MONITORING NEAR-SURFACE SOIL WATER LOSS WITH TIME DOMAIN REFLECTOMETRY AND WEIGHING LYSIMETERS

by

Michael Howard Young

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As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Michael Howard Young

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and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy

P.J. Wierenga — Date: Nov. 8, 1995

A.W. Warrick — Date: 8 Nov. 1995

M.L. Brusseau — Date: 8 NOV 95

T.C. Yeh — Date: 11/8/95

L.G. Wilson — Date: 11/8/95

Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copy of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

Dissertation Director P.J. Wierenga — Date: Nov. 8, 1995

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SIGNED: Michael [signature]

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ABSTRACT

Three goals of this research were: 1) to develop a field-scale research facility that could be used for conducting a variety of soil water experiments in both deep (greater than 2 meters) and near-surface soils where the soil water balance could be accurately determined; 2) to develop a transient experimental technique for calibrating time domain reflectometry (TDR) probes; and 3) to study the use of vertically-installed TDR probes for measuring near-surface soil water movement in a field setting, and to compare these measurements with those made by the weighing lysimeter. The weighing lysimeter facility consists of two lysimeter tanks, 4.0 m deep and 2.5 m in diameter, which rest atop a scale with a resolution of ±200 g, equivalent to ±0.04 mm of water on the surface. Data collection is completely automated with a data logger and personal computer. Both lysimeters are instrumented with TDR probes, tensiometers, and pore water solution samplers; thermocouples are installed in one lysimeter for measuring temperature. The TDR probes were calibrated using a transient method known as upward infiltration. The method is rapid, allows the soil to remain unchanged during the experiment, and provides many data points. The upward infiltration method was tested using two different length probes in soils of three textures. Results show that the upward infiltration method is stable, repeatable, and provides accurate dielectric constants and calibration curves. Four, vertically-installed TDR probes of different lengths (200, 400, 600, and 800 mm) were placed in the lysimeter at ground surface to measure water added and water lost during a one-month period in the presence of daily

irrigated turfgrass. The purpose of this study was to compare changes in soil water storage as measured by the TDR system, against measurements made using the weighing lysimeter. The TDR probes detected diurnal changes in water content due to irrigation and evapotranspiration, even when these amounts changed slightly from day to day. The TDR probes underestimated the measurements of both water added and water loss, as confirmed using measurements from the weighing lysimeter. The presence of a 47-mm thick biomass above the TDR waveguides retained water that otherwise would have percolated the soil surface into the measurement domain of the probes. Addition and loss of water in the biomass were recorded by the lysimeter, but not by the TDR probes, thus explaining the underestimation. Modeling of near-surface water movement with the HYDRUS model showed very similar water movement behavior as measured by the TDR probes. This confirms our hypothesis that TDR would a useful tool for measuring diurnal changes in water content for irrigation scheduling.

CHAPTER 1

INTRODUCTION

Explanation of the Problem and its Context

A strong need exists for understanding subsurface processes that can affect the movement of water and solutes. Irrigation scheduling for agricultural purposes is strongly dependent on evaporation and transpiration processes. Waste containment requires the isolation of hazardous material from the outside environment. Water balance studies in the arid and semi-arid southwestern United States require a strong understanding of near-surface soil/water processes, as these affect deep recharge to the water table. However, to monitor changes in the soil water environment, we need to use monitoring systems that can sample conditions at a frequency much higher than the natural variations that we expect. Moreover, the physical system being monitored must represent the natural environment.

Development of monitoring systems during the last 20 years now allows the collection of data at short times. Most of the components in these automated monitoring systems use electrical responses to infer changes in soil conditions. Electrical responses can be monitored with data loggers and computer systems at times in the seconds, usually much shorter than necessary to study changes in environmental conditions. These systems give us a window through which we can observe subsurface processes that otherwise would not be possible.

Another challenge to understanding soil-water processes is 1) the need to obtain representative laboratory samples for property characterization, and 2) the subsequent extrapolation of property values from these small samples to the field scale. First, by collecting many smaller samples from the field, and analyzing them in the laboratory, we can evaluate soil material over a wider spatial area. The larger number of samples can enhance our understanding of significant spatial variability of property values. Moreover, laboratory experiments can be done under highly controlled environments, encouraging us to collect data and information that would be very difficult in the field. Smaller samples can be collected more easily, and laboratory experiments often can be conducted with less staff effort, than large-scale experiments.

Second, and contrary to that above, the collection of small samples often destroys subtle features that can greatly affect the soil property heterogeneity and soil-water movement; for example, root holes can become truncated, or distinctive layering can be missed altogether in smaller samples. Larger samples tend to include more of these heterogeneities. Thus, we question the use of small samples analyzed in the laboratory for predicting field-scale properties.

In summary, small-scale samples can be analyzed in controlled settings, but the results may not be applicable to the field. Large scale experiments, on the other hand, are more representative, but the experimental conditions are very difficult to control, leaving us with uncertainties that must be resolved through estimation. This dissertation is directed toward the development of a large-scale experimental facility that addresses these issues. Subsequent experiments are run to test the use of time-domain reflectometry (TDR) as a viable monitoring technique for measuring irrigation and water loss in an agricultural setting.

Explanation of Dissertation Format

The main body of this dissertation consists of three research papers which are appended to this dissertation. The first two papers describe experimental setups, one field and one laboratory, and the integration of these results into a third project. The first and third papers are the results of projects conducted at the Karsten Desert and Turfgrass Research Facility, Campus Agricultural Center, University of Arizona, Tucson, Arizona (hereafter called the Karsten Center). The second paper provides the results from laboratory experiments conducted on the University of Arizona campus, in the Department of Soil, Water and Environmental Science. All projects were conducted from early 1993 to the present.

The first paper (Appendix A) describes the installation, calibration and operation of the weighing lysimeter facility. It provides useful information on the goals of the facility, and the data acquisition system used to monitor water and tracer movement in the lysimeter tank. The author, working closely with his advisor, provided considerable input to the design of the facility before its construction. He collaborated with the architect who designed the facility housing, the manufacturer of the tank and scale system, and vendors who supplied equipment for data collection, much of which was designed specifically for this research facility. After installation of the lysimeter tank at the site, the author managed the installation of all soil and monitoring systems. Since Summer 1993, the author has been the principal scientist collecting, analyzing, and distributing all data collected. At the time of this writing, four professors and their graduate students, are using or have used data from the weighing lysimeter facility. The project described in Appendix A was supported in whole or in part by the Karsten Manufacturing Company, Phoenix, Arizona; grant number ES04940 from the National Institute of Environmental Health Sciences, NIH; and the United States Golf Association, Turfgrass Research Program.

The second paper (Appendix B) describes the development of a transient laboratory experimental system designed to calibrate time domain reflectometry (TDR) probes, which significantly reduced the time necessary to calibrate these instruments. Current methods of TDR probe calibration rely on single point measurements of dielectric constant in soil that must be repacked at progressively higher water contents. The author developed the experimental procedure based on the original development of the upward infiltration method by a former student who used the method for soil hydraulic property analysis. The author of this dissertation developed the experimental goals and hypothesis for using upward infiltration for TDR probe calibration. With the help of another doctoral student (J.B. Fleming) the author conducted a series of experiments that showed how upward infiltration could be used successively for probe calibration. Most of the data analysis and authorship of the paper are attributed to the author. Funding for the research presented in Appendix B was provided by the Water Resources Research Center, College of Agriculture, University of Arizona, Grant 104 Program.

The third paper combined the findings of the first two papers (Appendix C). The weighing lysimeter and TDR systems were integrated into a project, designed principally by the author, whose goal was to evaluate the use of vertically-installed TDR probes for monitoring turf water use. In this study, the author installed TDR probes vertically into the soil at both lysimeters, and monitored water content by the TDR. The water content data were converted to soil water storage by multiplying water content with TDR probe length. Changes in soil water storage due to irrigation and evapotranspiration processes, as measured by the TDR, were compared with changes in mass as measured by the lysimeter. A one-dimensional finite difference model was used to simulate the observed changes in water storage as measured by TDR. Water content data were collected, analyzed and managed by the author for more than 1.5 years, but data collected during a one month time period was used for intensive analysis and included in the appendix. Funding for the research presented in Appendix C was provided in part by the Water Resources Research Center, College of Agriculture, University of Arizona, Grant 104 Program; and grant number ES04940 from the National Institute of Environmental Health Sciences, NIH.

These papers, taken together, provide a unique contribution to the disciplines of soil science and, specifically, soil physics. The weighing lysimeter facility has already produced data for several research projects, with resolution that rivals experimental facilities that are much smaller. The proposed method of TDR probe calibration can reduce the time necessary to complete this task from several weeks to days. It provides comparable precision to the current state-of-the-art method, and can be used in light and heavy-textured soils. Finally, the results of the third paper show that vertically-installed TDR probes are useful for monitoring turfgrass evapotranspiration, and water applied to soil by irrigation or rain. It was shown that TDR can also be used for tracking water content in the surface soil and for automatic scheduling of irrigation events.

CHAPTER 2

PRESENT STUDY

Summary

The literature review, data, methods, results, discussion and conclusions of this study are presented in the papers appended to this dissertation. The following is a summary of the most important findings in these papers.

Three primary goals of the research described in the appended papers were: 1) to develop a field-scale research facility that could be used for conducting a variety of soil water experiments in both deep (greater than 2 meters) and near-surface soils where the soil water balance could be accurately determined; 2) to develop a transient experimental technique for calibrating time domain reflectometry (TDR) probes; and 3) to study the use of vertically-installed TDR probes for measuring near-surface soil water movement in a field setting, and to compare these measurements with those made by the weighing lysimeter.

Previously-constructed lysimeter facilities have been limited in their ability to monitor changes in soil conditions accurately, or in their size which do not simulate field-scale conditions. The design of the two large weighing lysimeters described in this dissertation is unique from other facilities in operation today. The diameter and depth (2.5 m and 4.0 m, respectively) are adequate to simulate field conditions. The lysimeters are contained in vertically-installed, 4.9 m diameter highway culverts that allow 360° access to the lysimeter tank. The scale, and accompanying loadcell, measure changes in mass to ± 200 grams, equivalent to ± 0.04 mm. Each lysimeter is equipped with 96 sampling ports for installing a variety of monitoring devices. Tensiometers with pressure transducers, temperature thermocouples, and loadcells are sampled regularly with a data logger (model CR-7, Campbell Scientific, Inc., Logan, UT). TDR probes are sampled using a personal computer and multiplexer.

Soil placed in the lysimeter was sieved, air dried, and compacted to a bulk density of 1.503 Mg/m^3 and 1.490 Mg/m^3, for the West and East Lysimeters, respectively. For approximately 11 months after facility installation, the soil cover was left bare. After the soil surface was planted with 'Tifway' bermudagrass *(Cynodon dactylon x transvaalensis var. Tifway)*, and irrigation occurred at regular intervals, the monitoring system was continuously expanded to track the wetting front as it progressed downward through the soil profile. The monitoring system showed that the wetting front was uniform in nature, migrating at approximately 10 cm/d until full turf cover was achieved; no preferential flow was detected during the initial wetting experiment. The results presented in Appendix A show that deep percolation was reduced from 35.6% during turfgrass establishment, to 10.3% after establishment. Though 852 mm of water were added to the lysimeter during the 155 days analyzed, only 273 mm of water percolated through the soil profile beyond the root zone. These results show the effectiveness of plant-root uptake in removing surface soil water.

Though field experimentation is invaluable for understanding large-scale processes, laboratory procedures also are necessary. Environmental factors that influence experimental results can be isolated and controlled, improving experimental efficiency. This idea directed us to improve the method for calibrating TDR probes. The more commonly used laboratory procedure requires the user to add a known amount of water to a soil sample, and pack the soil-water mixture into a column at a prespecified bulk density. We found the steady-state method of packing soil cores to be problematic and time consuming. The method is problematic because of difficulties in consistently repacking soil columns to the same bulk density each time the soil is repacked, leading to the possibility that the dielectric response will be affected by water content and bulk density. This method is time-consuming because the user has to allow the wetted soil to equilibrate overnight for each increase in water content.

The research presented in Appendix B describes a transient method of calibrating TDR probes. The method relies on the upward infiltration method, which requires the user to pump test solution into the bottom of a soil column filled with dry soil. The TDR probe is installed from the top of the column and thus intersects the wetting front as it moves upward. The method has many advantages; easier control of the lower boundary, shorter experimental times, collection of many data points using a computer, and a need to pack the soil column only once. Because the column remains unchanged during the experiment, the effects of variable bulk density on the dielectric constant need not be considered. To analyze the data, the mass of water added to the soil column was taken used to compute a weighted average water content. Dielectric constants obtained from the cable tester and computer provide the paired values needed for the calibration curve.

To show that this idea provides accurate dielectric constant-water content relationships for a variety of probe lengths and soil textures, waveguides were used with lengths of 5.5 and 20.0 cm. Three soils of varying texture were used: Vinton fine sand

(Sandy, mixed Thermic Typic Torrifluvent), Casa Grande sandy loam (Fine-loamy, mixed hyperthermic Typic Natrilargid [reclaimed]), and Pima silt-loam (Fine-silty, mixed [calcareous] Thermic Typic Torrifluvent). Three experiments were run for each combination of probe length and soil texture.

The results showed that the method can be used successfully to calibrate TDR probes in a much shorter time than necessary when using the steady-state packing method. Most of the experiments were completed in one day. We obtained approximately 80 and 260 data points for the 5.5 and 20.0 cm probes, respectively, more than otherwise could be collected. Though perfect reproducibility was not achieved for some combinations of probe length and soil texture, the standard error for estimating the volumetric water content was within 2% of the true water content, a value often used as a criterion for accuracy of the TDR method.

The TDR method resolves many difficulties experienced in other monitoring programs. However, TDR has not been tested under field conditions and compared with another independent method operating with the same sampling frequency and scale of measurement. In the study fully described in Appendix C, we combined TDR and deep weighing lysimetry, and compared the results of water additions and water losses against each another. Therefore, our objectives in this study were: 1) to automate the collection of both TDR and lysimeter data and directly compare changes in soil water storage measured with TDR against changes in water mass measured with the lysimeter; 2) to study the use of vertically-installed TDR probes to measure evapotranspiration (ET); and 3) to test the TDR system as a tool for scheduling irrigation for turfgrass.

Four vertical probes of length 200, 400, 600, and 800 mm were installed vertically in each lysimeter. A one-month period was chosen for studying TDR during active irrigation (16 June - 14 July 1995 (DOY 167-195)), and a one-week drydown period (21-29 August 1995 (DOY 235-242)). The results of the one-month study showed clearly that the TDR method measured diurnal changes in soil water content. A regular pattern of water gain with subsequent water loss was measured with no clear trend in soil water storage over the 28-day period. The response of the TDR system to individual irrigation events appears quite good, especially for the 200-mm probe. It was apparent that the 200-mm probe recorded lower water contents, and that the average water content of the soil profile increased when deeper soil was included. Daily fluctuations of volumetric water content measured with the 200-mm probe varied by 0.03-0.04 m^3/m^3. Longer probes measured consistently lower amplitudes of daily fluctuations, but they were still significant. The daily reductions in shallow soil water content were clearly a result of transpiration processes from the full turfgrass cover and soil evaporation.

Experimental results also showed that the TDR underpredicted the water added as compared with the lysimeter. This was true for all probe lengths. Examination of the probes after the experiment ended showed that the probe handles were at the original soil surface layer (to allow short mowing), but that 25 mm of grass mass (e.g., stolons, thatch) had accumulated above the handle. Since the handle is 22 mm high, the probes never measured the water accumulation in the upper 47 mm of the "soil" profile. A second explanation for the underestimation could be the condition of the turfgrass surface at the time of irrigation. We found that differences between water added as measured by the lysimeter and as measured by the TDR increased after the turfgrass was cut, showing that water entry into the soil profile was inhibited by shorter stands of turfgrass.

The TDR system measured water loss due to ET and deep drainage reasonably well. Shorter probes measured less water loss than the longer probes. The poorer fit for the 200-mm probe in both lysimeters reflected plant-root uptake occurring deeper than the shorter probes. The trend of increasing water loss measured by the longer probes can be explained by considering the root-zone distribution and downward drainage of irrigated water below the waveguides. The percentage of total root volume for bermudagrass was found by investigators, in other research plots at the Karsten Center, to be 62% in the upper 305 mm, 27% from 305 to 610 mm, and only 10% below 610 mm. If ET is proportional to root volume, then 60% of the water is taken up in the top 300 mm and 90% in the upper 600 mm. Minimal changes in soil water content were found at depths equal to and exceeding 500 mm, indicating the absence of plant roots and minimal root-water uptake. Water loss measurements as made by longer TDR probes (600 and 800 mm) were affected by the measurement of downward drainage. This was confirmed by subtracting the depth of water removed from the bottom of the West and East lysimeters through suction candles (61 and 43 mm, respectively), from water loss measurements made by the 800-mm probes. The differences between measurements made by 200 and 800-mm probes at the West and East Lysimeters, were within 1.5% and 8.7%, respectively, confirming that the longer probes are more significantly influenced by downward drainage. To determine what happens under a less frequent irrigation regime, we performed a drydown experiment for six complete days in the West Lysimeter during which time no irrigation occurred. We found that only 45% of total water loss originated from the top 200-mm of soil. The rate of downward drainage normally observed in the West Lysimeter (i.e., 2.17 mm/d), was reduced to 1.2 mm/d during the drydown experiment, as measured by the 800-mm probe.

The HYDRUS model (Kool and van Genuchten, 1991) confirmed several field observations made by the TDR system. The model successfully predicted that the amplitudes of diurnal water change decreased when deeper soils were included in the average, because the volumetric water content of the deeper soils did not change significantly. Model predictions of peak water contents in the top 200 mm were higher than observed for several days. This is due, in part, to 47 mm of plant and soil material existing immediately above the TDR waveguides, a layer not included in the computer simulation. Water loss measurements made by TDR also were closely simulated by HYDRUS. Particularly during the drydown experiment, the 800-mm probe measured water loss to within 2% of that predicted by HYDRUS. Shorter probes recorded less water loss because the upper soil layers became depleted in available water, reducing the water uptake rate from the shallow soil.

Conclusions and Recommendations

The main focus of the research presented herein was the use of TDR for measuring water use and water added on a field-scale weighing lysimeter planted with turfgrass. This project involved the design, installation and calibration of the lysimeter facility, and the design of a laboratory method for calibrating TDR probes. The results of these research tasks were combined into a third task that compared lysimeter-measured mass changes, and TDR-measured water content changes. The favorable comparisons between results of the TDR and weighing lysimeter systems showed that vertically-installed TDR probes can be used to measure evapotranspiration on the field scale. TDR also can be used to estimate downward percolation of water from the root zone into deeper soil profiles. These results support our conclusion that TDR would be a useful monitoring tool for scheduling irrigation events on the field scale.

The next step in this study will be to install a remote TDR system in a plot next to the lysimeter and use it to monitor soil water content and trigger irrigation events. The results presented in Appendix C show that TDR probes need to be sampled only twice per day (at or near sunrise, and after sunset) to measure total water loss from the root zone; moreover, they can be sampled once per day to evaluate if the water content has fallen below a pre-designated lower limit, initiating an irrigation event. The results of this work also support the use of TDR for monitoring water content in other field situations, where the upper limits of acceptable water contents are specified by regulatory agencies.

APPENDIX A:

Large weighing lysimeters for water use and solute transport studies

M.H. Young[1], P.J. Wierenga[1], C.F. Mancino[2]

[1] Department of Soil, Water and Environmental Science, The University of Arizona, 429 Shantz Bldg., #38, Tucson, AZ 85721, USA e-mail: youngmh@ag.arizona.edu
[2] Department of Agronomy, The Pennsylvania State University, University Park, PA

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ABSTRACT

Two weighing lysimeters were installed at the University of Arizona's Karsten Center for Turfgrass Research. The goals of the facility are to accurately measure evapotranspiration (ET), and to facilitate soil water and solute transport experiments in a deep soil profile. Each tank is 4.0 m deep, 2.5 m in diameter, and equipped with 96 sampling ports for soil solution samplers, tensiometers, TDR probes, and thermocouples. A single neutron probe access tube was installed in the center of each lysimeter. The weighing scales have a capacity of 45 Mg, and can detect a 200-g mass change, equivalent to ±0.04 mm of water on the surface. The lysimeters were filled with Vinton fine sand (sandy, mixed Thermic Typic Torrifluvent). The air dry soil, which had a gravimetric water content ranging from 2.2 to 4.6%, was sieved through a 2-mm screen and compacted to a uniform bulk density of 1.5 Mg/m^3. Data are collected with a Campbell Scientific, Inc. datalogger (model CR-7), and a personal computer that operates the TDR cable tester and multiplexer. A central vacuum manifold connects 24 stainless steel and 18 ceramic solution samplers, so that samples are collected simultaneously. In May 1994, the lysimeter surfaces and surrounding area were planted with 'Tifway' bermudagrass (*Cynodon dactylon x transvaalensis var. Tifway*) and irrigation began. Irrigation application during establishment approached 110% of the true ET measured with the lysimeter. The data acquisition system was useful in determining the migration and uniformity of the wetting front depth. The advance of the wetting front was first detected by neutron probe, then by TDR, and finally by tensiometry. These differences are related to the sphere of influence of these devices.

INTRODUCTION

Lysimetry has been used since the late 19th century to research water use by vegetation, and water quality. Weighing lysimeters -- essentially soil tanks resting on scales -- have become valuable tools for agronomic research, because they allow direct measurements of changes in mass that can be attributed directly to plant water use. Non-weighing lysimeters are frequently used to study water movement in shallow soil profiles and recharge in deep soil profiles (e.g., Gee et al., 1994). However, without weighing mechanisms, recharge can only be quantified by measuring changes in water content. The ability to measure changes in lysimeter mass provides a more accurate measure of water use and recharge.

Several weighing lysimeter systems are in use today for a variety of purposes (see as examples, Pruitt and Angus, 1960; van Bavel and Myers, 1962; Kirkham et al., 1984; Dugas et al., 1985; and Marek et al., 1988), though the majority are designed to measure plant water uptake. They have found that carefully matching the weighing and recording systems improves the accuracy of mass-change measurements, which normally are between ± 0.02 - 0.05 mm water depth. However, a drawback to most lysimeter facilities is that they are too shallow for studies of water movement and solute transport in deep soil profiles. For example, of 23 different weighing lysimeter systems summarized by Marek et al. (1988), only two of these systems used tanks that were deeper than 2.0 m. Dugas et al. (1985) describe one system 2.5 m deep, and Harrold and Dreibelbis (1958) describe another system at 2.4 m deep. Neither of these facilities appear to consider deep soil water processes.

To improve the understanding of consumptive water use by turfgrasses in the semi-arid Southwestern US, and to study water movement and percolation of chemicals in soil, two deep weighing lysimeters were built at the University of Arizona Karsten Laboratory and Desert Turfgrass Research Facility (hereafter referred to as the Karsten Laboratory). The lysimeter construction lasted from late-1992 through mid-1993, after almost three years of design and planning. The main criteria were to design a facility to measure evapotranspiration (ET) with a resolution of ± 0.04 mm; to perform soil water and solute transport experiments, which could be conducted simultaneously with little to no adverse impacts to the ET measurements; and to design an automated weighing and measurement system that could provide data at time intervals of 10 minutes or less. In order to study water and solute movement, in addition to plant water uptake, our lysimeters are 4.0 m deep.

This manuscript describes the design and installation of two weighing lysimeters. It describes how the soil was treated and placed in the lysimeter, the soil monitoring system, and the scale calibration. We also provide results of the first experiment in which we track the wetting front during turfgrass establishment using a variety of monitoring devices.

MATERIALS AND METHODS

General Facility Description

The lysimeter facility is located at the Campus Agricultural Center (CAC), a 42.5 hectare experimental farm located in Tucson, Arizona. CAC provided about 0.1 hectares for the lysimeter facility and support area, including the irrigation system for the turfgrass plot. The support area was excavated to a depth of about 7.6 m, where concrete pads 0.75 m thick were constructed. Three pads were installed, two for immediate use, and a third for future use (Figure 1).

An irrigation system (courtesy Rainbird Golf Division, Glendora, CA) was designed and installed during Winter 1993 that could accommodate both effluent (reclaimed wastewater from the City of Tucson treatment plant) and potable water supplies. This double system was necessary because switching from effluent to potable sources using the same pipes is against code. We also needed the flexibility to switch water sources depending on experimental design. Currently, effluent water is used for the area surrounding the lysimeters. These perimeter sprinklers were directed away from the lysimeters to minimize possible drift onto the lysimeters. Potable water is used for the areas adjacent to the two lysimeters. Frequent, short duration irrigation cycles are used for these areas because the grasses are relatively short rooted. A total of four, low-trajectory, 4.6-m, 1/4-arc, sprinklers, spaced at 3.7 m, were installed for direct irrigation onto each lysimeter. This allows us to isolate the areas being irrigated.

A number of safety mechanisms have been incorporated into the design. A wind-speed sensor (model WA-21 Duel Set Point Wind Alarm, Weatherport, Grass Valley, CA[1]) was installed to ensure that irrigation did not occur if the wind speed exceeded 1.78 m/s for greater than 55 consecutive seconds. One master and one slave valve

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[1]The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by The University of Arizona or The Pennsylvania State University.

were installed in series at each lysimeter in case one valve failed. A third master valve connected to a latching solenoid shuts down the main line for the entire plot if more than 120 kg of water mass is added to either the East or West Lysimeter in a 6 h period. Thus, if large precipitation events occur, or if the valves fail, the irrigation system goes off-line.

Approximately 15 m south of the lysimeters, a series of weather towers were installed. One tower measures atmospheric conditions for controlling irrigation scheduling for the lysimeter area and the surrounding turfgrass research area. This tower is equipped to measure rainfall, solar radiation, relative humidity, and wind speed. Data are downloaded to a computer program (Maxi, ver. 4.5 r, Rainbird Golf Division, Glendora, CA) that calculates daily reference evapotranspiration using a modified-Penman Equation developed by Rainbird Golf Division. The second and third weather towers are operated by the Arizona Meteorological Network (AZMET), part of the University of Arizona Agricultural Extension Services. The dataloggers are connected to the main campus via phone lines, where data can be downloaded daily. The weather instruments consist of fine-wire thermocouples, anemometers, net radiometer, two Eppley pyrometers, and a Vaisala temperature/relative humidity gauge. These instruments are located at various heights above the soil surface. Intensive data collection began 24 July 1994. Data are collected with two Campbell CR-10X dataloggers every 10 seconds and averaged every ten minutes.

