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Noninvasive soil water content measurement using electromagnetic induction

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Abstract. The feasibility of soil water content measurement using electromagnetic induction was investigated in an arid region of southern New Mexico. Soil water measurements were taken monthly with a neutron probe at 65 equally spaced stations along a 1950-m transect. At the same time, noninvasive electrical conductivity measurements of the soil were taken with a Geonics EM-31 ground conductivity meter. Using 16 months of measurements, we found a linear relationship exists between bulk soil electrical conductivity and total soil water content in the top 1.5 m of the profile. A simple linear regression model was developed to describe the relationship between soil water content and bulk soil electrical conductivity. The spatial and temporal accuracy of the regression model is addressed as well as the total number of neutron access tubes needed to accurately calibrate the model. By comparison with the neutron scattering method the electromagnetic induction method is quite accurate for the prediction of water content changes over time. The speed and ease of use combined with the accuracy of the measurements make the ground conductivity meter a valuable tool for rapid, noninvasive soil water measurements.

Introduction

Soil water content data are needed to understand the ecosystems and hydrology of deserts and rangelands because soil water content is an important physical parameter in determining plant growth and controlling ecosystem processes in arid and semiarid areas. For example, *Schlesinger et al.* [1990] found that primary productivity and soil nutrient turnover are greatest during periods of soil water availability. *Noy-Meir* [1973] found that soil water has both a direct effect on plant productivity and an indirect effect through its influence on decomposition and nutrient mineralization. *Topp et al.* [1980] have demonstrated that knowledge of soil water contents is necessary for crop yield optimization and flood control. Information on areas of concentrated soil water may help in determining zones of recharge over large areas in arid regions [*Gee and Hillel*, 1988]. Unfortunately, measurement of soil water content over large areas is a difficult procedure. Common procedures such as "gravimetry with drying," "neutron scattering," or "time domain reflectometry" require a great deal of manpower or are too destructive for repeated measurements at the same location [e.g., *Hendrickx*, 1990]. Further, these methods are time-consuming to perform, especially over large areas of extremely heterogeneous rangelands. For example, it took approximately 1 day to determine soil water content with a neutron probe at five depths in 90 access tubes 30 m apart along a 2700-m-long transect in the Chihuahuan desert near Las Cruces, New Mexico (J. Anderson, personal communication, 1993). Before any of the neutron probe measurements could take place, the 90 access tubes had to be installed to a depth of 1.5 m. This was a difficult operation due to the presence of caliche layers up to 1 m thick just below the surface. There obviously exists a definite need for quick and nondestructive measurement methods of soil water content over large areas.

The relation between soil water content and soil electrical conductivity has been confirmed by several investigators [*Rhoades et al.*, 1976; *Hendrickx et al.*, 1992]. Recent investigations with ground conductivity meters have shown that electrical conductivity measurements using electromagnetic induction have the potential for quick noninvasive soil water content measurements. For example, *McNeill* [1980a] found the electrical conductivity of soil and rocks depends on the porosity and on the degree to which the pores are filled with water. *Kachanoski et al.* [1988] found that spatial variations of total water content stored in the top 0.5 m of a 1.8 ha field near Brantford, Ontario, Canada, were highly correlated to spatial variations of bulk soil electrical conductivity measured by electromagnetic inductive meters. In another study 50 km west of Saskatoon, Saskatchewan, Canada, *Kachanoski et al.* [1990] found that the bulk soil electrical conductivity explained more than 80% of the variation of water storage in the top 1.7 m of a moderately fine-textured, moderately calcareous soil along a 660-m transect. The latter two studies indicate that for soils with low concentrations of dissolved electrolytes, noninvasive electromagnetic induction measurements can be used to determine total soil water storage at the field scale. However, to date, no studies have been conducted to investigate the potential of ground conductivity meters to quickly monitor soil water content over large areas during long time periods. Therefore the objective of this study is to assess the capability of the ground conductivity meter for monitoring the spatial and temporal variability of soil water content in the Chihuahuan desert.

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Materials and Methods

Study Area

The study was conducted on the New Mexico State University College Ranch, 40 km northeast of Las Cruces, New Mexico. The area is part of the Long-Term Ecological Research Program (LTER) of the National Science Foundation designed to quantify the effects of human perturbations on the stability and productivity of major ecosystems in the United States. A 2700-m transect has been established here with 90 equally spaced neutron access tubes to monitor soil water content along the transect. All measurements for this study were taken along a 1950-m section of the transect, from station 11 to station 75. This segment will be called "the transect" in this study. To allow easy cross-reference to other publications about this LTER site, we will use the original station numbers. Stations 1–10 were omitted in this study because of their location in a playa with heavy clay soils where wide cracks cause a soil water regime completely different from the uphill locations along the transect. Stations 76–90 were omitted because of their close proximity to high voltage lines that affect the EM-31 instrument.

A thorough soil survey was performed along the transect in 1983 [*Nash and Daugherty*, 1990]. The sand and clay content of the soil along the transect is fairly homogeneous [e.g., *Wierenga et al.*, 1987]. The mean sand and clay content and their standard deviations are 72.5% ± 4.4 and 13.8% ± 3.9, respectively. No data are available on the electrical conductivities of the saturation extract along the transect. However, using a procedure developed by *Rhoades et al.* [1990] for the conversion of bulk soil electrical conductivities measured with an electromagnetic (EM) device into electrical conductivities of the saturation extract, we estimate that the average electrical conductivity of the saturation extract in the top 1.5 m of the soil profile along the transect varies between approximately 0.5 and 1.5 dS/m.

