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Evapotranspiration by Soil Water Balance Using TDR and Neutron Scattering[1]

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Abstract

The soil water balance method of estimating evapotranspiration (ET) has been widely used since it is considerably cheaper than alternative methods such as the use of weighing lysimeters. Neutron scattering (NS) is commonly used to measure soil water content. However, for water balance studies, the method has been criticized as imprecise due to difficulties of measurement near the soil surface. Precision can be improved with destructive soil sampling near the surface but this is incompatible with many cropping and experimental systems. We examined time domain reflectometry (TDR) for measuring near surface soil water contents, combined with NS measurements at deeper depths to achieve a non-destructive estimate of ET. TDR probes were installed at depths of 2, 4, 6, 10, 15, 20 and 30 cm at two locations in a large weighing lysimeter and measured every half hour. Neutron scattering measurements were made at two access tube sites on the lysimeter at depth increments of 20 cm from 10 to 190 cm. For a 16 day period, daily change in soil profile water storage in the top 40 cm of soil, as measured by TDR, averaged 88% of total change in storage measured by the lysimeter. Estimates of ET from TDR based change in storage and precipitation data were inaccurate on many days due to water fluxes through the bottom of the layer measured by TDR. However, the soil water storage, computed by the combined TDR measurements for the surface to 40-cm layer and NS measurements below 40 cm, was within 0.7 mm of that measured by lysimeter whereas change in storage based only on NS was in error by 3.6 mm. A combination of daily NS measurements at depth with TDR measurements near the surface holds potential for accurate daily ET estimation.

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Introduction

Weighing lysimeters have been used for many years for precise (e.g., 0.05 mm) measurement of evaporation (E) and evapotranspiration (ET) from bare and cropped soils (Howell et al., 1991). However lysimeter installations suffer from some serious drawbacks including disturbance of the soil profile, interruption of deep percolation and horizontal flow components and uneven management of lysimeter compared to field soil (Grebet and Cuenca, 1991). Other drawbacks include heat flux distortions caused by highly conductive steel walls (Black et al., 1968; Dugas and Bland, 1991) and high cost, e.g., US$ 65,000 (Lourence and Moore, 1991) and US$ 80,000 (Marek et al., 1988), to name a few.

Alternatives to lysimetry for the measurement of E and ET include mass balance techniques that involve measuring the components of the water balance equation for a soil profile of given depth:

$$\Delta S = P - (E \text{ or } ET) - D - R \qquad [1]$$

where ΔS is the change in soil profile water storage, P is precipitation (including irrigation), R is runoff and D is deep percolation, i.e., water moving across the bottom boundary of the soil profile (all in mm), and solving for E or ET:

$$E \text{ or } ET = -\Delta S + P - D - R \qquad [2]$$

Measurement intervals commonly range between hours and weeks and are usually no smaller than the required period of ET measurement. Measurement of each variable in the R.H.S. of 2 presents its own unique problems, and it should be stated that lysimetry has three sources of measurement error as well (lysimeter mass (ΔS), precipitation (P), and runoff (R)). However, the water balance technique is applicable in many situations for which lysimetry is inappropriate or impossible and is, in addition, much less expensive. The focus of this paper will be the measurement of the changes in water storage, ΔS, with combined TDR and NS compared with lysimeter measurements.

Soil profile water content measurement techniques range from destructive sampling using augers or coring tubes to non-destructive techniques such as gamma ray attenuation, neutron scattering and capacitance measurements in access tubes, and various sensors including resistance blocks, heat flux based sensors, and time domain reflectometry (TDR) probes that are buried at specific depths. Destructive techniques are commonly avoided due to the requirement to repeatedly measure the same locations and the time involved in handling the samples. Of the non-destructive techniques, neutron scattering (NS) was proposed by Van Bavel and Stirk in 1967 for ET studies and has often been used since (Cuenca, 1988; Wright, 1990). Due to the small changes in water content associated with single day ET and the limited precision of NS, especially near the surface, the water balance method has usually been restricted to measurement of ET over several day periods (Carrijo and Cuenca, 1992). Wright (1990) compared ET measured by a weighing lysimeter to that measured by soil water balance using NS and concluded that large errors in the water balance method occurred if the depth of the profile measured by NS did not exceed the depth of wetting due to irrigation. The errors were then due to excessive water flux through the bottom of the profile.

