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PURPOSE

The purpose of *USGA Turfgrass and Environmental Research Online* is to effectively communicate the results of research projects funded under USGA's Turfgrass and Environmental Research Program to all who can benefit from such knowledge. Since 1983, the USGA has funded more than 350 projects at a cost of $30 million. The private, non-profit research program provides funding opportunities to university faculty interested in working on environmental and turf management problems affecting golf courses. The outstanding playing conditions of today's golf courses are a direct result of ***using science to benefit golf***.

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Testing Rootzone Materials and Monitoring the Performance in Putting Greens using a TDR-tension Infiltrometer

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SUMMARY

North Dakota State University scientists investigate the use of TDR (time domain reflectometry)-tension infiltrometry methods to predict rootzone water content and movement. The study's findings include:

- Adjusting the wetting solution and procedures provides little improvement in the consistency of results for the current testing methods for putting green materials predominant in sand.
- Expanding the capillary porosity test to water release curve provides more information on hydraulic properties of the rootzone materials. One of the advantages is the prediction of total water and air capacity in the whole rootzone.
- In TDR-infiltrometer method water retentions and water conductivity are measured simultaneously. This eliminated the compaction after water retention measurement and before water conductivity measurement as in the traditional procedures.
- Measurement with TDR-infiltrometer is conducted in unsaturated range and reduced the effect by degree of saturations.
- Devices used in TDR-infiltrometer method are specially manufactured instruments and are more accurate and consistent than traditional methods.

The golf boom in the United States after the World War II stimulated many practical changes in golf putting green construction. One of the adjustments is increased use of sand as an amendment to the native push-up greens or using pure sand as putting green rootzone material. As a result of the research conducted in the 1950s, sand-based green specifications were generated by the USGA Green Section. These specifications have been revised several times since they were first published (8). The uniqueness of USGA green is the inclusion of a gravel layer below the sand profile thus creating a hanging water table, also called a "perched" water table. With an optimum size of sand particles, the rootzone can provide sufficient air space and remain less vulnerable to compaction. The artificially created water table helps to hold water, and the amount may be further increased by adding organic materials or inorganic soil amendments to the sand.

To meet the USGA specifications, the material has to satisfy certain standards. Presently, USGA recommends that total porosity be 35-55%, non-capillary porosity be 15-30% and capillary porosity be 15-25%. The current USGA recommendation listed saturated water conductivity of at least 6 inches hr^{-1}.

Using a TDR-equipped tension infiltrometer can also be used to monitor water conductivity *in situ* in the field and allows direct agronomic interpretation and comparison of laboratory test results.

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	Soil Separate			Sand Particle Diameter					
	Sand	Silt	Clay	Gravel 2 mm	Very Coarse 1 mm	Coarse 0.5 mm	Medium 0.25 mm	Fine 0.15 mm	Very Fine 0.05 mm
	-----------(%)-------------			----------------------------------(% Retained)--------------------------------					
Sand I	99.96	0.03	0.01	0.04	8.57	36.78	37.89	14.14	2.53
Sand II	99.28	0.57	0.15	0.28	3.78	21.79	40.19	21.01	12.23
Desired Values		≤ 5%	3%	≤ 3% Gravel ≤ 10% Combined		≤ 60%		≤ 20%	≤ 5%

Table 1. Particle analysis of the testing material used in the study.

It is important the material being tested before, during, and after the construction of the putting greens for the purposes of contracting, quality control, and inspection. The testing of physical properties starts with the particle size analysis which dictates other properties. The confidence interval for particle size analysis is +/-10 to +/- 35%, and that for water conductivity is +/- 20% using the USGA specified procedures. Confidence intervals (CIs) are used to compare differences between loads as they are mixed and are for quality control purposes. For instance, if the standard drains at 10 inches per hour, then each subsequent load should drain between 8 and 12 inches per hour based on the 20% CI for K_{sat}.

The inconsistency of those test results for rootzone materials between and within the labs has caused inconvenience in bidding and contracting processes during the construction. At times, architects, contractors, and superintendents did not know how to use the results and were applying much more stringent criteria than the K_{sat} tests were able to meet. Saturated water conductivity, K_{sat}, has been a magic phrase among golf course superintendents when talking about the greens. From the agronomical point of view, saturated water flow occurs only for a short period during a rain or irrigation event. Saturated water conductivity is only one fraction of the water movement characterizing rootzone materials. More information is needed on the unsaturated flow of water to better understand the rootzone materials. A superintendent may also want to know how saturated

		Capillary porosity (30 cm suction head)			
	Testing Solution	**Sand I**	**Sand II**	**Sand I:Peat (9:1)**	**Sand II:Peat (9:1)**
	---% (SD)--				
Wetting Pressure					
Saturation at ATM	Tap water	8.6 (0.08)	12.5 (0.12)	14.8 (0.17)	18.4 (0.23)
	Deionized water	8.8 (0.07)	13.4 (0.12)	15.4 (0.16)	19.8 (0.24)
	$CaSO_4$	8.3 (0.09)	11.2 (0.15)	12.6 (0.16)	16.4 (0.26)
Saturation at Vacuum	Tap water	10.4 (0.10)	16.3 (0.12)	15.8 (0.14)	20.5 (0.22)
	Deionized water	8.9 (0.07)	14.0 (0.10)	15.0 (0.14)	20.6 (0.19)
	$CaSO_4$	11.0 (0.10)	17.4 (0.14)	18.2 (0.23)	21.0 (0.30)

Table 2. Capillary porosity measured with different wetting solution and wetting conditions. It is commonly believed that the concentration of testing solution should be as close as possible to the soil solution so that no dispersion or reaction will affect soil structure. As shown here, the testing solution is not very critical for a sand-dominated medium, but using vacuum facilitated wetting does improve the saturating process.

