# Time Domain Reflectometry Accurately Monitors and Controls Irrigation Water Applications in Soilless Substrates

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## Abstract

**Most horticultural soilless substrates have a small range of easily-available water (EAW) for optimum plant growth, and therefore require frequent irrigations. Most soilless substrates generally hold EAW in the range from 0 to -10 KPa matric potential ($\Psi_m$), with most plant-available water in the range 0 to -5 KPa. Knowledge of the volumetric water ($W_v$) content of a substrate can be used to precisely define irrigation applications, if an accurate method for sensing $W_v$ is available. Until now, no technology has existed to do this in soilless substrates with any degree of precision. Accurate monitoring and control of irrigation water should retain nutrients in the root zone and maximize plant growth, while minimizing leaching volumes. Time Domain Reflectometry (TDR) has been shown to accurately measure $W_v$ in a few soilless substrates, but there is no information on the variability of such data or how substrate $W_v$ and plant water use are correlated. A range of soilless substrates, including Pro-Mix 'BX', a commercial pine-bark mix, a commercial hardwood-bark mix, medium-grade perlite, rockwool, and sieved sand were studied in a range of experiments designed to test these assumptions, using various column (container) heights. Mean TDR coefficients of variation ranged from 0.8% to 7.9% over all substrate and column heights, proving that TDR can precisely measure water contents in soilless substrates under most conditions. Water-release and TDR curves for each substrate indicate that $W_v$ is primarily determined by substrate characteristics, but also by container height. Experiments with azalea in growth chamber and greenhouse experiments showed that a TDR-monitored and controlled irrigation system precisely controlled cyclic irrigation events, with initiation at -10KPa and termination of irrigation at –1 KPa. TDR sensors need to be placed vertically in the rootzone, especially with drip emitters. Water and nutrient leaching volumes were significantly reduced compared to an irrigation method based on container weight.**

## INTRODUCTION

Horticultural soilless substrates generally have a greater proportion of large pore spaces in comparison to natural soils, with low water-holding capacities, and smaller ranges of easily-available water (EAW) for optimum plant growth (Handreck and Black, 1999). Easily-available water can be measured based on the matric potential ($\Psi_m$) of the substrate. Soilless substrates generally hold EAW in an $\Psi_m$ range from 0 to -10 KPa, with the majority of free water available from 0 to -5 KPa (de Boodt, 1972; Handreck and Black, 1999). Water release curves follow a characteristic shape, yet vary according to the substrate composition and particle size (de Boodt, 1972). Container geometry also affects the water retention characteristics of a substrate, particularly container height (Handreck and Black, 1999). Gravity acts in the vertical plane, with increased drainage from taller containers of the same volume. A taller container therefore holds proportionately less water, as a percentage of water content by volume (i.e. decreased $W_v$). Accurate irrigation parameters should therefore be based on specific substrate characteristics and container height.

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Water-release curve data can be used to define precise irrigation applications if an accurate method for measuring $W_v$ is available. Until now, no technology has existed to do this with any degree of precision in horticultural soilless substrates. Accurate monitoring and control of irrigation application amounts should retain nutrients in the root zone (by increasing the residence time) and maximize plant growth, while minimizing leaching volumes. Calibration of sensors based on measuring matric potential with simultaneous water content and time domain reflectometry (TDR) measurements can be used to define irrigation parameters (Campbell and Campbell, 1982; Topp, 1985). However, few data are available for calibrating TDR sensors in soilless substrates, or provide information on the variability of TDR sensor performance in substrates of different water holding capacities (Ansoult et al., 1985; Anisko et al., 1994; da Silva et al., 1998). There are also few data to indicate how $W_v$ and plant water use are correlated in soilless substrates, or if measurement of $W_v$ can accurately sense plant water stress.

