WATER RESOURCES BULLETIN
VOL. 30, NO. 1 AMERICAN WATER RESOURCES ASSOCIATION FEBRUARY 1994

SOIL MOISTURE SENSORS FOR CONTINUOUS MONITORING[1]

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ABSTRACT: Certain physical and chemical properties of soil vary with soil water content. The relationship between these properties and water content is complex and involves both the pore structure and constituents of the soil solution. One of the most economical techniques to quantify soil water content involves the measurement of electrical resistance of a dielectric medium that is in equilibrium with the soil water content. The objective of this research was to test the reliability and accuracy of fiberglass soil-moisture electrical resistance sensors (ERS) as compared to gravimetric sampling and Time Domain Reflectometry (TDR). The response of the ERS was compared to gravimetric measurements at eight locations on the USDA-ARS Walnut Gulch Experimental Watershed. The comparisons with TDR sensors were made at three additional locations on the same watershed. The high soil rock content (>45 percent) at seven locations resulted in consistent overestimation of soil water content by the ERS method. Where rock content was less than 10 percent, estimation of soil water was within 5 percent of the gravimetric soil water content. New methodology to calibrate the ERS sensors for rocky soils will need to be developed before soil water content values can be determined with these sensors.
(KEY TERMS: soil moisture; soil water; infiltration; instrumentation; soil moisture sensors.)

INTRODUCTION

A major objective of surface hydrologic research is to better understand surface fluxes in a semi-arid rangeland environment. One of the most important parameters affecting these fluxes is the moisture stored in the surface soil profile. Soil moisture also affects thermal properties of the soil (near-surface heat capacity and thermal inertial), infiltration and runoff production, and serves as the reservoir for the evapotranspiration process. Insufficient knowledge of the spatial and temporal variability of near surface soil moisture conditions in a natural environment is an important aspect of our difficulty in understanding and modeling the processes closely linked to soil moisture. Progress in characterization of soil moisture in time and space depends largely upon the development of economical measurement tools.

For years researchers have sought an instrument for obtaining rapid, reliable, economical, and continuous measurements of soil water content that could be made in the field and laboratory. Measurements of soil water content are based upon the sensing of various properties of the water molecule. These include measurements of mass, response to radiation, thermal properties, and electrical properties. The relationship between these properties and moisture content is complex and involves both the pore structure and constituents of the soil solution. No single universal technique will always provide a measure of the portion of the total water content of interest; rather, different techniques provide different information.

Many methods and types of instruments have been proposed or developed for estimating soil water content, including gravimetric, tensiometers, gypsum blocks, neutron probes, and Time Domain Reflectometry (TDR). Electrical properties of water are among the favorite candidate properties, due to the ability of water to conduct electricity and its high dielectric constant (Gardner, 1987). One of the most economical techniques involves measuring of electrical resistance within a fiberglass fabric that is in moisture equilibrium with the soil (Colman and Hendrix, 1949; Reynolds *et al.*, 1987). An additional advantage of electrical resistance sensors (ERS) is their ability of near-continuous monitoring of soil moisture via connection to data loggers. They can, therefore, be used

[1]Paper No. 93091 of the *Water Resources Bulletin*. Discussions are open until October 1, 1994.
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to provide a means of better understanding of the temporal evolution of soil moisture conditions and the energy/water budget.

The objective of this study is to discuss an electrical resistance sensor design, its laboratory calibration, response time, and the transformation equation employed to predict soil water content (percent volume). The motivation of this research was to investigate an inexpensive, easily producible, durable, sensor design. Water content estimates by this method were compared to gravimetric and TDR methods.

STUDY AREA

The experiment was conducted during the 1990 monsoon season in the USDA-ARS Walnut Gulch Experimental Watershed near Tombstone, Arizona (Figure 1). The watershed is representative of northern Chihuahuan Desert shrub steppe and grassland vegetation and soils.

Eight automated meteorological flux stations (METFLUX) were established on the upper half of the watershed in June of 1990 (Kustas *et al.*, 1991; Kustas and Goodrich, 1993). The surface soil texture of the eight METFLUX sites varied from gravelly sandy loam to gravelly loamy sand (USDA-SCS, 1993) for seven of the METFLUX sites (Table 1). METFLUX site 7, located in a floodplain, had significantly less rock in the soil profile and the surface soil texture was classified as a sandy loam.

Three permanent soil moisture study locations were prepared prior to the experiment. The locations were Lucky Hills, near METFLUX site 1, and Kendall north and south aspects near METFLUX site 5.

INSTRUMENTATION

The electrical resistance sensors (ERS) consists of two parts, the soil unit and the recording unit (Figure 2). The soil unit is intended to be installed permanently at the point where moisture measurements are required. It consists of a moisture-sensitive element enclosed in an aluminum case (4 cm x 4 cm x 0.3 cm) The element is a sandwich composed of two stainless steel screen electrodes (about 2 cm x 2 cm) separated by two thicknesses of fiberglass cloth and wrapped with two thicknesses of the same material. The aluminum case of the soil unit has nine holes on each side, about 0.3 cm in diameter. The outer case is immersed in liquid plastic as an insulator and dried for at least 12 hours. Two wire leads are spot-welded to the two electrodes. When the case is assembled, it serves to compress the fiberglass uniformly and ensures good capillary contact between soil and fiberglass because of the relatively thin design. The electrical resistance of the moisture-sensitive element varies in response to changes in water content of the soil in which the unit (sensor) is buried. The thinness of the fiberglass and its exposure to the soil on both sides (through the holes) minimizes the time required for the water content of the fiberglass to reach equilibrium with that of the soil in which it is buried.

The data-recording unit is an automated battery-powered data logger, and the resistance-type soil moisture sensors are wired to the data logger. Resistance readings were collected every 30 seconds, and 20 minute means and standard deviations were stored for later analysis.

The TDR technique (Topp *et al.*, 1980; Topp and Davis, 1985) utilizes a cable tester to measure the propagation velocity of an electromagnetic signal along a transmission line embedded in the soil. The transmission line developed for this study, adapted from Zegelin *et al.* (1989), consisted of three 15-cm-long stainless steel rods connected to 50-ohm coaxial cable. A cable tester was used to obtain the propagation velocity of the signal, which was converted to volumetric water content using a calibration curve determined *in situ* at each field location.

INSTRUMENT CALIBRATION

Sensors

The calibration moisture-resistance curve for individual electrical resistance sensors (ERS) was determined in the laboratory by embedding the sensors in representative samples of sieved soil (< 2 mm) in a shallow container. Sieved soil was used for simplicity of mixing and achieving a determinable soil water content for calibration. Ramifications of using sieved soil will be discussed.

Approximately 1.5 kg of a representative soil sample from each location was mixed thoroughly with a known quantity of distilled water to bring the soil sample to a calibration level soil water content. The soil sample was then stored overnight in a sealed plastic container to allow the water content to equilibrate throughout the soil volume. After this, the bottom of a second container was filled to a depth of 2 cm with soil and the dry sensors were placed along the length of the container and completely covered with approximately 3 cm layer of the same soil. This container then was covered and sealed.

