Soil Water Estimation Using Electromagnetic Induction

M. A. Akbar, A. L. Kenimer, S. W. Searcy, H. A. Torbert

Abstract. *Two published salinity models (designated the Rhoades and Mualem−Friedman models, respectively) were examined for application to real−time soil water estimation using apparent soil electrical conductivity. Field data were collected at two sites representing a range of soil types in central Texas: high shrinking−swelling Vertisols in Temple (the Heiden Clay site) and clay loam soils at the Texas A&M University Research Farm near College Station (the Westwood Scl site). The Rhoades−Corwin model developed for the Heiden Clay site yielded an R^2 of 0.72 following calibration, predicted soil water within ±0.02 g g^{-1} during validation, and was deemed generally applicable for real−time soil water estimation. The Rhoades−Corwin model developed for the Westwood Scl site gave an R^2 of 0.65 following calibration but could not be validated at the site and therefore was not considered applicable for real−time soil water estimation. A modified version of the Rhoades−Corwin model yielded a calibrated R^2 of 0.91 at the Westwood Scl site with validation predictions within ±0.02 g g^{-1}. The Mualem−Friedman model predicted soil water within ±0.05 g g^{-1} at the Heiden Clay site and was considered appropriate for real−time soil water estimation. At the Westwood Scl site, the Mualem−Friedman model could not be evaluated since saturation data were not available. Both models show promise for use for real−time, non−invasive soil water content estimation using apparent electrical conductivity, but additional testing is needed.*

Keywords. *Electromagnetic induction, Soil electrical conductivity, Soil water content, Vertisols.*

Procedures commonly used for measurement of soil water are often resource−intensive and may be too destructive for repeated measurement at the same location. In addition, high costs associated with frequently needed soil sampling for mapping field soil water content and other soil chemical and physical properties can discourage adequate sampling or make a sampling plan prohibitive altogether. Therefore, an accurate, fast, and inexpensive method for determining soil water is needed for producing site−specific maps of field−stored soil water at a level of resolution appropriate for precision agriculture. In soils with low salinity, using soil apparent electrical conductivity (EC_a) could be a relatively less costly and viable option for measuring soil stored moisture. However, its viability should be investigated. To estimate soil water using EC_a, site−specific calibration of ground conductivity meters (conductivity meters) involving simultaneous measurements of EC_a by conductivity meter and of water content by any standard soil water determining procedure is required. With conductivity meters accurately calibrated, it is possible to estimate soil water content with an approximate accuracy of 0.02 m^3 m^{-3} (Sheets and Hendrickx, 1995), an accuracy comparable to other field methods (Gardner, 1986; Topp et al., 1980; Bridge et al., 1996). However, at a given site, the requirement of same−day calibration of conductivity meters each time the field is mapped for EC_a for estimating soil stored moisture limits the use of this technology. Therefore, for estimating field soil water content using EC_a, a site−specific, one−time calibration procedure is needed.

To develop a site−specific procedure for estimating soil water content that requires minimal invasive sampling and equipment calibration, models relating EC_a and soil properties to soil water content are needed. This article describes development and testing of a procedure to estimate real−time soil water condition using apparent soil conductivity in central Texas using two models for soil salinity appraisal. One of these models was previously published by Mualem and Friedman (1991), and the other was based on the work of Rhoades and Corwin (1990). Specifically, the objective of this study was to examine the appropriateness of these two models for estimating real−time soil water using field−measured apparent soil conductivity.

Article was submitted for review in August 2003; approved for publication by the Soil & Water Division of ASAE in December 2004.

The authors are **Muhammad A. Akbar,** Researcher, Department of Renewable Resources, University of Alberta, Edmonton, Alberta, Canada; **Ann L. Kenimer, ASAE Member Engineer,** Associate Professor, and **Stephen W. Searcy, ASAE Member Engineer,** Professor, Department of Biological and Agricultural Engineering, Texas A&M University, College Station, Texas; and **H. Allen Torbert,** Soil Scientist, USDA−ARS National Soil Dynamics Laboratory, Auburn, Alabama. **Corresponding author:** Ann L. Kenimer, Department of Biological and Agricultural Engineering, 2117 TAMU, Texas A&M University, College Station, TX 77843−2117; phone: 979−845−3677; fax: 979−847−8828; e−mail: a−kenimer@tamu.edu.

Materials and Methods

This study was conducted at two sites representing a range of soil types and soil water regimes in central Texas. Soil salinity was generally below 2 dS m^{-1} at both sites. Sampling point locations were established using the differential global positioning system (DGPS). Each site was characterized for soil texture and profile thickness at these sampling locations. Data on soil water and apparent soil electrical conductivity were collected for two consecutive growing seasons. Mathematical models for analyzing the relationship of soil water to

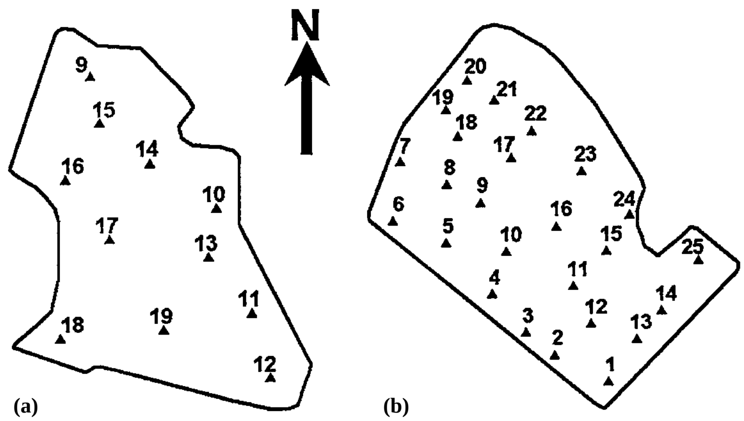

Figure 1. Field sampling locations at (a) the Heiden Clay site and (b) the Westwood Scl site.

apparent soil electrical conductivity and other field−measured variables were identified and evaluated.