There are five soil series recognized along the transect: Bucklebar (stations 11–25), Berino (Stations 26–45), Onite (stations 46–55), Dona Ana (stations 56–70), and Alladin (stations 71–89). All are classified as Typic Haplargids, mixed, thermic except Alladin which is a Torriorthentic Haplustoll. The Bucklebar and Berino soils are fine-loamy, and the Onite, Dona Ana, and Alladin soils are coarse-loamy. The Bucklebar soils are deep and well drained, consisting of sandy loam, sandy clay loam, and silty clay loam. They lack a calcic horizon within 1-m depth. The Berino soils are similar to Bucklebar soils, except that they have a calcic horizon within 1 m. The Onite soils are similar to Berino soils with a coarser texture. Onite soils are not calcareous in the first 5 cm from the soil surface. The Dona Ana Soils are similar to Onite soils, except that they are calcareous throughout the soil profile. The Alladin are similar to the Onite soils with a coarser texture.

Climate in the region is characterized by an abundance of sunshine, low relative humidity, and an average Class A pan evaporation of 2390 mm per year [*Malm and Houghton*, 1977]. Rainfall is extremely variable. Average annual precipitation is 230 mm with 52% of the rainfall occurring between July 1 and September 30.

Data Collection

Sixty-five measurement stations were established along the transect at 30-m intervals. Soil water content and the bulk soil electrical conductivity of the soil profile (EC_a) were measured simultaneously at each station 16 times between February 1992 and June 1993 (approximately once a month).

Neutron probe measurements. Soil water content was measured at the 65 stations with a neutron probe at depths of 30, 60, 90, 110, and 130 cm below the soil surface. Neutron probe readings were converted to volumetric water contents using a single calibration curve for the entire transect [*Wierenga et al.*, 1987]. Next, the water contents at each depth were used to calculate the total amount of water in the soil profile at each station to a depth of 1.5 m using the following equation:

$$\begin{aligned} \mathrm{TWC} = {} & \theta_{30}(450) + \theta_{60}(300) + \theta_{90}(250) \\ & + \theta_{110}(200) + \theta_{130}(300) \end{aligned} \tag{1}$$

where TWC is total amount of water measured in the top 1.5 m of the soil profile (millimeters per 1.5 m) and θ_n is soil water content (cubic meters per cubic meters) at a depth of n centimeters.

EM measurements. The EC_a was measured approximately 10 m south from each soil water measurement station with a Geonics EM-31 Ground Conductivity Meter. Measurements were located 10 m away from the neutron probe measurement stations because of the presence of steel supports for rain gauges and thermometers that would affect the readings. (Barbed wire fence, high voltage lines, or any large amounts of metal will affect the EM-31 readings.) The EM-31 measures the average EC_a from the soil surface to about 6-m depth in the vertical dipole mode coil configuration and 4-m depth in the horizontal dipole mode configuration. The EM-31 gives an average horizontal measurement approximately equal to its length, i.e., 4.0 m. Assuming conservatively a 0.2-m lateral extent of the EM-31 measurements, the sampling volume becomes 0.8 m^3. The low bulk soil electrical conductivities measured in this study along the transect make the penetration depth independent from the electrical conductivities of specific soil layers so that the EM-31 always measures to approximately the same depth. To obtain a better resolution with depth, the EC_a measurements were taken with the EM-31 held at three different heights (89 cm at hip height, 40 cm at knee height, and at the soil surface) and two different orientations (vertical, horizontal) at each station. An additional reading from the hip height/vertical mode was taken at each station on the return trip down the transect to determine the amount of instrument measurement error. A data logger was connected to the EM-31 and automatically logged each measurement in less than 3 s. It takes approximately 2 hours for the initial measurement of the transect with the instrument at the three different heights/orientations and 30 min for the return measurements down the transect, with the instrument at one height and orientation. In theory the Geonics EM-38, rather than the EM-31, would be the ideal instrument for this study because its penetration depth is approximately 1.5 m, thus coinciding with the neutron probe depth of measurement. However, the EM-38 could not be used due to the extremely high magnetic susceptibility of the soil. High concentrations of iron and manganese in the soil generate an outside signal that alters the readings of the EM-38, whereas the EM-31 has circuitry to null this outside signal. The spatial variability of EC_a around each station was measured on March 7 by taking 10 additional measurements at each station, 5 m on either side of the assigned station.

Slavich and Petterson [1990] reported that EC_a measurements vary considerably during the year due to changes in soil temperature. They concluded that it is necessary to standardize field measured EC_a values by conversion to an equivalent electrical conductivity at a reference temperature of 25°C through the use of a conversion table given by the *U.S. Department of Agriculture* [1954]. A curve was fitted to this conversion table to give the following temperature standardization equation:

$$EC_{25} = EC_a * [0.4470 + 1.4034e^{(T/26.815)}] \tag{2}$$

where EC_{25} is the standardized EC_a and T is the soil temperature in degrees Celsius. For the correction of EC_a we used temperature data at depths of 20, 50, 75, and 100 cm measured periodically with copper-constantan thermocouples at a weather station near the center of the transect.

Data Analysis

Linear regression analysis was used to study the relationship between the TWC in the soil profile and the EC_a at each station for each measurement day. We analyzed the data set two ways: (1) We regressed the measured TWC at each station from all 16 measurement days on the EC_{25} measurements from all measurement days combined ($n = 1040$) to produce a "single model" for the entire data set; and (2) we regressed the measured TWC at each station on the EC_a at each station for each individual measurement day ($n = 65$) to obtain 16 "monthly models."

The measured TWC using the neutron probe and the predicted TWC using the EM-31 at each station for each month were compared for each set of models. The accuracy of each model was evaluated by examining the standard deviations of the residuals between the measured and predicted TWC at each station and the R^2 values.

Each model was cross-validated by omitting one measurement station, generating a model, and then predicting the TWC for that station. This was done for 10 randomly picked measurement stations. The mean of the standard deviations of the residuals between measured and predicted TWCs for those 10 stations was calculated.

To establish how many neutron probe measurements are needed to accurately calibrate a single or monthly model, models were generated based on data from 2, 3, 5, 9, 17, and 33 measurement stations, and the standard deviation of their residuals were compared. For the two-station model we used the end points of the transect stations 11 and 75. Other stations used for this analysis were obtained by evenly dividing the transect. For example, the three-station model used stations 11, 43, and 75; the five-station model used stations 11, 27, 43, 59, and 75; the nine-station model used stations 11, 19, 27, 35, 43, 51, 59, 67, and 75; etc.

