TDR APPLICATION FOR AUTOMATED WATER LEVEL MEASUREMENT FROM MARIOTTE RESERVOIRS IN TENSION DISC INFILTROMETERS

D. Moret, M.V. López, J.L. Arrúe*

Departamento de Edafología, Estación Experimental de Aula Dei, Consejo Superior de Investigaciones Científicas (CSIC), PO Box 202, 50080 Zaragoza, Spain

* Corresponding author. Tel.: +34-976-716095; fax: +34-976-716145

E-mail address: arrue@eead.csic.es

Abstract

This paper describes the use of an automated method of measuring water level changes in Mariotte-type reservoirs via time domain reflectometry (TDR) and demonstrates its field application for measurements of soil hydraulic properties. The method is based on the assumption that the travel time of a TDR pulse propagating along a transmission line immersed in an air-water medium is the summation of the pulse travel times in the air and water phases. A TDR cable tester generates a pulse that propagates through a three-rod probe traversing the centre of the Mariotte reservoir from top to bottom. The reflection of the pulse is automatically transferred to a computer for waveform analysis with the water level being a simple function of probe length and the air, water, and air-water medium dielectric constants as measured by the cable tester. Water level measurements obtained with the TDR technique showed close agreement with those obtained using visual and pressure transducer procedures. The application of this TDR method as an alternative to more traditional methods was demonstrated in a field experiment using a tension disc infiltrometer. The TDR approach allows for automated water level measurements and is simple, accurate and easy to implement. Moreover, it allows for simultaneous TDR measurements of both water flow and volumetric water content of soil below the infiltrometer disc.

Keywords: Time domain reflectometry; Water level; Tension disc infiltrometer; Infiltration; Soil hydraulic properties

1. Introduction

Accurate characterisation of soil hydraulic properties is crucial to solving many hydrological, engineering, and environmental issues linked to soil water storage and transport in the vadose zone. In practice, this is achieved using field determinations of transient and steady-state infiltration rates of water into the soil, either under positive or negative head conditions (Angulo-Jaramillo et al., 2000). Both methods involve measuring the change of water level in a water-supply reservoir. Generally, this is done by visually noting the water level drop in a Mariotte column. However, this practice requires constant vigilance since visual readings have to be made at constant intervals and sometimes over long periods of time as in the case of slowly permeable clay soils. In other situations, when using early-time transient flow to infer soil hydraulic properties (Vandervaere et al., 1997), initial infiltration rates can be too rapid to be recorded with the required precision.

Over the last decade, the tension disc infiltrometer (Perroux and White, 1988) has become a popular tool in the study of saturated and near saturated soil water flows (Angulo-Jaramillo et al., 2000). To overcome the limitations of the standard visual technique, automated tension infiltrometers have been configured with either two gage transducers (Ankeny et al., 1988) or a single differential transducer (Casey and Derby, 2002). Though these infiltrometers are capable of providing accurate water level measurements, they depend upon accurate calibration.

When estimating soil hydraulic properties from disc infiltrometer measurements, determination of the initial and final soil volumetric water content below the infiltrometer disc is also required. This is usually done by extracting soil cores, an exacting and laborious task but one that could also be achieved using time domain reflectometry (TDR). Although TDR requires a relatively expensive equipment, this highly accurate technique is now widely used in many soil science and hydrology laboratories (Jones et al., 2002). Some studies have already explored the combined use of tension disc infiltrometry and TDR measurements of soil water content (Vogeler et al., 1996;

Schwartz and Evett, 2002). The present study further develops this idea more fully in exploiting TDR for the infiltration measurements themselves.

TDR technology has also been used to measure the elevation of ground water table depths (O'Connor and Dowding, 1999) and the water level in tanks collecting surface runoff from erosion field plots (Thomsen et al., 2000). In these and other applications, such as the "guided microwave" devices commercially available for level measurement of fluids in industrial containers, the measurement principle is the location of the TDR voltage reflection at the air-medium interface. However, errors are possible if the operator does not correctly identify such reflections, as can happen when TDR signatures are visually analysed to locate the air-water interface in piezometric tubes (O'Connor and Dowding, 1999). In contrast, the standard TDR method for automated measurement of soil water content considers the travel time of the TDR pulse along the whole length of the transmission line. We develop a similar approach here for the measurement of water level changes in order to calculate infiltration rates from a disc infiltrometer.