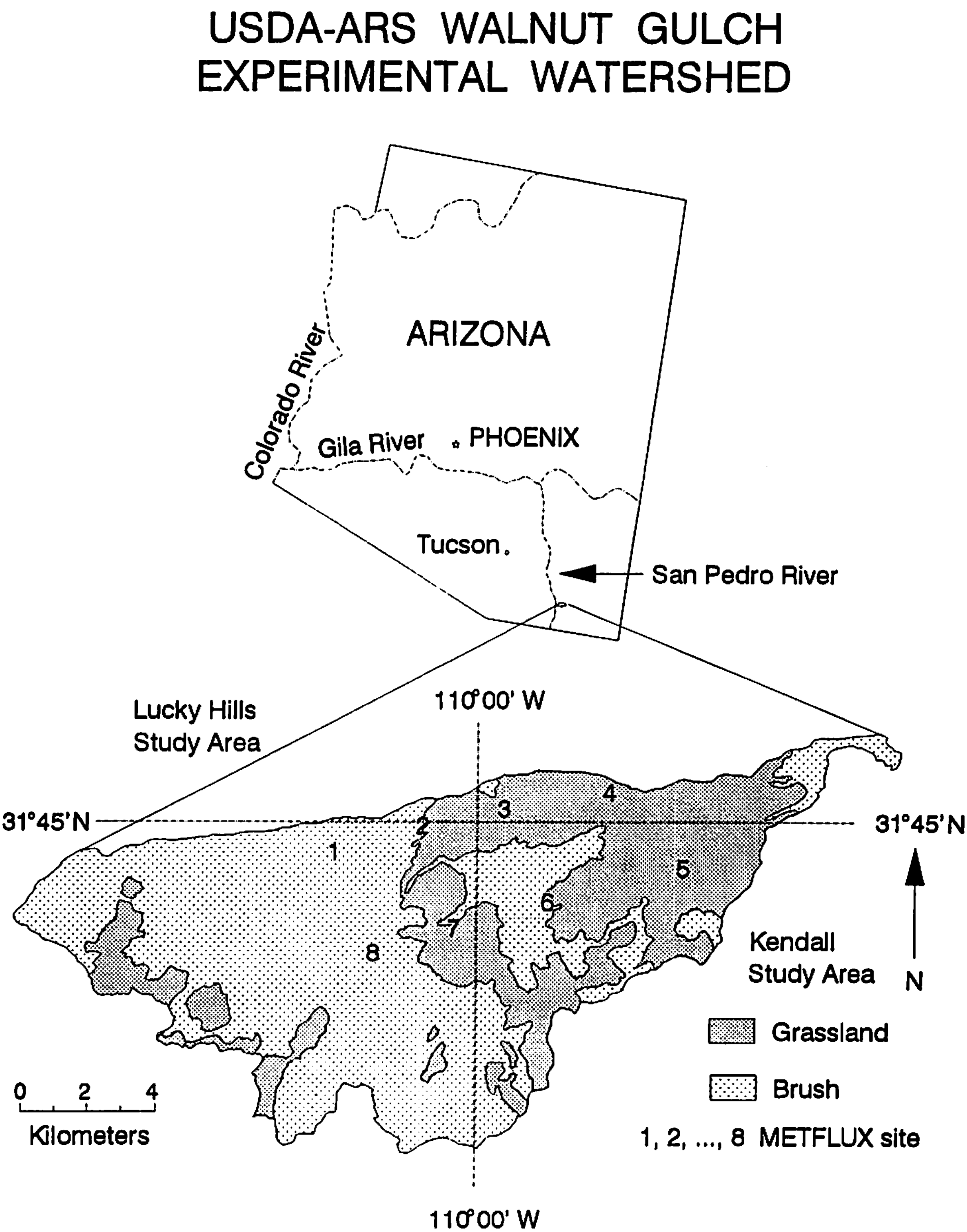


Figure 1. Location Map of METFLUX Sites and Permanent Trench Installation.

TABLE 1. Soil Characteristics of the METFLUX Stations on the Walnut Gulch Experimental Watershed.

METFLUX Site No.	Soil Name*	Soil Subgroup*	Surface Texture*	Bulk Density (g/cm^3)	Rock Content (% by weight)
1	Swisshelm	Fluventic Camborthids	Gravelly sandy loam	1.64	46
2	Stronghold	Ustollic Calciorthids	Gravelly loamy sand	1.83	48
3	Stronghold	Ustollic Calciorthids	Gravelly loamy sand	1.58	45
4	Hathaway	Aridic Calcuistolls	Gravelly loamy sand	1.82	59
5	Forest	Ustollic Haplargids	Gravelly sandy loam	1.61	54
6	Boracho	Petrocalcic Paleustolls	Gravelly loamy sand	1.44	52
7	Swisshelm	Fluventic Camborthids	Sandy loam	1.74	10
8	Monterosa	Ustollic Paleorthids	Gravelly loamy sand	1.47	58

*USDA-Soil Conservation Service, 1993.

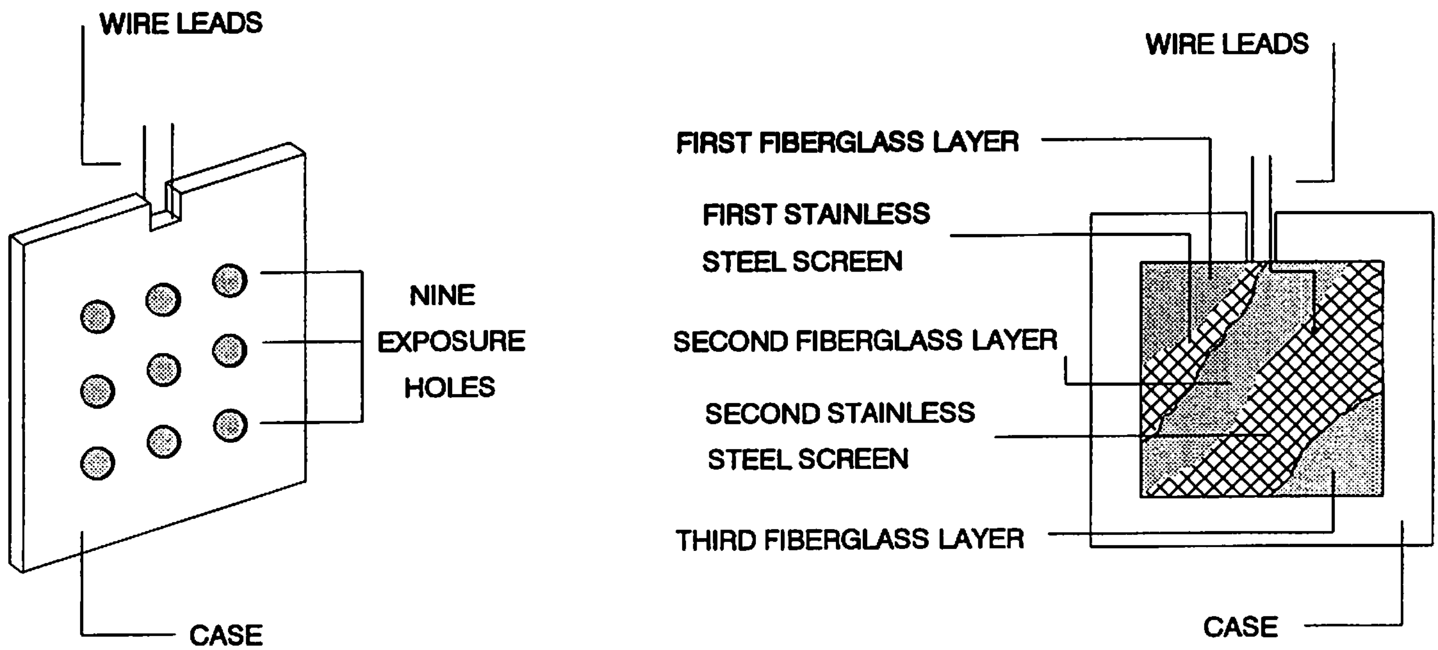


Figure 2. Fiberglass Soil-Moisture Electrical Resistance Sensor Design.