	Testing Solution	K_{sat} Sand I	Sand II	Sand I:Peat (9:1)	Sand II:Peat (9:1)
		--------------------------------cm hr-1 (SD)----------------------------------			
Wetting Pressure					
Saturation at ATM	Tap water	51.3 (3.0)	38.2 (3.8)	40.4 (3.1)	26.8 (2.1)
	Deionized water	54.6 (4.6)	35.7 (5.2)	36.2 (2.8)	22.9 (5.0)
	$CaSO_4$	53.7 (3.0)	39.1 (4.0)	41.8 (3.3)	25.4 (4.2)
Saturation at Vacuum	Tap water	54.6 (3.4)	46.2 (3.5)	52.0 (4.6))	35.2 (3.0)
	Deionized water	58.2 (5.1)	43.7 (4.1)	38.6 (4.4)	32.5 (3.4)
	$CaSO_4$	59.4 (2.9)	40.4 (3.7)	39.1 (3.8)	36.9 (3.2)

Table 3. Saturated water conductivity measured with different wetting solution and wetting conditions. Again, the testing solution is not very critical for a sand-dominated medium, but using vacuum during wetting does improve the saturating process and increase the measured values of water conductivity.

water conductivity changes over time and how it is affected by cultural practices.

The primary objective of this study was to develop a methodology that allows easy measurement and monitoring of water conductivity of rootzones without the need for destructive sampling. Some academic exercises were also involved to investigate factors that influence the accuracy and consistency of saturated water conductivity tests such as the soil packing process, dissolved air in testing water, wetting direction, and organic matter.

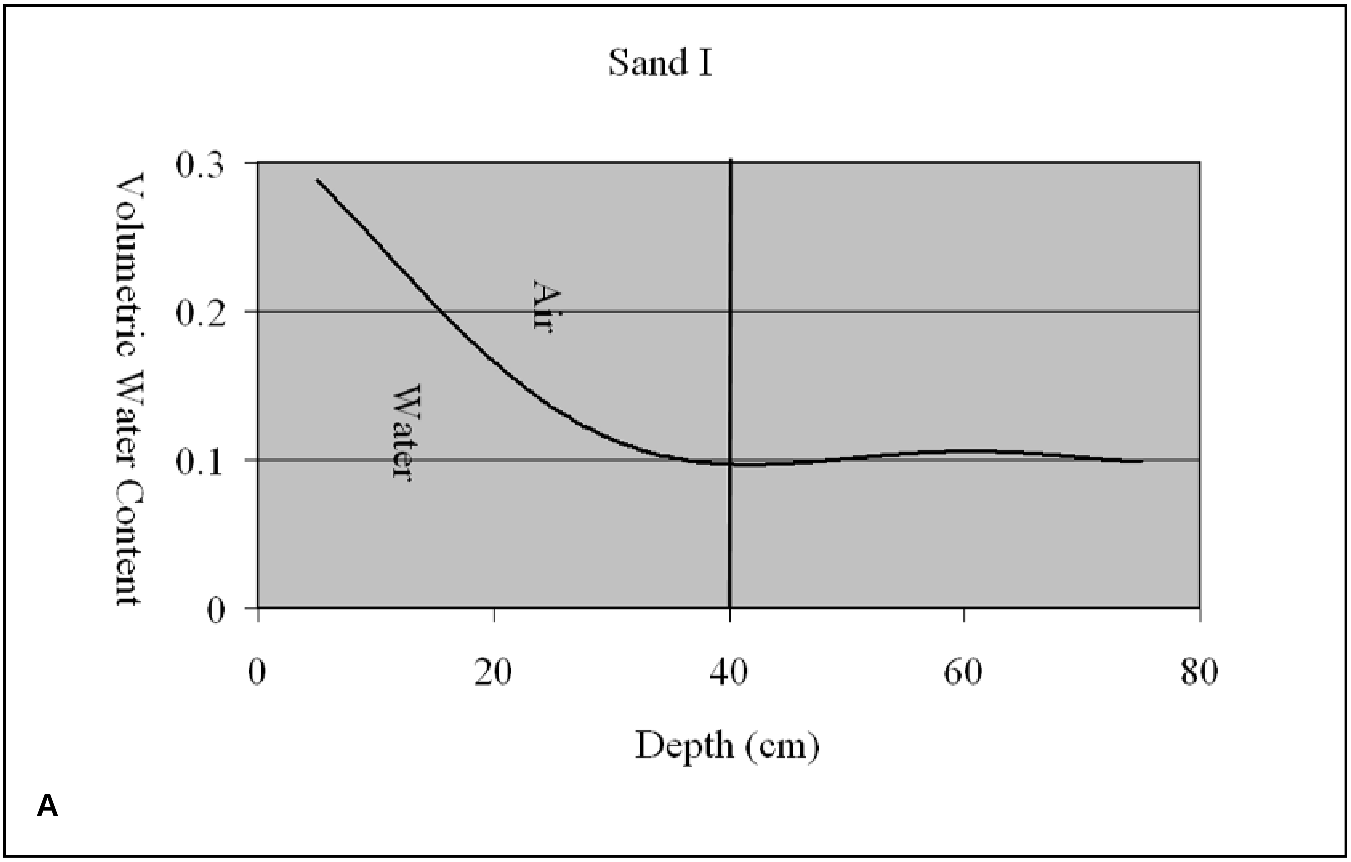
Water Conductivity Affected by Measuring Methods

Two sand sources were included in the study (Table 1). Sand I conformed to USGA specifications, while sand II was higher in the fine fraction. The soil materials were packed into brass rings at a moisture condition of 8%.