The objectives of this research were twofold: firstly, to test the use of TDR for automated, unattended measurement of water level changes in Mariotte-type reservoirs, and secondly, to demonstrate its field use with a tension disc infiltrometer to provide simultaneous TDR measurements of both water flow and soil water content.

2. Materials and methods

2.1. Theory

TDR relies on the determination of the propagation velocity of electromagnetic waves along parallel metallic probes embedded in the medium of interest. The fundamental physical property affecting the pulse transit time is the dielectric property of the medium with the propagation velocity (v) expressed as :

$$v = \frac{c}{\sqrt{\varepsilon}} \tag{1}$$

where c is the velocity of light in free space (3 x 10^8 m s^{-1}) and ε is the relative dielectric constant of the medium (Topp et al., 1980). By definition, the propagation velocity (v) along a TDR probe of length L is given in terms of the pulse transit time, t, and the path length, $2L$ (Dalton, 1992) as

$$v = \frac{2L}{t} \tag{2}$$

Equating Equation (1) and Equation (2) and solving for the transit time gives

$$t = \frac{2L\sqrt{\varepsilon}}{c} \tag{3}$$

In the case of a TDR probe vertically inserted in a stratified medium with different phases the measured total travel time of the TDR pulse is a summation of the travel times in the different phases (Ferré et al., 1996):

$$t = \Sigma_i t_i \tag{4}$$

where the subscripts refer to the different phases. In the case of a TDR probe of length L traversing from the top to the bottom of a Mariotte reservoir of height L partially filled with water (Fig. 1) we obtain

$$t = \frac{2L\sqrt{\varepsilon_{TDR}}}{c} = \frac{2x\sqrt{\varepsilon_{air}}}{c} + \frac{2(L-x)\sqrt{\varepsilon_{water}}}{c} \tag{5}$$

where ε_{TDR} is the apparent dielectric constant measured by the TDR cable tester; ε_{air} and ε_{water} are the relative dielectric constants of air and water measured previously with the same probe; and x is the probe length above water level.

Solving the equality (5) for x we obtain

$$x = L\frac{\sqrt{\varepsilon_{TDR}} - \sqrt{\varepsilon_{water}}}{\sqrt{\varepsilon_{air}} - \sqrt{\varepsilon_{water}}} \tag{6}$$

2.2. TDR-based water level sensing set-up: probe design and waveform analysis

On the basis of the above theoretical considerations, this paper presents a new system for automated water level measurements in a Mariotte column (e.g. the water-supply reservoir of a tension disc infiltrometer) using TDR (Fig. 1). This application comprises a three-rod coaxial TDR probe placed in the centre of the water reservoir and connected to a TDR pulser (Tektronix 1502C Metallic Time Domain Reflectometer) equipped with a SP232 serial communication port. The probe is firmly fixed to the water reservoir by means of an epoxy casing at the top and a PVC rod of 12 mm of diameter traversing the reservoir at the bottom. The cable tester generates electromagnetic pulses at predetermined intervals that propagate through the water reservoir along the probe. Reflections of the pulse propagate back to the receiving unit in the TDR pulser. The waveform is then transferred to the computer and automatically analysed using the software WinTDR'98 (Or et al., 1998).

The waveform characteristics of several three-wire TDR probe designs with different wire material (steel, tin and copper) and geometrical configurations were investigated before choosing copper rods with a diameter of 1.6 mm and a separation of 10 mm for the outermost rods.