The objectives of these studies were thus to characterize the relationship of substrate matric potential (KPa) with percent volumetric water content ($W_v$) and dielectric (TDR) sensor output in a range of soilless substrates used by the nursery and greenhouse industries. In addition, we investigated whether TDR could accurately sense plant water stress and precisely monitor and control irrigation scheduling for *Rhododendron azalea* plants grown in a greenhouse environment.

## MATERIALS AND METHODS

### Experiment 1

Murray et al. (2001) described how a modified tension table was used to repeatedly measure the volumetric water content ($W_v$) and TDR output of six soilless substrates at three column heights, and how each substrate has a very narrow range of EAW in the range of 0 to -10 KPa. The six soilless substrates were selected based on their prevalence in the container nursery industry and/or their differences in particle type: Pro-Mix 'BX', a commercial pine-bark mix, a commercial hardwood-bark mix, medium-grade perlite, rockwool, and sieved washed sand (as a uniform particle size control). The heights of each substrate column were equivalent to commercial #1, #3, and #5 containers with heights of 15, 20 and 25 cm, respectively.

### Experiment 2

*Rhododendron azalea* cv. 'Hot Shot' liners were transplanted into 20 cm high (7450 $cm^3$) containers and grown for one year in each of the six substrates (40 plants per substrate) in a greenhouse, under standard cultural conditions (Murray, 2001). Eight plants were randomly selected from each group and placed in a walk-in growth chamber in a randomized complete block design, with each block containing four replicate plants of each substrate (n=48). The growth chamber was fitted with metal halide and incandescent light bulbs that were programmed to increase light intensity during the day to simulate natural growth conditions; the temperature was maintained at a constant 25°C. The photoperiod consisted of a nine-hour dark period and a 15-hour light period, ramping up and down every 3 hours from 300 (low), to 600 (moderate) and 1000 $\mu mol\ m^{-2}\ s^{-1}$, (high light) respectively (Murray, 2001). Plants were kept well watered for 3 days prior to the start of the experiment and re-watered to container capacity on Day 1. TDR (and hence $W_v$) measurements were automatically logged on a continuous basis throughout the study period using a Campbell Scientific (Logan, UT) TDR100 system with 18 cm probes, coupled with a Campbell Scientific CRX-10 datalogger. Leaf stomatal conductance ($g_s$) of similarly aged leaves on each plant were measured mid-way through each incremental light period each day, using a LICOR (Lincoln, NE) 1600 Steady State Porometer. Measurements of $W_v$ were carried out until temporary leaf wilt at 14 days, whereas stomatal conductance measurements were taken until a sharp decline in $g_s$ was apparent (Murray, 2001).

## Experiment 3

The first objective of this greenhouse study was to determine whether sensor placement (in relation to irrigation method and emitter placement) had an effect on sensor performance for five of the soilless substrates (i.e. whether substrate porosity and/or other effects interfered with the precision of sensor performance). A second objective was to determine whether TDR could precisely maintain $W_v$ in these substrates within the parameters determined for TDR performance in experiment 1.

The experiment was set up as a 2 x 2 factorial in a completely randomized design (Murray, 2001). Sensor placement was the primary factor, with the sensor orientated in either the vertical or the diagonal plane (Fig. 1); the second factor was emitter type – spray vs. drip stake microirrigation. Forty plants per substrate (n = 10 per treatment) were used in this study. A Campbell TDR100 system with 18 cm sensors was used to sequentially monitor all 40 plants in each substrate, with a cycle time of approximately one second per sensor. This was an ideal monitoring interval to use with spray stakes due to their relatively large water output in comparison to drip emitters. Irrigation cycles were initiated at -10 KPa, and a -1 KPa set point (just below container capacity) was selected to terminate irrigation events. The moisture content of each of the treatments was logged every two hours with the CR10x datalogger for 7 days. Replicate leachate totals were collected every day and summed for the study period. Since some treatments had no leachate, this study required a nonparametric statistical analysis. Proc NPAR1WAY was used to analyze the data using a rank transformation procedure (SAS Institute, NC).

