

tering the waveguide length. The Enviroscan system requires downloading the data stored in its datalogger into a computer and then displaying the data using manufacturer-supplied software.

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

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Effectiveness of tensiometers and electrical resistance sensors varies with soil conditions

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Tensiometers, gypsum blocks, Watermark blocks and an electromagnetic conductivity meter were evaluated for their response to changes in soil moisture content. Tensiometers and Watermark blocks had similar responses, but the blocks operated better than tensiometers in drier soil. Gypsum blocks did not respond until some threshold moisture content was reached. The electromagnetic conductivity meter responded to changes in moisture content in fine-textured soil, but it did not respond in sandy soil.

Measuring or monitoring soil moisture content can help determine when to irrigate, how much water to apply, adequacy of wetting, patterns of soil moisture extraction by roots, and trends in increasing or decreasing soil moisture content with time. Such information can help improve crop yield, increase irrigation efficiency, stretch limited water supplies and reduce nonpoint-source pollution.

Traditional methods for monitoring soil moisture content include soil sampling, tensiometers, electrical resistance/conductance methods and neutron moisture meters. These devices must be calibrated to provide actual soil moisture contents. The calibra-

tions depend on soil texture, particularly for tensiometers and resistance blocks and less for the neutron moisture meter. More recently, dielectric sensors have been developed that determine soil moisture content based on the dielectric constant of the soil.

This project investigated the response of these sensors to changes in soil moisture content to evaluate their appropriateness for irrigation scheduling on farms. Criteria used to evaluate these instruments were ease of operation, ease of installation, maintenance and cost.

Evaluating monitoring devices

Tensiometers, electrical resistance blocks and an electromagnetic conductivity meter were evaluated at six sites in the San Joaquin Valley. These sites and their average percent sand, silt and clay were Sandy Loam-WAL (70-29-1), Loamy Sand-GR (82-17-1), Sandy Loam-PE (67-29-4), Silt Loam-WA (19-62-19), Silty Clay-WB (19-46-35) and Silt Loam-CO (19-52-29). The letters following soil type identify site location.

At Sandy Loam-WAL, silty clay loam occurred at 6 inches, and sandy loam at the deeper depths. Sandy loam occurred at 6 inches deep and loamy sand at the deeper depths for Loamy Sand-GR. Soil texture was fairly constant with depth for Sandy Loam-PE.

Tensiometer

Silt clay loam to silty clay occurred at Silty Clay-WB. Silt Loam-WA had smaller clay contents and larger silt contents compared with Silt Loam-CO. Sandy Loam-WAL was a flood-irrigated walnut orchard, Sandy Loam-PE was a flood-irrigated peach orchard, Loamy Sand-GR was a flood-irrigated vineyard, Silt Loam-WA and Silty Clay-WB were furrow-irrigated tomato fields, and Silt Loam-CO was a furrow-irrigated cotton field. Only data from Sandy Loam-WAL and Silty Clay-WB are shown in the following figures to simplify the illustrations. Results from these sites were representative of those from the other sites.

In this paper, we report on five devices evaluated at these sites:

1. Tensiometer (Irrometer Company, Riverside, CA; Soil Moisture Equipment Co., Santa Barbara, CA). A tensiometer is a plastic tube with a porous ceramic cup attached to one end

and a vacuum gauge to the other. It measures soil moisture tension up to a maximum of about 80 centibars at or near sea level. Even though the behavior of tensiometers is well understood, this device was evaluated for comparison purposes.

2. Watermark electrical resistance block (Irrrometer Co., Riverside, CA). This device consists of two electrodes imbedded in a sand-ceramic porous material. A wafer of gypsum is contained in the block to buffer salinity effects. The instrument used for this block converts measured resistance into equivalent centibars of soil moisture tension with a range between 0 and 199.

3. Gypsum electrical resistance block (Soil Moisture Equipment Co., Santa Barbara, CA). This electrical resistance block consists of two electrodes imbedded in gypsum. The instrument gives a relative reading between 0 (dry block) and 94 to 96 (saturated block). This sensor was recently discontinued.