To ensure that the sensor had reached equilibrium with the soil water content, resistance was measured every 10 minutes for 80 hours and the average of six consecutive readings was stored as an hourly value for analysis. Gravimetric samples were taken before and at the end of each run to determine the loss in moisture during the measurement period. Loss in the weight of the soil sample upon oven-drying gave the soil water content of the sample.

Conversion to volumetric water content (cm^3cm^{-3}) was accomplished using *in situ* bulk density values of soils at each location. Using this procedure, a soil water content was associated with a sensor resistance value. Other pairs of water content-resistance values were similarly obtained by repeating the procedure over a range of moisture contents from 5 percent to 18 percent. For the Walnut Gulch soils used in this study, water contents of greater than 18 percent (volume) were not evaluated because the sieved soil lost sufficient structure to adequately manage it.

The data showed that the response of soil moisture sensors to changes in soil water content was not linear. A power equation with three parameters was applied to develop a calibration curve for each individual sensor (Figure 3a). The power equation is in the form of:

$$Y = BD\left[\left(B_1 * x^{B_2}\right) + B_3\right] \tag{1}$$

where Y is the calculated volumetric soil moisture percentage; BD is bulk density (gcm^{-3}) derived from *in situ* measurements; B_1, B_2, and B_3 are estimated parameters; and x is the sensor resistance reading in ohms. The parameters (B_1, B_2, and B_3) were estimated using nonlinear regression techniques. The coefficient of determination (r^2) for the calibration equation of all sensors was highly significant, ranging from 0.88 to 0.98.

TDR Probes

Field calibration was performed for the TDR sensors at each of the three installation locations. Calibration was accomplished by comparing approximately 60 TDR readings at each site to volumetric water content measurements made with a water content/bulk density sampler. The TDR reading was obtained with a 15 cm probe inserted vertically from the soil surface. After the reading, the probe was removed and the bulk density sampler was placed at the exact location of the TDR probe. The sampler was designed to measure the same soil volume as that sensed by the TDR probe. Integrated bulk density from 0-15 cm was determined via an excavation technique, whereby volume measurements were made *in situ* and the excavated soil was weighed both wet and dry in the laboratory for calculation of water content and bulk density.

Calibration volumetric water content results for Kendall North are plotted in Figure 3b in addition to the relationship obtained by Topp *et al.* (1980). The discrepancy between the Topp curve and TDR data suggests the need for site specific calibration. However, tests in laboratory soil and water-filled columns demonstrated that identical readings were obtained for all probes, indicating that the calibration need only be performed for different soils, not for different probes.

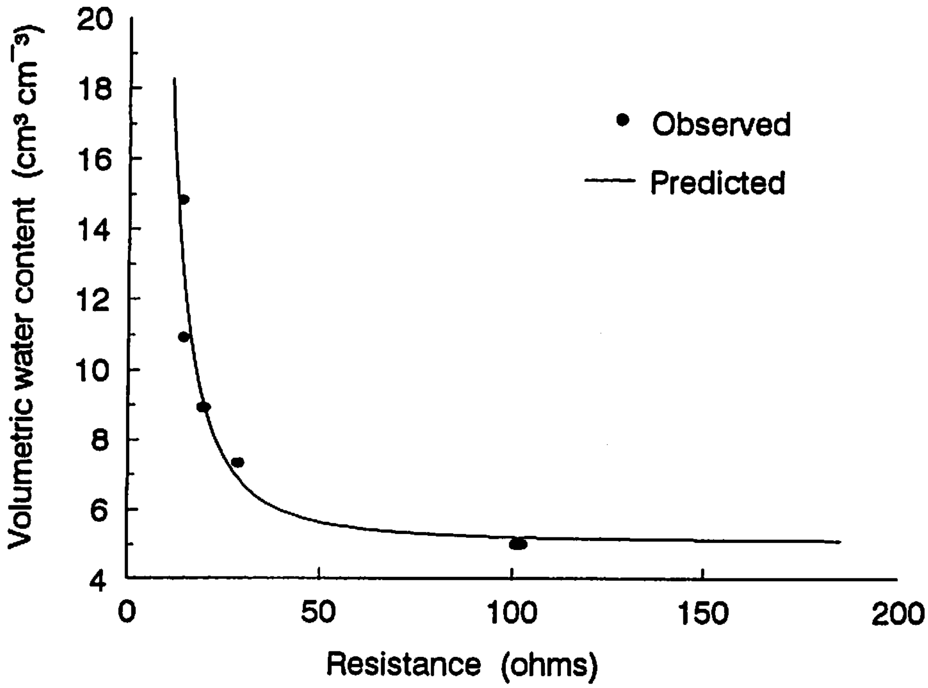
EXPERIMENTAL PROCEDURE

Three shallow (5 cm) trenches were excavated at each of the automated METFLUX stations. Two ERS were installed at a depth of 2.5 cm and two at 5 cm in each trench for a total of 12 sensors at each METFLUX site. A pilot slot, the same dimensions as the sensor, was made to a horizontal depth of 10 cm in the southernmost wall of the trench. The sensors were inserted in the pilot holes with the plane of the sensor horizontal and the slot carefully repacked with excavated soil. Wire leads of the sensors were looped to the bottom of the trench to prevent opportunistic flow for water onto the sensors. After the sensors were installed, the trench was back filled as close as possible to the original bulk density.

Daily gravimetric samples were collected adjacent (approximately 15 m) to each of the eight METFLUX sites from July 23, day of year (DOY) 204, to August 15, day of year 227. Each gravimetric sampling area was cordoned off to prevent extraneous disturbances to soil surface and a rectangular grid with nodes 30 cm apart was established. Three replicates were collected from consecutive grid nodes each day; the following days, samples were obtained starting at the next adjacent node. The samples, about 250 cm3, were collected from the surface soil, 0 to 5 cm, and converted to volumetric water content using *in situ* bulk density measurements. Bulk density values for each site were obtained from three repetitions of an excavation technique prior to the start of the experimental sampling period.

The ERS were monitored every 20 minutes throughout the measurement period using data loggers located at the automated METFLUX stations. The resistance readings were converted to volumetric water content using laboratory calibration coefficients from Equation (1) determined on representative soil samples obtained from the field sites and *in situ* bulk density measurements. An average water content was derived from the sensors at each station.

