Improved Installation Procedures for Deep-Layer Soil Moisture Measurements

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ABSTRACT

The Oklahoma Mesonet, an automated network of 115 meteorological observing stations, includes soil moisture monitoring devices at 60 locations. The Campbell Scientific model 229-L matric potential (water potential) sensor was chosen for operational use based on its capability to perform as a fully automated soil water measuring device. Extensive laboratory calibrations were performed on each sensor to ensure the quality of the matric potential measurements.

Examination of the data from the Norman site during July 1997 revealed significant inconsistencies between near-surface (5 and 25 cm) measurements of soil moisture and deep-layer (60 and 75 cm) measurements of soil moisture. In particular, a heavy precipitation event was followed by only a small increase in near-surface soil water potential values, while a much larger increase occurred in the deep-layer values. It is theorized that an installation flaw is the cause for these inconsistencies. A solution is proposed in the hope that future efforts to measure soil moisture will not be hindered by similar problems.

1. Introduction

Soil moisture is an important contributor in the exchange of mass and energy between the land surface and the atmosphere. Bare soil evaporation directly influences the partitioning of available energy at the surface into sensible and latent heat fluxes. Additionally, the available water contained in the soil provides sustenance for the vegetation. In turn, vegetation contributes to the exchange of mass and energy through transpiration and CO_2 exchange and by modifying the surface albedo (Sellers et al. 1997).

Unfortunately, the nature of surface–atmosphere interactions is not well understood due, in part, to a limited number of field observations. Emanuel et al. (1995) identified the fundamental physics of surface–atmosphere interactions as an important research topic for those wanting to improve numerical weather prediction models. Fortunately, soil moisture measurement technology has become more reliable and more affordable during the 1990s. Because of this, the Oklahoma Mesonet (Brock et al. 1995), an integrated network of 115 remote, automated meteorological stations across Oklahoma, was able to install soil moisture monitoring devices at 60 sites during 1996 and 1997. This network provides a unique opportunity to measure soil moisture at locations with a wide range of soil types and vegetation.

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2. Soil moisture measurements from the Oklahoma Mesonet

a. Theory

The amount of water in the soil is typically expressed in terms of potential. Soil water potential is defined as the amount of work needed to transfer a unit mass of water from the soil to a reference pool at the same elevation. Established convention dictates that these values are negative, thus higher absolute values of potential represent drier soils. Typically the work per unit mass of water (J kg^{-1}) is multiplied by the density of water (approximately 1000 kg m^{-3}) to get soil water potential expressed in terms of pressure (kPa; Marshall et al. 1996). Determining the soil water potential is crucial when considering the availability of water for vegetation sustenance. It is widely accepted that plants have great difficulty in extracting water from soils when the potential is less than about −1500 kPa (Dingman 1994). Thus, an estimate of soil water potential is a valuable resource to help understand both the flow of moisture

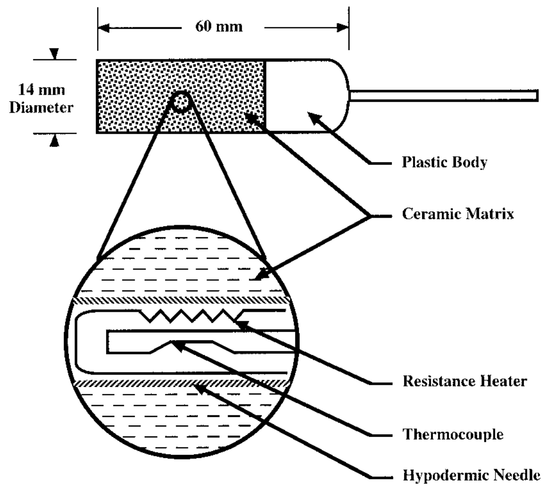

FIG. 1. The Campbell Scientific 229-L matric potential sensor (the enlarged diagram represents a cross section through the ceramic matrix).

within the soil and its impact on both the atmosphere and the biosphere.