To reduce conductive losses and improve the quality of the TDR waveforms and their analysis by using the double-reflection procedure (Heimovaara, 1993), probe rods were insulated with polyolefin heat-shrink tubing having a wall thickness of 0.5 mm. Figure 2 shows the effect of this type of coating. For a Mariotte reservoir full of water and with a probe without coating, the signature of the second reflection is poorly defined (Fig. 2a). By contrast, the definition substantially improves when the same probe is coated (Fig. 2b, waveform III). This improvement, which is maintained as the water reservoir empties (Fig. 2b), substantively improves the accuracy in finding the second reflection point on the wave trace by using the tangent lines procedure with either the classical sloped line method or the flat line method as designed in WinTDR'98 for well defined waveforms (Or et al., 1998). Once the apparent dielectric constant of the air-water medium within the water reservoir, ε_{TDR} , is obtained via Equation (3), the water level height $(L\text{-}x)$ is calculated from Equation (6). Values of ε_{air} and ε_{water} are measured with the Mariotte reservoir empty and full of water, respectively, immediately prior to the experimental runs.

2.3. Performance and field application

In order to evaluate the capability of the new TDR-based water level sensing technique for in situ automated water flow measurement by tension disc infiltrometry, two experiments were conducted. In both tap water with an electrical conductivity of 1.14 dS m^{-1} was used.

The first experiment was undertaken in the laboratory to test the performance and precision of the proposed TDR application under ideal conditions for measuring the water level in Mariotte reservoirs. TDR was compared with the standard visual technique, with readings made to the nearest millimetre, and a single differential pressure transducer. To this end, a vertical water reservoir, consisting of a 90 cm tube made of clear methacrylate plastic with 4.2 cm of internal diameter, was equipped with a coated three-wire TDR probe 86.5 cm long similar to that described previously (Fig. 1). A ± 30 psi differential pressure transducer (model 26PCDFA6D, Microswitch, Honeywell) was installed at the bottom of the reservoir and calibrated as described by Casey and Derby (2002). A transparent calibrated measuring tape was externally attached to the reservoir wall for visual water level measurements. To allow for stationary water level measurements, the reservoir was closed at the bottom by means of a rubber stopper having a PVC stopcock. Simultaneous visual, pressure transducer and TDR-based depth measurements were made at intervals of approximately 5-10 cm, from 0 cm (reservoir full of water) down to 86.5 cm (reservoir full of air). This procedure was repeated twice.

A second experiment to demonstrate the field use of the new TDR application was also carried out. It consisted of measuring the infiltration rate of a recently tilled loamy soil at a water pressure head (Ψ) of 0 cm using a 0.25-m diameter tension disc infiltrometer (Perroux and White, 1988). In this case, the TDR instrumented Mariotte column used in the laboratory experiment acted as the water-supply reservoir. As in the laboratory, it was also equipped with a measuring tape and a calibrated single differential transducer. Prior to the infiltration measurements, the reservoir was filled with water in situ by closing both the air-inlet stopcock at the bubbling tower and the valve between the reservoir and the base of the disc (Fig. 1). Then, opening the air-outlet and water-inlet stopcocks at the top of the reservoir allows air to evacuate while water is poured in to rapidly fill the Mariotte reservoir. The base of the disc was covered with a nylon cloth of 20-μm mesh and a thin layer of commercial sand (80-160 μm grain size) poured onto the soil surface to ensure good contact between the disc and the soil.

For the imposed tension, and taking into account the infiltration surface area and the cross sectional area of the reservoir tube and that of the probe rods, the cumulative infiltration was calculated from water-level drop in the reservoir every 30 seconds by the visual, pressure transducer (PT) and TDR methods.

Prior to the infiltration test, a single TDR probe of three stainless steel rods (diameter: 2 mm; length: 100 mm; spacing for the outermost rods: 25 mm) was carefully inserted horizontally into the soil beneath the infiltrometer disc at a depth of 4 cm to monitor the volumetric water content of soil (θ) (Fig. 1). TDR measurements of both cumulative infiltration and θ were synchronously and automatically made using WinTDR'98 (Or et al., 1998). To this end, the two TDR probes were connected to a multiplexer (model SDMX50, Campbell Scientific Inc.).

With the aim of testing the suitability of the TDR technique against the more common gravimetric method of obtaining the final water content of soil below the infiltrometer, six additional infiltration tests were performed also at $\Psi = 0$ mm. At the completion of each test (steady-state infiltration rate), the volumetric water content of a surface soil core (50 mm in diameter by 50 mm height) was determined gravimetrically.