Results and Discussion

The measured TWC varied widely over the 16-month study (Figure 1): the mean TWC of the transect measured in the 65 access tubes to a depth of 1.5 m varied from 100 mm of water in September 1992 to 250 mm of water in February 1992. The TWCs of our study period are representative of the wide range of TWCs observed over time along the transect.

Soil temperatures at different depths were used to calculate the temperature standardization coefficients with (2). These coefficients were evaluated on the basis of the R^2 values in the single linear regression model. The R^2 for the single linear regression model without temperature standardization was 35%. Using soil temperatures measured at depths of 20, 50, 75, and 100 cm, the R^2 values for the single model were 61, 64, 62, and 59%, respectively. These values indicate that the temperature standardization coefficients are not sensitive to the exact depth of soil temperature measurements taken under the conditions of this study. We selected the 50-cm depth to determine the temperature standardization coefficients. This depth agrees well with that of *Slavich and Petterson* [1990] who used soil temperature from depths of 50 cm during the winter and 70 cm in the summer for their coefficients. A soil temperature standardization coefficient is not needed for the monthly models because these relate EC_a and TWC on one specific measurement day.

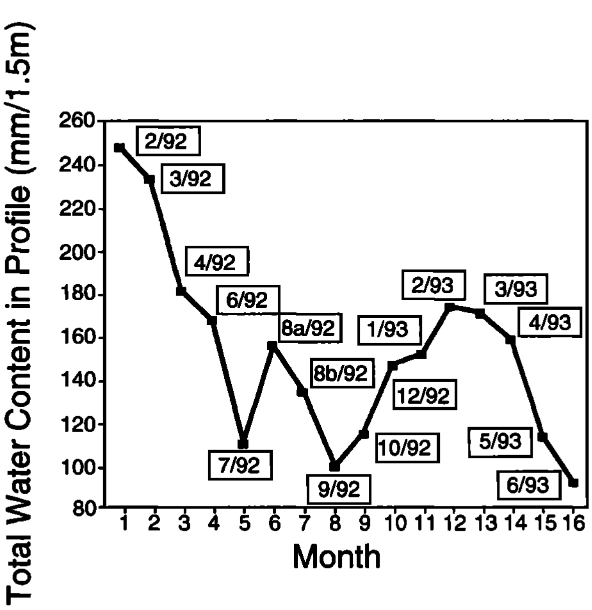

Figure 1. Average total water content in the soil profile (millimeters per 1.5 m) along the transect measured with the neutron probe.

In a preliminary study we tested which of the six height/mode configurations of the EM-31 yields the best correlation with TWC. It was found that, in general, the horizontal/soil surface mode (instrument held in the horizontal mode at the ground surface) performed best. However, this configuration is cumbersome to implement under many field conditions. Therefore we will compare this configuration with the vertical/hip mode (instrument held in the vertical mode at hip height, 89 cm), which is the most practical operating configuration for the EM-31.

Figure 2 shows the EC_a measurements taken on April 1, 1993, in the vertical/hip configuration. At each station, two measurements were available in this configuration: one going up the transect and one coming down. The initial measurements along the transect took approximately 150 min, as they were taken at three heights and in two modes. After a rest of 10 min the measurements down the transect took approximately 40 min, since they were only taken in the vertical/hip configuration. Therefore the time interval between measurements decreased from approximately 200 min at station 11 to approximately 10 min at station 75. It can be seen that the difference between upward and downward measurements is related to the time between the two measurements. For example, there is a difference of 0.5 mS/m at station 14 to 0.0 mS/m difference at station 70. The small change in EC_a with time on

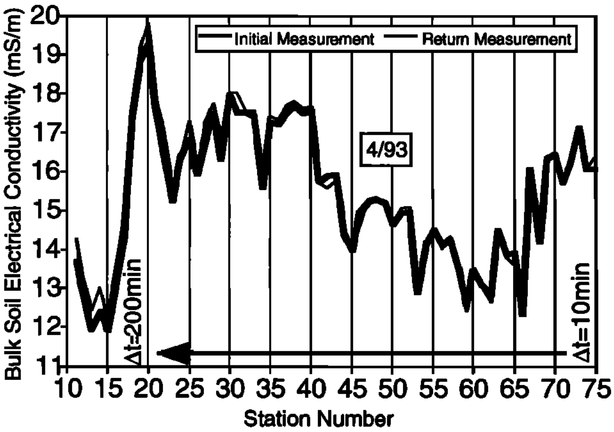

Figure 2. A plot of EC_a measurements taken on April 1, 1993, illustrating measurement error. Measurement error increases with the time difference (Δt) between measurements due to increased temperature of the soil.

Table 1. The Coefficients of the Linear Regression Models for all the Data (single model) With Their Respective F and R^2 Values

Height of EM-31,* cm	$a \times 10^{-3}$	$b \times 10^{-4}$	F Value	R^2, %
0	−21.5	101	1786	64
89	−49.2	111	1412	58

The model is TWC (millimeters) = $a + b$ (EC_{25}) (milliSiemens per meter) with 1040 data points. All coefficients, F, and R^2 values are significant at the 0.01 level.

*At the soil surface (0 cm) the horizontal measurement configuration is used; at 89 cm above the soil surface the vertical configuration is used.

April 1, 1993, is most likely caused by the increase in temperature of the soil surface layer since its order of magnitude agrees with estimates of temperature effects derived from (2) and the equations that govern the EM response [*McNeill*, 1980b]. Consequently, on the return trip down the transect an increase in EC_a is observed consistently at stations 11–40 where the time between measurements was 100 min or more. EC_a differences at stations 40–75 were less affected by the temperature effects due to the short interval of time between the subsequent measurements, so these differences represent the "instrument error." On the basis of the smallest differences regularly observed between upward and downward measurements, we have determined the maximum "pure error" at approximately 0.2 mS/m in the desert environment of this study.