Using a device that consists of a temperature sensor and a heating unit placed directly into the soil, Shaw and Baver (1939) demonstrated that the rate at which heat is dissipated in the soil can be an indicator of the matric potential (water potential) of the soil. Phene et al. (1971) developed a sensor using a germanium P–N diode as the temperature sensor and wrapped with 40-gauge copper wire that acted as the heating coil. The apparatus was then embedded in a porous block. Various materials such as gypsum, ceramics, and mixtures of ceramic and castone were tested as potential porous materials that could be used in the block. They determined that the ceramic block provided a stable solid matrix due to the linear response that the material exhibited during testing. Sensors based on the Phene et al. (1971) design have been successfully utilized in sandy loam (Phene and Howell 1984), clay loam (Phene et al. 1989), silt (Fredlund 1992), and clay (Fredlund 1992).

The latest sensor technology utilizes thermocouples as temperature sensors and resistors as heating elements. In particular, the Campbell Scientific Inc. model 229-L incorporates this design (Fig. 1). A thermocouple and a resistor are housed within a hypodermic needle. The hypodermic needle, in turn, is embedded within a ceramic matrix 14 mm in diameter and 60 mm long. Once the sensor is buried within the soil, the matrix must be permitted to come into equilibrium with the surrounding soil. Once equilibrium is attained, the thermocouple measures the soil temperature both before and after an electric current (50 mA passed through a 33 Ω resistor for 20 s) is sent through the resistor. After the current pulse, the temperature difference is higher (lower) in drier (wetter) soil since the heat produced at the resistor is conducted away from the sensor less (more) effectively. This difference is directly related to the soil water potential.

The 229-L sensors were subjected to a two-step laboratory calibration before being installed at remote sites. First, the sensors underwent an endpoint test, whereby heat dissipation (temperature rise of the sensor) was measured under both dry and saturated conditions. To accomplish this, the sensors were first subjected to a dry air environment using dessicant bags. The temperature rise for each sensor was then calculated over a 12-h period. Once this was completed, the sensors were immersed in distilled water and a similar set of measurements were performed over a 12-h period. Finally, a set of calibration coefficients was created using the endpoint data, and applied to each sensor's response to remove the inherent sensor-to-sensor variability:

$$\Delta T_{\mathrm{ref}} = m\Delta T_{\mathrm{sensor}} + b, \tag{1}$$

where ΔT_{ref} is the response of a ‘‘reference’’ sensor, $\Delta T_{\mathrm{sensor}}$ is the observed response of an individual sensor ($T_{\mathrm{after\,heating}} - T_{\mathrm{before\,heating}}$), and m and b are empirical coefficients unique to each sensor.

Sensor response also was compared with known potentials created in the laboratory. Subsequently, an equation was developed to convert temperature rises generated by a sensor into values of matric potential:

$$\psi = \frac{1}{a}\left(\frac{\Delta T_w - \Delta T_d}{\Delta T_{\mathrm{ref}} - \Delta T_d} - 0.9\right)^{1/n}, \tag{2}$$

where ψ is the matric potential (kPa), ΔT_d is the standard temperature difference for dry soil (4.0°C), ΔT_w is the standard temperature difference for saturated soil (1.45°C), and a and n are empirical coefficients (−0.01 kPa^{-1} and 0.77, respectively). An independent study by Reece (1996) indicated that the methodology described above is a reliable method for calculating the water potential of the soil.

It is also desirable to estimate the volumetric water content ($\mathrm{cm}^3_{\mathrm{water}}/\mathrm{cm}^3_{\mathrm{soil}}$) of the soil using the 229-L. During installation, soil samples from each site were acquired at each vertical depth at which the 229-Ls were installed. These samples were sent to Oklahoma State University to determine the soil characteristics of each sample. Once characteristics of the soil samples were known (percentage of silt, sand, clay), an empirical relationship to estimate volumetric water content was developed using soil textures (Arya and Paris 1981). Thus, an estimate of volumetric water content is determined using estimated values of water potential from (2):

$$\theta_{\mathrm{soil}} = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha(-\psi/100))^h]^{1-1/h}}, \tag{3}$$

where θ_{soil} is volumetric soil water content, θ_r and θ_s are the residual water content and saturated water content, respectively (values unique to soil texture), and α and h are empirical constants (values unique to soil texture).