3. Results and discussion

Figure 3 shows the results of the laboratory experiment. There was an excellent correlation between visual measurements of water level height in cm (h_{VIS}) in the Mariotte column and simultaneous measurements obtained using either the pressure transducer (h_{PT}) ($h_{PT} = 0.994\ h_{VIS}$ - 0.578, $r^2 = 0.998$) or TDR (h_{TDR}) ($h_{TDR} = 1.006\ h_{VIS} - 0.279$, $r^2 = 0.999$).

The variability observed among TDR water level readings for a given height was very low, as reflected by an average coefficient of variation of 0.11% obtained in an additional experiment in which TDR measurements were made in triplicate at 19 reference heights.

The field experiment demonstrated the performance of the proposed TDR-based technique during a typical infiltration test under field conditions (Fig. 4a). Again agreement between the visual and PT and TDR methods was excellent ($h_{PT} = 0.971\ h_{VIS} + 0.531$, $r^2 = 0.999$; $h_{TDR} = 0.996\ h_{VIS} + 0.593$, $r^2 = 0.999$).

If either the standard deviation of the regression (SD) or the root mean squared error (RMSE $= \sqrt{\sum_{i=1}^{n}(h_{TDR,PT} - h_{vis})^2 / n}$) is taken as a measure of the dispersion between measured (TDR or PT readings) and reference (visual) water level values, the proposed TDR method appears to be slightly more accurate than the PT method. For the laboratory experiment (n=18), those parameters were lower for the TDR method (SD = 0.42 cm; RMSE = 0.41 cm) than for the PT method (SD = 0.46 cm; RMSE = 0.73 cm). This was also the case for the field experiment, where the SD and RMSE values (n=28) for the TDR technique were lower (SD = 0.25 cm; RMSE = 0.47 cm) than for the PT method (SD = 0.79 cm; RMSE = 0.73 cm). The standard error for the TDR measurements in the laboratory and field experiments was 1.0 and 0.5 mm, respectively. Thomsen et al. (2002) reported a standard error of 2.5 mm for a calibration experiment under laboratory conditions in which visual measurements of water depth were compared with measurements taken with their prototype of TDR water level probe.

The new automated TDR technique has certain advantages over other methods of measuring the water level change in the water-supply reservoir of tension disc infiltrometers. Firstly, the TDR water level reading is not subject to uncertainties arising from visual measurement errors due to parallax viewing and potential errors in recording the reading time. Secondly, since the proposed TDR method does not require a full calibration before its use in the field (only a measurement of ε_{air} and ε_{water}), errors associated to pressure transducer calibration are also eliminated. Moreover, since the TDR method is based upon measurement of the changes in the apparent dielectric constant (ε_{TDR}) of an air-water medium, its precision is not affected by pressure fluctuations due to bubbling.

A singular feature of the automated water level sensing method tested here is that TDR can be used for simultaneous recording of both water flow and transient volumetric water content of soil (θ) underneath the infiltrometer disc. Figure 4a shows the cumulative infiltration obtained in our field infiltration experiment using TDR and other methods for water level measurements and the change of θ measured during the infiltration run. This is particularly useful when inferring soil hydraulic properties using inverse parameter estimation techniques (Angulo-Jaramillo et al., 2000; Schwartz and Evett, 2002) that require not only accurate measurements of either transient or steady-state water flow but also the initial (θ_i) and the final water content of soil (θ_f) below the disc.

By using TDR to measure θ_i and θ_f, difficulties and errors associated with the conventional method of collecting soil cores to obtain the dry bulk density needed to convert gravimetric water contents into volumetric values are avoided. In our field experiment, the TDR-measured values of θ_i and θ_f were 0.093 and 0.415 $m^3 m^{-3}$, respectively (Fig. 4a). The θ_f value was consistent with the average figures obtained in the infiltration tests performed on six locations under the same soil surface conditions, in which no significant differences were found between θ_f determined by TDR ($\bar{\theta}_f = 0.403$ m^3 m^{-3}) and gravimetrically on undisturbed soil cores ($\bar{\theta}_f = 0.423$ m^3 m^{-3}).