The effect of short range spatial variability on EC_a readings is evaluated with the 10 additional measurements taken at each station on March 7, 1993. The measurements were taken 5 m on either side of the station, 1 m apart. The standard deviation around each station was determined. Over the transect the standard deviations ranged from 0.87 mS/m at station 74 to 0.40 mS/m at station 59. The mean standard deviation of all stations was approximately 0.5 mS/m and, as expected, is considerably larger than the "instrument error" of the EM-31 device.

Single Models

Inspection of the data and evaluation of several multiple linear regression models including quadratic and logarithmic terms shows that a simple linear regression model best describes the relation between TWC and EC_a along the transect. The R^2 for the single model is 0.64 for the horizontal/soil surface configuration and 0.58 for the vertical/hip configuration. The regression coefficients for the respective models are presented in Tables 1 and 2. The best correlation with EC_a to TWC is found with the EM-31 at the surface in the horizontal mode. This was expected because, with the instrument in the horizontal mode, the relative sensitivity is greatest to material at the soil surface, as the soil to a depth of 1.5 meters contributes 50% of the measured EC_a in the horizontal mode and only 25% in the vertical mode [*McNeill*, 1980b].

The adequacy of the two single models was checked with a residual analysis and a lack-of-fit test [e.g., *Montgomery and Peck*, 1982]. Residual analysis revealed that the residuals are uncorrelated and normally distributed with zero mean, proving that the model satisfies the assumptions for linear regression analysis. Figures 3a and 3b present the histograms of the residuals for the two single models.

The standard deviation of the residual water contents for the single model is 32 mm for the horizontal/soil surface configuration and 35 mm for the vertical/hip configuration (Figure 3).

Table 2. The Coefficients of the Linear Regression Models for Each Monthly Data Set (Monthly Models) With Their Respective F and R^2 Values

Month	Height of EM-31,* cm	$a \times 10^{-3}$	$b \times 10^{-4}$	F	R^2, %
Feb. 1992	0	111.0	89.9	38	38
	89	125.0	78.7	14	19
March 1992	0	81.3	85.6	46	43
	89	70.4	90.9	21	26
April 1992	0	48.8	80.1	39	38
	89	16.8	87.7	25	28
June 1992	0	51.3	65.9	23	27
	89	3.7	91.7	20	25
July 1992	0	−5.5	75.6	20	25
	89	−26.1	82.3	15	19
Aug. 1992(a)	0	25.7	78.4	32	34
	89	5.23	89.6	20	24
Aug. 1992(b)	0	10.1	76.2	14	18
	89	−24.0	94.2	15	19
Sept. 1992	0	6.1	67.3	15	19
	89	−18.7	78.4	14	18
Oct. 1992	0	5.61	89.8	27	30
	89	23.5	63.0	8	11
Dec. 1992	0	50.2	96.9	28	31
	89	59.9	77.2	13	17
Jan. 1993	0	28.8	96.5	39	38
	89	37.2	85.4	16	20
Feb. 1993	0	80.8	84.3	47	45
	89	63.9	91.7	29	32
March 1993	0	31.2	98.9	53	46
	89	32.9	93.4	23	27
April 1993	0	−7.13	112	44	41
	89	−7.78	108	24	27
May 1993	0	−50.0	123	24	41
	89	−39.6	103	20	24
June 1993	0	−27.2	95.6	26	30
	89	−9.42	72.0	11	15

The models are TWC (millimeters) = $a + b$ (EC_{25}) (milliSiemens per meter) with 65 data points per month. All coefficients, F, and R^2 values are significant at 0.01 level.

*At the soil surface (0 cm) the horizontal measurement configuration is used; at 89 cm above the soil surface the vertical configuration is used.

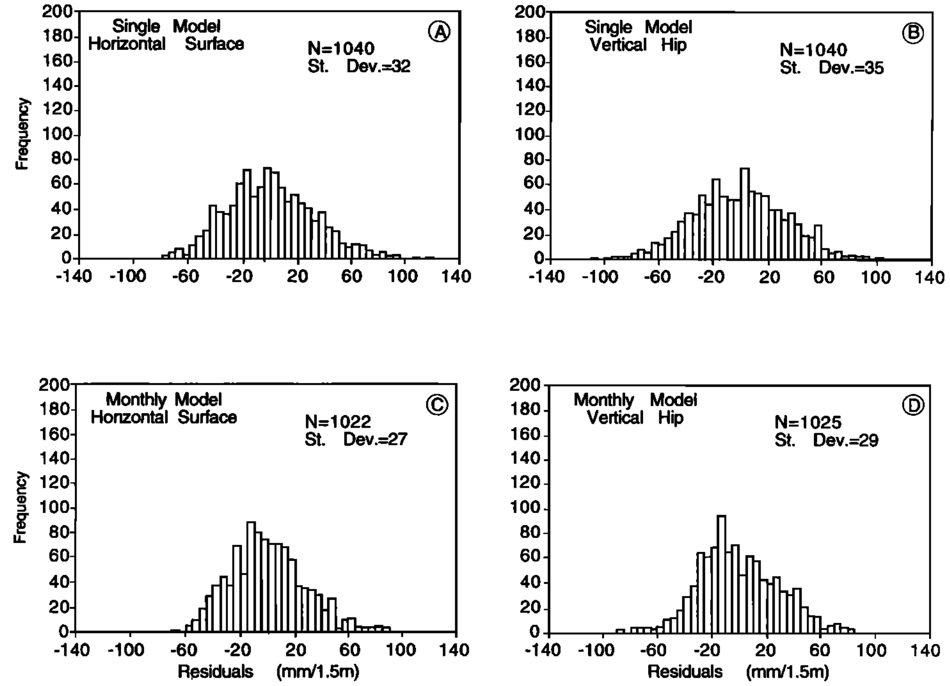

Figure 3. Distribution of total water content residuals for the single model in the (a) vertical/hip and (b) horizontal/surface orientations and for the monthly model in the (c) vertical/hip and (d) horizontal/surface orientations.