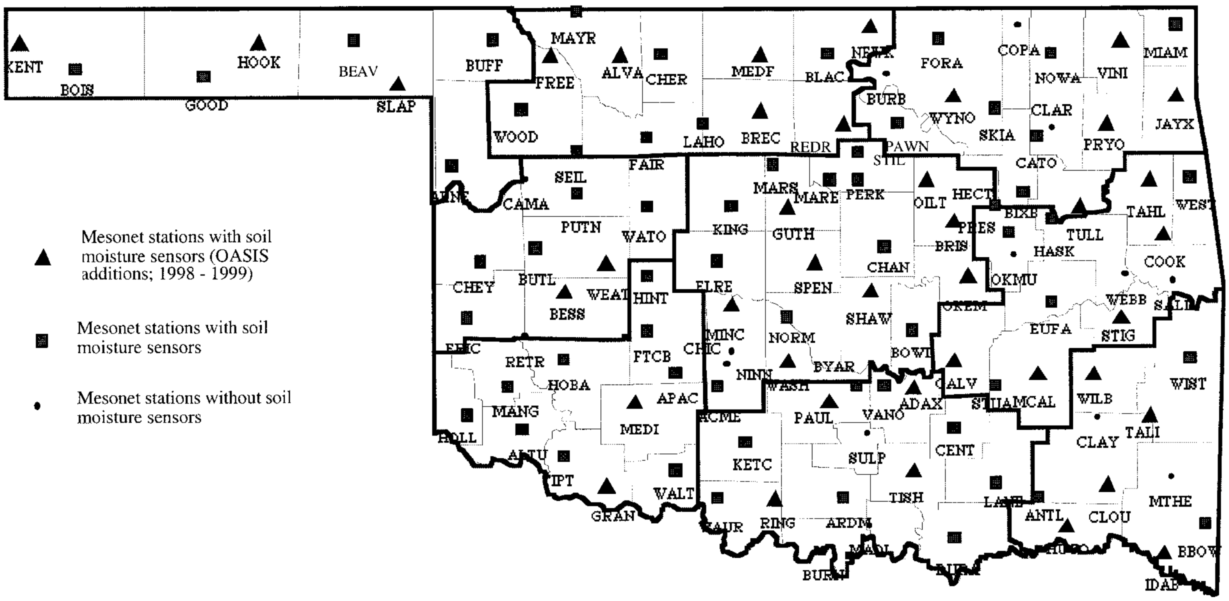

FIG. 2. The Oklahoma Mesonet.

b. Installation procedures

Once calibrated, the sensors were installed at each of 60 Mesonet site locations (Fig. 2). The installation of each soil moisture probe was performed in the same manner for all sites. First, a 3.7-m-long shallow trench was dug westward from the base of the Mesonet tower. A second 0.61-m-long shallow trench was then dug southward from the endpoint of the first trench. The purpose of these trenches is to provide a path for a protective conduit to house the wiring of each 229-L sensor.

At the end of the second conduit trench, three holes approximately 10 cm in diameter were created using a post-hole digger. The first hole, located east of the second trench endpoint, was dug to a depth of 5 cm. A second hole (25 cm deep) was dug at the endpoint of the second trench. Just west of the endpoint of the second trench, a hole 70 cm deep was dug. As the soil was excavated from each hole, great care was taken to preserve the original stratification of the soil. This was accomplished by placing each layer of soil removed in separate piles upon a tarp; each pile maintained the vertical stratification of the soil laid out in a horizontal manner.

The sensors at the 5- and 25-cm depths were installed horizontally, while the sensors at the 60- and 75-cm depths were installed at a 45° angle (Fig. 3). The actual sensor was inserted 10 cm into a small hole that was the width of the sensor (14 mm wide). Once inserted into the hole, a mixture of water and soil removed from the sensor hole were combined into a slurry. The slurry was subsequently squirted into the sensor hole to backfill the sensor hole completely in effort to promote complete contact between the sensor and the soil, and remove preferential pathways for water flow. Extreme care was taken when backfilling the installation holes both to replace the soil in a manner consistent with the preinstallation stratification. Once the installation holes were filled, the trench containing the sensor wires inside the conduit was also filled, thus burying the conduit.