Time domain reflectometry has more recently become available and lends itself to automated monitoring of soil water content (Baker and Allmaras, 1990; Heimovaara and Bouten, 1990). One disadvantage of TDR is the difficulty of installing probes at depth. However, since the short term rapid changes in soil water content due to infiltration events and evaporation may be confined to the near surface layers, TDR may be used for these measurements while NS is used at greater depth. The spatial sensitivity of TDR may be confined to a region as small as 2 cm above and below the plane of horizontally installed probes (Baker and Lascano, 1989; Alsanabani, 1991) so a great deal of information about the vertical variability of soil water content may be gathered relatively easily in the near surface soil where such variation is most likely to occur and where the NS technique is most difficult to calibrate and properly apply. This paper investigates the joint use of TDR and NS for estimating ET and compares it to weighing lysimeter measurements.

Methods

The experimental site was at Bushland, TX during 1992 from day of year (DOY) 80 to 108 in the northeast lysimeter field on a Pullman silty clay loam (fine, mixed, thermic Torrertic Paleustoll). The 3 m square by 2.3 m deep weighing lysimeter was in the center of a square 4.7 ha field. Lysimeter measurements of ET were precise to 0.05 mm (Howell et al., 1987). Winter wheat was planted the previous fall and leaf area index increased from 4.2 to 6.7 over the experimental period while crop height varied from 20 to 60 cm.

Prior to planting, TDR probes were installed in 2 vertical TDR/Temperature arrays in the lysimeter for measurement of soil water content. Probes were installed horizontally at 2, 4, 6, 10, 15, 20 and 30 cm depths with Cu-Co thermocouples at the same depths. Probe traces were automatically measured and recorded at 30 min intervals using an IBM PC/XT compatible computer equipped with an analog to digital conversion card. A Tektronix[3] model 1502 cable tester provided the TDR trace output. These older, analog cable testers are available for less than half the cost of the digital models and were modified for electronic control of trace output. A 16-channel multiplexer with 50 ohm characteristic impedance was designed to switch the TDR signals among probes while introducing minimal signal distortion. Signals were provided through the PC's parallel port for both switching and toggling the cable tester for trace output.

Three-wire TDR probes were used. Each consisted of an epoxy resin and polymethylmethacrylate handle from which extended three parallel, type 316 stainless steel rods. The rods were spaced in a single plane at 3 cm center to center and were 3.18 mm (nominal 1/8 inch) in diameter and 20 cm long from the tip to the point of emergence from the handle. The probes were inserted into the soil from the side of a pit so that the rods were parallel to the soil surface and the 3 rods for each probe were all the same distance from the soil surface. The outer two rods were soldered to the outer conductor of a type RG/58U coaxial cable and the inner rod was soldered to the inner conductor. The solder joints, proximal ends of the rods and distal end of the cable were encapsulated together in the handle.

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[3]Mention of trade names or other proprietory information is made for the convenience of the reader and does not imply endorsement by the USDA, ARS.

The three wire configuration is semi-coaxial in nature and eliminates the need for an impedance matching transformer (balun) used with a two rod design (Zegelin et al., 1989). In addition, the range of sensitivity above and below the plane of the rods is narrower for the 3 wire configuration than for the 2 wire configuration most commonly used in the past (Alsanabani, 1991) allowing for better discrimination of soil water content with depth.