Likewise, the proposed TDR method has proved to be satisfactory to estimate soil hydraulic properties from transient water flow data. Thus, soil sorptivity (S) for our field infiltration experiment (S = 0.641 mm s$^{-0.5}$) was estimated using the differentiated linearization method developed by Vandervaere et al. (1997) (Fig. 4b). According to this method, a saturated hydraulic conductivity (K) of 0.036 mm s^{-1} was calculated for our experimental soil from S and the TDR-measured values of θ_i and θ_f (Fig. 4b).

The new TDR application would be particularly suitable in studies where both hydraulic and solute transport properties in unsaturated soils are to be measured with tension disc infiltrometers at a large number of sites. While one TDR-based disc infiltrometer is automatically recording water flow at a site, a new measuring site can be prepared. Also, several TDR disc infiltrometers and TDR probes for measuring $\theta(t)$ below the disc can be multiplexed and programmed to run simultaneously by using public domain software for TDR system control such as WinTDR (Or et al., 1998) or TACQ (Evett, 2000). Finally, the TDR disc infiltrometer can be run at different tensions sequentially by refilling the water-supply reservoir with water or a tracer solution without removal of the infiltrometer from the soil surface.

4. Conclusions

Three major conclusions can be drawn from the study. First, the TDR technique developed for automated measurement of water level drop in Mariotte-type reservoirs is simple to use, easy to implement and provides an accurate alternative to visual or pressure transducer methods. Second, this technique can be used successfully with tension disc infiltrometers to obtain reliable estimates of soil hydraulic properties. Third, the new application allows for simultaneous TDR recording of both water flow and the transient volumetric water content of soil below the infiltrometer disc and the future possibility of integrating cumulative infiltration and soil moisture measurements into a single TDR system.

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Figure legends

Figure 1. Cross section of a tension disc infiltrometer configured with a TDR probe inside the water-supply reservoir.

Figure 2. Comparison of TDR signatures for the three-rod probe developed to measure water level changes in a Mariotte reservoir: (a) probe with uncoated rods and reservoir full of water; (b) probe with rods coated with polyolefin tubing and reservoir empty (I), half-full of water (II) and full of water (III).

Figure 3. Relationship between the water level determined using a TDR probe and a single differential pressure transducer (PT) and the water level determined visually in a Mariotte column 90 cm high under laboratory conditions.

Figure 4. Infiltration test performed with a tension disc infiltrometer on a recently tilled loamy soil at a pressure head, Ψ, of 0 cm: (a) cumulative infiltration (I) determined from TDR, pressure transducer (PT) and visual readings, and time curse of the volumetric water content of soil (θ) measured with a TDR probe horizontally installed under the infiltrometer disc at a depth of 4 cm; (b) soil sorptivity (*S*) and hydraulic conductivity (*K*) estimates from TDR-measured infiltration according to Vandervaere et al. (1997).