Calcium sulfate ($CaSO_4$)-thymol solution was prepared following the procedure by Klute and Dirksen (5). Thymol was used to inhibit the growth of micro organisms in the solution. Dissolved air was removed using a vacuum boiling apparatus prior to the use for measuring water release and conductivity.

Before the testing of capillary porosity, water retention curve, and water conductivity, soil samples were saturated either at normal atmospheric pressure or under a vacuumed condition with three test solutions: tap water, deionized water, and calcium sulfate-thymol solution. Since water conductivity increases exponentially with degree of saturation, a small variation at the saturating point can cause dramatic differences in saturated conductivity. The purpose of these procedures was to test if improvements made in the degree of saturation can help improve consistency of saturated water conductivity measurements. Tap water might disperse soil aggregates and cause underestimation of water conductivity, calcium sulfate was used to increase the concentration of testing water. The results are shown in Table 2.

Using deionized water or calcium sulfate - thymol solution did not seem to improve the consistency in the measurement of water holding capacity and water conductivity. One of the reasons might be the low clay content and lack of soil structure in the testing materials. Saturating the soil material under reduced pressure generally provided higher estimation of water conductivity (Table 3) without much improvement in consistency. This lead us to believe that other random errors induced during the sample preparation and testing process maybe underlying reasons for the



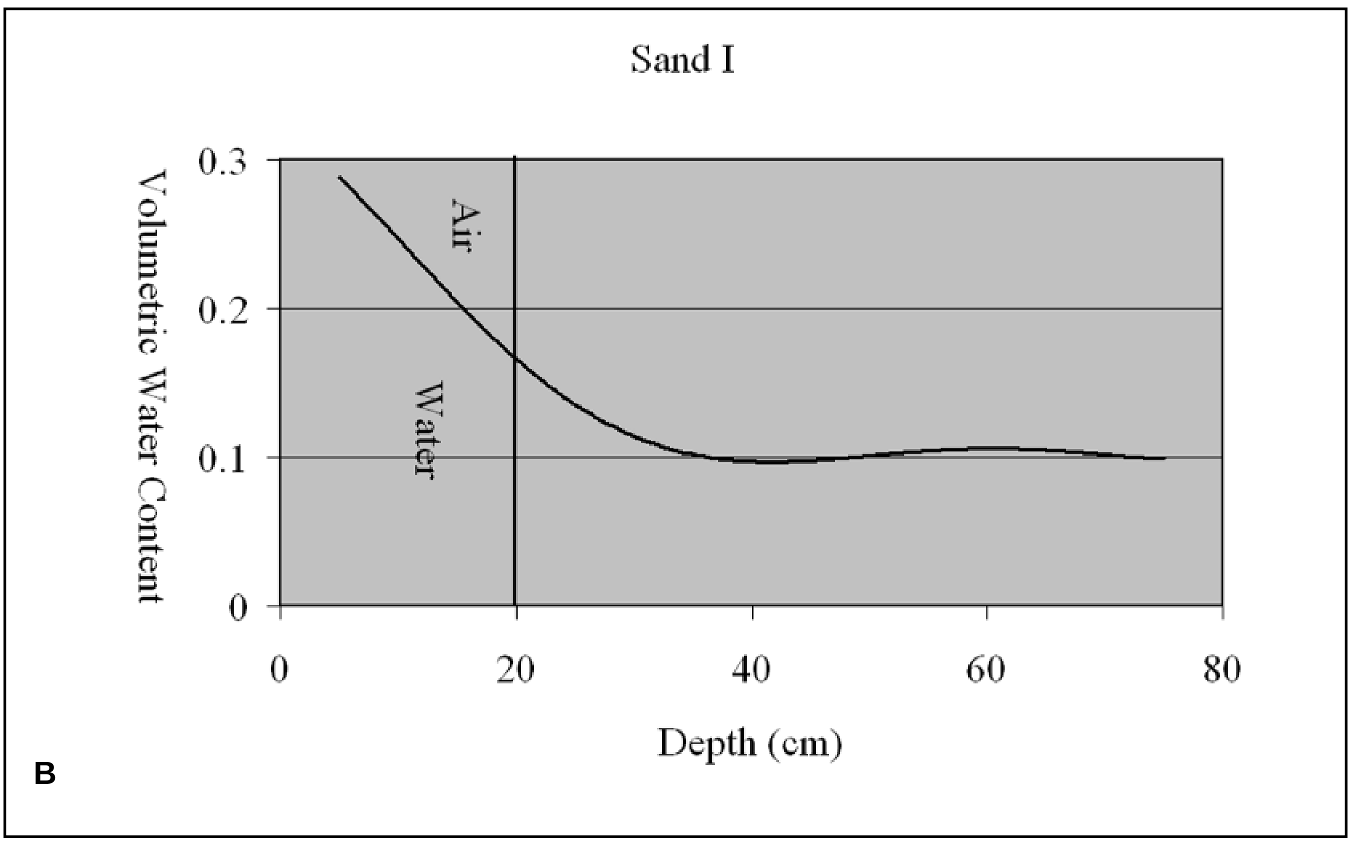
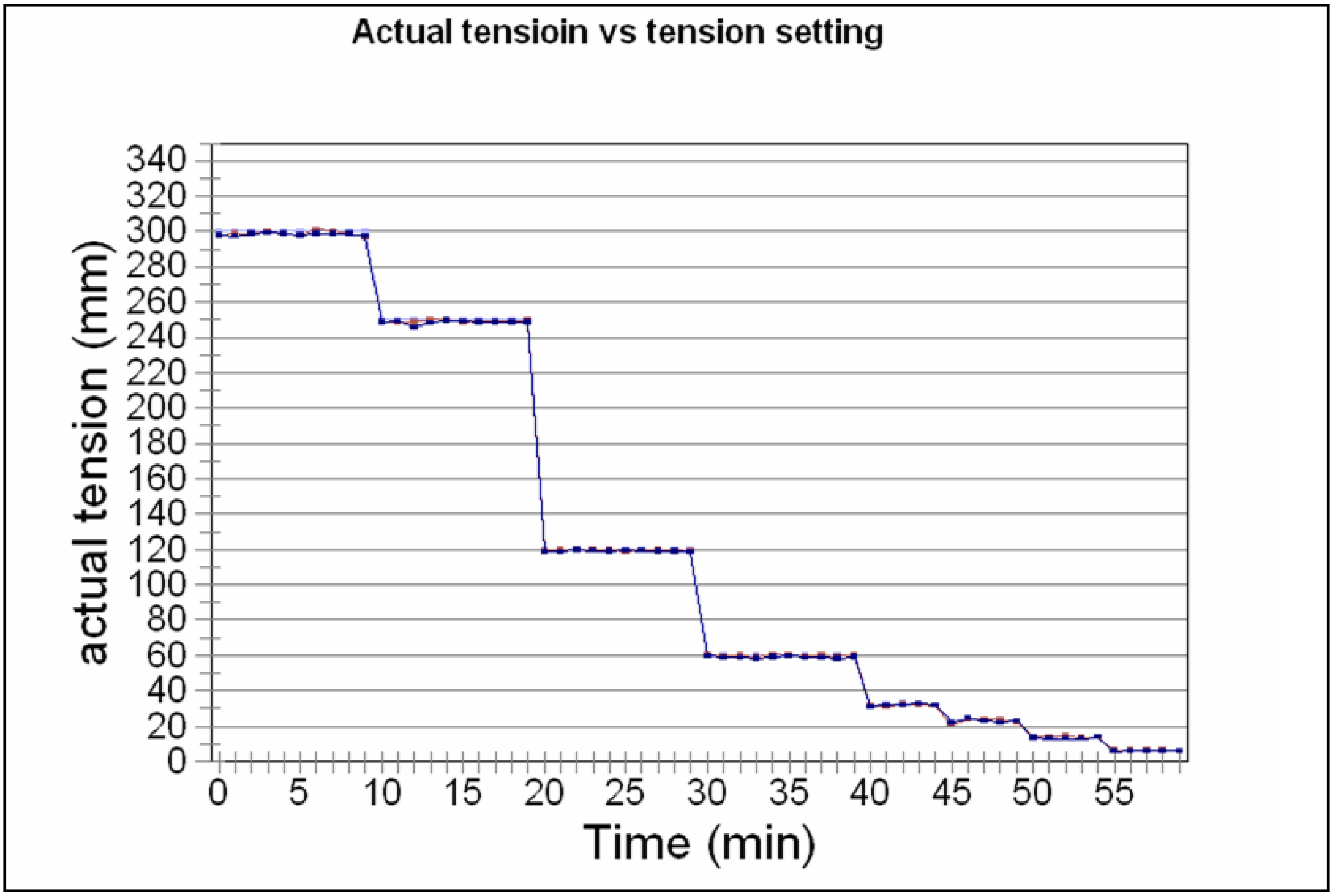


