and, therefore, to VWC. However, the relations between the period and VWC are not straightforward. Unlike the case of the HF-TDR, the WCR-type instruments are sensitive to soil type, temperature, bulk soil EC, and mutual complex interactions between them. Moreover, the exact relations are specific to the circuitry of the instrument that in a general way may be represented by

$$C = g\varepsilon \qquad [2]$$

Where C is the capacitance, g is a constant dependent on the geometry of the capacitor, and ε is the dielectric constant. Empirical calibrations are used to relate VWC to the frequency because of the uncertainty regarding the value of g and in the complex relationship between VWC and ε (Whalley et al., 1992).Typical examples of WCR are the CS615 and the CS616 (Campbell Scientific Logan, UT) that consist of a printed circuit board and two parallel rods that when installed in the soil enable it to affect the capacitance. The output is a square wave with a resultant oscillation frequency of 15–45 MHz. When this relatively low f is replaced in Eq. [1], the first term of the equation, representing the galvanic influence on the determined VWC, stays almost unchanged (relative to the 1.4 GHz case). Accordingly, it can be expected that with an increase in VWC and EC of the bulk soil components (e.g., pore solution, solid surfaces, organic matter) also T effect on VWC will increase. As expected, these were the findings of Seyfried and Murdock (2001) who tested the effect of T on the CS615 when installed in a combination of four soils, five T values, and a range of VWC: "With increase in WC (gravimetrically determined) there was a general divergence of T effect among the soils" (p. 28). The T effects on the sensor's response "were soil specific and couldn't be accounted for with a single, empirical correction factor" (Seyfried and Murdock, 2001, p. 32). Seyfried and Murdock (2001) concluded that the sensitivity of the WCR to EC may explain both the need for soil specific soil water calibration and the relatively strong T response. It should be stressed that: T correction and other calibration means applied to get more reliable VWC values still do not make the WCR an HF-TDR. According to Pepin et al. (1995), the TDR 1502 VWC values were affected by fractions of a percent with T changes (suggesting employing a factor of 0.00175VWC °C^{-1}, if at all).

In conclusion, based on our experimental findings, it seems that the TDR 300 principle of operation is similar to that of the WCR type devices rather than the HF-TDR ones. Therefore, users of the TDR 300 are advised to expect increasingly severe deviations in VWC from true values for clayey, saline, and wet soils having wide variations in T.

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