The TDR method depends on the change in apparent dielectric constant of the soil that occurs when soil water content changes. The dielectric constant of the mineral matter in soil varies between 3 and 5. Although air may make up a large part of the soil volume, its dielectric constant is negligible. By contrast, the dielectric constant of water is about 80 (depending on temperature). As soil wets and dries its apparent dielectric constant, K_a, changes accordingly, though not in a linear fashion. We computed K_a as:

$$K_a = \mu^{-1}[c_o t_T/(2L)]^2 \qquad [3]$$

where t_T is the two way travel time in s for the cable tester voltage pulse to travel from one impedance change to the other and back again (i.e., round trip from probe handle to end of rods), L is the distance in m between the impedance changes, c_o is the speed of light, m/s, and the magnetic permittivity μ was assumed to be unity. For four fine-textured mineral soils, Topp et al. (1980) experimentally determined a polynomial function describing the relationship between K_a and volumetric water content, θ:

$$\theta = (-530 + 292K_a - 5.5K_a^2 + 0.043K_a^3)/10^4 \qquad [4]$$

The Pullman clay loam is a similar soil and Topp's equation was used.

The TDR water contents and first derivatives with respect to time were smoothed and calculated using center weighted quadratic polynomial least squares estimation with weights computed using an algorithm given by Gorry (1990) that allows calculation of off-center weights for smoothing end points. A 9-point data smooth followed by a 5-point derivative smooth was used for water content data from the 2- to 20-cm depths; and, a 25-point data smooth followed by a 15-point derivative smooth was used for data from the 30-cm depth which, although noisier than that for shallower depths, did not change rapidly. Change in storage in mm per unit time was calculated by multiplying the layer thickness (mm) by the first derivative.

Water content measurements by NS were taken at two sites on each lysimeter at depths from 10 to 190 cm at 20-cm increments using a Campbell Pacific Nuclear model 503DR neutron moisture gage. Access tubes were 4.1-cm (1.62 inch) ID, 4.4-cm (1.75 inch) O.D. steel electromechanical tubing, 2.3 m long. Counts were taken for 32 s. Prior to and after measurements, standard counts were taken until at least three standard counts were obtained with χ ratios in the range $0.9 \leq \chi$ ratio ≤ 1.1. Standard counts taken after the measurements in the tubes showed that no appreciable drift occurred over the measurement time. All standard counts were taken with the neutron probe sitting on top of its case which rested on bare, dry soil.

The Pullman soil has three horizons that differ in ways that are important for neutron probe calibration. The A horizon extends from the surface to about 20-cm depth and is characterized by low bulk density. Also, its nearness to the surface may allow neutrons to

escape requiring a different calibration equation. The B horizon begins at about the 20-cm depth and is characterized by high bulk density and higher clay content than either the A or C horizons. A calcic C horizon (caliche) with lower clay content and up to 45% $CaCO_3$ (by mass) begins at about 130- to 140-cm depth but that boundary depth is quite variable. Separate calibration equations for each horizon are in Table 1.

Table 1. Neutron Moisture Gage Calibration Equations (Ser. No. H35066190)

Depths [cm]	Equation	N	θ Range	r^2
10	$\theta = 0.0271 + 0.2442(CR)$	7	0.20 - 0.34	0.91
30 - 110	$\theta = -0.1062 + 0.2908(CR)$	19	0.19 - 0.37	0.96
130 - 210	$\theta = -0.0580 + 0.2599(CR)$	20	0.12 - 0.33	0.97

CR is the count ratio, counts per standard count. Water content, θ, is in $m^3\ m^{-3}$.

Results

Although only separated by 40 cm horizontal distance, the two TDR arrays showed markedly different soil wetness (Fig. 1). This was due to array 1 being in the inter-row where soil surface wetness tended to be lower and wetness at depth higher than for array 2 which was in the wheat row.