The horizontal/soil surface configuration was consistently more accurate than the vertical/hip configuration, as was to be expected. Although the single simple linear regression models are significant and residual analysis does not reveal violation of the regression assumptions, the relatively low R^2 is not entirely satisfactory. Therefore we conducted a lack-of-fit analysis [e.g., *Draper and Smith*, 1981]. This analysis can only be carried out if repeat measurements are available. The data presented in Figure 2 and those obtained on other days indicate that many EC_a measurements are rather close together compared to the general spread of the EC_a values. Thus, although there are very few exact repeat measurements, we do have many approximate repeats. These are transformed to real repeats by rounding them to 0.2 mS/m, a value equal to the "instrument error." The lack-of-fit test conducted with the RSREG-procedure of *SAS Institute Inc.* [1985] did not reveal any significant lack of fit, which is another confirmation that the simple linear regression model is the best model. Because no model can explain the instrument error variation, an R^2 of 100% is impossible to obtain when repeat measurements exist [*Draper and Smith*, 1981]. Nevertheless, the R^2 obtained in this study (Tables 1 and 2) are much lower than the 96 and 80% obtained by *Kachanoski et al.* [1988, 1990]. Several factors may explain why our R^2s are lower. One is that *Kachanoski et al.* [1988] took their electromagnetic induction measurements at exactly the same locations where the soil water contents were measured, while *Kachanoski et al.* [1990] took them at a distance of 2 m. In our study the presence of steel support structures forced us to take the measurements 10 m away from the neutron access tubes. Although *Nash et al.* [1992] present evidence that 10 m is well within the range of dependence for soil water contents along the transect, their data also suggest that a 10-m distance may result in a 10 to 20% increase of variability. In addition to closer measurements, *Kachanoski et al.* [1988, 1990] used the average of two soil water content measurements at each location for determination of their regression models, a practice that obviously will increase the R^2 values. A final factor is the fact that *Kachanoski et al.* [1988, 1990] obtained their best results with an EM-38 device that has penetration depths almost equal to the depth of their invasive soil water content measurements. In our study the penetration depth of the EM-31 measurements was at least 4.0 m, while soil water content measurements were taken only to a depth of 1.5 m. It appears likely that soil water content measurements to a greater depth would have resulted in higher R^2s.

Model validation was conducted by cross-validation on 10 randomly selected stations. The standard deviations of the residuals from the cross-validation are 21-mm TWC for the horizontal/soil surface configuration and 22-mm TWC for the vertical/hip configuration. This indicates the model performs well in its intended operating environment.

An important question for future applications of electromagnetic induction for noninvasive soil water content measurements is the number of neutron access tubes needed to calibrate the EM-31 readings. We found that five neutron probe measurements were adequate to calibrate the single model in the vertical/hip configuration and nine neutron probe measurements were needed for the horizontal/surface configuration. There was no improvement in the model with the addition of any more stations (Figure 4).

Monthly Models

We analyzed the monthly models with the same methods as the single models. A residual analysis and the lack-of-fit test were conducted as described above for each of the monthly models to test their adequacy. The regression equation coef-

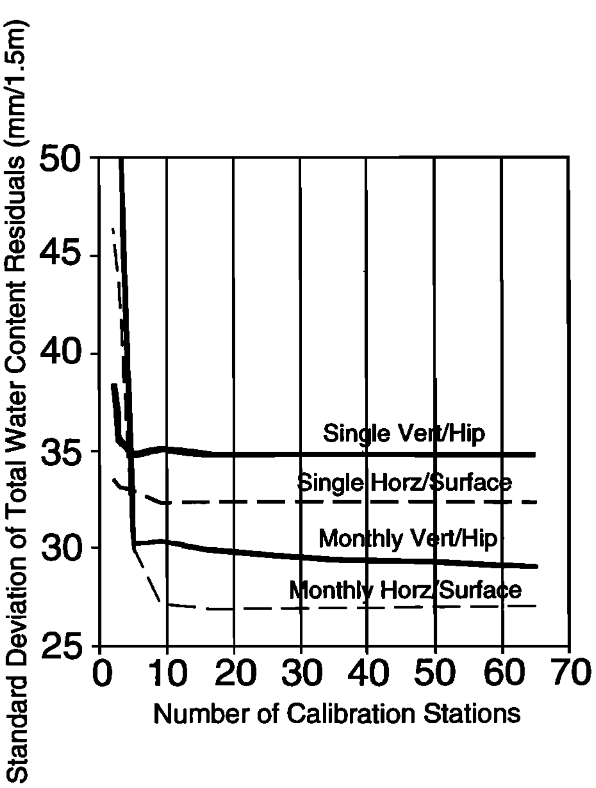

Figure 4. Relation between the standard deviation of the residuals of the total water content and the number of stations used to calibrate the single and monthly models.

ficients, F, and R^2 values are presented in Table 2. The residuals of the monthly models are normally distributed with mean zero indicating that the monthly models satisfy the requirements of linear regression analysis (Figures 3c and 3d). The standard deviations of the residuals for the monthly models are 27 mm TWC for the horizontal/soil surface configuration and 29 mm TWC for the vertical/hip configuration. Again, the horizontal/soil surface configuration was slightly more accurate than the vertical/hip configuration. The residuals of the monthly models are approximately 20% smaller than those of the single models. Thus the monthly models are more accurate than the single model for predicting the actual value of TWC. Note that a mean residual standard deviation of 29 mm over the 1.5-m soil profile represents a water content of 0.019 m^3 m^{-3}.

The standard deviations of the residuals from the cross-validation test for the monthly models are 19 mm and 21 mm TWC for the horizontal/soil surface configuration and the vertical/hip configuration, respectively. These residuals are 5–10% lower than those of the single models, indicating the monthly models performed better in the cross-validation test than the single model.