Site Selection

Two sites, the Heiden Clay site and the Westwood Scl site, representing a range of soil types and moisture regimes typical of central Texas, were used in this study. The Heiden Clay site represented the Vertisols, high shrinking−swelling clays of smectitic nature covering an area of about 6.5 million ha in Texas (Coulombe et al., 1996). The site was located on a private farm in Bell County (latitude 31.0282, longitude −97.2637), about 8.0 km southeast of Temple, Texas. The field covered an area of approximately 9.0 ha. The field was terraced with a relief of about 10.0 m. Heiden clay (fine, montmorillonitic, thermic, Udic Chromusterts; Order Vertisols) with 1% to 3% slope was the dominant soil type at the site. The soil profile was deep and relatively uniform in texture (USDA−SCS, 1977). For the last four years, the field was in a corn, winter−fallow, corn rotation.

The Westwood Scl site represented clay loam soils typically found in river bottoms in central Texas. The site was located at the Texas A&M Research Farm in Burleson County (latitude 30.5192, longitude −96.4105), about 16.0 km southwest of College Station, Texas. The field covered an area of about 16.0 ha. Westwood silty clay loam (fine−silty, mixed, superactive, thermic Udifluventic Ustochrepts; Order Inceptisols) with 0% to 1% slope was the dominant soil type at the site (USDA−NRCS Field Office for Burleson County, Texas, personal communication, 2000). The field at the Westwood Scl site was in a cotton, winter−fallow, corn rotation.

Data Collection

Eleven and 25 sampling locations were established at the Heiden Clay and Westwood Scl sites, respectively (fig. 1). For establishing the sampling point locations at the Heiden Clay site, an initial survey of EC_a was conducted using an electromagnetic induction sensor (model EM−38, Geonics Limited, Mississauga, Ontario, Canada) with a DGPS. The resulting EC_a map was developed in a geographical information system (GIS). Areas with relatively high variation in EC_a values were identified. Then, in these areas, point locations were selected at a suitable scale to develop a site/field−specific relationship between EC_a, stored soil water, and other soil properties. For the Westwood Scl site, sampling locations were selected based on field observations. A system of 1.0 ha grids was used as the basis for soil sampling at the Westwood Scl site. A single soil sample was collected from a random location within each established grid.

Two data sets were collected from each site, one under relatively wet conditions (wet data set), and the other under relatively dry conditions (dry data set). Table 1 summarizes the data collection dates, agronomic practices, rainfall, and tillage operations performed at the two sites, and tables 2 and 3 summarize the wet and dry data sets for each site.

Soil core samples were collected in plastic liners using a hydraulic soil probe (Giddings Machine Company, Inc., Ft. Collins, Colo.) to an intended sampling depth of 120 cm. However, the full sampling depth of 120 cm could not be achieved at all locations. Soil cores were divided into 15−cm sections. Soil samples were analyzed for gravimetric water content (w) using the oven method (Gardner, 1986) and soil texture with the hydrometer method (Gee and Bauder, 1986).

Table 1. Data collection dates, agronomic practices, and rainfall occurring during the 1999 and 2000 growing seasons at the Heiden Clay and Westwood Scl sites.

Site and Crop Rotation	Data Set and Collection Date	Crop Harvested before Data Collection, and Date	Rainfall and Tillage Operations between Harvest and Sampling Date
Heiden Clay, corn, winter−fallow, corn	Wet data set, 17 Dec. 1999	Corn, 2nd week of July 1999	Rainfall 80.0 mm; corn stalks disked in 1st week of September.
	Dry data set, 8 Sept. 2000	Corn, 2nd week of July 2000	Rainfall 12.0 mm; no tillage operation performed; corn stalks on the ground surface.
Westwood Scl, cotton, winter−fallow, corn	Wet data set, 25 Feb. 2000	Cotton, 1st week of September 1999	Rainfall 182.0 mm; cotton stalks shredded 2nd week of September; field deep chiseled and immediately disked in 3rd and 4th week of September.
	Dry data set, 24 Aug. 2000	Corn, 4th week of July 2000	Rainfall 6.0 mm; no tillage operation performed; corn stalks on the ground surface.

Soil samples were also analyzed for saturation extract conductivity (EC_e) and saturation percentage (SP) (U.S. Salinity Laboratory, 1954). Soil apparent electrical conductivity (EC_a) was measured with an EM−38 electromagnetic induction sensor at the ground surface in horizontal and vertical dipole modes at the location of each core sample and at the same time the samples were taken. Additional information regarding field sampling methods is available in Akbar et al. (2004).

Table 2. The Heiden Clay site: wet and dry data sets collected on 17 Dec. 1999 and 8 Sept. 2000, respectively. Averages of 15−cm sections through the profile are shown.