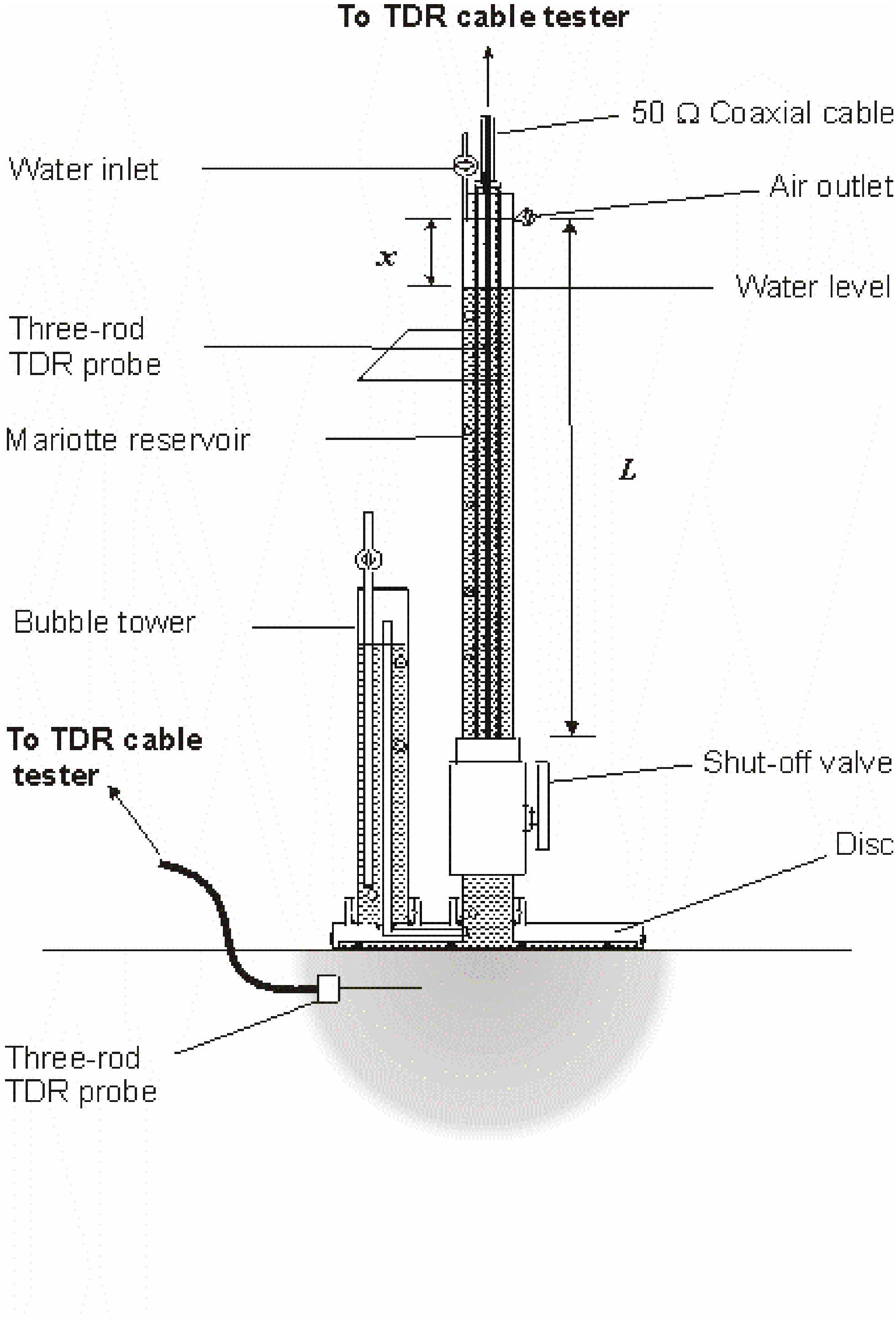