The fine-wire thermocouples measure air temperature at heights of 1, 2, and 3 meters, as do the anemometers to measure wind speed. The net radiometer measures net radiation (NR) 1 meter from the soil surface. The Eppley pyranometer measures incoming (SRi) and outgoing (SRo) short-wave radiation, with pyrometers installed 0.8 and 1.0 meter from the soil surface, respectively. Soil temperature (ST) and soil heat flux (SHF) are measured at 4 cm below ground, directly beneath the net radiometer. Finally, a Vaisala combination temperature and relative humidity (RH) gauge is located 2 meters from the soil surface. The temperature and wind speed at 2 meters, RH, SRi, and NR values are used in the calculation of reference evapotranspiration. These data are then compared to the lysimeter responses.

Facility Installation and Design

Once the concrete pads were prepared, corrugated highway culverts were lowered into the excavated area. Highway culverts were chosen as the primary building material because of their strength and low cost. Culverts of 4.9 m diameter were installed vertically onto each concrete pad, bolted into place, and sealed with high-density polyethylene liner and waterproofing tar to prevent leakage of water into the lysimeter room. Horizontally installed culverts of 2.44 m diameter were used for the entrance and connecting tunnels to each lysimeter. The entrance into the facility slopes toward ground surface. A stairway, similar to those used on seagoing vessels, provides access into and out of the facility. All connections between the horizontal and vertical culverts were weatherproofed using flexible membrane liners and sealer. Soil around the culverts was compacted at 95% standard Proctor bulk density to prevent settling.

The facility was designed with two important aspects in mind. First, to avoid the need for extra reinforcement, and to more closely approximate 1-dimensional water flow during infiltration, the lysimeters and surrounding culverts are cylindrical. Second, because the lysimeters and housing are cylindrical, 360° access is possible. Access to the entire facility allows us to monitor soil conditions anywhere in the lysimeters. Moreover, 360° access allows us to observe directly whether water is being released from the lysimeter into the room. The ability to monitor conditions around the entire lysimeter is particularly useful, given that a future lysimeter, planned for Fall 1995, will be used for studying remediation schemes for organic solvents and heavy metals.

Each lysimeter room is fully equipped with telephone and data lines, electricity, and potable and effluent waters. Two hydraulically isolated sump systems were installed at the facility. The first system was designed to drain both precipitation and irrigation waters that enter the facility from the stairwell. A small drain is in front of the entrance. The second system is designed to contain and remove potentially hazardous waters that drain from the lysimeters, and is connected to drains located in each lysimeter room.

The scales (model FS-8, Cardinal Scale, Webb City, MO) were assembled by Precision Lysimeters, Inc. (Red Bluff, CA), who also aided in lysimeter and scale system design. The scales are modified truck balances, outfitted with a weigh beam that connects to both a manual weight indicator, and an electronic loadcell with a 45-kg capacity (model Z-100, Cardinal Scale, Webb City, MO). The scale system has a maximum load of 45 Mg and a precision of ±200 g. Figure 2 provides a cross section of an individual lysimeter and weighing system.

The walls of the lysimeters are made of 6.4-mm thick steel plate, and the base plate is 12.7-mm thick. Before lowering the lysimeters into the ground, the inside surfaces were spray coated with Nucrel™ (DuPont, Wilmington, DE). Nucrel™, a highly inert material similar to Teflon™, was used to protect the steel lysimeter surface from corrosion. To seal off the lysimeter room from the outside, an outer ring, called a ring flashing, was lowered around the lysimeter and bolted to the concrete ceiling. Ripstop nylon was wrapped over the 1-cm free space between the outside of the lysimeter and the inside of the ring flashing. The nylon was designed to prevent grass clippings and debris from becoming lodged in the free space.

The Vinton fine sand (sandy, mixed Thermic Typic Torrifluvent) was chosen for use in the lysimeter facility. The Vinton soil is 90% sand (35% fine sand, 35% medium sand), 7% silt, and 3% clay. The saturated hydraulic conductivity was measured to be 175 cm/day. Unsaturated hydraulic parameters were obtained using the method of Hudson et al. (1994), and were found to be $\alpha = 0.0309\ cm^{-1}$, n = 2.094, m = 0.666, θ_s = 0.410, $\theta_r = 0.0311$, and fitted $K_s = 1.931 \times 10^{-3}$ cm/s, as defined by van Genuchten (1980). Approximately 140 m^3 of the Vinton fine sand was collected in May 1993, stockpiled adjacent to the borrow area, and allowed to dry. The soil was then transported to the Karsten Laboratory and sieved through 6.4-mm mesh screen. The soil was stored until placement in the lysimeters.

Soil packing began 1 June 1993 by sieving the soil through a 2-mm mesh screen, mounted on a large highway sieve. The soil was sieved directly into steel drums (208 L volume) fitted with trap doors on the bottom and eye hooks on the top. A boom truck was used to lower the drums into the lysimeter, where the trap door was opened and soil released in the lysimeter. Each drum contained about 285 kg of soil. Between two and three drums of soil were added to the lysimeter for each soil lift, which was about 7.6-cm thick.

To pack the soil in each lift to a bulk density of 1.5 Mg/m^3, the mass of air dry soil for each lift was measured with the lysimeter scale, and the gravimetric water content was determined by drying a representative subsample from each drum. The oven-dry soil mass was then calculated, and used to determine the lift thickness. The target depth of the soil surface was measured accordingly, and the inside of the lysimeter was scribed with a marking pen to ensure an accurate lift thickness. The soil was manually compacted until the necessary thickness was achieved.

At the 375-cm depth level, six suction candles (2.54-cm outside diameter (OD), 61-cm long stainless steel tubes (Soil Measurement Systems, Tucson, AZ)) were installed to maintain unsaturated conditions after the wetting front reached the bottom of the lysimeter. The candles were connected to large plastic containers mounted on the lysimeter; thus, drainage water flowing into the containers does not change the total mass of the lysimeter. The containers were in turn connected to a central vacuum system. Once a week, the plastic containers are drained manually, and measured volumetrically. The mass of drainage water removed is then added back to the total water change measured during the week to complete the mass balance.

Monitoring instruments were installed at 50-cm depth increments as the soil was being placed in the lysimeter. Generally, three of the same instruments (TDR probes, stainless steel and ceramic solution samplers) were installed per depth increment, from 100-cm deep to 350-cm deep. Figure 4 is a diagram of port locations and designations. Devices were installed as the soil was placed in the lysimeter (Table 1) so that the exact depth and final condition of the samplers would be known.

Soil installation was completed on 30 June 1993. The final bulk densities were very close to the targeted values of 1.5 Mg/m^3 (Figure 3). Average densities were calculated to be 1.490 Mg/m^3 and 1.503 Mg/m^3 for the East and West lysimeters, respectively.

On 3 June 1994 (Day of Year (DOY) 155), after preparing the study plot and installing the irrigation system, the lysimeter and surrounding areas were planted with 'Tifway' Bermudagrass (*Cynodon dactylon x transvaalensis var. Tifway*). Potable water application occurred five times per day to prevent exposed stolons from drying out and to encourage rooting. As establishment continued, irrigation became less frequent but of longer duration. Eventually, irrigation was scheduled once a day in the late afternoon or evening, when prevailing westerly winds were calmer.

Instrumentation and Data Acquisition

TDR probes are installed at six depths in the East Lysimeter and seven depths in the West Lysimeter; both lysimeters have three probes per depth. The TDR probes (Vadose Zone Equipment Corp., Amarillo, TX) are connected through RG 58/U, 50Ω coaxial cable, to a multiplexer (JFW Industries, Indianapolis, IN), which in turn is connected to a TDR cable tester (model 1502C, Tektronix Corp., Beaverton, OR). The

TDR probes consist of three 0.3-cm OD waveguides, which are 20-cm long and spaced 3.0 cm apart. Vertical probes, placed in both lysimeters after the soil was installed, have four lengths: 20, 40, 60, and 80 cm. Probe calibration was completed as described elsewhere (Young et al., 1995, Soil Science Soc. Am. J. Submitted). We calculated the sphere of influence to be 3 cm above the probe, using the method of Knight (1992).

The TDR cable tester is connected to the serial communications port, and the multiplexer is connected to the parallel port, of a personal computer which runs a computer program written in a hybrid C/QuickBasic language (LabWindows, version 2.3, National Instruments, Austin, TX). The program collects the TDR trace, analyzes it for electrical length and the impedance, and calculates the volumetric water content and bulk electrical conductivity of the soil.

Stainless steel solution samplers were constructed from 30.5-cm long, and 2.54-cm OD porous stainless steel tubing (Soil Measurement Systems, Tucson, AZ). Two 0.6-cm stainless steel tubes were welded into the top cap of each sampler for vacuum control and fluid drainage. The samplers were constructed with a single chamber and had a relatively uniform bubbling pressure of about 20 kPa. Ceramic solution samplers were constructed from 30.5-cm long 2.54-cm OD ceramic tubes (Soil Moisture Equipment Corp., Santa Barbara, CA), with nylatron tubing and end pieces. The stainless steel and ceramic samplers were installed about 15 to 20 cm from each other at the same depth, about 45 cm from the inside of the lysimeter wall.

A total of six wick samplers (courtesy Dr. John Selker, Department of Bioresource Engineering, Oregon State University, Corvallis, OR) were installed in the

West Lysimeter. No wick samplers were used in the East Lysimeter. These devices are passive-capillary samplers that use hanging fiberglass wicks to create a capillary potential gradient (Holder et al., 1991; Boll et al., 1992). The wick material (Amatex, 9.53-mm OD, high density, (as described by Knutson and Selker, 1994)) was unwoven at the upper end and attached to a stainless steel plate 30.5-cm long and 2.54-cm wide. The remaining length of the wick was inserted through a hole in the plate and into a 1.91-cm OD stainless steel tube. The tube had two 90° bends so that it could be fed through the sampling port and extended downward to a vertical drop of 150 cm.

Tensiometers and temperature thermocouples were installed after completion of soil packing. The tensiometers were constructed using 7.6-cm long, 1.25-cm OD, 100-kPa, high flow, porous ceramic cups (Soil Moisture Equipment Corp.). The cups were attached to translucent polycarbonate tubing with epoxy. The tensiometers were installed 25 cm from the lysimeter wall, and were equipped with pressure transducers (model 136PC15G2, MicroSwitch, Freeport, IL) fitted into the elbow. The top of the tensiometer was sealed with a septum stopper to independently measure the tension with a hand-held pressure sensing device (Tensimeter, Soil Measurement Systems, Tucson, AZ). Tensiometer cups have an effective sampling volume that is much smaller than either the neutron or TDR probes. The relatively small ceramic cups (7.62-cm long, 1.27-cm OD, 34.35 cm^2 effective surface area) were shown by Hendrickx et al. (1994) to have a response time that is slower than if larger cups had been used.

The temperature thermocouples were installed in the West Lysimeter only, due to the close proximity of this lysimeter to the datalogger. The thermocouples were constructed using 24-gauge copper-constantan wire (model TT-T-24, Omega Engineering, Inc., Stamford, CT) inserted into a 3.2-mm OD stainless steel tube and epoxied closed. Individual thermocouples were installed at depths of 0 (ground surface), 1, 5, 10, 25, 50, and 100 cm. All thermocouples, with the exception of the 50-cm unit, were installed horizontally. The 50-cm unit was installed vertically

To monitor potential soil settling, a stainless steel mesh (T.A. Caid, Tucson, AZ) attached to steel cable was used as a compaction gauge. Three gauges were used in each lysimeter. The meshes were placed at 1.5, 2.5, and 3.5 m depth, 0.66 m from the lysimeter walls. The steel cable was extended 0.50 m up in the profile, where it was threaded through a sampling port and allowed to hang freely. The steel cable was marked off in 1-cm increments, beginning immediately outside the lysimeter. The cable was checked periodically to see if the mesh was being pulled down with the soil as it settled. Any displacement of the cable could be used to calculate vertical settling of the soil profile.

A stainless steel neutron probe access tube (5.72-cm OD) was placed in the center of each lysimeter during filling. Periodically water content information was collected from both lysimeters using a neutron moisture meter (model 503 DR, Campbell Pacific Nuclear, Pacheco, CA). The neutron probe has, in this case, the highest spatial frequency with depth (15 points per lysimeter), the lowest temporal sampling frequency (usually seven days), with a relatively large soil sampling volume. The sampling radius for the neutron probe is between 15 and 35 cm (de Vries and King, 1961). A two-point calibration curve was generated *in-situ*.

A model CR-7 datalogger (Campbell Scientific, Inc., Logan, UT) was used to measure all electronic sensing devices installed in the West Lysimeter (except for TDR) and the loadcell used in the East Lysimeter. A total of two loadcells, 18 pressure transducers, and eight thermocouples are sampled by the datalogger. The 10-minute readings of water use (mass loss) and recharge (mass gain) for both lysimeters are compared to evapotranspiration estimates from the AZMET station described above.

Scale Calibration

Both scales were calibrated manually and electronically after soil packing. Manual calibration was carried out by adding a known mass to the lysimeter surface and recording the weight change from the scale. The electronic loadcell was calibrated both by hanging a known mass directly on the device, and by connecting it to the scale and adding mass to the lysimeter.

We calibrated both scales using mass increments from 200 g to 227 kg. The purpose was to determine the variability of readings for different mass increments, and the characteristics of the calibration equations for the loadcells. Hysteresis in the measurement system also was determined. To account for the effects of wind, data collected for calibration were averaged over several minutes. A tarpaulin was placed over the soil surface to reduce any potential soil evaporation.

Figure 5 provides the results of the calibration performed during Summer 1993, the last of three full calibration tests. Results show excellent linearity of the calibration data ($r^2 \geq 0.999$ for all cases) with virtually no hysteresis. We found slightly higher variability of measurements when using the smaller mass increments, likely caused by random electronic noise. During the past 18 months, the system has been calibrated three times. We currently use the average of all calibration coefficients.

A water balance method was used to track recharge and water use in the lysimeter. The simple water balance equation (P-ET = ΔS) assumes no runoff. P is measured as precipitation plus irrigation (any mass gain). ET is evapotranspiration and is calculated by summing the reductions in mass (converted to equivalent water depth) caused by evaporation and transpiration. ΔS is the change in soil water storage, or the difference between P and ET.

RESULTS AND DISCUSSION

The following results concentrate on West Lysimeter data only, given the presence of pressure sensing devices on the tensiometers and extra TDR probes located at the 50-cm depth.

Figure 6 shows the water budget for the first 155 days following planting (hydrosprigging) and the onset of irrigation. The data shown were plotted using hourly time intervals. The graph shows that for the first seven days most water applied to the lysimeter recharged the soil profile. Afterwards, the turf became more established and the ET rate increased. Three distinctly different phases of turf water use can be observed from the figure during the first 155 days of turf establishment. The first phase occurred from DOY 170 to 210, the second occurred from DOY 220 to 280, and the third occurred from DOY 290 to the end of record. Linear regressions performed for the depth of ET of these three phases yielded ET values of 2.83, 5.48, and 1.65 mm/day, respectively.

Phase 1 corresponded to turf establishment, with a low ET rate averaging 2.83 mm/day. Given that potential ET for this time period is 8 to 9 mm/d (as calculated from the AZMET data), this shows that soil surface evaporation was less than potential and that the surface may not have been moist enough to encourage root penetration. This could account for the slow rate of establishment observed with the bermudagrass. The Vinton sand has a very low water holding capacity and drains fast, which caused less than optimal moisture conditions near the surface for initial plant establishment. These results indicate that more frequent, shorter duration irrigation cycles would have led to better turf growth.

Phase 2 corresponded to the time period when full turf ground cover exceeded 80%, and the average ET rate increased to almost 5.5 mm/day. Figure 6 shows very little change in storage (3.3 cm) during this 60-day period; the total precipitation and ET were observed to be 35.2 and 31.9 cm, respectively. Over-irrigation by 10% was deliberate to prevent salt accumulation in the soil.

Phase 3 began on 29 September 1994 (DOY 290), after the lysimeters were overseeded with 'Froghair' intermediate ryegrass *(Lolium multiflorum x perenne)*. An ET rate of only 1.65 mm/day was measured during this phase. A large increase in water storage occurred during the first 10 days of this phase, because irrigation rates were increased to encourage dominance of the ryegrass over the bermudagrass.

The ET rates, measured with the lysimeter, were compared to the reference ET (ETO) calculated from the AZMET station. The direct comparison allowed us to study the accuracy of the ETO equation used in Arizona. The data can also be used to calculate crop coefficients for the bermudagrass and ryegrass species, an important issue in the State of Arizona where essentially all turf is irrigated. Figure 7 shows lysimeter ET and AZMET ETO for three days in September 1994 (DOY 250-252). The graph shows excellent correlation between the lysimeter-measured ET rate and the AZMET ETO. ET values were 6.12, 6.60, and 6.04 mm for the three days shown. ETo values for these days were 7.04, 7.20, and 5.85 mm, respectively. The ET and ETO values were used to calculate crop coefficients of 0.87, 0.92, and 1.03 for these three days. Because the ETo estimates evapotranspiration on a well-watered, full-cover, cool season grass surface, values less than one are expected. On 9 September, when the crop coefficient was greater than unity, we noted that strong winds were recorded after sunset. Average wind speeds between the hours of 18:00 - 22:00 were recorded to be 4.88 m/s, significantly higher than the monthly average for this time (1.73 m/s).

Figure 8 provides neutron probe water content profiles for five different days after the start of irrigation. The data show that the highest water contents were observed soon after the wetting front had migrated through a particular depth; as internal drainage occurred, the water content started to decrease (see especially DOY 211). The high variability of water content near the soil surface was due to evaporation and recharge processes, which dominated in the near-surface environment. Deeper in the soil profile, where evaporation was less significant, water contents approached steady state levels but still showed the effects of internal drainage.

We compared the behavior of the neutron probe and TDR system during this infiltration event. Figure 9 compares water content profiles as measured by the neutron and TDR probes. These devices clearly show the position of the wetting fronts for both days. The TDR readings taken ahead of the wetting front were essentially below the range of calibration; so, the dashed line corresponds to the volumetric water content of the soil at the time of packing. Though the trends in water contents are the same between the two devices, the TDR recorded slightly higher water content values than the neutron probe.

To obtain the equivalent water depth in the West Lysimeter, we integrated the water contents with respect to depth for the two days used in Figure 9, and found that the TDR system estimated only 0.94% more water than the neutron probe on DOY 168 (34.4 cm versus 34.1 cm, respectively) and only 1.22% more water on DOY 196 (41.2 cm versus 40.1 cm, respectively). The increase in water storage of the lysimeter also was measured through changes in lysimeter mass (Figure 6). Between DOY 168 and 196, the lysimeter mass increased by 4.93 cm. This is less than the 6.54 cm, and 6.72 cm increase measured with data from neutron and TDR probes, but still within the uncertainties of the indirect methods.

Data from the TDR probes and tensiometers, installed in the NE and SE ports of the West Lysimeter, are presented in Figure 10. The graphs show that the wetting front arrival near the soil surface, as signaled by increasing matric potential and water content, occurred almost simultaneously. As the wetting front migrated downward, arrival times became less uniform and the NE area of the lysimeter wetted more quickly than the SE area (Figure 10F). Thus, though the soil was uniform in texture and bulk density, a non-uniform wetting front was observed. The TDR device detected the wetting front consistently earlier than the tensiometers for each set of monitoring devices and each depth. We attribute this to an effective sampling volume that is larger for the TDR probes than for the tensiometer cups. The tensiometer cups have a much smaller surface area and, consequently, a smaller sampling volume. Comparing the results in Figure 10, for almost every depth, the arrival time of the wetting front was sooner for the device with the larger sampling volumes (e.g., TDR probe > tensiometer). Thus, based on the findings described above and the data observed in this study, we believe that the sample size and effective surface area can explain some differences in response time between the TDR probe and tensiometers.

CONCLUSION

The precision of the lysimeter facility allowed us to observe subtle changes in turf water use throughout three phases of turf growth: from turf establishment to overseeding. The direct measurement of ET, using the lysimeter, significantly reduced the error associated with performing a water balance study that derives ET by the difference between measured precipitation and predicted infiltration (i.e., increase in water storage). The monitoring devices also allowed us to determine the position and velocity of water percolating below the root zone.

The depth of the lysimeter, which is greater than other weighing lysimeter facilities, was advantageous to this study. By tracking the wetting front through the deeper profile, we observed relatively uniform flow processes throughout most of the cross-sectional area of the lysimeter. Unstable infiltration was not found to be significant during this experiment. The development of a dry spot near the western edge of the West Lysimeter likely is explained by drift of irrigation water due to prevailing westerly winds. Shallower lysimeters would have made observations like these difficult, if not impossible. The results provided in this report show that we can monitor very slight changes in flux through the soil surface.

The flexibility to add new monitoring devices, and to conduct separate experiments above and below ground, gives us a unique opportunity for conducting comprehensive studies of near- surface and deep profile processes.

<u>Acknowledgments</u>

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Table 1. Number of devices installed in each lysimeter.

	Number devices installed	
Device	East Lysimeter	West Lysimeter
TDR probes	22	25
stainless steel solution samplers	24	24
ceramic solution samplers	21	21
wick samplers	0	6
temperature thermocouples	0	7
compaction gauges	3	3

Captions to Figures

Figure 1. Map View of lysimeter facility.

Figure 2. Cross-section of tank and scale systems.

Figure 3. Bulk density profiles for East and West Lysimeters.

Figure 4. Map view of lysimeters, with sampling port locations and designations.

Figure 5. Results of lysimeter calibration - Summer 1993.

Figure 6. Graph showing the water budget for the West Lysimeter during initial infiltration.

Figure 7. Comparison between ET measured with the West Lysimeter, and ETo measured by AZMET weather station, calculated with the Penman Equation.

Figure 8. Water content profiles in the West Lysimeter using the neutron probe after irrigation begins.

Figure 9. Comparison between water content profiles using TDR and neutron probes for two days. Solid line drawn through the data points indicate that TDR data falls within calibration range. Dashed line indicates data falls outside of calibration range.

Figure 10. Graphs of instrument response during infiltration experiment. Dashed line represents devices on NE. Solid lines represent devices on SE. TDR water content and tension lines marked appropriately.

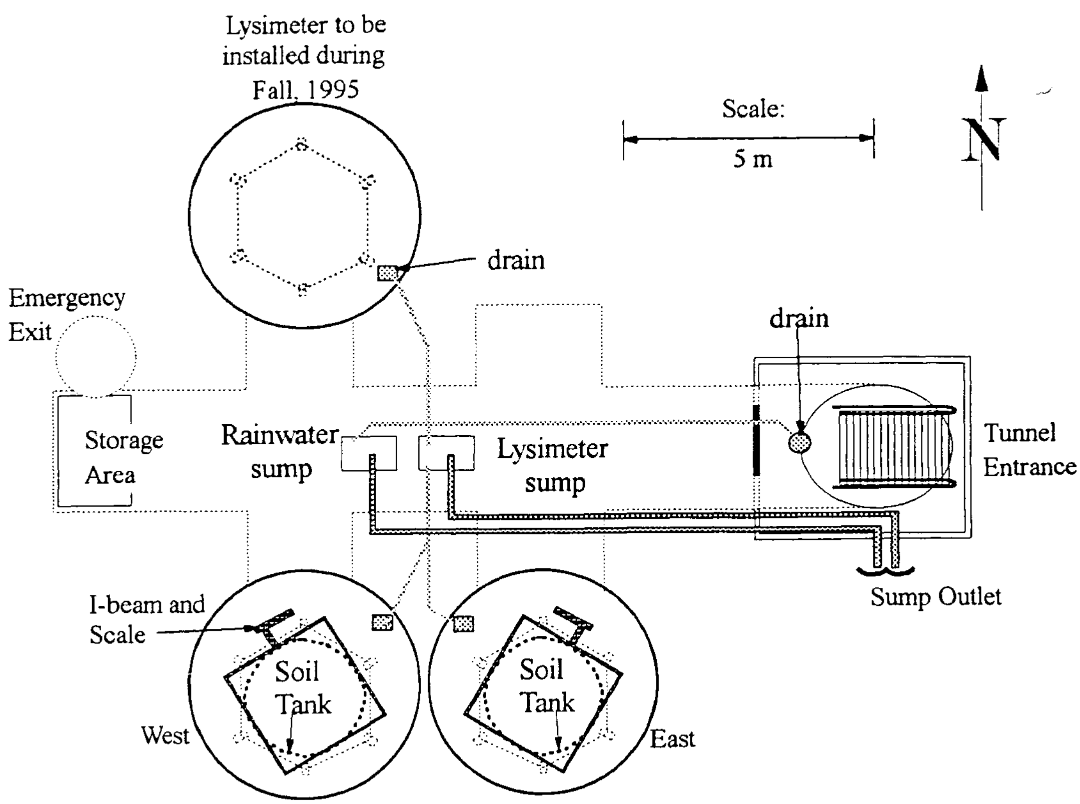


Figure 1. Map view of lysimeter facility.

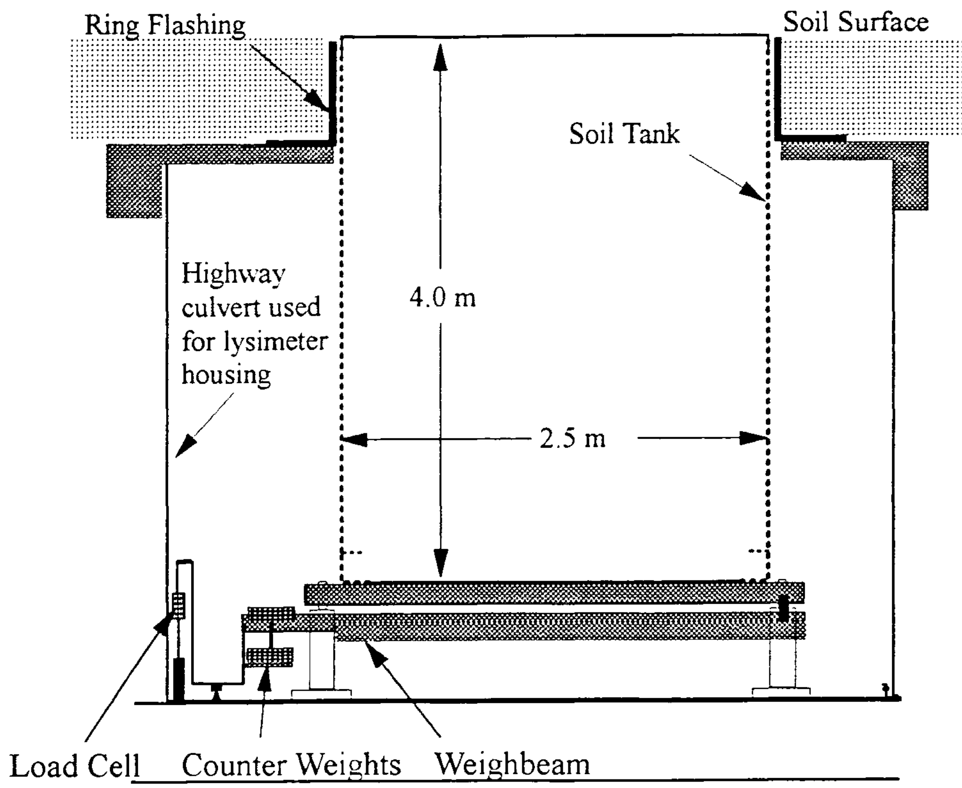


Figure 2. Cross-section of tank and scale systems.