4. EM-38 electromagnetic conductivity meter (Geonics Limited, Ontario

inch depth and for the deeper depths. We used these moisture contents as the standard for evaluating the soil moisture sensors.

It might be preferable to use volumetric soil moisture contents from soil samples as the standard. However, soil sampling would disturb the soil in the immediate vicinity of the instruments, thus requiring their frequent removal and reinstallation. The frequency of readings and the number of devices made soil sampling impractical so we used the NMM method.

All instruments were installed along a transect about 6 feet long at each site with the NMM access tube centered along the transect. Measurements were made at 6, 12, 18 and 24 inches deep at all sites. Measurements were made twice per week during the duration of the study (1 to 2 months, depending on the site).

Neutron moisture meter

The NMM calibration curves relate volumetric water content, expressed in percent water, to count ratio, which is the ratio of the actual count to a stan-

dent except at the 6-inch depth, where soil texture was sandy loam. At Silt Loam-CO (not shown), the tensiometers did not respond for the 6- and 12-inch depths.

Possible causes of poor responses include the following:

1. There may have been poor hydraulic contact between the porous cup and the loamy sand at Loamy Sand-GR.

2. Leaks caused by a poor seal or a cracked porous cup may have prevented any response at Sandy Loam-WAL (12 inches).

3. Excessive drying may have caused problems at Silt Loam-CO and Loamy Sand-GR. Although the tensiometers were periodically maintained, lack of an irrigation immediately following maintenance could desaturate the porous cup and prevent a response to subsequent irrigations.

Correlation coefficients between tensiometer readings and NMM moisture contents were negative because tensiometer readings increased as soil moisture content decreased. These coefficients were considerably smaller

TABLE 1. Regression equation coefficients and coefficients of determination for the calibration equations of the neutron moisture meter

Site	Slope	Intercept	r ²
Sandy Loam-WAL ac*	35.9 a	-7.0	0.83
Sandy Loam-PE, Loamy Sand-GR a	35.7 a	-7.3	0.79
Silt Loam-WA b	33.2 a	-10.9	0.78
Silty Clay-WB cd	56.1 bc	-22.9	0.78
Silt Loam-CO ad	46.3 ac	-15.2	0.67

*The small letters by each site indicate statistical equality at a level of significance of 5%.

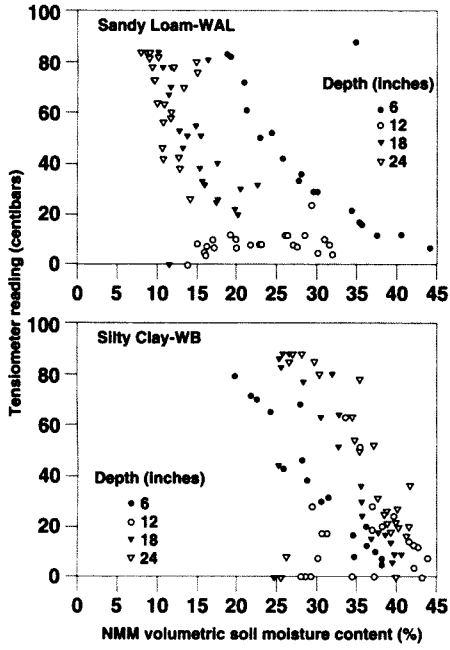


Fig. 1. Tensiometer readings versus neutron moisture meter (NMM) soil moisture contents for two locations.

cept 6 inches. As with the tensiometers, poor hydraulic contact apparently occurred between the loamy sand and the sensors.