3. Data analysis

Using the 229-L sensor, Basara (1998) demonstrated that physically consistent estimates of near-surface (5 and 25 cm) water potential can be obtained. Deep-layer estimates of water potential (60 and 75 cm) were not investigated in the Basara (1998) study. A preliminary investigation of the archived data suggests that the sensors were operating in a satisfactory manner. However, at some sites, and under certain conditions, the deep-layer sensors appear to perform in a manner that is inconsistent with the near-surface sensors, as demonstrated in Fig. 4. The calibrated values of ΔT_{ref} from (1) are plotted at 4-h increments between 13 July 1997 and 31 July 1997 for the Norman site. Temperature differences range from 4°C (very dry soil) to 1.45°C (saturated soil).

A heavy precipitation event (22.67 mm) occurred between 1015 and 1220 UTC on 18 July. However, no discernible change in ΔT_{ref} was noted at either 5 or 25 cm, while sharp, simultaneous decreases occurred at both the 60- and 75-cm depths. In the weeks preceding this particular precipitation event, a prolonged dry period occurred at the Norman site. As a result, the near-surface soil became extremely dry. Thus, when the heavy precipitation occurred very little water penetrated the top layer of soil down to the 5-cm level. Figure 5

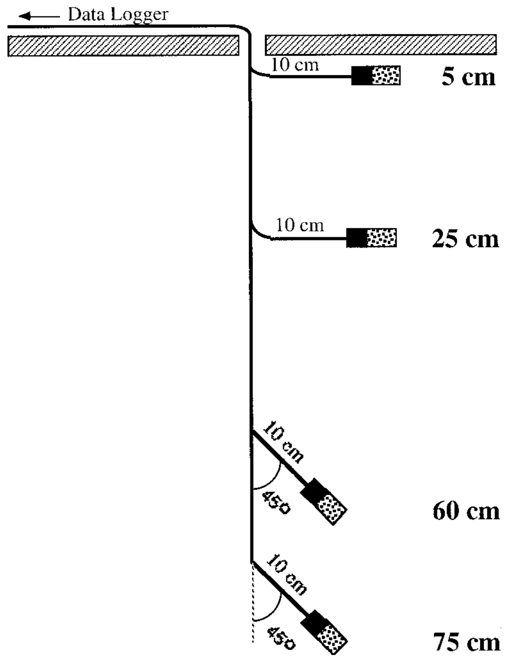

FIG. 3. The vertical profile (planar view) of 229-L sensors installed at Oklahoma Mesonet stations.

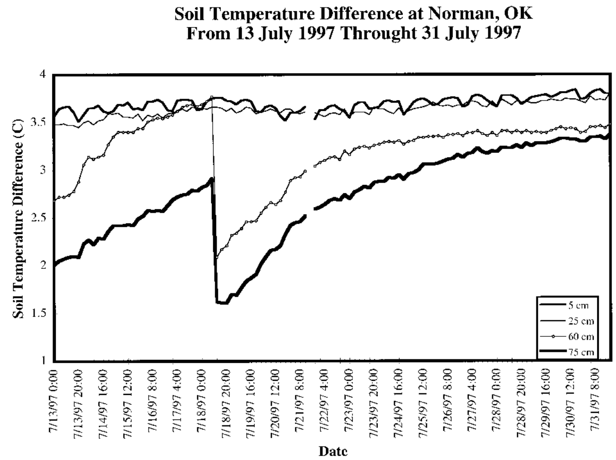

FIG. 4. Soil temperature difference at Norman from 13–31 Jul 1997.

shows the volumetric water content (at 4-h increments) that occurred at the Norman site between 13 July and 31 July. Note the significant moistening that occurred in the water content values at both the 60- and 75-cm depths, while the 5- and 25-cm depths were unaffected.