To adequately calibrate the monthly models, five neutron probe measurements were needed for the vertical/hip configuration, and nine neutron probe measurements were needed for the horizontal/surface configuration. These numbers are identical to those found for the single model. There was no improvement in the model with the addition of any more stations (Figure 4). Site specific soil water content measurements with the neutron probe (or with another soil water measurement method) will always be required for calibration of the EM method, but these results show that the number of neutron probe soil water content measurements can be greatly reduced. This is important because of the costs involved in installing neutron access tubes, especially in areas with stony soils or caliche layers. Five to nine probes along the transect mean one access tube every 200–400 m. Visualizing each calibration access tube in the center of a square with sides of 400–800 m, it appears that for our conditions, one access tube per 16–64 ha would be needed for calibration.

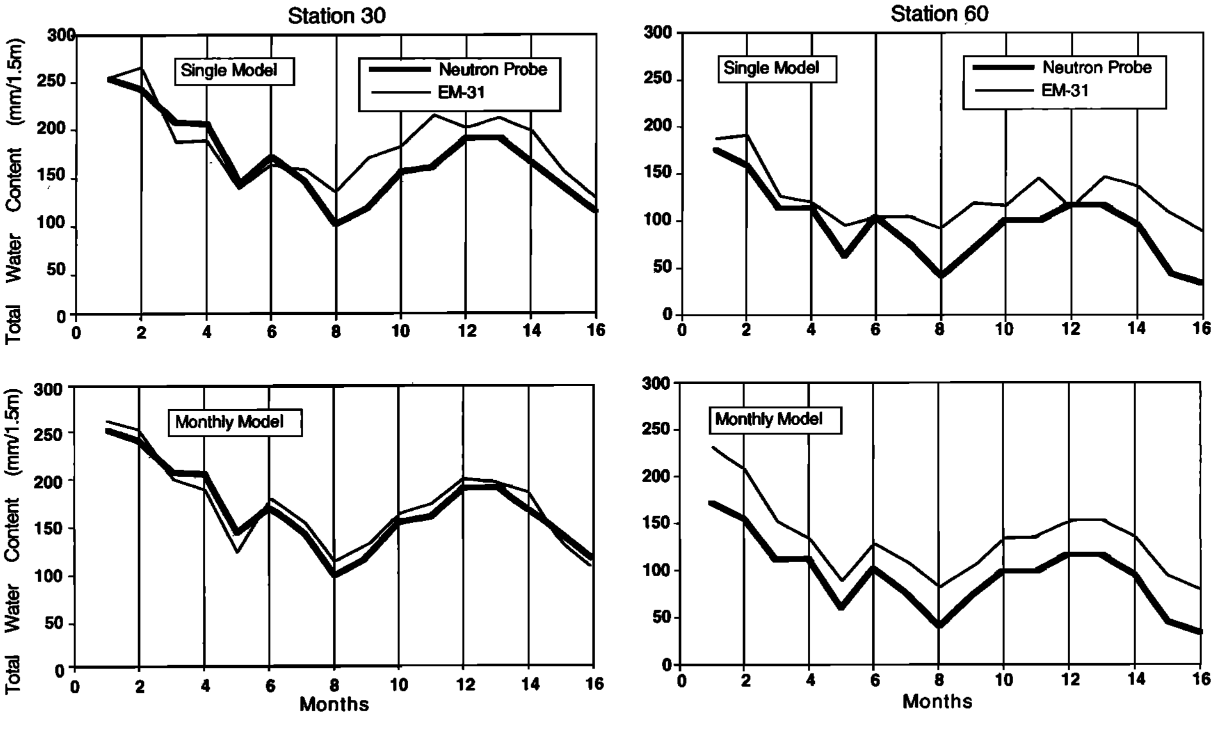

Figure 5. Total water contents at stations 30 and 60 as measured with the neutron probe and predicted from EM-31 observations with the single and monthly model.

Comparison of Single and Monthly Models for Predicting Changes in Soil Water

In many hydrological and ecological studies it is often of more interest to know the change in water content between two dates than the absolute water contents on these dates. Comparisons of Figures 3a and 3b with Figures 3c and 3d show that the predictive capability for soil water contents of the monthly model exceeds that of the single model. This is also illustrated in Figure 5 where we plot for two typical stations (30 and 60) the predicted and measured water content with time for both models. Although the predictions of the single model at station 60 are a few times closer to the measured values than the predictions of the monthly models, it appears that the latter have a greater capability to predict changes in soil water over time. The same trend can be detected at station 30. To further investigate the strength of the models to predict monthly changes in TWC, a plot of the differences of the predicted TWC from subsequent months versus differences of measured TWC from subsequent months was generated for each model (Figure 6). The linear trend for the monthly model versus the curved relationship for the single model clearly demonstrates the superior capability of the monthly model to predict changes in water content over time. Another indication is the plots (histograms) of the residuals between predicted and measured differences of TWC between subsequent months (Figure 7). The residuals for the single model have a larger distribution width than those of the monthly model. The width of the monthly model based on the horizontal/surface configuration is the smallest, with most of the data within ±30 mm, which equals a volumetric water content of $\pm 0.02\ m^3\ m^{-3}$ in the 1.5-m soil profile. This number compares favorable with invasive water content measurement methods when used in the field. For example, *Topp and Davis* [1985] concluded that the Time Domain Reflectometry (TDR) method can be used for irrigation scheduling without making a calibration for each field or soil because it gives an immediate soil water content measurement in the field with an accuracy of 0.02 $m^3\ m^{-3}$.

Temporal Variability Versus Spatial Variability of Soil Water

In Figure 8 we compare the measured and the predicted TWC along the transect for the single and monthly models during a relatively wet (March 1992) and dry month (May 1993) (see Figure 1). Although the models predict the trends quite well, there is less agreement between the measured and predicted values than found in Figure 5 where the models were used to predict changes in TWC over time for individual stations. It appears that both the single and monthly models predicted the temporal variability of TWC more accurately than the spatial variability. This observation is confirmed by comparing the pooled standard deviations of the residuals with respect to time and space for the single and monthly models. The standard deviations were consistently lower when calculated with temporal data. The contrast between the temporal and spatial standard deviations is greater with the monthly models, a fact which is yet another indication that the formulation of monthly models indeed increases the accuracy of the model prediction.