Figure 1. Comparing water and air capacity between 40-cm (A) and 20-cm (B) depth rootzones using the water-release curve generated from Sand I. Another way to look at this figure is rotate the figures 90 degree counter-clockwise and visualize the rootzone depth from the bottom. The total air and water capacity ratio changes as you change the rootzone depth.



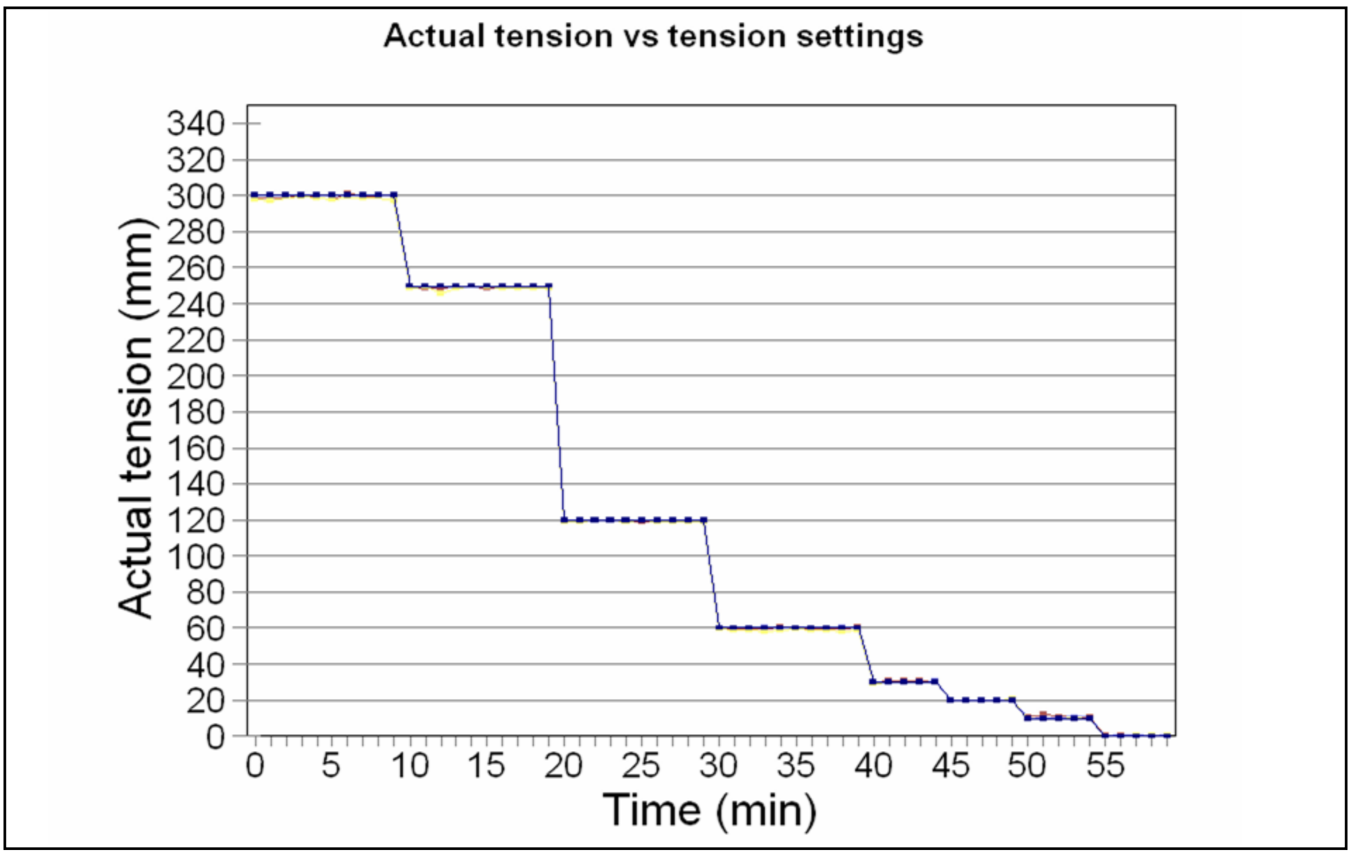


Figure 2. Actual tensions at the bottom of tension infiltrometer disk at different settings of tensions. a). Sand I b). Sand II.

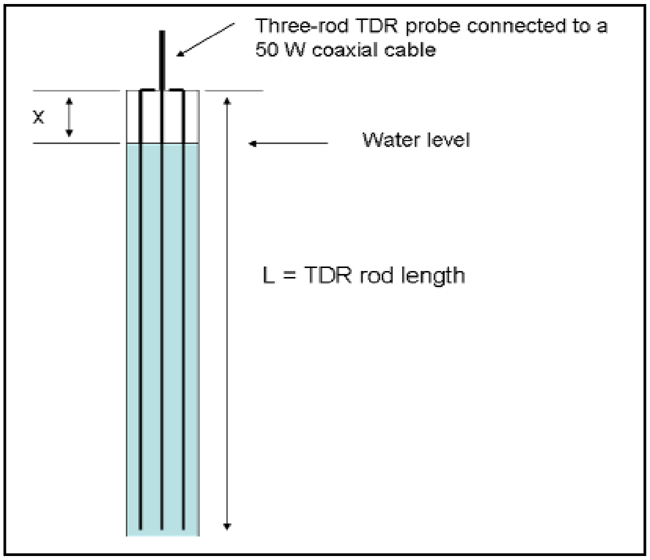


Figure 3. The design of TDR-equipped tension infiltrometer

poor repeatability. Since sand particle size distribution is fundamentally responsible for the pore size distribution and water conductivity, it is very important to have accurate estimation of the particle size analysis. This is especially true when organic materials are incorporated in the rootzone because a thorough mixing is very difficult to achieve.

Although there were large variations in saturated water conductivity, it may not be as problematic as commonly considered from the agronomic point of view. Saturated flow rarely happens under the real putting green conditions, and if it does happen, it is in a different way from the laboratory test where saturation starts from the bottom of the sample. Furthermore, saturated water conductivity decreases quickly as the green ages due to migration of fine particles, accumulation of fine organic materials, and layering. Essentially, good drainage is maintained through diligent cultural practices providing correct materials were used in the construction and for topdressing.

Including a water release curve in the current specified tests can be useful to bridge the gap between perception and reality. Water release curves provide more balanced information on hydraulic properties of the rootzone materials in addition to water holding capacity and saturated water conductivity. Instead of debating the pressure heads to be used to determine air porosity, water release curves allow the end user to interpret water holding capacity and air porosity based on the rootzone depth.

A separate study was conducted to test the hypothesis of varying depth putting green for water regime control (6). As shown in Figure 1, when the water release curve is rotated 90 degrees, total air and water volumes, as indicated in the figures, are determined by rootzone depth (0 being the bottom of the rootzone). Contrary to the traditional air porosity report which reflects only the average across the depth of soil core being used in the test, using the whole water release curve can provide information of air and water in the whole profile.