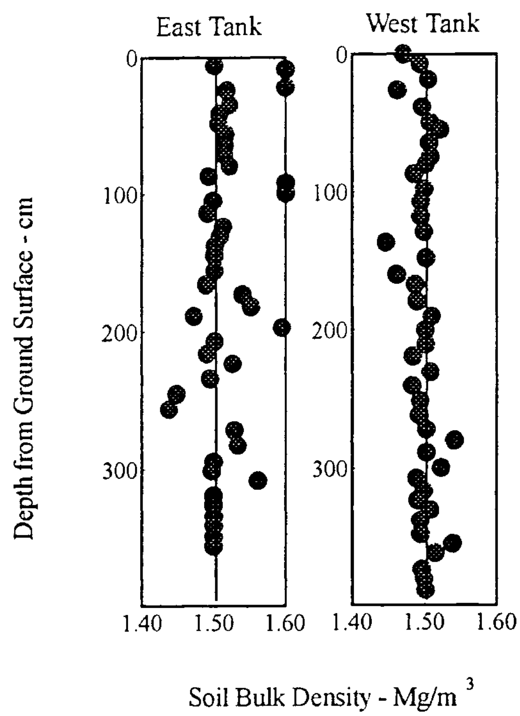
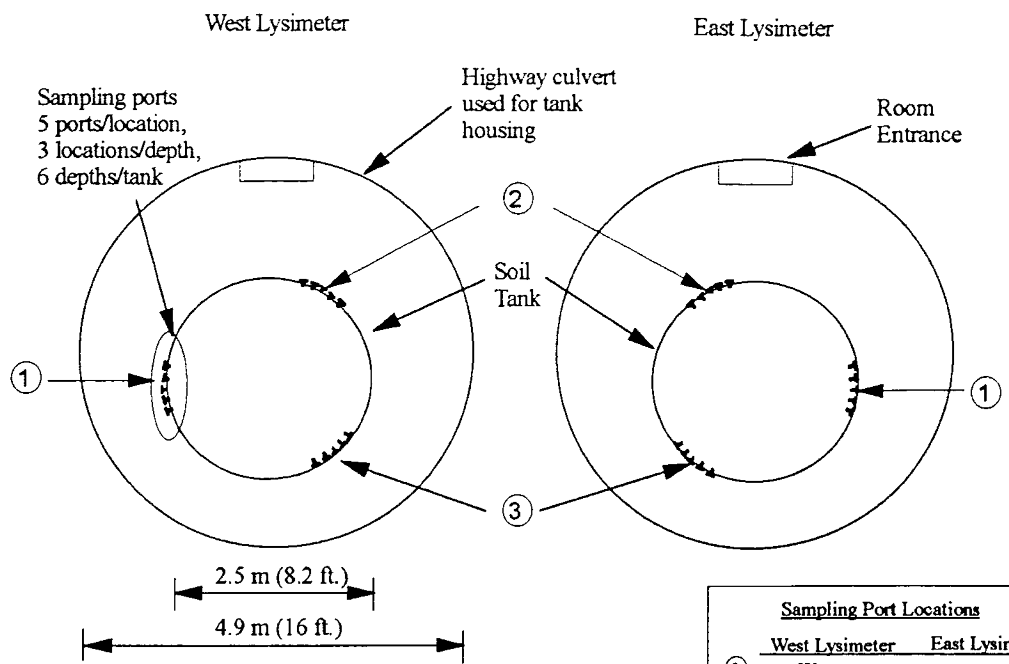


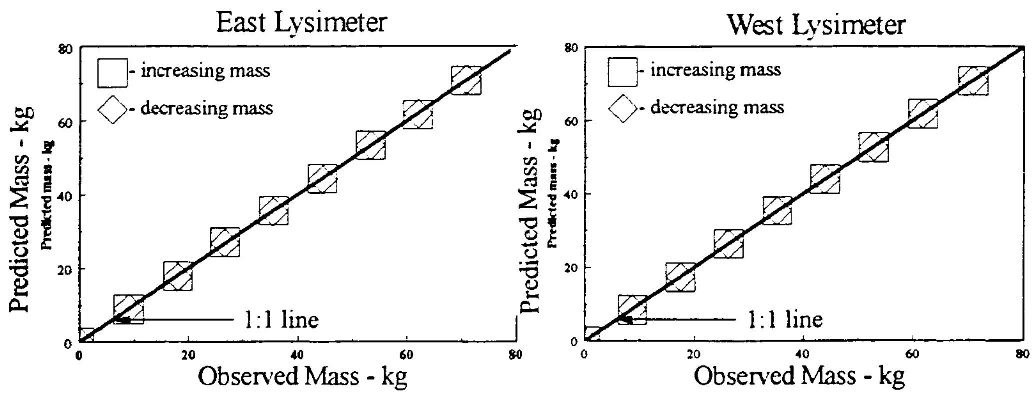
Figure 3. Bulk density profiles for East and West Lysimeters.



Sampling Port Locations

	West Lysimeter	East Lysimeter
1	W	E
2	NE	NW
3	SE	SW

Figure 4. Map view of lysimeter tanks, with sampling port locations and designations.



Statistics	East Lysimeter increasing mass	East Lysimeter decreasing mass	West Lysimeter increasing mass	West Lysimeter decreasing mass
r^2	0.9999	0.9999	0.9999	0.9999
Std. Error (kg)	.235	.280	.117	.047
Percent difference in calibration slope between increasing/decreasing mass	0.871		.229	

Figure 5. Results of lysimeter calibration - Summer 1993.

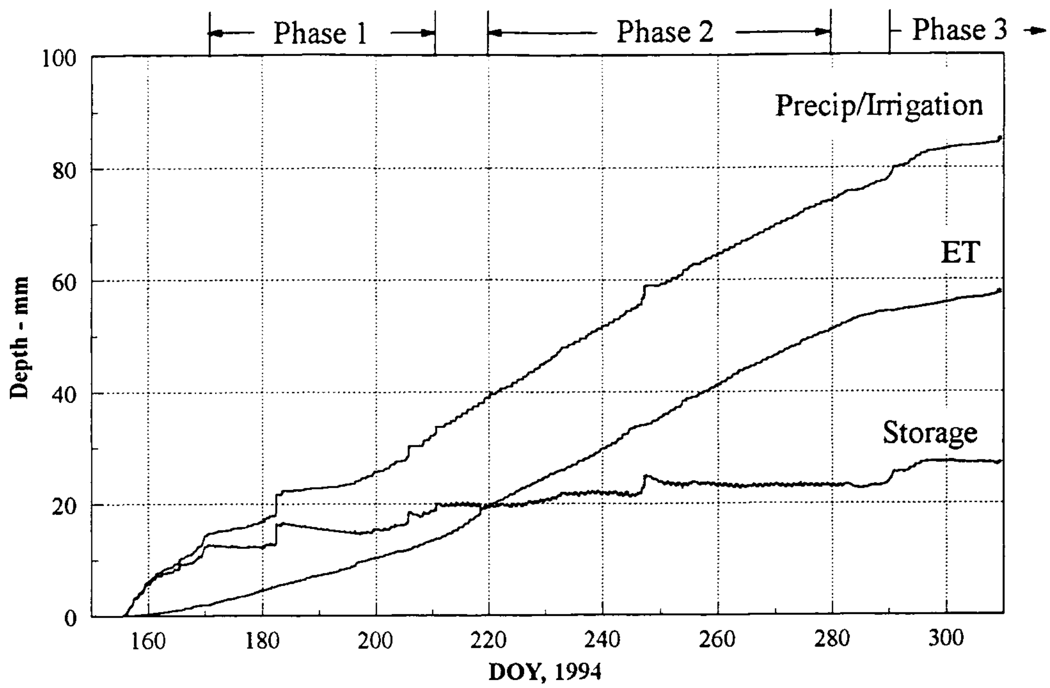


Figure 6 - Graph showing the water budget for the West Lysimeter during initial irrigation.

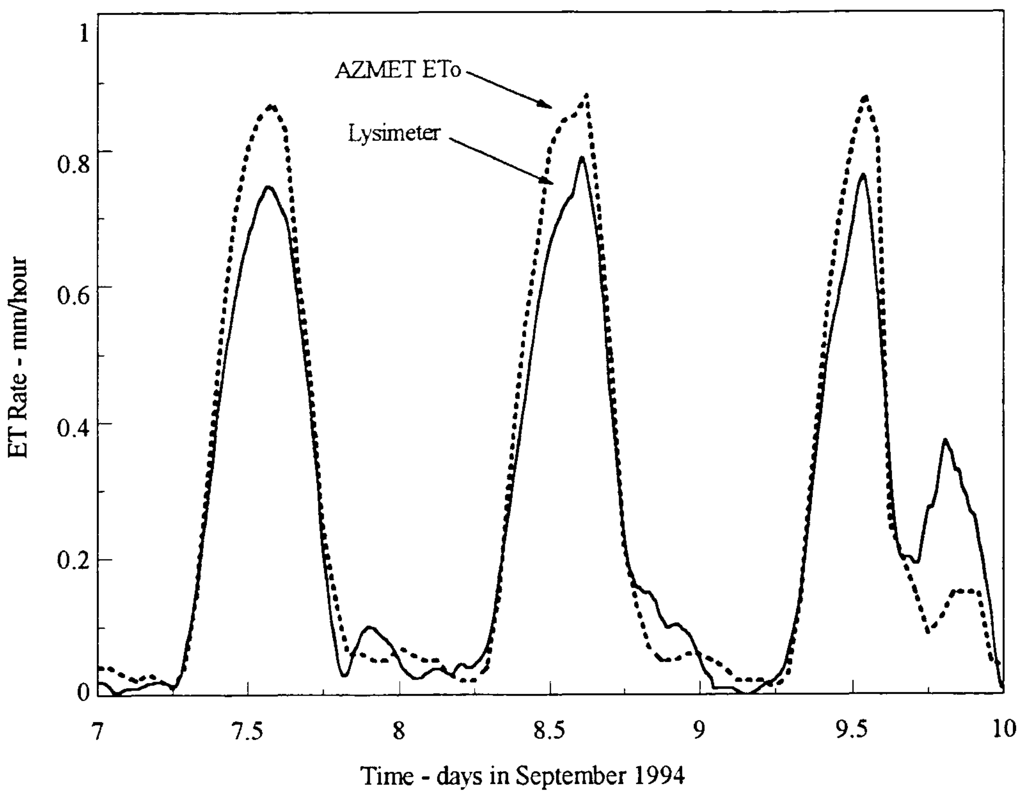


Figure 7. Comparison between ET measured with the West Lysimeter, ETo measured by AZMET weather station, calculated with the Penman Equation.

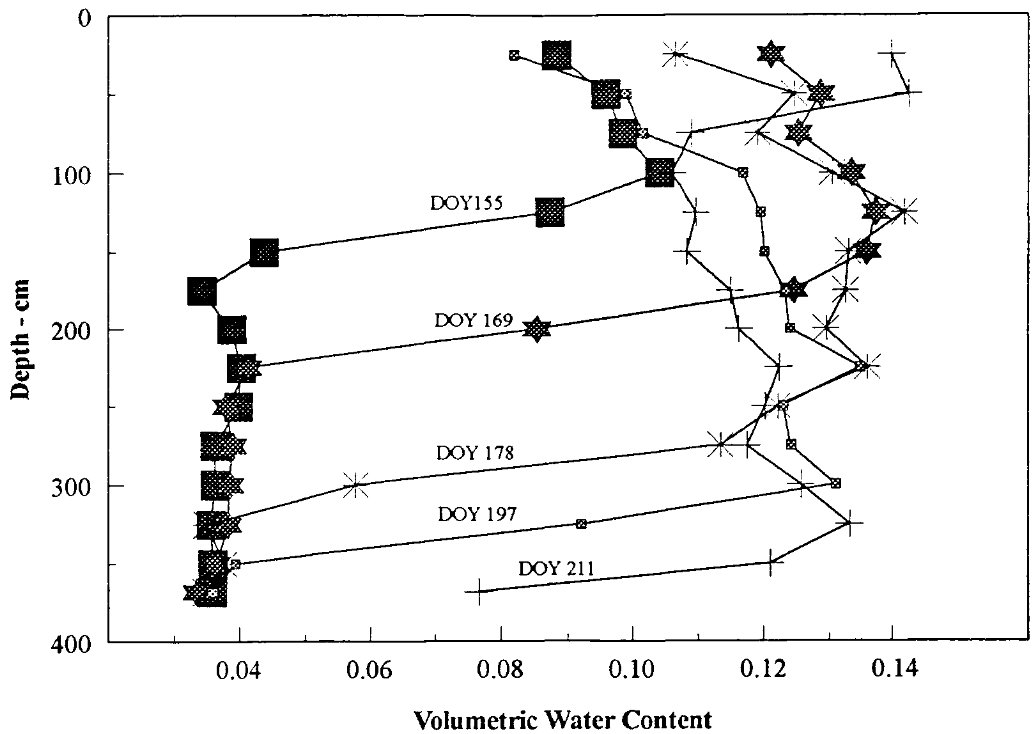


Figure 8. Water content profiles in the West Lysimeter using the neutron probe after irrigation begins.

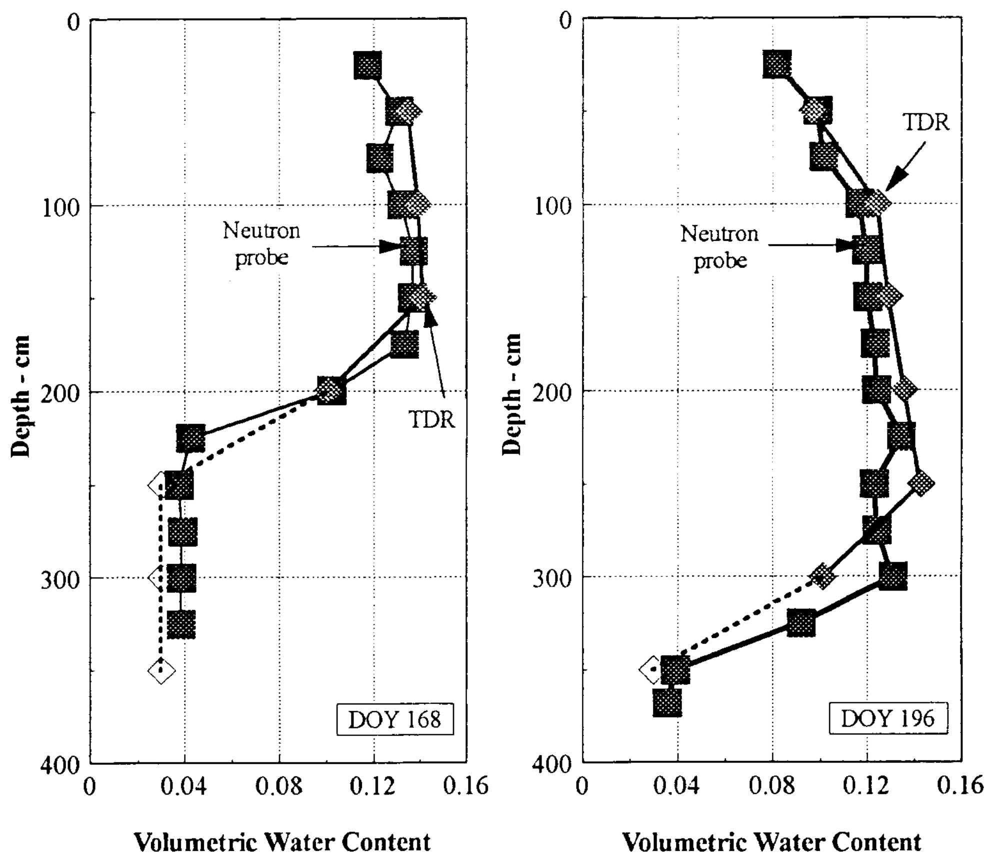


Figure 9. Comparison between water content profiles using TDR and neutron probes for two days. Solid line drawn through the data points indicate that TDR data falls within calibration range. Dashed line indicates data falls outside of calibration range.

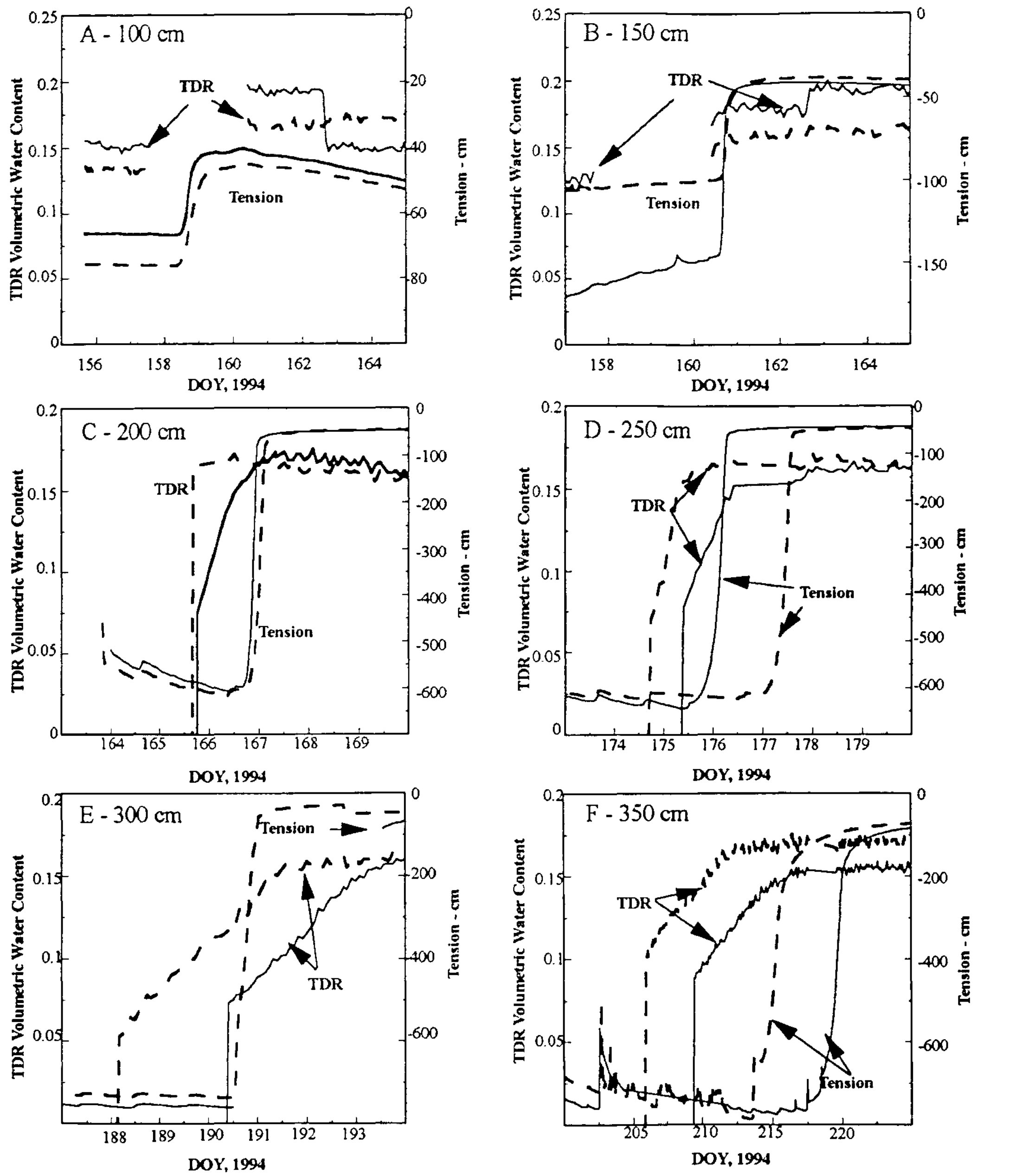


Figure 10. Graphs of instrument response during infiltration experiment. Dashed line represents devices on NE. Solid lines represent devices on SE. TDR water content and tension lines marked appropriately.

APPENDIX B:

Rapid calibration of TDR probes using upward infiltration

M.H. Young[1], J.B. Fleming[1], P.J. Wierenga[1], A.W. Warrick[1]

[1] Department of Soil, Water and Environmental Science, 429 Shantz Bldg., #38,
University of Arizona, Tucson, AZ 85721, USA

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ABSTRACT

Calibration of Time Domain Reflectometry (TDR) probes is time consuming and costly. Though TDR originally was thought not to require calibration, users have found that measurement errors can be reduced if the probe is calibrated *in-situ* with the soil in question. We propose an upward infiltration method to calibrate TDR probes. The method is rapid, allows the soil to remain unchanged during the experiment, and provides hundreds of data points. Experiments were conducted using two different length probes in soils of three textures. Calibration also was performed by packing soil cores with soil at progressively higher water contents (standard method). The data from the two methods were then compared to two forms of calibration curves available in the literature. Results show that the upward infiltration method is stable, repeatable, and provides accurate dielectric constants and calibration curves. The proposed procedure also can be used to identify the presence of wetting fronts along the length of the probe. This is done by calculating the dielectric constant from the water content behind the wetting front, and identifying a third inflection point along the TDR waveform where the electromagnetic wave encounters the wetted soil. The physical length of the wetted portion of the probe is then easily calculated.

INTRODUCTION

In 1980, Topp et al. established time domain reflectometry (TDR) as a rapid, non-destructive method for determining soil water content, and opened up a branch of monitoring techniques for soil scientists. Time domain reflectometry operates by measuring the decrease in electromagnetic signal velocity as it travels through media with different impedances. The impedance is related to the dielectric constant of the material, which in turn is related to the material water content. As TDR becomes a more established technique for determining the volumetric water content of soil, so does the need for accurately determining the relationship between the dielectric constant and the water content.

During the mid-1970's, a greater understanding of this relationship was obtained (e.g. Davis and Annan, 1977; Wobschall, 1977; and Wang and Schmugge, 1980). However, Topp et al. (1980) promoted TDR as a method which does not need calibration, and forwarded an empirical third-order polynomial equation that related dielectric constant to water content. Since that time, numerous researchers have studied the behavior of electromagnetic signals in soils, and have suggested different models. For example, the empirical approach (Topp et al., 1980; Campbell, 1990; Herkelrath et al., 1991), the three-component dielectric mixing model (Ansoult et al., 1984; Alharthi and Lange, 1987), the four-component dielectric mixing model (Dobson et al., 1985; Roth et al., 1990), and the use of the refractive index (Whalley, 1993; Heimovaara,

1993) call upon theoretical electromagnetic principles to describe the electromagnetic wave (EM) behavior in moist soil.

The empirical equation of Topp et al. (1980) remains in use by more researchers than any other relationship, in part because it can be generated using standard curve fitting programs, but also because it does not require other physical parameters, such as temperature or bulk density. Topps' equation is:

$$\theta_v = -0.053 + 0.0292\epsilon_a - 5.5\times10^{-4}\epsilon_a^2 + 4.3\times10^{-6}\epsilon_a^3 \tag{1}$$

where ϵ_a is the apparent dielectric constant, and θ_v is the volumetric water content. The coefficients in (1) were determined using data from numerous experiments with different materials (e.g. glass beads, vermiculite) and with soils of different textures.

In the subsequent three-component dielectric mixing model, the soil is treated as a continuum containing air, water, and soil material (Ansoult et al., 1984). These authors used the following dielectric constants: air =1, water = 78 at ambient room temperature, and dry soil varying between 3.9 and 7.2. The complex dielectric is then calculated as the fractional percentages of the three components contained in the bulk soil sample. Field measurements of the apparent dielectric constant are then fitted to the known volumetric water content.

A modification of this model was developed by Wang and Schmugge (1980), Dobson et al. (1985), and Dasberg and Hopmans (1992). They included the dielectric constant of bound water (ϵ_{bw}) in their four-component dielectric mixing model. In this model, the amount of bound water in the sample is calculated from the surface area of the soil, and the thickness of the Gouy layer surrounding the soil particle. The equation is (Dasberg and Hopmans, 1992):

$$\epsilon = [\theta_{bw}\epsilon_{bw}^{\alpha} + \theta_{fw}\epsilon_{fw}^{\alpha} + (1-\phi)\epsilon_{s}^{\alpha} + (\phi-\theta)\epsilon_{a}^{\alpha}]^{(1/\alpha)} \qquad \textbf{(2)}$$

where *bw* is bound water, *fw* is free water, *s* is soil, *a* is air, ϕ is porosity, and α is a curve fitting factor that is related to the applied electric field (Roth et al., 1992). The dielectric constants used in this equation are fairly well understood, with the exception of bound water dielectric constant. Wang and Schmugge (1980), for example, assume that bound water behaves similar to ice with a dielectric constant of approximately 3.2, whereas Dasberg and Hopmans (1992) used a value of ϵ_{bw} = 5.0. It appears that bound water dielectric most often is used as a fitting parameter.

Finally, the refractive index approach relies on the linear relationship of the refractive index and the water content (Whalley, 1993; Heimovaara, 1993). The approach is based on Snell's Law which describes refraction of EM waves traveling through different media. Travel time of the EM wave is assumed to be linearly related with the water content.

Though each approach differs in the assumptions taken, they all have two things in common: experiments for collecting $\epsilon(\theta)$ data are carried out using standard methods of soil treatment, and calibration curves relating dielectric constant to water content are generated by relating the waveform properties from the TDR cable tester to the measured soil water content. This standard calibration method relies on stepwise increases in soil water content and subsequent collection of TDR waveforms (i.e., Topp et al., 1980; Nadler et al., 1991; and Dirksen and Dasberg, 1993). The general technique is to add deionized water or water containing salt to the soil, mix thoroughly, and allow the soil to equilibrate either in an oven or at room temperature. The soil is then packed to a pre-specified bulk density, and the TDR waveforms are collected. Finally, the soil is removed, more water is added, and so on. Depending on the number of points one desires for the calibration curve, determining calibration curves with the above procedure can take several days to weeks. The main disadvantage of the method is the long experimental time. In addition, there is the difficulty in replicating bulk density as the water content increases (Dirksen and Dasberg, 1993), while relatively few data points are available to fit calibration curves.