ERS were installed at the depth of 5 cm alongside TDR probes in each of six trenches at the three additional locations. TDR probes were installed at 5 and 10 cm. The sensors and probes were installed horizontally into the soil profile by excavating a trench, placing the instruments into recessed slots in a trench wall, repacking the sensor holes with soil removed from those holes and carefully back filling the trench to the *in situ* bulk density. The procedure for ERS measurements and conversion to volumetric water content is identical to that at the METFLUX stations. The TDR data were collected once per day (approximately 0900 MST) and converted to volumetric water content using location specific calibration equations. For both measurement methods, an average water content of six trenches was calculated and these two were compared at the time of coincident measurements (approximately 0900).



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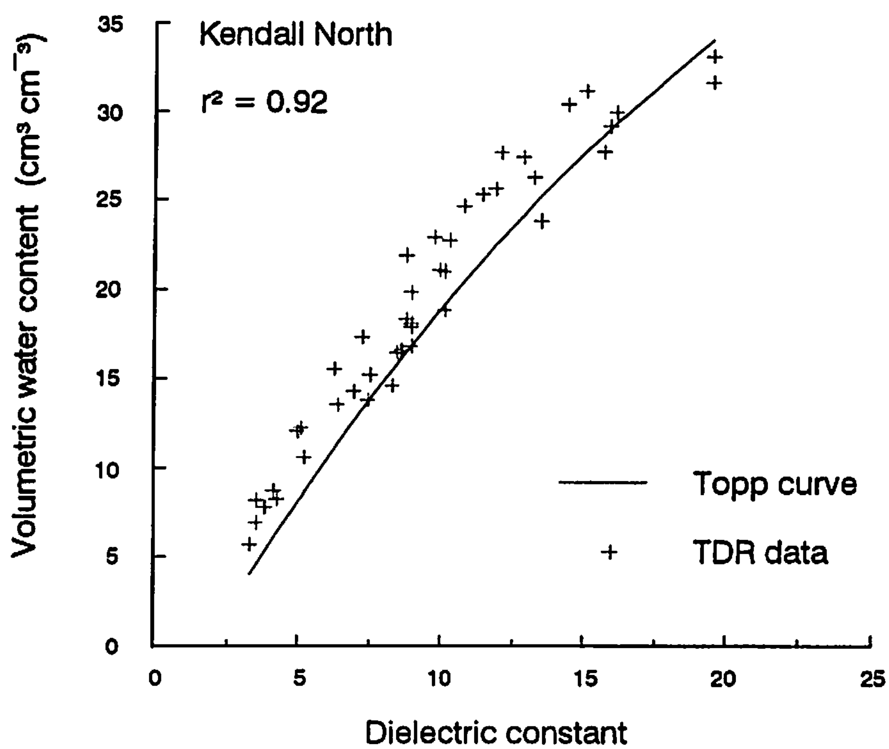

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Figure 3. (a) A Typical Power Equation with Three Parameters Fitted to ERS Calibration Data and (b) TDR Calibration Curve for Kendall North.

RESULTS AND DISCUSSION

Gravimetric Comparison

Initial reliability of ERS was poor; of 96 sensors installed, 36 failed. The number of sensors operating continuously for the duration of the experiment at each of the eight METFLUX sites ranged from a minimum of 4 to a maximum of 11.

Mean soil water contents (percent volume) and standard deviations were calculated from gravimetric measurements and resistance readings over time for all eight METFLUX sites. Plotted in Figures 4a and 4b are results for METFLUX sites 1 and 5, respectively. The results show that the electrical resistance sensors are sensitive to changes in soil water content. It should be noted that for the soils used in this study, extrapolation of water content values obtained from resistance readings beyond laboratory calibration range is not recommended, especially in the wet region (approximately 18 percent). The behavior of the power equation employed rapidly approaches infinity in wet soil (see Figure 3a) due to the negative exponent in Equation (1).

The results also showed that gravimetrically determined soil water contents were lower than those calculated using resistance readings over the measured range of soil water content. These differences are suspected to be due, at least in part, to temperature changes, calibration procedure, installation, sampling location, and rock content relative to sample size. It has been found that temperature changes cause slight variation in the resistance of the soil moisture sensors at a constant moisture content in laboratory studies (Bouyoucos and Mick, 1940; Colman and Hendrix, 1949). However, in a recent study, readings from ERS were not corrected for temperature (Reynolds *et al.*, 1987).

Another possible explanation for the relatively consistent bias of the ERS relates directly to the calibration procedures. Calibration was performed in the laboratory by embedding the ERS in a representative sample of sieved (passed through a 2-mm diameter sieve) soil, which is different from field conditions. The soil at the METFLUX sites under investigation has a concentration of surface rock (erosion pavement) in excess of 45 percent, except METFLUX site 7, which is located in the floodplain area and has minimal rock cover (10 percent) (see Table 1).

It was found in this study that there was up to 6 percent (absolute) volumetric water content variation among the triplicate gravimetric soil water content samples. However, volumetric water content calculated from recorded resistance readings was within 10 percent (absolute) of those determined gravimetrically at all METFLUX sites.

The ERS measurement recorded at the time closest to the gravimetric sample collection was used to evaluate the difference in ERS and gravimetrically sampled soil water content. A test of the hypothesis that the mean of the gravimetrically determined water content was equal to the mean water content from ERS measurements was rejected at a 10 percent significance level for more than 75 percent of the 1984 combined site-days. Isolating the periods before (drier soil) and after (moisture soil) major rainfall started, the rejection rates were 93 percent and 64 percent, respectively. Fifty-one of 80 site-days in the former period had gravimetrically determined water content less than the minimum range of calibration and the ERS consistently overpredicted soil water content. However, during the entire sampling period, when gravimetrically determined water content was within calibration range, the rejection rate was still greater than 50 percent.

Studies of the spatial variability of soil moisture conducted on the Lucky Hills watershed in 1990 and 1991 indicate negligible correlation beyond one meter (Whitaker *et al.*, 1991). Gravimetric and ERS sampling locations were approximately 15 meters from each other at each site; thus, soil moisture sampling was from two populations which are not expected to have identical means.

Additional gravimetric soil water content (percent volume) samples obtained at the same locations by Stannard *et al.* (1993) were found to be 3 percent higher on average than those obtained in this study. Absolute values of volumetric soil water content from ERS are closer to these gravimetrically determined values. This variation is suspected to be due, at least in part, to the size of the soil sample obtained. The containers utilized in this study were approximately twice the diameter of those utilized by Stannard *et al.* (1993). This difference in diameter resulted in larger rock fragments and less soil being incorporated into the gravimetric soil sampling procedure utilized in this study.

Daily fluctuations in soil water content, represented by the change over 24 hours in soil water content values coincident with the time of gravimetric sampling, are predicted reasonably well by ERS. At seven of eight METFLUX sites, the daily change of water content by ERS and gravimetric were the same at a 10 percent significance level. The time series of daily change for METFLUX sites 1 and 5 (5 being the site of the single rejection) are plotted in Figures 5a and 5b.