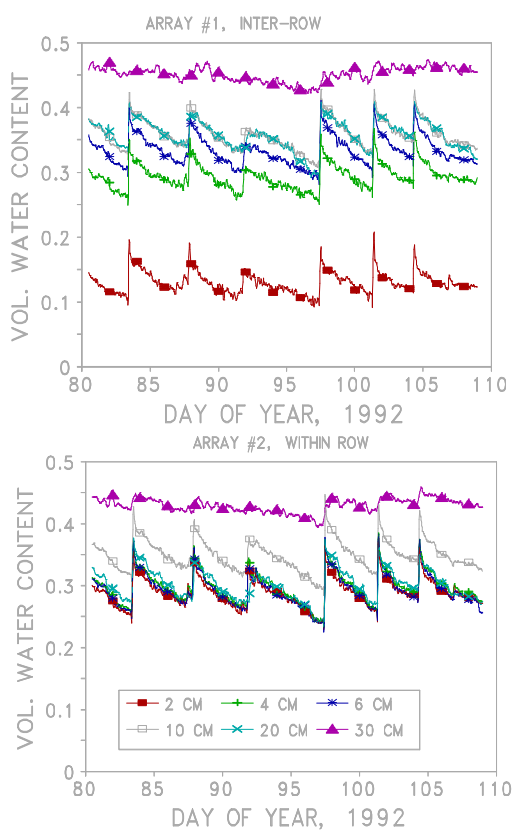

Figure 1. Smoothed TDR water contents.

Despite this difference, data from the two arrays reflected very well the dynamics of multiple infiltration and drying sequences. Mean water storage changes in the top 40 cm of the soil profile followed closely the whole profile storage as measured by the lysimeter including response to infiltration, daily drying and nighttime plateaus (Fig. 2). The daily storage change measured by TDR averaged 88% of that measured by lysimeter confirming that by far the largest part of daily change in storage was in the top 40 cm of soil (Fig. 3). Implications of this are threefold. First, TDR arrays may be used to measure precisely the largest part of daily storage change. Second, the NS method, no matter how well calibrated, is unlikely to ever give good daily storage change measurements because it is most imprecise near the surface where most storage change

occurs. Third, combining TDR with daily NS measurements holds great potential for precisely defining the daily change in soil profile water storage.

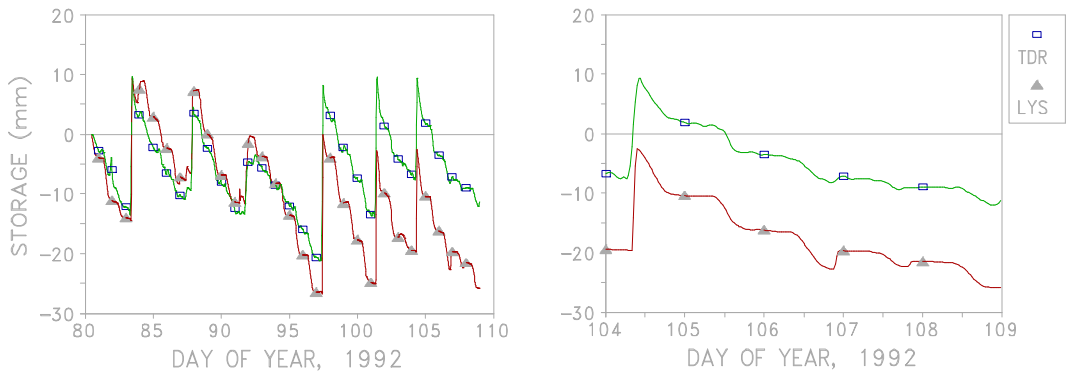

Figure 2. Lysimeter (LYS) storage compared to mean storage from TDR for the entire period (left) and final 5 days (right).

Deep percolation and runoff were zero for the lysimeter. Therefore, daily ET could be calculated from Eq. 2 by adding precipitation amount to storage change. There were large discrepancies between lysimeter measured ET and that calculated from change in storage based on TDR data alone (Fig. 4). The TDR method overestimated ET on precipitation (including irrigation) days in the first part of the period due to drainage flux out of the bottom of the 0- to 40-cm layer. These events were followed by dry periods during which the TDR method underestimated ET due to upward soil water flux into the 0- to 40-cm layer.

