Practical Use of Time Domain Reflectometry for Monitoring Soil Water Content in Microirrigated Orchards

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SUMMARY. We have found time domain reflectometry (TDR) to be a rapid and effective method of measuring soil water content (SWC) in microirrigated orchards, particularly in applications where many sites are monitored frequently. With simple modifications to commercially available systems, it has been possible to measure up to 100 sites per hour. TDR SWC measurements have been successfully applied for scheduling irrigation and for in situ determination of SWC characteristics. The determination of plant water use from changes in SWC of microirrigated trees, however, requires that a sufficient number of probes be used to detect the spatial distribution of water within the root zone. Due to water redistribution in the soil following an irrigation, measurements made near drip emitters depend highly on the time after irrigation that the measurement is made. It is therefore important to be consistent in the timing of SWC measurements relative to irrigation events if the effects on SWC of different irrigation management practices are to be compared.

The use of time domain reflectometry (TDR) for measuring soil water content (SWC) has expanded rapidly since this technology was introduced during the early 1980s. At the Summerland, B.C., and Harrow, Ont., research stations of Agriculture and Agri-Food Canada, we have used TDR technology since 1989 to monitor SWC in various sites in our irrigation management research plots. The purpose of this paper is to report our experience with the use of this technology for irrigation management and for determining soil water characteristics in microirrigated orchards.

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Theory of TDR soil and water measurements

TDR measures SWC indirectly by measuring the travel time through the soil of a short pulse of electromagnetic energy. The travel time of an electromagnetic wave through a given thickness of material is directly proportional to the square root of the dielectric constant of that material (Ramo et al., 1984). For soils, the apparent relative dielectric constant, K_a , varies greatly with volumetric SWC and ranges from 4 for dry soil to as high as 40 for wet soil. Studies by Topp et al. (1980) found the following third-degree polynomial (Eq. [1])

$$SWC = 5.3 \times 10^{-2} + 2.92 \times 10^{-2} K_a - 5.5 \times 10^{-4} K_a^2 + 4.3 \times 10^{-6} K_a^3$$

to be an accurate description of the relationship between relative dielectric constant and volumetric SWC. This relationship only slightly depends on soil texture, density, salinity, or temperature and can, therefore, be used for a wide range of agricultural soils. Determining SWC by TDR involves the following steps:

- 1) transmit a high frequency electromagnetic pulse through the soil,
- 2) measure travel time of the pulse through a known depth of soil,
- 3) calculate K_a from the travel time and depth of soil, and
- 4) calculate SWC from the SWC vs. K_a relationship given in Eq. [1].

TDR equipment

TDR WAVEGUIDES. In practice, a TDR waveguide of known length is inserted in the soil to transmit the electromagnetic pulse through the soil and subsequently determine travel time. A form of TDR waveguide commonly used for measuring SWC consists of two parallel metal rods with a specified rod diam-

eter to spacing ratio (Zeglin and White, 1989). Such waveguides can be user-fabricated economically by cutting commercially available lengths of metal rod to the desired probe length. The volume of soil sampled by a parallel rod waveguide is a cylinder the length of the rods, having a diameter slightly greater than the spacing between the rods (Baker and Lascano, 1989). The measurement is an integrated average of volumetric SWC over the entire length of the rods. We have encountered difficulties both in installing probes and in obtaining reliable readings when probe length exceeded 1.0 m, particularly in heavy soils.

To match impedances, a transformer (called a balun) is used to connect the parallel rod transmission line to the coaxial cable of the TDR instrument. Recent introduction of three-conductor waveguide systems has eliminated the need for a balun transformer (Zeglin and White, 1989). A further innovation in TDR probe technology consists of a segmented probe whose sections can be electronically switched to permit a discrete measurement for each section of the probe and thereby obtain a profile of SWC with soil depth (Hook et al., 1992).

TDR INSTRUMENT. The TDR instrument determines travel time of an electromagnetic wave along the waveguide by transmitting a high frequency pulse and measuring the voltage amplitude of the reflected pulse at a known time increment following the transmission of the pulse. The process is repeated to generate a graph of reflected voltage vs. time from which the travel time along the imbedded waveguides can be determined. In addition to determining the travel time, most commercial TDR instruments can directly calculate and display SWC and store measured data for subsequent transfer to a computer or printer. Most TDR systems also can continuously log SWC changes over time and, with the use of optional multiplexing systems, many probes may be measured and logged simultaneously. Because waveguides must be wired to the multiplexer, such systems are not portable and are practical only where all sites to be monitored are located near the multiplexing unit.