Water content and air capacity can be pre-

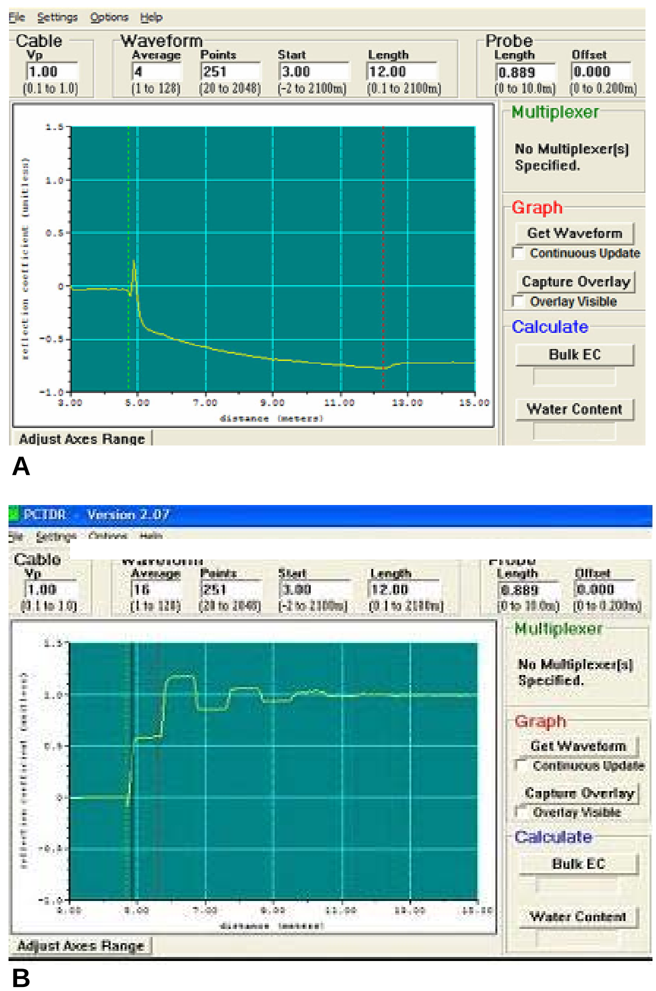


Figure 4. TDR evaluation in TDR-infiltrometer. A). Dielectric constant measurement in water, and B) dieclectric constant measurement in the air. The difference between the two graph shows the distance between the first reflection and the second reflection. In graph A, the distance at 100% water content is large with a bathtub shape, meaning that there can be better resolution for water content measurement.

dicted from the water release curve using van Genuchten equation (10, 11). Graphically, the water capacity is the area to the right of the curve enclosed by the curve, axis, and soil depth line, while the air capacity is the area to the left of the curve enclosed by the curve, the top line of water content, and the line of soil depth. In this case, the total water and air capacity is 20% and 10%, instead of 10% and 20%, respectively, for the 40-cm deep rootzone. The water content and air capacity would be 25% and 5%, instead of 17% and 13%, respectively, for the 20-cm deep rootzone.

Development of TDR-tension Infiltrometer

A tension infiltrometer equipped with a differential transducer as described by Casey and Derby (3) was used to measure water infiltration in the lab and in the field. Calibration of transducer was conducted on a suction table from saturation to 350 mm on 10 mm increments. A linear regression equation (r^2=0.99) was achieved between the voltage reading and the tension setting. Water tension at the bottom of the disk was monitored from the transducer by closing the water inlet briefly and checked against the flow rate of water.

Soil samples were also packed in brass rings 10 cm in diameter and 10 cm tall to a bulk density of 1.55 g/cm^3. Water infiltration was tested on the repacked soil cores and in the field using a TDR-tension infiltrometer. Materials were tested on 300, 250, 120, 60, 30, 20, 10, and 0 mm tension settings for 10 minutes for the first four settings and 5 minues for the last four settings. Transducer was logged every second for the first one minute and every two seconds afterwards. Water conductivity for 3-D infiltration in the field was calculated following a nonlinear regression method (7). Water conductivity of one-dimensional infiltration was calculated by the method described by Klute and Dirksen (5).

The tensions at the bottom of the infiltration disk were very close to the set tensions except minor differences for the Sand I (Figure 2). The discrepancy was contributed to the high flow rate at near saturation. The problem can be corrected through increasing the diameter of the connecting tube from the water reservoir to the infiltration disk and reducing the friction loss of the pressure head from the valves and fittings.

With inclusion of water measuring probes, such as TDR (time domain reflectometer), the water content can be measured during the same process of measuring water conductivity. The whole process can be automated to measure and estimate the major soil hydraulic properties at the same time with the same set up reducing human error and operation time.

Tensiometers were built with the same principle as described by Ankeny, et al. (1). Two dimensions of the infiltration disk were manufactured, 10 cm and 20 cm in diameter. The three-rod probes are 86 cm long, 0.25 cm in diameter, and spaced 1.5 cm apart (Figure 3). The performance of TDR probe was evaluated with a TDR-100 time domain refelectrometery (Campbell Scientific, UT) with water and air, respectively (Figures 4a and 4b). As indicated, the wave form provided enough resolution for precise measurement of water depth which was calculated from L-x,

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

where x is the distance of water surface to the top of the water supplying tower.

Sand materials were prepared as in Study I in a PVC-tube 10 cm in diameter and 7.8 cm in length with a double layer of cheese cloth attached at the bottom with a rubber band. At the side of the PVC tube, three access holes were drilled to insert a three-rod TDR probe with length of 5 cm. Both TDR probes in the soil and the TDR probe in the infiltrometer were multiplexed via a SDMX50 multiplexer to a data logger.

The performance of TDR automated water level measurement was compared with differential pressure transducer automated and visual observation (Figure 5). Water level measurement automated with TDR is as good as, or better than, differential pressure transducer automated measurements.