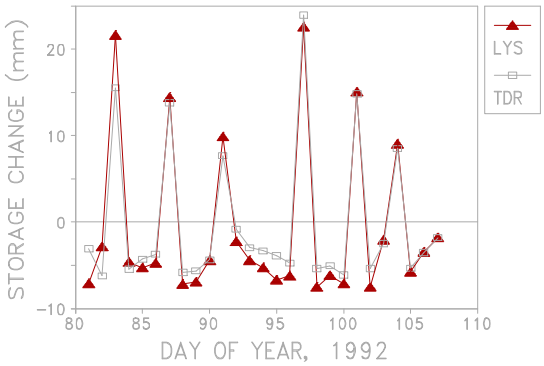

Figure 3. Daily change in storage from lysimeter (LYS) and TDR arrays.

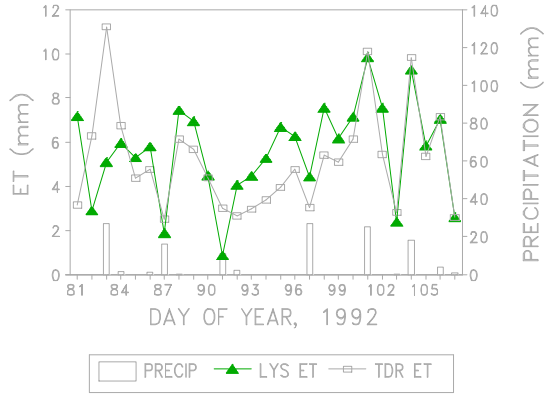

Figure 4. Evapotranspiration calculated from lysimeter and TDR change in storage.

Despite the underestimation, the TDR method followed the changes in daily ET well during the drying periods. Also, during the last 8 days of the period the TDR method matched closely the lysimeter measured ET even on days 101 (24 mm) and 104 (18 mm) when irrigation occurred. The good match for days 100 through 107 may be due to swelling

of the B horizon after repeated precipitation and irrigation events. Once the cracks close in this soil the hydraulic conductivity decreases markedly, effectively sealing the bottom of the 0- to 30-cm soil layer. There is also some evidence that soil swelling may increase root axial resistance to water flow. This, combined with the tendency for the root system to remove water from the top soil layers first, may have caused most root water uptake to occur in the top 30 cm of soil.

Lack of NS measurements precluded completion of the soil water balance on a daily basis. However, NS measurements on days 90 and 106 allowed the change in storage to be calculated for the intervening period. Lysimeter storage decreased by 9.31 mm over the 16-day period but NS measurements showed a 12.86-mm decrease or a 3.55-mm error. Combining the change in storage calculated for the 40- to 200-cm profile by NS with the TDR-based change in storage for the surface to 40-cm profile gave an 8.65-mm change in storage, or an error of 0.67 mm.

Conclusions

Vertical arrays of horizontally-installed TDR probes showed good potential for accurately measuring change in water storage in the top 40 cm of soil over periods of a day or less. Our TDR technology allowed us to show that, for our wheat crop, an average of 88% of the daily total soil profile change in storage occurred in the top 30 cm of soil. Since neutron scattering is most imprecise near the soil surface it thus becomes doubtful that neutron moisture gages alone could be used for daily ET estimates, no matter how well calibrated. However, the combination of neutron scattering measurements at depths below 40 cm with TDR measurements above 40 cm allowed the change in storage over a 16-day period to be calculated to within 0.7 mm of that measured by the weighing lysimeter. This error was one fifth of that realized when neutron scattering alone was used. Future research will combine daily neutron scattering measurements at depth with TDR measurements in the near surface soil of a lysimeter to find if accurate daily ET measurements can be made.