Correlation coefficients between

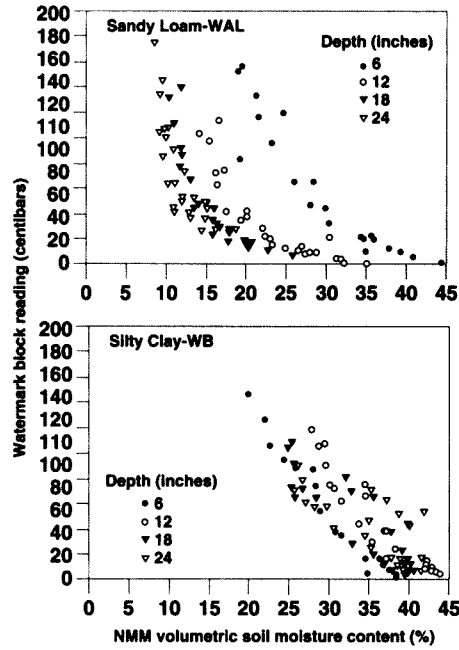


Fig. 2. Watermark block readings versus NMM soil moisture contents for two locations.

Soil texture at these sites was relatively constant with depth except at Silty Clay-WB. In a separate study in Northern California, however, possible effects of differences in soil tex

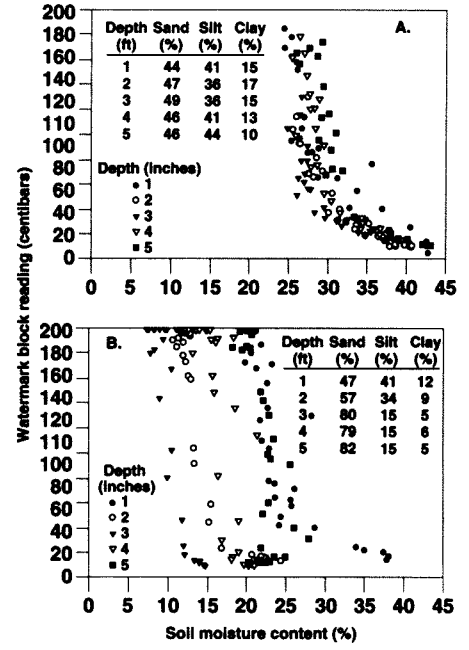
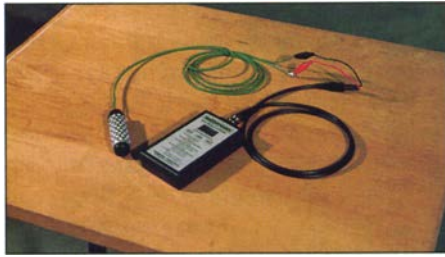


Fig. 3. The effect of soil texture on Watermark block readings for a soil profile with a uniform texture (A) and a soil profile with a nonuniform texture (B).

Threshold values depended on soil texture. These values ranged between 5% and 10% for Loamy Sand-GR, between 15% and 20% for Sandy Loam-WAL, between 20% and 25% for



Watermark block

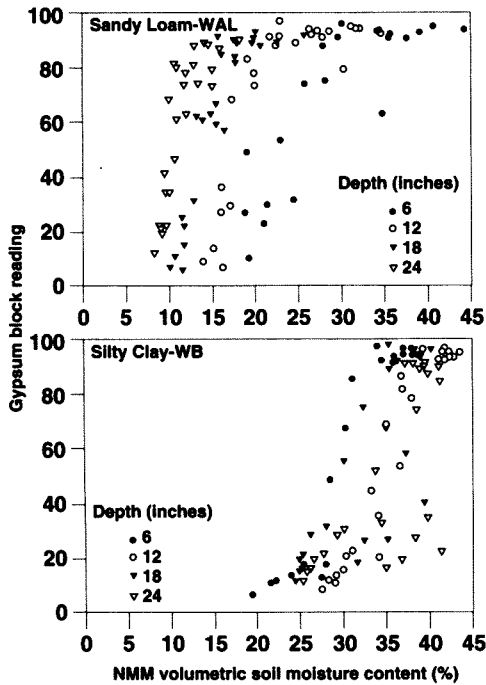


Fig. 4. Gypsum block readings versus NMM soil moisture contents for two locations.