The upward infiltration method has been used successfully for determining soil hydraulic property functions (Hudson et al., 1994). We propose to use a version of this method for calibrating TDR probes. The method has numerous advantages; easier control of the lower boundary condition, shorter experimental times, collection of numerous data points using a computer, and a need to pack the soil column only once. Because the column remains unchanged during the experiment, the effects of variable bulk density on the dielectric constant (Dirksen and Dasberg, 1993) need not be considered.

The method uses the findings of Topp et al. (1982), who showed that TDR measurements provide integrated averages of water contents along the length of the probe, even in the presence of steep wetting fronts. This concept also was used by

Knowlton et al. (1994) for tracking wetting front migration during tension infiltrometer experiments. However, to the best of our knowledge, upward infiltration has not been tested as a method for calibrating individual TDR probes.

MATERIALS AND METHODS

Experimental Setup

Calibration experiments were conducted in triplicate for each of three distinct soil types and two lengths of TDR probes. Soils included Vinton fine sand (Sandy, mixed Thermic Typic Torrifluvent), Casa Grande sandy loam (Fine-loamy, mixed hyperthermic Typic Natrilargid [reclaimed]), and Pima silt-loam (Fine-silty, mixed [calcareous] Thermic Typic Torrifluvent). Results of particle size analyses for the three soils are presented in Table 1. Soil columns were uniformly packed with air-dried soil, sieved through a screen with 2-mm openings, to bulk densities similar to those found in the field. Soil was packed at air dry water content for all experiments, allowing for dry soil dielectric constant determination.

Hudson et al. (1994) provide a complete description of the mechanics of the upward infiltration method. Pertinent aspects to the experimental procedure that involve TDR calibration are described below.

All TDR probes were constructed with three stainless steel rods, 3-mm in diameter. Short probe experiments were carried out using probe lengths of 5.44 cm length, spaced 2.24 cm apart. The probes were inserted vertically into soil columns measuring 7.63 cm in height by 7.63 cm in diameter. The longer TDR probes (Vadose

Zone Equipment Corp., Amarillo, TX) measuring 20 cm in length, with a spacing of 3.0 cm, were inserted vertically into soil columns 23.65 cm long with an inside diameter of 14.55 cm. Figure 1 provides a schematic of the experimental setup. Test fluid (0.01 M $CaSO_4$ with thymol as a bacterial inhibitor) was pumped at a constant rate into six locations at the base of the column using a syringe pump (Soil Measurement Systems, Tucson, AZ). A ruler attached to the column was used to measure the position of the wetting front as a function of time. The TDR probe was connected to a TDR cable tester (Model 1502C, Tektronix Corp; Beaverton, OR), and then to a personal computer. The entire core assembly was placed on a digital balance (Sartorius Corp., Bohemia, NY), and its weight recorded with time on a computer.

The top of the column, into which the TDR probe was inserted, was permanently epoxied to the plastic column. The bottom piece, used as the boundary for the flux, was designed with six input ports, one port in the center, and five oriented every 72°, halfway between the inner wall of the column and the center input port. The probe was cut approximately 1.25 cm shorter than the length of the soil column. This distance was used to allow for the wetting front to stabilize before reaching the probe.

Data were acquired every 300 seconds for the short probe experiments and every 180 seconds for the long probes. These collection intervals were chosen somewhat randomly; however, we have found through experience that fitting was not sacrificed significantly even if the data collection is less frequent. Rapid data collection leaves the user with enormous data sets that are cumbersome to manipulate. The collection intervals provided a balance between adequate time resolution and acceptable size of the output files.

Short probe experiments ran for approximately 6-7 hours, collecting about 70 paired values of TDR output and column weight, and long probe experiments ran for approximately 12-13 hours, collecting about 250 paired values, until the soil became saturated. Saturation was assumed when test fluid was seen leaking from the entry ports for the TDR probe. Flux rates using the syringe pump were approximately 0.44 cm/h (20.1 ml/h) and 0.53 cm/h (89.4 ml/h), for the short and long probe experiments, respectively. The volumetric water content at the end of each experiment was measured by oven drying the soil, and converting the gravimetric water content to a volumetric basis using the measured bulk density. In each case, these water contents compared favorably with those calculated from the change in mass of the core, normally with a difference less than 0.5% m^3/m^3.

Data acquisition was carried out with a microcomputer using a program written in QuickBasic/C (LabWindows, National Instruments, Austin, TX). The program collects the scale-measured mass of the column setup, collects the TDR waveform, and provides a preliminary dielectric constant by finding the maxima and minima of the waveform. This method of analyzing the waveform reduced the error-trapping requirements in the data acquisition program, while providing a good initial estimate of the dielectric constant.

Data Analysis

At the completion of the experiment, the individual waveforms were analyzed with a program that uses a technique similar to that of Heimovaara and Bouten (1990), which we call the Double Tangent Method (DTM). The program also is capable of identifying a third point along the waveform (e.g., the position of the wetting front in the soil core).

The main purpose of this program is to determine the maximum and minimum values of the signal magnitude versus the time plot (note the arrows on Figure 2), and from this, the horizontal distance between these values. This horizontal distance is called the apparent electrical length (L_s). To determine the data point corresponding to the arrival of the EM wave at the soil interface, ten to twenty data points were selected on the side of the point where the first derivative became negative (e.g. line 2 in Figure 2, the inflection point where voltage return begins to decrease). These points were then passed to a subroutine for determining the best fit regression line (Davis, 1973). The horizontal tangent at the numerical maximum also was determined (line 1 in Figure 2). The program then found the intersection of the horizontal tangent and the first regression line. The intersection of lines 1 and 2 represents the location where the electromagnetic (EM) wave enters the soil material. Similarly, the end reflection was determined by choosing points on the return portion of the EM wave, at the point of maximum slope (line 4), and the numerical minimum of the waveform (line 3). The intersection of these lines represent where the EM wave reaches the end of the probe. The electrical length of the waveform was determined by subtracting the distances corresponding to the points of intersection. The dielectric constant for that waveform was then calculated using the following equation:

$$\epsilon_a = \left(\frac{L_s}{L_{total} Vp} \right)^2 \tag{3}$$

where L_s is the apparent electrical length, L_{total} is the physical probe length (L), and Vp is the velocity of propagation set on the front panel of the TDR (dimensionless) (Cassel et al., 1994). Vp is essentially a scaling factor to account for the dielectric constant of the coaxial cable.

We found that, in some cases, the dry soil dielectric was very similar to the dielectric of the epoxy material used in the handle of the TDR probe. For probes without impedance matching transformers, or baluns, similarities in these dielectrics make detection of where the wave enters the soil difficult. This problem was solved by measuring the length of the coaxial cable, and the distance of the probe in the TDR handle (Heimovaara, 1993), including the thickness of the plastic base of the soil column. Knowing these distances made it possible to zero the cable tester at the length of the coaxial cable plus probe handle, and concentrate efforts on the reflection of the EM wave at the end of the probe.

The water content in the soil column for all times during the experiment was determined from the initial water content of the soil and the increase in water mass, as measured with the digital balance. Because the TDR probe provides integrated averages of water mass between the waveguides, it was not required to measure the position of the wetting front with time during the calibration experiments, though it was performed in the long probe experiments. The benefits of these measurements are discussed below.

Standard calibration experiments were performed to compare the results with the upward infiltration experiments describe above. All soil material was sieved through a 2-mm screen. Air dry water content was determined either by 24-hour drying in a soil oven, or by microwave drying. Water containing 0.01 M $CaSO_4$ was added to the soil using a spray bottle to minimize clumping. The soil was then thoroughly mixed, and stored at room temperature in an air-tight plastic bag overnight to equilibrate. Soil packing was done in a manner similar to Hudson et al. (1994). Moist soil was packed to bulk density targets of 1.50, 1.55, and 1.45 Mg/m^3, for the Vinton, Casa Grande, and Pima soils, respectively. TDR probes were inserted into the soil material as they were for the upward infiltration experiments. Over a dozen waveforms were collected for each water content, usually spanning several hours, sometimes overnight. After data collection, the soil was removed and tested again for the water content. Water was then added to the soil to bring up the water content for the next step. Experimental data collection normally took place almost immediately after the column was prepared, using the same data acquisition system and waveform analysis algorithm as for the upward infiltration experiments.

Dielectric constants were calculated for at least four water contents for each soil using the standard method. The range of water contents for these experiments was from about 10 to 30% volumetric water content. Measurements of dielectric constant for very dry and saturated soils were obtained from the initial and final conditions of soil used in the upward infiltration experiments. We consider this to be valid because no water content gradients exist in the columns at either of these times. Moreover, some differences existed in the bulk densities of the soil used in the standard method experiments between water content steps; thus, we view the end points as standard method points collected during snapshots of time. Standard method data were plotted along with the average calibration curves generated from the upward infiltration experiments, for each combination of probe length and soil texture.

RESULTS AND DISCUSSION

Table 2 provides the experimental conditions for the 18 experiments conducted. Note that densities varied somewhat between replicates; thus, it may be possible to observe whether the bulk density affected calibration curves from one experiment to another.

Figure 3 shows water content versus dielectric constant data for the short probe experiments. The solid lines in the figure represent the best fit of Equation 1 to the data. The data in Figure 3D and 3E show low amplitude oscillations embedded on top of the convex-shaped calibration curve. It is not immediately apparent why this oscillation existed for the short probe experiments, though we believe that it was due both to waveform characteristics and time dependence of the data values. For example, we noted that in dry soil with the short probes, the waveforms were rounded, without sharp inflection points at the end of the probe (points 3 and 4, Figure 2). This type of waveform was more difficult to analyze, because the computer algorithms were not robust enough to consistently find the end reflections from one waveform to another. As the soil wetted, the inflection became more apparent, and the characteristic relationship developed between water content and dielectric. We found that the oscillations slightly increased the overall variability of the $\theta(\epsilon)$, but the results are still well within the range of other investigators.

Table 3 provides the average coefficient values for the third-order polynomial (Equation 1), for each combination of column length and soil texture. All curve fitting was carried out using TableCurve for Windows (version 1.12, Jandel Scientific Software, Inc., San Rafael, CA). The experimental results show excellent correlation between the replicates for each soil and probe length, as shown by the standard deviation. Also noted is the difference in correlation between the short probe and long probe calibration equations. The longer probe produced more precise calibration curves (lower standard errors of water content estimates). For example, the standard error of estimates for short and long probes ranged from 0.77 - 1.0% and 0.25 - 0.39% volumetric water content, respectively. Though the standard error for the short probe is two to three times that of the long probe, both results represent improvements over those published by Topp et al. (1980) and Herkelrath et al. (1991), who published standard errors of $\pm$1.0-2.0% volumetric water content. The standard deviations in the coefficients for the short probe were, in most cases, higher than the long probe coefficients.

Figure 4 provides the same information as presented in Figure 3, except for the long probe experiments. Recall that data in Table 3 show the Vinton soil long probe experiments produced calibration curves with the lowest standard error and the highest correlation coefficient. A number of small discontinuities were observed in some of the Casa Grande and Pima experiments (e.g., Figure 4E). These coincided with changes that were made to the X-axis (time) and Y-axis (reflection coefficient) scaling parameters on the cable tester during the experiment. Theoretically, this should not have changed the results; however, if the length of the coaxial cable, plus the path length inside the TDR handle, is manually measured and used to zero the cable tester, changes in the scaling can cause small-scale jumps in the dielectric. We found that this problem could be minimized by careful determination of the cable length, both manually and through individual analyses of waveforms for probes in saturated soils. The similarities between the replicate experiments is apparent from Figure 4.

We noted that the polynomial fits to the data for a number of experiments using Casa Grande and Pima soils resulted in slight upward deflections of the curve at the wet end. This could be either an artifact of the curve fitting routine, or evidence of insufficient points at the wet end.

Figure 5 provides the fitted calibration curves for all 18 experiments. The fits are generally very consistent for the replicates. Casa Grande long probe experiments (Figure 5D) show the largest differences from one experiment to the next. The curve which terminates at the lowest ϵ is for the soil compacted to the highest bulk density (ρ_b = 1.609 Mg/m^3). Though previous investigators indicate that $\epsilon(\theta)$ measurements with TDR are sensitive to bulk density, and our results tend to confirm it (e.g. using data from

Casa Grande soil with long TDR probe), we do not have enough data to make more definitive conclusions.

Figure 6 provides a comparison between the fitted calibration curves for long and short TDR probes. The curves were generated using the arithmetic average of the coefficients from the replicate experiments (i.e. data from Table 3). The general form of the equations show strong similarities for each soil texture, especially for the Vinton Sand. Most striking in these comparisons is the systematic offset between short and long probes in Casa Grande and Pima soils. As mentioned earlier, dry soils can pose difficulties in waveform analyses because of rounded waveforms, resulting in uncertainties regarding tangent line locations. Several methodologies were used to choose the end reflection point on the waveforms; for example, fitting a horizontal tangent to the numerical minima and a sloping tangent to the highest first derivative of the return wave, or fitting a sloping tangent to the lowest first derivative corresponding to the wave traveling in wet soil and a sloping tangent to the highest first derivative of the return wave. Regardless of the algorithm used for dry soil, the same algorithm should be applied to all waveforms in the same experiment, rather than subjectively modifying the method based on the form of the waveform as the experiment proceeds. In this research, repeated use of the same methodology for the short probe experiments led to a systematic differences between water content values derived from long probe experiments performed in the same soil material. The long probe experiments provided TDR waveforms that were easier to analyze in the dry range.

Results of the standard method calibration experiments, and their comparisons with upward infiltration data are shown in Figures 7 and 8 for the short and long probe experiments, respectively. Some scatter exists in the short probe comparisons, especially for the Casa Grande soil, which likely were caused by the algorithms for analyzing the TDR waveform in dry soil (Figure 7). Of course, because of the difficulty in achieving identical bulk densities for the several standard method and upward infiltration experiments used in this study, direct comparisons may not be entirely valid. The results for the long probe experiments show good agreement for the Vinton and Casa Grande soils, but larger variability with the Pima soil. The differences were perhaps, in part, caused by the variability in bulk density achieved for the upward infiltration experiments (see Table 2) and the effects on the calibration curves (see Figure 5, Graph F). It appears that the variable densities led to differences in volumetric water content predictions for the same dielectric constants measured with the TDR. The bulk densities achieved for the standard method experiments ranged between 1.43 to 1.52 Mg/m^3, with a mean of 1.46 Mg/m^3 (all data not shown), whereas, the bulk densities for the three upward infiltration experiments ranged between 1.32 to 1.53 Mg/m^3, with a mean of 1.42 Mg/m^3. These results illustrate the sensitivity of TDR measurements to bulk density, though an insufficient number of experiments were performed to conclusively prove this point.

To illustrate that the measured dielectric constants are valid for calibration curves other than the form of Topps' equation, selected experimental results were fitted to Equation 2, the four-component dielectric mixing model (Dobson et al., 1985). We chose to fit parameters in Equation 2 for three long probe experiments only, namely Vinton Sand #1, Casa Grande Sandy Loam #2, and Pima Silt Loam #3. We fitted α, ϵ_{bw}, and ϵ_s, as defined above, while using $\epsilon_{fw} = 78.0$, and $\epsilon_a = 1.0$. Values of ϕ and θ were taken from the bulk density and experimental observations, respectively. Figure 9 provides the results of those fitting exercises, and Table 4 provides the fitted parameters and standard errors. We found that the fitted curve for the Casa Grande and Pima soils overestimated the water content during early times, but very closely approximated the observed data during later stages of the experiment. This likely was due to some overestimation of the end point reflection in very dry soil, where the TDR waveform lacked distinct inflection points. Once the waveguides were fully surrounded in moist soil, and a distinct inflection point developed, the data became much more stable, and were fitted with more confidence. From the general agreement observed in Figures 3, 4, and 9, it appears that the dielectric constant-water content relationships obtained during these experiments can be represented by both empirical and physically-based equations.

The upward infiltration method provides us with another important tool that the standard method cannot provide. The slow pumping of water into the core produces a very sharp wetting front that can be measured by eye or with tensiometer. By noting the mass of water pumped into the core when the wetting front position is recorded, we can measure the dielectric constant of the wetted portion of the soil profile without considering the dry soil.

Waveforms collected during the early stages of the experiment can be interpreted more rigorously to obtain a third inflection point (e.g. the position where the EM wave encounters the wetting front, deflecting the return voltage to the cable tester). During the long probe experiments, visual observations of wetting front positions were taken with time, and used with data from the digital balance for calculations of water content within the wetted portion of the column.

In this instance, the soil material behaved as two dielectrics, i.e., one dielectric for soil behind the wetting front, and the other for soil ahead of the wetting front (Figure 10). Positions 1 and 3 show where the wave entered the soil and where it reflected back from the end of the probe, respectively. Position 2 shows where the EM wave reflected back from the wet soil, leading to a significant deflection in the voltage. As the wetting front advanced upwards, allowing the soil pores behind the wetting front to fill with solution, positions 3 and 2 migrated away from each other. Position 2 migrated towards the probe handle (i.e. Position 1) as the wetting front approached the top of the column. Position 3 migrated away from the probe handle, as the travel time of the EM wave increased, reflecting the higher water content behind the wetting front. Using the position of the wetting front to calculate the wetted length of the probe, we can calculate the dielectric constant (and thus the water content) for the wetted soil:

$$\epsilon_{wet} = \left(\frac{L_{swet}}{L_{pwet} V_p} \right)^2 \tag{4}$$

where L_{swet} is the apparent electrical length of the portion of the probe in moist soil. Once this value is obtained, it is a simple matter to calculate the equivalent water depth at the waveguide and the depth of the wetting front. This concept was exploited by Knowlton et al. (1994) in their investigations using tension infiltrometers.

As the wetting front approached the top of the column, the ability to distinguish between the wetting front node and the entry node became problematic. Ideally, it is desirable to obtain distinct peaks where the EM wave encounters the dry soil and the moist soil at the wetting front. However, as the two peaks approached one another, they merged to form a hump, causing some ambiguity in identifying the separate peaks. Once the wetting front reached the top of the column, only two inflection points were chosen, making waveform analysis a more trivial matter.

SUMMARY AND CONCLUSIONS

A simple, transient laboratory method was used successfully for calibrating TDR probes and soil as a single system. The upward infiltration method, proposed here for TDR calibration, and for hydraulic property estimation (Hudson et al., 1994), allows the user to apply a well-controlled flux at the bottom boundary (no-flux upper boundary), with a vertically installed TDR waveguide inserted at the top of the column. Computer acquisition of TDR waveforms and column mass, together with an algorithm for analyzing the waveforms, provides an experimental system capable of collecting hundreds of data points with less labor. This method has distinct advantages over the more traditional standard calibration method of step-wise increasing the water content in a soil sample, followed by waveform collection. The latter method requires the user to remove the soil from the column, add water, allow the soil to equilibrate, and repack the column. Realistically, only 10-20 points can be collected in this way, and the researcher has to address potential uncertainties of different bulk densities for each step, as we discussed. Moreover, some soils are difficult to pack when moist. Finally, the time to complete this task can take several weeks, depending on the number of points used in the fitting procedures. In contrast, the upward infiltration method used herein is rapid (less than 12 hours), allows the soil to remain unchanged during the experiment, and provides numerous data points.

The ability to calibrate TDR probes in the presence of layered dielectrics (i.e. wet and dry soil) rests on the understanding that TDR provides an integrated average of water found between the waveguides. The theory behind this assumption was proposed by Topp et al. (1982), and later used by Dasberg and Hopmans (1992). Thus, it is not necessary to measure the position of the wetting front during the experiment, or calculate any type of weighted average. Water content determination is trivial, and, if the soil is well behaved, the algorithm to determine the dielectric constant is well understood. The dielectric constant for heavier textured soils appears to be more dependent on the bulk density, though this observation needs to be more fully investigated.

The use of vertical TDR in the presence of a wetting front can be exploited in infiltration experiments (Topp et al., 1983). For example, if the water retention curve of the soil is known, then the water content (and through the calibration curve, the dielectric constant) behind the wetting front can be estimated. By analyzing the TDR waveform for three inflection points, it is possible to calculate the electrical length (L_s) of the probe within the wetted portion of the soil, then back-calculate the physical length of the probe (L_p) contained in moist soil. Infiltration into initially dry soil produces a more sharp interface between wet and dry soil, while infiltration events into moist soil result in a more diffuse interface, thereby blurring the wetting front node on the TDR waveform. Additional work on waveform analysis under these circumstances will lead to more objective identification of inflection points on the waveform, which may lead to greater use of vertical probes for monitoring wetting front migration.

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Table 1. Particle size distributions for the three soils used.

Soil	Texture	% Sand	% Silt	% Clay
Vinton	Sand	90	7	3
Casa Grande	Sandy loam	66.8	19.6	13.6
Pima	Silt loam	23.6	57.2	19.2

Table 2. Experimental conditions for upward infiltration experiments.

Soil	Replicate	Probe length in soil (cm)	Bulk density (Mg/m^3)	Initial θ_v (m^3/m^3)	Final θ_v (m^3/m^3)	Flux rate (ml/min)
Vinton	1	5.10	1.50	.0146	.3590	0.33
Vinton	2	5.10	1.53	.0140	.3786	0.24
Vinton	3	5.10	1.49	.0132	.3771	0.27
Casa Grande	1	5.10	1.57	.0582	.3910	0.30
Casa Grande	2	5.10	1.57	.0385	.4343	0.24
Casa Grande	3	5.10	1.58	.0279	.3666	0.31
Pima	1	5.10	1.32	.0352	.4639	0.34
Pima	2	5.10	1.43	.0517	.4470	0.40
Pima	3	5.10	1.53	.0694	.4099	0.28
Vinton	1	18.74	1.54	.0123	.3380	1.36
Vinton	2	18.74	1.57	.0113	.3380	1.35
Vinton	3	18.74	1.50	.0111	.3458	1.50
Casa Grande	1	18.74	1.57	.0467	.3547	0.77
Casa Grande	2	18.74	1.61	.0595	.3393	0.74
Casa Grande	3	18.74	1.43	.0704	.3939	1.50
Pima	1	18.74	1.42	.0556	.4211	1.55
Pima	2	18.74	1.46	.0571	.4122	1.59
Pima	3	18.74	1.44	.0561	.4307	1.60

Table 3. Coefficients of 3rd-order polynomial form of calibration equation using upward infiltration method (a, b, c, d as used in Equation 1; i.e. $\theta_v = a + b\epsilon + c\epsilon^2 + d\epsilon^3$).

Soil	avg±std deviation in coefficient values				Std Error of θ_v Est. (%)	Avg r^2
	a	b	c	d		
SHORT PROBE CALIBRATION COEFFICIENTS						
Vinton	-.026±.046	.030±.015	-.0001±.001	-1.9E-5±3.1E-5	1.00	.988
Casa Grande	.007±.035	.024±.009	-.0004±.0005	5.9E-6±7.5E-6	.77	.991
Pima	-.087±.003	.025±.001	-.0003±2.4E-5	1.9E-6±1.4E-6	.82	.9949
LONG PROBE CALIBRATION COEFFICIENTS						
Vinton	-.047±.007	.042±.003	-.0017±.0002	3.1E-5±5.8E-6	.25	.9992
Casa Grande	-.080±.015	.031±.003	-.0009±.0001	1.5E-5±2.6E-6	.39	.9977
Pima	-.056±.015	.029±.007	-.0007±.0004	1.0E-5±7.0E-6	.38	.9985

Table 4. Results of fitting for dielectric mixing model for selected long probe experiments.

Parameter	**Vinton #1 Sand**	**Casa Grande #2 Sandy Loam**	**Pima #3 Silt Loam**
α	.61	1.0	1.0
ϵ_s	3.4	4.5	3.0
ϵ_{bw}	5.0	5.0	5.0
Std error of θ_v est. (%)	.69	.95	1.01
r^2	.994	.985	.991

Figure Captions

Figure 1. Experimental setup.

Figure 2. TDR trace showing critical points on the trace and apparent electrical length.

Figure 3. Volumetric water content versus dielectric constants for short probes (symbols). The solid lines (not always visible due to the multitude of points) represent Equation 1 fitted to the data. (A, B, C), (D, E, F), and (G, H, I) are replicates.

Figure 4. Volumetric water content versus dielectric constants for long probes (symbols). The solid lines (not always visible due to the multitude of points) represent Equation 1 fitted to the data. (A, B, C), (D, E, F), and (G, H, I) are replicates.

Figure 5. Fitted volumetric water content versus dielectric constant functions using Equation 1 for all short and long probe experiments. Some lines not always visible due to overlapping curves.

Figure 6. Comparison between average calibration curves for long probes versus short probes, using three soil textures.

Figure 7. Volumetric water content versus dielectric constant for short probe experiments. Lines represent solution of Equation 1 with average coefficients in Table 3. Diamonds represent data from standard calibration method.

Figure Captions - Continued

Figure 8. Volumetric water content versus dielectric constant for long probe experiments. Lines represent solution of Equation 1 with average coefficients in Table 3. Diamonds represent data from standard calibration method.

Figure 9. A comparison between observed and fitted curves using selected data from long probe upward infiltration experiments and the four-component mixing model of Dobson et al. (1985), Equation 2.

Figure 10. Typical TDR trace showing positions where wetting front intersects TDR probe.

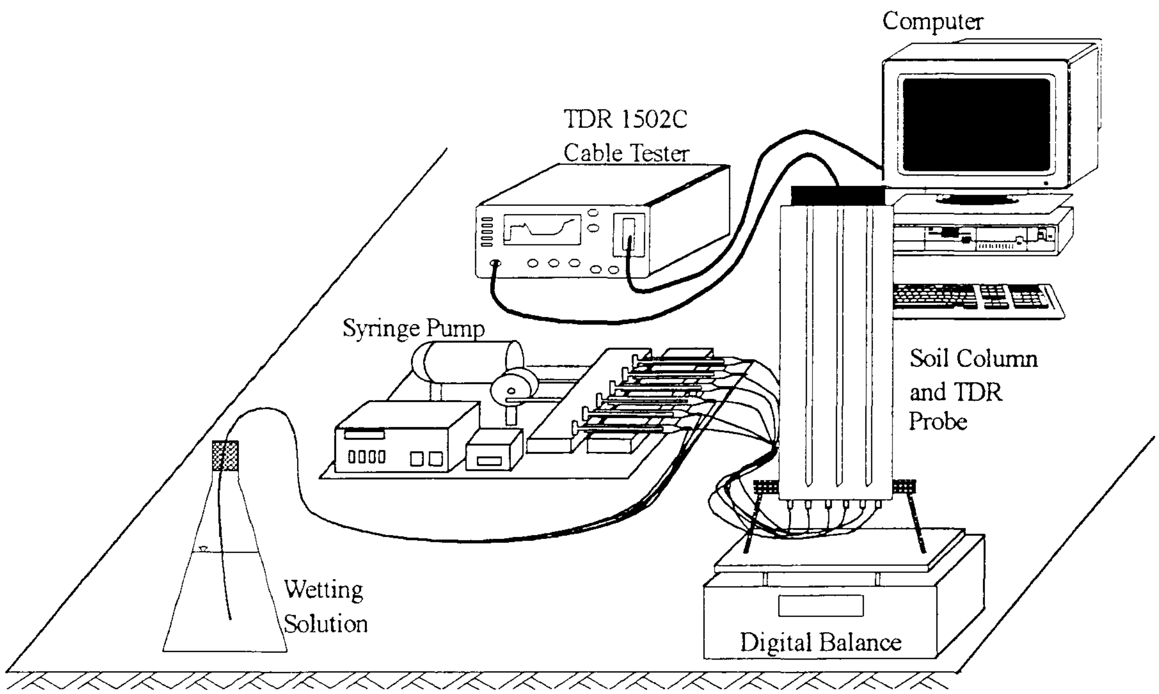


Figure 1. Experimental setup.