References

Alsanabani, M.M. 1991. Soil water determination by time domain reflectometry: sampling domain and geometry. Ph.D. thesis. Department of Soil and Water Sciences, Univ. of Arizona, Tucson, AZ 85721.

Baker, J.M., and R.R. Allmaras. 1990. System for automating and multiplexing soil moisture measurement by time-domain reflectometry. Soil Sci. Soc. Am. J. 54:1-6.

Baker. J.M., and R.J. Lascano. 1989. The spatial sensitivity of time-domain reflectometry. Soil Sci. 147:378-384.

Black, T.A., G.W. Thurtell, and C.B. Tanner. 1968. Hydraulic load cell lysimeter, construction, calibration and tests. Soil Sci. Soc. Am. Proc. 32:623-629.

Carrijo, O.A., and R.H. Cuenca. 1992. Precision of evapotranspiration estimates using neutron probe. J. Irrig. and Drain. Engrg., ASCE, 118(6):943-953.

Cuenca, R.H. 1988. Model for evapotranspiration using neutron probe data. J. Irrig. and Drain. Engrg., ASCE, 114(4):644-663.

Dugas, W.A., and W.L. Bland. 1991. Springtime soil temperatures in lysimeters in Central Texas. Soil Sci. 152(2):87-91.

Gorry, P.A. 1990. General least-squares smoothing and differentiation by the convolution (Savitsky-Golay) method. Anal. Chem. 62:570-573.

Grebet, R., and R.H. Cuenca. 1991. History of lysimeter design and effects of environmental disturbances. Pp. 10-18 in Lysimeters for evapotranspiration and environmental measurements, Proceedings of the International Symposium on Lysimetry, July 23-25, 1991, Honolulu, Hawaii. ASCE, 345 E. 47th St., NY, NY 10017-2398.

Heimovaara, T.J., and W. Bouten. 1990. A computer-controlled 36-channel time domain reflectometry system for monitoring soil water contents. Water Resour. Res. 26(10):1311-1316.

Howell, T.A., A.D. Schneider, D.A. Dusek, and T.H. Marek. 1987. Calibration of Bushland weighing lysimeters and scale performance as affected by wind. ASAE Paper No. 87-2505.

Howell, T.A., A.D. Schneider, and M.E. Jensen. 1991. History of lysimeter design and use for evapotranspiration measurements. Pp. 1-9 in Lysimeters for evapotranspiration and environmental measurements, Proceedings of the International Symposium on Lysimetry, July 23-25, 1991, Honolulu, Hawaii. ASCE, 345 E. 47th St., NY, NY 10017-2398.

Lourence, F., and R. Moore. 1991. Prefabricated weighing lysimeter for remote research stations. Pp. 432-439 in Lysimeters for evapotranspiration and environmental measurements, Proceedings of the International Symposium on Lysimetry, July 23-25, 1991, Honolulu, Hawaii. ASCE, 345 E. 47th St., NY, NY 10017-2398.

Marek, T.H., A.D. Schneider, T.A. Howell, and L.L. Ebeling. 1988. Design and construction of large weighing monolithic lysimeters. Trans. ASAE 31:477-484.

Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. Water Resour. Res. 16(3):574-582.

Van Bavel, C.H.M., and G.B. Stirk. 1967. Soil water measurement with and Am^{241}-Be neutron source and an application to evaporimetry. J. Hydrology 5:40-46.

Wright, J.L. 1990. Comparison of ET measured with neutron moisture meters and weighing lysimeters. Pp. 202-209 in Irrigation and drainage: proceedings of the National Conference. Durango, Colorado, July 11-13, 1990. ASCE, 345 E. 47th St., NY, NY 10017-2398.

Zegelin, S.J., I. White, and D.R. Jenkins. 1989. Improved field probes for soil water content and electrical conductivity measurement using time domain reflectometry. Water Resour. Res. 25(11):2367-2376.