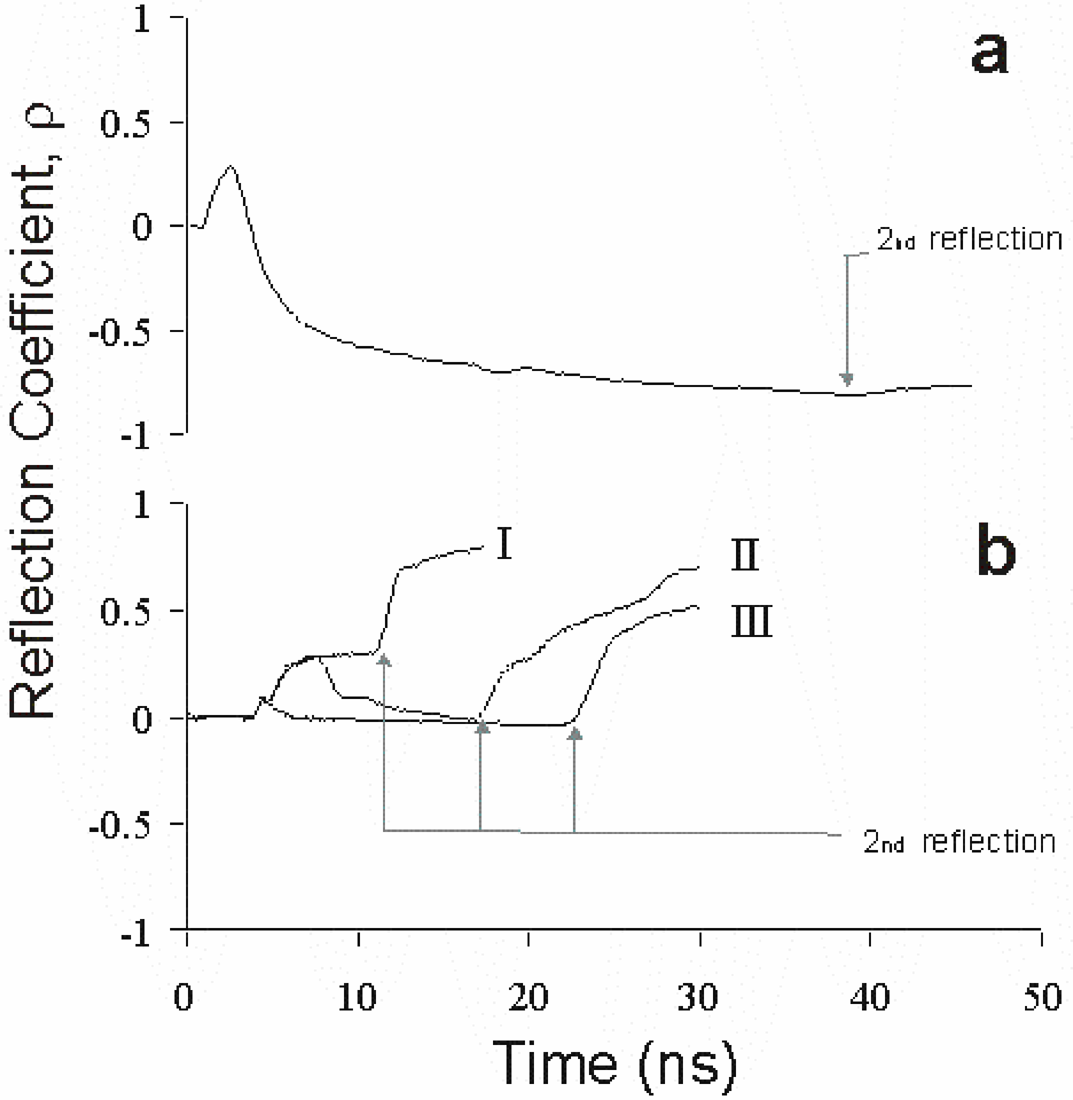