It is very unlikely that this unusual phenomena is physically representative of a typical soil process. Rather, it is much more likely that preferential pathways of water flow resulting from the initial installation of the 229-L sensors are the mechanisms producing the data contamination. Even though extreme care was taken when backfilling both the sensor hole and the access trench, cracks in the soil will preferentially form along paths of disturbance, or in this case where the instrument wires were installed. This, combined with the angled installation utilized at the deep soil depths (60 and 75 cm), provided a means by which water, under certain conditions, could moisten the deep-layer sensors while avoiding the near-surface sensors. Note, for example, how the deep-layer sensors are installed at a 45° angle with respect to the vertical axis (Fig. 3). In this case, the influence of gravity will cause water to continue to move toward the sensor. As a result, water may be allowed to travel through small cracks, fissures, or even along the sensor cable, which may have developed small spaces or pores with adjacent soil particles.

In addition, a period of 24 days transpired between precipitation events at the Norman site prior to the event on 18 July (5.2 mm of rainfall was observed on 23 June 1997). The result was significant shrinking of the near-surface soil due to the extended period of drying. Thus, when precipitation occurred on 18 July, infiltration through the near-surface soil was greatly reduced resulting in no appreciable change in water content observed by the 5- and 25-cm sensors.

Observations at the Norman site in 1999 have confirmed this behavior in the near-surface soil. Three significant, convective precipitation events (5.21 mm on 6 June, 5.47 mm on 4 September, and 17.72 mm on 8 September) were monitored to assess infiltration of water following sustained dry periods. In each case, the 229-L sensor at 5 cm measured no response to the precipitation events. Numerous soil cores collected at the Norman site following the precipitation events revealed the wetting front (the separation between moist and dry soils) rarely extended beyond 3 cm in depth and never beyond 4 cm. Thus, moisture from the precipitation events was contained within the very near-surface soil, and never penetrated to the 5-cm depth of the 229-L sensor.

Finally, it should also be noted that at both the 60-

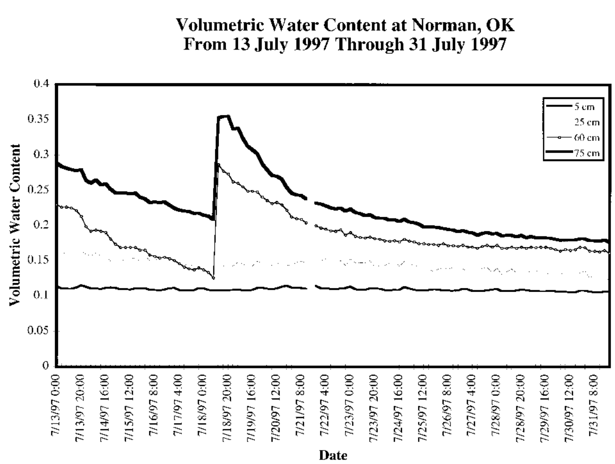

FIG. 5. Volumetric water content (cm^3_{water}/cm^3_{soil}) at Norman from 13–31 Jul 1997.

TABLE 1. Soil characteristics.

Site	Depth	Sand (%)	Silt (%)	Clay (%)	Gravel (%)	Classification
Norman	5 cm	19.06	56.62	24.32	—	Silt loam
Norman	25 cm	14.17	43.17	42.66	—	Silty clay
Norman	60 cm	18.49	39.66	41.85	1.91	Silty clay
Norman	75 cm	16.45	41.32	42.23	2.60	Silty clay
Hollis	5 cm	18.91	40.95	40.15	1.26	Silty clay
Hollis	25 cm	20.57	32.56	46.87	—	Clay
Hollis	60 cm	11.08	40.68	48.24	2.01	Silty clay
Hollis	75 cm	18.63	34.97	46.40	3.56	Clay

and 75-cm depths a pronounced drying trend (Figs. 4 and 5) was quickly established following the 18 July event. Basara (1998) showed that, when the near-surface sensors and the surrounding soil are sufficiently moistened, a lag period of up to a week can exist before a detectable drying trend resumes. Furthermore, in general, deep layer soil depths have a slower response toward drying following the infiltration of water than near-surface soil depths. Thus, it is likely that water managed to moisten only the tip of the 229-L sensors by utilizing preferential pathways in the disturbed soil. Upon reaching the depth of the sensor, the residual water was not in water potential equilibrium with the surrounding soil. Thus, due to the water potential gradient between the sensor and the surrounding soil, water was quickly diffused into the surrounding soil, resulting in the rapid transition toward drying observed in Figs. 4 and 5.