The recording rain gage nearest to each METFLUX station was monitored to study the apparent response time of ERS. The time of "visible" response of ERS to

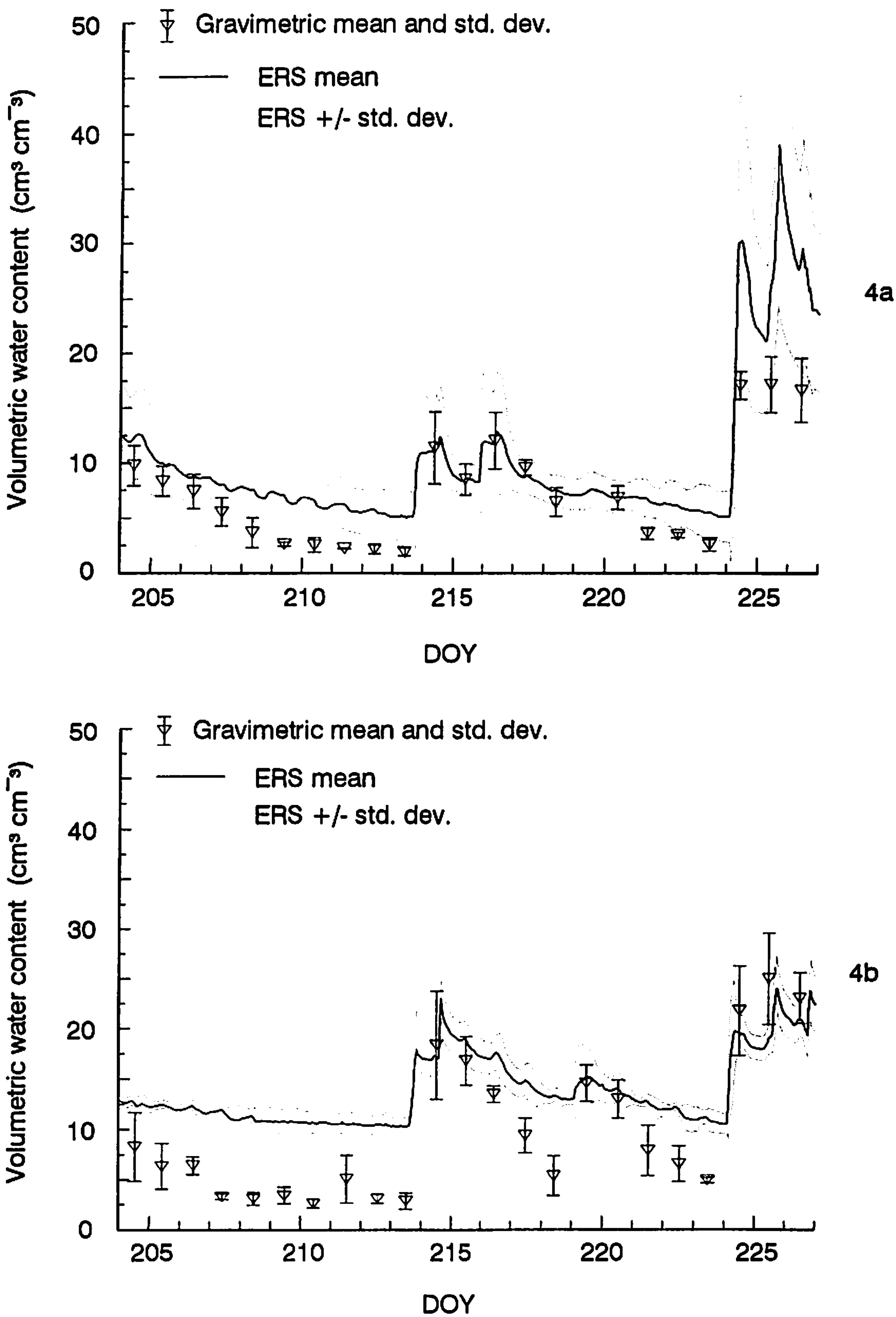


Figure 4. Soil Moisture Content (percent volume) Calculated Using Gravimetric and ERS Methods Over Time for (a) METFLUX Site 1 and (b) METFLUX Site 5.

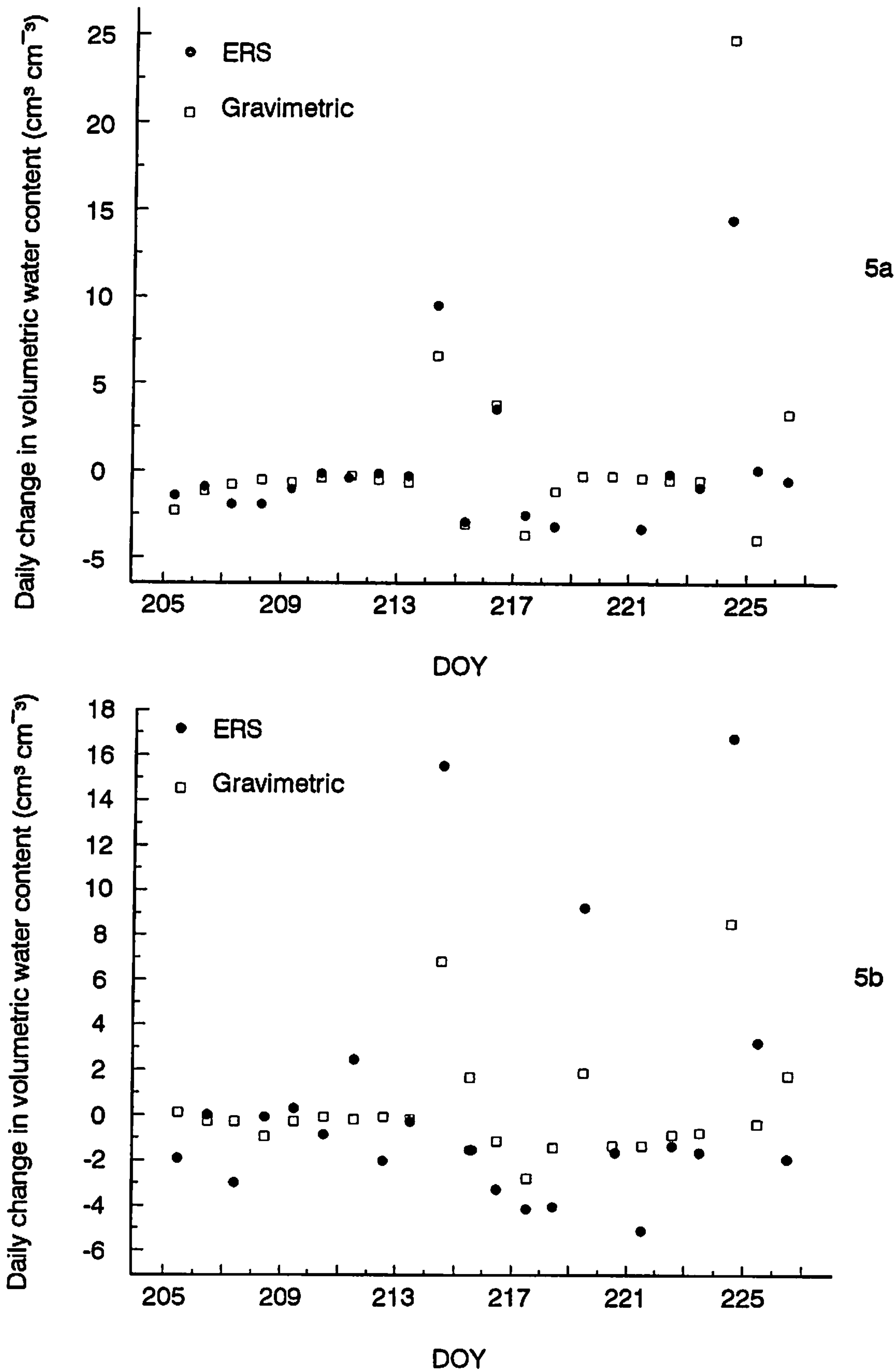


Figure 5. Daily Change in Mean Soil Water Content from ERS and Gravimetric Methods at (a) METFLUX Site 1 and (b) METFLUX Site 5.

rainfall events ranged from less than 30 minutes to several hours. For rainfall events with intensity greater than 25 $mmhr^{-1}$ which were not preceded by other rainfall for at least 24 hours, the time of response from start of rainfall is less than 1 hour. Intervening rainfall and diurnal fluctuations of soil moisture prohibited evaluation of all rainfall response episodes. For those event-response pairs which are distinguishable, response time of the ERS appears independent of both peak rainfall intensity and rainfall volume (Figures 6a and 6b).