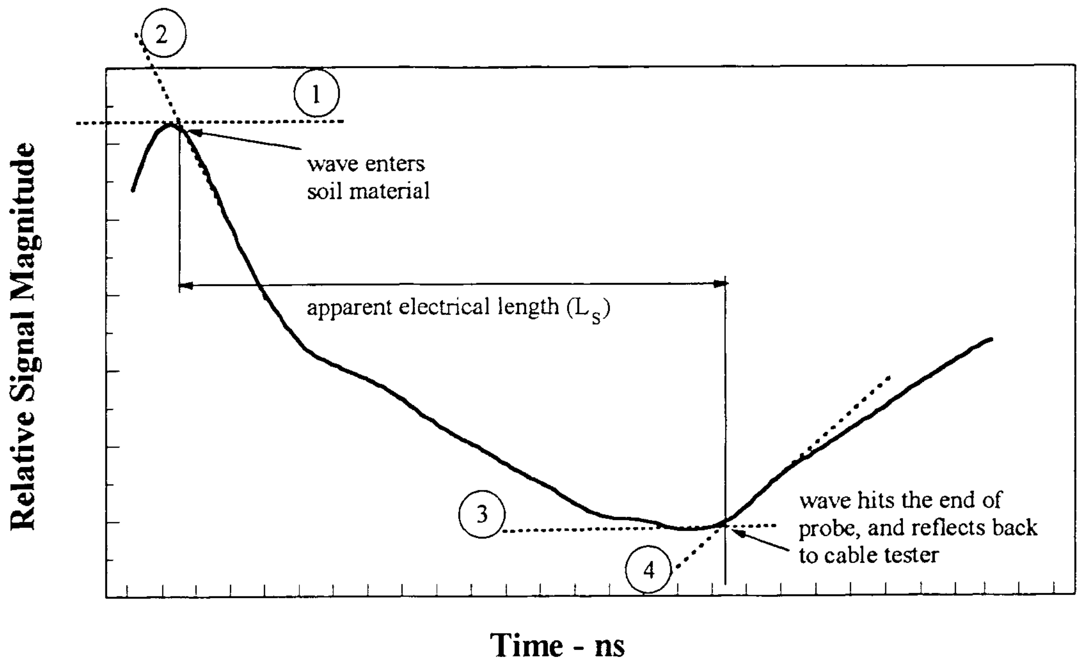


Figure 2 . TDR trace showing critical points on the trace and apparent electrical length.

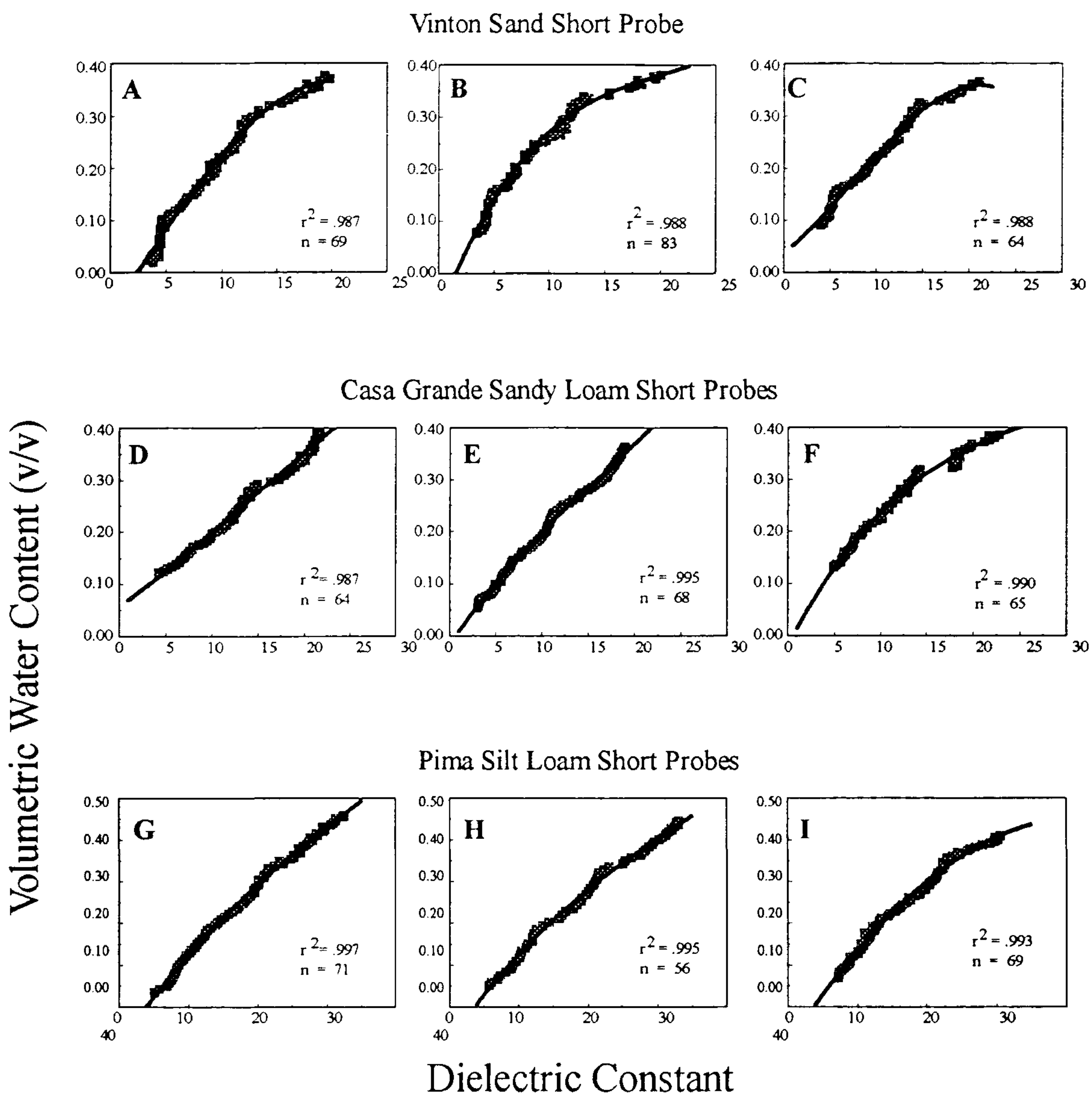


Figure 3. Volumetric water content versus dielectric constants for short probes (symbols). The solid lines (not always visible due to the multitude of points) represent Equation 1 fitted to the data. (A, B, C), (D, E, F), and (G, H, I) are replicates.

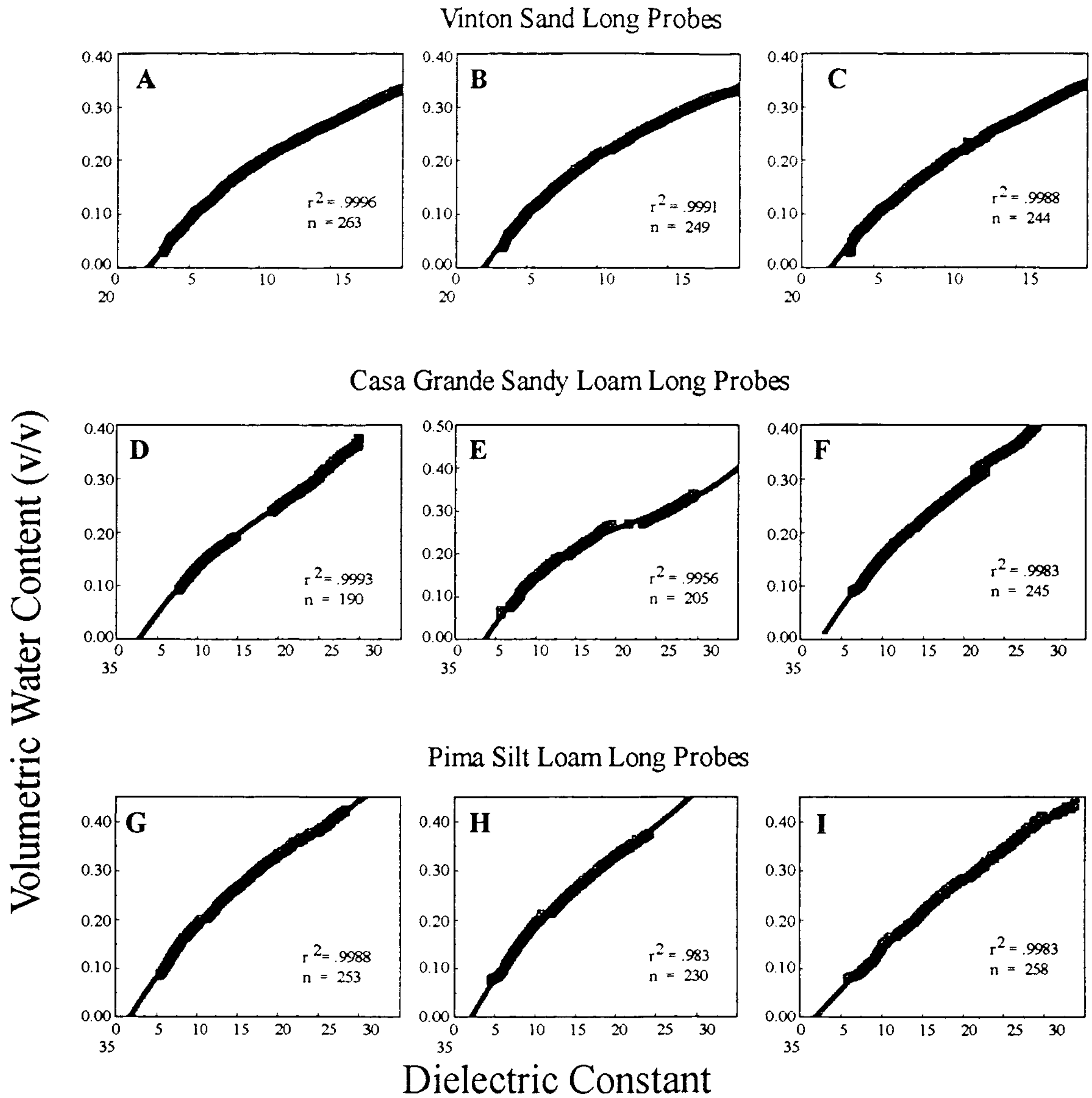


Figure 4. Volumetric water content versus dielectric constants for long probes (symbols). The solid lines (not always visible due to the multitude of points) represent Equation 1 fitted to the data. (A, B, C), (D, E, F), and (G, H, I) are replicates.

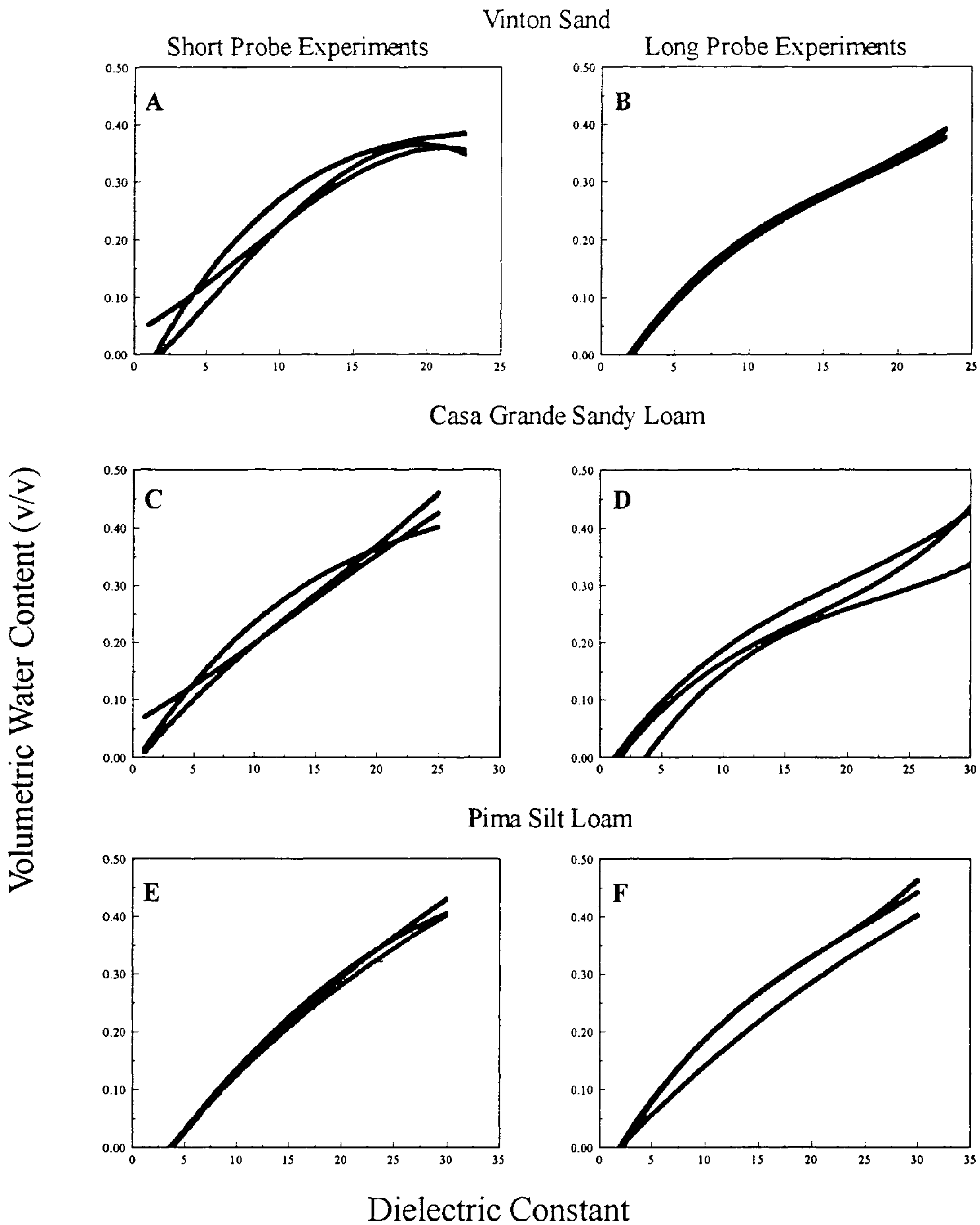
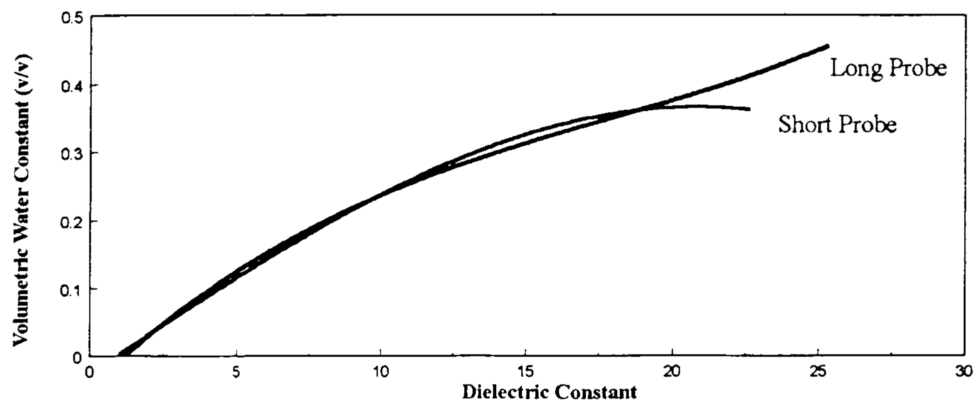
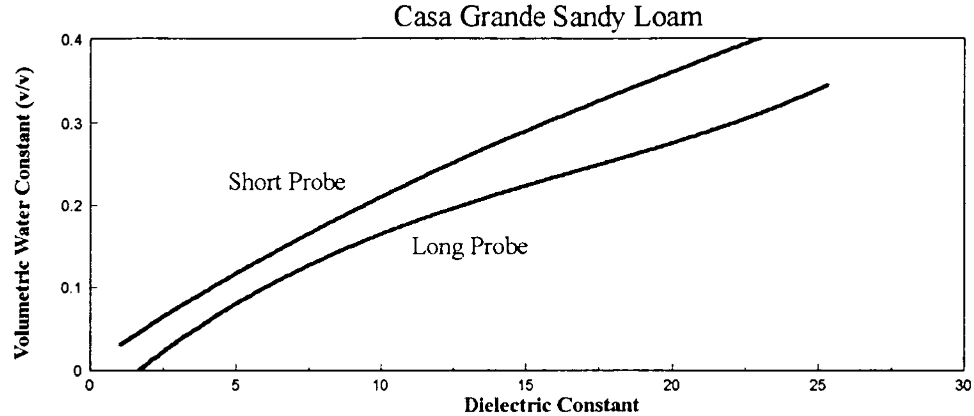


Figure 5. Fitted volumetric water content versus dielectric constant functions using Equation 1 for all short and long probe experiments. Some lines not always visible due to overlapping curves.

Vinton Sand



Casa Grande Sandy Loam



Pima Silt Loam

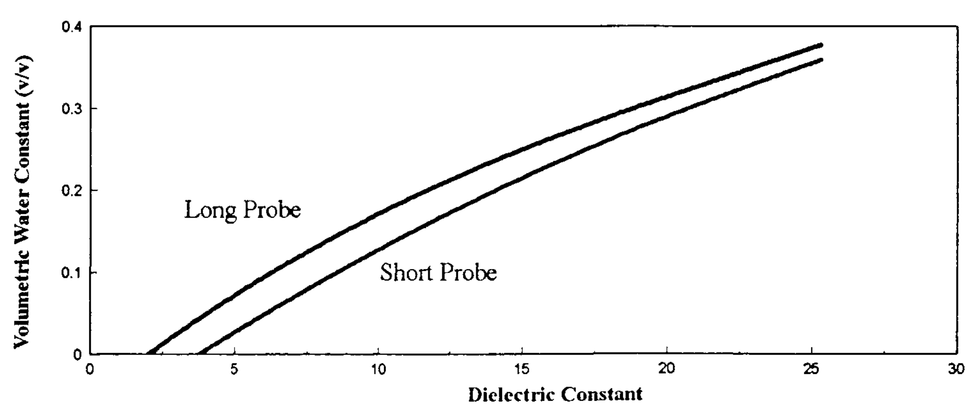


Figure 6. Comparison between average calibration curves for long probes versus short probes, using three soil textures.

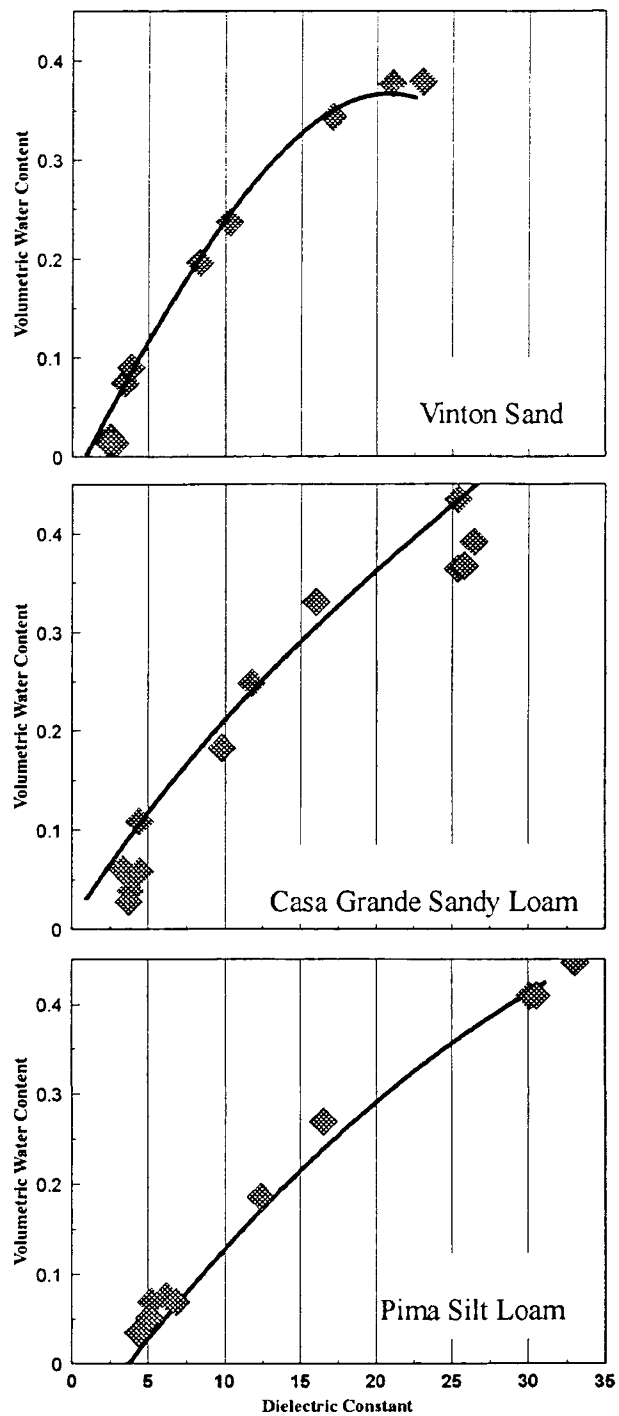


Figure 7. Volumetric water content versus dielectric constant for short probe experiments. Lines represent solution of Equation 1 with average coefficients in Table 3. Diamonds represent data from standard calibration method.

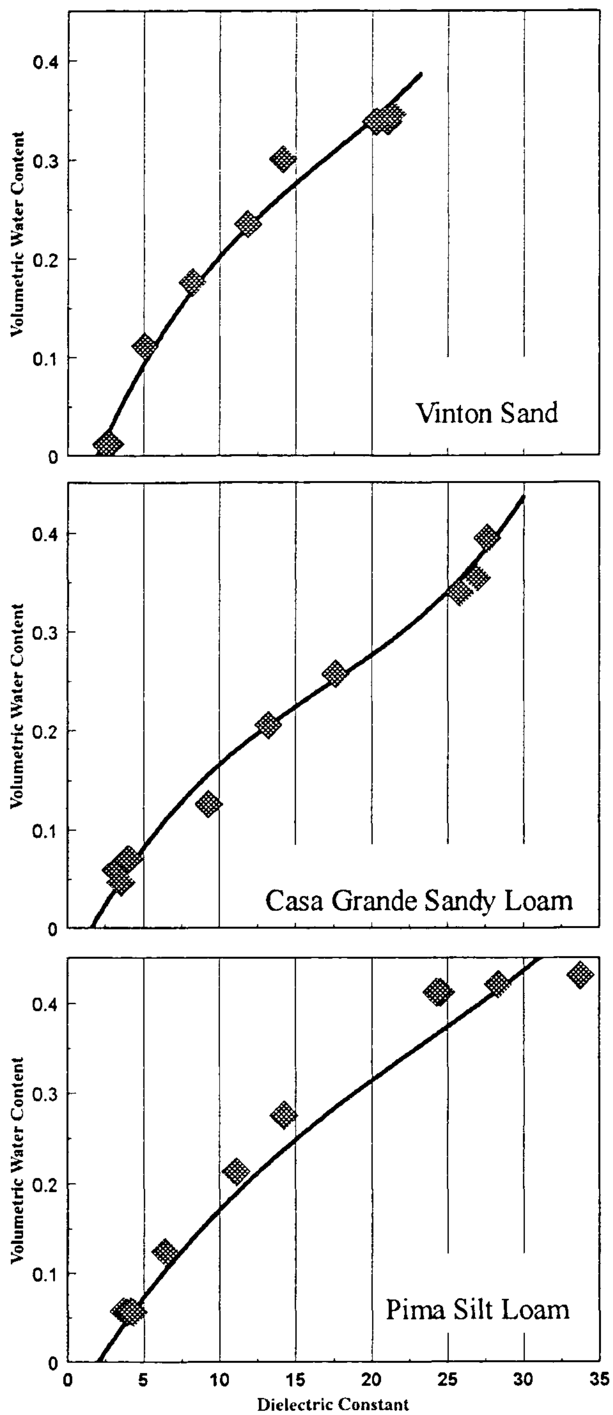


Figure 8. Volumetric water content versus dielectric constant for long probe experiments. Lines represent solution of Equation 1 with average coefficients in Table 3. Diamonds represent data from standard calibration method.