Sampling Location	Wet Data Set									Dry Data Set								
	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	w (g g^{-1})	EC_h (dS m^{-1})	EC_v (dS m^{-1})	EC_e (dS m^{-1})	SP (%)	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	w (g g^{-1})	EC_h (dS m^{-1})	EC_v (dS m^{-1})	EC_e (dS m^{-1})	SP (%)
9	107	10.1	27.3	62.6	0.29	0.99	1.26	0.62	103.9	122	10.2	28.3	61.5	0.22	0.52	0.92	0.66	80.7
10	91	13.4	49.3	40.2	0.28	1.36	1.95	3.34	97.8	122	10.6	39.9	49.6	0.20	0.74	1.20	1.83	77.7
11	61	9.6	46.6	43.8	0.30	1.22	1.79	3.05	106.1	122	12.3	36.6	51.1	0.26	0.88	1.46	2.33	75.8
12	76	7.9	53.6	38.6	0.32	1.25	1.75	4.44	98.3	122	12.0	29.3	58.7	0.24	0.9	1.47	2.38	88.2
13	107	14.4	31.1	54.5	0.30	1.01	1.44	0.97	79.2	122	11.9	32.6	55.6	0.23	0.72	1.13	1.13	92.0
14	91	11.4	31.8	56.8	0.31	0.98	1.40	0.66	87.1	122	9.2	29.8	61.1	0.24	0.61	0.95	0.51	91.3
15	107	10.2	29.6	60.2	0.27	0.75	1.12	0.56	87.0	122	11.0	32.7	56.3	0.22	0.52	0.66	0.51	89.7
16	122	8.3	28.8	62.9	0.30	0.97	1.38	0.80	111.1	122	6.3	28.3	65.5	0.22	0.69	1.10	0.75	93.3
17	107	10.8	32.6	56.7	0.31	1.35	1.87	2.29	89.5	122	9.4	30.3	60.3	0.27	0.97	1.55	1.60	102.7
18	107	9.7	30.0	60.3	0.26	1.03	1.39	0.74	100.2	122	7.7	28.1	64.1	0.22	0.74	1.10	1.06	91.5
19	122	12.0	30.5	57.5	0.27	1.08	1.42	0.79	115.2	122	10.7	30.1	59.2	0.22	0.53	0.84	0.59	85.7

w = soil profile average gravimetric moisture content.
EC_h = soil apparent conductivity, horizontal.
EC_v = soil apparent conductivity vertical (assumed equivalent to apparent soil conductivity, EC_a).
EC_e = saturation extract conductivity.
SP = saturation percentage

Table 3. The Westwood Scl site: wet and dry data sets collected on 25 Feb. 2000 and 24 Aug. 2000, respectively. Averages of 15−cm sections through the profile are shown.

Sampling Location	Wet Data Set									Dry Data Set								
	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	w (g g^{-1})	EC_h (dS m^{-1})	EC_v (dS m^{-1})	EC_e (dS m^{-1})	SP (%)	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	w (g g^{-1})	EC_h (dS m^{-1})	EC_v (dS m^{-1})	EC_e (dS m^{-1})	SP (%)
1	58.4	18.6	55.5	25.9	0.193	0.420	0.530	1.34	51.1	76.2	17.8	55.0	27.2	0.122	0.275	0.361	0.562	70.8
2	50.8	33.3	48.9	17.8	0.150	0.390	0.450	1.20	45.6	76.2	26.7	50.2	23.1	0.095	0.300	0.399	0.555	70.9
3	88.9	15.5	56.3	28.2	0.189	0.420	0.540	1.08	47.8	76.2	21.0	51.8	27.2	0.091	0.270	0.372	0.763	71.3
4	76.2	31.4	46.7	21.9	0.163	0.350	0.320	0.81	52.6	76.2	28.9	44.6	26.5	0.092	0.250	0.260	0.497	71.4
5	50.8	30.5	52.1	17.4	0.174	0.260	0.310	0.97	45.3	76.2	31.9	47.1	21.0	0.058	0.180	0.233	0.538	71.1
6	94.0	59.1	33.5	7.4	0.085	0.170	0.250	0.64	35.5	76.2	48.2	37.1	14.7	0.047	0.184	0.266	0.465	70.9
7	91.4	28.7	54.9	16.4	0.143	0.200	0.240	0.79	44.8	76.2	55.4	30.3	14.4	0.057	0.160	0.184	0.389	70.9
8	45.7	15.1	54.1	30.8	0.219	0.310	0.370	1.04	55.3	91.4	28.7	50.3	21.1	0.088	0.224	0.290	0.602	70.7
9	94.0	15.7	63.0	21.3	0.162	0.320	0.510	0.70	55.5	91.4	16.6	58.3	25.1	0.070	0.194	0.400	0.649	69.9
10	91.4	10.8	59.4	29.7	0.195	0.430	0.450	0.69	53.8	76.2	10.1	52.9	37.0	0.131	0.241	0.329	0.843	70.7
11	88.9	17.6	50.5	31.9	0.194	0.420	0.480	0.71	54.9	91.4	12.3	44.8	42.9	0.148	0.324	0.363	0.704	70.4
12	48.3	41.8	39.5	18.7	0.152	0.260	0.340	0.88	49.2	91.4	29.1	50.9	20.0	0.069	0.263	0.327	0.527	71.1
13	48.3	39.0	46.3	14.7	0.160	0.280	0.390	0.62	47.6	91.4	25.8	56.9	17.3	0.067	0.294	0.381	0.650	65.0
14	68.6	64.5	25.3	10.2	0.091	0.210	0.250	0.60	45.4	61.0	58.6	28.4	13.0	0.037	0.241	0.277	0.564	66.9
15	66.0	59.3	30.7	10.0	0.106	0.180	0.260	0.72	47.3	61.0	58.6	28.4	13.0	0.045	0.102	0.200	0.613	64.3
16	94.0	13.8	53.3	32.9	0.192	0.350	0.450	0.70	59.3	91.4	8.5	54.8	36.7	0.121	0.235	0.285	0.678	64.5
17	91.4	17.5	56.6	25.9	0.178	0.320	0.420	0.63	59.3	76.2	13.1	58.1	28.8	0.094	0.127	0.160	0.609	64.0
18	71.1	23.7	61.2	15.1	0.140	0.210	0.300	0.53	50.0	91.4	12.0	62.2	25.8	0.079	0.255	0.311	0.555	88.1
19	76.2	37.6	46.0	16.3	0.149	0.520	0.270	0.87	44.8	76.2	12.6	46.1	41.4	0.136	0.260	0.349	0.823	63.9
20	73.7	46.4	39.1	14.6	0.153	0.270	0.290	0.87	42.4	91.4	49.1	34.3	16.6	0.076	0.226	0.269	0.560	64.2
21	−−	−−	−−	−−	−−	−−	−−	−−	−−	91.4	10.5	59.8	29.7	0.091	0.118	0.164	0.648	66.5
22	78.7	10.2	62.7	27.1	0.189	0.350	0.390	1.06	53.6	91.4	10.6	58.1	31.4	0.116	0.140	0.205	0.558	63.5
23	−−	−−	−−	−−	−−	−−	−−	−−	−−	76.2	37.4	42.4	20.1	0.056	0.105	0.187	0.531	51.0
25	81.3	44.8	41.5	13.7	0.126	0.240	0.220	0.77	47.2	91.4	47.1	36.7	16.2	0.064	0.158	0.200	0.425	53.4