An example of the interplay between temporal and spatial variability is presented by the measurements at station 60. In Figure 8b it can be seen that the monthly models overpredicted the TWC at station 60 by approximately 50 mm water in March 1992 and May 1993. However, Figure 5 reveals that the changes in TWC at station 60 were predicted correctly by the monthly model. This was also quite typical for most other stations.

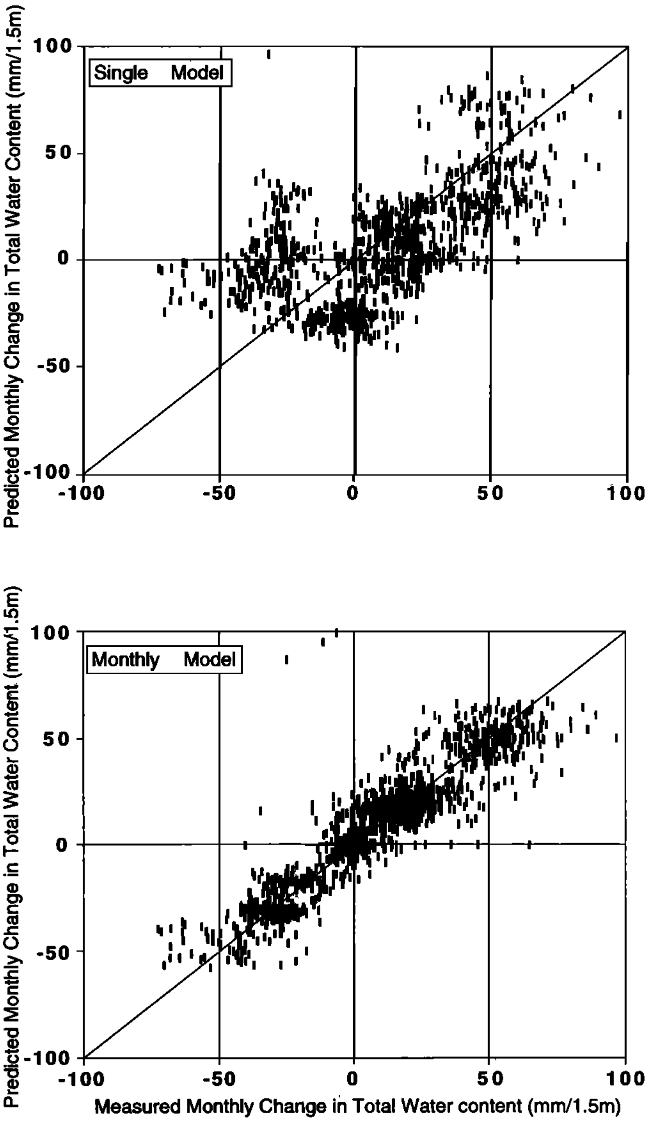

Figure 6. Plots of the predicted monthly change in total water content on the basis of EM-31 measurements versus the one measured with the neutron probe for the single and monthly models.

The cause for the relatively large deviations in space is due to the relative heterogeneity of the soils. As previously noted, five different soil series are recognized along the transect. There is little doubt that the development of a monthly model for each soil series would improve the predictions. However, there are a few drawbacks to this approach. First of all, we face the difficulty of how to determine the exact boundary between different soil series in the field. Next, it is almost certain that partitions of the transect according to soil series would increase the number of access tubes needed for calibration. Nevertheless, these questions should be addressed to obtain a better understanding of the possibilities of the EM technique for soil water measurements in semiarid regions.

One striking feature in Figures 8a and 8b is that the variability of the TWCs predicted on the basis of EM measurements is less than that on the basis of neutron probe measurements. This phenomenon can be explained by the fact that the volume of the EM-31 measurement is at least 4 times larger than the volume of the neutron measurements; thus much of

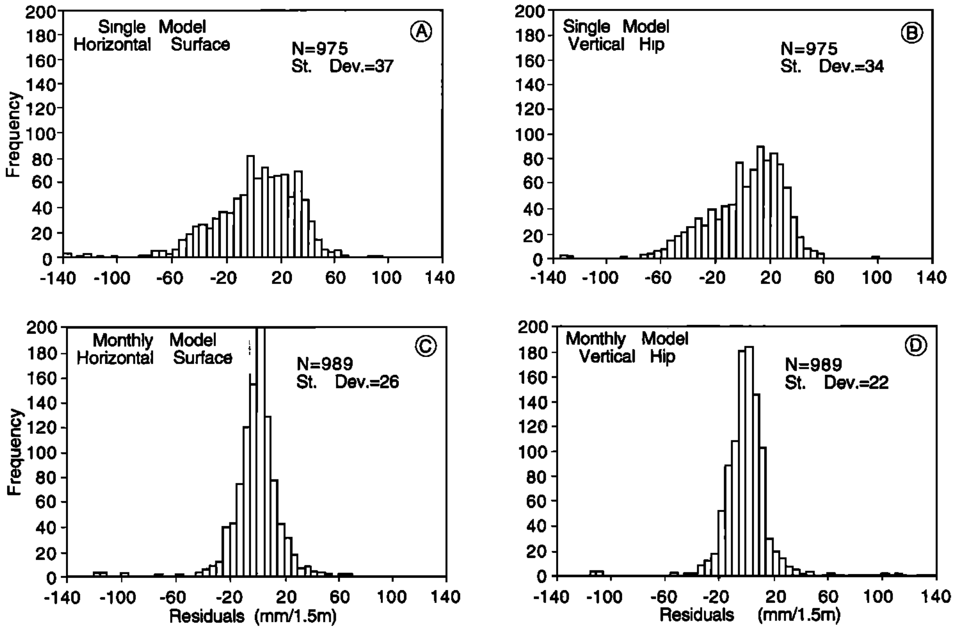

Figure 7. Distribution of the residuals resulting from the difference between the predicted monthly change in total water content on the basis of EM-31 measurements versus the one measured with the neutron probe. The upper plots result from the single model in, respectively, the (a) vertical/hip and (b) horizontal/surface orientations, respectively; the bottom plots result from the monthly model in the (c) vertical/hip and (d) horizontal/surface orientations, respectively.