TDR Comparison

Soil water contents by percent volume were estimated by ERS and TDR methods over time in the Kendall watershed on north and south facing aspects. The ERS and TDR sensors were approximately 0.5 km for the north aspect and 1 km for the south aspect from METFLUX site 5. Mean 5 cm deep soil water contents and standard deviations over time at the Kendall north location are illustrated in Figure 7a. Although both instruments were sensitive to changes in soil water content, volumetric water contents determined using ERS at 5 cm were higher than those calculated using the TDR at both 5 cm and 10 cm.

Soil water content calculated using ERS and TDR methods at 5 cm over time at Lucky Hills is shown in Figure 7b. Volumetric water contents calculated using the TDR technique at both depths were lower than those predicted using ERS, as at the Kendall sites.

Volumetric water content values of ERS do not correspond to TDR at either depth at daily time steps. At all three locations, the hypothesis that the mean ERS soil water content at the time of the daily TDR reading is equal to that of the TDR was rejected at a 10 percent significance level.

The daily change in soil water content for ERS and both depths of TDR were compared. Values were obtained by taking the difference of the mean water content recorded at the time of the TDR sampling for each pair of consecutive days. The daily change in mean ERS at time of TDR sampling was equal to the difference in daily TDR means at a 10 percent significance level. Figures 8a and 8b show the time series of the daily changes at Kendall north and Lucky Hills, respectively.

Higher ERS estimates of soil water content are suspected to be due, at least in part, to calibration procedure and sampling technique. As mentioned earlier, ERS were calibrated in sieved soil under laboratory condition, where TDR sensors were calibrated *in situ* (at each field location).

The TDR sampling technique involves measuring the propagation velocity of a reflected electromagnetic signal along a transmission line. The transmission line consists of three 15 cm rods. Thus, soil water content calculated using TDR sensors is an integrated measurement over the transmission line length (15 cm). Theoretically, sample volumes for the three rod probe design range from a narrow cylinder concentrated around the center rod (Zegelin *et al.*, 1989) to the entire volume defined by a radius equal to distance from inner to outer rods (Knight, 1992). On the other hand, the ERS measures electrical resistance of the moisture-sensitive element that is in moisture equilibrium with the soil enclosing it (see Figure 2). Hence, soil water content calculated using the ERS technique is an estimate of the amount of moisture in the soil that is in immediate contact with the fiberglass sandwich (4 cm x 4 cm).

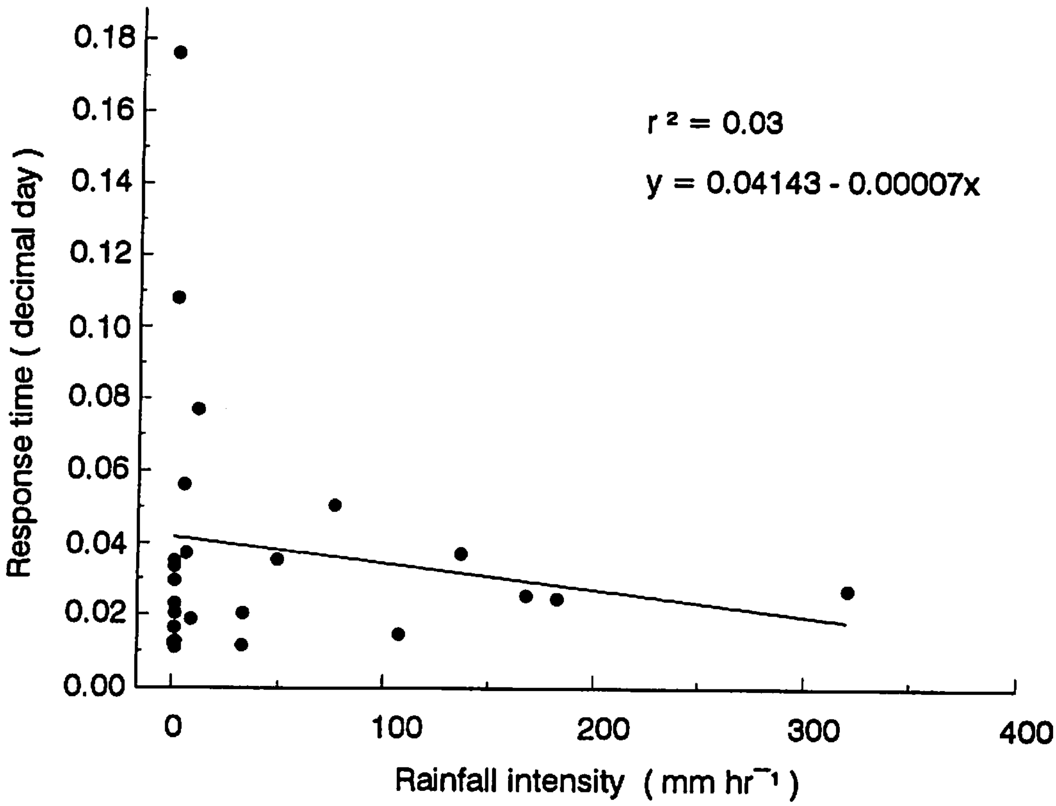
ERS Applications

Although an apparent bias was found in soil water content estimates from the electrical resistance sensors, they provide reasonable estimates of soil moisture changes on daily time scales. The ERS track diurnal trends nearly continuously, the details of which are missed by discrete daily soil moisture measurements.

The near continuous monitoring by ERS allows recording of diurnal and short term fluctuations in soil moisture. Within the limits of this study, the origins of this temporal change in soil water content cannot be determined, but it is obvious that the time scale of ERS measurements allow for potential investigations which are not available with daily sampling methods. These short interval episodes of near surface soil water content changes can be useful in verifying daily energy budget computations because the measurement time scales are comparable to sophisticated ground based energy measurement techniques.

Gravimetric sampling cannot be obtained in continuous mode because of cost and soil disturbance. Technology to sample continuously using TDR has recently become available (Baker and Allmaras, 1990; Heimovaara and Bouten, 1990), but it is considerably more expensive than this ERS method. The results using continuous ERS measurements demonstrate that information on short time intervals is available for validating soil water content and flux calculations made with eddy correlation and Bowen ratio methodologies.