w = soil profile average gravimetric moisture content.
EC_h = soil apparent conductivity, horizontal.
EC_v = soil apparent conductivity vertical (assumed equivalent to apparent soil conductivity, EC_a).
EC_e = saturation extract conductivity.
SP = saturation percentage.
−− = no data.

The first salinity model examined in this study, the Rhoades−Corwin model, was based on the work of Rhoades and Corwin (1990) and relates soil properties, EC_e, SP, and ρ_b (soil bulk density) to EC_a and total volumetric soil water content (Θ) through a product term ($EC_w \times \Theta$, where EC_w is the electrical conductivity of soil solution). This product term is designated "ECTH" throughout the following text. The inclusion of ECTH as a co−variate of EC_a in the Rhoades−Corwin model is based on the work of Rhoades and Corwin (1990), which indicated that, after rapid drainage is complete and soil reaches field capacity, an inverse proportional relationship between EC_w and Θ is established. Because of this inverse proportional relationship, the product ($EC_w \times \Theta$) within a given soil volume near field capacity does not change to a great extent and may be considered approximately constant following drainage. The Rhoades−Corwin model takes the form:

$$w_{pred} = a \times EC_a + b(EC_w \times \Theta) + c \tag{1}$$

where w_{pred} is predicted gravimetric soil water content (g g^{-1}); EC_a and the product term ECTH have units of dS m^{-1}; and *a*, *b*, and *c* are empirically determined regression parameters. The product term ECTH is estimated using equation 2 (Rhoades and Corwin, 1990):

$$EC_w \times \Theta = EC_e(SP/100)(\rho_b/\rho_e) \tag{2}$$

where

- EC_w = electrical conductivity of soil solution (dS m^{-1})
- Θ = total volumetric soil water content (cm^3 cm^{-3})
- EC_e = saturation extract electrical conductivity (dS m^{-1})
- SP = saturation percentage (gravimetric water content of the saturation paste)
- ρ_b = soil bulk density (g cm^{-3})
- ρ_e = density of aqueous extract (g cm^{-3}).

Rhoades and Corwin (1990) contend that changes in total soil volumetric water affect EC_a by influencing partitioning of Θ into the volumetric water content tied up with soil solids and in fine pores (series−coupled pathways) and the volumetric water content present in large pores (continuous liquid pathways). Therefore, an approximately linear decrease in EC_a occurs as Θ decreases below field capacity due to evapotranspiration. Under conditions of low salinity, EC_a is mainly influenced by Θ, which, in turn, is related to the soil properties used as input parameters in equation 2. Therefore, it was anticipated that variation in Θ at the time EC_a was measured would be better explained by using the product ($EC_w \times \Theta$) as a co−variate with EC_a in equation 1. However, because the range of soil water over which an approximate linear decrease in EC_a occurs as Θ decreases below field capacity could be different for each soil, site−specific calibration of the Rhoades−Corwin model might be needed. In addition, great deviation of Θ below field capacity can also impair model performance.