## RESULTS AND DISCUSSION

An example of the relationship between substrate $W_v$ and TDR output is given for Pro-Mix 'BX' (Fig. 2a, b) and pine bark substrates (Fig. 2c, d). Relationships shown here are indicative of changes for all soilless substrates studied in Exp. 1, except rockwool and sand. A summary of the variability of the TDR probes with 15 and 20 cm column height for four substrates is given in Table 1. The coefficients of variance for TDR measurements over all column heights and substrates ranged from 0.8% to 7.9% (Murray, 2001). Thus, it is apparent that TDR can precisely measure water contents in a range of soilless substrates at container heights that encompass most nursery containers. Substrate water-holding capacity decreased sharply between zero KPa and -10 Kpa (Fig. 2b, d) indicating that these substrates have relatively low water-holding capacities at high $\Psi_m$, in comparison to normal soil data. The variability of the water-release and TDR curves for each substrate indicate that $W_v$ is primarily determined by substrate physical characteristics, but container height also affects $W_v$ (Fig. 2b, d), especially at substrate $\Psi_m$ near zero KPa (container capacity). Thus, TDR sensors should be calibrated with $W_v$ data based on container height (Fig. 2a, c), if irrigation scheduling set points are close to 0 KPa. The initiation of irrigation cycles at -10 KPa appears ideal from these results, but only if the species does not experience water stress at that substrate $W_v$.

Stomatal conductance ($g_s$) values during a drying cycle are shown for azalea grown in Pro-Mix 'BX' (Fig. 3a) and pine bark substrates (Fig. 3b). Azalea plants in the other substrates showed similar trends but no correlations were made between substrates (7). All azalea plants showed a decline in $g_s$ when the $\Psi_m$ fell below -10 KPa (Fig. 3a, b). The $W_v$ of the substrate showed a steady decline after the last irrigation on day 1, as expected (Fig. 2). Interestingly, a decline in $g_s$ was evident from these data up to 9 days before visible leaf wilt was observed but more than 5 days after the last irrigation event. Both time periods were surprisingly long, perhaps suggesting that we may be over watering these woody perennials species if they are irrigated every day. More studies should be conducted to determine the precise $W_v$ at which ornamental plant species show declines in stomatal conductance and photosynthetic rate.

The TDR cyclic irrigation system precisely controlled irrigation events and reduced leaching volumes (Table 2), with an initiation at -10 KPa and a termination of irrigation at -1 KPa matric potential (Murray, 2001). However, the results indicate that TDR probes need to be placed vertically in the wetting zone to minimize leaching volumes, especially when the wetting zone is restricted (as with drip emitters). If not, large leaching volumes will occur with most substrates (Table 2). It is apparent that sensor placement is less important with spray stakes, but diagonal placement may also be preferable, since great care was taken in this study to ensure even coverage of the surface with each spray stake in each pot.

These experiments provide the first comprehensive study of TDR technology in soilless substrates. Conceptually, the technique has shown to be very precise and it can be adapted to accurately monitor and control irrigation schedules in horticultural situations. Further development of cheap wireless probes would enhance the adoption of this technology by the industry in the future.

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## Tables

Table 1. Time domain reflectometry regression equations and variability analysis for four representative soilless substrates at column heights of 15 and 20 cm.