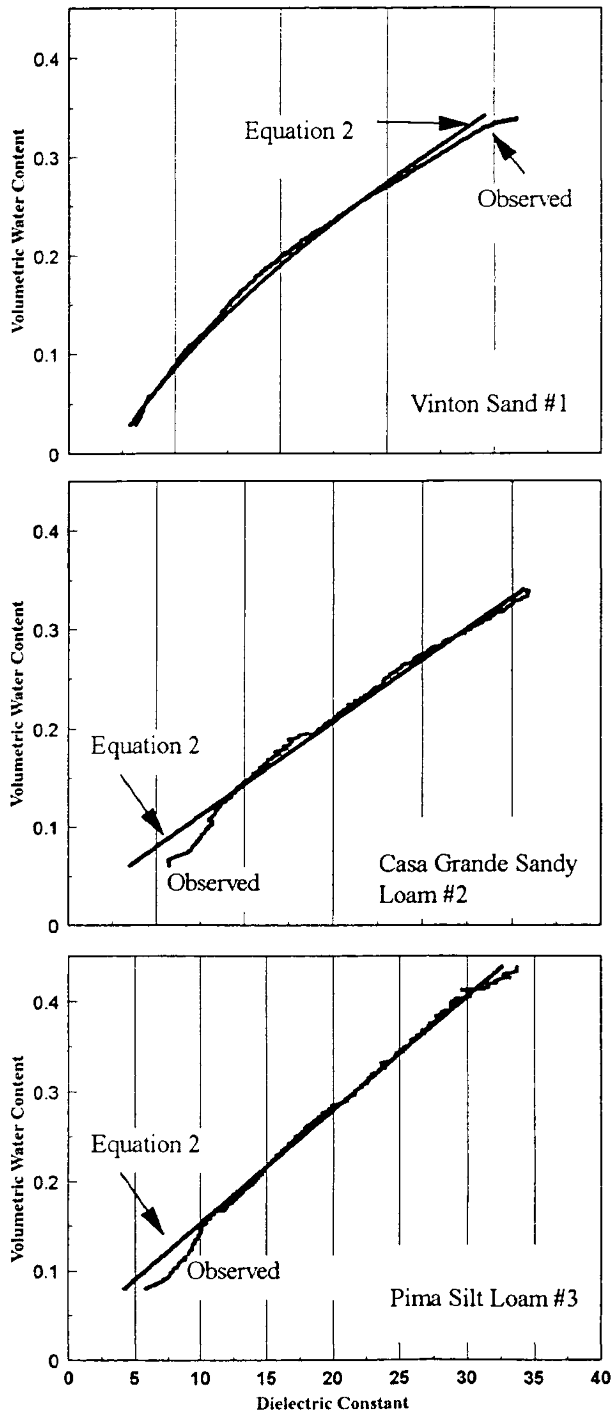


Figure 9. A comparison between observed and fitted curves using selected data from long probe upward infiltration experiments and the four-component mixing model of Dobson et al. (1985), Equation 2.

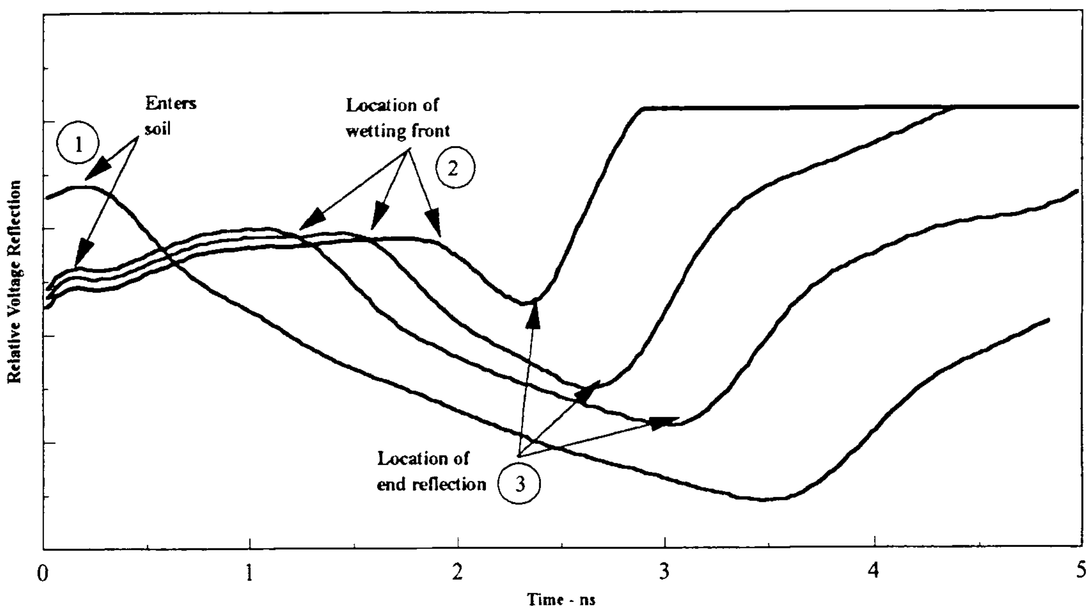


Figure 10. Typical TDR trace showing positions where wetting front intersects TDR probe.

APPENDIX C:

Time domain reflectometry and weighing lysimetry for measuring water loss by turfgrass

M.H. Young[1], P.J. Wierenga[1], C.F. Mancino[2]

[1] Department of Soil, Water and Environmental Science
University of Arizona, Tucson, AZ

[2] Department of Agronomy
The Pennsylvania State University, University Park, PA

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ABSTRACT

The purpose of this study was to compare changes in soil water storage as measured by an automated TDR system, against measurements made using a large weighing lysimeter, in a turfgrass (*Cynodon dactylon x transvaalensis var. Tifway*) setting. Four TDR probes of different lengths (200, 400, 600, and 800 mm) were installed vertically in each of two weighing lysimeters. Water content data were collected every 30 minutes for a 28-day period by TDR, and mass data were collected for the same time period by the lysimeter. We compared measurements of water added through daily irrigation, and water loss through evapotranspiration and drainage. A separate, six-day soil drydown experiment also was conducted and analyzed in the same way. The TDR system provided excellent temporal resolution of water content change. Shorter probes (200, 400 mm) measured significantly higher amplitudes of water content change. Longer probes recorded lower amplitudes of change, and higher overall water contents, reflecting the lack of transpiration from soil layers deeper than about 500 mm. TDR underestimated both water added and water lost as compared to the lysimeter. The presence of a stolon-rich layer 47 mm thick, immediately above the TDR waveguides, retained water that otherwise would have percolated the soil surface into the measurement domain of the probes. This water, retained in the upper surface layer, was recorded by the lysimeter, but not by the TDR probes. A numerical model (HYDRUS) successfully simulated near-surface soil water flow during both the 28-day period with active irrigation, and the six-day soil drydown period.

INTRODUCTION

Numerous studies have shown time domain reflectometry (TDR) to be a versatile tool for determining volumetric water content of soil. Following the critical development of Topp et al. (1980), a period of intensive research has led to many improvements in the use of TDR for soil water content measurements. Specifically, the development of data automation programs and coaxial multiplexers that allows the user to measure and record soil water content at many sites simultaneously with the same cable tester. TDR is now being used for monitoring water content in waste disposal systems, in road/runway construction programs, and in many agricultural settings.

As an example, Richardson et al. (1992) used TDR to measure consumptive water use by tall fescue in a greenhouse environment. They used 300-mm long TDR probes installed vertically into 600-mm long, soil columns. They found that TDR-measured water contents were statistically similar to gravimetrically determined water contents, but that ponding of water at the base of the column led to some erroneous results.

Herkelrath et al. (1991) used vertically-installed TDR probes, 500-mm long, to monitor the water budget in a temperate eastern site. They found excellent correlation in the timing of rainfall events between true (rain gauge) and predicted (TDR) measurements. However, the TDR systematically over predicted rainfall amounts, which could have been caused by surface-water runon or real differences in precipitation amounts between the test plot and rain gauge 100 m apart. Rudolph et al. (1991) and Celia et al. (1991) installed variable-length TDR probes, ranging from 250 to 2000 mm in length, in a glacial outwash deposit on Cape Cod, Mass. Their purpose was to monitor water and solute movement in a heterogenous soil profile. Water was applied via a sprinkler system, and then tracked using TDR, tensiometers and multilevel water samplers for determining tracer concentrations. Because they were unable to account for water lost to ET or gained from precipitation, the water mass balance could not be completed. Baker and Spaans (1994) used microlysimeters and TDR probes installed vertically with the end of the waveguide flush with the soil surface (i.e., handle positioned below the waveguides). They compared ET measured using TDR, against ET determined from micrometeorological measurements (i.e., Bowen ratio and rain gauge). Water accumulating on the bottom of the microlysimeter led to a systematic underestimation of water use determined by TDR; but, when water accumulation was accounted for, comparisons between TDR and micrometeorological readings were within 8.5%.

Topp and Davis (1985) used five different length probes to measure the depth to the wetting front, complemented by a like number of horizontally-installed probes installed at the termination depth of the vertical probes. They found that the vertical probes were useful in tracking the wetting front movement, but that water contents were more accurately determined using the horizontal probes.

Weighing lysimeters have become valuable tools for agronomic research, because they allow direct measurements of changes in mass that can be attributed directly to plant-root uptake and/or soil evaporation. Several weighing lysimeter systems are in use today for studying water use (Pruitt and Angus, 1960; van Bavel and Myers, 1962;

Dugas et al., 1985; and Marek et al., 1988), and soil water balance (Kirkham et al., 1988). However, to our knowledge, weighing lysimeters have not been used to validate the use of vertically-installed TDR probes for measuring ET of plants irrigated at frequent time intervals. The purpose of this study is to evaluate the use of TDR in a turfgrass setting for measuring water use, and to compare the TDR water use measurements with weighing lysimeter data.

Objectives are: 1) to automate the collection of both TDR and lysimeter data so that we can directly compare changes in soil water storage measured with TDR against changes in water mass measured with the lysimeter; 2) to study the use of vertically installed TDR probes to evaluate evapotranspiration (ET); and 3) to test the TDR system as a tool for scheduling irrigation for turfgrass.

MATERIALS AND METHODS

Experimental Setup

This research took place at the Large Weighing Lysimeter Facility at the University of Arizona Karsten Laboratory and Desert Turfgrass Research Facility (hereafter referred to as the Karsten Laboratory). Two lysimeters were constructed between Fall 1993 and Summer 1994, which were designed to investigate both plant-root uptake in a turfgrass setting and the recharge of water and solute into deeper soil profiles. Both lysimeters are 4.0 m deep and 2.5 m in diameter. They rest on scales for measuring changes in mass due to irrigation, precipitation and ET processes.

The scales used for this facility (model FS-8, Cardinal Scale, Webb City, MO) were assembled by Precision Lysimeters, Inc. (Red Bluff, CA), and are outfitted with an electronic loadcell with a 45-kg capacity (model Z-100, Cardinal Scale, Webb City, MO). The scale system has a maximum load of 45 Mg and a precision of ±200 g. Both loadcells are connected to a data logger (model CR-7, Campbell Scientific, Inc., Logan, UT). A complete description of the weighing lysimeter facility can be found in Young et al. (1995a).

Both lysimeters were filled with Vinton fine sand (sandy, mixed Thermic Typic Torrifluvent). The Vinton soil is 90% sand (35% fine sand, 35% medium sand), 7% silt, and 3% clay. The saturated hydraulic conductivity was found to be 150 cm/day using the constant head method of Klute and Dirksen (1986). Unsaturated hydraulic parameters were obtained using the method of Hudson et al. (1994). Soil installation was completed on 30 June 1993. The final bulk densities were calculated to be 1.503 Mg/m^3 and 1.490 Mg/m^3 for the West and East Lysimeters, respectively. The lysimeters were planted with 'Tifway' Bermudagrass (*Cynodon dactylon x transvaalensis var. Tifway*) in June 1994. Both lysimeters were irrigated with potable water until April 1995, when the West Lysimeter was switched to effluent water. Effluent is reclaimed water taken from the City of Tucson wastewater treatment plant. During the experiments described in this manuscript, the West Lysimeter was irrigated with effluent and the East Lysimeter was irrigated with potable water.

Four vertical probes and three horizontal probes were installed in the top 800 mm of the lysimeter for this study (Figure 1). The TDR probes (Vadose Zone Equipment

Corp., Amarillo, TX) consist of three 3.0-mm OD waveguides, spaced 30 mm apart. The vertical probes have four lengths: 200, 400, 600, and 800 mm, while all horizontal probes are 200 mm in length. The probes are connected through RG 58/U, 50Ω coaxial cable, to a multiplexer (JFW Industries, Indianapolis, IN), similar to that described by Baker and Allmaras (1990), and a TDR cable tester (model 1502C, Tektronix Corp., Beaverton, OR). The TDR cable tester is connected to the serial communications port, and the multiplexer is connected to the parallel port of a personal computer which runs a computer program written in a hybrid C/QuickBasic language (LabWindows, version 2.3.1, National Instruments, Austin, TX). The program collects the TDR traces, analyzes these for electrical length and the impedance, and calculates the volumetric water contents and bulk electrical conductivities of the soil. The method of trace analysis is similar to that described by Baker and Allmaras (1990). Probe calibration was completed using the method as described elsewhere (Young et al., 1995b). We conducted three calibration experiments that provided paired values of dielectric constant and volumetric water content. Data from all three experiments were fitted to a single calibration equation, of the form of Ledieu et al. (1985), using TableCurve (v.1.1.2, Jandel Scientific Software, Inc., San Rafael, CA).

Thermocouples were installed in the West Lysimeter to measure soil temperature. The thermocouples were constructed using 24-gauge copper-constantan wire (model TT-T-24, Omega Engineering, Inc., Stamford, CT) inserted into a 3.2-mm OD stainless steel tube and epoxied closed. Individual thermocouples were installed at depths of 0 (ground surface), 10, 50, 100, 250, 500, and 1000 mm. All thermocouples were installed vertically, with the exception of the 500-mm device, which was installed horizontally.

An irrigation system (courtesy Rainbird Golf Division, Glendora, CA) for the lysimeter facility was designed and installed to accommodate both effluent and potable water supplies. Frequent, short duration irrigation cycles were used for these areas because the grasses are relatively short rooted. A total of four, low-trajectory, 4.6-m, 1/4-arc, sprinklers, spaced at 3.7 m, were installed for direct irrigation onto each lysimeter. This makes it possible to irrigate the lysimeters with either effluent or potable water, depending on the experimental design.

A series of weather towers were installed approximately 15 m south of the lysimeters. One tower measures atmospheric conditions for controlling irrigation scheduling for the lysimeter area and the surrounding turfgrass research area, and two others are used by the College of Agricultural Extension Services. The former tower is equipped to measure rainfall, solar radiation, relative humidity, and wind speed. Data are downloaded to a computer using a program (Maxi, ver. 4.5 r, Rainbird Golf Division, Glendora, CA) that calculates daily reference evapotranspiration from a modified-Penman Equation developed by Rainbird Golf Division. The amount of daily irrigation was set to 90% of the reference ET. Irrigation occurred at approximately 0300 for each day when measured precipitation was less than reference ET.

Data Analysis

Two time periods were chosen for intensive analyses. The first period was between 16 June and 14 July 1995 (DOY 167-195). The time interval for data collection was 30 minutes, allowing us to compare the results with every third data point measured by the lysimeter. The second time period was between 21-29 August 1995 (DOY 241-247), during a six day soil drydown, permitting us to measure changes in water content without the added complications of daily water pulses percolating passed the probe ends. This will be referred to as the drydown period.

To account for the possible effects of temperature, we used the correction method of Pepin et al. (1995), namely:

$$\theta_{corrected} = \theta_{TDR} + 0.00175\ \theta_{TDR}\ (T_{calib} - T_{tc}) \tag{1}$$

where $\theta_{corrected}$ is the corrected volumetric water content, θ_{TDR} is the TDR-measured volumetric water content, T_{calib} is the temperature (°C) measured during laboratory calibration, and T_{tc} is the depth-averaged temperature (°C) measured with the thermocouples in the field. Average temperatures were calculated for each length TDR probe by finding the depth at the mid-point between two thermocouple sensors, and then weighting the temperature according to the relative thickness of the soil layer on either side of the thermocouple. Thus, the average temperature for the top 200 mm of soil, using thermocouples at 0, 10, 50, 100, and 250 mm depth, is calculated using:

$$T_{tc} = \frac{((5T_0)+(25T_{10})+(45T_{50})+(100T_{100})+(25T_{250}))}{200} \quad \textbf{(2)}$$

where T_{XXX} designates the depth of the thermocouple. Average temperatures that include deeper soil are computed similarly. Each TDR measurement was used for calculating the corrected water content, and the soil water storage for each probe length (i.e., soil water storage = probe length * θ_v).

Water added to the lysimeter from irrigation and precipitation was determined by obtaining data at specific time intervals and finding the increase in soil water storage. Water lost from the lysimeter from ET (or deep percolation in the case of the TDR probes) was determined by finding the decrease in soil water storage that occurred during a specific time interval. Thus, water added was found from the difference in water content multiplied by probe length from just before an irrigation event to just after an irrigation event (typically at 0100 hours and 0400 hours, respectively). Water lost was found from the difference in water content multiplied by probe length from just after an irrigation event to just before the next irrigation event (typically at 0400 hours and 0100 hours, respectively). Water content data were first smoothed using the method of Gorry (1990), following Baker and Spaans (1994).

Water content changes in the top 800 mm during the summer and drydown periods at the West Lysimeter were modeled using the HYDRUS code (Kool and van Genuchten, 1991). HYDRUS is a one-dimensional, variably-saturated, iso-thermal, water flow and solute transport finite-element model which accounts for plant-root uptake. The model solves Richards' Equation:

$$C\frac{\partial h}{\partial t}=\frac{\partial}{\partial z}\left(K(\theta)\frac{\partial h}{\partial z} - K(\theta)\right)-S(z,t) \tag{3}$$

where C is the soil water capacity (L^{-1}), h is the pressure head (L), K is the hydraulic conductivity (L/T), θ is volumetric water content (L^3/L^3), S is a sink term for root water uptake and is defined as:

$$S(z,t) = E_p(t)\left(\frac{\zeta(z)}{\int_0^{l_r}\zeta(z)dz}\right)\left(\frac{1}{(1+[(h+h_0)/h_{50}]^p}\right) \tag{4}$$

where E_p is the potential evapotranspiration, ζ is the uptake distribution function, l_r is the depth of root penetration, h_0 is related to the osmotic head (assumed zero), h_{50} is the pressure head at which transpiration is reduced by 50%, and p is a constant. The uptake distribution function is normalized as shown and is represented in Kool and van Genuchten (1991) as $\zeta'(z)$.

The purpose of the modeling was to qualitatively describe the changes in water content and soil water storage in the upper lysimeter profiles, and compare the predicted changes with TDR measured changes. Though values for the root-uptake parameters were not available specifically for Tifway bermudagrass, we used the same methodology as Cardon and Letey (1992) for calculating the parameters used in our model. We specified in the model a constant root distribution from 0 - 300 mm, decreasing linearly from 300 - 600 mm, below which no roots would exist (e.g., l_r = 600 mm). This is generally consistent with the root zone distributions found for bermudagrass by Mancino (1995). Parameter values used in the model are listed in the Results and Discussion section.

The soil hydraulic properties used in the model were obtained from laboratory measurements and by calibrating the model hydraulic properties to lysimeter data, such that general agreement was obtained between simulated and observed soil water contents, soil water tensions, and lysimeter outflow. Agreements were sought using daily ET and irrigation for one month, as measured from the lysimeter mass, and adjusting the hydraulic properties (K_s, α, and β) as defined by Kool and van Genuchten (1991), until the soil water tension and lysimeter outflow approximated observed values. Final hydraulic property values, optimized on the lysimeter data, were used to generate a soil water retention curve very close to that using laboratory-determined values (Figure 2). These final parameter values were then used in a near-surface modeling effort (0 to 800-mm depth), using irrigation and ET measured with the lysimeter as upper boundaries.

RESULTS AND DISCUSSION

Use of TDR for measuring diurnal changes in soil water content

Figures 3 and 4 show the variations in water content as measured by TDR, and the daily water input as measured with the lysimeter, for the West and East Lysimeters, respectively. The data are unsmoothed, but have been adjusted for temperature. The data show a regular pattern of water gain with subsequent water loss, and no clear trend in soil water storage over the 28-day period. For both graphs, it is apparent that the 200-mm probe is recording lower water contents, and that the deeper soils are wetter. The daily reductions in surface water content are clearly a result of transpiration processes from the full turfgrass cover and soil evaporation. Daily irrigation may cause significant soil evaporation, because of the wet surface. Evaporation from the wet canopy further increases the ratio of evaporation over transpiration. Higher volumetric water contents measured with the longer TDR probes indicate that the subsoil remains at a higher water content and does not dry out by root-water uptake, as does the 0-200 mm surface layer. The amplitudes of the daily fluctuations in water content recorded with the longer probes are less then recorded for the shorter probes, but still significant. Thus, even though the daily fluctuations at 500 mm and below are minimal, as is evident from water contents measured with the horizontal probes at 500 mm (see Figure 5), the depth-averaged values shown in Figures 3 and 4 show significant variations because of the large variations near the surface.

Daily irrigation depths are represented on the top of each graph. During this period of record, the West Lysimeter received approximately 11% more water than the

East Lysimeter. This was due to differences in operation of the potable water system versus the effluent system. Because of the lower irrigation amounts applied to the East Lysimeter, the daily TDR fluctuations show smaller amplitudes. Furthermore, the 400-mm probe from the East Lysimeter recorded lower water contents than from the West Lysimeter. This may have been caused by root-water uptake from deeper soil when near-surface soil is depleted of available water (Hasegawa and Kasubuchi, 1993). Given that the East Lysimeter was irrigated with less water, and that this water also contained less nitrogen, phosphorus and potassium than the effluent water used on the West Lysimeter, we would expect the roots in the East Lysimeter to propagate more deeply than in the West Lysimeter.

The response of the TDR system to individual irrigation events appears quite good, especially for the 200-mm probe. Note especially the TDR response to the reduced irrigation on DOY 178 on the West Lysimeter (Figure 3). Even small differences in irrigation depths were recorded by the TDR system, as is clear from the drop in water contents for both lysimeters after lower irrigation depths on DOY 170 and 171.

Use of TDR for measuring water addition

Figure 6 compares water input computed from soil water storage before and after each of 28 daily irrigation events, for the West and East Lysimeters. Each graph shows the best-fit linear regression line through zero as well as the 1:1 line. Table 1 provides statistical summaries of the regression calculations. The graphs in this figure clearly show that the TDR under measures the water applied to the lysimeter. This is true for all probe lengths. The reasons for this under prediction are not clear, but there are two possible explanations. Examination of the probes after the experiment showed that the tops of all probe handles were at the original soil surface layer (to allow short mowing). However, a biomass layer 25 mm thick was found above the top of the handle, and the handle itself was measured to be 22 mm high, leaving a 47-mm thick biomass layer above the waveguides.

A second explanation for the underestimation could be the condition of the turfgrass surface at the time of irrigation. In Figure 7 we have plotted for each day the differences in water added as measured with the lysimeter, as compared to the water added as measured with TDR probe. The arrows indicate when the grass was cut. This figure shows that differences increased after the turfgrass on the lysimeters was cut. In fact, a significant increase in the difference between the amount of water measured immediately followed the day after cutting in several instances, indicating that the water was inhibited from entering the soil profile when the grass was shorter. Though very little research has been done on this subject, it is plausible that after cutting, the shorter blade lengths encouraged more water to be directly absorbed by the thatch located immediately above the soil surface, or that the smoother turf surface allowed more water to remain near the surface. Though the thatch layer at the lysimeter was observed to be thin, a combined thatch and stolon-rich layer was observed.

Use of TDR for measuring water loss

Figure 8 shows water loss measured by TDR for four probe lengths versus water loss by the lysimeter. Table 2 provides statistical summaries of the regression fits. The solid lines are the best-fit regression lines. For the West Lysimeter, there is agreement between water losses measured by the two methods, except for the 200-mm probe. For the East Lysimeter, water lost as measured by the TDR probes is consistently less than water added as measured by the lysimeter, except for the 800-mm probe. Thus, the accuracy of the West Lysimeter TDR system in terms of measuring water lost is much better than the East Lysimeter system, especially for the 400, and 600-mm probes. The TDR system of the East Lysimeter closely predicted water loss during several days in which lower than average ET was recorded from the scale system and for the 800-mm probe. The poor fit for the 200-mm probe in both lysimeters reflects plant-root uptake occurring beyond the shorter probes. In particular, the 200-mm probes recorded averages of only 2.7 and 3.1 mm for the West and East Lysimeters, respectively, about half the total ET recorded by the lysimeter scales.

This trend of increasing water loss measured by the longer probes (see 8B, 8C, 8D, and 8H) can be explained by considering downward drainage. We know that the lysimeters are being over-irrigated because water is collected at the bottom of the lysimeter. Thus, water which is not removed in the uppermost 200-mm interval will percolate downward into the next interval, where it will partition into water that percolates downward and water taken up by ET processes. This partitioning will continue until the presence of plant roots is no longer significant. Data by Mancino

(1995) shows, for the species of bermudagrass grown in the lysimeter, that 62% of the total root volume is found in the upper 305 mm, 27% is found from 305 to 610 mm, and only 10% is found below 610 mm. If ET is proportional to root volume, then 60% of the water is taken up in the top 300 mm and 90% in the upper 600 mm. Thus, with daily irrigation, minimal changes in soil water content at 600 mm would be expected. This was confirmed by data from the three TDR probes installed horizontally at the 500-mm depth in the West Lysimeter (Figure 5). These data showed relatively small daily fluctuations in water content of about 0.2 - 0.3 cm^3/cm^3, but a larger increase on DOY 168 after two days of irrigation exceeding 9 mm. The slight diurnal fluctuations show temporally consistent minima around noon, followed by increasing water content until midnight, suggesting that they are influenced by the irrigation events. However, these changes are very small when compared to the vertical probes, indicating little influence from root-zone uptake. Therefore, if 90% of total water loss occurred in the top 600 mm, a higher percentage of the water loss, as recorded by the shorter probes, would be caused by ET.

Probes that extend beyond the root zone will be influenced additionally by downward percolation and record larger total water loss. For example, if we subtract out the drainage water collected at the bottom of the lysimeter, from the total water loss measured by the 800-mm TDR probe (and assume that the soil in the lysimeter is at steady state, implying that the drainage rate at 800-mm is equal to the drainage rate at the bottom of the lysimeter), we can then compare the water loss measured with the 800-mm probe against the 200-mm probe. During the 28-day period, 61 mm and 43 mm were removed from the bottom of the West and East lysimeters through suction candles, respectively. Subtracting these depths from the total water losses measured by the 800-mm probes in the West and East lysimeters (see Table 2), the water loss attributed to ET was reduced to 102.8 mm and 91.1 mm, respectively. These values are within 1.6 and 7.3 mm (1.5% and 8.7%) of the cumulative water losses measured by the 200-mm long probes, in the West and East Lysimeters. These comparisons illustrate that the 200-mm probes do present a fairly accurate measure of ET from daily irrigated turfgrass.

Confirmatory dry-down experiment

From the previous discussion, we know that the measurement of ET and drainage is dependent on the length of vertically-installed probes. The daily irrigation patterns that characterize the management practices at the Karsten Laboratory complicate the predictions of TDR-measured ET, because water continuously moves upward and downward into or beyond the reach of TDR probes. To determine what happens under a less frequent irrigation regime, we performed a dry-down experiment for six complete days in the West Lysimeter during which time the irrigation system was shut down.