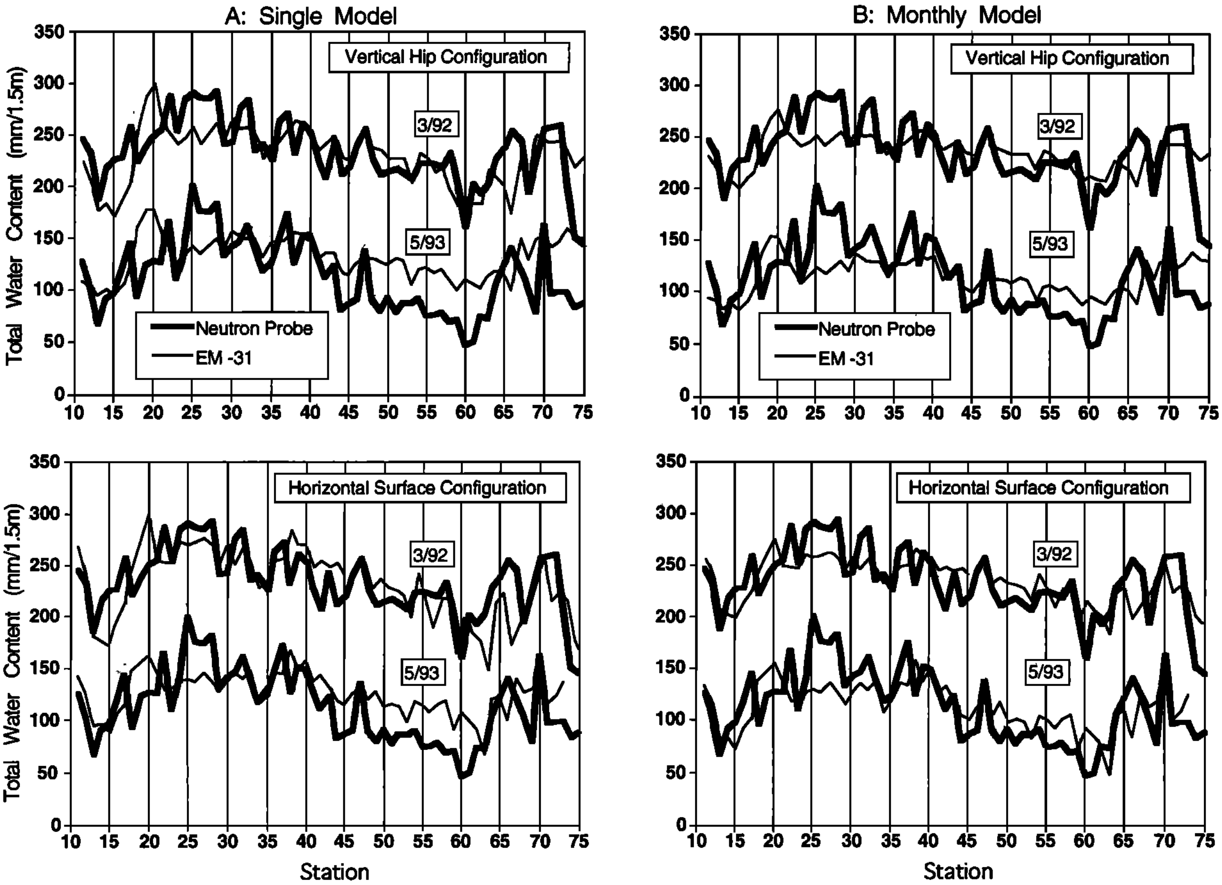

Figure 8. Total water contents for a relatively (top) wet month and (bottom) dry month as measured with the neutron probe and predicted from EM-31 observations with the (a) single and (b) monthly models.

the small-scale water content variability is averaged out. An important consequence of this observation is that water content measurements with the EM instrument will be more reliable than those with the neutron probe. This means that at least part of the mismatch between predicted and measured values is caused by variability of the neutron probe measurements and not by the failure of the model or EM equipment. Another part of the mismatch can be explained by the fact that the EM measurements were taken 10 m south of the access tubes, a distance that is certainly large enough to cause discrepancies between neutron probe and EM measurements.

Conclusions

The results of our study demonstrate that electromagnetic induction is a viable method for measurement of total soil water content (TWC) in the soil profile over long periods of time if the measurements are standardized for the soil temperature.

Regression analysis of simultaneous soil water content measurements with the neutron probe and bulk soil electrical conductivity measurements with the EM-31 revealed that a simple linear relationship exists between TWC and the electrical conductivity of the soil (EC_a). As is the case with other methods for soil water content measurement such as neutron scattering and Time Domain Reflectometry, it is necessary to use a calibration curve to relate TWC and EC_a because this relationship is site specific. In this study involving a 1950-m transect it was found that approximately one neutron access tube per 200-400-m length yielded a reliable calibration curve. Prudent areal extrapolation of this number would suggest that for calibration one access tube is needed every 16–60 ha.

For accurate results it is necessary to take calibration measurements with the neutron probe each time the EM-31 is used for water content determination. Doing so, the EM method is capable of detecting soil water content changes with an accuracy of approximately 0.02 $m^3\ m^{-3}$, which is comparable to that of other field methods.

The tremendous advantages of the EM instruments are their speed and ease of use. Measurements taken with the instrument in the vertical/hip configuration are almost as accurate as those taken in the horizontal/soil surface configuration, so measurements can be taken as fast as one can walk. For this transect the measurement time would be about 40 min as compared to 1 day with the neutron probe.

This study demonstrates that electromagnetic induction has great potential for quick detection of soil water content changes over large areas of semiarid rangeland and arid desert once the area of investigation has been calibrated with neutron scattering. Previous work by *Kachanoski et al.* [1988] in a humid climate suggests that the presented method is not restricted to semiarid regions. Therefore electromagnetic induction is an ideal tool for long term ecological and hydrological water balance studies that cover large spatially variable areas.

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