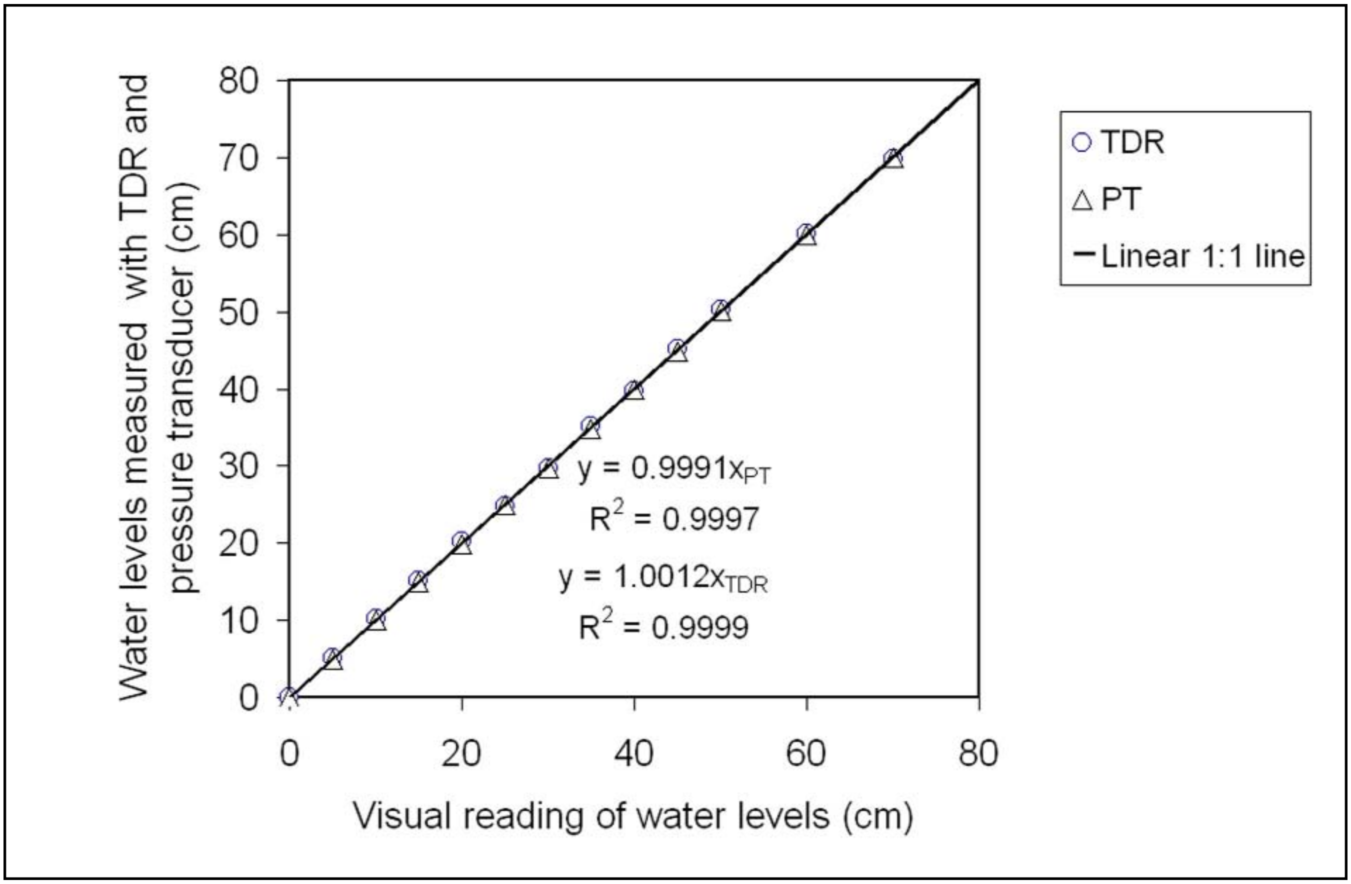


Figure 5. Comparison of accuracy of automated water level measurements of TDR, Pressure Transducer (PT), and visual readings.

Water content and infiltration measured at 10 cm water tension is shown in Figure 6. Soil sorptivity (S) for the laboratory materials were estimated using the differentiated linearization method developed by Vandervaere et al. (9). Saturated water conductivities were calculated according to this method, as well. Water release curve could be established from the tension and water content in the soil cores. Alternatively, air porosity was derived from the water content and bulk density measurement at the 30-cm tension set on the infiltrometer. Both saturated water conductivity and air porosity data are shown in Table 4.

Application of the TDR-tension Infiltrometer

Using the tension infiltrometer equipped with TDR for water level monitoring, we were able to monitor water level without the need for calibration for each measurement, which is required for transducers. Water content in the

Material	K_{sat}		Air Porosity	
	Measured	Estimated	Measured	Estimated
	---------cm hr^{-1} (SD)--------		--------------% (SD)-----------------	
Sand I	51.3 (3.0)	47.2 (2.6)	8.5 (0.08)	8.2 (0.10)
Sand II	38.2 (3.8)	35.4 (2.2)	12.7 (0.11)	11.4 (0.09)
Sand I : Peat (9:1)	40.4 (3.1)	37.8 (2.6)	15.1 (0.16)	13.8 (0.14)
Sand II : Peat (9:1)	26.8 (2.1)	24.1 (1.3)	18.2 (0.20)	16.9 (0.18)

Table 4. Measured (traditional ASTM specified methods) and estimated (TDR-Infiltrometer) saturated water conductivity and air porosity (n=10).