4. Summary and discussion

The method utilized when installing CSI 229-L matric potential sensors in the Oklahoma Mesonet at depths of 60 and 75 cm contains a fundamental flaw that can lead to significant errors in soil moisture observations under certain conditions. By installing the sensors at a 45° angle with respect to the vertical, water that flows down the instrument wire can moisten the sensor without affecting the rest of the soil layer. This phenomenon has

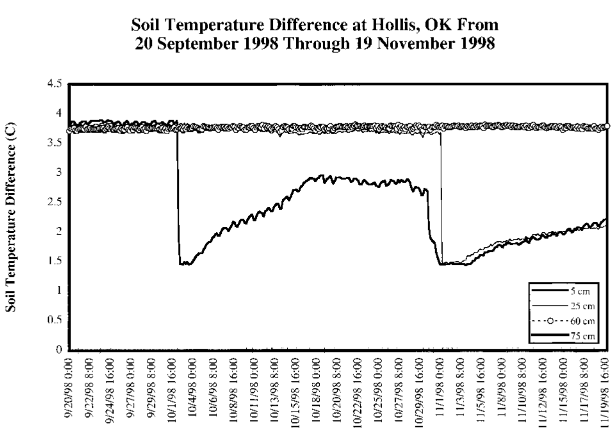

FIG. 6. Soil temperature difference at Hollis from 20 Sep–19 Nov 1998.

also been observed at other Mesonet site locations (at least 13 sites during July 1997; Crawford 1998). The particular case presented in Figs. 4 and 5 from the Norman site is a typical manifestation of the problems associated with the sensor installation. However, it should also be noted that no evidence has been found (at any Mesonet site location) indicating that the 5- or 25-cm sensors are susceptible to contamination by water flow due to preferential pathways. Thus, the authors strongly suggest that similar sensors should be installed horizontally (at all levels) to minimize the possibility of measurement error.

It should also be noted that the installation error is an anomaly in the standard operation of soil moisture sensors across Oklahoma. Of over three million observations of soil moisture conditions observed between 1996 and 1999, the number of observations affected by this installation error account for less than one percent.

In addition, the errant deep-layer values of soil moisture have been detected following extended dry periods in soils consisting of mainly silt and clay particles. However, in most cases and at most sites, measurement errors do not occur. For example, the southwest corner of Oklahoma experienced extremely hot and dry conditions during the summer of 1998. The Hollis Mesonet site is located in southwest Oklahoma (Fig. 2), and has similar soil characteristics throughout the soil profile as the Norman Mesonet site (Table 1). Even though soil conditions were extremely dry at all levels during September (Fig. 6), the profile responded normally to precipitation events which occurred in September, October, and November (including a 31.55 mm event on 1 November 1998).

5. Conclusions

Due to the results of this study, we recommend that new 229-L sensors in the Oklahoma Mesonet (and in future observing networks) at the 60- and 75-cm depths be installed horizontally. In fact, 229-L sensors have been installed at 15 additional Mesonet sites (during 1998 and 1999) since the installation error was noted. Deep-layer sensors (60 and 75 cm) have been installed horizontally at these locations. Following installation, the soil moisture profiles at these sites have shown no evidence of the measurement error described in this paper.

Current Mesonet sensors installed at the 60- and 75-cm depths will not be replaced due to the labor intensive process of excavation and to the brittleness of the sensor. However, in the case that a sensor at the deep layers fails completely, and a new sensor is required at either of the deep layer depths, the new sensors will be replaced horizontally.

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