EVALUATION OF DIELECTRIC SOIL MOISTURE SENSORS FOR IRRIGATION SCHEDULING ON FARMS

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ABSTRACT

Seven dielectric soil moisture sensors were evaluated for their response to changes in soil moisture content and their appropriateness for irrigation scheduling on farms. The devices were the Sentry 200-AP, TRIME, TRASE, Aquaterr moisture meter, Enviroscan instrument, Hydra Soil Moisture Probe, and ThetaProbe. Results showed the TRASE and ThetaProbe devices to be relatively accurate compared to the other instruments. Calibration of the other instruments may be necessary under some conditions. In the fine-textured soils, the TDR devices sometimes would not operate. The Enviroscan has the advantage of high-frequency measurements, but tended to overestimate soil moisture contents.

INTRODUCTION

Recently, dielectric sensors have been developed that determine the soil moisture content based on measurements of the dielectric constant of the soil. Dielectric devices include time-domain-reflectometry (TDR) sensors and capacitance sensors, also called frequency-domain reflectometry sensors.

Numerous studies have been conducted on using the TDR and capacitance methods. Because of space limitations, however, the literature review is omitted. A comprehensive review of both techniques is in White and Zegelin (1995).

Field use of several dielectric instruments revealed readings that were unrealistic and contrary to reported laboratory calibrations. Thus, a project was initiated to investigate the response of dielectric methods to changes in soil moisture content and their appropriateness for irrigation scheduling on farms.

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PROCEDURE

Two approaches were used for this project. The first approach evaluated three dielectric soil moisture sensors at six locations in the San Joaquin Valley. Soil texture at the six locations ranged from silt clay to loamy sand. The sensors evaluated were the Sentry 200-AP, TRIME TDR, and TRASE TDR. The Sentry 200-AP is a capacitance device that requires installing a plastic access tube such that no air gap exists between the tube and the soil. A probe containing two electrodes separated by a dielectric is lowered into the access tube to the desired depth and a measurement is made. The TRIME TDR device requires a fiberglass access tube installed in the soil. A depth probe 7.9 in (200 mm) long containing two waveguides is lowered into the access tube to the desired depth, and a measurement is made. The TRASE TDR device involves driving two steel rods or waveguides into the soil parallel to each other. Two sets of rods were used with one set measuring over a 1-foot (0.3-m) depth interval and the second set measuring over a 2-foot (0.61-m) depth interval.

In addition, an Enviroscan instrument was evaluated at four other locations containing fine-texture soil. The Enviroscan system is a capacitance device consisting of a series of electrodes installed in a plastic access tube. The sensors are connected to a data logger. For this study, measurements were made at 4 in (0.1 m), 12 in (0.3 m), 20 in (0.64 m), 28 in (0.71 m), and 36 in (0.91 m) depth. Two of the locations corresponded to two of the above mentioned sites.

With the exception of the TRASE device, these devices require carefully installed access tubes. Because the installation and removal of the access tubes is time-consuming and difficult and because of the large number of measurements, it was not practical to collect volumetric soil samples each time measurements were made. This would have disrupted the soil adjacent to the access tubes and would require frequent removal and reinstallation of the tubes. Thus, soil moisture contents were measured with a neutron moisture meter (NMM) calibrated for each site. These NMM moisture contents were compared with the dielectric instruments' readings to evaluate their accuracy and their response to changes in soil moisture. In spite of concerns about different zones of influence between the NMM and dielectric sensors and possible errors due to the NMM calibration and its random counting rate, the results showed that the NMM data provided a reasonable description of the performance of the dielectric sensors.

All instruments were installed along a 6-foot (1.8-m) long transect at each site with the NMM access tube installed at the middle of the transect. The sensors were located as close together as possible to minimize any small-scale variability in soil moisture content, yet not interfere with each other.