| Treatment | Regression Equation | $R^2$ | Goodness of Fit (Probability) | Mean CV (%) |
|---|---|---|---|---|
| 15 cm - Pro-Mix | $y = 3.562 – 0.157x + 0.006x^2 – 0.0001x^3$ | 0.71 | $P < 0.05$ | 5.3 |
| 15 cm - Pine Bark | $y = 3.445 – 0.171x + 0.004x^2 – 0.0001x^3$ | 0.68 | $P < 0.05$ | 4.7 |
| 15 cm - Perlite | $y = 2.758 – 0.078x + 0.003x^2 – 0.0001x^3$ | 0.59 | $P < 0.07$ | 7.4 |
| 15 cm - Sand | $y = 2.851 – 0.179x + 0.007x^2 – 0.0001x^3$ | 0.62 | $P < 0.05$ | 3.5 |
| 20 cm - Pro-Mix | $y = 4.192 – 0.145x + 0.005x^2 – 0.0001x^3$ | 0.66 | $P < 0.05$ | 3.9 |
| 20 cm - Pine Bark | $y = 5.237 – 0.204x + 0.007x^2 – 0.0001x^3$ | 0.82 | $P < 0.01$ | 4.0 |
| 20 cm - Perlite | $y = 3.622 – 0.108x + 0.004x^2 – 0.0001x^3$ | 0.59 | $P < 0.07$ | 4.7 |
| 20 cm - Sand | $y = 3.632 – 0.177x + 0.007x^2 – 0.0001x^3$ | 0.58 | $P < 0.08$ | 2.7 |

Table 2. The effect of emitter and sensor placement on mean leaching volume (± standard error) in ml/plant per irrigation event in five soilless substrates. Significance of placement effects (vertical vs. diagonal) indicated by P-value.

| Substrate | Drip Vertical (ml) | Drip Diagonal (ml) | Significance (P-value) | Spray Vertical (ml) | Spray Diagonal (ml) | Significance (P-Value) |
|---|---|---|---|---|---|---|
| Pro-Mix | 33 (± 13) | 276 (± 38) | $P < 0.001$ | 0 (± 0) | 27 (± 27) | $P = 0.22$ |
| Hardwood Mix | 0 (± 0) | 37 (± 9) | $P < 0.001$ | 1 (± 1) | 12 (± 8) | $P = 0.15$ |
| Pine Bark Mix | 0 (± 0) | 623 (± 42) | $P < 0.001$ | 14 (± 8) | 32 (± 9) | $P = 0.33$ |
| Perlite | 0 (± 0) | 168 (± 30) | $P < 0.001$ | 0 (± 0) | 6 (± 4) | $P = 0.21$ |
| Sand | 8 (± 4) | 57 (± 15) | $P < 0.03$ | 70 (± 27) | 9 (± 5) | $P = 0.09$ |

## Figures

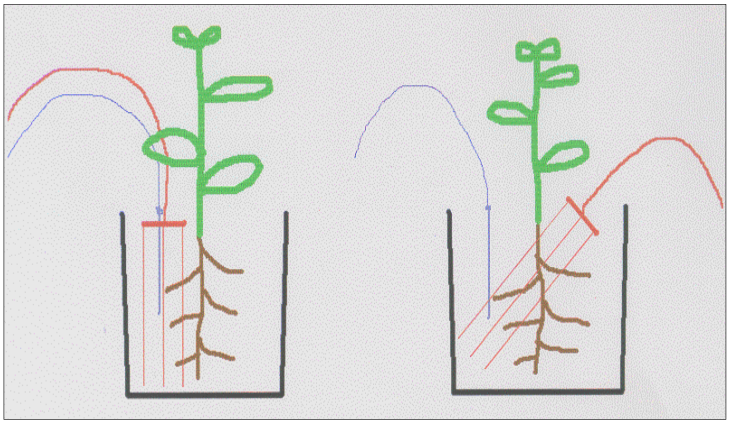


Fig. 1. Schematic of a drip or spray stake (represented by the line at the left of the plant stem) and TDR probe placement in the plant container. At left is a vertical sensor placement in the plane of the emitter (Drip-Vertical or Spray-Vertical). At right is the diagonal placement (Drip-Diagonal or Spray-Diagonal).