Field installation and use

During the summer, SWC of soils whose texture ranges from sand to silt loam is monitored weekly at >500 sites in

Fig. 1. Soil water content during and following 0.5 h of irrigation measured by a 40-cm vertical time domain reflectometry probe located 25 cm from a 4 L·h⁻¹ drip emitter.

Fig. 2. Change in average root zone water content of drip-irrigated apple trees resulting from different durations of irrigation.

various research plots at the Summerland Research Station. Since these sites are widely scattered and consist of different length probes, we have found it most convenient to measure one probe at a time with a portable TDR unit (TRASE, Soil Moisture Corp., Santa Barbara, Calif.), rather than using a permanently wired multiplexed system. By cutting commercially available 6.3-mm-diameter stainless-steel rod to desired probe lengths, it has been possible to fabricate waveguides much more economically than purchasing manufactured waveguides supplied with the TDR system.

The rods are inserted vertically, 5.1 cm apart, to form waveguides at standard locations relative to the tree and emitter. Two waveguides—one 40 cm and one 80 cm—are installed along the tree row midway between the emitter and the tree, usually ≈ 25 cm from the tree trunk. A second similar set is installed 40 cm from the base of the tree, perpendicular to the row. While such an arrangement does not give a detailed assessment of SWC distribution within the root zone, averaging the readings from all four probes provides a reasonable estimate of average SWC within the root zone and how it is affected by different irrigation management procedures.

When installing the probes, metal guides at the top of the rods and at the soil surface are used to ensure that the rods are inserted parallel and at the correct spacing. The rods are inserted so that ≈ 1 cm protrudes above the soil surface for attachment of the TDR instrument. The inserted rods are usually difficult to locate and could be inadvertently damaged by orchard machinery. We have found it helpful to mark their location with a brightly colored ribbon attached to a wire stake.

Unless the rods are installed precisely, it is difficult to fit their protruding ends into the sockets of the balun connector. To facilitate connection of the balun to the probes, we have fabricated adapters with oversize sockets that fit over the ends of the rods more readily. When using the adapters, the zero reference point that identifies the

beginning of the waveguide must be established with the adapters attached to the connector.

Measurements are made by positioning the balun connector (with adapters attached) over the protruding ends of the rods and pressing the measure button on the TDR instrument. The measured SWCs are stored electronically by the TDR instrument and can be transferred later to a computer for further analysis. Up to 100 measurements can be made in 1 h using this system.

Field applications of TDR soil water measurement

MONITORING SWC DURING AN IRRIGATION CYCLE. SWC following an irrigation as monitored by a 40-cm vertical probe located within 25 cm of a $4 \text{ L} \cdot \text{h}^{-1}$ drip emitter is illustrated in Fig. 1. Water content continues to rise after the termination of irrigation due to continued movement of water from the dripper location to the probe, then decreases rapidly due to either radial redistribution of soil

Fig. 3. Average soil water content measured 24 h after irrigation for irrigation applied according to the scheduling procedure of Eq. [2].

Fig. 4. In situ saturated soil water content determined by monitoring a 40-cm vertical time domain reflectrometry probe during continuous irrigation with a 4 L·h⁻¹ emitter.

water, plant water extraction, or leaching below the probe depth. However, because TDR gives only an overall average reading of SWC rather than its distribution over the depth of the probe, it is not possible to distinguish between these potential causes. The continued decline in SWC during the night suggests that either radial redistribution or vertical leaching, rather than plant water use, may have been the major contributing factor. The foregoing figure illustrates the dependence of TDR SWC measurements on the time within the irrigation cycle that the measurement is made and the need to be cautious when interpreting results. When comparing SWCs of different irrigation practices, it is important to be consistent in the time after irrigation that SWC is measured.

IRRIGATION SCHEDULING. The use of TDR has greatly facilitated the application of SWC-based irrigation scheduling procedures in several of our research plots. As an example, in an experimental treatment that required maintaining the average SWC in the sandy loam root zone of young apple trees at $\approx 15\%$, the

duration of regularly scheduled biweekly irrigation was determined from the average SWC measured before irrigation with 64 TDR probes located throughout the plot. At the beginning of the experiment, it was necessary, however, first to determine the change in SWC caused by a known irrigation duration. This was accomplished by irrigating for durations ranging from 2 to 16 h and measuring the resulting change in SWC 24 h after irrigation was completed (Fig. 2). From this calibration procedure it was determined that for the specific soil, crop and irrigation system design of the experimental plot, SWC was increased by 0.4% for each hour of irrigation.