The second approach consisted of comparing readings of an Aquaterr Moisture Meter, Hydra Soil Moisture Probe, and a ThetaProbe with volumetric soil moisture contents determined from soil samples. These devices are highly portable, thus allowing them to be easily moved. Soil textures used for this approach ranged from sandy loam to clay loam. The soil samples, each 59.5 cm^3 in volume, were taken about one inch (25 mm) from the dielectric instrument. The Aquaterr meter is a capacitance meter with a steel rod containing two electrodes at its tip. The rod is pushed into the soil to the desired depth and a reading obtained. A color-coded chart relates the instrument's reading to a qualitative indicator of soil moisture content. The ThetaProbe is a plastic cylinder 4.9 in (125 mm) long and 1.6 in (40 mm) in diameter with four steel rods, each 2.4 in (60 mm) long, attached to one end. The sensor is connected to a hand-held meter that reads in volumetric soil moisture content. The design of the Hydra Soil Moisture Probe is similar to that of the ThetaProbe. Both the ThetaProbe and Hydra Probe require a hole augered to the desired depth of measurement.

Linear regression equations were developed relating instrument readings to soil moisture contents. A single equation was developed for each site by combining the data of each depth of measurement. The coefficients of these equations were statistically compared to those of a one-to-one (1:1) line (slope =1, intercept = 0). Root mean square errors were also calculated between the actual and measured values where appropriate. A level of significance of 0.05 was used for all statistical tests.

RESULTS

Sentry

Figures 1a and 1b show the response of the Sentry instrument to changes in soil moisture content for two soil textures. For the coarser texture soils, a strong linear relationship existed between Sentry readings and soil moisture contents, but deviated from a 1:1 line (dashed line). For the fine-texture soils, the Sentry readings sometimes greatly overestimated soil moisture contents. Values exceeded 50 percent at a silt loam site, while for the silt clay site, moisture contents ranged between about 45 percent and nearly 120 percent, clearly unrealistic.

Coefficients of the linear regression equations showed the slopes of the regression equations to be less than one for the coarser texture soils, while for the fine-texture soils, slopes were between 1.76 and 3.00 even though the unrealistically high values were excluded from the statistical analysis. Coefficients of determination ranged between 0.54 and 0.73. Slopes and intercepts of the regression equations were statistically different from those of a 1:1 line.

TRASE

The TRASE values represent an average reading over depth intervals of 0 to 1 foot (0.30 m) and 0 to 2 feet (0.61 m), thus soil moisture contents were averaged over the same depth intervals. For the coarser texture soils, measurements showed a strong linear relationship between instrument readings and soil moisture contents for both depth intervals (Fig. 1c). At one of the silt loam sites, little correlation occurred between TRASE readings and soil moisture contents, reasons for which are unknown. For the other fine-texture sites, linear relationships were found such as shown in Fig. 1d. For all finer texture soils, measurements could not be made for the 2 foot (0.61 m) interval.

Coefficients of determination ranged from 0.85 to 0.98 except for the previously mentioned silt loam site ($r^2 = 0.02$) and the loamy sand site ($r^2 = 0.64$). Slopes of the linear regression equations ranged from 0.68 to 0.74 for the coarse-texture sites and between 0.78 and 1.47 for the two fine-texture sites. Slopes were not statistically equal to that of the 1:1 line for all sites except for the slope of the 0.61-m interval for sandy loam 1. The slopes of the coarse-texture soils were statistically equal to each other.

TRIME

Measurements were made only at one coarse texture soil because of a limited number of access tubes. In a sandy loam, TRIME readings nearly equaled soil moisture contents for moisture contents greater than about 25 percent (Fig. 1e). For moisture contents less than about 25 percent, TRIME readings exceeded soil moisture contents. This behavior occurred at all depths of measurement. Relatively little scatter occurred about the trend in the data.

At the silt loam site, TRIME readings greatly overestimated soil moisture contents although a linear relationship occurred. The sensor would not read at the 18 in (0.45 m) depth. The instrument underestimated soil moisture content at the two silt loam sites (Fig. 1f).