The second model evaluated in this study, designated the Mualem−Friedman model, was derived from a salinity model published by Mualem and Friedman (1991). The Mualem−Friedman model was identified as a candidate model for its simplicity and small number of input parameters. As suggested by Mualem and Friedman (1991), the model is potentially applicable only to soil types with coarse texture and stable structure, similar to those present at the Westwood Scl site. However, it was decided to also evaluate this model at the Heiden Clay site, where the soils had high clay content. The Mualem−Friedman model mainly comprises equation 3:

$$EC_r(\theta) = \frac{EC_a(\theta)}{EC_a(\theta_{sat})} = \left(\frac{\theta}{\theta_{sat}}\right)^{n+2} \tag{3}$$

with

$$\theta = \left[\left(\frac{EC_a(\theta)}{EC_a(\theta_{sat})}\right)(\theta_{sat})^{2.5}\right]^{\frac{1}{2.5}} \tag{4}$$

where

- EC_r = relative electrical conductivity
- θ = available soil volumetric water content (cm^3 cm^{-3})
- $EC_a(\theta)$ = apparent soil electrical conductivity measured at θ (dS m^{-1})
- $EC_a(\theta_{sat})$ = apparent soil electrical conductivity at saturation (θ_{sat}) (dS m^{-1})
- θ_{sat} = soil volumetric water content at saturation (cm^3 cm^{-3})
- *n* = an empirical parameter.

Other associated empirical relationships suggested by Mualem and Friedman (1991) for estimating some of the input parameters in equation 4 include:

$$\theta_{sat} = \Theta_{sat} - \Theta_{15} \tag{5}$$

$$\Theta_{sat} = 1 - \rho_b/\rho_s, \ (\rho_s = 2.65 \text{ g/cm}^3) \tag{6}$$

$$\Theta_{15} = (0.068S_a + 1.71)\rho_b \tag{7}$$

$$S_a = 5.780 \times CF - 15.064 \tag{8}$$

where

- Θ_{15} = soil volumetric water content near wilting point (1.5 M Pa)
- Θ_{sat} = total soil volumetric water content at saturation (cm^3 cm^{-3})
- ρ_b = bulk density of soil (g cm^{-3})
- S_a = specific surface area of soil (m^2 g^{-1})
- CF = clay percentage.

For the parameter *n* in equation 3, Mualem and Friedman (1991) found a value of 0.50 as the optimum value for mainly sand, loam, and soils of stable structure. Thus, equation 4 was obtained using the value of 0.50 for the parameter *n* in equation 3 and rearranging algebraically. The value for θ_{sat} estimated using equation 5 and the EC_a (θ_{sat}) measured for a particular soil type at a site of interest could be considered relatively stable. With $EC_a(\theta)$ measured, soil water content (θ) could be estimated using equation 4.

The two models evaluated in this study predict different measures for soil water content. The Rhoades−Corwin model predicts gravimetric soil water content, while the Mualem−Friedman model predicts volumetric soil water content. While this difference impaired comparison of one model against the other, we chose to evaluate the models as they were originally developed and to focus on their individual capacity to predict soil water as a function of EC_a.

Since field measurements of soil water were determined on a gravimetric basis, it was necessary to convert these gravimetric soil water content measurements to volume basis for evaluating the Mualem−Friedman model. Since soil bulk densities were not measured at either site, literature values of 1.35 g cm^{-3} and 1.50 g cm^{-3} were used for the Heiden Clay and Westwood Scl sites, respectively (Yule and Ritchie, 1980; USDA−NRCS Field Office for Burleson County, Texas, personal communication, 2000). The assumption of near−constant soil bulk densities for the Heiden Clay site was based on a study by Fox (1964) on a shrinking−swelling clay (Houston Black), similar to that present at the study site. In that study, Fox (1964) reported that a highly significant relationship between bulk density and water content became invalid with soil moisture decreasing below 0.35 g g^{-1}. The highest soil moisture measured at the Heiden Clay site, in both wet and dry datasets, was 0.32 g g^{-1}. The assumption of near−constant bulk density was also considered valid at the Westwood Scl site since the dominant soil type was a silty clay loam with non−smectite clay content not exceeding 37%. With low shrinking−swelling clay content in this soil, water content was not expected to have a significant impact on soil bulk density. Moreover, since the overall goal of this study was to examine methods for real−time, non−invasive estimation of soil moisture, considering soil bulk density near−constant also provided the opportunity to eliminate a field variable that can be costly to determine.

MODEL EVALUATION

Adequacy of a model was determined using residual analysis (residuals uncorrelated and normally distributed with 0 mean and a constant variance; Montgomery and Peck, 1982), whereas the overall efficiency of a model was judged based on the model's intended use. For soil water estimation, an error of ±0.02 cm^3 cm^{-3} has been suggested as acceptable for indirect methods of soil water determination requiring field calibration (Gardner, 1986; Topp et al., 1980; Bridge et al., 1996). However, Stafford (1988) suggested that, for applications such as seed placement and irrigation, a high level of accuracy is not required. For control of a seed drill, for example, he indicated that it was only necessary to know that seed was being placed in a zone with moisture content greater than a threshold value. Whereas for irrigation, determination of start and stop times might require accuracy of 0.02 to 0.04 g g^{-1}.