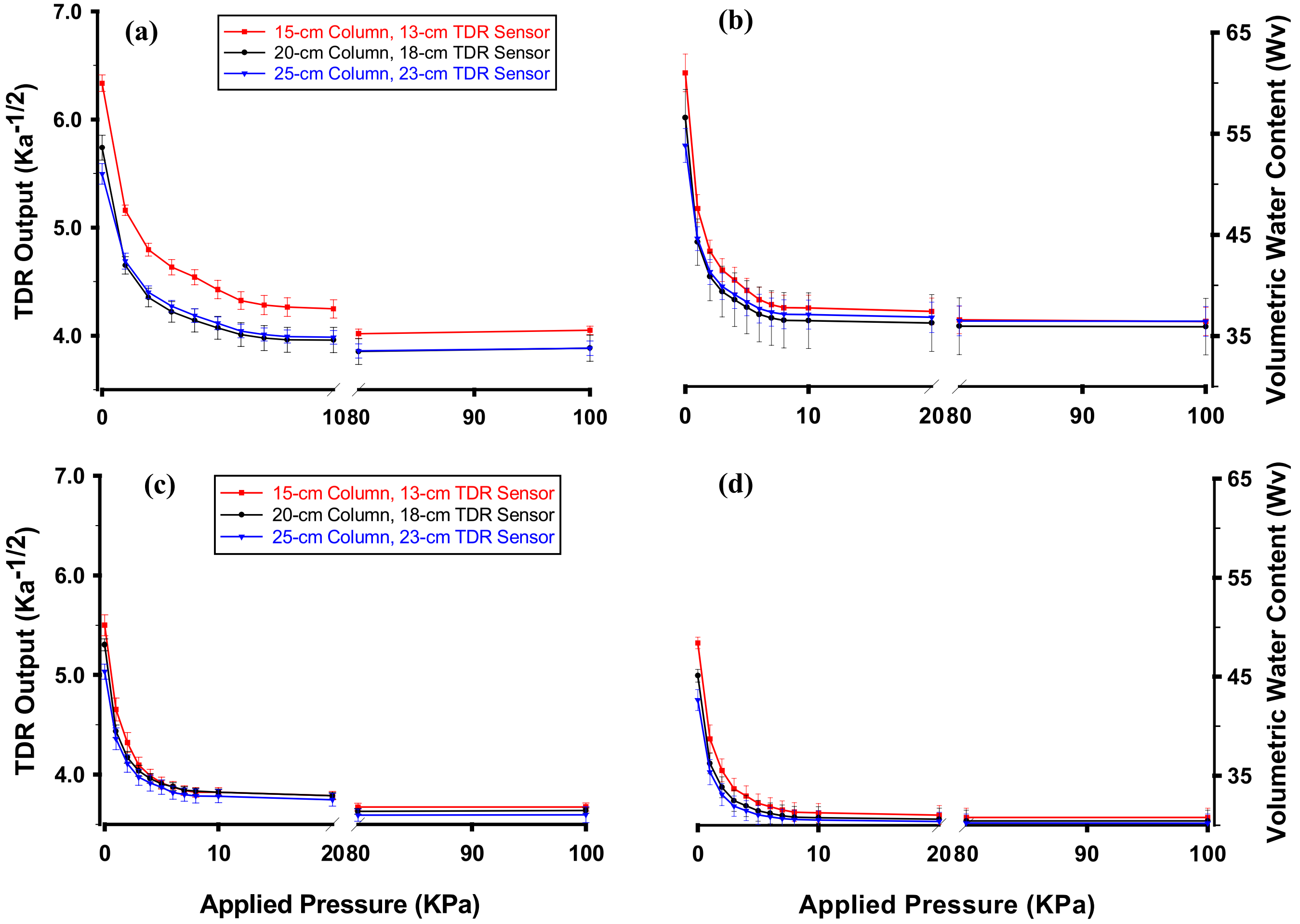
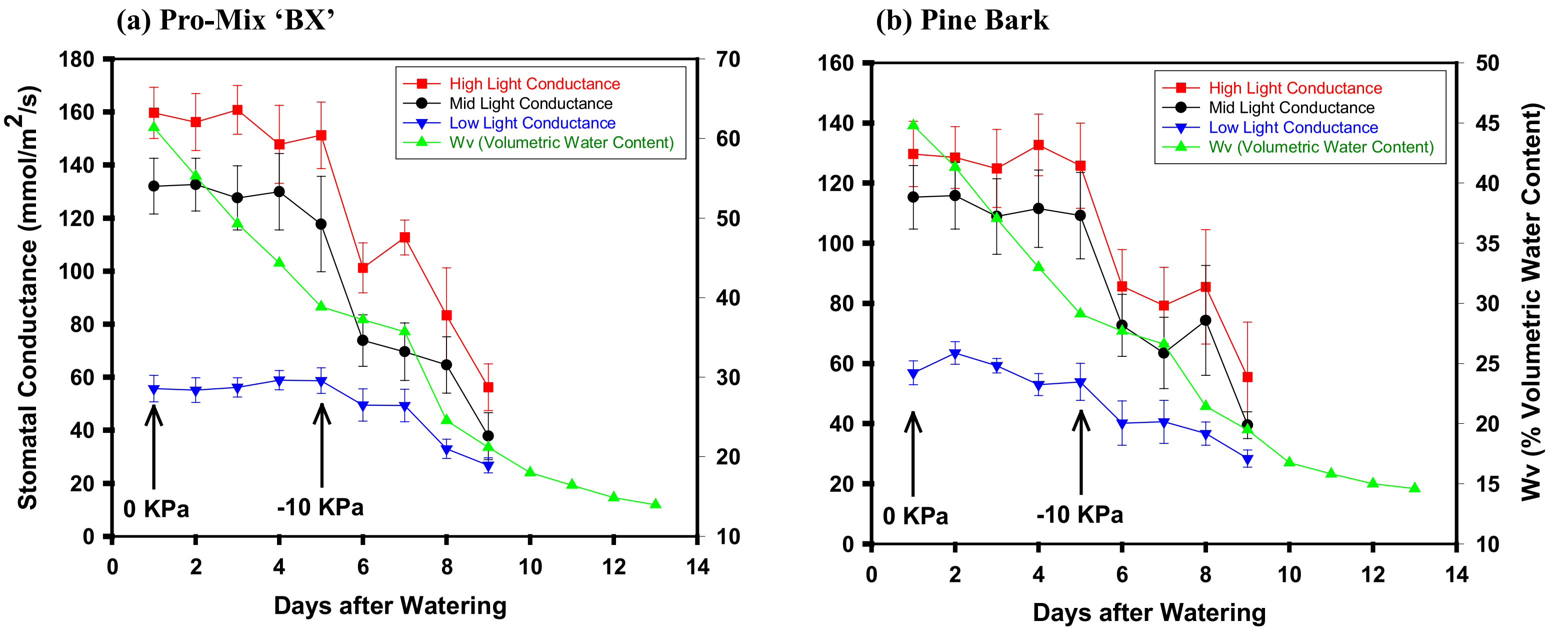


Fig. 2. Standard Time Domain Reflectometry (TDR) curves (a; c) and Volumetric Water Content ($W_v$) curves (b; d) for Pro-Mix ‘BX’ (a; b) and Pine Bark (c; d) soilless substrates at column heights of 15, 20, and 25 cm respectively. Error bars represent the standard error about the mean (n=6).


(a) Pro-Mix ‘BX’

(b) Pine Bark

Fig. 3. Mean stomatal conductance of Azalea plants in (a) ‘Pro-Mix’ substrate and (b) Pine Bark substrate at high (1000), mid (600), and low (300 µmol m$^{-2}$ s$^{-1}$) light levels, on successive days after irrigation to container capacity (day one). Arrows indicate the day at which substrate matric potential measurements were 0 KPa and -10 KPa.