Coefficients of the regression equations showed slopes ranging between 0.55 and 1.41 and intercepts ranging between -22.01 and 21.63. Coefficients of

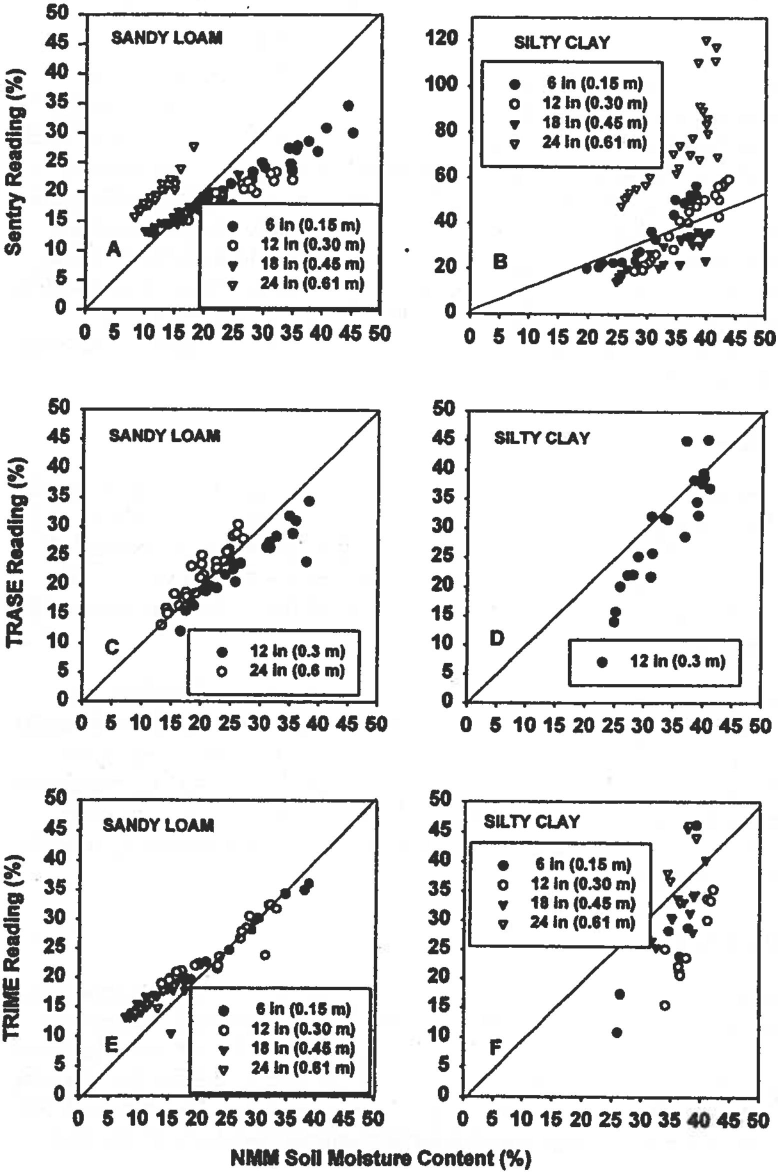

Fig. 1. Response of Sentry, TRASE, and TRIME sensors.

determination ranged between 0.35 and 0.91. Slopes of these equations were statistically different from those of a 1:1 line except for one of the silt loam sites.

Enviroscan

Figures 2a and 2b show NMM and Enviroscan readings with depth for two different measurement dates at the silt loam and silty clay sites. This approach was used because Enviroscan readings could not be directly compared with NMM readings due to different depths of measurements. Each set of data consists of readings in a relatively wet soil and in a relatively dry one. These data show that the Enviroscan readings generally were much greater than the NMM readings. Most of the Enviroscan readings were at least 1.5 times greater than the NMM values. The ratio of Eviroscan reading to NMM reading increased as soil moisture content decreased. However, at each location, the ratio for the shallowest measurement depth only ranged between 0.9 and 1.16. Similar behavior occurred at a silt loam site.

ThetaProbe

ThetaProbe readings plotted against soil sample volumetric soil moisture content are shown in Fig. 2c and 2d for a sandy loam and a clay loam sites. Data of the seven sites sampled showed a strong linear response of ThetaProbe readings to changes in soil moisture content with data points relatively close to a 1:1 line. Data of the sites with sandier soil tended to better fit the 1:1 line than the data of the other sites.