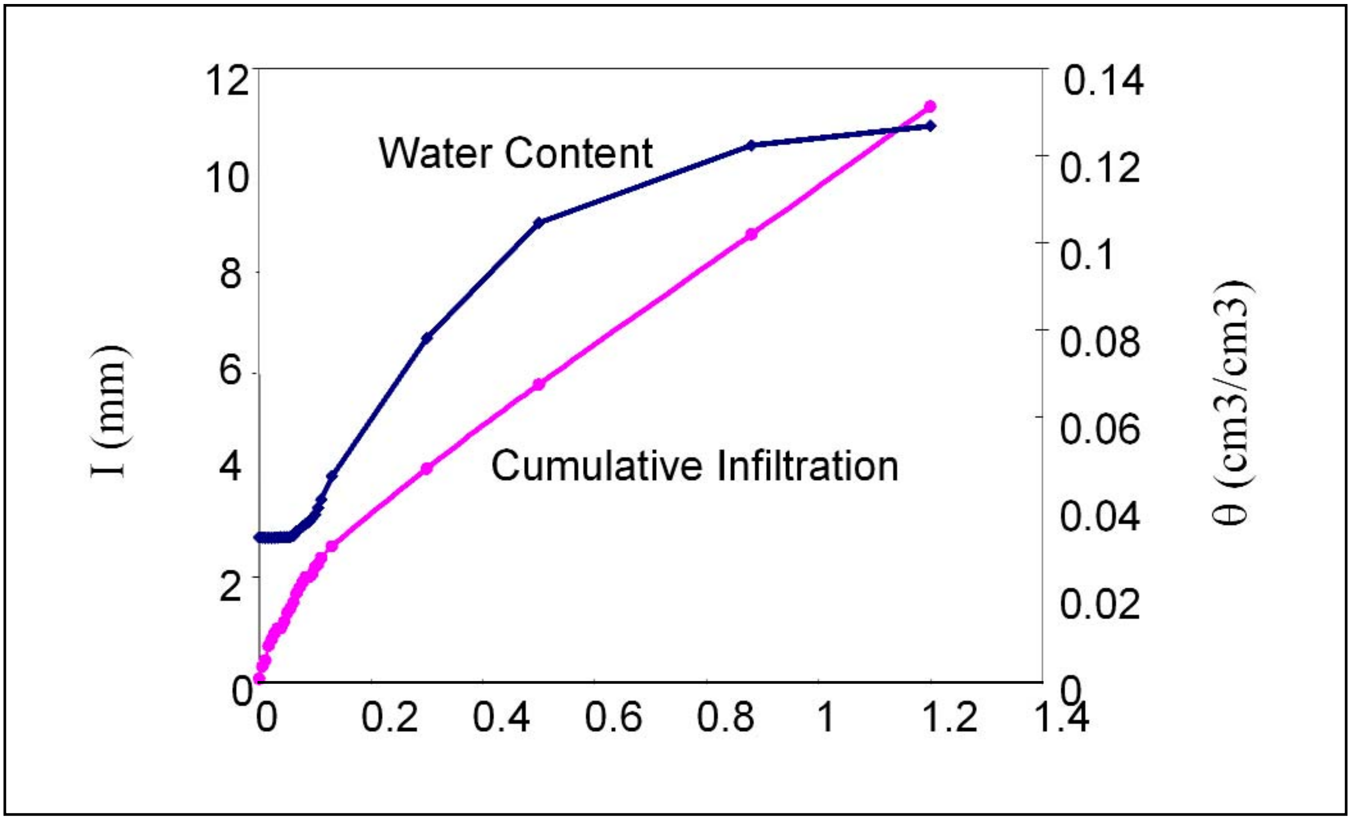


Figure 6. Infiltration and water content measurement of sand/peat mixture. Cumulative water infiltration (mm) is represented by the pink line and water content in the soil core (cm^3/cm^3) is represented by the dark blue line.

sample immediately below the infiltrometer was also measured with a TDR probe at the same time infiltration was measured. Thus, the soil water retention and water conductivity can be measured simultaneously. Whereas in the traditional procedures, water retention and water conductivity are measured in two separate steps.

The following points highlight the differences between the TDR-equipped infiltrometer approach and the traditional approach specified in the ASTM methods.

- The TDR-infiltrometer method uses core soil samples 10 cm in diameter--twice as big as in traditional methods. The TDR-infiltrometer method has less error introduced by marginal flow effects.

- Since water retention and water conductivity are measured simultaneously, compaction of soil samples after water retention measurements and before water conductivity measurement as in the traditional procedures is avoided, thus greatly reducing variations associated with compacting.

- Measurements of the TDR-infiltrometer method is conducted in the unsaturated range of soil samples, thus reduced the inconsistency of saturation which contributes to major vatiation in the water conductivity measurement.

- Wetting direction in the TDR-infiltrometer method is the same for laboratory and field samples. It can also be used to monitor water conductivity *in situ* in the field and allows direct agronomic interpretation and comparison of laboratory test results.

- Devices used in traditional methods are usually fabricated by individual laboratories, while TDR-infiltrometer method uses a more accurate, specially manufactured instrument. The initial cost can quickly be offset by savings in labor and time.

Confidence intervals of the water holding and water conductivity test results can be reduced among and within laboratories. Soil hydraulic properties from the laboratory test can be compared with the field performance because of the consistent methodology. The TDR-infiltrometer method can also be used to collect soil water movement information to be used for subsurface irrigation control and estimation of chemical movement within soil profiles.

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