Figure 9 shows nearly linear cumulative water loss measured with the lysimeter, even though no irrigation occurred. Though visual observations of the turfgrass clearly showed that it was stressed, the data show that the rate of root-water uptake was constant during the six-day period without irrigation, when the total soil profile was considered. The dryness of the 0-200 mm depth interval is shown by the divergence of water loss rates; only about 45% of the total water use originated in this top layer. As deeper soils continued to dry, they too began to diverge from the water loss rate measured by the lysimeter and the 800-mm probe. The 400 and 600-mm probes responded almost identically, indicating little to no downward drainage from the 400-600 mm increment and a decreasing ET rate after approximately 3-4 days without water. Approximately 7 mm of drainage occurred over the six-day experiment between 600-800 mm, as determined from the difference between water losses measured with the 600 and 800-mm probes. Close inspection of the 800-mm probe shows that drainage contributed to higher water loss through the first several days of the experiment, but that eventually, the deeper soils dried to a level which inhibited downward movement.

Results of HYDRUS modeling

The HYDRUS model was used to simulate water content changes as measured with the TDR, during a time of active irrigation, and during the six-day drydown experiment. For the first objective, we modeled DOY 167-184 for the West Lysimeter only, using irrigation and ET flux data for the upper boundary as measured with the lysimeter. The lower boundary was specified to be free draining with zero pressure gradient (e.g., unit gradient). Near-unit gradient conditions were observed throughout the lysimeter using tensiometers with pressure transducers (data not shown). As indicated above, we subdivided the top 800-mm soil profile into two, 400-mm layers. The significantly lower water content from 0-200 mm (Figure 3), could not be simulated using a single layer model, regardless of changes in the hydraulic properties or the root zone distribution functions. In order to be able to successfully simulate the observed water contents (increasing average water content with increasing depth), we had to lower the K_s from 150 to 10 cm/d in the lower 400-mm layer, thereby reducing the internal drainage rate in the profile, and maintaining a higher water content. Table 3 lists the hydraulic property values for the Vinton Sand as derived from laboratory experiments and from model calibration. Similar to the modeling for the full 3000-mm depth, we used outputs of water tension and water content data from previous simulation runs, and used them as input to subsequent runs. Several runs were necessary until the change in soil water storage became negligible, and the model was essentially at steady state. At this time, the predicted deep drainage very closely matched observed values. For example, 2.17 mm/d of deep drainage were removed from the suction candles at the bottom of the lysimeter, and HYDRUS estimated 2.21 mm/d of drainage for the same time period.

Figures 10 shows observed and simulated water contents for DOY 167-175, using the 200, 400, 600, and 800-mm probes and HYDRUS, respectively. HYDRUS overestimated the water contents in the top 200 mm, and slightly underestimated the average water contents when incorporating soil from 200-400 mm depth. Averaging soil water contents down to 600 and 800 mm greatly improved the overall fit. The fit between observed and modeled data for the 0-800 mm interval (Graph D) is encouraging, and shows that the two-layer model was successful in predicting water content changes in the full profile. Thus expected, the predicted daily fluctuations in water content followed the TDR-measured average water contents closely. For example, HYDRUS simulated subtle changes in the soil water after sunset quite well as a result of decreasing ET. In some cases, i.e., DOY 169 and 173, the rate of change in water content almost perfectly simulated observed conditions.

The slight decrease in water content after 1900 hours, when a no flow upper boundary was specified, indicates that HYDRUS was predicting some internal drainage. The similarity between observed and predicted data lends credence to our hypothesis that TDR lumps together deep drainage and ET.

With the exception of DOY 174 on Figure 10a, HYDRUS overestimated the water content after irrigation. This is consistent with the water addition data in Figure 6, where it was shown that TDR underestimated the water added from each irrigation. Possible reasons are that water irrigated onto the lysimeter surface does not enter the soil surface as readily as HYDRUS predicts, which could be caused by 1) hydrophobicity of dry turfgrass that inhibits water entry, 2) the development of a thatch layer that retains a percentage of the water, 3) the presence of longer blades of turfgrass that capture water before it enters the soil, or, of course, 4) insensitivity of the TDR system to detect these relatively small changes in surface water content.

The HYDRUS model was also used to simulate the six-day drydown period. Lysimeter-measured water fluxes were used as upper boundary condition from 0600 to 1900. Figure 11 shows observed (TDR) and predicted (HYDRUS) depth-averaged volumetric water content. Simulation results for the 0-200 mm depth very closely matched observed measurements, including the diurnal decreases in water content resulting from ET. HYDRUS underestimated actual water contents for the 0-400 mm interval, but it modeled the changes in water content (.07 m^3/m^3 for HYDRUS and .07 m^3/m^3 for TDR) and water loss (28.2 mm for HYDRUS and 27.6 mm for TDR) almost perfectly, indicating that the processes of water movement in the top 400 mm were modeled correctly. As more of the soil profile was included in the averaging process for the model, HYDRUS overestimated changes in water content. The TDR readings indicate that pore water contained in the bottom 400 mm of the modeled regime is not draining as predicted by HYDRUS. Part of the error in prediction also may be due to assumption of a non-hysteretic soil material. Hysteresis could be significant in this field soil, given the daily irrigation cycles and the observation that water pulses are percolating downward on a daily basis.

Variance in measurements

We now identify three possible sources of variance that could be quantified for each TDR measurement made herein: calibration error, measurement bias (systematic error), and simple random error. We also discuss briefly the effect of instrument settings on possible error. Calibration error can lead to significant uncertainty if the user is interested only in water content, and not in changes in water content, because of possible differences in the regression constant. A perusal of commonly used calibration equations will reveal that the slopes normally are very similar for soil with sandy texture like the Vinton sand, and that using the curves for measuring changes in water content may be less prone to uncertainty. For example, Topp et al. (1980) and Herkelrath et al. (1991) both indicated that their calibration curve had standard errors of around 2% volumetric water content. Using their standard errors to determine absolute water content leads to a possible error of 16 mm in soil water storage for an 800-mm probe. However, because we are more interested in the change in water content than the absolute value, an accurate estimate of the slope of the calibration curve will reduce this possible error. The standard error of estimating water content from the calibration experiments conducted using the Vinton fine sand was 0.8% ($n = 735$, $r^2 = 0.989$).

The measurement bias is a measure of the departure of the statistical true value from the scientific true value (Greacen, 1981). Applying this idea to neutron moderation, Greacen (1981) noted that the instrument bias can be reduced if the same soil and conditions are used for calibration as the population soil. For the study described herein, Vinton soil was packed in soil columns during calibration to the same bulk density as found in the lysimeters. Thus, we believe that our instrument bias has been reduced to the extent possible, and will not be pursued further.

The estimation of simple random error was quantified in the same manner as Baker and Spaans (1994). We chose a 3.5-hour time period between 1000 and 0130, and determined the variance of measurement for each TDR probe and both lysimeters for the 28-day time period. During these hours, ET is nearly insignificant leading to a period of negligible change in measured water depth (we also neglect downward drainage for the sake of simplicity). Table 4 provides the standard errors of measurements due to simple random error. The results for the lysimeter data are about five times less than any of the TDR probes; thus, we will assume for this study that the lysimeter provides unbiased data with no variance. Note that variance in water content measurements is very low, in most cases, an order of magnitude less than the calibration error, yet significant when considering the total possible error in water stored in a given depth of soil.

The instrument settings, namely the resolution of the x-axis (either distance or time) affects the precision of the cable tester, which can affect resultant water content values. During these experiments, we set the distance/division parameter to values of 0.05, 0.05, 0.10, and 0.25 for the 200, 400, 600, and 800-mm probes, respectively. We determined the amount of error that would occur if the reflection points on the TDR trace varied by one data point on the cable tester; the differences in volumetric water content were found to be 0.17%, 0.17%, 0.28%, and 0.21% for each data point collected from the cable tester, for the 200, 400, 600, and 800-mm probes. This corresponds to 0.3 mm, 0.7 mm, 1.7 mm, and 1.7 mm of potential error in soil water storage. Though this uncertainty could be significant for individual water content measurements, we are looking at changes in water content, using identical algorithms for analyzing all four TDR probes. Thus, any bias would affect all the probes in the same way, and should cancel each other out when calculating change in soil water storage.

By summing the sources of uncertainty, we found that standard errors sum to totals exceeding 1% volumetric water content only in the case of the 200-mm probes. In all cases, the majority (between 66% and 93% of the total error) was due to calibration.

CONCLUSIONS

Vertically installed TDR probes were tested by comparing water losses as measured by TDR probes with water losses measured by large weighing lysimeters. Automatic data collection with the TDR system and the lysimeter continued for over 15 months, at time intervals as often as 15 minutes. We found that TDR provided very reasonable diurnal changes in water content that can be attributed mostly to plant-root uptake. The TDR system generally underestimated water added during the period of record, though the longer probes more closely approximated water added as measured by lysimeter. The shorter probes underestimated water added because of the possibility that some of the irrigated water never infiltrated the soil profile; rather, a portion of the water was absorbed by organic material located immediately above the TDR waveguides. Longer probes were subject to some underestimation, but more closely predicted water added. This is likely because longer probes averaged thicker soil sequences, removing some of the larger variability that is more likely present at the surface. The TDR system also underestimated the water loss for some of the same reasons given above. Generally, the longer probes measured higher water losses, but this was due to downward drainage of water that was lumped into the estimate of ET. This was shown by subtracting the drainage water removed from the lysimeter, from the water loss total measured by the 800-mm probe and comparing the differences with water loss totals measured by the 200-mm probe. The comparisons showed very similar water loss totals attributable to ET.

A confirmatory drydown experiment showed nearly linear cumulative water loss rates as measured with the West Lysimeter. These rates correlated very closely to measurements made by the 800-mm probe. Shorter TDR probes measured less water loss than the lysimeters, presumably because the available soil water was depleted in the shallow soils, requiring root-water uptake from deeper soil. The TDR system showed that approximately 80% of total soil water loss, as measured by the lysimeter, occurred in the top 600 mm of soil.

The HYDRUS code simulated diurnal changes in water content during an 8-day simulation period during daily irrigation (DOY 167-175, 1995). Simulation results were improved when the saturated hydraulic conductivity of the lower 400-mm of soil was reduced from 150 to 10 cm/d. Differences between observed (TDR) and predicted (HYDRUS) water contents in the 0-200 mm interval is possibly attributable to the condition of the turfgrass layer itself (i.e., mowing height and schedule, and presence of a stolon-rich layer). HYDRUS slightly overestimated water content changes in the top 400 mm, but very closely modeled changes in the soil profile when the entire soil profile (0-800 mm) was incorporated into the averaging. HYDRUS also simulated water content changes during the drydown experiment. The model slightly overestimated water use in deeper soil horizons, possibly because HYDRUS did not consider hysteresis in the Vinton soil. Because hysteresis would lead to higher hydraulic conductivities for draining soil than for wetting soil, the internal drainage would be correspondingly higher as well, explaining the overestimation in water use in deeper soils. Three significant sources of error were identified (calibration, simple random, and bias), as well as the possibility of error from the cable tester instrument settings. These sources can explain the random fluctuations observed during data collection.

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Table 1. Summary of regression calculations and comparisons between water added as measured by TDR versus water added as measured by lysimeter for the West and East Lysimeter for the 28-day analysis period.

West Lysimeter				
Measurement Device	Std. Error of θ_v Estimate m^3/m^3	r^2	Total Water Added mm	Percent of Lysimeter Total
200 mm	1.24	0.35	109.0	42.7
400 mm	1.19	0.61	183.8	72.0
600 mm	1.35	0.55	174.5	68.3
800 mm	1.59	0.67	169.8	66.6
lysimeter	n/a	n/a	255.1	n/a
East Lysimeter				
Measurement Device	Std. Error of θ_v Estimate m^3/m^3	r^2	Total Water Added mm	Percent of Lysimeter Total
200	1.14	0.13	86.4	37.9
400	1.18	0.23	102.6	451
600	1.25	0.31	119.5	52.5
800	1.02	0.36	135.1	59.3
lysimeter	n/a	n/a	227.8	n/a

Table 2. Summary of regression calculations and comparisons between water lost as measured by TDR versus water lost as measured by lysimeter for the West and East Lysimeter for the 28-day analysis period.

West Lysimeter				
Measurement Device	Std. Error of θ_v Estimate m^3/m^3	r^2	Total Water Lost mm	Percent of Lysimeter Total
200 mm	1.28	0.24	104.4	56.5
400 mm	1.08	0.55	177.0	95.8
600 mm	1.25	0.38	168.9	91.4
800 mm	1.80	0.20	163.8	88.6
lysimeter	n/a	n/a	184.9	n/a
East Lysimeter				
Measurement Device	Std. Error of θ_v Estimate m^3/m^3	r^2	Total Water Lost mm	Percent of Lysimeter Total
200	1.09	0.44	83.8	52.1
400	1.05	0.61	100.6	62.6
600	1.07	0.64	116.1	72.3
800	1.06	0.53	134.1	83.4
lysimeter	n/a	n/a	160.7	n/a

Table 3. Laboratory derived and modeled calibrated hydraulic properties for the Vinton Sand. Bottom three parameters correspond to sink term in HYDRUS model.

Parameter	Laboratory Derived	Model Calibrated	
		Layer 1	Layer 2
α (cm^{-1})	0.031	0.032	0.032
n	2.094	2.500	2.500
m	0.666	0.600	0.600
θ_s (cm^3/cm^3)	0.410	0.400	0.400
θ_r (cm^3/cm^3)	0.031	0.031	0.031
K_s (cm/d)	150.000	150.00	10.00
$\zeta'(z)$	n/a	0.0238*	
h_{50} (cm)	n/a	250.00*	
p	n/a	5.00*	

* - independent of soil layer

Table 4. Standard errors of measurements for TDR and lysimeter systems during time period of analysis.

Day of Year 167-195, 1995				
	West Lysimeter		East Lysimeter	
Measurement device	θ_v m^3/m^3	depth mm	θ_v m^3/m^3	depth mm
200 mm	0.150	0.300	0.205	0.409
400 mm	0.085	0.342	0.064	0.256
600 mm	0.074	0.442	0.040	0.242
800 mm	0.058	0.463	0.040	0.340
lysimeter	n/a	0.071	n/a	0.075

Note: standard error calculated using:

$$\sigma_m = \frac{\sigma_s}{\sqrt{n}}$$

where: σ_m = standard error
σ_s = standard deviation
n = number of measurements

Figure Captions

Figure 1. Cross-section of lysimeter facility, showing surface monitoring system.

Figure 2. Laboratory-Derived and Model-Calibrated Retention Curves for Vinton fine sand.

Figure 3. Response of West Lysimeter TDR system to daily input of water.

Figure 4. Response of East Lysimeter TDR system to daily input of water.

Figure 5. Water content measurements made with horizontally-installed TDR probes located at 500-mm depth in the West Lysimeter. SE, NE, W indicate the southeast, northeast, and west locations in the lysimeter. Average is the average of the three water contents at each time.

Figure 6. Water added as measured by TDR using different length probes versus water added as measured by lysimeter. Numbers under graph label are probe lengths. Solid line is best-fitted regression line, and dashed line is 1:1 line.

Figure 7. Water added as measured with TDR probes of four different lengths, minus water added as measured by lysimeter. The vertical lines represent days when the bermudagrass was cut. Graph A represents West Lysimeter and Graph B represents East Lysimeter.

Figure Captions - Continued

Figure 8. Water loss as measured by TDR using different length probes versus water added as measured by lysimeter. Numbers under graph label are probe lengths. Solid line is best-fitted regression line, and dashed line is 1:1 line.

Figure 9. Sum of water lost from the root zone during 7-day soil drydown experiment on West Lysimeter.

Figure 10. Results of HYDRUS modeling during active irrigation. Solid line represents water contents collected by TDR. Dashed line presented predictions using the HYDRUS model.

Figure 11. Observed (TDR) and predicted (HYDRUS) average water contents for soil in the West Lysimeter during drydown experiment. Observed and predicted water contents were averaged over the depth of the TDR probe given in each figure.

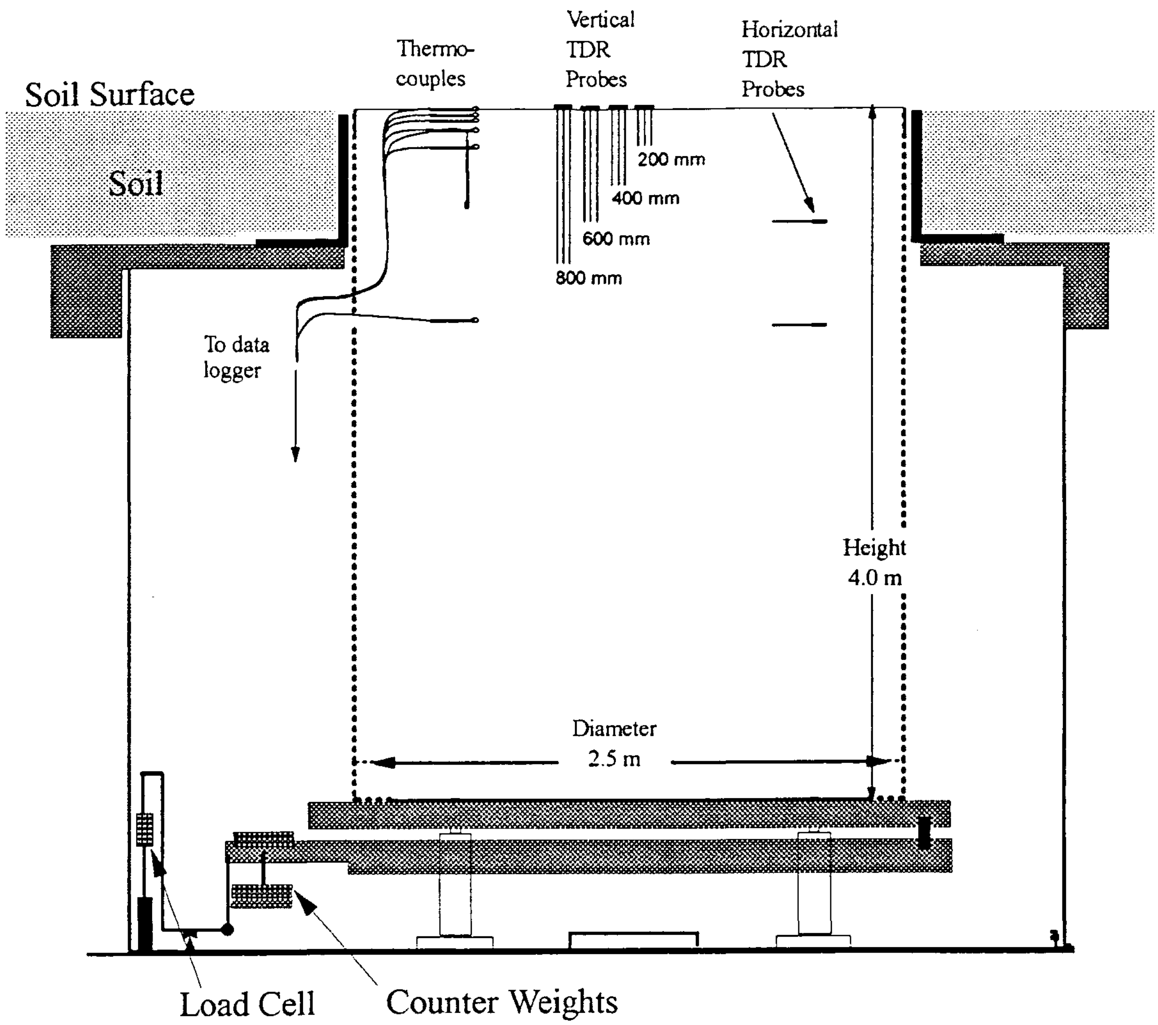


Figure 1. Cross-section of lysimeter facility, showing surface monitoring system.

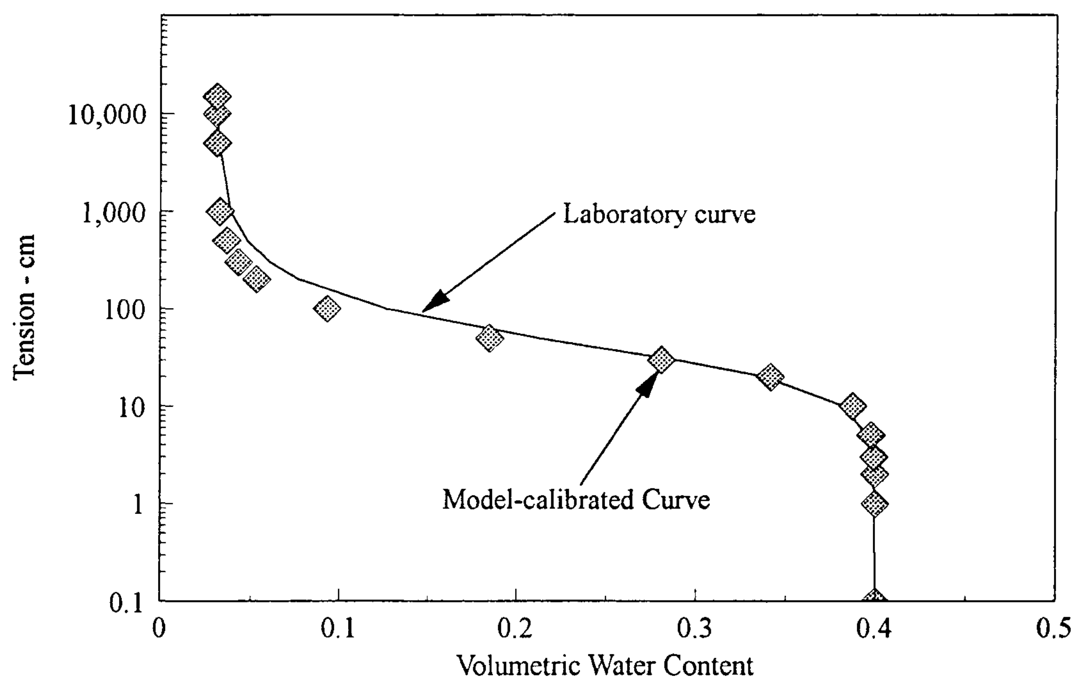


Figure 2. Laboratory-derived and model-calibrated retention curves for Vinton Fine Sand.

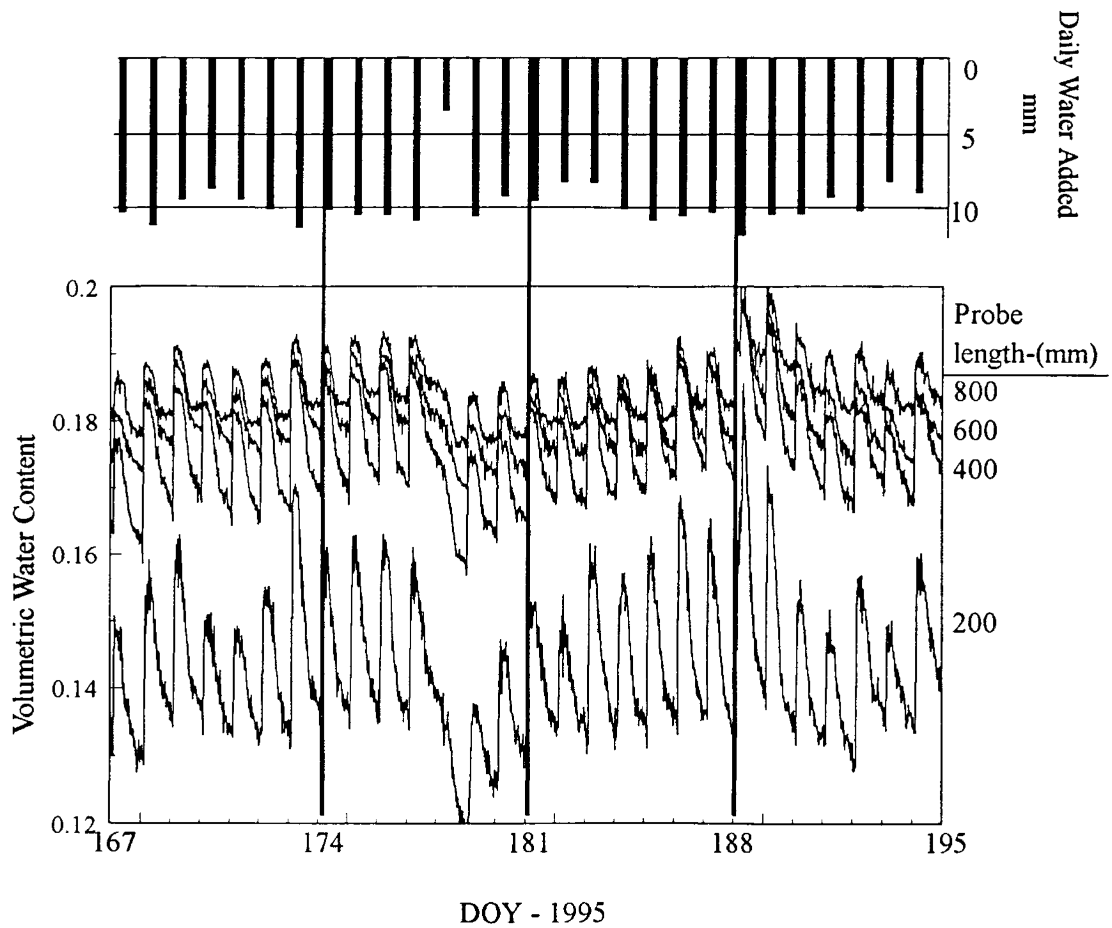


Figure 3. Response of West Lysimeter TDR system to daily input of water.