Regression coefficients showed similar slopes and intercepts among the finer-textured soils, but these coefficients were statistically different from the slope and intercept of a 1:1 line. Similar regression coefficients were found among the sandier sites, which were statistically similar to those of a 1:1 line. Coefficients of determination ranged between 0.68 and 0.91 with all but one site greater than 0.79. Regression equations of the fine-texture soils were not statistically equal to those of the sandier soils.

Aquaterr Meter

Aquaterr meter readings plotted against soil moisture contents are shown in Fig. 2e and 2f for three sites. In general, Aquaterr readings responded to changes in soil moisture content although considerable scatter occurred in the data. However, outliers appeared to exist over the dryer values of soil moisture at a clay loam site, while for a sandy loam site, little change in Aquaterr reading with changes in soil moisture content was found. Reasons for this behavior are unclear at this time.

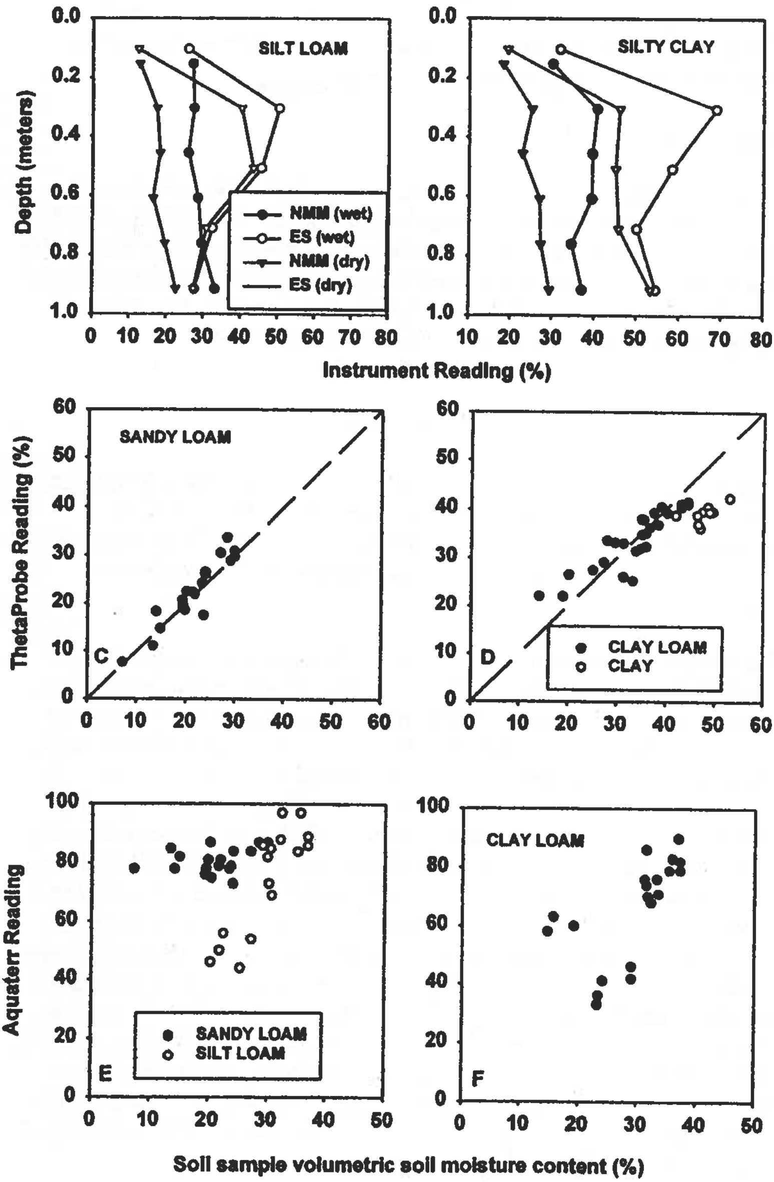

Fig. 2. Response of Enviroscan (ES), ThetaProbe, and Aquaterr sensors.