All statistical analyses required for model evaluation were performed using SAS (SAS Institute, Inc., Cary, N.C.). Significance was reported at a probability level of 0.05 or less. Multicolinearity among predictor variables was checked with the variance inflation factor at a value of 10 or less (Freund and Littell, 1986). Residuals were plotted against the predicted and regressor variables for both calibration and validation. Finally, a model with the smallest possible range of residuals and with few or no pronounced trends was selected.

RESULTS AND DISCUSSION

THE RHOADES-CORWIN MODEL

At the Heiden Clay site, the Rhoades−Corwin model was calibrated to the dry data set. In this data set, soil water content was near the wilting point, and change in total water content influenced EC_a through the quantity ECTH, as suggested by Rhoades and Corwin (1990). Regression analysis using equation 1 gave an R^2 of 0.54. Regression analysis using a logarithmic transformation of the variable ECTH yielded good residual distribution and an R^2 of 0.72:

$$w_{pred} = 0.06661 + 0.16585 \times EC_a - 0.06347 \times \log(ECTH) \quad (9)$$

where w_{pred} is in g g^{-1}, and EC_a and ECTH are in dS m^{-1}.

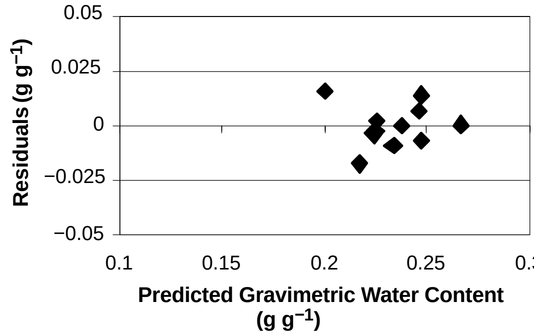

Figure 2. Residuals of the Rhoades−Corwin model following calibration with the dry data set from the Heiden Clay site. Residuals from prediction are plotted against predicted soil water content.

Plots of residuals for equation 9 are shown in figure 2. Residuals ranged within ±0.02 g g^{-1} and showed no apparent trend. The magnitude of the residuals and their random distribution showed that equation 9 was an adequate estimator for the dry data set.

After calibration with the dry data set, equation 9 was validated with the wet data set. Weak patterns were noticed in residuals (fig. 3). The relatively large magnitude of the residuals for sampling locations 11, 12, and 18 (0.035, 0.081, and −0.033 g g^{-1}, respectively) compared to those for the other locations (between −0.0177 and 0.0128 g g^{-1}) rendered equation 9 apparently inadequate for prediction purposes. However, values of EC_a and EC_e determined at locations 11 and 12 were relatively large (table 2). With these points excluded, equation 9 could generally be considered an adequate model for the Heiden Clay site.

While the predictive capability of the Rhoades−Corwin model for the Heiden Clay site wet data set was adequate, it did not match the performance observed for the dry data set. For the wet data set at the Heiden Clay site, significant relationships among variables as anticipated in the Rhoades−Corwin model (eq. 1) could not be found. Soil profile average moisture content in the wet data set ranged between 0.26 and 0.32 g g^{-1} and was very close to field capacity (Yule and

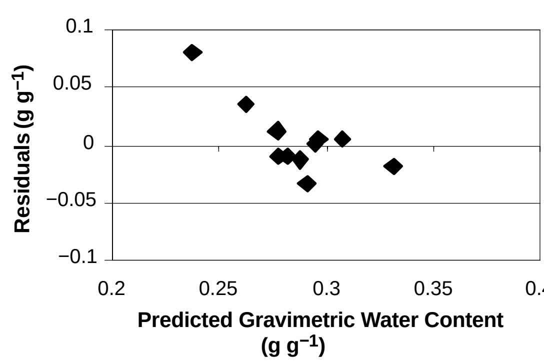

Figure 3. Residuals from the Rhoades−Corwin model following validation with the wet data set at the Heiden Clay site. Residuals from prediction are plotted against predicted soil water content.

Ritchie, 1980). In this data set, soil water content near field capacity and clay content did not correlate, and neither of these factors had any effect on EC_a. At soil water content near field capacity and higher, water was not limiting; hence, the quantity ECTH became nearly constant in a given volume of soil. For these wetter conditions, current paths became fully connected and showed the highest conductivity values at a given salt concentration and temperature. Thus, the only factor that influenced EC_a was change in salt content. Therefore, a significant relationship between soil water content and the two variables (EC_a and ECTH) of the Rhoades−Corwin model could not be found.

At the Westwood Scl site, the Rhoades−Corwin model was calibrated to the wet data set. Taking the form of equation 1, this relationship provided an R^2 of 0.57:

$$w_{pred} = 0.04739 + 0.16494 \times EC_a - 0.08424 \times ECTH \quad (10)$$

Logarithmic transformation of the two variables in equation 1 gave a higher R^2 value of 0.65.

Validation of the Rhoades−Corwin model using the dry data set at the Westwood Scl site was not successful. In the dry data set at the Westwood Scl site, soil water ranged between 0.037 and 0.148 g g^{-1}. Due to these extremely dry conditions, sufficient moisture was not available to form soil solution. In addition, salinity was low (0.39 to 0.84 dS m^{-1}). Therefore, EC_a did not respond to changes in soil water below a threshold soil water content of 0.13 g g^{-1}. For these reasons, the Rhoades−Corwin model as described in equation 1 was not sensitive to the term ECTH. Consequently, equation 10 could not be validated using the dry data set.