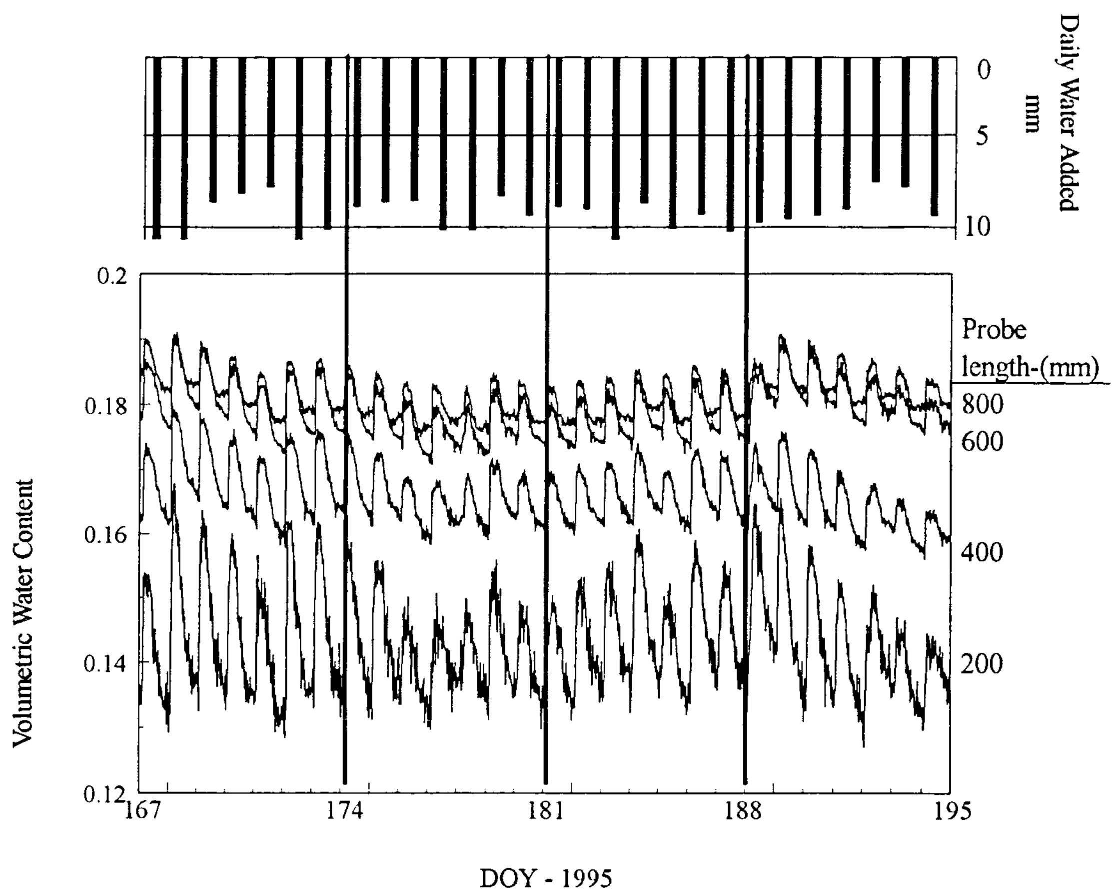


Figure 4. Response of East Lysimeter TDR system to daily input of water.

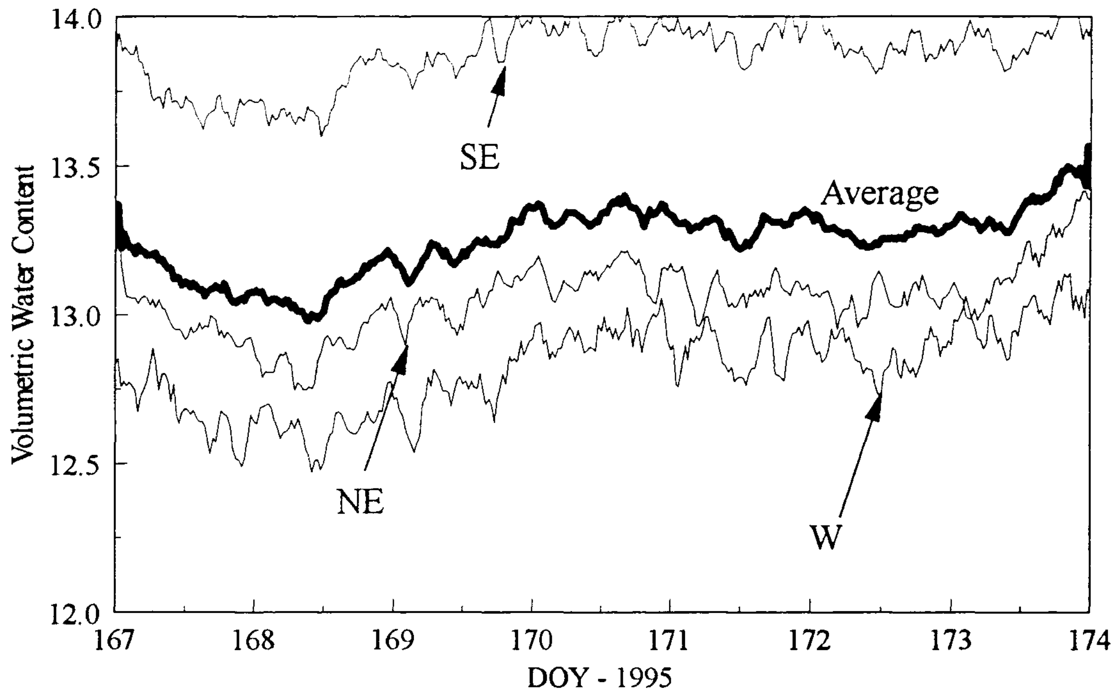


Figure 5. Water content measurements made with horizontally-installed TDR probes located at 500-mm depth in the West Lysimeter. SE, NE, W indicate the southeast, northeast, and west locations in the lysimeter. Average is the average of the three water contents at each time.

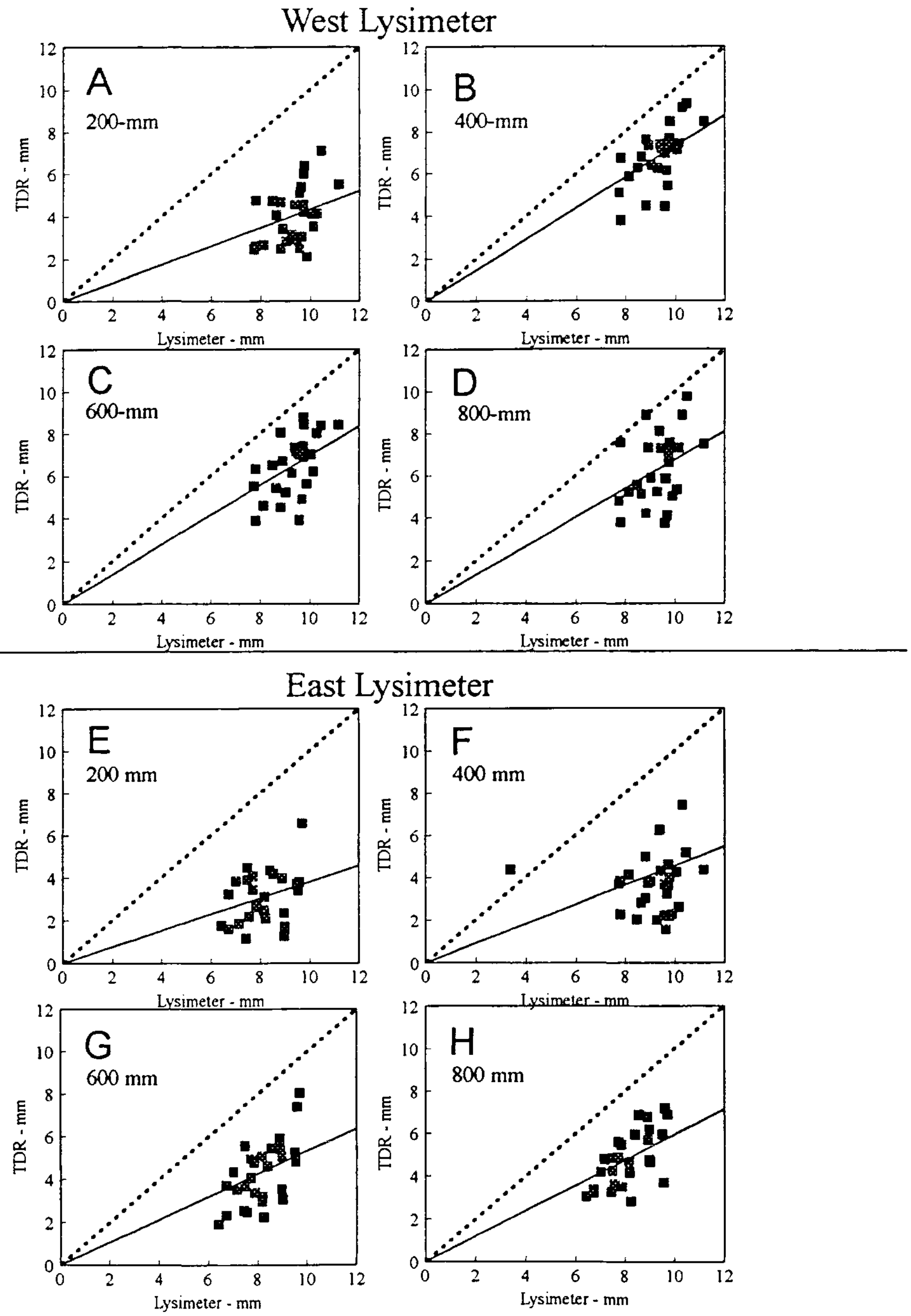
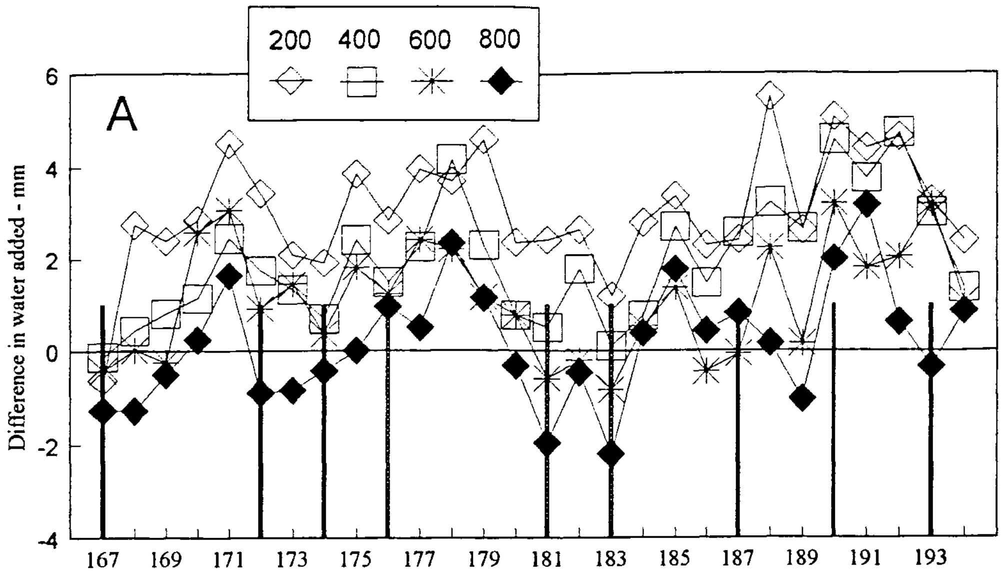


Figure 6. Water added as measured by TDR using different length probes versus water added as measured by lysimeter. Numbers under graph label are probe lengths. Solid line is best-fitted regression line, and dashed line is 1:1 line.



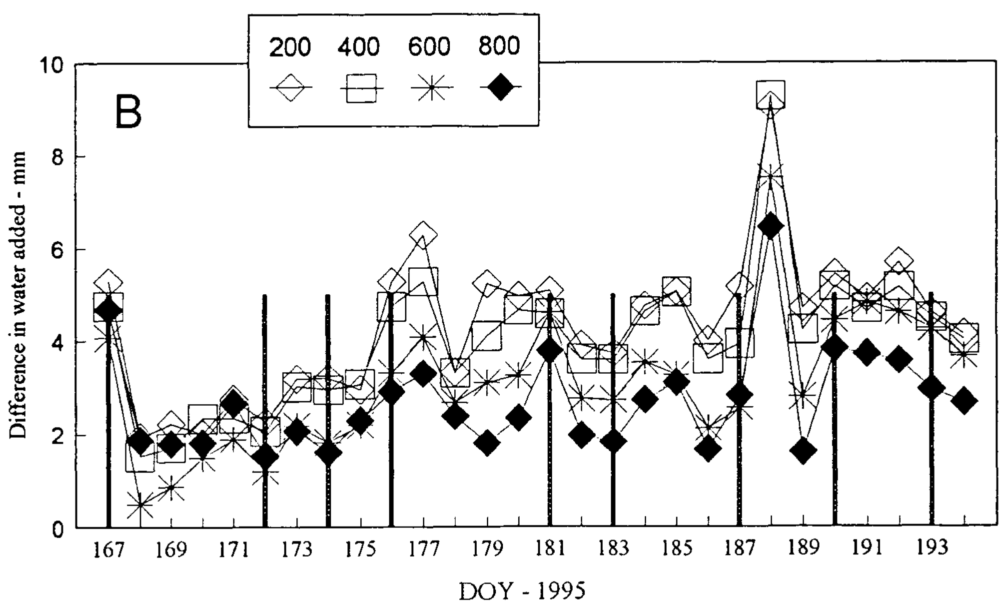


Figure 7. Water added as measured with TDR probes of four different lengths, minus water added as measured by lysimeter. The vertical lines represent days when the bermudagrass was cut. Graph A represents West Lysimeter and Graph B represents East Lysimeter.

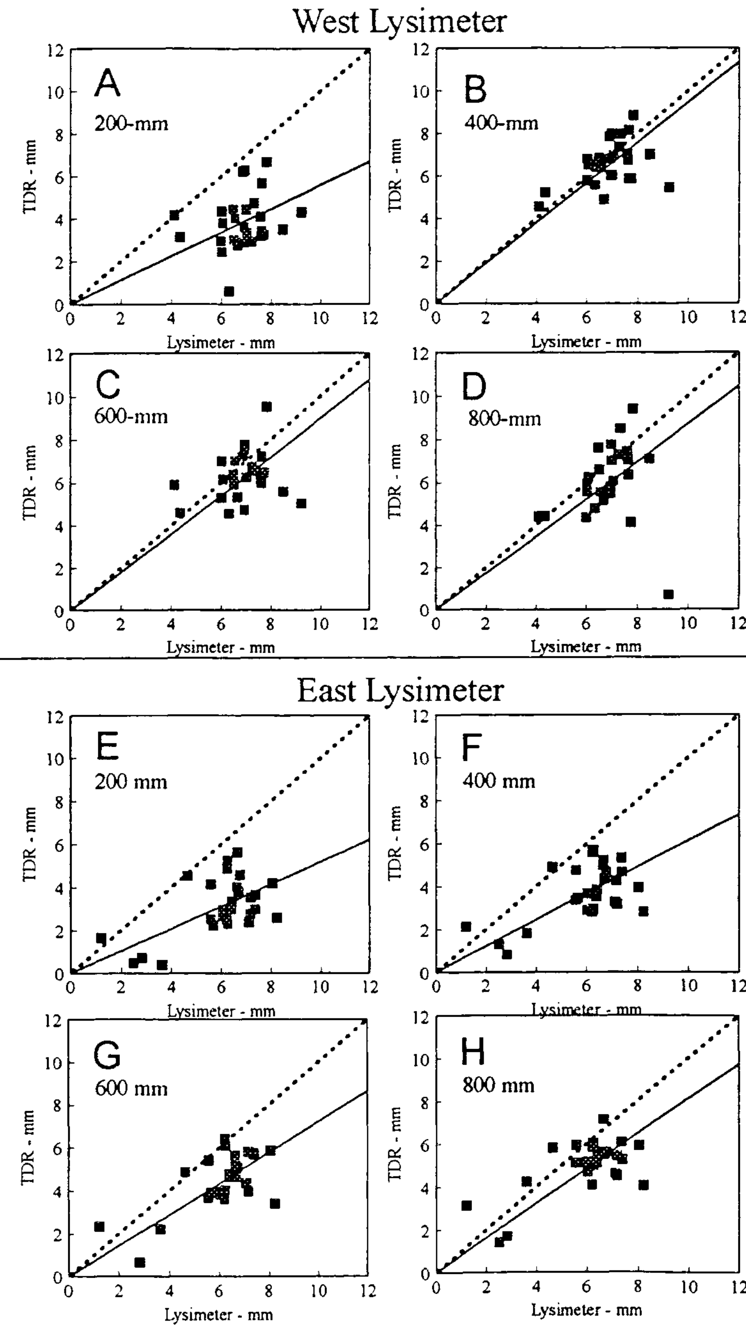


Figure 8. Water loss as measured by TDR using different length probes versus water added as measured by lysimeter. Numbers under graph label are probe lengths. Solid line is best-fitted regression line, and dashed line is 1:1 line.

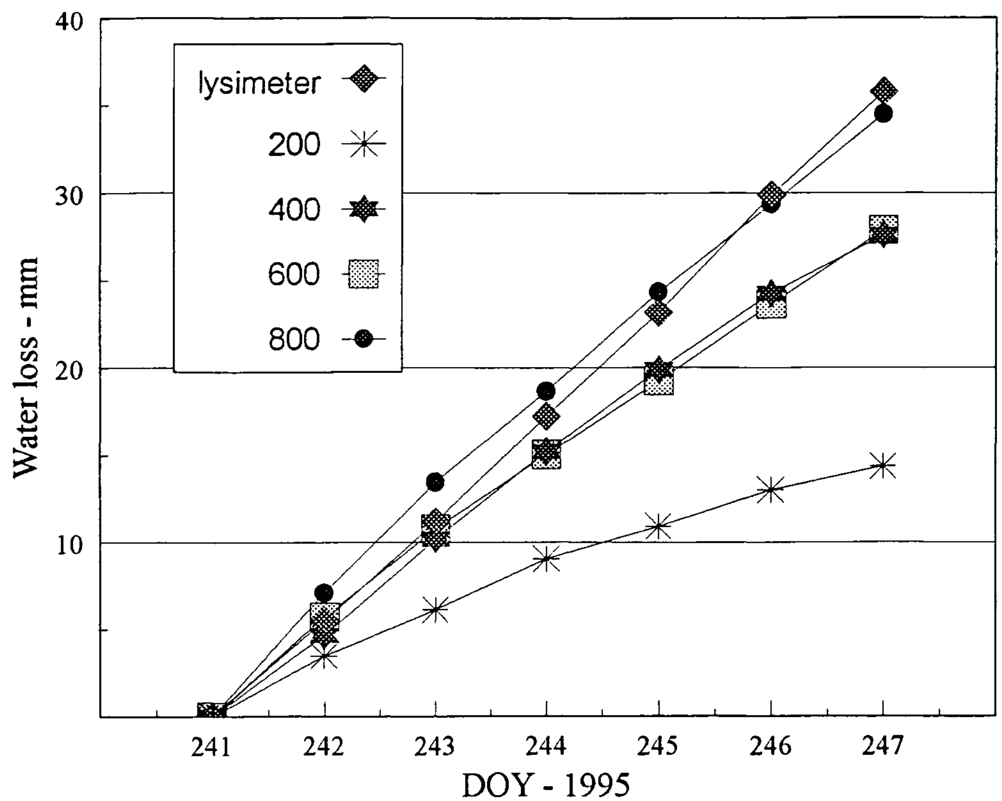


Figure 9. Sum of water lost from the root zone during 7-day soil drydown experiment on West Lysimeter.

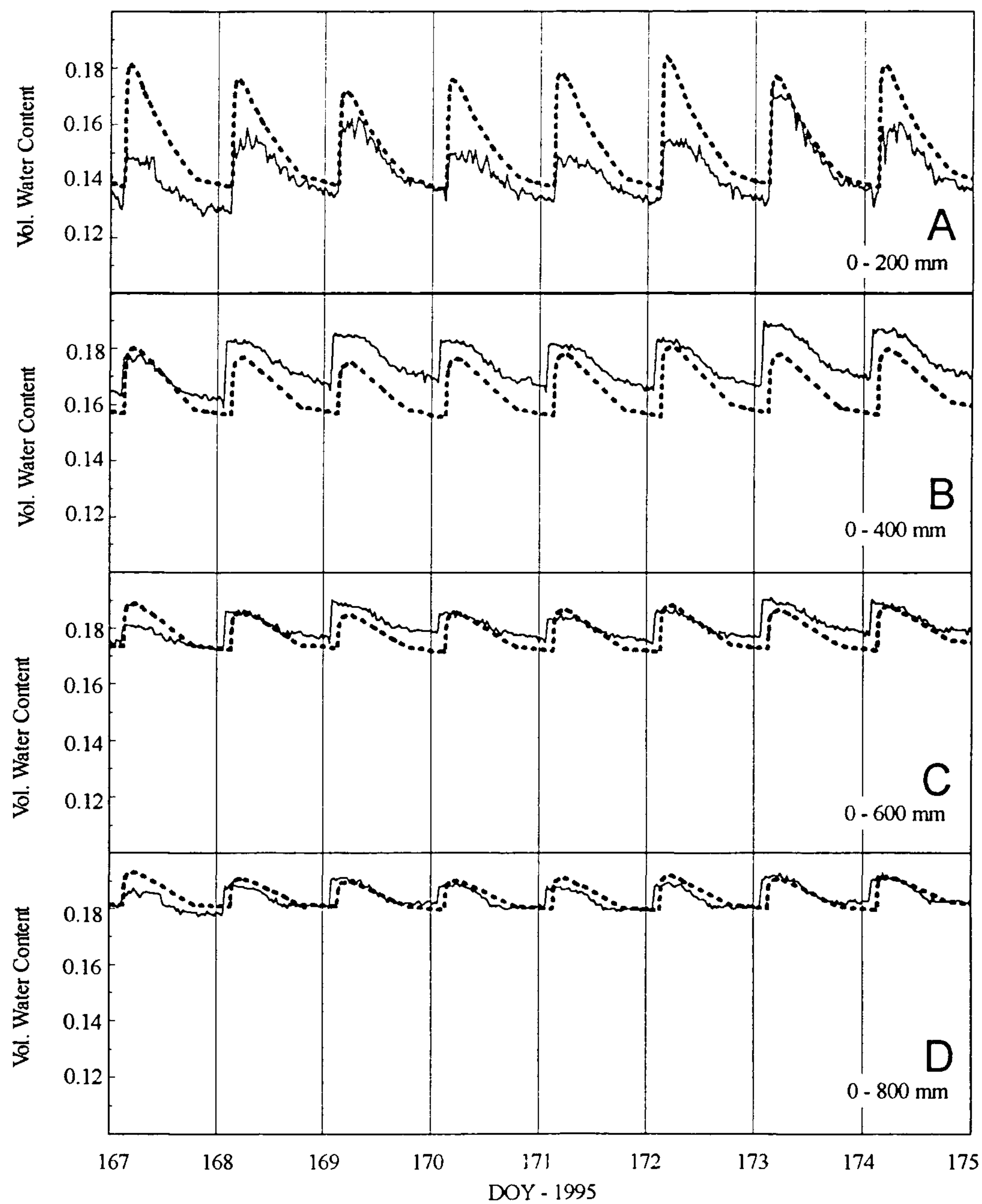


Figure 10. Results of HYDRUS modeling during active irrigation. Solid line represents water contents collected by TDR. Dashed line presents predictions using HYDRUS model.

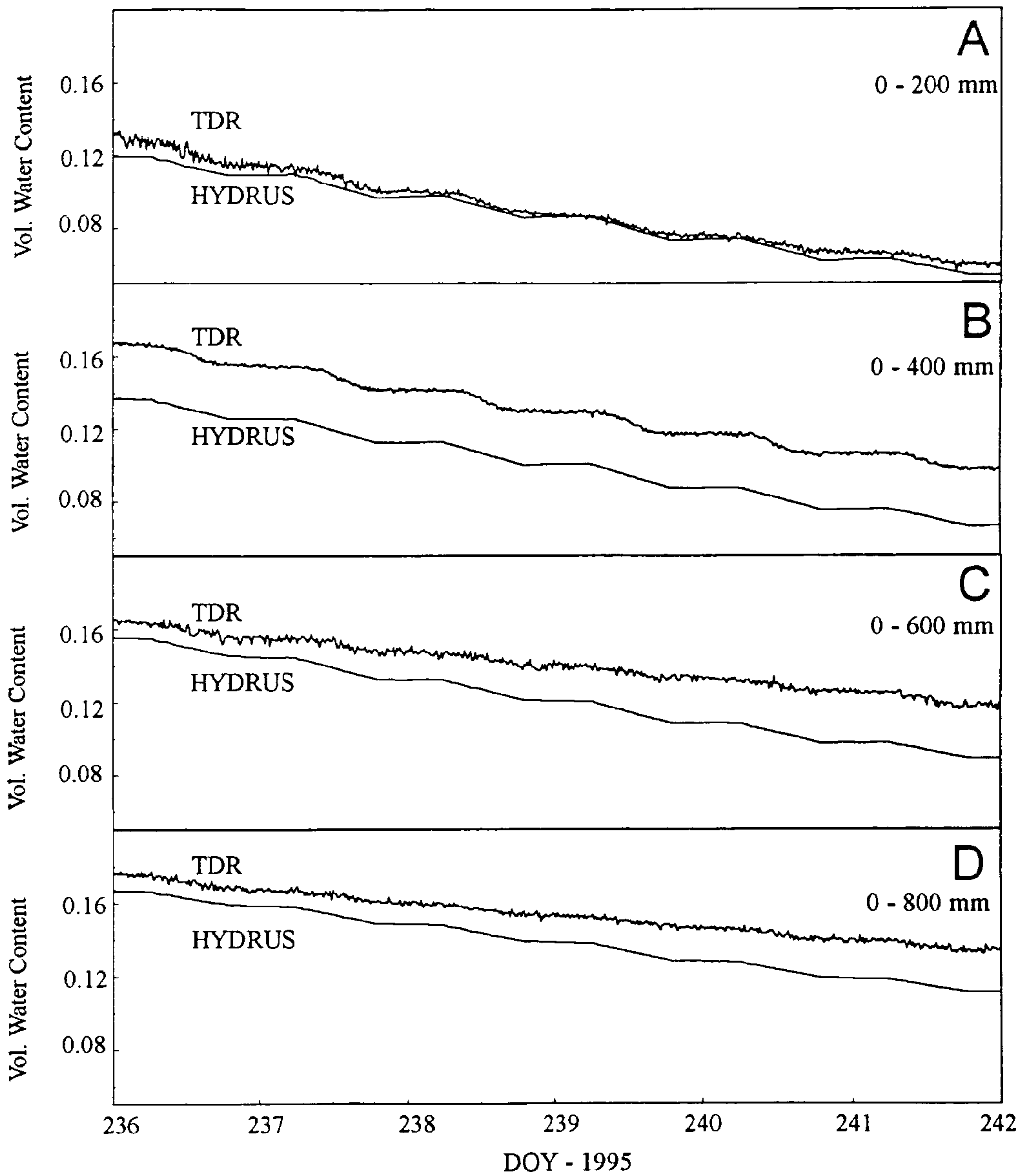


Figure 11. Observed (TDR) and predicted (HYDRUS) average water contents for soil in the West Lysimeter during drydown experiment. Observed and predicted water contents were averaged over the depth of the TDR probe given in each figure.

REFERENCES

Kool, J.B. and M. Th. van Genuchten. 1991. HYDRUS, version 3.3.1. User's Manual for the One-dimensional variably saturated flow and transport model. U.S. Salinity Laboratory, USDA-ARS, Riverside, CA.