Regression coefficients and coefficients of determination show considerable variation between the sites. Coefficients of determination ranged between 0.18 and 0.77 indicating that much of the variation in the Aquaterr readings is not explained by the variation in soil moisture content.

Hydra Soil Moisture Probe

The Hydra Soil Moisture Probe readings were much larger than soil moisture contents for the three sites evaluated thus far (not shown) with RMS errors of 8.4 (sandy loam), 11.6 (silty clay), and 12.9 (silt loam). However, a linear relationship was found between soil moisture contents and probe readings with coefficients of determination ranging of 0.50, 0.80, and 0.91 for the three sites. All of the regression equations were statistically different from the 1:1 line.

DISCUSSION

It should be emphasized that these results are specific to these soils. While factors affecting the performance of dielectric sensors are not well-identified, some factors appear to be soil salinity, soil texture, and type of clay. These sensors used in locations with little soil salinity and a different type of clay may respond differently.

The ThetaProbe was the most accurate of the instruments over a wide range of soils with RMS errors ranging from 2.5 to 4.9. The TRASE instrument was also accurate over these soil types with RMS errors ranging from 1.8 to 5.6 with the exception of the silt loam site (Table 1). However, it would not read over the 0.6 m depth interval in the fine-texture soils. The TRIME instrument was relatively accurate in the coarse-texture soil, but accuracy was marginal at the sites with fine-texture soils with RMS errors greater than 8.3 (Table 1). Accuracy also was marginal for the Sentry in the coarse-texture soil with RMS errors ranging from 5.3 to 6.3 and was poor in the fine-texture soils with errors ranging from 8.9 to 36.2 (Table 1). The errors of the TRASE and TRIME instruments in the coarse-texture soils were similar to the RMS errors of the NMM, thus suggesting that the error in the NMM calibration curve might contribute significantly to differences between NMM and TRASE readings. (The RMS error of the NMM is based on the difference between calibration soil sample moisture contents and the predicted moisture contents from the calibration equation.) Accuracy of the Enviroscan system in these fine-texture soils was poor. Aquaterr readings were relative, and thus RMS errors were not calculated. Accuracy of the Hydra Soil Moisture Probe was poor for the three sites evaluated thus far.

Instruments with poor accuracy can be used for irrigation scheduling, but field observations and measurements will be necessary to interpret the instruments' readings relative to irrigation needs. The Aquaterr meter provides a qualitative reading only and will require field calibration.

The TRASE, ThetaProbe, and Aquaterr meter are relatively easy to install in a wet soil, but were difficult to use in relatively dry conditions. The Sentry, TRIME, and Enviroscan instruments require carefully-installed access tubes, which increases their difficulty of installation. Special installation equipment supplied by the manufacturers is recommended. Technical support is also required to set up the Enviroscan system.

An advantage of the ThetaProbe and Aquaterr meter is their portability, which allows many measurements to be made throughout a field. An advantage of the Enviroscan system is its ability to make very frequent measurements and to rapidly display the data on manufacturer supplied software.

The Aquaterr meter is the least expensive (about US$500) followed by the ThetaProbe (US$850 for a minimum kit). Minimum costs for the other instruments ranged between US$8,000 and nearly US$14,000.

REFERENCES

White, I. and Zegelin, S. J. 1995. Electric and dielectric methods for monitoring soil-water content. In: Handbook of Vadose Zone Characterization and Monitoring (ed: L. G. Wilson, L. G. Evertt, and S. J. Cullen). Lewis Publishers.

Table 1. Root mean square errors (percent) of the NMM and dielectric instruments at the six sites.

Site	NMM	Sentry	TRIME	TRASE
Sandy Loam 1	2.9	6.3	4.1	3.5
Sandy Loam 2	2.8	5.3	*	1.8
Loamy Sand	2.8	5.5	*	1.8
Silt Loam 1	3.1	29.8	14.1	8.7
Silty Clay	3.3	8.9	9.6	5.6
Silt Loam 2	3.7	36.2	8.3	4.8