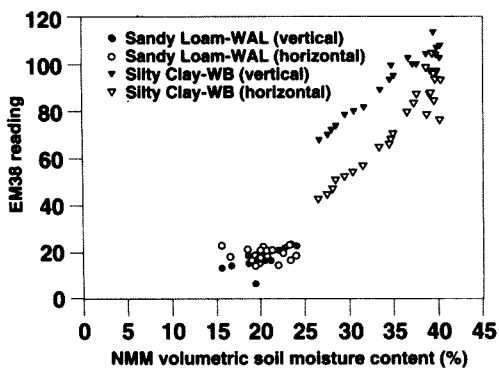


Fig. 5. EM-38 readings versus NMM soil moisture content for horizontal and vertical modes at two locations.

EM-38 readings occurred with soil moisture content at Sandy Loam-WAL (fig. 5), Sandy Loam-PE and Loamy Sand-GR where nonsaline soils existed. This response was due to very low levels of soil salinity, the result of using irrigation water with an electrical conductivity less than 0.1 dS/m.

TABLE 2. Regression coefficients and coefficients of determination for the EM-38 electromagnetic conductivity meter

Site	Slope	Intercept	Coefficient of determination
Vertical Mode			
Silt Loam-WA a	2.76 a	-3.46	0.92
Silty Clay-WB b	2.20 b	-27.74	0.79
Silt Loam-CO c	3.11 abc	-31.90	0.79
Horizontal Mode			
Silt Loam-WA d	3.69 d	-52.51	0.92
Silty Clay-WB e	3.88 d	-10.88	0.87
Silt Loam-CO f	3.64 d	-67.89	0.87

*The same small letter indicates that equations and slopes are statistically similar at a level of significance of 5%.

At the other sites, EM-38 readings decreased substantially as soil moisture content decreased (fig. 5). Differences occurred between the horizontal and vertical modes except at Silt Loam-WA. The electrical conductivity of the irrigation water used at these sites generally was greater than about 0.5 dS/m.

Correlation coefficients between EM-38 readings and soil moisture contents were greater than 0.89 at Silt Loam-WA, Silty Clay-WB and Silt Loam-CO, while at Sandy Loam-WAL and Loamy Sand-GR, correlation coefficients were less than 0.17. Coefficients for Sandy Loam-PE ranged from 0.64 to 0.75 for the vertical and horizontal modes, respectively.

A statistical analysis of the coefficients of the regression equations for both vertical and horizontal modes for Silt Loam-WA, Silty Clay-WB and Silt Loam-CO showed that the equations were not all statistically equal for the vertical mode (table 2). For the horizontal mode, the slopes for all sites were statistically equal. This slope similarity suggests that the EM-38 could be used to monitor changes in soil moisture between irrigations for these soil types and salinity levels.

Tools have different strengths

Tensiometers, Watermark blocks, and gypsum blocks provide a measure of soil moisture tension. They are easy to install, operate and maintain, and are relatively inexpensive. They are appropriate for determining when to irrigate, but calibration is needed to estimate actual soil moisture contents from their readings. Watermark block readings tended to lag the tensiometer readings, but they were more reliable

than tensiometers and responded over a much larger range of soil moisture contents. This characteristic of the Watermark blocks makes them particularly appropriate for irrigation scheduling.

The gypsum blocks also responded over a wide range of soil moisture contents, but little response occurred until a threshold content was reached.

The EM-38 responded poorly where little soil salinity occurs. Where some soil salinity occurs, linear relationships between EM-38 readings and soil moisture contents were found. This suggests that this device might be able to reasonably estimate changes in soil moisture content, but field calibration will be needed to correlate changes in EM-38 readings with changes in soil moisture contents. At the sites used for this instrument, EM-38 readings changed an average of 3.74 units (horizontal mode) for each 1% change in soil moisture content. The main advantage of this device is its relatively large volume of measurement. Its disadvantage is its cost — at least \$7,000, depending on configuration.

Detailed discussions concerning installation and use of tensiometers and electrical resistance blocks is contained in Hanson et al. 1999.

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