To TDR cable tester
50 Ω Coaxial cable
Water inlet
Air outlet
x
Water level
Three-rod
TDR probe
Mariotte reservoir
L
Bubble tower
To TDR cable
tester
Shut-off valve
Disc
Three-rod
TDR probe

Fig. 1 - Moret



a
b
I
II
III
2nd reflection
2nd reflection
Reflection Coefficient, ρ
Time (ns)

Fig. 2 - Moret

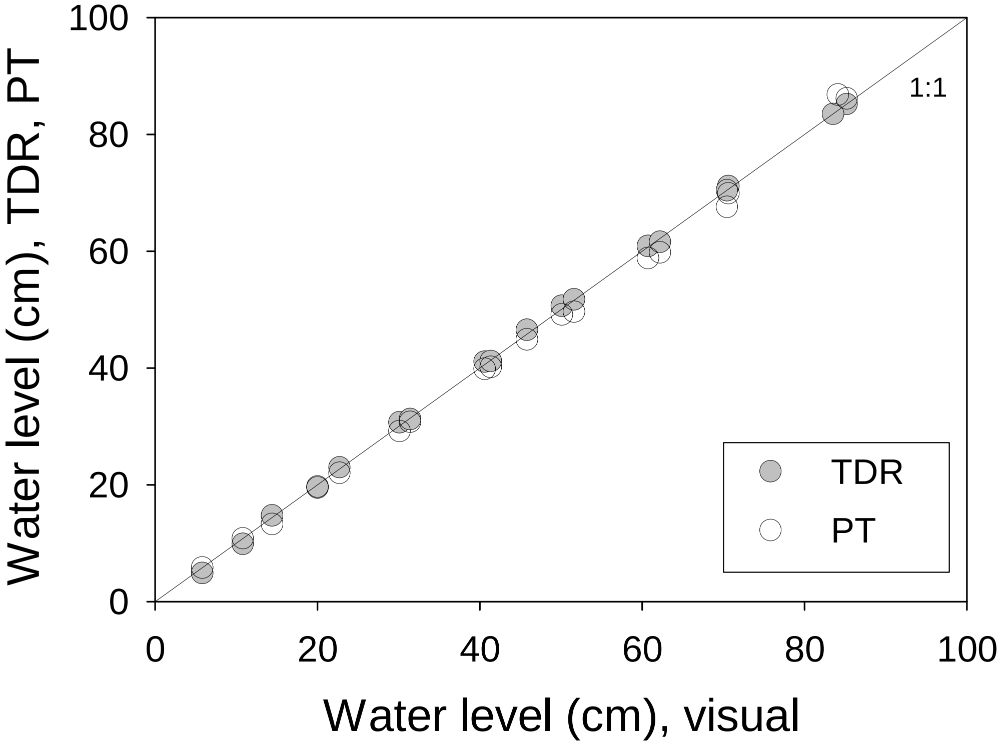
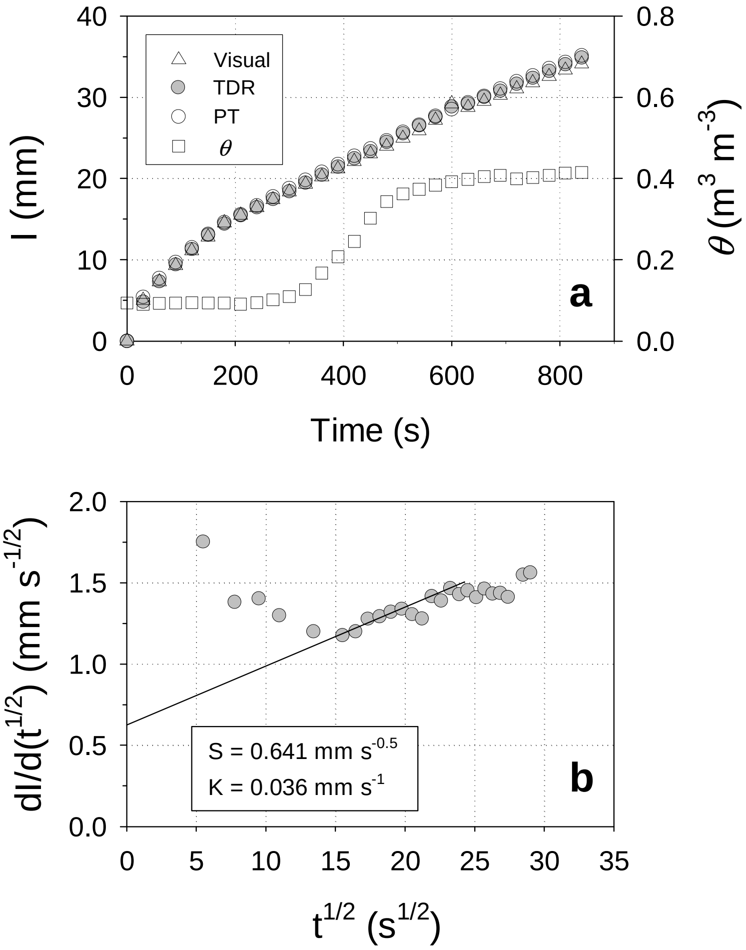

100
80
60
40
20
0
Water level (cm), TDR, PT
0
20
40
60
80
100
Water level (cm), visual
1:1
TDR
PT

Fig. 3 - Moret



Visual
TDR
PT
θ
I (mm)
θ (m3 m-3)
Time (s)
a
dI/d(t1/2) (mm s-1/2)
t1/2 (s1/2)
S = 0.641 mm s-0.5
K = 0.036 mm s-1
b

Fig. 4 - Moret