Irrigation application required to restore SWC to the desired 15% level was then determined by measuring SWC before irrigation and calculating the duration needed to cause the required change in SWC, as shown in Eq. [2]:

$$\text{Hours of irrigation} = (15\% - \text{SWC}_{\text{before}}) / (0.4\%/h)$$

The effectiveness of this TDR-based scheduling procedure in maintaining root zone SWC near the 15% target level is illustrated in Fig. 3.

IN SITU DETERMINATION OF SATURATION AND FIELD CAPACITY SWC. The ability to continuously monitor changes in SWC with TDR enables the in situ determination of soil water characteristics such as saturation water content and field capacity.

Saturation SWC of a gravelly silt loam soil to be used for a deficit irrigation experiment was determined by positioning a 40-cm vertical waveguide within 25 cm of a continuously flowing 4 L·h⁻¹ drip emitter. The irrigated area was covered by a 3 × 3-m plastic sheet to prevent evaporation and SWC was monitored at 10-min intervals. Saturation SWC was estimated from the point on the resulting SWC vs. time graph (Fig. 4) where SWC did not increase substantially as more water was added.

Field capacity was determined by allowing the soil to drain following irrigation to saturation and monitoring the resulting change in SWC (Fig. 5). Although SWC continued to decrease for >1 month after irrigation was termi-

Fig. 5. Field capacity determined in situ by monitoring soil water content during drainage following saturation.

Fig. 6. In situ moisture release curve of a sandy loam soil constructed from simultaneous measurements of soil water with a 40-cm vertical time domain reflectrometry probe and water potential with a 30-cm deep tensiometer.

nated, field capacity was considered to have been reached when the rate of change in SWC had become slow and steady, ≈ 2 d after irrigation. A similar procedure was successfully used by C.S. Tan (personal communication) for in situ determination of field capacity of several different soil types at the Harrow, Ont., Research Station of Agriculture Canada.

IN SITU WATER RELEASE CURVE.

Knowledge of water-holding capacity of soil is important for the design and operation of irrigation systems. Such information is usually obtained from moisture release curves of water content vs. water potential derived by extracting moisture from soil samples with a pressure-plate apparatus (Klute, 1986). Pressure-plate moisture release curves are not only time consuming to construct but also may not accurately represent the true water content vs. water potential relationship due to disturbance of the soil sample.

However, by simultaneously measuring SWC with TDR and water potential with a tensiometer, moisture release curves can be readily constructed under actual field conditions without disturbing the soil, except for insertion of TDR probes and tensiometers. The in situ moisture release curve shown in Fig. 6 was constructed from SWC and water potential measurements with a 40-cm vertical TDR probe and a 30-cm deep tensiometer placed <10 cm apart in a sandy loam soil. Measurements were made at regular intervals as the soil dried between irrigations. Since the average SWC over the 0 to 40 cm depth measured by the TDR probes may not be similar to the SWC at the 30-cm tensiometer depth, the resulting SWC vs. water potential curve is only quantitative in nature. Nevertheless, it may have potential application for management of high frequency micro-irrigation systems.

PLANT WATER USE. Water use of field crops is commonly estimated from the decrease in SWC during the interval between irrigations. However, in our studies with drip irrigated apple trees, evapotranspiration estimated from pan evaporation was poorly correlated with root zone SWC depletion measured by TDR. Correlation of evaporation from a class A pan during several 5-d intervals during the summer with SWC depletion during the corresponding time periods resulted in $r^2 < 0.40$. The poor correlation in our drip

irrigation trials suggests that determining plant water use from soil water depletion measurements of drip-irrigated trees requires more intensive instrumentation than the four TDR probes we used. In addition, factors other than plant water use, such as drainage or soil water redistribution, may have contributed to the observed decrease in water content.

OTHER APPLICATIONS OF TDR. In addition to the uses of TDR soil water measurements that have been outlined thus far, it is evident from examining scientific literature that this technology is being used for many other agricultural applications. Whereas volumetric SWC is derived from the travel time through soil of a high-frequency electromagnetic pulse, the bulk electrical conductivity of soil can be determined simultaneously from the attenuation of the reflected pulse (Dalton et al., 1984; Nadler et al., 1991; Topp et al., 1988). Kachanoski et al., (1992) used the change in soil electrical conductivity with time determined in this manner to estimate the vertical mass flux of a solute past the ends of a TDR probe. The ability to make a large number of nondestructive SWC measurements with relative ease has enabled researchers to compare the vertical and horizontal water distribution patterns of drip and microjet emitters (Pelletier and Tan, 1993) or detect localized areas of soil compaction from the spatial variability in volumetric SWC (Rajkai and Ryden, 1992). In another instance, TDR probes inserted directly into the trunks of trees were used to determine the internal water status and detect moisture stress of the trees (Contantz and Murphy, 1990).

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