The ERS have the potential to access, in general terms, wet versus dry conditions of the soil surface. The ERS continuous monitoring of the near surface



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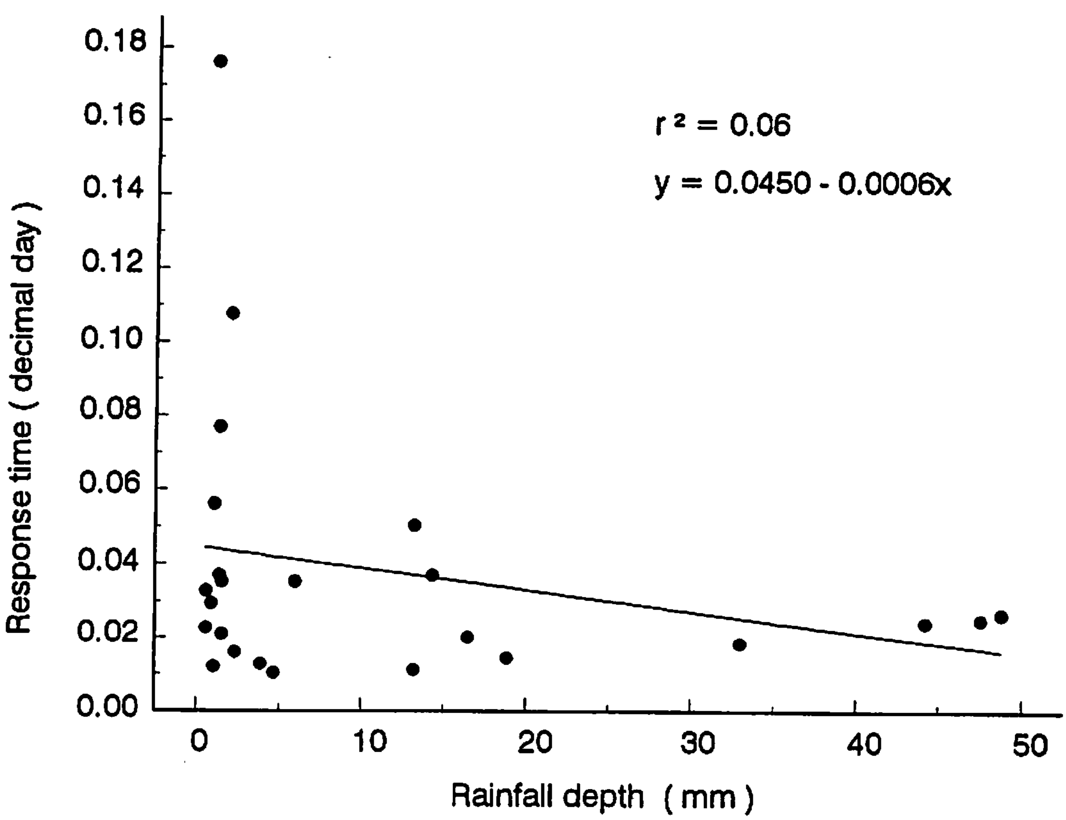

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Figure 6. Correlation of ERS Response Time from Start of Rainfall to (a) Peak Rainfall Intensity and (b) Rainfall Amount.

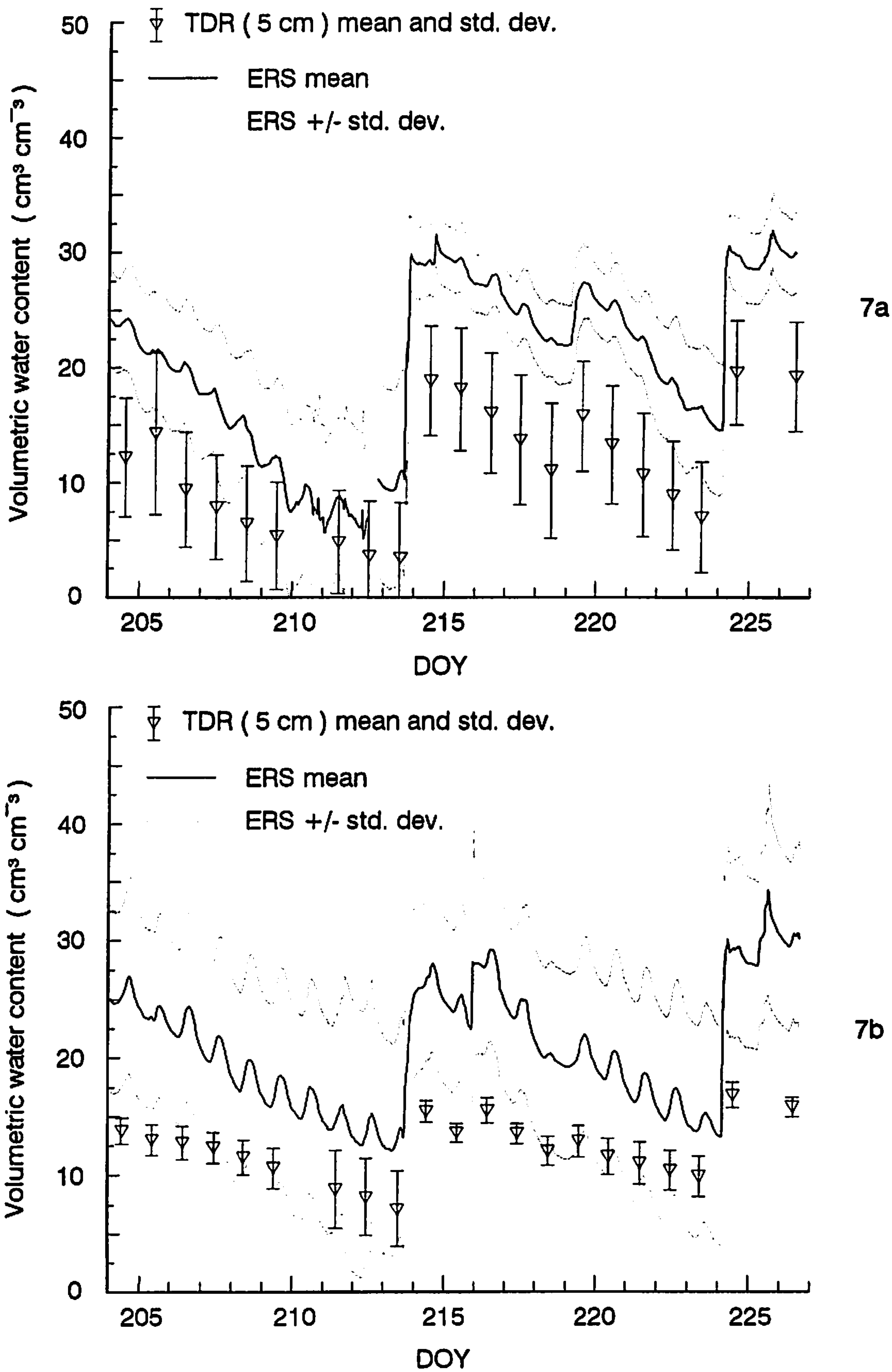

Figure 7. Comparison of ERS and TDR Methods of Soil Moisture Content (percent volume) at 5 cm at (a) Kendall North and (b) Lucky Hills.