The Rhoades−Corwin model was reexamined at the Westwood Scl site using an alternate approach. For this modified Rhoades−Corwin model, the term ECTH was replaced with another variable, a product of EC_a and clay content. Addition of clay content was made to reflect the influence of soil texture, particularly clay content, on EC_a measurements (Hartsock et al., 2000; Moore and Wolcott, 2001). Equation 11 is the modified Rhoades−Corwin model calibrated to the wet data set (R^2 = 0.91):

$$\theta_{pred} = 0.0875 - 0.2115 \times EC_a + 0.0787 \times \log(EC_a \times CF) \quad (11)$$

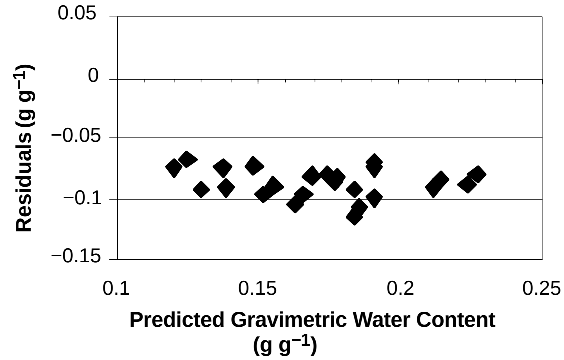

Figure 5. Residuals of the modified Rhoades−Corwin model following validation with the dry data set at the Westwood Scl site. Residuals from validation using the dry data set are plotted against predicted soil water content.

where θ_{pred} is in g g^{-1}, EC_a is in dS m^{-1}, and CF is in percent. A plot of residuals using equation 11 is presented in figure 4.

After calibration with wet data, equation 11 was validated with the dry data set. Validation results are shown in figure 5. Equation 11 estimated the moisture content well within an error of ±0.02 g g^{-1}. No trends or patterns in residuals were noticed (fig. 5); however, the model overpredicted in the range of 0.06 to 0.12 g g^{-1}. This overprediction was attributed to the sensitivity of EC_a under dry conditions to soil characteristics other than moisture.

The Mualem−Friedman Model

The Mualem−Friedman model consisted mainly of equation 4. Input data included $EC_a(\theta_{sat})$, soil water content at saturation, soil bulk density, and clay content. For the Heiden Clay site, the Mualem−Friedman model was calibrated using the wet data set. The value $EC_a(\theta_{sat})$ was estimated as the arithmetic average of EC_a from all sampling locations (1.5 dS m^{-1}) recorded near field capacity in the wet data set (table 2). It was assumed that this average value was equivalent to that expected at near−saturation. This assumption was based on the observation that, at a given salinity (EC_e) level, EC_a did not respond to increasing moisture content while the average soil water content was near field capacity. Soil volumetric water content at saturation (θ_{sat}) was estimated using equation 5. Average values of soil bulk density (ρ_b) and soil volumetric water content near the wilting point (Θ_{15}) for the

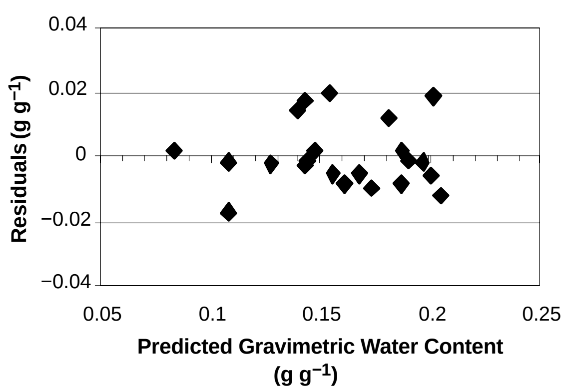

Figure 4. Residuals of the modified Rhoades−Corwin model following calibration with the wet data set at the Westwood Scl site. Residuals from validation using the dry data set are plotted against predicted soil water content.

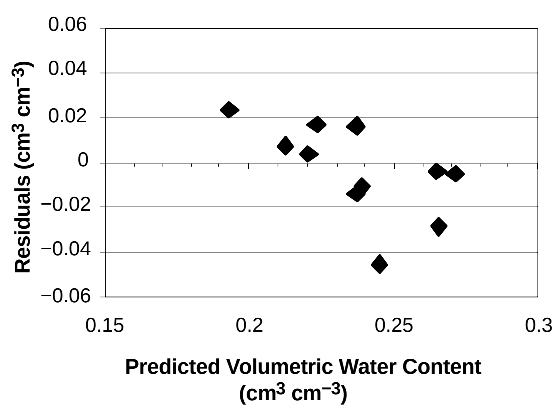

Figure 6. Residuals of the Mualem−Friedman model following validation with the dry data set at the Heiden Clay site. Residuals are plotted against soil water content predicted for the dry data set.

Heiden soil series (pasture) were taken as 1.348 g cm^{-3} and 0.238 cm^3 cm^{-3}, respectively (Yule and Ritchie, 1980). Total soil volumetric water content at saturation (Θ_{sat}) was estimated from equation 6.

Following calibration, the Mualem−Friedman model was validated using the dry data set. Residuals ranged between −0.05 and +0.03 cm^3 cm^{-3} and showed an inverse relationship with predicted moisture content (fig. 6). However, since the trend was not particularly strong, the model was considered adequate for moisture prediction at the Heiden Clay site. The Mualem−Friedman model could not be evaluated for the Westwood Scl site because near−saturation data on EC_a were not available.

CONCLUSIONS

Conclusions drawn for the Rhoades−Corwin model were different for the two sites. At the Heiden Clay site, moisture content in the dry data set was near the wilting point, normally the lowest level (the driest condition) moisture could attain in Vertisols under field conditions (Yule and Ritchie, 1980). Since equation 9 was developed under similar moisture conditions, it appears that it can be applied to similar soils as long as soil water is less than field capacity, although site−specific calibration might be needed. In other words, with EC_a measured with conductivity meters, the approach taken in the Rhoades−Corwin model could be used to estimate soil water in Vertisols similar to those present at the Heiden Clay site as long as EC_a is under the combined influence of soil water content and salt concentration. However, model applicability is contingent on the stability of the variable ECTH, a quantity that depends on EC_e, which, in turn, might change between cropping and fallowing seasons.

The modified Rhoades−Corwin model appears potentially applicable to real−time water content estimation in dry areas with sandy soils similar to those present at the Westwood Scl site. It follows that with clay content determined once and EC_a measured at any moisture content, soil water content could be estimated across a field. Information about water content variability across a field could be integrated into management units of similar characteristics that, in turn, could aid decision making for the type of crop and the amount of inputs needed for economically viable production.

The Mualem−Friedman model appears promising at the Heiden Clay site for moisture prediction. However, further investigation is needed at moisture levels higher than the wilting point, as observed in the dry data set. Further, model performance should be assessed for soils of light texture and stable structure similar to those at the Westwood Scl site.

In general, it was concluded that the models evaluated in this study could prove useful for real−time moisture estimation using EC_a.However, the utility of this procedure over a wider range of soil types and over various field management and moisture conditions should be determined.

REFERENCES

Akbar, M. A., A. L. Kenimer, and S. W. Searcy. 2004. Estimating soil profile depth with apparent electrical conductivity for a Texas Vertisol. *Trans. ASAE* 47(4): 1087−1092.

Bridge, B. J., J. Sabburg, K. O. Habash, J. A. R. Ball, and N. H. Hancock. 1996. The dielectric behaviour of clay soils and its application to time domain reflectometry. *Australian J. Soil Res.* 34: 825−835.

Coulombe, C. E., L. P. Wilding, and J. B. Dixon. 1996. Overview of Vertisols: Characteristics and impacts on society. *Adv. Agron.* 57: 289−375.

Fox, W. E. 1964. A study of bulk density and water in a swelling soil. *Soil Sci.* 98: 307−316.

Freund, R. J., and R. C. Littell. 1986. SAS System for Regression. SAS Series of Statistical Applications. Cary, N.C.: SAS Institute, Inc.

Gardner, H. W. 1986. Water content. In *Methods of Soil Analysis, Part 1: Physical and Minerological Methods*, 493−544. A. Klute, ed. Madison, Wisc.: ASA.

Gee, G. W., and J. W. Bauder. 1986. Particle size analysis. In *Methods of Soil Analysis, Part 1: Physical and Minerological Methods,* 383−411. A. Klute, ed. Madison, Wisc.: ASA.

Hartsock, N. J., T. G. Mueller, G. W. Thomas, R. I. Barnhisel, and K. L. Wells, and S. A. Shearer. 2000. Soil electrical conductivity variability. In *Proc. 5th International Conference on Precision Agriculture*, CD−ROM. P. C. Robert et al., eds. ASA Misc. Publ. Madison, Wisc.: ASA, CSSA, SSSA.

Montgomery, D. C., and E. A. Peck. 1982. *Introduction to Linear Regression Analysis.* New York, N.Y.: John Wiley and Sons.

Moore, S. H., M. C. Wolcott. 2001. Mapping and interpreting electrical conductivity in production fields. *Louisiana Agriculture: The Magazine of the Louisiana Agricultural Experiment Station* 44(3): 25−26.

Mualem, Y, and S. P. Friedman. 1991. Theoretical prediction of electrical conductivity in saturated and unsaturated soil. *Water Resour. Res.* 27(10): 2771−2777.

Rhoades, J. D., and D. L. Corwin. 1990. Soil electrical conductivity: Effects of soil properties and application to soil salinity appraisal. *Commun. Soil Sci. Plant Anal.* 21(11&12): 837−860

Sheets, K. R., and J. M. Hendrickx. 1995. Noninvasive soil water content measurement using electromagnetic induction. *Water Resour. Res.* 31(10): 2401−2409.

Stafford, J. V. 1988. Remote, non−contact and in−situ measurement of soil water content: A review. *J. Agric. Eng. Res.* 41(3): 151−172.

Topp, G. C., J. L. Davice, and A. P. Annan. 1980. Electromagnetic determination of soil water content: Measurement in coaxial transmission lines. *Water Resources Res.* 16(3): 574−582.

U.S. Salinity Laboratory. 1954. Diagnosis and improvement of saline and alkaline soils. Agric. Handbook No. 60. Washington, D.C.: U.S. Government Printing Office.

USDA−SCS. 1977. Soil survey of Bell County. Washington, D.C.: U.S. Government Printing Office.

Yule, D. F., and J. T. Ritchie. 1980. Soil shrinkage relationships of Texas Vertisols: I. Small cores. *SSSA J.* 44(6): 1285−1291.