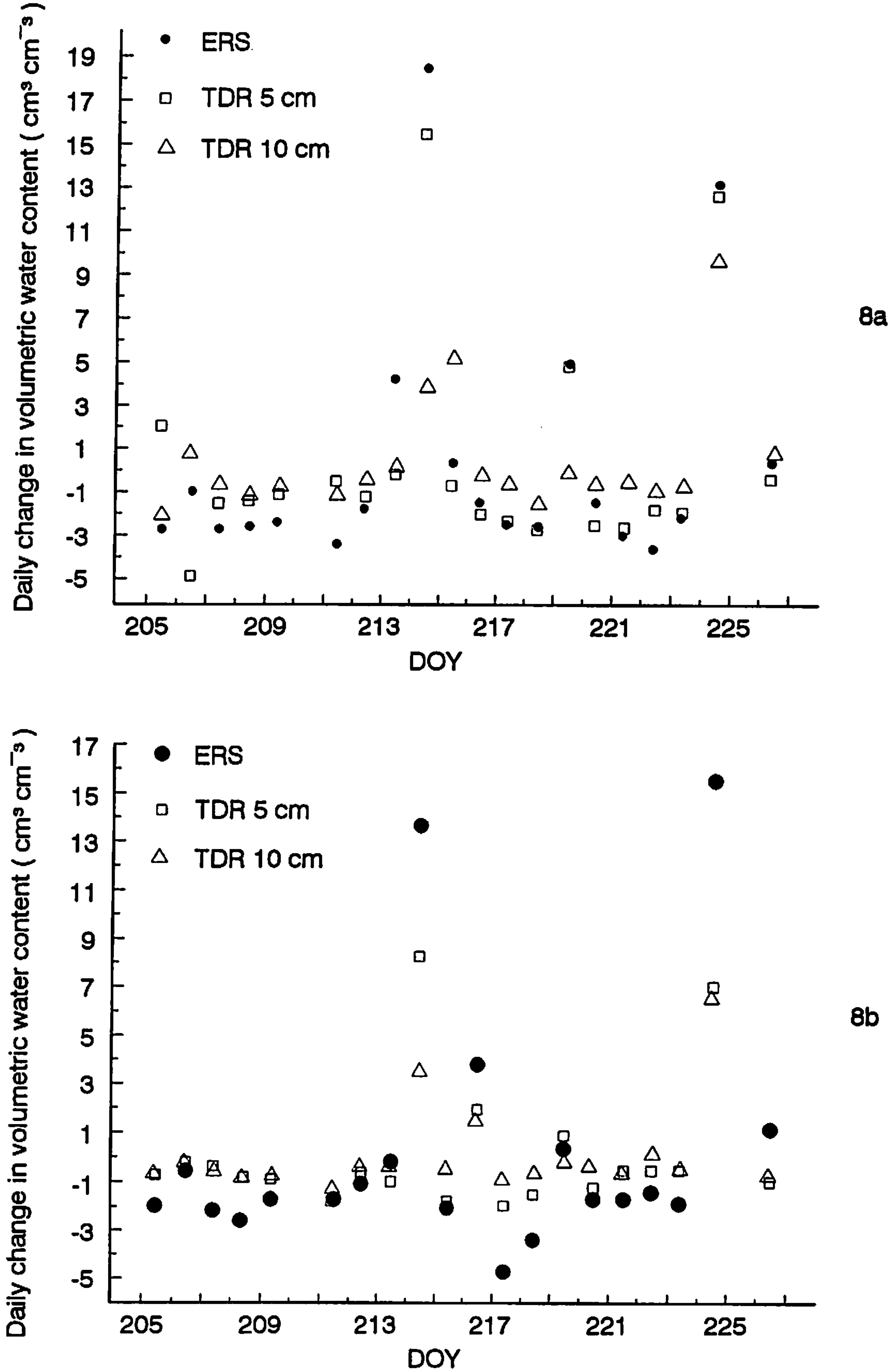

Figure 8. Daily Change in Mean Soil Water Content from ERS and TDR Methods (2 depths) at (a) Kendall North and (b) Lucky Hills.

soil water content offers the possibility of incorporating the probable aspect of precipitation and soil water relations into a description of seedling environment necessary for plant establishment.

The germination rates and seed survival of native grasses are dependent on the length of time the soil is above some critical soil moisture threshold and the length of the following drying cycle (Frasier, 1987). The absolute soil water content is not essential as long as it is above or below this threshold (Frasier, 1987; Frasier *et al.*, 1985). Understanding of the dynamics of soil water content for germination and survival characteristics of grass seeds for reclaiming disturbed lands is essential.

These ERS are being studied in multilevel arrays to a depth of 30 cm in the soil profile for wetting front detection. This technique would have various applications, including evaluation of effectiveness of trench cap designs against soil water breakthrough.

The proposed ERS has advantages and disadvantages. Some of the advantages are particularly important in semi-arid and desert landscapes: first, because the sensors measure moisture at discrete points, they are suited to indicating soil moisture at very shallow depths (Hunter and Greger, 1986); second, the range of soil moisture contents measured is important. Semi-arid soils wet to field capacity for only a very limited period (< 1 day), then dry to essentially air-dry moisture content within 1 to 2 weeks (Hunter and Greger, 1986). The point nature of the moisture determination allows us to not only evaluate water balance, but also identify the dynamics of the wetting and drying cycle.

SUMMARY AND RECOMMENDATIONS

An electrical resistance method of measuring soil water content under field conditions for hydrologic applications has been described. Electrical resistance sensors were permanently imbedded in the soil. The moisture content of the fiberglass varies with that of the soil; hence, resistance readings can be used as an index of soil moisture content. The sensors are mechanically strong and may possibly survive several years in the field, but considerable initial failure was encountered in this study.

The development of the electrical resistance method of monitoring soil water content arose from the difficulties involved in typical labor intensive gravimetric sampling procedures and the impossibility of obtaining successive measurements at the same location. This method is an economical alternative technique for obtaining rapid, *in situ*, permanent, long term and near continuous measurements of soil water content. This enables a more thorough and accurate understanding of the most dynamic of soil characteristics and the ability to monitor the short and long term evolution of soil moisture.

On the basis of the current and the foregoing investigations, the proper procedure to employ in the use of this method is as follows:

1. *In situ* field calibration may be more feasible and provide more accurate measurements than laboratory calibration, especially for rocky soils.
2. Multiple redundant ERS should be installed in expectation of high initial failure.
3. A close contact must be maintained between the outside of fiberglass sandwich and soil.
4. Wire leads of a sensor should not pass vertically from the sensor up through the soil surface to ensure against the possibility of water flow down along the sensor wires.
5. Resistance readings should be corrected for temperature.
6. Gravimetric samples should be obtained as close to the sensors as possible and at the same depth so that the moisture content of the sample is representative to that of the sensor. However, sampling at less than 15 cm from the sensor is not recommended.
7. Gravimetric samples should be as small as possible so that repeated sampling will not disturb the area under investigation.
8. Replication of gravimetric soil moisture samples is recommended.
9. Gravimetric sampling should be made periodically to check ERS condition and to monitor response time.

ACKNOWLEDGMENTS

The authors wish to thank the employees of the USDA-ARS-SWRC field office in Tombstone, Arizona, for their assistance in this project. Support for this research was provided by the NASA Interdisciplinary Research Program in Earth Sciences (NASA Reference Number IDP-88-086) and NASA/EOS Grant NAGW2425.

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